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The University of Arizona, 1988

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COMPUTER MODEL OF A FOCAL PLANE ARRAY

by

Tom Arnold Thvedt

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A Thesis Submitted to the Faculty of the
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN ELECTRICAL ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

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Professor of Electrical Engineering

April 29, 1968
Date

DEDICATION

This thesis is dedicated in loving memory of my parents, John A. and Evalyne, who were always proud of everything I accomplished, and to my wife Stephanie, our son Bryan, and daughter Robyn, without whose love and patience I could not have finished.

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This thesis and research work initially started out only in developing a computer model simulation of a focal plane array as part of a project for the Optical Sciences Department at the University of Arizona. The project was requested through them by TRW, Inc. located in Redondo Beach, California. The author's involvement stemmed from having just completed a course on charge-coupled devices (OPTI 568) offered at the University of Arizona. The project went through many iterations, and was a small part of an overall program of an image processing system. Through the evolution of the computer program, the thesis idea came about naturally.

The initial work and the core of this paper was presented at the 31st Annual International Technical Symposium on Optical & Optoelectronic Applied Science and Engineering sponsored by SPIE-The International Society for Optical Engineering. This was held from August 16-21, 1987 at San Diego, California. The paper that was presented at the Conference on Infrared Technology XIII has been published in the Proceedings of SPIE, volume 819, pp. 250-262. It had as coauthors Eustace L. Dereniak of the Optical Sciences Department at the University of Arizona, Charles T. Willoughby of TRW, Inc., and Michael M. Salcido of Cincinnati Electronics.

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ABSTRACT

The background and operation of charge transfer devices is reviewed, and a computer model simulation of focal plane arrays is presented. The model provides an option to predict the performance of a focal plane. With this program, any of the allowed materials, detectors, readout structures, or preamplifiers that make up a focal plane, may be selected to create new designs for analysis. Only surface channel devices are considered, and only references to the spectral dependence are presented.

The computer model's operation and validity is supported by over 70 equations and more than 50 figures, including actual computer screen printouts. Standard equations followed by brief discussions are used to support the menu driven program. The structure and operation of the computer model is presented, but not the actual software source code.

CHAPTER 1

INTRODUCTION

The charge-coupling principle was first presented in the classic papers by Boyle and Smith (1970) and by Amelio, Pompsett and Smith (1970). Basically, the charge coupled device (CCD) is a shift register formed by a string of closely spaced metal-oxide-semiconductor (MOS) capacitors. A CCD can store and transfer charge by minority carriers, either holes or electrons, and they may be introduced either electrically or optically. Amelio (1972) published the first computer modelling paper in 1972, and Pompsett (1972) further described the use of these charge transfer devices for digital memory, analog delay, and image sensing in a paper published later that same year.

Many new developments in technology have surfaced since that time. In another classic paper, Barbe (1975) discussed the uses of the charge-coupled concept in infrared (IR) imaging. This was further enhanced by Steckl et al. (1975) in late 1974 to early 1975.

Previous computer simulations have been done by Martinson, Gaffney, and Meyer (1977), Cwik et al. (1979), and Michaelson et al. (1979). The successful integration of CCDs and high density IR detectors (McCaughan and Holeman,

1979) has opened a new technological field known as IR focal plane technology. However, the ensuing complexity has led to the need for an increased consideration of the operation and architecture of focal plane arrays (FPA) starting from the design of the unit cell (Chan, 1981).

This paper attempts to fill that need by providing a means of viewing what happens to the output when changing various focal plane array input parameters. This has been accomplished using an engineering station-type personal computer and the Turbo Pascal computer language (Borland Version 3.0).

The main focus of this paper is the development of a computer program to simulate a focal plane array. Chapter 2 gives the background on what comprises a focal plane array, while Chapter 3 gives a descriptive overview of the computer model. It is imperative to note that this model deals only with surface channel devices, and also does not take into consideration any spectral dependence. Chapter 4 describes in detail the architecture of a focal plane and the required parameters. Chapter 5 discusses the background behind what the computer model analysis will look at and analyze. Chapter 6 describes the computer model screen output displays and gives sample output plots of the default device, a Fairchild CCD222. Appendix A describes the symbols, nomenclature, and units for all terms used in the following paragraphs. Henceforth, units will be omitted. Appendix B

lists the menu structure, and Appendix C gives the program flow diagrams as used to develop the model.

For a further treatise on the subjects of charge-coupled devices and charge transfer devices, the reader should consult the following: Barbe, (1975, 1980); Howes and Morgan, (1979); Dereniak and Crowe, (1984); Beynon and Lamb, (1980); Sequin and Tompsett, (1975); Hobson, (1978); Kazan, (1977); and Thvedt et al. (1987).

CHAPTER 2

BACKGROUND ON FOCAL PLANE ARRAYS

This chapter provides a general background on focal plane array (FPA) architecture. The specific details relating to the computer model program are discussed in Chapter 4, except for the analysis and output values which are discussed in Chapter 5. The FPA and what it consists of is best described as shown in Figure 1. It consists of a detector, possibly with some type of input circuit, that feeds into the readout/signal process section. From there, an on-chip (i.e. fabricated as part of the device) preamplifier then converts the electrons transferred through the device into a voltage at the output of the FPA. The complexity of the focal plane architecture is dependent on the application. In systems with small focal lengths, one array of detectors may suffice as the focal plane, for which the complexity of the architecture may not be so obvious. For large focal length optical systems, many closely packed arrays are required to form a fully populated focal plane. An example of such a system is a space-borne sensor, a weather satellite could be used for example, where the focal plane may be used to form an image of the entire earth or an extended segment of the earth. The paper presented here will

Materials

1. Silicon
2. InSb
3. HgCdTe

Infrared Detector

1. MIS
2. Photovoltaic
3. Schottky

Hybrid Input Ckt

1. Direct Inj.
2. Buffered Direct Inj.
3. Gate Modulation
4. Fill/Spill
5. Injection Efficiency

Input Values

1. Physical Geometry
2. Quantum Efficiency

Readout

1. CCD
2. Switched FET
3. Bucket Brigade
4. CID

Analysis

1. Dark Current
2. CTE
3. MTF/sampling smearing
4. Noise
5. Time Constants self-induced thermal fringe field t4 transit time
6. Losses fixed proportional nonlinear
7. Surface Potential
8. Depletion Region

Output Types

1. Destructive Current-sensing Floating-Diffusion
2. Non-Destructive Charge-sensing Floating gate Distributed Floating gate

Output Values

1. Response
2. V_{out}

FIGURE 1. Typical Focal Plane Array.

deal only with small focal length systems, or a single focal plane array.

Focal Plane Architectures

There are two technologies of focal plane architecture, monolithic and hybrid. Monolithic focal planes using intrinsic silicon are constrained to only the visible and near infrared spectral regions and room or near-room temperature operation. Monolithic extrinsic silicon is used for the infrared spectral region and requires cooling down to cryogenic temperatures (less than 40 degrees K). Extrinsic silicon operation also relies on so many different types of doping materials that it will be excluded from any further discussion.

Other materials are intrinsic narrow band semiconductors for use in the infrared spectral bands, and they include, but are not limited to, Indium Antimonide (InSb) and Mercury Cadmium Telluride (HgCdTe). These materials require cooling down to 77 degrees Kelvin for operation, and are limited in spectral range to 3-5 μm (InSb and HgCdTe) and 8-13 μm (HgCdTe only) (Holeman, 1979). The one common constraint to all monolithic focal planes is that the detector layer and the CCD region cannot be optimized (Chan, 1981).

Hybrid focal plane architecture involves the hybridization of the detector and the readout (e.g. CCD), most typically by a planar construction using Indium-bump bonds as

depicted in Figure 2. These bonds are lined up with each pixel, or picture element. Another newer hybrid construction is the use of Z-technology (Carlson et al. 1980). However, this will not be considered here for a hybrid architecture type since this technology is still being developed, and the planar construction described above is far more common.

All hybrid arrays are constrained in spatial resolution by the center to center spacing of the Indium-bumps and the limited CCD area below the detector pixel (Chan, 1981). Another constraint on the size of the array results from the thermal mismatch between the detector and CCD layers. InSb and HgCdTe are the most common materials used for the detector, while silicon is used for the readout process.

Focal Plane Readout

The signal processor architecture of a focal plane consists of a direct coupled multiplexer of charge transfer device design or direct readout. The charge transfer device can be a charge injected device (CID), a charge-coupled device (CCD), or a bucket brigade device (BB).

The direct readout, or switched FET, is a relatively new development for charge transfer, and it is still in the experimental/research stage. The main use of direct readout is with hybrid architecture types of focal plane arrays. The switched FET, or direct readout, design did not have enough

(a)

(b)

Figure 2. Typical hybrid focal plane array. (a) A three dimensional view of planar construction cut away to show interconnects. (b) The bonding techniques using indium solder bumps.

supporting data with which to verify the accuracy of this model, and will not be included in any further discussions.

The BB device has usually been associated only with the monolithic architecture. It is a charge transfer device which operates much like a bucket of water being transferred down a line of people. It was the forerunner to the CCD and CID transfer devices. The descriptive language and the analysis of the performance is much like that of a MOSFET (Tompsett, 1972). However, CCD technology is capable of doing everything that the bucket brigade can do with a greater transfer efficiency, a greater packing density, and higher yields (Milnes, 1980). Consequently, the bucket brigade, as used for a readout/signal process, will not be considered any further and will not be included in the computer model simulation.

