DEVELOPMENT OF TECHNIQUES TO CHARACTERIZE ELECTRON BOMBARDED CHARGE COUPLED DEVICES

by

Nathan Eric Howard

Copyright © Nathan Eric Howard 2002

A Dissertation Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2002
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Nathan Eric Howard entitled Development of Techniques to Characterize Electron Bombarded Charge Coupled Devices and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Hans Roehrig
Dec 10, 2002
Date

Eustace Dereniak
Dec 10, 2002
Date

John Greivenkamp

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director, Hans Roehrig
Dec 11, 2002
Date
STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the copyright holder.

SIGNED: [Signature]

[Name]
ACKNOWLEDGEMENTS

The author would like to thank several individuals and institutions for making this dissertation possible.

Dr. Hans Roehrig – for being my major professor and assisting in the details of putting together a dissertation.

Kevin Albright at Los Alamos National Laboratories – for first introducing me to the concept of EBCCDs and early mentoring in CCD technology

Nick King and George Yates – for providing employment at LANL while I began researching EBCCDs.

Eustace Dereniak – for supporting me in my research during the early years while still at Optical Sciences Department.

Mark Wadsworth at NASA JPL – for being a source of great knowledge in CCD detector theory and application. He knows the most about CCDs than anyone else I’ve ever met.

David Gardner at Silicon Mountain Design – for providing employment during the actual research and supplying the Hamamatsu CCDs

Laura Pagano at Hamamatsu – for assisting in acquiring needed technical documents from the device manufacturers in Japan.

Rob Brown at Eglin AFB – for funding research in EBCCD technology

My parents Gene and Irma Howard – for giving me a love of learning early in life. Thanks for all you have done for me. I hope I make you proud.

Kathy Smith – for praying that I might get this dissertation done! What an encouragement.

Charlie McMullen at SMD – for programming the FPGA according to the cryptic specs given us and assisting me in getting the right clocks at the right time.

Jesus Christ – for allowing me the opportunity to live on this earth and glorify Him through scientific research.
This dissertation is dedicated to my wife, Jennifer Howard, who has encouraged me throughout the 10 years in graduate school. Without her support – I never would have finished.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF FIGURES</td>
<td>10</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>14</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>15</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>16</td>
</tr>
<tr>
<td>1.1 Overview and relevance of EBCCD intensifiers</td>
<td>16</td>
</tr>
<tr>
<td>1.2 Research accomplishments</td>
<td>18</td>
</tr>
<tr>
<td>1.3 The need for image intensification</td>
<td>21</td>
</tr>
<tr>
<td>1.4 Previous research on EBCCDs</td>
<td>23</td>
</tr>
<tr>
<td>1.4.1 Conclusion of Previous EBCCD Research</td>
<td>26</td>
</tr>
<tr>
<td>2 THEORY</td>
<td>28</td>
</tr>
<tr>
<td>2.1 Detection</td>
<td>28</td>
</tr>
<tr>
<td>2.2 Detectors</td>
<td>31</td>
</tr>
<tr>
<td>2.2.1 Photocathodes</td>
<td>31</td>
</tr>
<tr>
<td>2.2.2 Charge Coupled Devices</td>
<td>32</td>
</tr>
<tr>
<td>2.3 Gain Mechanisms</td>
<td>36</td>
</tr>
<tr>
<td>2.3.1 Phosphors and cathodoluminescence</td>
<td>36</td>
</tr>
<tr>
<td>2.3.2 Secondary electron generation using microchannel plates</td>
<td>38</td>
</tr>
<tr>
<td>2.3.3 Electron Bombarded Semiconductor (EBS)</td>
<td>41</td>
</tr>
<tr>
<td>2.4 EBCCD imaging system</td>
<td>49</td>
</tr>
<tr>
<td>2.4.1 Device construction</td>
<td>49</td>
</tr>
</tbody>
</table>
2.4.2 Predicted performance of an EBCCD tube

3 METHODS OF ANALYSIS

3.1 Mean Variance / Photon Transfer Analysis

3.1.1 Mean Variance / Photon Transfer Measurement setup

3.1.2 Photon noise theory

3.1.3 Mean Variance / Photon Transfer Calculations

3.2 Operating gain measurement

3.3 Noise related measurements

3.4 Using multi-photon PHDs to measure single photon PHD

3.4.1 Multiple photon PHD

3.4.2 Single photon PHD

3.5 Aluminum thickness and variation induced gain fluctuations

3.5.1 Aluminum thickness measured by optical means

3.5.2 Pin-defects

3.5.3 Gain variance resulting from aluminum thickness variation

3.6 EBCCD Tube MTF

3.7 Secondary Electron Capture Probability

3.7.1 Capture model basis

3.7.2 Generation of model

3.8 EBCCD Figures of Merit

3.8.1 Gain

3.8.2 Dynamic range

3.8.3 Non-Linearity

3.8.4 Signal to Noise Ratio
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8.5 Noise Figure</td>
<td>94</td>
</tr>
<tr>
<td>3.8.6 Detective Quantum Efficiency</td>
<td>95</td>
</tr>
<tr>
<td>3.8.7 Fixed pattern noise</td>
<td>95</td>
</tr>
<tr>
<td>4 RESULTS OF EBCCD CHARACTERIZATION</td>
<td>97</td>
</tr>
<tr>
<td>4.1 Non-Intensified CCD parameters</td>
<td>97</td>
</tr>
<tr>
<td>4.1.1 Tube #1 Non-intensified Measurements</td>
<td>99</td>
</tr>
<tr>
<td>4.1.2 Tube #2 Non-intensified Measurements</td>
<td>103</td>
</tr>
<tr>
<td>4.2 Intensified EBCCD Measurements</td>
<td>107</td>
</tr>
<tr>
<td>4.2.1 Operating gain v. energy for both N7220 types</td>
<td>107</td>
</tr>
<tr>
<td>4.2.2 Linearity</td>
<td>108</td>
</tr>
<tr>
<td>4.2.3 Radiometric Sensitivity</td>
<td>110</td>
</tr>
<tr>
<td>4.3 Pulse Height Distributions</td>
<td>114</td>
</tr>
<tr>
<td>4.3.1 Multiple photon PHD</td>
<td>114</td>
</tr>
<tr>
<td>4.3.2 Single photoelectron PHD extraction</td>
<td>122</td>
</tr>
<tr>
<td>4.4 Noise Related Measurements</td>
<td>128</td>
</tr>
<tr>
<td>4.4.1 Signal to Noise Ratio</td>
<td>128</td>
</tr>
<tr>
<td>4.4.2 Noise Figure</td>
<td>131</td>
</tr>
<tr>
<td>4.4.3 DQE</td>
<td>135</td>
</tr>
<tr>
<td>4.5 Al layer</td>
<td>137</td>
</tr>
<tr>
<td>4.5.1 Measurement of thickness from light penetration data</td>
<td>138</td>
</tr>
<tr>
<td>4.5.2 Number of pin-defects found and size class</td>
<td>139</td>
</tr>
<tr>
<td>4.5.3 Gain variance due to non-uniform aluminum coating</td>
<td>139</td>
</tr>
<tr>
<td>4.6 Electron capture probability</td>
<td>144</td>
</tr>
<tr>
<td>4.7 MTF</td>
<td>147</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS - continued

4.8 Pictures with EBCCD camera system ..................................................148

5 DISCUSSION .....................................................................................158

5.1 Discussion of newly developed characterization methods ...............158

5.2 Discussion of actual vs. theoretical predictions of EBCCD performance .............159

5.3 Discussion of Tradeoffs to Achieve Optimal Performance .................161

5.4 Discussion of major benefits of EBCCD tubes ....................................161

5.5 Applications of EBCCD .................................................................163

5.5.1 Tactical low-light level imaging ......................................................163

5.5.2 Law enforcement ...........................................................................163

5.5.3 High speed imaging ......................................................................163

5.5.4 Needs of commercial markets .......................................................163

5.6 Future research areas .......................................................................164

5.6.1 Better aluminum coverage ............................................................164

5.6.2 Improve electron capture probability .............................................164

6 APPENDIX A – EBCCD CAMERA .....................................................165

6.1 Camera Description ........................................................................165

6.1.1 General structure of readout electronics .......................................166

6.1.2 Camera electronics ......................................................................167

6.2 Hamamatsu EBCCD .......................................................................169

6.2.1 Tube architecture .........................................................................169

6.2.2 CCD description ...........................................................................170

7 REFERENCES ....................................................................................174
TABLE OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Diagram of a proximity focused EBCCD tube</td>
<td>16</td>
</tr>
<tr>
<td>1-2</td>
<td>Transmitted light is blurred under photocathode</td>
<td>20</td>
</tr>
<tr>
<td>1-3</td>
<td>Serially connected gain stages</td>
<td>23</td>
</tr>
<tr>
<td>2-1</td>
<td>Image of target with contrast between areas A and B</td>
<td>28</td>
</tr>
<tr>
<td>2-2</td>
<td>Quantum limited resolution vs. illumination (resolution measured in LP/MM)</td>
<td>31</td>
</tr>
<tr>
<td>2-3</td>
<td>Three phase CCD potential well</td>
<td>33</td>
</tr>
<tr>
<td>2-4</td>
<td>Potential distribution in CCD</td>
<td>34</td>
</tr>
<tr>
<td>2-5</td>
<td>Phosphor energy band diagram</td>
<td>37</td>
</tr>
<tr>
<td>2-6</td>
<td>Single channel of an MCP</td>
<td>38</td>
</tr>
<tr>
<td>2-7</td>
<td>Channel tilt within MCP</td>
<td>39</td>
</tr>
<tr>
<td>2-8</td>
<td>Device schematic of Gen II type image intensifier</td>
<td>39</td>
</tr>
<tr>
<td>2-9</td>
<td>PHD vs. gain for MCPs</td>
<td>40</td>
</tr>
<tr>
<td>2-10</td>
<td>Normalized dE/dx loss function</td>
<td>46</td>
</tr>
<tr>
<td>2-11</td>
<td>X-ray generation efficiency vs. energy</td>
<td>48</td>
</tr>
<tr>
<td>2-12</td>
<td>CCD mounting on ceramic header with flip-chip attachment</td>
<td>50</td>
</tr>
<tr>
<td>2-13</td>
<td>Radial emission of proximity focused photodiode</td>
<td>51</td>
</tr>
<tr>
<td>2-14</td>
<td>EBCCD imaging system diagram</td>
<td>52</td>
</tr>
<tr>
<td>2-15</td>
<td>Predicted EBCCD gain vs. applied voltage</td>
<td>54</td>
</tr>
<tr>
<td>2-16</td>
<td>Noise associated with electron capture of a Fano limited secondary distribution</td>
<td>55</td>
</tr>
<tr>
<td>2-17</td>
<td>System noise diagram</td>
<td>56</td>
</tr>
<tr>
<td>2-18</td>
<td>Plot of magnitude of noise sources in a EBCCD</td>
<td>57</td>
</tr>
<tr>
<td>2-19</td>
<td>Theoretical signal to noise ratio vs. incident photons at a EBS gain of 1100</td>
<td>58</td>
</tr>
<tr>
<td>2-20</td>
<td>Theoretical noise figure vs. incident photons at a EBS gain of 1100</td>
<td>58</td>
</tr>
<tr>
<td>3-1</td>
<td>Photon transfer setup</td>
<td>62</td>
</tr>
<tr>
<td>3-2</td>
<td>Photon transfer curve</td>
<td>66</td>
</tr>
<tr>
<td>3-3</td>
<td>Hamamatsu factory gain measurement method diagram</td>
<td>71</td>
</tr>
<tr>
<td>3-4</td>
<td>Current flow diagram for factory measurement of input current</td>
<td>72</td>
</tr>
</tbody>
</table>
FIGURE 4-23 PHD AT 5.93 kV ................................................................. 119
FIGURE 4-24 MEAN AND VARIANCE OF PHD AT 5.93 kV ......................... 119
FIGURE 4-25 PHD AT 6.9 kV .................................................................. 120
FIGURE 4-26 MEAN AND VARIANCE OF PHD AT 6.9 kV ......................... 120
FIGURE 4-27 PHD AT 8.00 kV ................................................................. 121
FIGURE 4-28 MEAN AND VARIANCE OF PHD AT ENERGY 8kV ................... 121
FIGURE 4-29 GRAPH OF STANDARD DEVIATION OF GAIN VARIANCE FOR TUBE #1 ......................................................... 123
FIGURE 4-30 SINGLE ELECTRON DETECTION CAPABILITY FOR TUBE #1 ................................................................. 124
FIGURE 4-31 GRAPH OF STANDARD DEVIATION OF GAIN VARIANCE FOR TUBE #2 ......................................................... 125
FIGURE 4-32 SINGLE ELECTRON DETECTION CAPABILITY FOR TUBE #2 ................................................................. 126
FIGURE 4-33 GAUSSIAN ESTIMATIONS OF SINGLE PHOTOELECTRONS PHD FOR TUBE 1 ......................................................... 127
FIGURE 4-34 GAUSSIAN ESTIMATIONS OF SINGLE PHOTOELECTRONS PHD FOR TUBE 2 ......................................................... 128
FIGURE 4-35 SNR COMPUTED AT 3.98 kV FOR TUBE #2 .............................. 129
FIGURE 4-36 SNR COMPUTED AT 4.99 kV FOR TUBE #2 .............................. 129
FIGURE 4-37 SNR COMPUTED AT 6.75 kV FOR TUBE #2 .............................. 130
FIGURE 4-38 SNR COMPUTED AT 8.00 kV FOR TUBE #2 .............................. 130
FIGURE 4-39 NOISE FIGURE PLOT VS. ACCELERATING VOLTAGE FOR TUBE #1 ......................................................... 132
FIGURE 4-40 NOISE FIGURE VS. OPERATING GAIN FOR TUBE #1 ..................... 132
FIGURE 4-41 NOISE FIGURE PLOT VS. ACCELERATING VOLTAGE FOR TUBE #2 ......................................................... 134
FIGURE 4-42 NOISE FIGURE VS. OPERATING GAIN FOR TUBE #2 ..................... 134
FIGURE 4-43 DQE VS. ACCELERATING VOLTAGE FOR TUBE #1 ..................... 135
FIGURE 4-44 DQE VS. OPERATING GAIN FOR TUBE #1 ..................... 135
FIGURE 4-45 DQE VS. ACCELERATING VOLTAGE FOR TUBE #2 ..................... 136
FIGURE 4-46 DQE PLOTTED VS. OPERATING GAIN FOR TUBE #2 ..................... 136
FIGURE 4-47 PICTURE OF PIN-DEFECTS IN TUBE #2 ................................ 137
FIGURE 4-48 PROBABILITY DISTRIBUTION OF PIN-DEFECT ADU VALUES ......................... 140
FIGURE 4-49 PLOT OF ALUMINUM THICKNESS VS. LIGHT LEVEL (ADU) ................. 140
FIGURE 4-50 DISTRIBUTION FUNCTION OF LIGHT LEVELS ABOVE THRESHOLD (PIN-DEFECTS) ................................. 141
FIGURE 4-51 NORMALIZED DISTRIBUTION FUNCTION OF THICKNESS OF PIN-DEFECTS ......................... 142
FIGURE 4-52 PIN-DEFECT THICKNESS DISTRIBUTION AND RETAINED ENERGY FOR DIFFERENT AL THICKNESS ......................................................................................... 142
FIGURE 4-53 ENERGY LOST IN ALUMINUM BETWEEN 97 NM AND 127 NM VS. BEAM ENERGY ................................. 143
LIST OF TABLES

TABLE 1 Light Levels .................................................................................................................. 22
TABLE 2 Estimated accuracies of measurements related to mean variance test .... 77
TABLE 3 Photon transfer data format ......................................................................................... 78
TABLE 4 Acquisition matrix for multi-photon PHD measurement ............................................ 82
TABLE 5 Measured values of EBCCD Figures of Merit ............................................................... 97
TABLE 6 Noise figures for Tube #1 ............................................................................................ 131
TABLE 7 Noise figures for Tube #2 ............................................................................................ 133
TABLE 8 Aluminum defect number and size class ................................................................. 139
ABSTRACT

Electron Bombarded Charge Coupled Devices (EBCCDs) are a new hybrid image intensifier tube device that allows photoelectrons to be directly detected by a CCD placed as the tube anode. These devices have many significant advantages over traditional image intensified systems, due to their lower noise figure, high intra-scene dynamic range, and high signal to noise ratio. EBCCDs are not subject to some of the deleterious effects that plague traditional intensifiers including veiling glare, “chicken wire” patterns, and ion scintillation. Currently, there is not a standardized set of characterization methods used to measure the performance of these hybrid devices. Furthermore, the normal method of measuring device gain as a ratio of output current (measured as current through the anode substrate) to input current (as measured through the photocathode) does not apply to EBCCDs. This dissertation presents several new methods that have been developed to characterize in situ EBCCD tubes. The new characterization methods that have been developed are:

- How to measure the actual gain of an EBCCD when operated as a CCD (normal operating mode)
- How to measure the mean and variance of a single electron pulse height distribution when only multiple electron pulse height distribution data is available
- How to measure the spatially varying probability of secondary electron capture by the CCD potential wells
- How to measure the thickness of an aluminum overcoat using only optical measurements
- How to measure the gain variation due to aluminum thickness variations

These methods have been designed to enable characterization of the EBCCD even after it has been mounted in a camera. This will allow both tube and camera manufacturers to measure performance in a production setting.

These new methods were employed, along with other standard measurement techniques, to characterize a commercially available EBCCD (Hamamatsu N7220) controlled by a camera designed by the author. Several figures of merit were measured as a function of accelerating potential including the gain, device signal to noise ratio, detective quantum efficiency, and noise figure. The tube MTF, radiometric sensitivity, aluminum thickness, dynamic range, and probability of secondary electron detection were also measured.
1 Introduction

1.1 Overview and relevance of EBCCD intensifiers

This dissertation is about characterizing a new class of image intensifiers known as Electron Bombarded CCDs (EBCCDs). These devices are quite unique, compared to the traditional microchannel plate and phosphor readout based Gen II and III intensifiers, in that they combine the intensification stage with an electronic signal generating CCD in the same device. Operational EBCCD devices have been reported for almost 25 years; however, these devices have been laboratory devices – not commercially viable intensifiers. Only recently has the combination of CCD thinning techniques, flip-chip bonding, and processing techniques developed to the point where commercially viable EBCCD imagers can be manufactured. Furthermore, with the increasing need for detectors that have quantum-limited spatial resolution and single photon detection capability, along with high dynamic range, EBCCDs have recently received a considerable amount of attention by the military and medical communities.

EBCCDs operate by placing the silicon CCD inside the vacuum tube and directly detecting electrons emitted by a photocathode. Figure 1-1 shows the salient features of a proximity focused EBCCD. There is only one energy conversion, from photons to electrons, which occurs at the photocathode. A voltage bias between the photocathode and the CCD (anode) accelerates the photoelectrons toward the CCD. These energetic primary electrons create tens to hundreds of secondary electrons when they are absorbed by the silicon CCD – these secondary electrons are simply captured by the CCD potential well and read out in a normal CCD fashion. This single energy conversion is in contrast to the three energy conversions present in
traditional image intensifiers, where photons create photoelectrons at the photocathode, which are then multiplied in an MCP, converted back to photons at the phosphor, which are then converted into electrons when they are detected by the imaging CCD. Often, a thin layer of aluminum is placed over the back surface of the CCD to block light that is transmitted by the photocathode. This prevents an out of focus optical image from decreasing the contrast of the image formed by the photoelectrons.

Traditional intensifiers have higher gains than EBCCDs—but high gains are not always desirable. By nature of their low—but sufficient—gain, EBCCDs can detect single photons and still retain a very large dynamic range, so that brighter areas can still be detected without exceeding the maximum input signal level (set by the full well capacity of the CCD). In order for a Gen II/III tube based imaging system to detect single photons, the tube must be operated at such a high gain that a single photon will produce sufficient output current to saturate the output phosphor—limiting the tube to a very small dynamic range (basically bright and dark). EBCCDs on the other hand can detect single photons at a relatively low gain. When the gain is set so that it is sufficient to overcome the system noise, the tube can detect hundreds to thousands of photons in one pixel, while detecting single photons in another (a large intra-scene dynamic range). In addition, “Gen I/II/III” series of intensifiers are direct view devices—which must be coupled to an optical detector in order to generate an electronic signal for analysis or transmission. This cascading of systems places even further restrictions on the various figures of merit (MTF, SNR, Dynamic Range, etc.). In contrast, the EBCCD device combines the photon detection, signal amplification, and electronic signal generation into one device (EBCCDs must employ a separate display unit if they are to be used as direct view devices).

Furthermore, due to only one energy conversion from photons to electrons, the overall efficiency is can be greater than that found in Gen II and III based intensified CCD cameras. Since the Detective Quantum Efficiency (DQE) is proportional to the inverse square of the noise figure, lower noise figures indicate higher DQE values for a given photocathode quantum efficiency. The EBCCD measured in this dissertation achieved a noise factor of 1.2, much less than traditional intensified CCD cameras. Due to the hybrid mode of operation, some of the traditional methods of characterizing the relevant figures of merit for low-light level imagers do not apply, and specialized methods of characterization need to be developed.
This dissertation discusses the development of such characterization methods and the application of these methods will be demonstrated by characterizing two EBCCD tubes produced by Hamamatsu. The first section will discuss the motivation of this research, why image intensifiers are used, and previous research on EBCCDs. The second section addresses the theoretical basis for resolution limitations under low light conditions, various gain generation mechanisms, basic principles of Charge Coupled Devices, and the theoretical basis of EBCCDs. Following this, the third section will present the newly developed techniques and algorithms specifically designed for characterizing in situ EBCCD intensifiers. The fourth section presents the results of characterizing an actual EBCCD, and salient features of the results. The fifth and final section will summarize the results and discuss the relationships between the presented results, how it compares to the “ideal” EBCCD imager mentioned in section two, and proposes several areas for future research and possible performance enhancements, based upon findings. Appendix A addresses the electronic design behind the camera used to make the measurements.

Traditional image intensifiers have received billions of research dollars over the past 30 to 40 years in an effort to improve the efficiency, performance, manufacturing yield, etc. EBCCDs are still in a developmental “infancy” stage, and as a result, there is still a lot of room for improvement between the current state of the art, and the theoretical limits of device operation. It is hoped that this dissertation will serve future researchers in understanding the device physics and system parameters to future EBCCD devices.

1.2 Research accomplishments

There is not a set of recognized set of “standard procedures” used to characterize EBCCDs. Since the device is a hybrid between photocathode / tube and solid-state CCD technology, methods that simply analyze one aspect (either the tube or solid-state aspects) do not fully characterize this hybrid device. In order to advance the state of the art in EBCCD characterization and performance testing, several new methods have been developed, all of which allow the EBCCD tube to be tested even after it has been mounted in a camera. In this way, no special equipment is needed, other than what would be found at most camera production facilities (such as an integrating sphere, controlled light source, and calibrated radiometer). The five newly developed methods for in situ EBCCD tube characterization include:
1. How to measure the actual gain of an EBCCD when operated as a CCD (normal operating mode)

2. How to measure the mean and variance of a single electron pulse height distribution when only multiple electron pulse height distribution data is available

3. How to measure the spatially varying probability of secondary electron capture by the CCD potential wells

4. How to measure the thickness of an aluminum overcoat using only optical measurements

5. How to measure the gain variation due to aluminum thickness variations

The first developed method, which details an improved gain measurement method, is a significant improvement over the standard technique of biasing the CCD as a photodiode and measuring the ratio of output current through the CCD substrate to the input current through the photocathode. Since the CCD is biased as a photodiode, almost all of the secondary electrons generated will be detected as substrate current. However, only a fraction of the secondary electrons are able to diffuse from the back surface to the front of the CCD where the potential wells exist (assuming a nominal CCD substrate thickness of 15 μm). An EBCCD operating in a "normal CCD" fashion would not collect all of the secondary electrons. Thus, the "ratio of currents" method is not truly measuring the realizable gain.

Measuring the Pulse Height Distributions (PHDs) can be a powerful way of characterizing detectors that can detect discrete quanta, such as photons. EBCCDs are capable of detecting single photoelectrons, however, in order to maximize the dynamic range of a particular device, the maximum operating gain may be chosen so that the single photoelectron pulse height distribution cannot be directly measured. The single photoelectron PHD may be below the system noise, as in the case of the EBCCD measured in this dissertation. The second developed method allows the mean and variance of a single photoelectron PHD to be measured from information gained from multiple photoelectron PHDs, which can easily be acquired.

As was discussed earlier, only a fraction of the secondary electrons generated from an incident primary electron are actually captured by the CCD potential well and read out through the output amplifier. Since the primary electrons are absorbed within the first micron of silicon
(for primary electron energies under 10 keV), the secondary electrons must diffuse across many microns (10-20 microns for a backside thinned CCD) in order to be captured. Thus, it is desirable from a detection point of view to make the CCD as thin as possible, however such a thin CCD would be extremely fragile – necessitating some reasonable thickness. Optimizing these constraints can be furthered by understanding what the spatially varying probability of detection is for a given CCD. Thus, the third developed method permits a measurement of this probability, helping engineers and researchers design better EBCCD devices.