The CCD and CID technologies are both attractive to the readout/signal processing requirements of focal plane arrays as both have low power dissipation and can perform at cryogenic temperatures (Holeman, 1979). The main differences between the two include the fact that the CCD is a sequential transfer of charge device and the CID is a random access type of device; the CID also requires a lower transfer efficiency of charge than the CCD. Transfer efficiency will be discussed later.

Additionally, the CID architecture provides excellent antiblooming protection in both directions, needs neither

diffusion nor implantation, and is easier to operate. The ratio between the sensitive area and the whole array matrix is higher in a CID than in a CCD, but the CID has a higher overall capacitance and, thus, greater noise contributions. The higher capacitance is due to the separate multiplexer required for each row and column in a CID. In addition, the CID readout is not suitable for Time Delay Integration (TDI) which is easy to carry on in a CCD (Sirieix et al. 1978). Both of these structures will be discussed in greater detail later.

Focal Plane Preamplifier

There are two types of readout, destructive and non-destructive. Destructive readout is the process where data is read and subsequently destroyed, such that it is no longer available for further readout. Examples of the destructive readout are a current-sensing output, where the current is sampled, and the floating diffusion output. Only the floating diffusion output is considered in the computer model as it is one of the most common types of outputs used for a FPA output structure.

The non-destructive readout reads the data but leaves it in a state that can be read again if desired. Examples are a charge sensing output where the charge is sensed at the output of the multiplexer, a floating gate output, and a variation of that, termed the distributed floating gate.

Only the floating gate output will be used as part of the computer model as it too is one of the most common output structures used on a focal plane. The distributed floating gate and charge sensing structures will not be discussed any further. More details on the structure of the on-chip preamplifier will be presented in Chapter 4.

Focal Plane Considerations

There are further considerations that must be addressed when selecting a focal plane. For example, some materials are better suited to be used with one kind of detector than another. Some readouts are better suited to being used with certain materials than others. The following comments are indicative, in general, of what should be considered when selecting a focal plane array.

One possibility is to use a monolithic structure with intrinsic detection by an MIS structure in a semiconductor of a narrow bandgap. With this approach, a CCD or CID readout system is integrated in the detection semiconductor. The detection capability of such structures is apparently limited to the 3-5 μ m spectral range because, beyond this spectral range, tunnel-effect generation prevents the MIS structure from operating correctly (Felix et al. 1980).

Another possibility is to use a monolithic structure with photovoltaic detection in a semiconductor that has been epitaxially grown onto another semiconductor (with a wider

bandgap) which carries the readout circuit (Felix et al. 1980). The spectral range for this type of structure is 8-12 μm . Signals from infrared detectors can best be read out by using a CCD because of its low noise level, large dynamic range, and low power consumption. Some of the problems associated with this type of structure include the compatibility of the two materials, or lack of it, and the difficulty in making electronic circuits in these materials.

Another possibility is the hybrid structure using intrinsic photovoltaic detection with electronic readout in silicon. Such a structure would have several advantages over the other types that have been discussed. The detection and readout parts of the device can be optimized separately and, for a given spectral range, the operating temperature is higher than for MIS devices (Felix et al. 1980). The higher operating temperature is due to the fact that, unlike MIS devices, they can be operated with a very low reverse bias when coupled to the readout circuit and, hence, exhibit a low dark current (Longo et al. 1978).

All of the above possibilities are included in the computer model program presented here. More combinations are possible when the different materials that could be used for either of the architecture structures are included. Even more possibilities are encountered when the main two types of output preamplifier circuits are also included. Therein lies the versatility of the computer modelling approach.

CHAPTER 3

COMPUTER MODEL SIMULATION

The basic program flow of this menu driven simulation is shown in Figure 3. The computer program is basically broken into an architecture section and an analysis section. Each section will be further described in the following chapters through the use of researched reference material. In the beginning of the program, the user has a choice of choosing either the architecture set-up or analysis menus; however, it is suggested that the architecture menu be selected first in order that the focal plane array to be analyzed is set up properly. It should also be noted (since it is not shown in Figure 3) that once these parameters are defined, the user can write (save) the data to a file and then read (load) that data file at some future time.

Since this computer program was developed using Turbo Pascal Version 3.0, there were some limitations imposed by its compiler. Among these limitations is the fact that the code, as well as the data, is limited to 64K bytes of memory information. This limitation was overcome through the use of overlays in the program code, the use of "include" (.INC) files, and by the use of "chaining" (.CHN) files together. The main program is compiled to a "command" (.COM) file,

FIGURE 3. Basic Program Flow.

which is the only stand-alone executable file in this particular version of Turbo Pascal.

The FPA simulation program begins by executing the .COM file and then chaining, or branching off to a subprogram, and thereby passing the executive control to each .CHN file. Each chain program transfers data to and from each other by the use of shared global variables. This is accomplished since chained programs occupy the same space in memory, and thus, save valuable disk space by assuming the runtime library is already in memory. The structure of the program, using the file extensions .COM and .CHN, is shown in Figure 4. Note in the figure that the directional arrows point both ways between chain files, but in only one direction from the main executable file. This chaining process allows the user enough flexibility to be able to continuously alter any of the particular variables. These variable changes are all global, and the effects of these changes can then be readily seen by switching to the other areas of interest.

The main program is controlled by a menu structure built upon various submenus. For a detailed listing of the architecture and analysis submenus, see Appendix B. The submenu structure includes the global variables that may be modified. These global variables were chosen to represent those parameters that can be modified by a user; for example, voltages, substrate thicknesses, operating temperature,

FIGURE 4. Program structure by file extensions (.COM and .CHN). Note that each .CHN file is a descriptive name of the program code each executes for plotting curves or for pictorial architecture.

doping concentrations, etc. These variables and their effects will be discussed in the following chapters on the computer model detail. A more detailed flow diagram showing these variables is given in Appendix C.

Sample Architecture Operation

In order to provide the default information for the model's operation, data for a real monolithic and a theoretical hybrid FPA architectures is used for the default structures. The monolithic data is from the 1987 Fairchild Weston CCD Databook for a CCD222 area scan CCD sensor. The hybrid data is from a paper by Steckl and Koehler (1973). Some of the data necessary for the model operation is not explicitly stated in either of these references and must be either inferred or known by the user. The default data can easily be changed to fit any particular application by editing the proper data file and recompiling that chained file. The exact sequence to be followed has been detailed in a separate unpublished document entitled "Owner's Manual and Operating Guide for the Focal Plane Simulation Model." That document is available directly from the author, and is not included as part of this work.

The program is started by typing FPA followed by Enter (i.e. carriage return), and the first screen that will be seen is the introductory page. A sample of the screen has been reproduced in Figure 5. The notes describe some of the basic operating instructions for moving within the menus, and

W E L C O M E to the M O D E L

FOCAL PLANE ARRAY SIMULATION

Use left and right arrow keys to move across the top of the screen. HOME and END will also return the cursor back to "exit". Using the "Esc" key will return control to the previous menu.

Use the up and down arrow keys to move inside of the submenu choices before pressing ENTER to continue.

If the program terminates prematurely during analysis, re-enter and "Load" the data. The data file TEMPOR.DAT is always created whenever leaving the "Arch" portion of the program.

Press ENTER to begin the program

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FIGURE 5. Computer Model Introductory Page

a general note about an always created temporary data file. This temporary data file is also used as a link between the architecture and analysis portions of the model.

After pressing Enter again, the screen will clear and the first menu to be displayed is the "MAIN MENU" and is reproduced in Figure 6.

Exit Arch Analysis
Exit to Previous Menu

FIGURE 6. The MAIN MENU Screen Display

The "MAIN MENU" comes up with 'Exit' as the default choice, and is highlighted by appearing on the screen as a different shade of the monitor's current color. Therefore, if Enter is pressed, the program will then prompt the user with a series of two beeps and displays the question "Are you sure? Data file saved? (Y/N)?". The default value is "N" and pressing Enter will return control to this menu. A "Y" response will cause the program to exit to the system prompt. The right and left arrows are used to move across this menu to the desired selection. To move to 'Arch,' the following sequence is used: -->, Enter. This will then clear the screen and display the following submenu (Figure 7):

Exit Mono Hybrid Analysis Display Load Save
Exit to Previous Menu

FIGURE 7. Architecture Main Submenu

This menu will appear with 'Exit' being the highlighted default choice. Pressing Enter here will again ask the same question as previously stated. Note that this menu still includes all of the other choices available to the user. Here the user now has the choice of a monolithic structure for the focal plane array, or a hybrid structure. If a data file was previously saved from another session, the user could move to the 'Load' menu choice, press Enter, and then type in the "filename.DAT" and Enter. Note that the 'Load' menu choice may be called at any time that the architecture submenu is present, and that the loaded data file will override any changes that may have been made. In either case, an architecture structure is displayed, without any other submenus displayed on the screen. See Figure 8 for a reproduced screen display of the default monolithic architecture.