Photocathodes transmit approximately 50% of the incident light. If an imaging lens is arranged so that the image of the object is formed at the surface of the photocathode, the light that is transmitted will form a blur on the CCD directly beneath the photocathode, as diagrammed in figure 1-2.

![Diagram showing transmitted light blurred under photocathode](image)

**Figure 1-2 Transmitted light is blurred under photocathode**

Since CCDs are also sensitive to light, the signal generated by the photons illuminating the CCD would cause a substantial reduction in the detected image contrast. To prevent light from being absorbed by the CCD, a thin layer of aluminum is often placed over the back surface of the CCD. The thickness of the aluminum layer is critical – it must be thick enough to block visible light photons, but thin enough so that the accelerated photoelectrons can still penetrate it. The fourth developed method allows an “all optical” means of measuring the thickness of the aluminum.

Any variation of the aluminum thickness over the surface of the CCD will cause a variation in the number of secondary electrons generated (tube gain), since more of the of incident primary electron energy will be deposited into the silicon (see section 3.5 for further
explanation). The fifth developed method permits the aluminum thickness variation induced component of the gain noise to be measured.

These methods were carried out by characterizing a commercially available EBCCD (Hamamatsu N7220). Most of the data is derived from the mean-variance test, which is discussed in section 3.1. Section 4 of this dissertation presents the results of measuring the following parameters:

1. Non-intensified Linearity / Camera response
2. Camera conversion gain
3. Full well capacity
4. Read noise
5. Fixed pattern noise
6. Dynamic range
7. Operating gain vs. accelerating voltage
8. Intensified linearity
9. Intensified radiometric sensitivity
10. Multiple photoelectron pulse height distributions vs. accelerating voltage
11. Statistics of single photoelectron pulse height distributions vs. accelerating voltage
12. Signal to Noise ratio at varying light levels vs. accelerating voltage
13. Camera Noise Figure vs. accelerating voltage
14. Detective quantum efficiency vs. accelerating voltage
15. Nominal thickness of aluminum layer
16. Amount of variation of aluminum thickness
17. Relative sizes of aluminum thickness variations
18. Induced gain noise due to aluminum thickness variation
19. Probability of detection of secondary electrons by the CCD potential wells
20. Device MTF

1.3 The need for image intensification

The primary means by which man perceives the world around him is by the sense of sight. In terms of information rate, sight is by far the preferred method of detecting the status of his environment. Typical light levels are shown in Table 1. However, when the sun goes down, he loses this method of perception for all but the largest objects. As the scene illumination
decreases, the ability to resolve objects decreases to the point that it is impossible to see the proverbial "hand in front of one's face". The human eye is actually quite sensitive to light, however, it can take over 30 minutes for it to adapt to low light situations. It is often necessary to "see" in low light situations when there is insufficient time to allow the eye to "dark adapt".

The fundamental limit to resolution is determined by the quantum nature of light. This statistical fluctuation in the light level reduces the ability to resolve objects as the light level decreases. "Quantum limited spatial resolution" is a term expressing the limitation of resolution ability due to the statistical fluctuations of the light quanta. Tactical military applications generally require the use of night vision intensifiers at light levels below about 0.1 lux, as referenced in table 1.

**Table 1 Light Levels**

<table>
<thead>
<tr>
<th>Sky Observation</th>
<th>Illuminations in lux</th>
<th>Typical Imaging Device Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overcast starlight</td>
<td>$10^4$</td>
<td>Intensifier</td>
</tr>
<tr>
<td>Starlight</td>
<td>$10^3$</td>
<td>Intensifier</td>
</tr>
<tr>
<td>Quarter Moon</td>
<td>$10^2$</td>
<td>Intensifier</td>
</tr>
<tr>
<td>Full Moon</td>
<td>1</td>
<td>Sensitive CCD camera</td>
</tr>
<tr>
<td>Deep twilight</td>
<td>1</td>
<td>Sensitive CCD camera</td>
</tr>
<tr>
<td>Twilight</td>
<td>10</td>
<td>CCD camera</td>
</tr>
<tr>
<td>Very dark day</td>
<td>$10^2$</td>
<td>CCD camera</td>
</tr>
<tr>
<td>Overcast day</td>
<td>$10^3$</td>
<td>CCD camera</td>
</tr>
<tr>
<td>Daylight</td>
<td>$10^4$</td>
<td>CCD camera</td>
</tr>
<tr>
<td>Direct sunlight</td>
<td>$10^5$</td>
<td>CCD camera</td>
</tr>
</tbody>
</table>

In an effort to be able to detect objects even in dark situations, considerable effort has gone into developing devices that have greater detection efficiency and lower noise than the human eye. During the 1930's the photocathode was developed, which for the first time enabled man to construct a device that could detect an image electronically - and with greater efficiency than the eye. Photocathodes served as the primary two-dimensional imaging detector until about 1970 when the Charge Coupled Device (CCD) was invented. Since then, CCDs have surpassed the performance of photocathodes in most areas of imaging - except low-light level imaging, because CCDs have no means of internal gain at visible wavelengths. CCDs can only be
"amplified" by placing an electronic high gain amplifier at the output of the CCD. This "amplification" however amplifies all noise sources inherent to the CCD including dark current, read noise, and the fundamental photon fluctuation. Furthermore, CCDs have a higher dark current than photocathodes. It is for these reasons that photocathode based detectors (including EBCCDs) remain the photon detector of choice for low-light level imaging, particularly for the light levels occurring at the quarter moon and darker levels as seen in Table 1.

Consider figure 1-3 where a series of gain stages are arranged in serial fashion, each having an associated gain $G_i$ and noise $\sigma_i$.

![Figure 1-3 Serially connected gain stages](image)

The composite gain ($G_i$) and variance ($\sigma_i^2$) of the gain system can be calculated as:

$$G_i = G_1G_2G_3...G_n$$

$$(1.1)$$

$$\sigma_i^2 = \sigma_1^2G_2^2\sigma_3^2...G_n^2 + G_1\sigma_2^2G_3^2...G_n^2 + G_1G_2\sigma_3^2...G_n^2 + ...$$

The largest gain is placed as close to stage 1 as possible in order to minimize the total amount of cascaded noise. Intensifiers (gain stages) are used in low-light imaging systems because they provide a large gain stage prior to the introduction of many noise sources. These equations are important because EBCCDs themselves are composed of multiple gain stages that will need to be taken into account during modeling and performance characterization.

There are two types of image intensifier systems: those that are intended for direct viewing by a human observer, and those that generate an electronic signal for direct acquisition by a computer or remote display for a human observer. The EBCCD is a signal generating tube, as there is no re-conversion of the amplified electronic signal back to an optical signal.

### 1.4 Previous research on EBCCDs

Several researchers have been instrumental in furthering EBCCD technology. During the past 20 years, EBCCDs have been built and several properties measured, and these have served as
building blocks in the technology advances that are now incorporated in a new generation of EBCCD tubes. The following list is a synopsis of the research performed by several key researchers.

**JC Richard**

Richard, Bergonzi, Lemonier were researchers at Philips Laboratories in France and constructed a prototype EBCCD image tube. The tube used a Philips NXA 1011FT 604x288 thinned CCD and an S-25 photocathode. The devices were thinned between 10 μm and 15 μm, and were sealed by encasing the CCD (leaving the backside open) in glass. The glass cylinder, containing the CCD, was then placed in the backside of an existing image tube. They measured the tube gain at values ranging from 150 at 6 kV, 650 at 10 kV, to 2000 at 15 kV accelerating voltages. Richard, et.al, were able to measure single photoelectron pulse height distributions at 15 kV and 20 kV. They also measured the dark current generation as a function of illumination and time, with the dark current raising to 47% of full well (150,000 electrons) after \(10^4\) lux illumination at the photocathode for 10,000 hours at 14 kV accelerating voltage. This device never became a commercial product for Philips for unknown reasons.

**Williams**

Williams, et.al., were recent researchers who fabricated an EBCCD and attempted to market it as a commercial product. The team was composed of engineers at the SiTe corporation (which used to be the Solid-State Division of Tektronix), who made the CCDs, and a group from Intevac EO Sensors, who manufactures image tubes. Together, they built an EBCCD tube using a SiTe 502AB CCD, but the device did not work for more than about 2 weeks due to leakage problems. The majority of the results presented by Williams was derived by using a Hitachi SEM to generate the electrons. The team measured the gain vs. voltage along with the Contrast Transfer Function to characterize the spatial resolution. While the EBCCD device was operational, the CTF was measured and showed marked improvement over standard backside illuminated CCD, with both devices operating at 16 ms integration time and a scene irradiance of \(6.6 \times 10^7\) footcandles on the faceplate.

**Dalienko**

Dalienko, et.al, studied single stage "Gen I" type EBCCD image tubes with 18mm S-20 type photocathodes. Two different CCD pixel formats were studied, 532x290 and 780x290, and the spatial resolution as a function of faceplate illumination was measured. The larger array had a
CCD floating diffusion sensitivity of 2.5 μV/e⁻. The resolution for the larger array was measured to be 580 TV lines at 5 x 10⁻⁴ lux with a threshold sensitivity of 5 x 10⁻⁵ lux.

**Ravel & Reinheimer**

Ravel and Reinheimer, who worked for the SiTe corporation studied the electron bombarded gains of CCDs when exposed to energetic electrons. They measured their device’s tube gains ranging from 50 at 1kV acceleration to gains greater than 1600 at 10 kV accelerating voltages. Due to their limited electronics, they were unable to measure the single electron pulse height distribution. The CCD was manufactured by SiTe and featured 24 μm x 24μm pixels in a 532 x 64 array. At a readout rate of 7 MHz, a read noise of 300 was measured. Two different substrate thicknesses were used (16 μm and 26 μm) to study the effects of different thicknesses of the field free region (see section 2.2.2.2 for further discussion). A Cambridge Model SEM 250 Scanning Electron Microscope was used as the electron source. This SEM was capable of generating variable accelerating voltages, and could focus electrons in a small spot so that the user could scan the beam across the CCD. Ravel and Reinheimer used a SiLi detector to measure the X-ray generation as a function of accelerating voltage. Due to the large uncertainties in acceptance solid angle, and detector efficiency, their X-ray generation data was only accurate to a factor of 2.

**Stearns & Wiedwald**

Stearns and Wiedwald measured the response of CCDs to direct electron bombardment. They used three different CCDs: RCA SID501, Tektronix TK512M, and TI4849. Each CCD was placed in a Princeton Scientific Gen V camera, which provided the driving electronics, and was bombarded by electrons generated from a Scanning Electron Microscope. The detection efficiency of the CCDs was measured as a function of incident electron energy. Their analysis was based on measuring the ratio of detected current to the input current. By scanning the beam across the CCD, a line-spread response was measured and the spatial resolution calculated from the results. They observed that charge spreading does not significantly affect the spatial resolution when the pixel size is 30 μm x 30 μm.

**Daud**

Daud et.al. working at the NASA Jet Propulsion Laboratories used a Scanning Electron Microscope (SEM) to illuminate a backside thinned CCD with electrons. Their paper presents a
nice review of the theoretical basis and report on the EBS gain measured with and without backside treatment.

Suyama

Suyama, et.al., design engineers at Hamamatsu, wrote a paper on the N7220 EBCCD tube developed by Hamamatsu in 1997. This paper serves to state the present state of the art in EBCCD imagers. This paper gives a brief overview of the accomplishments and the preliminary performance characteristics of this device. They quoted a gain of 600 at 8 kV bias, and a linear dead layer voltage of 4.7 kV. The tube gain was measured using a current measurement ratio technique (discussed later in this document). The EBCCD was cooled to −20 C and the output rate was 150 kpixels/sec. The spatial resolution was measured to be 50% at 8 lp/mm, 20% at 14 lp/mm and 10% at 18 lp/mm. This is the same device that the author used for the measurements presented in this dissertation.

1.4.1 Conclusion of Previous EBCCD Research

The current state of the art in EBCCD characterization primarily revolves around the measurement of the “gain”. All researchers have measured the “gain” of their tubes and some have investigated other parameters as well. Each researcher has contributed in some manner to the methods used to characterize EBCCDs. Steams and Wiedwald investigated measuring the probability of detection of secondary electrons. Ravel has characterized the x-ray generation rates from electron bombardment. Richard has measured single electron pulse height distributions at very high accelerating voltages. Suyama measured the MTF for a specific EBCCD.

The author of this dissertation has no disagreement with the methods and results presented by the previous researchers, except for their methods of measuring “gain” and its interpretation. All of the previous researchers biased the CCD as a large diode during gain measurement. While this does measure the EBS gain, the final user of an intensified detector is only interested in the actual gain generated by the intensifier. The actual gain that is generated by the intensifier is the number of output electrons generated – when the EBCCD is operating in a clocked CCD fashion – per input photoelectron. The author of this dissertation believes that while the intensifier production community is well meaning in their characterization of EBCCDs, such a current ratio measurement is not an accurate measure of the realizable gain.
This dissertation details for the first time the methods that can be used to characterize an in situ EBCCD tube's gain operating in the CCD mode – instead of the inaccurate method of using photodiode current ratios.
2 Theory

2.1 Detection

At some point in the detection process, there is an observer. More than likely, this observer is a human. Whether the scene is seen with a "direct view" intensifier, or an image of the scene taken with an intensified video camera and displayed on a viewing monitor, the human is the final interpreter of the scene. With the advent of sophisticated machine vision algorithms, computers are replacing humans as the final observer, but only in well-controlled environments. Albert Rose studied the requirements for a human observer to detect, classify, and recognize different types of objects based upon the amount of spatial resolution that the human observer is permitted to detect.

We shall now derive an expression that relates the ability of an optical system to resolve a target as a function of the amount of light coming from that target.

![Diagram of image formation](image.png)

Figure 2-1 Image of Target with contrast between areas A and B

The ability to discern objects becomes increasingly difficult as scene illumination decreases. Consider figure 2-1 where a scene, containing areas “a” and the surrounding elements “b”, is imaged by an imaging system with magnification m. The image of each of the areas “a” and “b” (labeled A and B respectively) have linear dimension of d and area d², and that an average of $N_{p,A}$ and $N_{p,B}$ photons are detected by the detector. We can define the contrast C between the two different areas as:
Since the photon exitance is described by Poisson statistics, we note that the variances 

\( \sigma_{p,A}^2 \) and \( \sigma_{p,B}^2 \) are equal to the means,

\[
\sigma_{p,A}^2 = N_{p,A} \quad \text{and} \quad \sigma_{p,B}^2 = N_{p,B}
\]

and hence

\[
\sigma_{p,A} = \sqrt{N_{p,A}} \quad \text{and} \quad \sigma_{p,B} = \sqrt{N_{p,B}}
\]

We shall assume that \( N_{p,A} \) and \( N_{p,B} \) are similar in magnitude such that the variances are similar, and thus:

\[
\sqrt{\sigma_{p,A}^2 + \sigma_{p,B}^2} = \sqrt{2}\sigma_{p,A}
\]

In order to detect the contrast difference, there must be difference between the means of the A and B regions, and this "signal" must be greater than the noise by some factor \( k \) as:

\[
N_{p,A} - N_{p,B} = k\sqrt{2}\sigma_{p,A}
\]

We can then find an expression for the minimum number of photons required to resolve the scene contrast for a given threshold signal to noise ratio as in eq. 2.6.

\[
C = \frac{k\sqrt{2N_{p,A}}}{N_{p,A}} \quad \Rightarrow \quad N_{p,A} = \frac{2k^2}{C^2}
\]

If we assume that the object being imaged is a Lambertian surface, we can estimate the detector irradiance by:

\[
E_{\text{detector}} = \frac{\pi L_{\text{scene}}}{4(F/\#)^2} = \frac{M_{\text{scene}}}{4(F/\#)^2} = \frac{\rho E_{\mathrm{scene}}}{4(F/\#)^2}
\]

where \( E_{\text{detector}} \) is the irradiance on the detector, \( L_{\text{scene}} \) is the irradiance of the scene, \( M_{\text{scene}} \) is the exitance of the object, \( \rho \) is the object reflectivity, \( E_{\text{scene}} \) is the scene irradiance in photons per second per area illuminated by another light source, and \( F/\# \) is the effective f-number of the imaging lens. Equation 2.7 is not valid for a self-luminous object. Thus, the irradiance on the
detector is given in units of photons per unit area per unit time. We can recast eq. 2.7 in terms of
the number of detected photons.

$$\eta_{det}E_{detector} = \frac{\eta_{det}\rho E_{scene}}{4(F/\#)^2} = \frac{N_{R,A}}{d^2t} = \frac{2k^2}{C^2d^2t}$$  \hspace{1cm} (2.8)

where \(t\) is the integration time. If we solve for \(d^2\), which is the area of the image of
object A, we see that:

$$d^2 = \frac{k^28(F/\#)^2}{C^2\eta_{det}\rho E_{scene}t}$$  \hspace{1cm} (2.9)

so that the linear dimension \(d\) (in terms of the other quantities) becomes:

$$d = \frac{k(F/\#)}{C} \sqrt{\frac{8}{\eta_{det}\rho E_{scene}t}}$$  \hspace{1cm} (2.10)

Defining the maximum resolution frequency on the detector, \(f_{max}\), according to the
Nyquist frequency, \(1/2d\), we see that:

$$f_{max} = \frac{C}{4k(F/\#)} \sqrt{\frac{\eta_{det}\rho E_{scene}t}{2}}$$  \hspace{1cm} (2.11)

Equation 2.11 is plotted in figure 2.2.
where $C$ was chosen to be 100% (maximum contrast), $k=3$ (based upon an acceptable false positive rate), $F/# = 1.4$, $\rho = 1$, and $t = 1$ sec. It is important to note that this is the physical limit that can be achieved at low light levels – limited by the quantum nature of the light itself (hence the term quantum limited spatial resolution). Thus, to increase the resolution of an optical system, according to eq. 2.11, for a given scene contrast and illumination, we have the ability to change the following parameters:

- detection threshold
- integration time
- effective $F$-number of optical system
- spectral quantum efficiency of detector

It is important to note that these are the only parameters we may manipulate in order to obtain higher resolution images at low light levels. At this point, imaging optics are limited to about $F/1$ while still providing "decent" resolution. Thus in order to detect and resolve objects at low light levels (such as below .1 lux), it is usually necessary to employ some method of intensification to be able to detect and register as many photons incident upon the detector as possible.

### 2.2 Detectors

Since this dissertation is about a new type of detector, we will discuss the dominant methods of detecting visible optical radiation – namely photocathodes and CCDs, both of which are present in EBCCD tubes. Detectors serve to convert an incoming signal into another, more convenient form. An exhaustive treatment of different types of optical detectors is beyond the scope of this dissertation, but the reader is directed to Dereniak\textsuperscript{12}, Boyd\textsuperscript{13}, and Wolfe\textsuperscript{14} for further study.

#### 2.2.1 Photocathodes

While higher quantum efficiencies and wider spectral ranges can be achieved using photoconductive and photovoltaic detectors\textsuperscript{15}, it is very difficult to achieve a high signal to noise ratio at low signal levels. This is primarily due to the difficulty of these detectors to possess both extremely low dark current with an internal mechanism for low-noise amplification. With the
advent of Avalanche Photodiodes (APDs), this technology has come closer to the ideal, but even APDs have fairly high noise factors (from 2 to 10, increasing exponentially with gain\textsuperscript{16}. To date, no detector has been able to combine extremely low dark current and quantum efficiency better than the photocathode.

Photocathode operation is based on the photoemission of electrons. In the case of metallic photocathodes, atoms may emit an electron from the surface into a vacuum provided that the atom absorbed a photon with sufficient energy to overcome the work function of the metal. For semiconductor-based photocathodes (such as GaAs), the emission may be considered a three-step process\textsuperscript{17}. First, valence band electrons are elevated into the conduction band upon the absorption of a photon. Second, these electrons are transported across the thickness of the semiconductor. Third, the electrons escape into the vacuum after overcoming the surface energy barrier.

Photoemission occurs only if the absorbed photon energy $E_{\text{photon}}$ is greater than the work function $\phi_0$ of the semiconductor - vacuum system given by:

$$\phi_0 = E_A + E_G$$

(2.12)

where $E_A$ is the electron affinity and $E_G$ is the semiconductor bandgap energy. In the case of metallic photocathodes, such as the multi-alkali photocathode found in most Gen II type tubes, the work function $\phi_0$ is simply the energy difference between the Fermi level and the vacuum level. Any excess energy may be imparted to kinetic energy ($E_{\text{kinetic}}$) of the emitted photoelectron:

$$E_{\text{kinetic}} = E_{\text{photon}} - (E_A + E_G)$$

(2.13)

Multi-alkali photocathodes (such as the S-20 type (Na$_2$K$_3$Sb)Cs) are themselves semiconductors composed of metal alloys and have an effective electron affinity on the order of 0.4 eV, even though the actual surface electron affinity is closer to 1.4 eV. This great reduction is due to the presence of a positively charged surface region, caused by the filling of the acceptor levels by a cesium layer at the surface.

2.2.2 Charge Coupled Devices

The Charge Coupled Device (CCD) was developed by Boyle and Smith\textsuperscript{18} in 1970. Since their inception, CCDs have virtually replaced imaging tubes for all applications requiring video
signal generation. Their low lag, high linearity, all solid-state construction marks CCDs as the dominant imaging detector. It is assumed that the reader is familiar with the basic operation of CCDs, and is referred to Theuwissen if not.

2.2.2.1 CCD potential creation

A complete treatise of CCD theory is beyond the scope of this dissertation, however, some explanation is given to the relevant topics that effect the operation, modeling, and design of EBCCD devices. Consider the n-channel MOS CCD structure as seen in figure 2-3:

![Figure 2-3 Three phase CCD potential well](image)

The poly-Silicon gate structures and the substrate form a capacitor capable of holding charge when a potential difference exists between them. The potential (V) within the CCD can be calculated by employing Poisson's equation,

\[ \nabla^2 V = -\frac{\rho}{k_e \varepsilon_0} \tag{2.14} \]

Where \( \rho \) is the charge density, \( k_e \) is the relative dielectric strength of silicon, and \( \varepsilon_0 \) is the permittivity of free space. This implies the following relations:
\[
\begin{align*}
\frac{d^2V}{dx^2} &= 0 & -d_{ox} < x < 0 \\
\frac{d^2V}{dx^2} &= -\frac{qn_n}{k_\varepsilon_0} & 0 < x < x_n \\
\frac{d^2V}{dx^2} &= +\frac{qn_n}{k_\varepsilon_0} & x_n < x < x_n + x_p \\
\end{align*}
\]  

where \(x\) is the distance measured from the front silicon-oxide interface, \(q\) is the electronic charge of an electron, \(n_a\) and \(n_d\) are the acceptor and donor densities, \(d_{ox}\) is the thickness of the oxide, \(x_n\) is the thickness of the n-implant (assumed to be a stepped junction for purposes of modeling), and \(x_p\) is the thickness of the p+ region (see figure 2-4).

Figure 2-4  Potential distribution in CCD

As the donor density decreases from the p+ layer to the p substrate, occurring at \(x=x_p\), the potential decreases and eventually becomes zero at \(x=x_d\), the depletion depth. Typically, the depth of this depletion region is about 5-10 \(\mu m\) to the right of the oxide-silicon interface as shown in figure 2-4. The distance that the depletion region extends into the substrate is dependent on the thickness and doping concentration of the n and p' layer and the impurity concentration in the substrate.

The potential is zero from the back edge of the depletion region to the back surface of the silicon (see figure 2-4). This region is known as the field-free region. At the back surface, another depletion region forms due to the un-terminated bonds and trapping sites at the interface between the substrate and the naturally occurring surface oxide. This depletion region traps electron hole pairs generated near the back surface until they recombine. Since electrons with
energy under 8 keV from the photocathode are absorbed within the first 700 nm of silicon (discussed in section 2.3.3.2.1), they would normally be trapped by the back surface depletion region. In order to overcome this, it is necessary to create an accumulation layer at the back surface, which will be discussed in section 2.2.2.3.

2.2.2.2 Field free region

Most CCDs are fabricated on silicon wafers that are 540 µm thick. Once the frontside is processed, a layer of oxide, known as a passivation layer, is deposited on the top of the wafer to protect the circuitry. When the device is operated at nominal levels, the depletion depth for most commercial and scientific CCDs extend approximately 5-10 µm below the oxide layer. Thus, almost all of the 540 µm thick CCD has no electric field.

In order to detect electrons, since they are absorbed at the surface, a decision must be made as to which surface to use. Since the front side, of the CCD is covered by a layer of polysilicon that is several microns thick, incident electrons would be absorbed by the polysilicon layer and would never reach the depletion region. This leaves the back surface as the only viable candidate. Electrons incident at the back surface, as well as generated secondaries, would have to diffuse through the "field free region" in order to be collected by the potential well. Furthermore, there is only a short time (hundreds of microseconds) for the electrons to do so before they recombine with their associated holes. Therefore, CCDs are usually thinned to between 10 and 25 microns to minimize the thickness of the field free region. The Hamamatsu imager used in the EBCCD that was studied in this dissertation was thinned to approximately 15 microns. Such thin membranes are very delicate and can be easily broken if care is not taken. In the Hamamatsu EBCCD, the membrane is not supported and the CCD is only supported on the thick frame surrounding the center thinned imaging portion.