In Figure 8 (and all subsequent figures of reproduced screen displays), window A is the main operating submenu from which the other menus/windows are subsets. Window B is the area where all user prompts and inputs will be handled, whereas window C lists the submenu choices that window B will act upon. Note that each time the submenu goes down to another submenu, the menus will shift accordingly between windows A and C. Window D will always display the currently defined architecture, and window E will display either other architecture related values or other variables and calculated

Exit	Mono	Hybrid	Analysis	Display	Load	Save	A	
Modify Monolithic Parameters							B	
Physical Layout				C	CURRENT VALUES			E
Pixel Type					Read noise electrons: 100			
Configuration					Fat Zero electrons: 3.0E+002			
Material Type					Clock phases: 2			
R/O Type					Silicon doping conc.: 1.0E+014			
Preamplifier								
Monolithic Architecture				D				
Material Type: Si					Preamp width/length ratio: 4.0			
Pixel Type: MIS					Preamp Nd doping: 1.0E+015			
Readout Type: CCD					Source/drain Voltage: 10.00			
Preamplifier: FG					Preamp load resistor: 1.0E+006			
Configuration: Intline					Preamp Oxide thickness: 1000.0			
Layout - X: 300.000					Floating Gate Ref. Voltage: 10.00			
by - Y: 400.000								
Width X (um): 12.000								
Length Y (um): 10.000								
Spacing X-X (um): 30.000								
Y-Y (um): 10.000								
Ins R/O Thick (Ang): 1000.000								
Filling Efficiency: 0.400								

FIGURE 8. The default Monolithic Architecture Screen Display.

Exit	Mono	Hybrid	Analysis	Display	Load	Save	
Modify Hybrid Parameters							
Physical Layout					CURRENT VALUES		
Detector Material					Read noise electrons: 300		
Readout Material					Fat Zero electrons: 3.0E+002		
Preamplifier					Clock phases: 2		
Readout Type					Silicon readout doping: 1.0E+015		
Input type							
Hybrid Architecture							
Construction Technique: Planar					Nd input doping: 1.0E+015		
Detector Material: InSb-n					Voltage applied: -1.000		
Input Circuit: DirInj					Input width/length ratio: 4.0		
Preamplifier: FG					Preamp width/length ratio: 4.0		
Readout Type: CCD					Preamp Nd doping: 1.0E+015		
Layout - X: 62.0000					Source/drain Voltage: -1.00		
by - Y: 50.0000					Preamp load resistor: 1.0E+004		
Width X (um): 65.000					Preamp Oxide thickness: 1000.0		
Length Y (um): 65.000					Floating Gate Ref. Voltage: 10.00		
Spacing X-X (um): 76.000							
Y-Y (um): 76.000							
Ins R/O Thick (Ang): 1000.000							
Filling Efficiency: 0.731							

FIGURE 9. The default Hybrid Architecture Screen Display.

results from the analysis section of the model. The reproduced screen display for the default hybrid architecture is shown in Figure 9.

There will now be two highlighted menu items; the submenu highlighted default is 'Physical Layout', and either 'Mono' or 'Hybrid' depending on which architecture is chosen. Therefore, if Enter is pressed when either of the above two menus (Figures 8 and 9) is displayed, then the action taken is to go to the 'Physical Layout' submenu. A reproduced example is shown in Figure 10. Note that the submenus have changed in windows A and C, and that window B displays a different user prompt. Although, before Enter is pressed, any of the other choices may be selected by using the up and down arrows to move in the submenu of window C.

For example, if the 'Mono' architecture is chosen and the user chooses to change the 'Physical Layout', the reproduced screen display as shown in Figure 11 will result. Again, note the changes in windows A, B, and C, particularly in window B where the user is prompted to enter a new value. All of the current architecture values are displayed in windows D and E so that if no changes are needed, the user will need to "Exit" to the main architecture submenu before proceeding to the analysis.

The user can also use the right and left arrows to move across to another submenu choice in order to view what the other submenu choices are, and what might need to be

Exit	Layout	Pixel	Config	Matl	R/O	Preamp
Select Physical Layout						
Pixel Numbers				CURRENT VALUES		
X- and Y- spacing				Read noise electrons: 100		
Pixel Active Area				Fat Zero electrons: 3.0E+002		
				Clock phases: 2		
				Silicon doping conc.: 1.0E+014		
Monolithic Architecture						
Material Type:				Si		
Pixel Type:				MIS		
Readout Type:				CCD		
Preamplifier:				FG		
Configuration:				Intline		
Layout - X:				300.000		
by - Y:				400.000		
Width X (um):				12.000		
Length Y (um):				18.000		
Spacing X-X (um):				30.000		
Y-Y (um):				10.000		
Ins R/O Thick (Ang):				1000.000		
Filling Efficiency:				0.400		
				Preamp width/length ratio: 4.0		
				Preamp Nd doping: 1.0E+015		
				Source/drain Voltage: 10.00		
				Preamp load resistor: 1.0E+006		
				Preamp Oxide thickness: 1000.0		
				Floating Gate Ref. Voltage: 10.00		

FIGURE 10. Monolithic Architecture First Submenu Screen Display.

Exit	Number	Spacing	Area
Enter number pixels x-dir:			
# of X	CURRENT VALUES		
# of Y	Read noise electrons: 100		
	Fat Zero electrons: 3.0E+002		
	Clock phases: 2		
	Silicon doping conc.: 1.0E+014		
Monolithic Architecture			
Material Type: Si			
Pixel Type: MIS			
Readout Type: CCD			
Preamplifier: FG			
Configuration: Intline			
Layout - X: 300.000			
by - Y: 400.000			
Width X (um): 12.000			
Length Y (um): 18.000			
Spacing X-X (um): 30.000			
Y-Y (um): 10.000			
Ins R/O Thick (Ang): 1000.000			
Filling Efficiency: 0.400			
Preamp width/length ratio: 4.0			
Preamp Nd doping: 1.0E+015			
Source/drain Voltage: 10.00			
Preamp load resistor: 1.0E+006			
Preamp Oxide thickness: 1000.0			
Floating Gate Ref. Voltage: 10.00			

FIGURE 11. Monolithic Architecture Second Submenu Screen Display.

changed, before pressing Enter or exiting to the main submenu. It is highly recommended to 'Save' the architecture data file before continuing with the simulation.

In a similar fashion, if the user had chosen the 'Hybrid' architecture, used the up/down arrows to change the 'Detector Material' to HgCdTe, and again used the up/down arrows to change the molar concentration of cadmium in the compound, the monitor screen display would result in what is reproduced in Figure 12. Note that window D has been updated to show the current chosen architecture, and window E has been changed to reflect the additional architecture parameters such as doping concentration, molar value, and PV detector characteristics.

Another example is shown in Figure 13 for the other detector material type, InSb, assuming that a hybrid architecture has still been chosen. In this case, note that window D and window E have, again, made their respective changes. That is, the detector material of window D has been changed, and the doping concentration as shown in window E has been appropriately modified.

When the user is prompted for some change in window B, it should be noted that an Enter response will have the effect of using whatever has been defined by the global variable data file. Also, the program does have some protection against inputting other characters than what should be received, and against certain out-of-bounds

Exit	InSb	HgCdTe
Enter Doping Concentration of HgCdTe: 1.2E15		
HgCdTe_Na molar Cd		CURRENT VALUES
		Read noise electrons: 388
		Fat Zero electrons: 3.8E+002
		Clock phases: 2
		Silicon readout doping: 1.0E+015
Hybrid Architecture		
Construction Technique:	Planar	HgCdTe doping conc.: 1.0E+015
Detector Material:	HgCdTe	Nd input doping: 1.0E+015
Input Circuit:	DirInj	Voltage applied: -1.000
Preamplifier:	FG	Input width/length ratio: 4.0
Readout Type:	CCD	
Layout - X:	62.8888	Preamp width/length ratio: 4.0
by - Y:	58.8888	Preamp Nd doping: 1.0E+015
Width X (um):	65.888	Source/drain Voltage: -1.00
Length Y (um):	65.888	Preamp load resistor: 1.0E+004
Spacing X-X (um):	76.888	Preamp Oxide thickness: 1888.0
Y-Y (um):	76.888	Floating Gate Ref. Voltage: 18.00
Ins R/O Thick (Ang):	1888.888	
Filling Efficiency:	0.731	

FIGURE 12. Hybrid Architecture First Submenu Screen Display for HgCdTe.

Exit	InSb	HgCdTe
Enter Doping Concentration of InSb: 1.2E16		
InSb_Na p- or n-type		CURRENT VALUES
		Read noise electrons: 388
		Fat Zero electrons: 3.8E+002
		Clock phases: 2
		Silicon readout doping: 1.0E+015
Hybrid Architecture		
Construction Technique:	Planar	InSb doping conc.: 1.0E+016
Detector Material:	InSb	Nd input doping: 1.0E+015
Input Circuit:	DirInj	Voltage applied: -1.000
Preamplifier:	FG	Input width/length ratio: 4.0
Readout Type:	CCD	
Layout - X:	62.8888	Preamp width/length ratio: 4.0
by - Y:	58.8888	Preamp Nd doping: 1.0E+015
Width X (um):	65.888	Source/drain Voltage: -1.00
Length Y (um):	65.888	Preamp load resistor: 1.0E+004
Spacing X-X (um):	76.888	Preamp Oxide thickness: 1888.0
Y-Y (um):	76.888	Floating Gate Ref. Voltage: 18.00
Ins R/O Thick (Ang):	1888.888	
Filling Efficiency:	0.731	

FIGURE 13. Hybrid Architecture First Submenu Screen Display for InSb.

conditions. However, these conditions assume that the user has prior knowledge of the operation of charge transfer devices, and cannot protect the program from aborting if an obviously erroneous input is received.

Sample Analysis Operation

After making sure that all of the architecture parameters are properly set up or loaded in from a data file, the next choice is 'Analys'. Upon entering into the analysis menu, the monitor screen will clear and the reproduced screen display of Figure 14 will be seen.