2.2.2.3 Backside depletion region

At the backside of a CCD, the un-terminated Si bonds cause a surface potential well (depletion region) at the back surface that can be as deep as 1 µm. This depletion region, if left unmodified, will attract any electron generated in this region preventing it from being collected by the potential well formed by the CCD gate structure. In order to collect these electrons into the desired potential well, the backside surface depletion region must be removed by creating an accumulation region.
There are several ways the backside surface can be modified to create an accumulation (assuming a p substrate) rather than a depletion region. The simplest technique is to treat the thinned back surface by depositing a thin layer of boron. The boron will act as acceptor sites, creating an electric field at the back surface so that electrons are repelled from the back surface and directed towards the potential well. The Hamamatsu EBCCDs were treated to remove the surface depletion region, but the probability of detection was a factor of 10 lower than first order theory predicts, as will be shown in the measurements section (section 4). This would have been even worse had the surface not been treated with a thin layer of boron doping.

2.3 Gain Mechanisms

Let us consider the primary modes of creating gain within image intensifiers. Current Gen II/III type intensifiers utilize microchannel plates (MCPs) to provide gain using secondary electron multiplication, as well as phosphor output screens, utilizing cathodoluminescence. Cathodoluminescence is a process where the excess energy of an incident electron - with sufficient kinetic energy - is converted into one or more photons. EBCCDs operate using only secondary electron multiplication within the silicon CCD. A brief synopsis of relevant aspects of phosphors and microchannel plates are presented to aid the reader in later discussions where EBCCDs are compared to traditional image intensifiers. Following the discussion of phosphors and microchannel plates, the theoretical basis for the EBCCD gain mechanism, namely electron bombarded semiconductor (EBS) gain, will be presented.

2.3.1 Phosphors and cathodoluminescence

Phosphor screens are used in image intensifiers to convert the kinetic energy of an electron into photon energy, via cathodoluminescence. Phosphor screens are composed of layers of a luminescent material. The process of light emission begins when an energetic electron strikes atoms of the phosphor material and produces an excited atomic state at a luminescent center, diagrammed in fig. 2-5. Then, after a period of time, the atom relaxes to a lower energy state, and in so doing may emit a photon of light. The time it takes a phosphor atom to relax and emit a photon is very dependent on the type of material used.
With the exception of direct view intensifiers, the final image transducer of a low-light level imaging system is usually a visible-wavelength imaging CCD camera that is optically coupled to the traditional image intensifier's output phosphor screen. The electronic signal $S$ detected by the CCD (in arbitrary units) is functionally dependent on the spectral exitance of the phosphor screen, $M_{\text{phosphor}}(\lambda)$, and the spectral sensitivity of the CCD, $R_{\text{ccd}}(\lambda)$, as:

$$S = \int M_{\text{phosphor}}(\lambda) R_{\text{ccd}}(\lambda) \, d\lambda$$

(2.16)

where $\lambda$ is the wavelength. In order to design a sensitive imaging system, it is important to match the spectral exitance of the phosphor and the responsivity of the detector, so that the integral of the product in eq. 2.16 is as large as possible, maximizing the detected signal. Due to the finite number of available phosphor types, there is not a continuum of characteristics in terms of spectral emission, decay time, efficiency, resolution, etc. Thus, the system designer must take into consideration that the final "detected" signal is proportional to:

- quantum efficiency of the photocathode
- gain of the intensifier
- efficiency of the phosphor
- spectral matching between the phosphor and the final detector (such that the detector has a high quantum efficiency at wavelengths where the phosphor emits)

The requirement for spectrally matching the visible light CCD to the output of the phosphor is removed when we consider EBCCDs, since there is no re-conversion from photoelectrons back to photons (as in a traditional intensifier).
2.3.2 Secondary electron generation using microchannel plates

2.3.2.1 Principles of operation

While cathodoluminescence utilizes excited energy states as a gain stage, a microchannel plate (MCP) produces a gain stage when multiple secondary electrons are emitted from the surface following the absorption of a high-energy primary electron. For an in-depth treatise of micro-channel plates, the reader is referred to references Pollehn\textsuperscript{22} and Kazan\textsuperscript{23}. An MCP is a device that acts like a continuous dynode strip. The wall is processed to become a material that is highly resistive, and has a low work function. A voltage is applied between the front and rear surfaces of the channel creating an accelerating field inside the channel and along the channel wall.

When an electron strikes the inner surface of the microchannel, secondary electrons are generated which are accelerated by the potential gradient in the channel (see figure 2-6).

![Figure 2-6 Single channel of an MCP](image)

These “initial” initial secondary electrons then strike the inside of the channel and create more secondary electrons. This process continues along the length of the channel – generating perhaps millions of secondary electrons emitted from the end of the channel, depending on the length to diameter ratio and voltage bias. Typical bias voltages range between 800 V to 1500 V producing gains from 1000 to 1,000,000. The channels are usually tilted between 5-10 degrees from the plate normal so that the incident electrons do not pass straight through the channel, but strike the wall, liberating secondary electrons (see figure 2-7).
A traditional Gen II/III type image intensifier combines both phosphor gain and secondary electron multiplication by using a microchannel plate placed between the photocathode and output phosphor as shown in figure 2-8.

The gain, \( G_{\text{MCP}} \), of a microchannel is dependent on the number of collisions of the electrons with the walls of the channel and of the secondary electron coefficient\(^{24} \delta \), and can be described by the following formula\(^{25} \)
where \( G_{MCP} \) is the average gain, \( C_{gain} \) is a device dependent constant. The standard deviation of the gain, \( \sigma_{MCP} \), is given by:

\[
\sigma_{MCP} = \sqrt{G_{MCP} \left( 1 + G_{MCP} \right)}
\]

This type of distribution is found when the MCP is operating well below saturation, and the pulse height distribution (PHD) is shown in the "low gain" line in figure 2-9. When the MCP is operated at a very high gain, i.e. above \( 10^5 \), the channel operates in a saturated mode. As the gain is further increased, the pulse height distribution begins to evolve into a peaked PHD, as seen in the "high gain" line:

![Figure 2-9 PHD vs. gain for MCPs](image)
Microchannel plates have the property that the bias voltage is increased, with a resulting increase in gain, the noise figure of the MCP decreases. When the MCP operates in a pulse-saturated mode, the noise figure is reduced greatly – and can approach values of 1.05.3

It is important to note that single electron detection is possible only at saturation gain levels. Thus, the detection is binary – either an electron was detected or not. This limits the dynamic range of the device to 2 discrete levels, making two-dimensional photon detection limited imaging difficult with traditional image intensifiers. This limitation is removed when EBCCDs are discussed since they can detect single electrons while still maintaining high dynamic range.

2.3.3 Electron Bombarded Semiconductor (EBS)

2.3.3.1 EBS background

We now consider the gain mechanism utilized in EBCCDs, namely electron bombarded semiconductor (EBS) gain. When an energetic electron bombards a silicon lattice, secondary electrons are generated. These secondary electrons increase the number of available conduction band electrons, which creates a gain stage. Rittner first described the EBS effect in 1948, and was awarded several US patents for various electron devices based on EBS.3 Other experiments were conducted at the Bell Telephone Laboratories; no papers were written, but one patent was granted.3 Other research groups carried on work during the 1950s, including the University of London and RCA Princeton Laboratories. The first successful realization of an EBS device was Brown working at IBM in 1963. Most of the early uses of EBS devices were for high power diodes and RF amplifiers. In time, camera tubes utilizing this principle as a gain mechanism were developed.

2.3.3.2 Scattering and secondary electron creation mechanisms

2.3.3.2.1 Electron scattering processes

The interaction of an energetic electron with a crystalline matrix of atoms is manifested in many different forms, some elastic (where energy is conserved during the interaction), others inelastic (where energy is not conserved). Elastic scattering can change the direction of an electron anywhere from 0 to 180 degrees while maintaining its energy, and inelastic scattering events can decrease the electron energy by an amount from as low as 1eV up to several keV,
depending on the nature of the scattering process, but the trajectory of the electron is changed only slightly. We are primarily interested in inelastic scattering events, because in order to create a gain stage, the energy of the single primary electron must be imparted to the creation of many lower energy electrons (called secondary electrons or secondaries).

There are several types of inelastic event types. The first type of event is where several low energy electrons are generated when the primary electron interacts with the valence electrons of the atomic lattice. Typically, the amount of energy transferred to these secondary electrons is on the order of 1-50 eV. Another inelastic scattering mechanism is the generation of higher energy electrons (above 100 eV) resulting from the interaction with more tightly bound electrons of the lattice. These occurrences are much more rare than the creation of low energy electrons, but due to the increased energy, these higher energy secondary electrons have a greater range than the typical 5 nm range of the lower (1-50eV) energy electrons. This causes greater spatial spreading of the “secondary cloud” of electrons generated through the various scattering mechanisms. Primary electrons can also interact with the free electron “gas” present in metals and some semiconductors. These can create oscillations of the gas known as plasmons. Finally, the primary electron can decelerate as it passes through the Coulomb field of the atom. The energy lost during this deceleration is converted into electromagnetic radiation known as “bremsstrahlung” or “breaking radiation”. The amount of energy lost can be anywhere from a small to large fraction of the primary electron’s original energy. We will address only the creation of secondary electrons since it is the dominant energy loss mechanism.

2.3.3.2.2 Creation of secondary electrons

In practical aspects, if we collect all “non-secondary-creating” energy loss mechanisms and normalize them by the number of events that occurred, we can treat this as an “efficiency” parameter \( \eta_{\text{loss}} \). Thus, all remaining events are secondary electron creation. Each incident electron generates a certain number of electron-hole pairs \( N_{\text{ehp}} \) given by

\[
N_{\text{ehp}} = (1 - \eta_{\text{loss}}) \frac{E_{\text{beam}}}{E_{\text{ionization}}}
\] (2.20)

where \( E_{\text{beam}} \) is the energy of the incident electron, and \( E_{\text{ionization}} \) is the “ionization” energy of the electron-hole pair. Klein measured the ionization energies for many semiconductors and noted a linear relationship between the bandgap \( E_{\text{gap}} \) and the ionization energy \( E_{\text{ionization}} \).
\[ E_{\text{ionization}} = 2.3E_{\text{gap}} + 1.3 \quad (\text{Eionization in eV}) \] (2.21)

The number of secondary electrons created within the silicon crystal as a result of a single bombarding electron is known as the quantum yield, or the EBS gain \( G_{EBS} \). Previous research\(^\text{37} \) has shown that the quantum yield for silicon can be described by:

\[ G_{EBS} = \frac{E_{\text{absorbed}} (eV)}{3.65 (eV)} \] (2.22)

where 3.65 eV is the ionization energy for silicon, and \( E_{\text{absorbed}} \) is the energy of the primary electron that is absorbed within the silicon. Since the bandgap energy of silicon is 1.1 eV, over two-thirds of the absorbed energy goes into loss mechanisms\(^\text{38} \) other than secondary electron creation.

### 2.3.3.2.3 Statistics of secondary creation

As in all natural processes, there is a variance associated with the number of secondary electrons actually created. Due to the high degree of correlation\(^\text{39} \) between the generation of secondary electrons related to the small amount of phonon creation compared to electron–hole pair production, the variance of the number of secondary electrons ( \( \sigma_{\text{gain}}^2 \) ) is not Poisson, but is actually a modified Poisson distribution according to:

\[ \sigma_{\text{gain}}^2 = F\text{ano} \cdot G_{EBS} \] (2.23)

where the Fano factor\(^\text{40} \) is the ratio of the mean to the variance of a distribution. For a purely Poisson process, the Fano factor is unity.

For a phenomenological explanation of why the variance is less than the mean, consider the case where two fictitious scintillators are used to detect a high energy x-ray photon. Suppose scintillator A has an ionization energy of 100 eV to create a 2 eV visible photon, in which case 98 eV is lost via various - and random - energy loss mechanisms including heat, phonon creation, etc. As a result, this large amount of energy loss through random discrete mechanisms is governed by Poisson statistics. Now, consider the case of scintillator B that is perfectly efficient - with a 2 eV ionization energy such that it converts a 100 eV x-ray photon into 50 2eV visible photons (100% energy conversion efficiency). Since all available energy goes into the creation of "signal", there is no energy loss - so there is no variance. The probability distribution function is a delta function.
As shown in eq. 2.20, a secondary electron is generated for every 3.65 eV of primary electron energy. The secondary electron has an energy of 1.1 eV (the bandgap energy of silicon). Thus, approximately 2.55 eV of energy goes into other loss mechanisms. Compared to our earlier example of having a 2% efficient (98 eV loss), the 28% efficient EBS conversion is considerably higher. This places the statistics that govern the EBS secondary creation somewhere between the purely Poisson distribution and the delta function distribution. Thus, the Fano factor modification is intuitively warranted. This reduction in the variance compared to a Poisson case is very important in understanding some of the significant theoretical performance increases that EBCCD based detectors possess.

### 2.3.3.3 Absorption depth of primary electrons

There are several inter-related functional dependencies that describe the absorption of electrons within a solid. The differential energy loss, \( \frac{dE}{dx} \), by the primary electron as it penetrates the silicon is given by the depth dose relation derived by Bethe\(^1\)

\[
\frac{dE}{dx} = \left( \frac{2\pi N_A q}{A} \right) \left( Z \rho \right) \left( \frac{1}{E_{\text{beam}}} \ln \left( \frac{E_{\text{excitation}}}{2} \right) \right)
\]

(2.24)

where \( x \) is the distance into the solid, \( N_A \) is Avogadro’s number, \( q \) is the electronic charge, \( Z \) is the atomic number, \( A \) is the atomic gram weight, \( \rho \) is the density of the material in \( \text{g/cm}^3 \), \( E_{\text{beam}} \) is the beam kinetic energy, \( e \) is the Naperian constant (2.71828), \( E_{\text{excitation}} \) is the mean excitation energy (in eV) for electron energy loss in a solid, for \( Z>6 \) is given by\(^2\)

\[
E_{\text{excitation}} = (9.76 + 58.82Z^{1.19}) \ Z
\]

(2.25)

Everhart and Hoff\(^3\) have measured the average energy loss profile for 5-25 keV electrons with atomic number \( Z=10 \) to 15 and produced an empirical fit to the observed data given by the equation:

\[
\frac{dE}{dx} = \left( 1 - 0.5\eta_{bs} \right) \frac{E_{\text{beam}}}{R_G} \lambda \left( \frac{x}{R_G} \right)
\]

(2.26)

where \( \eta_{bs} \) is the backscatter coefficient (discussed in section 2.3.3.4) and \( \lambda(x) \) is an empirically derived function (found by Everhart and Hoff) and is given by:
\( \lambda(x) = .6 + 6.21 \frac{x}{R_G} - 12.4 \left( \frac{x}{R_G} \right)^2 + 5.69 \left( \frac{x}{R_G} \right)^3 \) \hspace{1cm} (2.27)

where \( x \) is the distance into the solid, and \( R_G \) is the Grün range given by:

\[ R_G = \frac{4 \times 10^{-2} \frac{E_{beam}^{1.75}}{\rho}} \]

\( (2.28) \)

where \( R_G \) is given in \( \mu m \), \( E_{beam} \) is the beam energy in keV and \( \rho \) is the density of silicon in gm/cm\(^3\) (2.33 g/cm\(^3\)).

The function \( \lambda(x) \) is defined such that the integral shown in eq. 2.29 is equal to 1.

\[ \int_{0}^{1.13R_G} \lambda(x) \, dx = 1 \]

\( (2.29) \)

Equation 2.29 states that the primary electron has lost all of its energy at a depth of 1.13 \( R_G \). Equations 2.26 and 2.28 are of utmost importance to the research presented in this dissertation, because they describe how an electron loses energy as it enters and propagates into the silicon crystal. The average energy that is actually deposited in the substrate is given by the product of \((1-0.5\eta_b)\) and the initial energy \( E_{beam} \). As the primary electron scatters in the silicon, it loses energy according to a certain energy loss profile \( dE/dx \). This function is properly interpreted as the number of electron-Volts that a primary electron loses per unit distance (in this case, microns) at a given depth below the back surface of the CCD. Since any given electron trajectory involves random scattering events, the specific \( dE/dx \) will vary. However, the ensemble average of a one dimensional energy loss model is accurately represented by the differential energy loss equation, eq. 2.26.

Figure 2-10 is a plot of \( dE/dx \) at several primary electron energies: 2 keV, 3 keV, 4 keV, 5 keV, 6 keV, 7 keV, 8 keV.
Several features of figure 2-10 are worthy of discussion. The Grün range for each energy is found where the \( \frac{dE}{dx} \) function approaches zero. Also, note that the 2 keV primary electron has lost all of its energy at 50 nm, whereas the 8 keV loses energy over a broader range up to 700 nm. Since aluminum and silicon have similar densities (2.7 and 2.33 g/cm\(^3\) respectively), the Grün range is similar for each material and hence the curves shown in figure 2-10 are similar for penetration into aluminum and silicon, according to eq. 2.28. If the EBCCD is covered by a 140 nm thick layer of aluminum to block incident visible photons, then the primary electron will need to have at least 4 keV of energy to penetrate the aluminum layer and deposit energy into the silicon where secondary electrons are created.

### 2.3.3.4 Backscattering

When the photoelectron enters a material, it is scattered by the material’s atomic structure. As was discussed in the introduction to EBS physics, the angle that the electron scatters into is largely dependent on the pre-scattering energy. Even after penetrating the aluminum layer, there is a probability that after a few (or even one) scattering events, the electron
will scatter 180 degrees from its initial vacuum trajectory, and leave the silicon crystal. These electrons are known as backscattered electrons, and represent a loss of efficiency to EBCCDs. Because of the electric field that exists between the photocathode and CCD, the backscattered electron will re-enter the silicon, but at a lower energy. When this occurs, the contrast of the image is degraded and the MTF is decreased.

An estimation of the backscattering coefficient $\eta_{bs}$ has been measured by Darlington and Coslett\(^{49}\) who studied the electron backscattering properties of Aluminum, with an atomic number of $Z=13$. An empirical curve fit to this data\(^{46}\) is given by:

$$\eta_{bs} = 0.42 - 0.047 \ E_{beam} + 0.0021 \ E_{beam}^2$$  \hspace{1cm} (2.30)

Where $E_{beam}$ is the energy of the incident beam (measured in keV), and the average energy of the backscattered electron ($E_{backscatter}$) is estimated by Daud\(^{47}\)

$$E_{backscatter} = \int_{bs} E_{beam} \ f_{bs} = 0.45 + .002Z \ for \ .2 < E_{beam} < 32keV$$  \hspace{1cm} (2.31)

where $Z$ is the atomic number.

As seen figure 2-10, as the energy increases, the energy is dissipated deeper into the silicon. Since a higher energy primary electron can penetrate further into the silicon, we expect that the chance that it will re-emerge at the surface (giving rise to a backscattered electron) decreases – giving an explanation as to why the backscattering coefficient decreases with increasing energy.

Electrons that are backscattered from the CCD exit the surface with approximately 50% of their incident energy\(^{48}\) and usually are driven back toward the surface by the electric field. Thus, only a fraction of the initial energy is deposited in the substrate. The effect of the backscattered electrons can be neglected in most cases when the tube dead layer is approximately half of the maximum primary electron energy under consideration, since any returning backscattered electron will not be able to penetrate the dead layer. Stated simply, when an electron is backscattered by the silicon, that electron is absorbed by the aluminum layer. Such assumptions are valid in the characterization studies presented in section 4 of this dissertation.

2.3.3.5 X-ray generation

When electrons within a silicon atom are excited to an energy greater than 1.78 keV, there is a possibility that when the atom relaxes to a lower energy state, that the conservation of
energy will be satisfied by emitting a k characteristic x-ray. These x-rays are emitted in a random direction - into 4π sr. The emission of x-rays is significant because if the x-ray is absorbed within the oxide layer of the CCD, the generated electron hole pairs cannot recombine. As a result, the charge is trapped. This causes a voltage shift in the potential of the Si-SiO₂ layer and reduces the channel potential. A reduction in the channel potential is manifested by a smaller depletion region and lower full well capacity of that pixel.

X-rays that are absorbed within the bulk material are not damaging, as the electron hole pairs simply recombine. This can still pose a performance degradation, as the x-ray may be absorbed in a neighboring pixel, causing a false signal, and thereby reducing the image contrast. The x-ray generation probability \( \eta_{x\text{-}\text{ray}} \) is dependent on the energy of the exciting electron, and was measured by Ravel and Reinheimer as:

\[
\eta_{x\text{-}\text{ray}} = 1.31 \times 10^{-5} (E_{\text{beam}} - 1.839)^{1.602}
\]

Where \( E_{\text{beam}} \) is the energy of the incident beam (measured in keV). Equation 2.32 is plotted in figure 2-11.

As seen in figure 2-11, if \( 10^6 \) electrons at 5 keV are injected into the silicon, approximately 90 x-rays will be generated. Over time, if enough x-rays are absorbed by the oxide layer, the full well capacity of that pixel is reduced to zero, and the pixel does not respond anymore. Rheinheimer has shown that some performance can be regained by heating the CCD
up so that thermal energy can aid in the recombination of trapped charge. Nevertheless, over
time, a build-up of trapped charge in the oxide layer will render the device useless.

2.4 EBCCD imaging system

2.4.1 Device construction

As discussed in the introduction, an EBCCD image tube consists of a photocathode
detector, and an EBS gain stage. The silicon CCD acts as both the gain stage and the detector,
forming a complete imaging system with only two primary components. A thin layer of
aluminum (140 nm) may be placed over the rear surface of the CCD to shield it from photons
depending on the intended application. A thickness of 140 nm reduces the light transmission into
the CCD by a factor of about 900. The addition of aluminum does decrease the energy of the
primary electron emitted from the photocathode, which is manifested in a lower gain than would
be achieved had the aluminum not been present.

2.4.1.1 EBCCD manufacturing and processing

The difficulties involved in the assembly and manufacture of EBCCD tubes have been
the primary limitation to their development and widespread use. The author developed an
assembly process and is well acquainted with the issues involved, which will be surveyed here.

The first step in EBCCD assembly is the selection and thinning of a suitable CCD. Once
the CCD is thinned, the backside must be treated to remove the surface depletion region. This
normally involves a boron implant deposition. Since the thinned CCD is about 15-20μm in
thickness in the image zone, any processing steps that involve movement of the CCD is risky
since the silicon membrane can easily rupture. Following the boron deposition, a thin layer of
aluminum may be deposited to shield the CCD from photons, if so desired. Once the CCD is
thinned and treated, it is usually be attached to the ceramic substrate using Indium bump bonds as
shown below in figure 2-12.
Figure 2-12 CCD mounting on ceramic header with flip-chip attachment

Typically, the bottom of the image tube is made of a co-fired ceramic with electrical feedthroughs that connect the top of the ceramic plate (the vacuum side - where the CCD attaches) to the bottom of the plate (where the connections pins are placed for connection to the camera electronics). The method used to affix the CCD to the header is dependent on how the tube is cleaned.

As discussed previously, photocathodes operate based on photoemission. Emission of an electron from a photocathode is a very surface dependent phenomenon. As a result, any deposition of an impurity can severely affect the performance. It has been shown\(^{31}\) that if a mono-atomic layer of "residual gas" were deposited on a S-20 photocathode, it would be rendered useless as an electron emitter. Thus, not only must the vacuum level in an image intensifier be extremely low (on the order of \(10^{-11}\) Torr), but the entire tube must be heated (often up to 350 degrees C) to remove any oxygen, hydrocarbons, water vapor, etc. that might have been absorbed by the ceramic and metal components of the image tube – including the CCD in EBCCD devices.

Recall that the CCD is attached to the header, and that the majority of the CCD is very thin. When the CCD is heated to 350 deg. C, it will expand based on normal thermal expansion. The thermal coefficient of expansion (TCE) for silicon is \(3.1 \times 10^{-6}\). If the CCD is attached to the ceramic header (with TCE of \(7 \times 10^{-6}\)) using a solder or glass frit whose melting point is higher than 350 deg. C, the resulting thermal strains induced in the CCD would literally rip the CCD apart when it is heated some 330 degrees above its nominal operating temperature. The design developed by the author and also used by Hamamatsu is to attach the CCD in a flip-chip\(^{52}\) arrangement. The process side of the CCD is attached to the header using an indium "bump bond" method, where a small ball (50 \(\mu\)m diameter) of indium is placed on the electrical pads of...
the header (in physical registration with the aluminum pads on the CCD) and the CCD is mechanically pressed onto these balls. This approach allows both mechanical and electrical connections to be made between the header and CCD.

### 2.4.1.2 Electrostatic field focusing

The EBCCD tube that is discussed in this dissertation uses electrostatic proximity focusing. This was done to achieve a minimum size for the tube, use simple electron optics, and minimize distortion. The proximity focused arrangement does limit the maximum voltage that can be applied to the photocathode, since electron field emission is strongly dependent on the electrical field. As a result, there is an upper limit that is placed on the achievable gain. Furthermore, the spatial resolution is not as good as can be achieved using electrostatic and magnetic focusing arrangements. The focusing of the photo-emitted electrons is accomplished by placing the photocathode and back surface of the CCD in close proximity, on the order of about 2 mm. Thus, the electrostatic field established by the bias of several thousand volts directs electrons toward the CCD surface. Since the electron emitted from the photocathode has some radial velocity component, the point spread function will be limited by the characteristics and amount of this radial velocity as diagrammed in figure 2-13.