Exit	Analys	Arch	Disp	Load	Save
Exit to Previous Menu					

FIGURE 14. Analysis Main Submenu

Note that the choice of returning to the architecture submenu or loading in a data file exists at this submenu. The default will again come up at "Exit" and if Enter is pressed, the same prompt as previously described will appear. However, a "N" response will still retain control at the analysis main submenu.

To enter the analysis portion, 'Analys' is selected, and the monitor screen is reproduced in Figure 15. Here, the other default highlighted choice is 'Dark Current', where if Enter is pressed, the reproduced screen of Figure 16 will

Exit Analys Arch Disp Load Save
 Modify Parameters of the Focal Plane Array

Dark Current
 Spatial Charge Movement
 Sensitivity
 MTF of Samples
 Noise

FIGURE 15. Analysis First Submenu Screen Display.

Exit Current Spatial Sens MTF Noise		
Modify Dark Current parameters		
Temperature		Dark Current Analysis of FPA
Oxide Thickness		
Gate Voltage		Temperature (K): 3.000E+002
Integration Time		Gate Voltage (volts): 1.000E+001
Pixel Active Area		Energy Band Gap (eV): 1.120E+000
		Thermal Velocity: 1.000E+007
		Capture Cross Section: 1.000E-015
Monolithic Architecture		Integration Time (msec): 2.500E+000
Material Type: Si		Pixel Active Area (cm ²): 1.003E-004
Pixel Type: MIS		Minor Carr Lifetime (sec): 1.000E-004
Readout Type: CCD		Surface State Density: 1.000E+010
Preamplifier: FG		
Configuration: Intline		Intrinsic carrier conc.: 1.360E+010
Layout - X: 300.000		Depletion Width (um): 1.161E+001
by - Y: 400.000		Empty Well Potential (v): 1.033E+001
Width X (um): 12.000		Full Well Potential (v): 2.304E-001
Length Y (um): 10.000		Dark Curr Density (A/cm ²): 2.165E-000
Spacing X-X (um): 30.000		Dark Curr Noise (electrons): 1.840E+002
Y-Y (um): 10.000		Maximum Signal (electrons): 2.252E+000
Ins R/O Thick (Ang): 1000.000		
Filling Efficiency: 0.400		

FIGURE 16. Analysis Dark Current First Submenu Screen Display for the default device.

appear. The other choices available are 'Spatial Charge Movement', 'Sensitivity', 'MTF of Samples', and 'Noise'. A reproduced example of each screen display at the default choice sublevel is given in Figures 17, 18, 19, and 20, respectively.

For all of the submenus of the analysis section, the calculations and other related parameters of interest are displayed in window E. Every time one of the global variables in window C is changed, accomplished via a prompt in window B, all of the calculations for the analysis is recomputed and redisplayed. The recomputation is necessary due to the interdependence amongst the many equations used for the calculations. This interdependence will become apparent during the following chapters on the detail behind the computer model simulation.

Other Computer Model Features

The last major submenu is the 'Display' choice and a sample screen is reproduced in Figure 21. Any of the numerical values followed by 'Enter' may be selected. The actual screen displays for choices 1, 2, and 3 will be seen in Chapter 4. Choice 4 will cause the program to write the data file "Parout.TXT" for future printout if a printer is available. Choice 5 will display another menu shown reproduced in Figure 22. Choice 5 allows the user to select any of the plots to be displayed on the monitor for a quick graphical interpretation of each particular parameter shown.

Exit Current Spatial	Sens	MTF	Noise
Modify Spatial Charge Movement			
t4 Time Constant		Spatial charge movement of FPA	
		Temperature (K):	3.888E+002
		Gate Voltage (volts):	1.088E+001
		Diffusion Constant:	3.493E+001
		Empty Well Potential:	1.033E+001
		Full Well Potential:	2.384E+001
		Integration time (msec):	2.500E+000
Monolithic Architecture			
Material Type:	Si		
Pixel Type:	MIS		
Readout Type:	CCD	Self-induced tSI(sec):	4.517E-006
Preamplifier:	FG	Thermal Time tTH(sec):	1.044E-007
Configuration:	Intline	Fringe Field tFF(sec):	8.142E-008
Layout - X:	388.888	t4 Time Constant (sec):	2.620E-007
by - Y:	488.888	Charge up time tC(sec):	1.133E+001
Width X (um):	12.888	Max. stare time tS(sec):	1.659E+001
Length Y (um):	18.888	CTE:	9.999E-001
Spacing X-X (um):	38.888		
Y-Y (um):	18.888		
Ins R/O Thick (Ang):	1088.888		
Filling Efficiency:	0.488		

FIGURE 17. Analysis Spatial Charge Movement Screen Display for the default device.

Exit Current Spatial	Sens	MTF	Noise
Modify Sensitivity			
Noise Equivalent Flux Responsivity		Sensitivity Analysis of FPA	
		Integration time (msec):	2.500E+000
		Quantum Efficiency:	1.588E-001
		Conversion Gain:	1.463E-002
		Pixel Active Area (cm ²):	1.883E-004
		Wavelength (Ang):	1.888E+002
		Bkgd Flux (pho/s-cm ²):	1.888E+015
		Spatial BWidth (lines/mm):	3.333E+001
Monolithic Architecture			
Material Type:	Si		
Pixel Type:	MIS		
Readout Type:	CCD		
Preamplifier:	FG	CTE:	9.999E-001
Configuration:	Intline	Noise Equiv Flux:	1.188E+014
Layout - X:	388.888	Dw:	4.357E+008
by - Y:	488.888	Rarray:	8.313E-012
Width X (um):	12.888	Vout:	8.339E-001
Length Y (um):	18.888		
Spacing X-X (um):	38.888		
Y-Y (um):	18.888		
Ins R/O Thick (Ang):	1088.888		
Filling Efficiency:	0.488		

FIGURE 18. Analysis Sensitivity Screen Display for the default device.

Exit	Current	Spatial	Sens	MTF	Noise
Modify the Modulation Transfer Function					
cell MTF			MTF of Samples of FPA		
epsilon MTF					
diffusion MTF					
Monolithic Architecture			Illumination: Front		
Material Type:	Si		Folding Freq (cycles/mm):	1.667E+001	
Pixel Type:	MIS		Normalized Spatial Freq:	5.000E-001	
Readout Type:	CCD		Periodicity (cm):	3.000E-003	
Preamplifier:	FG		Inefficiency:	1.000E-004	
Configuration:	Intline		Number of Transfers:	1.736E+003	
Layout - X:	388.000		Diffusion Length (um):	5.910E+002	
by - Y:	488.000		Dist from Depl Area(um):	1.000E+000	
Width X (um):	12.000		Cell MTF:	6.013E-154	
Length Y (um):	18.000		Diffusion MTF:	9.999E-001	
Spacing X-X (um):	38.000		Epsilon MTF:	8.486E-001	
Y-Y (um):	18.000		Total MTF - X dir:	7.014E-001	
Ins R/O Thick (Ang):	1000.000		Total MTF - Y dir:	4.576E-001	
Filling Efficiency:	0.400				

FIGURE 19. Analysis MTF of Samples Screen Display for the default device.

Exit	Photon	Input	Transfe	Trappin	Dark	Float	Preamp
Modify Photon Noise Parameters							
Photoconductive Gain				Noise Analysis of FPA			
Quantum Efficiency				Temperature (deg K):	3.000E+002		
Photon Irradiance				Photon Noise (electrons):	0.700E+001		
Pixel Active Area				Input Noise (electrons):	4.020E+002		
Integration Time				Transfer Noise (electrons):	2.010E+002		
Monolithic Architecture				Trapping Noise (electrons):	5.589E+003		
Material Type:	Si			Dark Curr Noise (electrons):	1.040E+002		
Pixel Type:	MIS			Reset/Partition Noise (elc):	1.100E+001		
Readout Type:	CCD			Preamp Noise (electrons):	7.010E+002		
Preamplifier:	FG			Total Noise (rms electrons):	5.655E+003		
Configuration:	Intline			Gain:	1.000E+000		
Layout - X:	388.000			Quantum Efficiency:	1.500E-001		
by - Y:	488.000			Photon Irradiance:	1.000E+011		
Width X (um):	12.000			Pixel Active Area (cm 2):	1.003E-004		
Length Y (um):	18.000			Integration Time (msec):	2.500E+000		
Spacing X-X (um):	38.000			Transfer Inefficiency:	1.000E-004		
Y-Y (um):	18.000			Signal Carriers:	2.027E+000		
Ins R/O Thick (Ang):	1000.000			Surface State Density:	1.000E+010		
Filling Efficiency:	0.400			Spatial BWidth (lines/mm):	3.333E+001		
				Transconductance (mhos):	9.961E-005		

FIGURE 20. Analysis Noise Screen Display for the default device.


```
DISPLAY MENU
-----
1. Readout Address type
2. Preamplifier out
3. Hybrid Input type
4. Hardcopy of FPA parameters
5. Plot Variables Menu
6. RETURN to menu

SELECT DISPLAY - 1,2,3,4,5,6
```

FIGURE 21. Display choice Submenu Screen Display

```
PLOT VARIABLES MENU
-----
1. Dark current vs. Temperature
2. Integration time (to full well) vs. Temperature
3. Total noise vs. Temperature
4. Total noise vs. Integration time
5. Charge up time vs. Temperature
6. Voltage out vs. Integration time
7. Voltage out vs. Irradiance in
8. RETURN to DISPLAY MENU

SELECT DISPLAY - 1,2,3,4,5,6,7,8
```

FIGURE 22. Plot Variables Submenu Screen Display

When the particular plot is selected, the user will then be prompted at the bottom of the screen for the range of the x-coordinate variable to be plotted. This will in most cases be either versus temperature or versus integration time. Almost any range may be selected, however, since only twenty points are calculated for each plot, the data of interest may not be easily seen if too wide of a range is selected. Again, it is assumed that the user has prior knowledge of charge transfer devices and will select a suitable, but not unreasonable, range to be plotted.