![Figure 2-13 Radial emission of proximity focused photodiode](image)

The equations relating the radial emission velocity to the spread of the electron beam on the CCD is related by:

\[ v_{\text{radial}} = \sqrt{\frac{2E_{\text{radial}}}{m_{\text{electron}}}} \quad d_{\text{spread}} = 2r_{\text{dist}} \sqrt{\frac{E_{\text{radial}}}{V_{\text{bias}}}} \] (2.33)
where $E_{\text{radial}}$ is the radial component to the energy, $m_{\text{electron}}$ is the electron mass, $V_{\text{bias}}$ is the accelerating voltage, $d_{\text{spread}}$ is the diameter of the blur spot on the CCD, $L_{\text{dist}}$ is the distance between the photocathode and the CCD surface, and $v_{\text{radial}}$ is the radial velocity component.

### 2.4.2 Predicted performance of an EBCCD tube

#### 2.4.2.1 EBCCD system device schematic

![EBCCD imaging system diagram](image)

The EBCCD imaging system shown above in figure 2-14 is used to collect light from the object with radiance $L_p$ through a lens of numerical aperture NA, generating an irradiance $E_p$ on the photocathode. The irradiance is related to the object exitance by:

$$E_p = \pi L_p (NA)^2 \quad (2.34)$$

#### 2.4.2.2 Efficiency in signal generation

As stated earlier, the number of electrons generated within the silicon is dependent on the energy of the primary electron, and the nature of any energy barriers that must be penetrated for the primary electron to get to the silicon. The mean number of electrons that are actually collected in the potential well of the CCD can be calculated as follows:

$$S_{\text{EBCCD}} = \eta_{pe} \cdot N_p \cdot (1 - \eta_{bs}) \cdot G_{\text{EBS}} \cdot p \quad (2.35)$$

where $S_{\text{EBCCD}}$ is the mean number of electrons that are actually collected, $\eta_{pe}$ is the quantum efficiency of the photocathode, $N_p$ is the number of photons that are incident on the photocathode in an area equivalent to a pixel, $G_{\text{EBS}}$ is the EBS gain, $\eta_{bs}$ is the backscattering coefficient, and $p$ is an empirically defined parameter representing the probability that a created secondary is collected into the potential well. This formula assumes that backscattered electrons...
do not participate in the creation of signal electrons. This assumption is justified on the basis that backscattered electrons return to the silicon with less than half of their initial energy, contributing a negligible amount of additional secondary electron generation.

As seen in equation 2.35, we can increase the number of secondary electrons collected by the CCD in many ways:

1. Increase the quantum efficiency of the photocathode
2. Increase the accelerating voltage to increase the EBS gain
3. Increase the probability of capturing any generated secondary electron
4. Increase the number of incident photons

Usually, in low-light level imaging applications, one maximizes the throughput of the optical system preceding the photocathode such that #4 above is optimized for performance and cost. Due to the finite number of photocathode types, #1 above is maximized as much as possible for a given spectral region. We can only increase the voltage (#2) to the extent limited by the available power supply and the maximum values permitted by the tube (limited by field emission and x-ray generation). Thus, the only available area for further increase in future devices is to maximize the collection of any generated secondary electron. This is normally accomplished by eliminating the back surface depletion region and extending the CCD potential well depletion region to the back surface of the silicon. Returning to #2 above, another possible area of increase is to reduce the energy barriers (dead layer voltage caused by the deposited aluminum layer and any surface oxides) so that a primary electron with a given energy can deposit more of that energy in the silicon, less in the dead layer. This would require either thinning or eliminating the aluminum coating on the CCD, since the aluminum layer is the majority contributor to the dead layer. It would then be necessary to find a different method to block photons that pass through the photocathode from creating charge in the CCD.

If we assume a 4 kV dead layer voltage imposed by the 140 nm thick aluminum layer and native oxide (20 nm thick) covering the silicon, and assume that all secondary electrons are captured by the potential well, the operating gain should equal the EBS gain, which is plotted as a function of accelerating voltage below in figure 2-15:
We shall see in the results section that since the operating gain and EBS gain are in fact not equal, our assumption of all secondary electrons being collected is incorrect. This has substantial implications in terms of the way an EBCCD should be designed and how such an EBCCD should be characterized.

2.4.2.3 EBCCD Noise

2.4.2.3.1 Gain variance

The variance of the actual number of secondary electrons generated per incident primary is fundamentally limited by the Fano-noise discussed earlier. It is very difficult to achieve this noise limitation, because it is necessary to collect all secondary electrons. The number of collected electrons, \( N_{e,\text{captured}} \), generated by a single photoelectron is given by:

\[
N_{e,\text{captured}} = G_{EBS} p
\]  

(2.36)

Where \( G_{EBS} \) is the EBS gain (given by equation 2.21) and \( p \) is the probability of secondary electron detection. The theoretical limit of the noise (\( \sigma_{\text{capture}} \)) related to the variance of the number of electrons actually captured is given by (in units of electrons):

Figure 2-15 Predicted EBCCD gain vs. applied voltage
where $F_{\text{Fano}}$ is the Fano factor, $p$ is the probability of collection, with statistics described by a binomial distribution. Since $p$ is an empirically defined parameter, it is difficult to predict its value. It is the goal of any EBCCD design to collect as many secondary electrons as possible, and efforts are taken to extend the CCD depletion region to the rear surface of the CCD in an effort to make the "$p$" value unity. However, $p$ is normally less than unity. When this is so, the theoretical noise limit increases from Fano limited operation (shown in eq. 2.23) to that described by eq. 2.37. If we assume $G_{\text{EBS}} = 1100$ and a Fano factor of 0.1, we can plot eq. 2.37 as a function of $p$ as seen in figure 2-16:

![Figure 2-16 Noise associated with electron capture of a Fano limited secondary distribution](image)

Even though figure 2-16 shows that the total noise is not at a global minimum at $p = 1$, the signal to noise ratio formed by eq. 2.36 and eq. 2.37 is a maximum when $p = 1$ – showing that collecting all secondary electrons is desirable.

### 2.4.2.3.2 Predicted values of Signal to Noise ratio

Consider figure 2-17 showing the sources of noise in an EBCCD. Each process in conversion is shown and numbered 1 through 5, with the gain and standard deviation (noise) shown in a $(G, \sigma)$ format.
Figure 2-17 System Noise diagram

The formula for cascaded noise was given in eq. 1.1. At conversion "1" in figure 2-17, the incident photons are converted to electrons $N_e$ at the photocathode with efficiency $\eta_{pc}$, where $N_e = \eta_{pc}N_p$ such that the generated number of electrons $N_e$ has a related noise $\sqrt{N_e}$. At conversion "2", the electrons strike the silicon interface and are absorbed with efficiency of $\gamma$ (where $\gamma = 1 - \eta_{bs}$) with associated noise of $\sqrt{\gamma(1-\gamma)}$. Upon entering the silicon, many secondary electrons are generated according to the EBS theory presented above with conversion efficiency $G_{EBS}$ and associated noise of $\sigma_g$. These secondary electrons then propagate to the CCD well where they are collected with efficiency of $p$ and associated noise $\sqrt{p(1-p)}$. At the CCD output (stage 5) additional noise is added where $\sigma_{RN}$ is the CCD read noise, $g_{dark}$ is the dark current generation rate in electrons per second, and $t_{int}$ is the integration time. Thus, the total noise in electrons is shown in the following formula:

$$\sigma_{total}^2 = f_1 + f_2 + f_3 + f_4 + f_5$$

(2.38)

$$f_1 = N_e \gamma^2 G_{EBS}^2 p^2$$

(2.39)

$$f_2 = N_e \gamma (1-\gamma) G_{EBS}^2 p^2$$

$$f_3 = N_e \gamma \sigma_g^2 p^3$$

$$f_4 = N_e \gamma G_{EBS} p(1-p)$$

$$f_5 = \sigma_{RN}^2 + g_{dark}t_{int}$$
If we assume appropriate values of $G_{EBS} = 1100$, $\gamma = 0.68$, $p = .1$, $\sigma_e = 110$ e, $g_{dark} = 1500$ e/sec, $t_{int} = 1$ sec, $\eta_{pe} = 11\%$, $\sigma_{RN} = 20$ e, then we can plot each term to discover the relative magnitude of each source as a function of photons per pixel, as shown in figure 2-18.

![Figure 2-18 Plot of magnitude of noise sources in a EBCCD](image)

Note that at the lowest light levels, below approximately 3 photons per pixel, the dark current and read noise dominate the system noise. Above 3 photons per pixel, photon noise fluctuations dominate the system noise—thus, the signal to noise ratio is close to the physical limits imposed by the Poisson nature of the incident photon stream. The resulting signal to noise ratio is plotted in the figure 2-19, and the noise figure is plotted in figure 2-20.
Figure 2-19 Theoretical Signal to Noise ratio vs. incident photons at a EBS gain of 1100

Figure 2-20 Theoretical Noise figure vs. incident photons at a EBS gain of 1100
2.4.2.4 Radiometric sensitivity

The limit of radiometric sensitivity is set by the number of primary electrons required to generate a sufficient signal so that a chosen SNR threshold is exceeded. Clearly, the actual number of photons that are required to generate this required number of electrons is completely dependent on the quantum efficiency of the photocathode. Thus, if we desire a threshold signal to noise ratio of 5, assuming the same values in section 2.4.2.3.2, the rms noise would be 53 electrons. Thus, to detect a single "primary" electron, the operating gain would need to be 265.

2.4.2.5 Dynamic range

The dynamic range of the EBCCD is given by the maximum signal divided by the minimum detectable input signal. The minimum detectable signal is equal to the greater of the system noise level or the gain when it is such that a primary electron generates more signal than the noise floor. We expect an intra-scene dynamic range to be limited by the ratio of the full well capacity to the system noise, or 170,000 electrons / 53 read noise electrons = 3207 (note that the 53 electrons is the noise found in section 2.4.2.4).

2.4.2.6 MTF

The spatial resolution of an EBCCD is fundamentally determined by 1) the diameter of the secondary charge cloud just prior to collection and 2) the size of the CCD pixel.

Usually the diameter of the charge cloud is much smaller than the pixel size so the dominant factor in determining the MTF is the pixel size. The MTF of a proximity-focused EBCCD is limited by the CCD pixel pitch ($d_{\text{pixel}}$), the separation of the photocathode to the back surface of the silicon ($L_{\text{dist}}$), and the radial energy distribution of electrons emitted from the photocathode. If we assume a 100% pixel fill factor, which is reasonable for a back illuminated device, then the MTF introduced by the CCD is given as:

$$MTF_{\text{CCD}} = \text{sinc}(d_{\text{pixel}}f)$$

(2.40)

where $f$ is the spatial frequency in cycles per mm. Similarly, the point spread function due to radial spread of emitted electrons can be accurately described as a Gaussian profile, with a parameter "s" representing the "width" of the function. Thus, the MTF of the electron optics ($MTF_{\text{spread}}$) is the modulus of the Fourier transform of the electron point spread function:

$$MTF_{\text{spread}} = \text{Gaus}(sf) = \exp\left(-\pi (sf)^2\right)$$

(2.41)
The width of the electron point spread function on the surface of the CCD is dictated by
the spreading of the photocathode emitted electron in a proximity focused arrangement, as
discussed in section 2.4.1.2 above. Csorba\textsuperscript{56} gives a formula for estimating the MTF of a biplanar lens configuration with a Maxwell energy distribution of emitted electrons as:

\[ MTF_{\text{tube}} = \exp \left( - \frac{2\pi I_{\text{dist}}}{V_{\text{bias}}} \sqrt{\frac{E_{\text{mp}}}{V_{\text{bias}}}} f \right) \]  

(2.42)

Where \( MTF_{\text{tube}} \) is the predicted MTF of the tube electron optics, \( E_{\text{mp}} \) is the voltage equivalent of the most probable emission energy, \( L_{\text{dist}} \) is the photocathode to anode distance, \( V_{\text{bias}} \) is the bias voltage, and \( f \) is the spatial frequency in cycles per mm.

Thus, if we assume a most probable emission energy of .14 eV\textsuperscript{57}, pixel size of 24 μm, and a bias voltage of 6kV, then the expected EBCCD tube MTF has a 3% cutoff at approximately 30 lp/mm as seen in figure 2-21.

![Figure 2-21 Estimated MTF of an EBCCD tube](image)

**Figure 2-21** Estimated MTF of an EBCCD tube
3 Methods of Analysis

This dissertation explains several diagnostic tests that were developed by the author to characterize EBCCD tubes after they have been manufactured and assembled into a camera system. As discussed earlier, EBCCDs are hybrid image intensifiers, requiring different characterization tests than those to which traditional image intensifiers are subjected. Specifically, the author developed the following techniques to characterize in situ EBCCD tubes:

- A method to measure the realizable "system" gain of an EBCCD using the mean variance analysis method
- A method to measure single electron pulse height distributions given only information about multiple photon pulse height distributions
- A method of measuring the thickness and associated variation of aluminum coatings applied to the back surface of the CCD
- A method to measure the operating gain variation of an EBCCD resulting from thickness variations of aluminum coatings applied to the back surface of the CCD
- A method to measure the electron detection probability at the back surface of the CCD

The following sections will present these methods along with corresponding theory.

3.1 Mean Variance / Photon Transfer Analysis

In any measurement system, there is an assumption that the standard of measurement is correct. When a length is measured, one assumes that the ruler is correct. When one desires to measure different parameters of a CCD, it is difficult to directly measure many of the properties such as the full well capacity, read noise, sensitivity, etc..

The basis of the mean variance / photon transfer technique is that one property of nature, namely the Poisson distribution of photon exitance of a thermal source, can be used as a standard to measure CCD parameters. The mean variance / photon transfer technique uses statistical information related to the CCD responsivity collected at different illumination levels to indirectly measure:
• full well capacity
• read noise
• dynamic range
• linearity
• signal to noise ratio
• sensitivity

3.1.1 Mean Variance / Photon Transfer Measurement setup

A majority of the data required for the characterization of in situ EBCCD tubes is found by performing a mean variance test. The quality control equipment at Silicon Mountain Design (where the data was acquired) consists of a station where photon transfer measurements are made of all cameras. A NIST traceable calibrated photodiode is used to measure the illumination within a 12” diameter integrating sphere, as diagrammed in figure 3-1. Light is provided using an incandescent bulb that is filtered by a 550 nm filter (10 nm bandpass width). The actual light level is servo-controlled from the measured light level.

Figure 3-1 Photon Transfer Setup

Due to the fact that the EBCCD camera is very sensitive to light, a ND 2 filter was placed over the photocathode to decrease the actual light irradiance on the photocathode by a factor of 100. The solid angle was decreased very slightly as a result, and was taken into account during the computations. The sequence of events is as follows:

1. Turn off all light into the sphere
2. Acquire two frames, compute the difference, and compute the rms noise (this is the camera read noise).
3. Turn on light and servo to desired level

4. Acquire two frames and compute the mean and standard deviation. Repeat this step to average computations

5. Increase the light level and repeat step 4 until the maximum light level is reached.

### 3.1.2 Photon noise theory

Photon noise can be understood either as the randomness in the arrival time of individual photons emitted from a source or as the randomness in detection of a stream of photons. A thermal source also emits photons in random directions – into $4\pi$ steradians. This randomness is manifested as a temporal fluctuation in the signal produced by the detector. While noise is usually an undesired consequence of nature, we can use this noise as a "measuring ruler" in the mean variance / photon transfer technique, since the noise is well understood. The probability of exactly $N_p$ photons arriving is given by the Poisson distribution function $P(N_p)$:

$$P(N_p) = \frac{(\bar{N}_p)^{N_p}}{N_p!} e^{-\bar{N}_p}$$

(3.1)

The mean of the Poisson distribution $P(N_p)$ is equal to $\bar{N}_p$ and the variance is also equal to $\bar{N}_p$. The standard deviation is given by the square root of the variance, so that:

$$\sigma_p = \sqrt{\bar{N}_p}$$

(3.2)

The mean number of electrons ($N_e$) produced by a detector with quantum efficiency $\eta_{pc}$, when illuminated by $\bar{N}_p$ photons, is given by:

$$N_e = \eta_{pc}\bar{N}_p$$

(3.3)

The variance of the number of electrons ($\sigma_e^2$) generated is given by:

$$\sigma_e^2 = \bar{N}_p\eta_{pc}(1-\eta_{pc}) + \eta_{pc}^2\bar{N}_p$$

(3.4)

The first term is the variance associated with the detection of a photon, and the second term is the variance associated with the temporal fluctuation of the photon arrival rate. Collecting terms in eq. 3.4 we see that the standard deviation is given by:
The incident photon flux has a signal to noise ratio (SNR) given by:

$$\text{SNR} = \frac{\bar{N}_p}{\sigma_p} = \sqrt{\frac{\bar{N}_p}{\eta_{pc}}}$$  \hspace{1cm} (3.5)

This SNR is a function of the nature of photon emission and cannot be improved by using better detectors or electronics. It is a fundamental physical limitation.

If the detector is limited by photon noise, we can define a “detector” signal to noise ratio:

$$\text{SNR}_{\text{output}} = \frac{\eta_{pc}\bar{N}_p}{\sigma_e} = \sqrt{\eta_{pc} \bar{N}_p}$$  \hspace{1cm} (3.6)

Note that the input and output SNRs are related by the quantum efficiency:

$$\text{SNR}_{\text{output}} = \eta_{pc} \text{SNR}_{\text{input}}$$  \hspace{1cm} (3.7)

Due to the finite size of the CCD potential well (the full well capacity), there is a maximum SNR that can be attained with an EBCCD camera:

$$\text{SNR}_{\text{max}} = \sqrt{\eta_{pc} W}$$  \hspace{1cm} (3.8)

where $W$ is the full well capacity of a pixel.

### 3.1.3 Mean Variance / Photon Transfer Calculations

In order to measure the CCD parameters of interest, data must be collected and analyzed. Since the user has access only to the digital numbers (Analog Digital Units - ADUs) that are output by the camera, the mean variance / photon transfer plot uses these values. Since the photon noise appears at each detector element, we can acquire a two-dimensional image and each pixel will have the same type of photon noise fluctuation, assuming uniform illumination. The data is collected by acquiring two images (referred to as images a and b), and analyzing a subsection (i.e. a 100 x 100 pixel) of the image. The means ($\mu_a$ and $\mu_b$) and variance ($\sigma^2$) of the digital pixel values within the section are computed according to:

$$\mu_a = \frac{1}{N_{\text{pixels}}} \sum_{i=1}^{N_{\text{pixels}}} x_{ai}$$  \hspace{1cm} (3.10)
\[ \mu_b = \frac{1}{N_{\text{pixels}}} \sum_{i=1}^{N_{\text{pixels}}} x_{b_i} \]  

(3.11)

\[ \sigma^2 = \frac{1}{2 \left( N_{\text{pixels}} - 1 \right)} \sum_{i=1}^{N_{\text{pixels}}} \left( \left[ x_{a_i} - \mu_a \right] - \left[ x_{b_i} - \mu_b \right] \right)^2 \]  

(3.12)

where \( x_{a_i} \) and \( x_{b_i} \) are the actual measured pixel values in the subsection, \( \mu_a \) is the mean of the subsection in the first image, \( \mu_b \) is the mean of the same subsection in the second image, \( N_{\text{pixels}} \) is the number of pixels in the subsection, and \( x_{a_i} \) and \( x_{b_i} \) are the pixel values for the first and second images respectively.

By subtracting the two consecutive images, fixed pattern noise is eliminated. These two values, the mean and variance, are computed for each pair of images as the light level is increased from complete darkness to a light level such that the number of electrons generated within a pixel exceeds the full well capacity. Note that when the two images are subtracted, we must correct for the additional noise, since the calculated variances add during subtraction. This is taken into account in all future calculations. Note that both the mean and variance is given in terms of ADUs. The mean variance test is a plot of the calculated variance (\( \sigma^2 \)) vs. the mean \( \mu_a \). The photon transfer plot is generated by plotting the log (base 10) of the standard deviation vs. the log of the mean and results in a graph that looks like figure 3-2. The mean variance test and photon transfer test are different only in the shape of the plot and the calculations used in the data reduction.
At low light levels, the variance is dominated by noise from the electronics associated with the camera including the amplifier, correlated double sampler, A/D converter, etc. As the light level increases, noise from the photon rate fluctuation dominates the contribution to the variance until the full well capacity is reached. Once the pixel can no longer hold any more charge, any additional charge begins to spill into adjacent pixels or into anti-blooming structures. This has the effect of averaging and the variance decreases rapidly above full well.

The following sections (3.1.3.1 through 3.1.3.8) discuss the calculations performed to reduce the figure of merit data from the mean variance / photon transfer curve information.

**3.1.3.1 Camera Response Transfer Function**

Since the mean is calculated for each light level, a plot of the mean signal vs. light level shows the transfer curve relating image plane irradiance to the average ADU output by the camera.
3.1.3.2 Non-Linearity

This parameter is computed by measuring the absolute error between the least-squares linear fit to the linear portion of the camera transfer curve and the actual signal produced. The differential non-linearity (DNL) is computed by:

\[
DNL = \left( \frac{|actual - best\ fit|}{4096} \right) \cdot 100\%
\]  

(3.13)

3.1.3.3 Read Noise

The read noise is computed by noting the standard deviation when there is no incident light on the CCD. Since there is no light, there is no photon noise, and all noise is due to the CCD and camera electronics.

3.1.3.4 Dynamic range

The dynamic range of the camera is defined by the maximum usable signal divided by the minimum usable signal. If the camera gain is set where full well capacity of the CCD occurs at about 4050 ADUs, this is the maximum usable signal. If the read noise is greater than 1 ADU, i.e. 1.2 ADUs, the minimum usable signal is the read noise. However, if the read noise is less than 1, the minimum usable signal is 1 ADU.

3.1.3.5 Camera gain

The camera gain is the conversion factor that relates the ADU value to the number of electrons collected by a pixel. Recall that the data output by the camera is in units of ADUs. Nevertheless, it is possible to determine the actual number of electrons necessary to produce one ADU by the following simple analysis.

The number of ADUs output by the camera \( S_{ADU} \) is related to the number of sensed electrons \( N_e \) by the camera gain:

\[
S_{ADU} = K_{ADU/e} N_e
\]  

(3.14)

where \( K_{ADU/e} \) is the number of ADUs generated for each electron, which is the parameter we desire to measure.

We also note that the variance \( \sigma_{ADU}^2 \) (in terms of ADUs) is related to the standard deviation of the number of electrons produced in a pixel \( \sigma_e \) due to photon noise is given by:
\[ \sigma_{ADU}^2 = (K_{ADU/e} \sigma_e)^2 \]  

(3.15)

if we then form a ratio of equation 3.15 to 3.14, the result is the desired conversion factor:

\[ \frac{\sigma_{ADU}^2}{S_{ADU}} = \frac{(K_{ADU/e} \sigma_e)^2}{K_{ADU/e} N_e} = K_{ADU/e} \]

(3.16)

since \( \sigma_e^2 = N_e \) as seen from equation 3.5.

We can also extrapolate the least squares linear fit to the photon noise dominant region to the x-axis where \( \sigma_{ADU}^2 = 1 \) (refer back to figure 3.2).

Since

\[ \sigma_{ADU}^2 = K_{ADU/e} S_{ADU} \]

(3.17)

then at \( \sigma_{ADU}^2 = 1 \),

\[ K_{ADU/e} = \frac{1}{S_{ADU}} \]

(3.18)

or its reciprocal

\[ K_{e/ADU} = S_{ADU} \]

(3.19)

where \( K_{e/ADU} \) is the number of electrons produced per ADU and is the reciprocal of \( K_{ADU/e} \). The mean-variance method of measuring the operating gain is to measure the slope of the mean-variance curve, the inverse of which yields the conversion gain in electrons per ADU.

**3.1.3.6 Full well capacity**

The "full well capacity" of a CCD is the amount of charge that can be held in the potential well of a pixel without spilling into adjacent pixels. The common metaphor for this is a 5 gallon bucket – the bucket can hold 3 gallons of water, but cannot hold 6 gallons of water, as it will overflow the walls of the bucket. Likewise, the architecture and physical realization of the CCD pixel has limits as to how many electrons it can hold. It is possible to observe a camera response signal larger than the full well signal. This is observed as "spilled" charge flowing down the vertical channel into the serial readout register. Typically, the serial readout register has a larger full well capacity than the vertical channel regions in the image area. When excess charge flows into the serial register, it is collected and dumped onto the sense node and appears as
a larger signal. Nevertheless, the actual image zone full well capacity is readily observed by noting the point on the graph where the variance is greatest.

The full well capacity is computed simply by analyzing the photon transfer curve and determining the maximum variance produced (seen along the y-axis of figure 3-2) and then finding the corresponding signal value, $S_{\text{max ADU}}$ (seen along the x-axis of figure 3-2). The actual number of electrons $N_{\text{fullwell}}$ corresponding to the full well capacity is then computed by the equation:

$$N_{\text{full well}} = K_{\text{el ADU}} S_{\text{max ADU}}$$  \hspace{1cm} (3.20)

### 3.1.3.7 Fixed pattern noise

All pixels do not respond to light in the exact same manner. Some pixels are more sensitive to light than others (called a photo-response non-uniformity or PRNU), some pixels have a greater dark current (a hot pixel), or perhaps a slightly different active response area. In a photon transfer measurement, fixed pattern noise can be removed by subtracting two consecutive images from each other. The standard deviation of the resulting distribution will still contain the random fluctuation in photon arrival rate, however, since variances add, the standard deviation will increase by the square root of 2 (=1.414). This will be taken into account by the data extraction algorithm.

### 3.1.3.8 Signal to Noise Ratio

The camera Signal to Noise ratio is computed by forming the ratio of the offset corrected signal and the standard deviation measured during data collection.

$$\text{SNR} = \frac{S_{\text{ADU}}}{\sigma_{\text{ADU}}}$$  \hspace{1cm} (3.21)

### 3.2 Operating gain measurement

The primary function of an image intensifier is to provide a low noise gain stage as close to the photon detector as possible – as noted in eq. 1.1, the lowest noise occurs when the highest gain is placed earliest in the chain. The amount of gain that the EBCCD generates is dependent on the accelerating voltage, and is thus a controllable parameter. Previous methods of measuring the gain of an EBCCD employ some technique of generating an electron beam of a known current, bombarding the silicon CCD biased as a diode, and measuring the amount of current
generated in the silicon as a result of EBS secondary production. Note that the CCD is not operated as a CCD, but is simply biased so that the secondary electrons and holes created during bombardment separate allowing a current to flow. There is only one current loop for the secondary electrons to flow, and as a result, all secondary electrons flow through the “output” (which is the CCD substrate). When this method is used to compute the device gain, the resulting value is higher than is found using the method described in this dissertation (called the “operating gain”). The manufacturer’s (Hamamatsu) procedure for measuring gain is stated on the next page – many of the device’s signal names (or their function) are not described by the manufacturer for proprietary reasons. The Ln and Lp are contacts to the N and P wells on the substrate. This description and figure 3-3 is included as a reference only and is not used in any computations in this dissertation. Unfortunately, during conversations with Hamamatsu, they were not willing to explain the meaning of the steps in the procedure – they simply stated that this is the procedure to follow.

In the top part of figure 3-3, current is measured out of both the “Ln” and “Lp” outputs to ground, whereas in the bottom part of figure 3-3, current is measured out of the “Ln” output when “Lp” is connected to ground.
The signal lines Ln and Lp are actually the electrical connections to two groups of connected pins. The Ln line is connected to: RD, OS, OD, ISH, ISV (N-well). The Lp line is connected to: RG, OG, SG, PxH, PxV, PGxH, PGxV. Each of the connections is defined on the EBCCD datasheet.

- Measurement of input current:
- Ln and Lp are connected as shown (top diagram in figure 3-3).
- HV is supplied to the EBCCD.
- The light source and ND filter are adjusted so that the current is set to approx. 1 nA (I_{in}).
- The mechanical shutter is closed, and the current is measured in dark conditions (I_{dark}).
- Input current (I_{in}) is the difference between I_{in} and I_{dark}.
- Measurement of amplified current, flowing to the N-well:
- Ln is connected to ammeter, and Lp is connected to GND as shown in the bottom diagram.
• HV is supplied to the EBCCD.
• \( I_{\text{out}} \) is the current measured at same light level in the previous procedure.
• \( I_{\text{outd}} \) is the current measured in the dark (mechanical shutter closed).
• \( I_{\text{out}} \) is the difference between \( I_{\text{out}} \) and \( I_{\text{outd}} \).
• The gain is then calculated as \( G = \frac{I_{\text{out}}}{I_{\text{in}}} \).

**Diagram of figure 3-3**

Figure 3-4 Current flow diagram for factory measurement of input current

Figure 3-5 Current flow diagram for factory measurement of amplified current

Figure 3-4 gives a schematic view of the factory measurement of the input current, where the input current flows through the photocathode and out of the two signal connections \( L_n \) and \( L_p \). This is a valid measurement as it measures the current that flows through the photocathode. However, as seen in figure 3-5, the output current is measured from a connection to the P substrate and N-well, rather than through the output sense node and that the N-well and P-substrate form a diode, allowing holes and electrons both contribute to the current. Holes are not
collected in a CCD potential well. Hamamatsu states that this connection allows measurement of the “amplified” current through the substrate, which is comprised of the secondary electrons generated by electron bombardment. This does not measure the realizable gain through the floating diffusion output sense node. It is not the gain that a system designer can use in calculating radiometric sensitivity performance. It is a measure of the substrate current, which includes both electrons and holes, and also includes electrons that would not normally diffuse to the potential well.

The fundamental difference in this gain measurement method is the fact that, when the CCD is biased as a photodiode (as in the manufacturer’s procedure), there is an assumption that all of the current generated in the photodiode mode would be collected by the CCD potential well. This is very incorrect. As explained in other sections of this dissertation, the combination of a field free region and finite lifetime of electron hole pairs, along with the very short absorption depth causes only a fraction of the electrons to be collected in the well. While there can be a correlation between the number of secondary electrons captured by the potential well and the total number of secondary electrons created, this method does not measure the “gain” of the EBCCD, but only the EBS gain – two different parameters indeed. The EBCCD designers at Hamamatsu have acknowledged this.

![Figure 3-6 Current flow measurement](image)

Figure 3-6 shows the input current from the photocathode splitting into two current paths. The left path is the “signal” path (electrons which are output by the floating diffusion sense node) that contributes to a higher-level system output. The other current loop (shown as the dashed line on the right side of figure 3-6) involves a secondary electron existing in the field free region, or at the back surface depletion region, and later re-combining with a hole or exiting the CCD through the substrate connection to ground. This contributes nothing to the CCD output signal, and is a
loss mechanism. For this reason, a measurement of "gain" can only be properly determined by measuring the number of "signal generating" electrons created, as readout through the CCD readout amplifier number and dividing this number by the number of photoelectrons generated by the photocathode. The method used by other researchers and manufacturers does not differentiate between the number of secondary electrons created, and the number of electrons that actually contribute to output signal.

We are concerned now with how to differentiate these two current loops such that the input electron flux is known, and only the output signal is measured. Fortunately, CCDs are extremely efficient in transporting electrons through the device to the output node. A charge transport efficiency (CTE) of 99.99% is considered "marginally acceptable" today, with 99.999% being the typical value for high-end commercial grade CCDs. As a result, we can use the CCD as its own diagnostic device. In order to do this, we must accurately know several parameters in order to calculate the number of electrons per ADU output by the camera:

- The number of microVolts produced per electron at the output of the CCD
- The gain of the post-CCD amplifier stage(s)
- The conversion gain of the A/D converter

It is for this reason that extensive characterization of the non-intensified CCD was conducted, presented in section 4.1. In order to inject a known electron flux into the CCD, it is necessary to know two quantities accurately: 1) the quantum efficiency of the photocathode, and 2) the light level.

The data collected for this series of tests uses a calibrated photodiode operated in its linear region, and provides an accurate measurement of the light level. The quantum efficiency has been measured by the manufacturer and is taken as a known quantity. Due to the fact that the EBCCD is much more sensitive to light than the photodiode, a calibrated ND 2 filter was placed over the surface of the photocathode. This permits operation of the photon transfer curve measurement at higher light level so that illumination measurements are more accurate. The light is then attenuated by a factor of 100 before it reaches the photocathode.

Known or measurable quantities:

- Light level
- Response of CCD in ADUs (Analog-Digital Units)
- Integration time
• Quantum efficiency of the photocathode

The operating gain is the ratio of the number of collected secondary electrons produced for each incident electron. This can be measured by determining the average signal produced at a known light level as the acceleration voltage is increased. By using the photon transfer curve, an accurate measure of this gain is possible.

For each accelerating voltage, the light level inside the integrating sphere is increased and the photon transfer (camera response vs. light level) is recorded, as shown in figure 3-7. Then a least-squares linear fit to the transfer curve is calculated. The slope of the line is equal to the ADU/μW/cm^2.

![Camera response transfer curve](image)

**Figure 3-7 Camera response transfer curve**

We can convert the slope of this line from units of ADU/μW/cm^2 to ADU/photons/sec per pixel using the relation:

\[
R_{\text{photons/sec}} = \frac{E_{\text{light}}}{\frac{hc}{\lambda}} \cdot A_{\text{pixel}}
\]

(3.22)

where \(R_{\text{photons/sec}}\) is the number of photons per second per pixel, \(E_{\text{light}}\) is the irradiance [Watts/cm^2], \(A_{\text{pixel}}\) is the pixel area, and \(hc/\lambda\) is the energy of a photon at wavelength \(\lambda\).
Once the photon irradiance is known, the input electron flux can be determined by multiplying the photon flux by the quantum efficiency of the photocathode at 550 nm, \( \eta_{pc} = 11\% \). The input electron flux is calculated using the following formula:

\[
N_e = R_{\text{photons/sec}} \eta_{PC} t_{\text{int}}
\]  

(3.23)

where \( N_e \) is the number of electrons emitted from the photocathode, \( \eta_{PC} \) is the quantum efficiency of the photocathode at 550 nm, and \( t_{\text{int}} \) is the effective integration time (including any additional readout time).

The number of secondary electrons collected by the CCD is determined by the depth of the depletion region, the thickness of the CCD, and the backscatter coefficient. The CCD acts as its own diagnostic tool, and the number of collected electrons is simply calculated from a knowledge of the conversion gain of the CCD (\( G_{\text{CCD}} \)) which will be measured in section 4.1.2.2), electronic system gain (\( G_{\text{amp}} = 6.89 \)), and the conversion gain of the A/D converter. The A/D conversion gain is the number of volts per ADU, and in the present case is 2V per 4096 ADUs.

\[
G_{\text{CCD}} = 1.8 \mu V/e
\]  

(3.24)

\[
K_{e/\text{ADU}} = \frac{2V}{(4096 \text{ ADU})(G_{\text{CCD}})(G_{\text{amp}})} = 39 e/ \text{ ADU}
\]  

(3.25)

\[
N_{e,\text{collected}} = S_{\text{ADU}} K_{e/\text{ADU}}
\]  

(3.26)

where \( N_{e,\text{collected}} \) is the number of electrons generated in a certain pixel, and \( S_{\text{ADU}} \) is the converted digital value output by the camera. Thus, by knowing the ratio of the number of primary electrons, \( N_{e,\text{incident}} \) to the number of electrons collected by the CCD, \( N_{e,\text{collected}} \), we can determine the operating gain at that particular accelerating voltage.

\[
\text{Operating gain} = \frac{N_{e,\text{collected}}}{N_{e,\text{incident}}}
\]  

(3.27)

The slope of the linear portion of the plot of camera response vs. electron flux yields the operating gain, so that a least squares linear fit can be performed using all the data obtained in the photon transfer curve measurement to calculate an accurate measurement of the operating gain.

The accuracy of the measurement of the operating gain can be calculated by noting the approximate standard deviations associated with each parameter used to compute the operating gain, as tabulated in table 2.
Table 2  Estimated accuracies of measurements related to mean variance test

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Magnitude of Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light level</td>
<td>5%</td>
</tr>
<tr>
<td>Number of electrons per ADU</td>
<td>5%</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Pixel area</td>
<td>2%</td>
</tr>
<tr>
<td>Integration time</td>
<td>2%</td>
</tr>
</tbody>
</table>

Using normal propagation of errors for statistically independent variables:

\[ \sigma_{total}^2 = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 \sigma_{x_i}^2 \]  

(3.28)

where \( \sigma_{total}^2 \) is the square of the total error, \( N \) is the number of variables with uncertainties, \( \frac{\partial f}{\partial x_i} \) is the partial derivative of the functional dependence with respect to each of the variable \( x_i \), and \( \sigma_{x_i}^2 \) is the square of the error associated with the variable \( x_i \). Since the number of incident electrons is given by eq. 3.23, the uncertainty in the operating gain measurement is approximately 11%. Thus, this method is an accurate method of determining the operating gain and is more accurate than the direct current measuring method.

Due to the fact that the mean variance / photon transfer measurement was repeated for different values of accelerating voltage, we can compute the operating gain for each voltage according to the method just described. Then, the values of the individual slopes can be plotted as a function of the accelerating voltage – yielding a graph of the operating gain vs. accelerating voltage, as will be shown later in figures 4.10 and 4.11. It is important to note that since the slope is used to measure the operating gain, and the slope is found by calculating a linear fit of many data points, we can be quite confident in the precision of the final value obtained since it is the
result of averaging literally millions of pixels. The photon transfer data generated is tabulated by the image acquisition program in a text file according to the following format shown in table 3:

Table 3 Photon transfer data format

<table>
<thead>
<tr>
<th>Incident light $\mu W/cm^2$</th>
<th>Signal produced</th>
<th>raw sigma</th>
<th>corrected sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000000</td>
<td>100.019</td>
<td>6.294</td>
<td>2.399</td>
</tr>
<tr>
<td>0.0014347</td>
<td>107.925</td>
<td>7.245</td>
<td>3.477</td>
</tr>
<tr>
<td>0.0067095</td>
<td>157.427</td>
<td>13.505</td>
<td>8.031</td>
</tr>
<tr>
<td>0.0137424</td>
<td>210.844</td>
<td>17.613</td>
<td>11.750</td>
</tr>
<tr>
<td>0.0190171</td>
<td>252.111</td>
<td>20.357</td>
<td>14.298</td>
</tr>
<tr>
<td>0.0260501</td>
<td>309.986</td>
<td>23.380</td>
<td>17.213</td>
</tr>
<tr>
<td>etc...</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thus, for each light level, the incident light level is known (the actual light level striking the photocathode is reduced by the use of a calibrated ND filter, which is taken into account). For our use, we can disregard the “raw” sigma (this is reported as an intermediate result). The signal and rms noise of the sub-section are also reported. The photon transfer data can be viewed as a tabulation of the mean and standard deviation of a multi-photon distribution. The “signal” is the mean of a multi-photon distribution, and the “corrected sigma” is the standard deviation of that distribution. In figures 3-8 to 3-10, several EBCCD camera response transfer functions are plotted to illustrate the linear relationship between the incident number of electrons and the number of collected electrons (ADU output times e/ADU). The best linear fit line is plotted as a dashed line. Since the response is so linear, the single slope value measures the operating gain for that particular accelerating voltage.
Figure 3-8  Plot of number of output electrons vs. input electrons at 3.98 kV

Figure 3-9  Plot of number of output electrons vs. input electrons at 5.77 kV
Figure 3-10 Plot of number of output electrons vs. input electrons at 8.00 kV

3.3 Noise related measurements

The photon fluence for thermal sources is governed by Poisson statistics and poses a fundamental limit to the signal to noise ratio of any detector. The mean number of the photoelectrons generated by the photocathode $N_e$ is given by:

$$ N_e = \eta_{pc} N_p $$

(3.29)

where $\eta_{pc}$ is the quantum efficiency and $N_p$ is the number of photons incident on the detector. The standard deviation of the number of photoelectrons generated ($\sigma_e$) is given by:

$$ \sigma_e = \sqrt{\eta_{pc} N_p} $$

(3.30)

such that the ratio yields the signal to noise ratio of the number of photoelectrons:

$$ SNR = \frac{N_e}{\sigma_e} = \sqrt{\eta_{pc} N_p} $$

(3.31)
Using the data from the photon transfer curve measurement allows the actual signal to noise ratio of the detector to be calculated. The noise figure is defined as:

$$NF = \frac{SNR_{input}}{SNR_{output}}$$  \hspace{1cm} (3.32)

Thus, if the input SNR is given by the SNR of the photoelectron current, and the output SNR is calculated using the photon transfer data, the noise figure is simply the ratio of the SNRs, as given by equation 3.32.

The SNR is calculated by:
1. quadrature subtraction of the read noise from each of the standard deviations recorded in the photon transfer data
2. subtracting the offset from the signal values
3. forming the ratio at each measured light level of the signal to noise

### 3.4 Using multi-photon PHDs to measure single photon PHD

#### 3.4.1 Multiple photon PHD

When the EBCCD is illuminated with a known mean light level, we can measure the response to that level and plot the histogram of ADUs generated by the camera – forming a multiple photon pulse height distribution. The incident photon stream will be Poisson distributed, and any increase in the measured variance is due to noise sources present within the camera. The pulse height distribution is a way of measuring the variance of the output given a known input.

It is useful to measure the response of the camera to different light levels each at different accelerating voltages. This two dimensional matrix can be represented by two sets of plots: the camera response at several different accelerating voltages for each irradiance level, and the camera response at different irradiance levels for each accelerating voltage. The same information is presented in both sets of figures; however, each set of plots illustrates different facets of the data. The data used in this dissertation is composed of many image sequences, each having 10 frames, taken at different settings of accelerating voltage and levels of photocathode irradiance according to table 4:
Table 4 Acquisition matrix for multi-photon PHD measurement

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>500</th>
<th>2000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.01</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>3.98</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.49</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.96</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.27</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.93</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.24</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.90</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.18</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.59</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to eliminate fixed pattern noise, successive frames (in a 100 x 100 subsection) were subtracted during the multiple photon PHD acquisition. The resulting pattern was analyzed to determine the standard deviation of the frame. The average value (mean) of the subsection was computed for each frame, and these two values were stored. After analyzing each of the 10 frames (9 data points due to frame subtraction), both the mean and standard deviation were themselves averaged and the numbers stored in a data file. The actual histograms were also stored in this data file, and are shown in figures 4-18 through 4-20 in section 4.3.

The figures presented in section 4.3 were generated by plotting the histograms of each measured accelerating voltage level at a given photocathode irradiance. These figures give an indication of the energy discrimination of the EBCCD. Since the light level is held constant, the "width" of a particular distribution is due to the variance generated in the multiplication process. It is important to realize that, assuming the light level is truly constant, one electron is produced for each photon that interacts with the photocathode. The number of secondary electrons that are actually produced is dependent on the random scattering parameters, discussed in section 2.3.3.2.1. The actual number of primary electrons emitted from the photocathode is a function of the Poisson noise distributed incident photon flux. However, the camera response to the average
number of secondary electrons produced per primary electron is not dependent on the incoming photon noise, but only upon the mean value of the photon flux.

### 3.4.2 Single photon PHD

Due to the operating environment of the EBCCD tube measured in section 4 (room temperature at maximum frame rate), it is not possible to measure (with sufficient determinism) the CCDs response to a single primary electron. This was confirmed by the Hamamatsu engineers. However, assuming that the statistics of secondary creation is uncorrelated with the incident photon flux, then it is possible to indirectly measure the single electron pulse height distribution.

Let us consider the noise sources discussed in section 2.4.2.3.2. While five different noise sources are shown, there are three main groups of noise sources.

1. Noise from incident photoelectron stream (#1 in figure 2-17)
2. Noise associated with the gain process (#2, 3, 4 in figure 2-17)
3. Noise associated to the CCD readout structure (#5 in figure 2-17)

Some definitions are in order:

- $N_p$ is the number of electrons emitted when a photocathode with quantum efficiency $\eta_p$ is illuminated by $N_p$ photons.
- $G_G$ is the number of secondary electrons that are collected by a pixel from a single photoelectron (the “Operating gain”).
- $K_{e/ADU}$ is the number of electrons detected at the output amplifier per ADU.
- $\sigma_G$ is the standard deviation of the number of collected secondary electrons produced by one incident electron.
- $\sigma_m$ is the standard deviation (in electrons) of the pulse height distribution when multiple photons (electrons) are detected.
- $\sigma_{mADU}$ is the standard deviation (in ADUs) of the variance in CCD response when uniform illumination is incident over a sub-section of the image (typically 100 x 100).

$N_p$ and $\sigma_{mADU}$ are the only two quantities that we can directly measure.
The number of electrons liberated by the photocathode is given by:

\[ N_e = \eta_p N_p \]  

(3.33)

and the mean number of electrons generated within a pixel is given by:

\[ \mu_m = N_e G_G \]  

(3.34)

In figure 3-11, we note the two PHDs are related such that the mean number of secondary electrons produced by a single photoelectron is equal to the operating gain \( G_G \), and the mean of the multiple photoelectron PHD is equal to the number of photoelectrons times \( G_G \) as shown in equation 3.34.

![Pulse Height Distribution from single photoelectron input](image)

![Pulse Height Distribution from multiple photoelectron input](image)

**Figure 3-11 Single and Multiple Pulse Height Distributions**

We will collect the terms associated with the gain process into one “noise source” and label it as \( \sigma_G \). We can now derive an equation relating the multiple photoelectron PHD variance to the variance associated with a single photoelectron PHD. Assuming the distribution functions are uncorrelated, we may add variances according to the rules for cascaded gain stages, as shown in eq. 1.1 (note that the addition of the read noise is not “cascaded” but additive).

\[
\begin{align*}
\sigma_m^2 &= N_p \eta_p^2 G_G^2 + N_p \eta_p (1 - \eta_p) G_G^2 + N_p \eta_p \sigma_G^2 + \sigma_{\text{CCD}}^2 \\
\sigma_m^2 &= N_p \eta_p^2 G_G^2 + N_p \eta_p \sigma_G^2 + \sigma_{\text{CCD}}^2 \\
\sigma_m^2 &= N_e G_G^2 + N_e \sigma_G^2 + \sigma_{\text{CCD}}^2 = N_e (G_G^2 + \sigma_G^2) + \sigma_{\text{CCD}}^2
\end{align*}
\]  

(3.35)

We can relate the actual standard deviation (in electrons) to the standard deviation (in ADUs) by the conversion factor \( K_e/\text{ADU} \):
\[
\sigma_{\text{mADU}} = \frac{1}{K_{\text{e/ADU}}} \sigma_m
\]  
(3.36)

Making this substitution,
\[
\left( \sigma_{\text{mADU}} K_{\text{e/ADU}} \right)^2 = N_e \left( G_G^2 + \sigma_G^2 \right) + \sigma_{\text{CCD}}^2
\]  
(3.37)
\[
\frac{\left( \sigma_{\text{mADU}} K_{\text{e/ADU}} \right)^2 - \sigma_{\text{CCD}}^2}{N_e} = G_G^2 + \sigma_G^2
\]  
(3.38)
\[
\sigma_G^2 = \frac{\left( \sigma_{\text{mADU}} K_{\text{e/ADU}} \right)^2 - \sigma_{\text{CCD}}^2}{N_e} - G_G^2
\]  
(3.39)

and finally solving for the standard deviation of gain creation, in terms of measurable quantities:
\[
\sigma_G = \sqrt{\frac{\left( \sigma_{\text{mADU}} K_{\text{e/ADU}} \right)^2 - \sigma_{\text{CCD}}^2}{N_e} - G_G^2}
\]  
(3.40)

Note that if:
\[
G_G^2 \left( \sigma_{\text{mADU}} K_{\text{e/ADU}} \right)^2 - \sigma_{\text{CCD}}^2 \quad \text{or} \quad G_G^2 \left( \sigma_{\text{mADU}} K_{\text{e/ADU}} \right)^2 - \sigma_{\text{CCD}}^2 \quad \eta_{\text{pc}} N_p
\]  
(3.41)

then the radical will become negative, and the gain standard deviation will be imaginary – a non-physical result.

It is important to emphasize that the data acquired in the mean variance / photon transfer analysis is in fact recording the mean and standard deviation of a multiple photon PHD, acquired at a particular light level (multiple photons incident). Due to the large number of data points taken in this procedure, the mean variance / photon transfer data is used in practice to extrapolate the means and variances corresponding to single photon illumination.

When this technique is applied, it is possible to measure the standard deviation of the single electron pulse height distribution, which is the uncertainty of the exact number of electrons that will be collected following absorption of a single photoelectron.
3.5 Aluminum thickness and variation induced gain fluctuations

3.5.1 Aluminum thickness measured by optical means

It is possible to measure both the thickness of the aluminum coating deposited over the CCD and parameters relating to the size and thickness variation of the defects found in this coating (such as the difference in operating gain caused by the defects). This is accomplished using empirical knowledge of the underlying CCD quantum efficiency and the approximate absorption of the photocathode material. The aluminum layer was deposited on the back of the silicon using an evaporative process where aluminum was vaporized and allowed to condense on the surface of the silicon. Since the CCD back surface is not perfectly planar and small bumps and thin portions are left from non-uniform etching, as diagrammed in figure 3-12. These bumps affect the thickness of deposited aluminum due to shadowing effects and differences in adhesion.

![Figure 3-12 Aluminum thickness variation diagram](image)

The variation in thickness of aluminum causes a variation in the amount of energy deposited by a primary electron in the silicon. In order to measure this gain variance we must first measure the variance of the aluminum thickness in those regions defined as “pin-defects”. It is then necessary to determine the statistics of the aluminum thickness. This is measured by observing the statistical distribution of the amount of light transmitted through the aluminum layer.

The aluminum thickness variations are measured using knowledge of the optical properties of aluminum and the CCD response to optical radiation. It is first necessary to define a threshold value of optical response where values larger than the threshold are classified as pin-
defects. The optical response of the EBCCD detector is measured when it is uniformly illuminated by light with no applied accelerating voltage. Then, a histogram of values above the defined threshold is created. Using the results found in the nominal thickness determination, the optical response histogram is mapped to create a histogram of aluminum thickness values.