Once into the "Plot Variables" menu, it is necessary to 'Return to Display Menu' first before returning to the main submenu. Pressing 'Enter' after viewing the plot or, as in the case of the "Display Menu" choices, viewing the chosen architecture types, will return the screen to the menu previously displayed before the graphics subroutines were entered. Actual screen displays of the various plots will be shown and discussed in the later chapter on the results of the computer model simulation.

The graphics subroutines in version 3.0 of Turbo Pascal are very machine dependent, and consequently, the graphics card used by the personal computer on which this model simulation is run must be specified and compiled accordingly. The different graphics cards that can be supported by this program include the IBM color graphics adapter card (CGA), or IBM extended color graphics adapter

card (EGA), Hercules monochrome graphics card, and the Zenith Z80 graphics card. The necessary steps to adapt to any one of these graphics cards is again detailed in the unpublished "Owner's Manual and Operating Guide", and also in the "Turbo Pascal Graphix Toolbox" book published by Borland, International.

One more point to be made concerning the operation of the computer model is that no action will be taken until 'Enter' is pressed. This is particularly useful during the architecture section when it may be desired to quickly view the submenus available for change, by using the right/left arrows and moving across the submenu choices displayed in window A. This, in turn, will display the submenus in window C, but no action will be taken.

CHAPTER 4

COMPUTER MODEL ARCHITECTURE DETAIL

The first step in any model simulation and analysis is to define what the problem is to be modelled. In the case of this computer program, the first step is to define the architecture. This involves describing the physical geometry of the layout, including the pixel detector and material used for the detector fabrication. It is also necessary to define the doping concentration, oxide thickness, and type of detector to be used. In addition, the type of construction (monolithic or hybrid) as well as the type of output pre-amplifier must be selected. Each of these will be discussed separately.

Physical Layout

The physical layout consists of the pixel detector size, spacing between the adjacent detectors, and the total quantity of detectors in each direction. These are the most important architecture parameters, as they will considerably affect the overall performance of the device, no matter what type of array is chosen. These parameters are used in many of the equations, and they will be noted in the following chapter on the analysis of the focal plane array.

The inputs required by the program include the width of the detector (ΔX), and the length of the detector (ΔY). The center-to-center spacing in each direction (X-X and Y-Y), and the total number of detectors in each direction are also required inputs. From this information, the program will calculate the filling efficiency, which is expressed as the total active area divided by the total area of the detector array. All of the above values are displayed as part of the architecture section of the screen display as depicted in the previous Chapter 3.

Input Structure

The input structure into the focal plane is another important architectural parameter; it deals with what type of pixel is used as the detector for photon detection. The detector types that are used are a photoconductive, a Schottky-barrier using internal photoemission, a photovoltaic, and a metal-insulator-semiconductor (MIS), with the latter two types being the most common. Figure 23 gives a schematic cross section of the above detectors except for the Schottky-type. The detectors can also be either frontside or backside illuminated. The illumination (frontside or backside) and its effects on the FPA will be discussed later.

The Schottky-barrier detector has only been used in a monolithic device (Kohn, 1975). With this device, charge carriers are generated by internal photoemission in a

PHOTOCONDUCTIVE

PHOTOVOLTAIC

METAL-INSULATOR-
SEMICONDUCTOR

Figure 23. Schematic cross sections of the three technologically significant types of detectors. These are the photoconductor, the junction photodiode (or photovoltaic), and the metal-insulator-semiconductor structures.

metal/silicon Schottky-barrier. This approach has several noticeable features including the use of silicon and its well known properties. Another feature is the photodetection in a metal film which results in a highly uniform but low photoemissive yield (Steckl, 1976). This approach is not very common and has been limited to only monolithic devices so far, although it is fast becoming a suitable detector. However, it will not be used in the computer model for simplicity reasons.

Because FPAs are used in infrared (IR) applications and often at very low temperatures, the total power consumption of the FPA is limited by practical considerations of IR detector cryogenics to a few watts (Bluzer and Jensen, 1987). Each detector and associated readout circuitry is limited to below 1 milliwatt. Because a photoconductor is of low resistance (10-1000 ohms), the detector will require readout electronics (i.e. a separate preamplifier) that use more than 1 milliwatt per detector. Consequently, the photoconductive detector type is unsuitable when considering many thousands of detectors used in focal plane arrays.

On the other hand, a photovoltaic sensor is a diode and, hence, consists of a high resistance (greater than 1 Megohm) in parallel with a capacitance (a few picofarads). This high resistance makes the photovoltaic detector suitable for application in low power, large-area second-generation

multi-spectral IR imagers (Bluzer and Jensen, 1987). In addition to the low power dissipation, there is good linearity, a uniform response, and low $1/f$ noise (Iwasa, 1977).

From the above discussion, it is clear that the photovoltaic sensor is far more suited for use in a FPA than a photoconductive sensor. Thus, the photoconductive sensor will not be included in the computer model simulation.

The last input sensor to be discussed is the MIS input structure. An MIS sensor consists of a semiconductor substrate covered with a thin insulating layer upon which transparent electrodes have been deposited. Carriers created by photon absorption in the semiconductor are stored in a deep depletion well produced by a voltage applied to the electrode (Sze, 1980). The storage procedure can be continued as long as the steady-state corresponding to the applied voltage is not reached (Sirieix et al., 1978). When the integration time is over, the stored charge is read out either by injection into the substrate, or through transfer under an adjacent electrode. The essential feature of these devices is that the sensor and the charge transfer section (readout) are constructed on the same substrate.

There are two different categories of MIS, inversion-mode and accumulation-mode. The latter type of operation occurs when the gate voltage induces the same majority

carrier type at the insulator-semiconductor interface as in the bulk of the semiconductor. This condition falls in the category of extrinsic silicon operation, and as previously stated, will not be considered any further.

Inversion-mode operation is based on the generation of an inversion region at the insulator-semiconductor interface where the photogenerated carriers are collected. The bandgap of the semiconductor determines the absorption peak, and it must be chosen such that it falls within one or more of the atmospheric windows (Steckl, 1976). Thus, the MIS inversion-mode will be considered as one of the pixel types used in the computer model.

Hybrid Input Structures

For the hybrid architecture focal planes, a coupling circuit or technique is required to transfer the photocurrent from the detector to the readout. This coupling should be achieved with high efficiency, low noise, and a simple architecture. The input coupling circuits considered in this model are divided into two types, direct injection and indirect injection. The indirect injection circuits are a voltage-to-charge conversion type and include gate modulation and the fill and spill technique. Each will be described separately.

Direct Injection. For this type of input, a photovoltaic detector is directly bonded to a diffusion on the device (e.g. CCD). Figure 24 is the actual monitor screen

Figure 24. Actual monitor screen display for a direct injection hybrid input.

Figure 25. Actual monitor screen displays for an indirect injection hybrid. Two types are shown.

display for a direct injection input and gives a pictorial representation of this input type. The gates V_G and V_D are held at a negative voltage to produce a depletion condition, which causes the charge to flow directly under V_D . The transfer gate, ϕ_T , is held at zero potential during the integration time, and then driven negative by a pulse so that the charge under the V_D gate is transferred through the clocking gates. This approach is only good for high impedance detectors where the charge is photogenerated.

Indirect Injection. Indirect injection devices use a buffer stage between the photodetection stage and the readout shift register (e.g. CCD). Two such circuits are known as the fill and spill technique and gate modulation. Figure 25 shows an actual monitor screen display that pictorially represents both of these types. The major difference between the two is that the gate modulation has a voltage source directly coupled to the doping channel. Both employ a diode-resistor type buffer circuit.

Readout/Signal Process

The two major types of readout considered here were discussed and contrasted earlier, but there is more to their respective operations. The architectural layout of each is significantly different with the CCD having multiple address schemes. Each will be discussed here in further detail.

Charge Injection Device Readout

In CID structures, charges are injected through the substrate which has been selected for readout. Figure 26 shows an actual monitor screen display of a CID structure. Each cell consists of two electrodes, one connected to an addressable row, and the other to a column. Injection of any particular cell (i.e. random access) is performed by selecting the corresponding row and column. When either electrode voltage is driven to zero, charge is then transferred under the second electrode.

Charge-Coupled Device Structures

The CCD readout type involves a sequential transfer of charge across the array to the readout amplifier at the boundary of the matrix. There are two basic types of transfer-address schemes in a CCD, an interline address transfer and a frame field transfer.

Interline Transfer Address. This type of transfer is shown pictorially by an actual monitor screen display as shown in Figure 27. The interline transfer design has separate sites for optical integration and charge transfer which gives it a good modulation transfer function (MTF), but the opaque charge transfer regions make it unsuitable for backside illumination (Sequin and Tompsett, 1975). The charge transfer is carried out from the imaging columns (the

Figure 26. Actual monitor screen display of a Charge Injection Device structure.

Figure 27. Actual monitor screen display of a CCD Interline transfer address scheme.

Figure 28. Actual monitor screen display of a CCD frame field transfer address scheme.

detector sites) to the storage columns on opposite phases of a two-phase clock for successive interlace periods.

Frame Field Transfer. The frame field transfer design is shown pictorially by an actual monitor screen display as shown in Figure 28. This design has simple clocking requirements. The image is integrated for one interlace period (i.e. half a frame period) and then it is all clocked out rapidly into the intermediate storage area. From here, the line information is fed sequentially to the output by transferring one bit from each column at a slower clock rate into the output register. Only half the number of sensing elements are required for interlaced outputs if the clock organization has a two-phase form.

Computer Model Readout Parameters

In addition to deciding which type of readout to use, CCD or CID, there are additional inputs required from the user. The thickness of the insulator readout and the number of clock phases to be used are necessary inputs to the model. The device 'read noise' and the amount of fat zero charge carriers is also requested here in lieu of any better place in the menu sub-choices.

On-Chip Preamplifier

The on-chip preamplifier is fabricated as part of the substrate, and it is the last link of the FPA to the outside

world. As was previously discussed, the two most commonly used types are the floating diffusion and floating gate architectures.

Floating Diffusion Output

The floating diffusion output is shown pictorially by an actual monitor screen display as shown in Figure 29. In the figure, when ϕ_4 goes low, the electrons are transferred to the output gate through the screen gate, V_{SCR} . The electrons transferred to the floating diffusion cause the node to go negative toward ground and, simultaneously, the source follows.

The output signal is the difference between the reset level and the negative-going pulse, and, to get this signal (ΔV_{FD}), V_{out} is typically differentially sampled after reset and after charge transfer. This is called correlated double sampling (Dereniak and Crowe, 1984). A fast analog-to-digital converter is then used to digitize the signal. Sometimes a gate is placed between the reset clock phase and the diffusion in order to reduce clock feedthrough noise.

Floating Gate Output

The floating gate output is shown pictorially by an actual monitor screen display in Figure 30. A gate is in series with the phase transfer gates that senses charge as it moves past. However, this gate is connected to a reference

Figure 29. Actual monitor screen display of a floating diffusion output preamplifier.

Figure 30. Actual monitor screen display of a floating gate output preamplifier.

voltage through a reset gate and an output floating gate. the reset gate sets the floating potential to V_{ref} , and, as charge is passed under the gate, the voltage is reduced. The change in voltage is the signal voltage (Milton, 1980).

Detector Materials

As was previously discussed, there are three types of materials of primary interest to this computer model; they are silicon (Si), indium antimonide (InSb), and mercury cadmium telluride ($Hg_{1-x}Cd_xTe$), where x represents the molar fraction of cadmium present in this compound. Each of these has their own particular material parameters such as lifetime of the minority carriers, or simply the time a charge carrier will reside in the conduction band, and the energy bandgap. Other parameters include the intrinsic carrier concentration, the electron mobility, and the density of surface states.

These parameters are all either temperature dependent or dependent upon another parameter that is temperature dependent. This dependence is often only found from making measurements, and the information may be presented by graphical means where the dependence is qualitative rather than quantitative. However, quantitative information is necessary in order to simulate the behavior of the material.

Intrinsic Carriers

In absolutely pure semiconductors, conduction electrons and holes result only through the breakage of

bonds. Thus, the concentration of electrons (n) equals the concentration of holes (p). These concentrations are called the intrinsic carrier concentrations n_i of the semiconductor (Grove, 1967). The intrinsic carrier concentration should also be a function of the energy required to break a bond, which in terms of the energy band diagram, corresponds to the width of the forbidden gap, E_g .

The concept of majority/minority carriers can be explained by using an extrinsic-type material example as follows. Semiconductors can be of either a p-type or an n-type, and carriers can be either holes or electrons. The carrier whose concentration is the larger of the two is referred to as the majority carrier and the other one is referred to as the minority carrier. In the charge transfer concept, electrons are usually the minority carrier.

Electron Mobility

Electron and hole mobilities reach a maximum value at low impurity concentrations corresponding to the lattice-scattering limitation (Grove, 1967). Both hole and electron mobilities decrease with increasing impurity concentration, eventually approaching a minimum value at high concentrations. The mobility of electrons is larger than the mobility of holes in many semiconductors. The mobility used here is the inversion layer mobility, or that of the electron.

Surface State Density

The density of surface states can be defined as the high density of energy states in the forbidden gap near the interface of the readout. It is caused by the disruption of the periodic lattice structure at the readout interface (Kim, 1979). The density of the surface states depends on the orientation of the substrate which for a (111) orientation is about a three times higher density than for a (100) orientation (Kim, 1979).

A surface state is considered to be a donor state if it is neutral when it is occupied by an electron and positively charged when it is empty. If the state is negatively charged when occupied by an electron and neutral when empty, it is considered to be an acceptor state. When charge is stored under an electrode, some electrons will make the transition to these surface states and become trapped. When the remainder of the electrons in the conduction band are transferred to the next electrode, the surface states start to emit electrons. If the electron is emitted when the surface potential is no longer pushing charge to the next electrode, the electron cannot join the main charge packet, and the result is charge transfer inefficiency. The charge transfer inefficiency will be discussed in the next chapter.

Silicon Properties

The properties of silicon are listed in Table 1. The values shown were taken from various references. The values for the energy gap E_g , mobility μ , and the relative dielectric constant are shown for three temperatures (Sato et al, 1987). For the computer program, a second order least squares fit is used to derive an equation for each of these versus temperature. The intrinsic carrier concentration equation is from Wolf (1969). The density of states and minority carrier lifetime values are from Sequin and Tompsett (1975) and, although they will be indirectly affected by temperature, these values are assumed to remain relatively constant over the temperature ranges used.

Indium Antimonide Properties

The properties of InSb are listed in Table 2. The values were taken from many references and, except for the energy bandgap and intrinsic carrier concentration, all values are given for 77 degrees Kelvin. The relative dielectric constant and mobilities (for a p-type and an n-type substrate) are given by Steckl et al. (1975). The density of states is given by Nummedal et al. (1975), and the minority carrier lifetime is from Thom et al. (1975). The intrinsic carrier concentration is from Barbe (1980). The energy bandgap information was obtained from Salcido (1987) where the data is linear from 77-300 degrees Kelvin, and is relatively unchanged below 77 degrees Kelvin.

TABLE 1. Silicon Material Properties

$$n_i = 3.73(10^{16})T^{3/2}e^{(-7014/T)}$$

Property	Temperature (degrees Kelvin)		
	12	77	300
E_g	1.17	1.16	1.12
k_s	11.5	11.6	11.8
μ	300000	20000	1350
τ_n	-	-	2.5×10^{-3}
N_{ss}	-	-	1×10^{10}

TABLE 2. InSb Material Properties Used
(values are at 77 degrees Kelvin except where indicated)

$$n_i = 5.7(10^{14})T^{3/2}e^{(-0.125/kT)}$$

$$k_s = 17.0$$

$$\mu = 8(10^4) \quad (\text{p-type})$$

$$\mu = 3(10^3) \quad (\text{n-type})$$

$$N_{ss} = 1(10^{11})$$

$$\tau_n = 1(10^{-7})$$

Temperature (degrees Kelvin)			
	4.2	77	300
$E_g =$	0.224	0.223	0.18

Mercury Cadmium Telluride Properties

The material properties for HgCdTe are shown in Table 3, and the values were again taken from several references. The relative dielectric constant, minority carrier lifetime, and mobility are from Steckl et al. (1975). The density of states is found in Willardson and Beer (1981). These properties are given at the main operating temperature of 77 degrees Kelvin for HgCdTe. The energy bandgap versus temperature is given by Hansen, Schmit, and Casselman (1982), and the intrinsic carrier concentration versus temperature is given by Hansen and Schmit (1983).

TABLE 3. $\text{Hg}_{(1-X)}\text{Cd}_X\text{Te}$ Material Properties
(values given at 77 degrees Kelvin)

$$E_g = -0.302 + (1.93X) + (5.35(10^{-4})T(1-2X) - 0.81X^2 + 0.832X^3$$

$$n_i = \left[5.585 - 3.820X + 1.753(10^{-3})T - 1.364(10^{-3})XT \right] (10^{14}) T^{3/2} E_g^{3/4} e^{(-E_g/2kT)}$$

$$k_s = 18.0$$

$$\mu = 600$$

$$N_{ss} = 1(10^{11})$$

$$\tau_n = 1(10^{-7})$$

CHAPTER 5

COMPUTER MODEL ANALYSIS DETAIL

The analysis of a focal plane array consists of many different but interactive elements. The many features of interest has been broken down into five major areas of concern to the user. They are: (1) the dark current of the array, (2) the noise associated with the array, (3) the spatial charge movement across the array, (4) the modulation transfer function of the array, and (5) the sensitivity of the array. Each of these are discussed in detail in the subsequent paragraphs.

There are also some general equations which are required for performing calculations for many of the five different areas; they include the oxide capacitance, empty well and full well potentials, the depletion depth, the maximum charge attainable by any single well, and the quantum efficiency of the focal plane. These general equations are presented first followed by discussion of the main areas of interest in analyzing a focal plane array. Information is presented along with the equations to clarify the reason for choosing these equations and quantities. For a further understanding of any of these concepts and ideas, it is

suggested that the reader consult the referenced material, especially those listed at the end of Chapter 1.