If we estimate that the photocathode absorbs roughly 50% of the light incident upon it, and know that the CCD quantum efficiency ($\eta_{ccd}$) is 40% at 550 nm, we can calculate the expected number $N_e$ of electrons to be collected by the CCD pixel as:

$$N_{e,expected} = D_{absorb} A_{pixel} E_{light} t_{in} G_{light} \eta_{ccd}$$

where $D_{absorb}$ is the percentage of light absorbed by the photocathode, $A_{pixel}$ is the area of the pixel, $E_{light}$ is the irradiance on the photocathode in photons per second per unit area, $t_{in}$ is the integration time (including readout), $G_{light}$ is the conversion between irradiance and photons/(sec*cm$^2$) at 550 nm. We calculate the actual number of electrons from the equation:

$$N_{ADU} = \frac{N_{e,measured}}{K_e/ADU}$$

where $N_{ADU}$ is the camera response at a pixel, and $K_e/ADU$ is the conversion between ADUs and electrons. The thickness of the aluminum coating can be estimated by using the Beer-Lambert law of absorption:

$$I = I_0 e^{-\alpha d}$$

Where $I_0$ is the initial intensity of the source, $\alpha$ is the attenuation coefficient, $d$ is the distance into the object, and $I$ is the intensity at distance $d$. The actual thickness of the aluminum can then be determined by measuring the average light level of pixels that are clearly covered with a uniform thickness of aluminum. The ratio of the measured pixel value and the predicted pixel value given by eq. 3.42 is substituted into equation 3.44 to determine the thickness:

$$d = - \frac{\ln\left(\frac{N_{e,measured}}{N_{e,expected}}\right)}{-\alpha}$$

### 3.5.2 Pin-defects

A pin-defect in the aluminum is defined somewhat subjectively, and for the purposes of this dissertation will be defined as any region on the CCD whose optical response is greater than
275 ADUs at a light level of .5 \mu W/cm^2. This value was chosen by observing the image and noting the ADU value above which only bright spots were evident. It is important to note that a pin-defect is not a "hole" in the aluminum, but is a local region of less than nominal aluminum thickness, as diagrammed in fig 3-12. A cluster is defined as a contiguous grouping of one or more "pin-defects". The cluster size is the number of contiguous pin-defects. The image was analyzed using a computer routine that thresholds all values below 275 and used a region growing algorithm to find contiguous pixels with values above the threshold. Each cluster group was recorded along with the number of "pin-defects" making up the cluster, thus determining the cluster size.

The number of pin-defects and the cluster size determination is important because different thicknesses of aluminum impose a different dead layer voltage, affecting the variance of the EBS gain.

### 3.5.3 Gain variance resulting from aluminum thickness variation

Now that the distribution function of pin-defect thickness is known, we can estimate the effect on the dead layer voltage variation caused by the thickness variation according to (3.46)

$$\Delta E = \int_{d_\text{th}}^{d_{\text{nominal}}} \frac{dE_{\text{beam}}}{dx} \, dx$$

where \(d_\text{th}\) is the distance according to the thinnest portion of the aluminum and \(d_{\text{nominal}}\) is the nominal thickness of the aluminum. The relative change in energy, \(\Delta E\), of an electron is equal to the amount of energy change due to different penetration thickness compared to the nominal thickness.

The measure of the deviation of the gain due to Aluminum thickness variation will be to determine the gain variation at the maximum and minimum thicknesses found for pin defects. This establishes the maximum difference of the energy lost and referred to as \(\Delta E\).

The effect on the gain due to the energy deposition variance is calculated by:

$$m_{\text{gain}} = \frac{dG(E_{\text{beam}})}{dE_{\text{beam}}} (\Delta E)$$

where \(G(E_{\text{beam}})\) is the gain vs. energy function, \(\Delta E\) is the energy lost, and \(m_{\text{gain}}\) is a parameter describing the maximum gain variation corresponding to the energy variance.
3.6 **EBCCD Tube MTF**

The spatial resolution of the EBCCD was measured by imaging a line edge with a high-resolution lens. The lens MTF is much higher than that of the detector array so that it does not degrade the relayed image quality.

Figure 3-13 Line edge picture taken with EBCCD

A line profile, called the edge response $e(x)$, is measured perpendicular to the diagonal line shown in figure 3-13. The spatial derivative of $e(x)$ is computed and yields the line response $l(x)$. The MTF is then calculated by taking the modulus of the Fourier transform of the line response, scaling the distances appropriately.

$$MTF = \left| \mathfrak{F} \left[ l(x) \right] \right| = \left| \mathfrak{F} \left[ \frac{d}{dx} (e(x)) \right] \right| \quad (3.48)$$

3.7 **Secondary Electron Capture Probability**

3.7.1 **Capture model basis**

As mentioned in the section discussing the predicted performance of the EBCCD, there is a probability associated with the collection of a secondary electron by the CCD potential well. Thus, the actual gain is less than the number of secondary electrons generated as given in eq. 2.22. Relating back to a previous point, if you measure the gain by a simple ratio of currents, you will most likely measure the actual EBS gain – this is however NOT a useful parameter for EBCCDs. While EBCCDs operate based upon EBS gain, only a fraction of this gain is usable in a two-dimensional imaging system. The “ratio of currents” method can provide a figure of merit,
useful for industrial scale manufacturing diagnostics, but does not measure what the actual device is capable of in normal operation. Furthermore, two EBCCD tubes with identical EBS gain measurements using the ratio of currents method, may have quite different operating gains.

We then follow the proposal of Stearns and Wiedwald\(^2\) who proposed the concept of an electron capture probability function that is depth dependent— a function that describes the probability \(p(x)\) that a secondary electron generated at depth \(x\) will be captured by the CCD potential well.

Stearns and Wiedwald proposed a semi-empirical model of the collection efficiency as:

\[
p(x) = 1 - (a_0 e^{-x/L})^2
\]

Where \(x\) is the distance into the material, and \(a_0\) and \(L\) are empirical constants. This functional form will be adopted as the basis of our method of measurement of the probability of secondary electron capture.

From a phenomenological viewpoint, consider a EBCCD with a 15 \(\mu\)m thick silicon thickness. The minimum electron energy (highest potential) occurs very close to the MOS oxide layer, perhaps 2-3 \(\mu\)m below it (as diagrammed in fig. 2.4). The majority of incident primary electrons below about 3 kV do not produce many, if any, secondary electrons, and thus we surmise that the probability of detection at the Grün range of a 3 keV electron is very low. Similarly, if a primary electron dissipated most of its energy near the CCD buried channel, the detection probability is close to 100 %. Thus, there is a spatially varying probability that an electron will be captured, as diagrammed in figure 3-14. Obviously, whether a secondary electron is captured is largely dependent on the energy of the primary electron. However, the following method will allow the primary energy to be removed as a parameter, leaving only the spatially varying (in the depth dimension) detection probability to be measured. Due to the very small radial component of the velocity, electrons enter the silicon normal to the surface and the angular affect of velocity can be neglected in determining the capture probability.
This is a powerful technique because it is impossible to use a physical probe to measure the potential at very shallow depths below the back surface.

Both EBCCD tubes have a dead layer (comprised of mostly aluminum coating and surface oxides) of approximately 4 kV as measured and reported in section 4.2.1. Thus, according to eq. 2.22, at an 8 kV potential between the photocathode and the CCD, 4 keV of energy is deposited in the CCD. This should yield a measured gain value of approximately 1095, but in reality only yields about 110. Hamamatsu measured a gain of 600 at 8 kV bias (again, this was using their ratio of currents method described in section 3.2). It is expected that the expected number of secondaries are in fact created within the CCD; however, conditions are such that only about $\frac{1}{10^6}$ of these secondaries are actually collected by the CCD potential well. Engineers at Hamamatsu Corp. have confirmed this, although the explanation was not given and was classified as "company proprietary". If the gain really was 1095, then at a conversion factor of 39 electrons per ADU (measured in section 4.1.2.2), a single photoelectron would have produced a signal of 28 ADUs – which would have been easily distinguished during analysis. Since the suspicions of actual gain being different were verified, a model of the probability of detection is warranted and both a phenomenological and quantitative treatise is presented.

Since secondary electrons are created at different distances from the CCD buried channel, according to the absorbed dose curve (discussed in section 2.3.3.3), and that the existence of a field free region allows a certain number of electrons to recombine with their associated holes implies that the probability of a given secondary electron actually reaching the buried channel potential well of the CCD (and thus becoming "signal charge") is spatially dependent in the "thickness" dimension.

A simple "linear dead layer" model does not reflect the continuously varying collection efficiency that is necessary for an accurate model.
3.7.2 Generation of model

We begin with a discussion of the creation of the probability detection model. The integral of the differential energy loss function yields the total energy ($E_{dissipated}$) lost by an electron beam as it penetrates a material:

$$ E_{dissipated} = \int dx \left( \frac{dE}{dx} \right) $$

The functional form of $dE/dx$ is given by eq. 2.26.

We use the functional form $p(x)$ described in eq. 3.49 which describes the probability of electron capture as measured from the back surface of the CCD (including the thin aluminum coating layer), the amount of energy deposited ($E_{absorbed}$) within the capture range of the CCD well is given by:

$$ E_{absorbed} = \int_0^d dx \left( \frac{dE}{dx} \right) p(x) $$

where $d$ is the thickness of the CCD. From other experiments, including the mean variance data, we know the actual number of secondary electrons captured by the potential well as a function of the photocathode bias – namely the operating gain. Thus, we can equate the operating gain as a function of energy, $G(E)$ with the absorbed energy, using eq. 2.22, with eq. 3.51 or:

$$ 3.65 \cdot G(E) = \int_0^d dx \left( \frac{dE}{dx} \right) p(x) $$

If the function $p(x)$ were identically equal to unity, then any deposited energy would result in secondary electron capture by the potential well. Another way of saying this is that there would be no dead layer, and first order EBS theory would accurately model the system. This can be expressed mathematically as:

$$ EBS \ gain = \frac{Energy}{3.65} = \int_0^d \left( \frac{dE}{dx} \right) dx $$

The question then becomes: What is the functional form of $p(x)$ such that eq. 3.52 holds true for all measured values of $G(E)$? Using a Levenberg-Marquardt minimization technique, we can find the coefficients “$a_0$” and “L” in eq. 3.49 such that the following equation:
\[ \varepsilon = \int_0^d \left( \frac{dE}{dx} \right) p(x) dx - 3.65 \cdot G(E) \] (3.54)

has a minimum value of \( \varepsilon \).

Once the parameters describing the \( p(x) \) function are found, the model can be validated by back substitution into eq. 3.52 and the error noted between the measured \( G(E) \) function and the integrated collection efficiency function \( p(x) \).

### 3.8 EBCCD Figures of Merit

Section 3.1.3 discussed figures of merit for visible light imaging CCDs that can be reduced from the mean variance / photon transfer curve information. The figures of merit in this section are related to CCDs used for direct electron detection. Some of the figures of merit are similar (such as the dynamic range), and will be replicated here with additional information relating the figure of merit to electron detection.

#### 3.8.1 Gain

The primary purpose of an image intensifier tube is to provide a gain stage. Thus, the primary figure of merit for such device is the amount of gain that is generated by the tube. Direct-view image tubes normally specify the gain in terms of the luminous gain, that is, the ratio of photocathode irradiance (foot candles or lux) to output phosphor luminance (foot Lamberts). Gain can also be specified in terms of the radiant power gain, or power on the photocathode (Watts) to the power radiated by the phosphor (Watts). For signal generating tubes, in particular the EBCCD, the gain should be specified in terms of the quantum gain, or the ratio of the number of electrons detected by the camera to the number of photoelectrons generated by the photocathode – defined earlier as the “operating gain”. In this way, there is no ambiguity as to spectral region of interest or assumptions made regarding the angular distribution of exitance when evaluating direct-view devices. The operating gain is then completely dependent on the gain and detection mechanism, not on the photocathode. The radiometric sensitivity is then easily determined by multiplying the operating gain by the quantum efficiency of the photocathode – yielding a ratio of the number of incident photons to the number of collected “signal” electrons detected by the CCD.
3.8.2 Dynamic range

The dynamic range is a figure of merit that characterizes the ability of a device to respond to different signal levels present in a given scene. It is computed by forming the ratio of the largest to smallest signals that the device can measure. In the case of the EBCCD, the largest signal is limited by the full well capacity of the CCD, and the smallest signal is defined as the noise floor, which may be limited at high gain levels, by the discrete nature of photoemission.

3.8.3 Non-Linearity

The non-linearity of a device is a measure of the deviation from linear operation. The differential non-linearity (DNL) is a measure of the maximum error difference between the actual response, and the best "linear fit" to the camera response.

3.8.4 Signal to Noise Ratio

The signal to noise ratio (SNR) is a measure of the ability of a device to convey usable information. Every real device contributes additional noise to a communication channel, as well as generating some output signal for a given amount of input.

3.8.5 Noise Figure

The noise figure of a device is closely related to the SNR and describes the additional noise a device contributes. The noise figure is computed by the ratio of the SNR of an "ideal" device (SNR\text{ideal}), that is, the theoretical maximum SNR achievable, to the actual SNR (SNR\text{actual}) of the device. For an image intensifier, the maximum SNR that can be achieved is when the SNR is limited only by photon noise:

$$SNR_{\text{ideal}} = \sqrt{\eta_{pc} N_p}$$

where $\eta_{pc}$ is the quantum efficiency of a photocathode, and $N_p$ is the number of incident photons. Thus, the noise figure is given by:

$$NF = \frac{SNR_{\text{ideal}}}{SNR_{\text{actual}}} = \frac{\sqrt{\eta_{pc} N_p}}{SNR_{\text{actual}}}$$

For example, if there are 1000 photons incident on the photocathode, which has a 10% quantum efficiency, the number of photoelectrons would be 100, and the ideal SNR would be 10,
according to eq. 3.55. If the signal to noise ratio of an EBCCD was measured to be 5, with 1000 photons incident on the photocathode, then the noise figure would be 2, according to eq 3.56.

### 3.8.6 Detective Quantum Efficiency

The detective quantum efficiency is a parameter that characterizes the input and output fluctuations including noise rather than just the input and output amplitudes (such as the quantum efficiency). It is a measure of the overall utilization efficiency of a device—how many photons, out of 100 that enter the system, are actually used to produce a signal. The DQE is defined as:

\[
DQE = \frac{SNR_{out}^2}{SNR_{in}^2}
\]  (3.57)

Thus, when a photocathode detector is limited only by photon noise, we find:

\[
SNR_{in} = \sqrt{N_p}
\]  (3.58)

\[
SNR_{out} = \sqrt{\eta_{pc}N_p}
\]  (3.59)

where \(\eta_{pc}\) is the quantum efficiency of the photocathode. Therefore, in the ideal situation with no additional device noise, the maximum DQE \((DQE_{max})\) for any detector is given by its quantum efficiency:

\[
DQE_{max} = \eta_{pc}
\]  (3.60)

Any reduction in the DQE is a measure of what percent of the incident signal is actually detected by a device. It is related to the noise figure, defined in eq. 3.56, by the equation:

\[
DQE = \frac{\eta_{pc}}{(NF)^2}
\]  (3.61)

### 3.8.7 Fixed pattern noise

Fixed pattern noise is a spatially dependent, but not temporally dependent, variation of detector response under uniform illumination. Typically, fixed pattern noise results from imperfect manufacturing processes. The noise can arise from non-uniform response to electrons and the variation in the thickness and presence of holes in the aluminum layer deposited on the silicon. The fixed pattern noise of an imaging system can easily be measured by measuring the standard deviation of the average output signal from each pixel when the detector is uniformly

...
illuminated. This allows measurement of the difference in average pixel response by separating the time dependent noise due to photon and electrical noise sources.
4 Results of EBCCD Characterization

The following Table lists the results of the measurements techniques applied to both tubes.

Table 5 Measured values of EBCCD Figures of Merit

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Tube 1</th>
<th>Tube 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max non-intensified DNL (%)</td>
<td>2.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Sense Node Gain (μV/e)</td>
<td>2.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Full Well Capacity (e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read Noise (e)</td>
<td>37</td>
<td>55</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>3150</td>
<td>2925</td>
</tr>
<tr>
<td>Radiometric Sensitivity (non-intensified) nW/cm²/ADU</td>
<td>Unavail</td>
<td>1.89</td>
</tr>
<tr>
<td>Operating Gain at 8kV</td>
<td>81</td>
<td>110</td>
</tr>
<tr>
<td>Operating Gain at 5kV</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Standard Deviation of Operating Gain at 8kV</td>
<td>75.4</td>
<td>34.8</td>
</tr>
<tr>
<td>Standard Deviation of Operating Gain at 5 kV</td>
<td>26.9</td>
<td>21</td>
</tr>
<tr>
<td>Max intensified DNL (%)</td>
<td>2.3</td>
<td>3</td>
</tr>
<tr>
<td>Radiometric Sensitivity at 8kV(non-intensified) fW/cm²/ADU</td>
<td>676</td>
<td>269</td>
</tr>
<tr>
<td>Noise Figure at 8 kV</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>DQE at 8 kV (%)</td>
<td>5</td>
<td>7.2</td>
</tr>
<tr>
<td>Aluminum Thickness (nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probability &quot;L&quot; parameter (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTF at 3% (lp/mm)</td>
<td>12</td>
<td>Unavail</td>
</tr>
</tbody>
</table>

4.1 Non-Intensified CCD parameters

EBCCD intensifiers are devices that combine aspects of a photocathode / tube with a silicon electron gain stage and output multiplexer. Thus, a complete characterization of the tube requires analysis of both the gain and CCD transport mechanisms.

Note: Section 4 presents information found from applying the characterization methods to two EBCCD tubes and assumes familiarity with the theory presented in section 2 and the methods discussed in section 3 of this dissertation.
Several measurements of the gain stage parameters require knowledge of the CCD behavior, since we can only measure the number of electrons produced per pixel after they have passed through the CCD. We begin by measuring several parameters related to the CCD before the high voltage is applied and the device operated in an EBCCD mode. These parameters (such as the camera gain, read noise, etc.) are measured using the mean variance analysis discussed earlier in section 3.1. Due to the aluminum coating covering the back surface of the CCD, as well as the absorptive photocathode above it, the radiometric sensitivity of the CCD is quite poor, but this is by design. These measurements are necessary so that we may determine the noise sources and effects related to the CCD so that we can then measure the system as a whole – thereby allowing measurements of the hybrid device decoupled from the operation of a normal CCD. Once these measurements are performed, the CCD is then operated as a EBCCD – where we characterize the response to electrons as opposed to photons.

Two different tubes of equivalent design are characterized in the following sections. While both tubes were manufactured similarly, the first tube (Tube 1) suffered damage from an unknown source, which greatly affected its performance. By the time part of the research had been complete, the damage was sufficient to prevent testing of the aluminum coverage. As a result, some measurements were made with only one tube. The second tube (Tube 2) is indicative of the nominal behavior of these particular tubes (Hamamatsu N7220).
4.1.1 Tube #1 Non-intensified Measurements

4.1.1.1 Linearity – tube 1

Figure 4-1 Camera Response for Tube #1

Figure 4-1 is a plot of the camera transfer function for CCD contained in Tube #1 – through the Aluminum coating. Again, these tests were performed with no accelerating voltage, and the CCD is responding to photons – not electrons. This is a “mapping” of the camera’s response produced at a given light level. The first figure of merit that can be extracted from the camera transfer plot is a measure of the camera linearity. By plotting the camera response (in ADUs) against the illumination level and calculating a least-squares linear fit, each measured data point can be compared to the “best fit” line. Using the formula:

\[ DNL = \frac{|actual - best\ fit|}{4096} \times 100\% \]  \hspace{1cm} (4.1)

the differential non-linearity (DNL) can be calculated (the 4096 in the denominator is the full scale output of the 12 bit camera). The DNL is plotted in figure 4-2:
The electronics have been independently characterized and have less than .5% INL (integral non-linearity). Thus, the majority of the non-linearity comes from the CCD itself. A 1-2% DNL is within the limits of acceptability given current processing methods using a single stage, on-chip, FET follower amplifier. At the upper range of the output, the output at the FET follower becomes quite non-linear because of saturation of the sense node.

4.1.1.2 CCD sense node conversion gain – tube 1

Figure 4-2 DNL for Tube #1

Figure 4-3 Mean-Variance plot for Tube #1
The node sensitivity can be measured using the mean variance analysis. The mean variance plot for Tube #1 is shown in figure 4-3, and the linear “best-fit” has the equation:

\[
\text{variance} = 0.0353 \cdot \text{signal} + 15.2
\]  \hspace{1cm} (4.2)

The slope is in units of ADUs/electron, such that the inverse yields the number of electrons per ADU as 28.3. Since we know the different gains occurring in the electronics following the CCD, we can compute the sense node conversion gain. Each ADU is equivalent to 488\(\mu\)V, the pre-amp has a gain of 6.89, and the camera conversion gain was measured to be 28.3 e/ADU.

\[
\text{conversion gain} = \frac{2V}{(4096 \text{ ADU})(6.89)(28.3 \text{ e/ADU})}
\]  \hspace{1cm} (4.3)

Thus, the sense node conversion gain is 2.5 \(\mu\)V/e\(^{-}\).

The measured values shown in figure 4-3 become erratic beyond about 2800 ADUs for unknown reasons.

**4.1.1.3 Full Well capacity – Tube 1**

![Graph of Variance vs Signal]  \hspace{1cm} Figure 4-4 Another Mean Variance Plot for Tube #1 (taken on 4/20/1998)

Mean variance data taken prior to the tube damage is shown in figure 4-4. For this data set, the peak variance occurs at a signal level of 2493, and the linear portion of the curve between the signal values of 0 and 2493 ADUs yields a linear curve fit of
\[ \text{variance} = 0.014689 \cdot \text{signal} + 13.02 \]  

(4.4)

The conversion gain in electrons per ADU is the inverse of the slope, or 68 e/ADU. The full well capacity is then calculated to be 68 x 2493 = 170,000 electrons. The conversion gain mentioned in this measurement section is different than used in other sections (such as the 28.3 e/ADU discussed in section 4.1.1.2) because the gain of the op-amp configuration was altered for this full well capacity measurement. The full well capacity is a property of the CCD device architecture and independent of the conversion gain, and is valid regardless of the post-CCD signal processing electronics.

4.1.1.4 Read noise – tube 1

The read noise for Tube #1 was measured to be 1.312 ADU or 37 electrons. This is measured by computing the subtracted standard deviation when the camera was in total darkness.

4.1.1.5 Fixed pattern noise – tube 1

![Graph](image)

Figure 4-5 Unsubtracted noise for Tube #1

Figure 4-5 illustrates the total amount of pattern noise present at various light levels. If the noise were purely due to photon shot noise, the plot would follow a square-root dependence and would attain a unsubtracted sigma maximum value of approximately 10-13 ADUs (corresponding to a full well capacity of approximately 170 ke). The plot indicates that the maximum value (350 ADUs) is much higher than the shot noise limited case (13 ADUs), indicating that there is a large amount of fixed pattern noise. This is as expected due to the large number of pin-defects in the aluminum layer deposited over the back surface of the CCD. The standard deviation decreases from its maximum value attained at 2.9 \( \mu \text{W/cm}^2 \) due to some of the
pixels beneath pin-defects reaching a full well condition and spilling excess charge into neighboring pixels – causing on-chip averaging which reduces the standard deviation.

4.1.1.6 Dynamic range – tube 1

As was previously discussed, Tube #1 suffered damage from an unknown source during testing. As a result, the data used for dynamic range results is taken from early “pre-damage” measurements. During the month of March, 1998, the EBCCD had a rms noise floor of 1.3 ADU rms, and a full scale of 4095, thus, the dynamic range is 4095/1.3 = 3150. Again, the doubling of the variance was taken into account during noise subtraction.

4.1.2 Tube #2 Non-intensified Measurements

4.1.2.1 Linearity – tube 2

![Figure 4-6 Camera Response vs. illumination Tube #2](image)

Figure 4-6 is the camera response for Tube #2. Clearly the tube is very linear except at the highest illuminations where the sense node begins to saturate.
Figure 4-7  CCD Non-linearity vs. illumination Tube #2

Again, the same comments discussed in 4.1.1.1 hold true regarding figure 4-7 that shows the Differential Non-linearity for Tube #2. The maximum DNL of 2% is quite acceptable given the single stage, loaded FET follower, amplifier as exists in the output structure of the CCDs.
4.1.2.2 CCD sense node conversion gain – tube 2

Observing figure 4-8, we note that the variance rises linearly with signal (due to photon noise) up until about 1200 counts. At this point, the graph changes to a slope equal to about half of the initial slope. At this point, light coming through the open portions of the aluminum causes certain pixels to reach full well. Once the pixel reaches its full well capacity, charge spills over into neighboring pixels, which has the effect of averaging the amount of charge in nearby pixels, reducing the noise. Nevertheless, by fitting a line to the first part of the graph, we can compute the camera conversion gain. The equation of the best-fit line to the first portion of the above graph is:

\[ \text{variance} = 0.02534 \cdot \text{signal} + 10.419 \]  

The slope is in units of ADUs/electron, such that the inverse yields the number of electrons per ADU as 39.5. Thus, the sense node conversion gain is computed as:

\[ G_{\text{cod}} = \frac{2V}{(4096 \text{ ADU})(6.89)(39.5 \text{ e/ADU})} \]  

Thus, the sense node conversion gain is 1.8 μV/e⁻.
4.1.2.3 Full well capacity – tube 2

The photon transfer station was unable to provide sufficient illumination to create a full well condition in the Tube #2, due to the aluminum layer – since it reduces the incident flux by approximately 900.