General Equations

Many of the specific analysis equations use some of the following general ideas. The depletion depth is the distance under the gate known as the depletion region. The full well potential is where the strong inversion occurs, and it is the minimum value that the potential will attain. The empty well potential is actually the surface potential per se and it is at a maximum when no signal charge is collected. The maximum number of electrons occurs when the surface potential reaches the full well value. In addition, the charge transfer efficiency, quantum efficiency, and injection efficiency will also be treated. The input transconductance of a CCD defines the injection efficiency, which is used for a hybrid architecture only.

Surface Channel Well Potentials

The basic building block of the charge transfer device is the MOS capacitor. An energy diagram for the MOS capacitor is shown in Figure 31. When a positive voltage is applied to the gate it causes the mobile positive holes in the p-type semiconductor (a silicon substrate is assumed) to migrate toward the ground electrode, since like charges repel, and this positive charge-depleted region is called the depletion region. A small positive voltage causes the energy

Figure 31. Energy-band diagrams for surface channel MOS capacitors. (a) The MIS structure, band bending at deep depletion and the empty potential well representation. (b) Band bending with mobile charge at the Si-SiO₂ interface and the partially filled potential-well representations.

bands to bend downward, and the majority of carriers are depleted in this region. This depleted region is modeled by what is called the "depletion approximation," which assumes that the edge of the depletion region is abrupt and that no mobile majority charge carriers exist in this depletion region.

The electron potential at the semiconductor-insulator interface under the electrode is lower than that in the bulk of the semiconductor by amount ϕ_{SO} ; thus, a "potential well" of depth ϕ_{SO} is formed at the semiconductor-insulator interface under the electrode. If charge is collected at the potential well as a result of photon absorption or injection from an input diffusion or thermal generation, the potential across the insulator and the semiconductor will be redistributed as shown in Figure 31(b). If a photon with energy greater than the energy gap is absorbed in this depletion region it produces an electron-hole pair. The hole is mobile and moves out of the depletion region, but the electron is held in the depletion region against the oxide interface.

A one-dimensional model of the MOS capacitor including its cross section, charge distribution, electric field, and potential versus distance is shown in Figure 32. The charge distribution can be substituted into the Poisson equation to solve for the potential cross section of the MOS capacitor. The derivation itself is not given here, but it would begin with the following equation (Dereniak and Crowe, 1984)

Figure 32. One-dimensional MOS model. (a) The MOS cross section in one dimension. (b) The charge distribution versus x . (c) The electric field versus x . (d) The potential distribution versus x .

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{\partial^2 \phi}{\partial x^2} = \frac{-\rho}{k} = \frac{q N_A}{k} \quad (5.1)$$

where ϕ is the potential distribution, x is the distance, k is the dielectric constant, ρ is the charge density, q is the electron charge, and N_A is the acceptor doping concentration.

The basic electrostatic design equation for a surface channel CCD is obtained by solving Kirchhoff's voltage equation for an MOS capacitor. This will relate the surface potential ϕ_s to doping density N_A , oxide thickness d (or t_{ox}), and gate voltage V_g . The electrostatic equation is

$$V_g - V_{FB} = \phi_s + V_{ox} \quad (5.2)$$

where V_{FB} is the flatband voltage and V_{ox} is the voltage drop across the oxide.

However, $V_{ox} = (1/C_{ox}) * (\text{mobile} + \text{fixed charge density})$, and it can be expressed as

$$V_{ox} = \frac{1}{C_{ox}} * (qN + N_A q X_d) \quad (5.3)$$

where $C_{ox} = (\epsilon_{ox}/t_{ox})$ for an MIS detector, and $\epsilon_{ox} = k_o \epsilon_0$. For a PV detector, C_{ox} will be defined following the full well potential equation given in a subsequent paragraph. Also, k_o is the oxide relative dielectric constant, ϵ_0 is the permittivity in free space, q is the electron charge, X_d is the depletion depth, N_A is the doping concentration, and N is the number of mobile electrons per unit area.

Using the depletion approximation, the width (i.e. depth) of the depletion region, X_d , is (Grove, 1967)

$$X_d = \left[\frac{2 \epsilon_s \phi_s}{q N_A} \right]^{1/2} \quad (5.4)$$

where $\epsilon_s = k_s \epsilon_0$ is the relative dielectric constant of the semiconductor region.

By combining the above equations (5.2, 5.3, and 5.4), the following equation is obtained:

$$V_g - V_{FB} - \frac{qN}{C_{ox}} = \phi_s + \frac{1}{C_{ox}} (2qN_A \epsilon_s \phi_s)^{1/2}. \quad (5.5)$$

Solving equation (5.5) for ϕ_s gives the following expression for the surface (empty well) potential:

$$\phi_{s0} = (V_g - V_{FB}) + \frac{qN_A k_s \epsilon_0}{C_{ox}^2} - \frac{qN}{C_{ox}} - \frac{1}{C_{ox}} * \left[2qN_A k_s \epsilon_0 (V_g - V_{FB} - \frac{qN}{C_{ox}}) \right]^{1/2} + \left(\frac{qN_A k_s \epsilon_0}{C_{ox}} \right)^2. \quad (5.6)$$

Equation (5.6) describes how barriers can be controlled by proper choice of gate voltage, doping density, and oxide thickness (Amelio, Bertram, Jr., and Tompsett, 1971). For example, when the acceptor doping concentration, N_A , and also when the oxide capacitance, C_{ox} , are decreased, then the empty well potential ϕ_s will also decrease. On the

other hand, the minimum (or full) well potential occurs at the steady state condition where the inversion charge has accumulated at the interface. This has the effect of reducing the surface potential, as well as the depletion depth, and is given for an MIS type by (Steckl et al, 1975)

$$\phi_s(t \rightarrow \infty) = \phi_{sf} = \frac{2kT}{q} \ln \frac{N_A}{n_i} \quad (5.7)$$

where ϕ_{sf} is the full well potential. Here, k is Boltzmann's constant, T is the temperature, q is the electron charge, n_i is the intrinsic carrier concentration, and N_A is the doping concentration. It should also be noted that by convention the full well potential is equal to twice the built-in Fermi level potential (i.e. $\phi_{sf} = 2\psi_f$, Sze, 1981).

In the case of a PV detector, the full well potential is given by (McCarthy, 1982)

$$\phi_{sf} = V_{bi} = \frac{kT}{q} \ln \left[\frac{N_A N_D}{n_i^2} \right], \quad (5.8)$$

and the oxide capacitance is given by (McCarthy, 1982)

$$C_{ox} = \frac{1}{2} \left[\frac{2qk_s \epsilon_0 (N_D + N_A)}{N_D N_A (V_{bi} - V_{appl})} \right] \quad (5.9)$$

Here, V_{appl} is the voltage applied to the detector, N_D is the donor doping concentration, N_A is the acceptor doping concentration, and V_{bi} is the built-in voltage potential.

Flat Band Voltage

The flat band voltage is the gate voltage required to bring about the flat band condition in the semiconductor, and it is the difference of the modified work functions (Grove, 1967). It is given by

$$V_{FB} = \phi_{MS} - \frac{Q_{ss}}{C_{ox}} \quad (5.10)$$

where $\phi_{MS} = \phi_M - \phi_S$, and these are the work functions (measured to the top of the valence band) of the metal and semiconductor, respectively. In Equation 5.10, Q_{ss} is the surface state charge density and equals $N_{ss} \cdot q$, and C_{ox} is the oxide capacitance.

In the model, aluminum is assumed to be used as the gate metal and its metal work function is $\phi_M = 3.2$ (McCarthy, 1982). The semiconductor work function, ϕ_S , is the total work function of the semiconductor minus the Fermi potential plus one-half of the energy band-gap. For silicon, the total work function, ϕ_S' , is 4.35 (McCarthy, 1982) assuming a (111) crystal structure, and $E_g = 1.12$ at 300 degrees Kelvin.

The work function for an aluminum gate n-channel device (p-type substrate) then becomes $\phi_{MS} = 3.2 - (4.35 - (1.12/2) + \phi_F) = -0.59 - \phi_F$. The Fermi potential here is one half of Equation (5.7). The equation for ϕ_{MS} is only good for silicon with an aluminum gate and a n-channel structure. Figure 33 is a diagram showing the energy levels for this type of structure.

Figure 33. The energy levels and work functions for a metal-oxide-semiconductor with an aluminum gate. (McCarthy, 1982).

If a p-channel device (n-type substrate) is used, as could be the case if InSb is the semiconductor, then the substrate Fermi-level will be below the ionization energy level. This results in the semiconductor work function subtracting the Fermi potential instead of adding.

It is necessary to modify $\phi_{S'}$ to use this equation for other materials. Some data found for InSb was for a (110) crystal structure (Gobeli and Allen, 1966). From that data, $\phi_{S'} = 5.08$. Then, $\phi_{MS} = 3.2 - (5.08 + (E_g/2) - \phi_F)$, or $\phi_{MS} = -1.88 - (E_g/2) + \phi_F$ for InSb with an aluminum gate and a p-channel device (n-type substrate).

Gobeli and Allen, (1966), stated that "it will probably be unwise to predict that the work functions and photothresholds of the (100) and (111) faces of the III-V compounds are very close to those reported here for (100) surfaces." Further elaborating on this statement, they reported that some unpublished work suggests a difference of about 0.5 eV for these faces. Supporting this statement is some data furnished from Cincinnati Electronics (Salcido, 1987) which gave $\phi_{S'} = 4.57$. The equation for the work function then becomes $\phi_{MS} = 3.2 - (4.57 + (E_g/2) - \phi_F)$ or $\phi_{MS} = -1.37 - (E_g/2) + \phi_F$. This value for ϕ_{MS} will be used by the computer program for calculating the InSb flatband voltage.