4.1.2.4 Read noise – tube 2

The read noise for Tube #2 was measured to be 1.4 ADUs or 55 electrons.

4.1.2.5 Fixed pattern noise – tube 2

\[
\begin{array}{c|c|c|c|c|c|c|c}
\hline
\text{Illumination (uW/cm}^2) & 0 & 1 & 2 & 3 & 4 & 5 & 6 \\
\hline
\text{Unsubtracted sdev (ADU)} & 0 & 100 & 300 & 500 & 700 & 900 \\
\hline
\end{array}
\]

Figure 4-9 Unsubtracted Noise for Tube #2

It is useful to compare figure 4.5 (unsubtracted noise Tube#1) with figure 4-9. Note that the unsubtracted noise for Tube #2 is much greater than Tube #1. This is a consequence of many more defects (aluminum thickness variations) in the aluminum coating in Tube #2.

4.1.2.6 Dynamic range – tube 2

The dynamic range of Tube #2 is calculated to be 4095/1.4 ADUs = 2925.

4.1.2.7 Radiometric sensitivity – tube 2

The slope of the camera response curve (in the linear region) is given in units of ADUs/(\mu W/cm^2). This same number is also equal to the radiometric sensitivity of the unbiased CCD. That is, the sensitivity when there is no high voltage bias between the CCD and the photocathode. As a result, only photons can create signal within the CCD because there are no
photoelectrons that are accelerated by a voltage bias which could cause additional signal to be generated. The slope of the camera response curve for Tube #2 is 529 ADUs/(μW/cm²), thus, 1 ADU is equivalent to a surface irradiance of .00189 μW/cm².

4.2 **Intensified EBCCD Measurements**

We now turn our attention to characterizing the device’s response to electrons – the goal of our studies. The operating gain is measured according to the methods outlined in section 3.2.

4.2.1 **Operating gain v. energy for both N7220 types**

4.2.1.1 **Operating gain for Tube #1**

![Graph: System gain and Gain noise vs. energy](image)

**Figure 4-10 Operating gain vs. accelerating voltage for Tube #1**

The measured operating gain vs. accelerating voltage is shown in figure 4-10. Tube #1 achieves a maximum operating gain of 82 at an accelerating voltage of 8 kV. The standard deviation of the gain for both tubes will be discussed in section 4.3.2.
4.2.1.2 Operating gain for Tube #2

The measured operating gain vs. accelerating voltage for Tube #2 is shown in figure 4-11. Tube #2 achieves a maximum operating gain of 110 at an accelerating voltage of 8 kV. Note that the maximum operating gain of Tube #2 is 34% higher than the maximum operating gain of Tube #1, for unknown reasons.

4.2.2 Linearity

We can measure the linearity of the EBCCD’s response to light using a similar method described in section 3.2. The linear region of the operating gain plot (defined as those values 5 kV and above) can be compared to the least squares linear fit and the differential non-linearity can be computed as

\[ DNL = 100 \cdot \left| \frac{\text{system gain} - \text{linear fit}}{\max(gain)} \right| \% \]  

(4.7)
where \( \text{max}(\text{gain}) \) is the maximum gain measured (which for Tube #2 is 110).

Recall that since DNL is a percentage error from true linearity, the values are the absolute value of the error – thus the shape of the figures 4.12 and 4.13 are shifted parabolas (positive and negative portions), which have been reflected due to the absolute value operator.

### 4.2.2.1 Differential Non-linearity of CCD in Tube #1

![DNL Graph](image)

**Figure 4-12** DNL of Operating gain for Tube #1 vs. Accelerating Voltage
4.2.2.2 Differential Non-linearity of CCD in Tube #2

Figure 4-13 DNL of Operating gain for Tube #2 vs. Accelerating Voltage

4.2.3 Radiometric Sensitivity

Figure 4-14 shows a plot of the radiometric sensitivity (in units of fW/cm²/ADU) as a function of accelerating voltage. These plots are generated by computing the slope of the camera response curve in units of ADUs per photon incident on the photocathode directly above a pixel. For each tube, the radiometric sensitivity is plotted vs. accelerating voltage. Due to the 1/x shape of the graph, the plot is presented in log form to show greater detail at the higher voltages. Since the number of electrons generated for a given number of illuminating photons is related by the photocathode quantum efficiency, we can plot the number of electrons that are incident on a pixel per ADU. Note that as the sensitivity of the EBCCD camera increases above 1 electron / ADU, the EBCCD is capable of detecting a single electron emitted from the photocathode. Thus, the claim can be made that the imaging system can detect single photons. While the finite quantum efficiency of the photocathode does not “detect” every photon (i.e. only about 11% of photons generate photoelectrons), if a photon does create a photoelectron, the EBCCD can “statistically” detect that photoelectron – in terms of a pixel by pixel SNR.
4.2.3.1 Radiometric Sensitivity of Intensified EBCCD Tube #1

Figure 4-14 Radiometric Sensitivity of Tube #1 vs. Accelerating Voltage

The radiometric sensitivity of Tube #1 is shown in figure 4-14 (note the y axis log scale).
Figure 4-15 Incident Electron Sensitivity of Tube #1 vs. Accelerating Voltage

Referring to figure 4-15, note that the number of electrons incident to create 1 ADU of signal does not reach unity until 8 kV – which is the highest voltage the tube is rated for. The number of electrons per pixel per ADU is simply a measure of the ratio of the system response to a single photoelectron. As the number of electrons per pixel per ADU decreases, single photoelectron detection becomes more achievable. Recall that a Gen II/III tube must operate at very high gains (limiting the intra-scene dynamic range) to achieve single photon detection.
4.2.3.2 Radiometric Sensitivity of Intensified EBCCD Tube #2

The radiometric sensitivity of Tube #2 is shown in figure 4-16 (note the y axis log scale). Even though the first tube suffered damage to the readout structure, both tubes show significant ability to image scenes at extremely low light levels.
As seen in figure 4-17, Tube #2 reaches the single electron sensitivity at 6kV of accelerating potential and by 8kV, a single electron produces a digital output of over 2 ADUs.

4.3 Pulse Height Distributions

4.3.1 Multiple photon PHD

The first series of graphs (figures 4-18 through 4-20) plots the multiple photon PHDs formed at different accelerating voltages at a given light level. The following figures (4-21 through 4-28) are plots of the multi-photon PHD at different values of detector irradiance for a given accelerating voltage.
Figure 4-18  PHD at 15 electrons per pixel per frametime (.001 uW/cm²)

Figure 4-19  PHD at 30 electrons per pixel per frametime (.002 uW/cm²)
Figure 4-20 PHD at 45 electrons per pixel per frametime (.003 uW/cm²)

The next series of figures (figure 4-21 through 4-28) illustrates several features of the EBCCD response including linearity and the ability to discern different light levels at a given accelerating voltage (again referring to the detection theory presented in section 2.1). The figure shown at the top of each page was generated by plotting the histogram for all images taken at different light levels for a given accelerating voltage. The corresponding bottom figure is a plot of the mean and variance for each of the histograms, along with a linear fit of the acquired data points. In the upper figure, the numbers above each histogram correspond to the mean number of electrons incident per pixel per frametime. These numbers correlate to the mean values which are plotted in the lower figure. The number of incident electrons was calculated from knowledge of the light level and quantum efficiency of the photocathode. The variance, as expected, increases with light level due to the dominant photon noise.

As discussed in the previous chapter, the y-intercepts of the linear extrapolations are in fact the variance and mean for a single electron pulse height distribution. Due to the very limited number of actual data points collected per accelerating voltage (from 3 to 5 data points) in this data set, the intercepts are not accurate enough to be used to measure the single electron PHD. In
order to maximize the number of data points used to calculate the standard deviation of the single photoelectron PHD, the data from the mean variance analysis technique will be used (where thousands of data points are collected and averaged), and results presented in section 4.3.2.

For the following figures, the camera integration time was 300 ms.
Figure 4-21 PHD at 3.98 kV

Figure 4-22 Mean and variance of PHD at 3.98 kV
Figure 4-23 PHD at 5.93 kV

Figure 4-24 Mean and variance of PHD at 5.93 kV
**Figure 4-25** PHD at 6.9 kV

**Figure 4-26** Mean and variance of PHD at 6.9 kV
Figure 4-27 PHD at 8.00 kV

Figure 4-28 Mean and Variance of PHD at energy 8kV
4.3.2 Single photoelectron PHD extraction

We can extract the mean and standard deviation related to single photoelectron pulse height distributions from data acquired for multiple photoelectron pulse height distributions using the techniques discussed in section 3.4.2. Figures 4-29 and 4-31 show a plot of the operating gain vs. accelerating voltage, along with the standard deviation of the gain value (shown as asterisks) for each tube. These two plots contain the results of the single photon PHD extraction discussed in section 3.4.2. We only have knowledge about the mean and standard deviation of the distribution – we do not know the type of distribution. Even though the standard deviation of the gain increases, the gain is increasing at a greater rate than the “noise”, as shown in figures 4.30 and 4.32. As the voltage is increased, the ratio of the average gain to the standard deviation of the gain increases and an observer can make a statistically meaningful determination as to whether one or two electrons were absorbed by a given EBCCD pixel – a desired capability which could be used in the future for additional diagnostic tests based on binning values based on the number of electrons incident on a given pixel. This is similar to the “detection” theory discussed in section 2.1, where the ratio of the average gain to standard deviation of the gain can be interpreted as a “pixel signal to noise ratio” for purposes of detecting an electron in the presence of background noise. A large standard deviation is not necessarily indicative of a poor device since the gain standard deviation applies to the pulse height distribution of single photon events, not the multiple photon events measured in the mean variance analysis. In addition, note that the gain of Tube #2 is substantially greater than the standard deviation at accelerating voltages above 6 kV.
Figure 4-29  Graph of standard deviation of gain variance for Tube #1
Figure 4-30 Single electron detection capability for Tube #1

Figure 4-30 and figure 4.32 show the relative signal to noise ratio for the EBCCDs response to a single photoelectron. It is a plot of the relative ability to discern single vs. multiple photoelectron events.
Figure 4-31 Graph of standard deviation of gain variance for Tube #2
Figure 4-32 Single electron detection capability for Tube #2

As seen in figure 4-32, the ratio of the gain to the standard deviation of the gain is increasing as the accelerating voltage is increased.

Using the statistical extraction technique discussed in section 3.4.2, it is possible to find the value of the standard deviation of the gain, but not the functional form of the distribution function. However, if we assume a normal distribution function, we may plot a function with the measured values of the standard deviation of the operating gain in figure as shown in figures 4-33 and 4-34.
Figure 4-33 Gaussian estimations of single photoelectrons PHD for Tube 1
4.4 Noise Related Measurements

4.4.1 Signal to Noise Ratio

The next set of figures (4-35 through 4-38) present the actual measured signal to noise ratio using the mean variance technique. Notice that as the accelerating voltage increases, and thus the operating gain, the EBCCD SNR approaches the photon limited SNR, indicating a reduction of the noise figure. The calculated gain standard deviation is relatively large compared to the gain. However, since the mean gain increases faster than the noise, the added gain overcomes noise in successive stages in the multiple photon measurements (such as the photon transfer method) and improves the overall signal to noise ratio.
Figure 4-35 SNR computed at 3.98 kV for Tube #2

Figure 4-36 SNR computed at 4.99 kV for Tube #2
Figure 4-37 SNR computed at 6.75 kV for Tube #2

Figure 4-38 SNR computed at 8.00 kV for Tube #2
4.4.2 Noise Figure

As discussed in section 3.8.5, the noise figure is the ratio of the input and output signal to noise ratios of the device, where were shown in section 4.4.1 above. Table 6 lists the measured noise figure for Tube #1. Figure 4-39 is a plot the values listed in table 6, where the noise figure is plotted vs. beam energy. Figure 4-40 plots the noise figure versus the operating gain.

Table 6 Noise Figures for Tube #1

<table>
<thead>
<tr>
<th>Energy</th>
<th>NF</th>
<th>Sdev of Operating Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.02</td>
<td>4.179</td>
<td>3.2</td>
</tr>
<tr>
<td>3.11</td>
<td>3.897</td>
<td>4.1</td>
</tr>
<tr>
<td>3.32</td>
<td>3.450</td>
<td>5.2</td>
</tr>
<tr>
<td>3.46</td>
<td>3.163</td>
<td>5.4</td>
</tr>
<tr>
<td>3.62</td>
<td>3.006</td>
<td>7.0</td>
</tr>
<tr>
<td>3.87</td>
<td>2.659</td>
<td>10.4</td>
</tr>
<tr>
<td>4.00</td>
<td>2.529</td>
<td>12.1</td>
</tr>
<tr>
<td>4.20</td>
<td>2.401</td>
<td>15.3</td>
</tr>
<tr>
<td>4.40</td>
<td>2.245</td>
<td>17.5</td>
</tr>
<tr>
<td>4.58</td>
<td>2.178</td>
<td>20.8</td>
</tr>
<tr>
<td>4.68</td>
<td>2.149</td>
<td>21.4</td>
</tr>
<tr>
<td>4.78</td>
<td>2.117</td>
<td>22.0</td>
</tr>
<tr>
<td>4.90</td>
<td>2.034</td>
<td>25.1</td>
</tr>
<tr>
<td>5.01</td>
<td>1.948</td>
<td>26.9</td>
</tr>
<tr>
<td>5.30</td>
<td>1.922</td>
<td>30.6</td>
</tr>
<tr>
<td>5.61</td>
<td>1.804</td>
<td>37.6</td>
</tr>
<tr>
<td>6.00</td>
<td>1.756</td>
<td>42.3</td>
</tr>
<tr>
<td>6.32</td>
<td>1.659</td>
<td>49.0</td>
</tr>
<tr>
<td>6.64</td>
<td>1.601</td>
<td>51.9</td>
</tr>
<tr>
<td>7.01</td>
<td>1.576</td>
<td>58.5</td>
</tr>
<tr>
<td>7.36</td>
<td>1.556</td>
<td>64.7</td>
</tr>
<tr>
<td>7.67</td>
<td>1.562</td>
<td>79.7</td>
</tr>
<tr>
<td>7.95</td>
<td>1.508</td>
<td>75.4</td>
</tr>
</tbody>
</table>
Figure 4-39 Noise figure plot vs. accelerating voltage for Tube #1

Figure 4-40 Noise figure vs. operating gain for Tube #1
Table 7 lists the measured noise figures for Tube #2, and these values are plotted in figure 4-41. Figure 4-42 plots the noise figure versus the operating gain for Tube #2.

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>NF</th>
<th>Sdev of Operating Gain</th>
<th>NF</th>
<th>Sdev of Operating Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.18</td>
<td>1.561</td>
<td>23.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.36</td>
<td>1.522</td>
<td>25.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.58</td>
<td>1.471</td>
<td>28.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5.77</td>
<td>1.432</td>
<td>29.7</td>
<td></td>
</tr>
<tr>
<td>3.29</td>
<td>5.93</td>
<td>1.396</td>
<td>31.6</td>
<td></td>
</tr>
<tr>
<td>3.48</td>
<td>6.12</td>
<td>1.398</td>
<td>33.2</td>
<td></td>
</tr>
<tr>
<td>3.51</td>
<td>6.31</td>
<td>1.363</td>
<td>33.4</td>
<td></td>
</tr>
<tr>
<td>3.61</td>
<td>6.53</td>
<td>1.336</td>
<td>34.6</td>
<td></td>
</tr>
<tr>
<td>3.8</td>
<td>6.75</td>
<td>1.317</td>
<td>35.8</td>
<td></td>
</tr>
<tr>
<td>3.89</td>
<td>6.93</td>
<td>1.307</td>
<td>35.2</td>
<td></td>
</tr>
<tr>
<td>3.98</td>
<td>7.09</td>
<td>1.292</td>
<td>36.4</td>
<td></td>
</tr>
<tr>
<td>4.11</td>
<td>7.22</td>
<td>1.298</td>
<td>36.2</td>
<td></td>
</tr>
<tr>
<td>4.27</td>
<td>7.44</td>
<td>1.276</td>
<td>35.7</td>
<td></td>
</tr>
<tr>
<td>4.39</td>
<td>7.62</td>
<td>1.254</td>
<td>36.6</td>
<td></td>
</tr>
<tr>
<td>4.55</td>
<td>7.87</td>
<td>1.252</td>
<td>35.5</td>
<td></td>
</tr>
<tr>
<td>4.71</td>
<td>8</td>
<td>1.238</td>
<td>34.8</td>
<td></td>
</tr>
<tr>
<td>4.86</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4-41 Noise figure plot vs. accelerating voltage for Tube #2

Figure 4-42 Noise figure vs. operating gain for Tube #2
4.4.3 DQE

The measured DQE for Tube #1 is plotted versus the accelerating voltage in figure 4-43, and against the operating gain in figure 4-44.

![DQE vs. accelerating voltage](image1)

**Figure 4-43** DQE vs. accelerating voltage for Tube #1

![DQE vs. operating gain](image2)

**Figure 4-44** DQE vs. operating gain for Tube #1
The measured DQE for Tube #2 is plotted versus the accelerating voltage in figure 4-45, and against the operating gain in figure 4-46.

**Figure 4-45** DQE vs. accelerating voltage for Tube #2

**Figure 4-46** DQE plotted vs. operating gain for Tube #2
As seen in figures 4-44 and 4-46, tube 2 has a better DQE than tube 1, most likely due to the increased operating gain and lower overall noise.

### 4.5 Al layer

Figure 4-47 is a picture taken with Tube #2 with no accelerating voltage of a uniform white background. Note the many white spots in the picture – these correspond to local “thin” areas of the deposited aluminum.

![Picture of pin-defects in Tube #2](image-url)
4.5.1 Measurement of thickness from light penetration data

It is important to know the thickness variation of the aluminum that is deposited on the back surface of the CCD since the incident photoelectrons must penetrate this aluminum layer. Variations in the thickness of the aluminum manifest as variations in the dead layer in front of a given pixel. Several images were taken with the EBCCD camera, with no high voltage applied to the photocathode, at different illumination levels. The integration time for each frame was 2.75 seconds. Using knowledge of the radiometric sensitivity of the CCD used in this EBCCD tube, we can measure the thickness of the aluminum layer deposited on the back surface. The quantum efficiency of the CCD (with no aluminum overcoat) is 40% at 550 nm. The effective area of the pixel is $5.76 \times 10^{-6}$ cm$^2$. At an incident light level of 2 $\mu$W/cm$^2$, the CCD (un-coated) would have generated an average output of 448,400 ADUs. The actual measured output was 498, some 896 times smaller. The attenuation coefficient of aluminum at 550 nm is 0.0485/nm$^2$. Thus using eq. 3.45, we solve for the thickness as:

$$x = \frac{\ln \left( \frac{I}{I_0} \right)}{-\alpha} = \frac{\ln(0.00116)}{-0.0485} = 140 \text{nm}$$

The dead layer voltage for Tube #2 was measured to be 4.48 kV. Using the linear dead layer model, the associated Grün range corresponding to a 4.48 kV dead layer is calculated as:

$$R_G = 0.015E_d^{0.75} = 207 \text{nm}$$

Similarly, using the optically derived aluminum thickness of 140 nm, the estimated dead layer would be:

$$E = \exp \left( \ln \left( \frac{R_G}{0.015} \right) \right) / 1.75 = 3.58 \text{kV}$$

Thus, there is a difference between the measured dead layer of 4.48 kV, and the computed dead layer of aluminum of 3.58 kV. This difference is accounted for by considering the effect of a dead layer presented by the native silicon dioxide growth between the aluminum layer and silicon, as well as the dead layer formed by any remaining depletion region at the back surface of the CCD.
4.5.2 Number of pin-defects found and size class

Each of the pin-defect areas was analyzed to determine the cluster size in pixels. A cluster size of 1 indicates that the pin-defect was 1 pixel in area, a cluster size of 12 indicates the pin-defect was 12 pixels in size.

<table>
<thead>
<tr>
<th>Cluster size</th>
<th>Number found</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2545</td>
</tr>
<tr>
<td>2</td>
<td>2590</td>
</tr>
<tr>
<td>3</td>
<td>1154</td>
</tr>
<tr>
<td>4</td>
<td>1407</td>
</tr>
<tr>
<td>5</td>
<td>232</td>
</tr>
<tr>
<td>6</td>
<td>115</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 8 lists the cluster statistics found in Tube #2. Thus, a total of 18924 pin-defects were found in 8076 clusters.

4.5.3 Gain variance due to non-uniform aluminum coating

Figure 4-48 shows the histogram of measured light values seen in the image shown in figure 4-47.
Figure 4-48 Probability distribution of pin-defect ADU values

It is now necessary to determine the thickness of the aluminum that corresponds to the light levels shown in figure 4-48. Each light level corresponds to a particular value of aluminum thickness, where figure 4-49 is a plot of eq. 4.8, and shows the thickness value associated with a given light level (expressed as camera ADU units).

Figure 4-49 Plot of Aluminum thickness vs. light level (ADU)
It is important to realize that due to the large number of pixels, about 256,000 of which only 18924 are "pin-defects", the histogram shown in fig. 4-48 is dominated by the small fluctuations of the nominal thickness, where there are some pin-defects that allow light levels up to 1200 ADUs to be measured. Such an ADU value corresponds to a thickness of about 93 nm. Figure 4-50 is a plot of the values above the threshold value of 275 found in the histogram shown in fig. 4-48 (the selection of this value is discussed in section 3.5.2):

![Figure 4-50 Distribution function of light levels above threshold (pin-defects)](image)

Using eq. 4.8 to convert light levels to Aluminum thickness values, we can compute the statistical distribution function of the aluminum thickness in those regions defined as pin-defects as seen in figure 4-51:
In figure 4-52, the “rE” values are the computed retained energy of electrons that were incident upon the silicon at initial values of 8, 6, 4, and 2 keV as a function of the distance from
the back surface of the aluminum layer. As the electron propagates through the silicon lattice, energy is lost and the amount of retained energy at a given depth is plotted in figure 4-52. The sloped line rising from 95 nm and peaking around 127 nm is a relative plot of the normalized probability distribution function (\( \text{tp}(x) \)) of the Aluminum thicknesses. The \( \text{tp}(x) \) values shown in fig. 4-52 are scaled by a factor of 5 so that it can be viewed on the same plot.

![Figure 4-53 Energy lost in Aluminum between 97 nm and 127 nm vs. beam energy](image)

The large range of aluminum thickness creates the effect of a spatially varying "dead layer", and affects the amount of energy that is dissipated in the aluminum. The thin pin-defects, with thicknesses between 90 and 127 nm, dissipate less energy than the nominal 140 nm thick Aluminum and thus there is more operating gain generated within the pixels underneath these thinner pin-defects. Figure 4-53 shows the amount of energy lost between the thickness of 97 nm and 127 nm for different initial electron energies. The graph shows that at low energy levels, the difference in energy loss is small because there is virtually no penetration of electrons to 90 nm. At high energy levels, the electrons lose very little energy owing to the associated high Gr"un range. Thus, from a phenomenological perspective, it is intuitive that a peak energy loss should exist between these two ranges – and according to the calculations, exists at approximately 4.6 keV.

Another interesting aspect is the fact that the thin pin-defects have a lower dead layer than the nominal thickness of 140 nm. This is most likely responsible for the larger than expected operating gain below the nominal dead layer as seen in figures 4-10 and 4-11. In addition, the
higher gains below the dead layer skew the computation of the single electron PHD width (the standard deviation of gain), since the square of the gain is subtracted as part of equation 3.40.

![Graph showing the operating gain and its variations](image)

**Figure 4-54 Total variance of energy loss through pin-defects**

Figure 4-54 indicates that a large portion of the gain variance is due to the pin-defect thickness variance, where \( gain \) is the calculated operating gain, \( pgd \) is the pin-defect induced deviation of the gain (see section 3.5), and \( sgain \) is the measured standard deviation of the gain. The "i" subscript is an artifact of the plotting program. Clearly, if the aluminum coating thickness were more uniform, the gain variance would be greatly reduced – especially at low energy levels. Also, since the pin-defect thickness variation is spatially dependent, the gain variance is also spatially dependent.

### 4.6 Electron capture probability

Using the procedure outlined in section 3.7, we can measure the electron capture probability function of the EBCCD tube. This minimization computation was performed using MathCAD 8.0 using the "minerr" function. The \( a_0 \) parameter was measured to be 1.101, and the \( L \) parameter was measured to be 3.806 microns. The computed value of \( a_0 \) indicates that the probability associated with detecting an electron generated at \( x=0 \) (the back surface of the
aluminum) is zero. Physically, the $a_0$ factor cannot be greater than one, since there cannot be a negative probability of detection. However, for a “best fit” equation, $a_0$ was computed as 1.101. The computed value for “L” is 3.806 μm, indicating that 63% of the secondary electrons generated are collected for electrons that can diffuse to 3.8 microns into the CCD. If we plot the function $p(x)$ along with the measured gain function and modeled gain functions, we find:

![Graph showing measured and calculated gain functions](image)

**Figure 4-55 Electron Capture Probability model accuracy**

In figure 4-55, “GainSW(E)” is a plot of the operating gain model using the $p(x)$ electron capture probability function (using eq. 3.52), and the “gain” trace is a plot of the measured operating gain as a function of beam energy. Note the very close agreement between the two functions, indicating the accuracy of the derived $p(x)$ function.
Figure 4-56 Electron Capture Probability $p(x)$ plot

Referring to figure 4-56, $p(x)$ is the probability of secondary electron capture equation, where $x$ is given in microns measured from the back surface of the CCD. Since data exists only to 8 kV (the maximum tolerable voltage of the tube), we cannot directly measure the electron capture probability function past about 1 μm from the back surface. We assume that close to the front surface, the depletion region is well formed and $p(x)$ is essentially unity. We can surmise that indeed a semi-field free region does exist, since $p(x)$ rises only to about 0.2 at 1 μm from the back surface, and becomes unity at $x = 15$ μm, the thickness of the CCD. The $p(1 \mu m) = 0.2$ is indicative of the deposited charge cloud expanding via thermal diffusion and Coulomb interaction, and only the fraction of that charge cloud nearest the potential well is collected by the CCD. This further corroborates the large standard deviation of the operating gain measured previously in section 4.3.2.

As seen in the operating gain plot (Fig 4.10 and 4.11), the gain at 3 kV is very low, and the “linear dead layer model” value is about 4 kV. This indicates that primary electrons dissipate their energy at depths where the probability detection function is very low. This is undesirable for an EBCCD imager, since we desire to collect every generated secondary electron. This technique gives researchers a valuable diagnostic to probe the characteristics of the back surface.
of an electron illuminated CCD. Using this technique of the collection probability distribution function permits investigation of surface passivation techniques and the ability of a dopant to create an accumulation layer to prevent the backside depletion region from forming. It is also a measure of the amount of charge lost due to recombination in the field free region.

4.7 MTF

Figure 4-57 is a picture of the line edge taken with the EBCCD camera

Figure 4-57 Line edge response imaged by EBCCD

The line response and MTF are shown in figures 4-58 and 4-59 respectively.
4.8 **Pictures with EBCCD camera system**

Several pictures of objects were taken with the EBCCD camera designed and built by the author to give some representative images that can be acquired with this new hybrid intensifier.
Notice the pin-defects in figure 4-60 (which show up as small white dots) that are evident in the above picture. Compare the pin-defects in this picture with the ones that are barely visible in figure 4-61. This is a pragmatic demonstration of the percentage reduction in the pin-defect thickness induced gain variation as the applied voltage is increased.

Figure 4-60 3.01 kV MTF chart
Figure 4-61 4.96 kV MTF bar chart

The smearing in lower left hand corner of figure 4-61 is due to a specular reflection of a piece of aluminum in the background.
Comparing this picture seen in figure 4-62 with the previous two, a certain amount of "grain" is evident. This is due to the photon noise that begins to be evident at the lower light levels.

Using separate red, green, and blue filters that were placed over the lens of the EBCCD camera, three images were taken (one for each filter shown in figures 4-63 through 4-65) to generate the composite color picture shown in figure 4-66.
Figure 4-65 Image with blue filter
The author took the picture shown in figure 4-66 and is believed to be the first-ever known color composite picture taken with an EBCCD imager. The ambient light level was approximately 0.0001 lux. The hull of the boat is red, and the seating is green. Color low-light level imagery is currently of great interest to the U.S. Navy and these images have demonstrated the usefulness of this device to provide such imagery.

Figure 4-66 Composite color image from red, green, blue images
Figure 4-67 Image showing visible pin-defects visible (no accelerating voltage)

Figure 4-67 shows another picture, where the pin-defects are clearly evident (again, the pin defects show up as small white dots in the picture). This picture was taken at a relatively high light level (normal room illumination), where the accelerating voltage has been turned off. Thus, the image is generated from optical photons passing through the aluminum coating and creating signal electrons within the CCD.
The picture shown in figure 4-68 is identical to that shown in figure 4-67, except that it was taken at a much lower light level (approximately $5 \times 10^5$ lux) and with 6 kV of accelerating voltage applied to the EBCCD. The pin-defects are no longer evident, but the photon noise induced “grain” is visible now.
The picture shown in figure 4-69 was the first visible EBCCD picture taken with the author's EBCCD camera on 24 Feb 1998 (the man is not the author).
5 Discussion

This dissertation has presented both theoretical and experimental methods associated with characterizing EBCCDs. All of the tests presented in the dissertation can be performed, as was demonstrated, in a production setting with the tube intact and attached to the readout electronics. This is an important advantage of the developed methods because it provides a way to perform quality control tests on a production scale, should EBCCDs become common commercial detectors.

5.1 Discussion of newly developed characterization methods

The improved gain measurement method has been discussed in great detail within the text of the dissertation. The author believes that the tube gain should be measured when the EBCCD is operating in a "normal fashion" – as a clocked CCD – and not by the ratio of substrate current to photocathode current method.

The results of using multiple electron PHD data to obtain the mean and variance of a single electron pulse height distribution appear reasonable. It would have been advantageous to be able to compare the indirect measurement results with a direct measurement, but this was not possible. It is to be noted that the gain variance, \( \sigma_g^2 \), does increase with accelerating potential. Thus, the associated tube noise is increasing. This seems to contradict the measured values of the noise figure decreasing with increased accelerating potential. Since the noise figure is a ratio of the input signal to noise ratio to the output signal to noise ratio, it is important to remember that even though the gain noise is increasing, the ratio of the gain to the gain noise is increasing. Referring back to figure 4-32, the ratio of the gain to the gain noise is increasing with increasing voltage, so that it makes sense that the noise figure would decrease with increasing voltage.

Proximity focused intensifiers are by nature small and compact and lend themselves well to inclusion in cameras for the military, scientific, and commercial markets. Because of this, it is likely that aluminum will continue to be used to block the light that is transmitted by the photocathode. The methods related to the measurement of the thickness of the aluminum and resulting gain variation caused by variation in the aluminum thickness are therefore useful diagnostic tools to assess the expected dead layer introduced by the aluminum, and whether the gain non-uniformity is outside acceptable limits from a tube production or camera design point of view. Aluminum is used because it is a semiconductor process friendly metal, and almost all CCDs use aluminum in the processing of the frontside structures. It is possible to deposit
uniform coatings of aluminum on the CCD, but it is still necessary to confirm that the actual
deposition is as uniform as it should be.

In order to maximize the DQE, it is desirable to collect all of the secondary electrons.
The method to measure the probability of detection in situ can be a useful tool to gain insight into
factors influencing behavior occurring at the back surface where the electrons are generated.

The great advantage of the developed diagnostic tests is that they require very simple
instrumentation, which is easily calibrated. The mean variance test is extremely accurate, due to
the very large number of data points collected (literally millions of data points). The
photocathode illumination can be accurately measured using a calibrated photodiode, and the
accuracy of the signal processing electronics is limited by the accuracy of the components used
(1% components in this case). Thus, knowledge of the operating gain – the ratio number of
electrons emitted by the photocathode to the number of electrons output by the camera – is easily
and accurately measured. Due to the high accuracy of this test, the signal to noise ratio and noise
figure can also be accurately measured.

Since the developed methods are based on photon illumination (which can be measured
accurately – on the order of +/- 3% error), several other tests can be performed including the
determination of the aluminum thickness, and the gain variation resulting from non-uniform
coating of the aluminum. If the optical tests were not accurate, it would be impossible to separate
the relatively small variances caused by local thickness variations in the aluminum from other
larger errors. The operating gain was easily determined through the use of the mean variance
technique, and gives a much more accurate gain value than measurement of electron current
ratios.

5.2 Discussion of actual vs. theoretical predictions of EBCCD performance

The results of the noise figure tests were in close agreement with the predicted values of
section 2.4.2.3.2. The predicted and actual noise figures are plotted in figure 5-1.
Figure 5-1 Comparison of predicted and measured noise figures

The device MTF was also measured to a cutoff value of 14 lp/mm, which was about half of the predicted value of 30 lp/mm. This is most likely due to poor contrast of the image taken with the EBCCD (figure 4-58). The aluminum thickness was also measured to be 140 nm, using knowledge of the optical properties of aluminum, and the accuracy of the measurement was within the error of the reported measurement of the thickness during the fabrication of the device. The dynamic range of the device was limited by the full well capacity of the CCD and the read noise set by the CCD amplifier and post-CCD processing electronics.

Perhaps the most obvious deviation from theory was the “tube gain”. With a dead layer of approximately 4 kV, the EBCCD should have exhibited a gain of approaching 1100, while in fact only achieved a gain of 110.

Due to the low conversion gain of the sense node of the Hamamatsu EBCCD (most scientific imagers have conversion gains around 8 to 10 μV/electron), it was not possible to directly measure single electron pulse height distributions. This was fortuitous, because the inability to measure these PHDs directly prompted the development of a method to measure them indirectly. The width of the PHDs was much larger than a “Fano-limited” width, primarily due to the low probability of detection. The PHD was further widened by the variation in gain resulting from the non-uniform aluminum coating. The gain standard deviation for Tube #2 (36 electrons at 8 kV accelerating voltage) is much less than for Tube #1 (75 electrons at 8 kV accelerating...
voltage), as seen in figures 4-32 and 4-34, for unknown reasons. It is expected that the larger noise in Tube #1 was due processes related to the deterioration of the CCD readout structure.

Unfortunately, the floating diffusion sense node amplifier at the CCD output was poorly designed, and a large amount of reset feedthrough was present in the output video signal. This limited the amount of post-CCD gain that could be applied in order to increase the number of ADUs per electron, which would have allowed even more accurate determinations of single electron PHDs. This has apparently been corrected in recent revisions of the Hamamatsu N7220.

5.3 Discussion of Tradeoffs to Achieve Optimal Performance

As in all design efforts, there are tradeoffs between desired features. When the operating gain increases such that one primary electron incident on the CCD creates a signal larger than 1 ADU, the imaging system dynamic range begins to decrease due to the discrete nature of electrons. The MTF could be increased by decreasing the spacing between the photocathode and CCD, but this is limited by the maximum voltage bias. The voltage bias can be reduced provided the operating gain is sufficient to overcome the noises present. This would require a lower dead layer energy value, and would probably preclude the use of an aluminum coating to block unwanted photons from creating charge within the CCD.

Increasing the charge capacity of the pixel, which usually requires using larger pixels, can increase the dynamic range. Clearly, there is a tradeoff between spatial resolution and dynamic range.

5.4 Discussion of major benefits of EBCCD tubes

EBCCDs can have several advantages over Gen II/III based intensified cameras. Due to the combined inefficiencies of the intensifier tube, optical coupling method, and CCD camera, according to eq. 3.61, the DQE of a detector will not achieve more than $1/NF^2$ factor of the photocathode quantum efficiency, where NF is the system noise figure. Traditional intensified cameras have system noise figures that are rarely below 2 and can be as high as 60, depending on the tube gain. The EBCCD DQE rises to 7.5% (which is 68% of the limit set by the quantum efficiency of the photocathode) at 8 kV accelerating potential, corresponding to the highest gain. This corresponds to a system noise figure of 1.2. Within the scientific and military communities, such a relative high DQE at high dynamic range drives research into EBCCDs. The EBCCDs efficient use of every photon is definitely an improvement over current technology. Furthermore, the fact that single photon detection can be obtained with high intra-scene dynamic range imagery
is also a major benefit of EBCCD tubes. This is mainly due to the EBCCD's low gain, but high system efficiency. This combination allows high dynamic range images to be recorded when a traditional image intensifier would have to operate at such high gain that the image intrascene dynamic range would be severely limited.

The EBCCD measured in this dissertation achieved a signal to noise ratio of 34 at 8 kV accelerating potential. This is substantially higher than the highest-grade Gen III device currently manufactured by ITT, the FS9910C Ultra, which has a maximum signal to noise ratio of 21. This SNR was achieved using a photocathode (GaAs) that is over 4 times more sensitive that the multi-alkali S-20 photocathode used on the EBCCD. If the EBCCD used a GaAs, the signal to noise ratio would have been even greater than the measured value of 34. The EBCCD noise figure had a lowest value of 1.24 at 8 kV accelerating potential, compared to a typical noise figure of 3 for Gen III type devices.

EBCCD image intensifiers exceed many figures of merit of traditional image intensifiers at light levels above .0001 lux, but far exceed the capabilities of normal image intensifiers at light levels below about 100 photons per pixel. EBCCDs also do not suffer from decay time restrictions or "image burn-in" like phosphor based intensifiers. There is no "chicken-wire" or fiber optic distortion present with EBCCDs. In addition, the removal of the phosphor screen, fiber optic coupler, and "optical" CCD detection losses present in current intensified CCD cameras, the EBCCD DQE is higher than a traditional intensified system for high dynamic range images.

If one were to compare the two types of tube designs on the basis of spatial resolution, it would be necessary to cite specific examples in order to make a fair comparison. Furthermore, since so many factors are inter-related, a rigorous treatment would limit the generality of such comparison. Nevertheless, several comments can be made. Elimination of the fiber optic bundle would eliminate the disturbing "Moiré" patterns seen in fiber-optic coupled intensified CCD cameras, due to aliasing between the pixels of the CCD and the fiber pattern, as well as the often noticeable distortion. Phosphor screens themselves are capable of very high resolutions (where resolution is dependent on the screen thickness and can approach 200 lp/mm). However, the cascading of the MTFs of each component degrades the system MTF, which is of final interest. Several current Gen III tubes have MTF cutoff frequencies approaching 64 lp/mm. This is a higher MTF cutoff value than can be achieved with scientific EBCCD devices given current CCD pixel sizes (above 10 µm). However, it is important to realize that the 64 lp/mm specification is for the image quality at the output phosphor. Comparing similar systems, it is necessary to
include the MTF effects of the fiber optic coupling and the CCD attached to the Gen III device. If this is taken into account, the system MTF is much lower than 64 lp/mm and is usually around 20 lp/mm for CCDs with small (12 micron) pixels.

5.5 Applications of EBCCD

5.5.1 Tactical low-light level imaging

Most tactical (military environment) low-light imaging systems must deal with high dynamic range scenes. In such cases, it is important to provide some type of anti blooming structure on the CCD to prevent the image from being contaminated from bright locations in other areas. One of the advantages of EBCCD devices is the high level of dynamic range that can be obtained at a given EBS gain setting.

5.5.2 Law enforcement

The needs of low-light imaging systems for the law enforcement industry is growing with increased amounts of surveillance and observation being conducted at night, often in remote settings such as non-suburban areas and over water.

5.5.3 High speed imaging

Weapons systems research, and other related activities, continues to require new high-speed imaging systems for different programs. EBCCD imagers, in conjunction with a custom CCD design for ultra high-speed digital imaging (as fast as 1 million frames per second) could be used in ultra-high speed camera systems. One of the benefits of EBCCD devices is that it circumvents the problem of the brightness of output phosphors on current image intensifiers not being sufficient for high repetition rate camera systems.

5.5.4 Needs of commercial markets

The commercial community is not without many uses of extremely low-light level imagers. Several anticipated applications are listed below:

- Medical/Fluoroscopy imaging such as FISH (Fluorescence In-Situ Hybridization), GFP, Ca ratioing, mamography
- Low level spectroscopy
• Search & Rescue, and marine overboard conditions
• X-ray crystallography - protein research for drug development
• Industrial security - increasing need to have secure facilities for companies both in the US, and especially in third world countries

5.6 Future research areas

5.6.1 Better aluminum coverage

The aluminum layer deposited on the two EBCCDs tested had much non-uniformity, and many pin-defects. As explained earlier, this is due to a “less than ideal” planar surface on the thinned CCD. If the surface had been more planar (requiring a better thinning technique), the aluminum coverage would be much more uniform – decreasing the associated gain variance.

5.6.2 Improve electron capture probability

The single most important factor in achieving a low noise, high operating gain device is to capture every secondary electron created. If EBCCDs are ever to compete with the nearly ubiquitous Gen II/III image intensifier, the operating gain must be high. This would also allow lower voltages to be used, since an acceptable gain figure could be achieved at a lower photocathode bias. This decreases the amount of field emission noise as well as the number of kα x-rays emitted within the silicon – increasing tube life.
6 Appendix A – EBCCD Camera

6.1 Camera Description

The EBCCD system used to test the developed methods was designed and built by the author. The camera body is shown in figure 6-1.

Figure 6-1 EBCCD camera body

The system block diagram is shown in figure 6.2.
The camera modes are changed by commands sent up from the computer through the RS-232 connection. Camera data is sent over the data cable to the framegrabber, and power is supplied from the external power supply.

6.1.1 General structure of readout electronics

6.1.1.1 Design considerations

Due to the fact that the EBCCD on-chip amplifier has a bandwidth limitation such that the maximum output pixel rate is 1 Mpixel/sec, we were able to use standard CMOS drivers to drive all clocked signals on the CCD. By including a series resistor between the driver output and the pin, the rise and fall times can be controlled by utilizing the intrinsic capacitance of the horizontal and vertical CCD clocks. It is important to control the rise and fall times since two-phase CCD architectures need a certain amount of overlap between the clocks for efficient charge transfer.

Correlated Double Sampling (CDS) is performed using a Thomson THX7882 IC. This particular CDS is optimized for readout rates between 2MHz and 20MHz, limited on the low end by the droop rate of the on-chip hold capacitor. While the 1 MHz pixel rate is below the specification of the CDS circuit, the induced error is repeatable and systematic, and can be removed.

The camera is designed using a modular approach to camera construction. There are four printed circuit boards used in this camera: a headboard containing the CCD, preamplifier, and driver circuitry, a DC board supplying all of the biases and power for the camera, an A/D board which contains the CDS circuitry, A/D converter and RS-422 drivers used for data output, and a
clock board which generates the clocking signals for the CCD and supplies all timing functions for camera operation.

The readout chain is composed of an emitter follower using a 2N3906 PNP transistor which is AC coupled to an op-amp which provides signal gain and buffering to the input of the CDS. Once the signal is sampled at the reset pedestal and at the video output locations, the voltage difference is generated, resulting in the actual video level. The signal is then buffered and digitized by a 12 bit A/D converter. The digital value is then sent to the framegrabber via 12 channels of RS-422 differential transmission. All camera and diagnostic electronics were built by the author with the exception of the clock board and A/D board, which were based upon the existing designs at Silicon Mountain Design.

6.1.2 Camera electronics

6.1.2.1 Head board

The headboard serves as the backplane where all the support electronic modules connect. Since the EBCCD has a maximum operating rate of 1 Mpixel/sec, all clocks can be driven by simple CMOS drivers (shown in figure 6-3). The TLC4420 has a maximum peak current rating of 6 Amps, and can drive a 10,000 pF load with a 14 V swing and a 25 ns rise time.

Figure 6-3 CCD Clock driver circuitry

Since it is important for the rise and fall times to be shaped in a controlled manner, for maximum charge transfer efficiency, resistors are placed in series with the clock pins (such as R14 above). These resistors form a single pole RC network, limiting the rise and fall times, with the clock phase capacitance. The shortest duration pulse that is applied to the CCD is the reset pulse, lasting 150 ns.
The output circuitry (see figure 6-4) is composed of a DC coupled emitter follower preamplifier using a low noise PNP 2N3906 transistor. The output of the pre-amp is AC coupled to the non-inverting input of a low noise CLC400 op-amp with a gain of 1.3. This output is filtered by a single pole RC network at the connector to the A/D board.

![Figure 6-4 CCD output preamplifier](image)

6.1.2.2 Timing board

The timing board is used to generate all timings necessary for operation of the camera. A programmable Xilinx FPGA (Field Programmable Gate Array) controls the vertical clocks and serves as a state machine to control the order of events. A faster Lattice PLD (Programmable Logic Device) is used to generate the clocks for the horizontal clock phases, reset pulse, and sample and hold pulses for the CDS circuitry.

6.1.2.3 DC board

The dc board contains the voltage regulators that create the necessary dc references needed by the camera electronics and the CCD. National LM317 and LM337 regulators are used with filtering capacitors to create clean dc voltages.

6.1.2.4 A/D board

The A/D board contains the CDS chip along with the A/D converter and differential transmitters.
6.1.2.5 Computer system / Frame grabber

The frame grabber used was an Imaging Technologies ITI PCI 4.0 W95 Kit with AMDIG 16D-HS daughterboard and is capable of sustained data transfer rates of 60 MB/sec from the camera to the PCI bus of the PC.

In order to automate part of the testing, the accelerating voltage is controlled by commands given to a DAC onboard the camera, which controlled an internal high voltage power supply.

6.2 Hamamatsu EBCCD

6.2.1 Tube architecture

![Diagram of Hamamatsu EBCCD construction]

Figure 6-5 Hamamatsu EBCCD construction

The EBCCD tube architecture is shown in figure 6-5. The S-20 type photocathode is located approximately 2 mm above the CCD. The on-chip output amplifier is a single stage MOSFET source follower. The floating diffusion sense node has a sensitivity (according to the data sheet) of 2.0 µV/e\(^-\). The substrate is thinned to approximately 15-20 µm that allows electrons injected to the backside of the device to be collected by the potential wells formed by the clock voltages acting as MOSFET gates. The back surface is treated with a thin layer of boron to create an accumulation layer so that electrons are not trapped at the back surface.

The CCD uses a Multi-Pinned Phase (MPP) architecture that minimizes dark current generation at the surface of the silicon-oxide interface. This is accomplished by pinning, or holding the surface voltage, at the same value as the substrate. This causes any dark current electrons that are generated at the surface to be bled off to an area that prevents them from being swept into the potential well. The CCD is attached to a ceramic carrier by Indium solder balls at the four corners of the chip. The thinned silicon membrane is left unsupported.
Due to the fact that the CCD generates 200 electrons per pixel per second at 0 C, and since the dark current doubles every 6 C, at a nominal temperature during operation of 30 C, it is expected that 6000 electrons will be generated during a 1 sec. integration. Since the device is a MPP device, the dominant source of dark current is from the bulk silicon, and only refinements in silicon processing technology are capable of reducing the intrinsic dark current to much lower levels. The only method available to the camera designer to reduce dark current is to cool the imager. A thermo-electric cooler (TEC), which utilizes the Peltier effect to move heat from one object to another, is attached to the EBCCD tube. The cold side of the TEC is placed against a small aluminum block 10 mm wide x 15 mm long x 8 mm tall which serves as a cold finger when attached to the back side of the EBCCD package. The hot side of the TEC is attached to a large block of aluminum inside the camera body, allowing heat to transfer from the CCD to the heat sink. The heat sink is in contact with the outer surface of the camera, and fans are used to cool the heat sink system. Since it takes a finite amount of time for the small aluminum cold finger to cool, the dark current rises for approximately 10 minutes as the CCD begins to heat up. Then, once the heat is removed from the cold finger, the CCD begins to cool and dark current decreases.

6.2.2 CCD description

The CCD architecture is shown in figure 6-6, and the output sense node circuitry is shown in figure 6-7:

![Figure 6-6 Diagram of CCD architecture](image)
The first tube characterized (Tube #1) was damaged sometime during the months of June through August, 1998. At first, the damage was minor, but decreased slowly over time until April 1999, when the sensitivity of the charge sampling circuitry would be reduced by 50% per week. As seen in the following oscilloscope traces (figures 6-8 and 6-9 which were taken in May 1999), the output signal was reduced so that no further testing could be accomplished on this device.

**Figure 6-7** Charge sampling circuitry on CCD

**Figure 6-8** Tube #1 analog video signal with no light on CCD
Note that the output signal does not change from figure 6-9 with no incident light to figure 6-10 with greater than 50 $\mu$W/cm$^2$. Most CCDs today show output signal saturation at levels below 3 $\mu$W/cm$^2$. From these two figures, it is clear that the output node of the CCD in Tube #1 became "non-operational". Figures 6-8 and 6-9 can be compared with the figures 6-10 and 6-11, which show the signal output for Tube #2, which appears to be free from damage and operating nominally.
It is clear that there is a marked difference in the sensitivity of the two imagers. Unfortunately, there are no oscilloscope plots of the original imager before the damage to Tube #1 occurred, but the output signal looked very similar to figure 6-11.
References


Sons. p 86. 1983


24 Ibid.


30 Kirkpatrick and Sears. Semiconductor signal translating device. US patent 2,589,704.


37 Canfield, Kerner and Korde, Appl Optics 28 940 (1989)


40 Ibid.


42 Ibid.


51 McMullan and Powell. “Residual Gases and the Stability of Photocathodes".


57 Value from table, private communication from Dr. Hans Roehrig.

58 Private email communication between the author and Hamamatsu


60 Discussion with David Gardner, president of Silicon Mountain Design with expertise in CCD manufacturing processes.

61 Hamamatsu datasheet for CCD used in N7220 EBCCD


Moran, et.al. "Intensified CCD (ICCD) dynamic range and noise performance". 

Ibid.