The HgCdTe work function has been the most difficult to obtain any values for $\phi_{S'}$. In fact, even though there is

a lot of literature on HgCdTe, none of the sources specifically stated what the work function was. Some literature plotted curves of $(V_g - V_{FB})$ versus other parameters, but this does not work for the program here. Another source (Wu and McGill, 1985) made mention that the difference in the energies between the valence bands of HgTe and CdTe was essentially zero, but no mention was made about HgCdTe. As a result, the computer program treats the flat band voltage for HgCdTe as equaling zero.

Maximum Charge

The preceding equation (5.6) can also be used in order to calculate the maximum electron density that can be stored on an MOS capacitor (i.e. $N = N_{max}$) when the well potential is at a minimum (or at ϕ_{sf}). Solving (5.6) for N_{max} gives the following equation as the result for a surface channel device:

$$N_{max} = \frac{C_{ox}}{q} (V_g - V_{FB} - 2\psi_{sf} - \left[\frac{4qN_A \phi_s \epsilon_s}{C_{ox}} \right]^{1/2}) \quad (5.11)$$

where $\epsilon_s = k_s \epsilon_0$ and k_s is the semiconductor dielectric constant. Typically, V_{FB} , $2\psi_{sf}$, and the last quantity in the equation are much smaller than V_g , so the following approximate expression is often used

$$N_{max} \approx (C_{ox} V_g) / q \quad (5.12)$$

However, in the computer model presented here, the exact expression is used as opposed to the approximation in order to determine the maximum charge density. Note that this equation is a charge density, and it must be multiplied by the area of the gate electrode in order to determine the number of electrons at saturation in any cell.

Depletion Depth

By substituting the well potential equation (5.6) into the voltage drop equation (5.3), an expression for the depletion depth for an MIS detector can be found,

$$x_d = \left[\frac{2k_s \epsilon_0}{qN_A} \left(V_g - V_{FB} - \frac{Q_s}{C_{ox}} \right) + \left(\frac{k_s}{k_o} t_{ox} \right)^2 \right]^{1/2} - \frac{k_s}{k_o} t_{ox} \quad (5.13)$$

where t_{ox} is the oxide thickness, k_o is the oxide relative dielectric constant, and $Q_s = qN$. In a similar fashion, for a PV detector, the depletion area is given by (McCarthy, 1982)

$$x_d = \left[\frac{2k_s \epsilon_0 (N_D + N_A) \text{abs}(V_{bi} - V_{appl})}{q N_A N_D} \right]^{1/2} \quad (5.14)$$

where V_{bi} is the built-in voltage potential, V_{appl} is the applied voltage, N_D is the donor doping concentration, N_A is the acceptor doping concentration, q is the electron charge, k_s is the semiconductor relative dielectric constant, and ϵ_0 is the permittivity of free space.

Charge Transfer Efficiency

Charge is transferred from one spatial location to another by three mechanisms; they are self-induced drift, thermal diffusion, and fringe field drift. These mechanisms operate with a free charge transfer model, that is, free electrons in the conduction band (Boyle and Smith, 1970; Carnes, Kosonocky, and Ramberg, 1972). As these are not perfect mechanisms, not all of the charge is transferred, and some signal charge is left behind after the transfer process.

Figure 34 shows a cross section of a three-phase CCD, its surface potential profiles, and its clocking waveform that drives the transfer of charge. If the shifting of charge is done at a high frequency, that is, if the time duration for a well to collapse is less than that required for complete charge transfer to the following well, a significant portion of this charge flows back into the preceding stage, i.e. the backward flow concept. Bhattacharya et al. (1979) have developed a transfer function for a three-phase CCD taking into account the backflow of signal charge. The net effect of backflow is to increase the inefficiency.

Charge transfer efficiency (CTE) is the ratio of the charge transferred to the initial charge present. Another closely associated term that is often used is the transfer inefficiency, ϵ , and is defined as $\epsilon = 1 - \text{CTE}$. The effect of nonunity CTE is to cause the signal packet to be spread to

Figure 34. A simplified three-phase CCD. (a) Cross-sectional view showing input section, transfer section, and output section. (b) Surface-potential profile showing potential wells under the ϕ electrodes. (c) Surface-potential profiles showing the progression of charge transfer during one clock period. (d) Clocking waveforms used to drive the CCD during transfer. (Barbe, 1975).

gates that are adjacent to the signal-carrying gate, that is, to smear the image or reduce the modulation transfer function (MTF). The definition of the charge transfer efficiency is given below (Dereniak and Crowe, 1984)

$$\text{CTE} = \exp \left[\frac{1}{M} \ln \left[1 - \frac{\Delta N_1}{\Delta N} \right] \right] \quad (5.15)$$

where M is the number of transfers. Here, ΔN_1 is the number of carriers lost in the first packet, and ΔN is the maximum number of signal carriers. Since this equation depends upon measured data, the following expression will be used in the computer model as an approximation of the charge transfer efficiency over the entire array,

$$\text{CTE} = (1 - \epsilon)^M \quad (5.16)$$

The effects of charge transfer efficiency can be depicted as shown in Figure 35. Figure 35a shows the effect of 100 electrons for a perfect charge transfer, whereas Figure 35b shows the effect of a CTE of 0.999 over 100 gates. Figure 35c depicts how the output packets of charge might appear for this simplified view.

As noted earlier, the three basic mechanisms that are most important for efficient charge transfer in a CCD are the self-induced drift, thermal diffusion, and fringing field drift. However, experience with all CCDs tested to date has shown that these mechanisms are of only secondary importance,

Figure 35. Effects of charge transfer efficiency. (a) A perfect transfer (CTE = 1.0) output after 100 transfers. (b) The output after 100 transfers for a CTE = 0.999. (c) A group of signal-carrying gates showing transfer loss.

and the CTE is generally influenced by another factor called the "spurious potential packet" (Janesick et al. 1987). This term essentially represents the loss of charge during transfer due to improper potential well shape and/or depth beneath the pixel. These effects are often due to channel width variation, polysilicon edge lifting, and typical boron lateral diffusion; these effects have been examined elsewhere (Chen et al, 1979; Taylor, 1980). These spurious potential pockets are commonly found in the best of CCDs and they ultimately limit CTE performance, depending on the number and size of the pockets. The pockets may be large enough to trap up to 100,000 electrons depending on the array clock bias (Janesick et al. 1987).

Loss Mechanisms. The loss mechanisms that contribute to the charge transfer inefficiency can be divided into three groups: fixed loss, proportional loss, and nonlinear loss. Fixed loss is the loss of a fixed amount of charge during each transfer which is independent of the size of the signal charge and is associated with surface state and bulk state trapping. When operating with a fat zero, the fixed loss is eliminated (Broderson et al. 1975).

Proportional loss results in a dispersion that can be described by the transfer inefficiency which, for this type of loss, is independent of the signal amplitude. Although the proportional loss decreases with increasing fat zero, it usually cannot be eliminated.

Nonlinear loss is a more general description of transfer loss. It includes the dependence of loss on the signal amplitude, which can be nonlinear (Broderson et al. 1975). The proportional and fixed losses are actually special cases of the nonlinear loss. The amount of charge left behind after a signal charge makes one transfer is

$$N_{\text{Loss}} = \epsilon N_{\text{sig}} \quad (5.17)$$

where N_{Loss} is the number of lost charges, ϵ is the transfer inefficiency, and N_{sig} is the number of signal carriers. However, Equation 5.17 will not be used in this thesis because only the number of signal carriers is necessary for making the calculations used in the computer model.

Quantum Efficiency

The quantum efficiency η , is defined as the ratio of free photogenerated carriers to incident photons at the detector surface, and it is generally determined experimentally (Dereniak and Crowe, 1984). The quantum efficiency depends largely on the thickness of the photosensitive volume, and it varies considerably depending on the technology employed (Janesick et al. 1987). Because of this dependence, the quantum efficiency parameter will be treated as a user-defined input to the computer program.

It is necessary to point out that there are two cases of detector structure. The first is the transverse configuration, and it is the conventional one with radiation

incident perpendicular to the current. The second is the longitudinal case which is encountered in many FPA structures where the incident radiation is admitted through a transparent electrode parallel to the current (Marsh et al. 1981). Figure 36 shows a diagram of each type of structure.

The quantum efficiency also has an effect on the spectral response depending on whether the device is backside illuminated or frontside illuminated. In the backside case, there is a poor response in the ultraviolet and blue range, and there is the additional problem of loss of photons due to interference and electrode absorption. One solution is to provide backside charging to improve the quantum efficiency, but another newer development, the flash gate solution, shows more promise (Janesick et al. 1987). The flash gate structure is a thin film of high-work-function metal deposited on the backside of the CCD, and this is very effective in permanently accumulating the backside of the CCD. An additional increase in the quantum efficiency can be obtained by the deposition of an antireflection coating on the backside after the flash-gate deposition. This has been shown to substantially improve the response over the entire spectral range from the near-infrared to the soft x-ray (Janesick et al. 1987).

Frontside illuminated CCDs generally have a poor response in the blue range due to the absorbing gate layers above the potential wells. It also shows instabilities in

Figure 36. Diagram of (a) transverse, and (b) longitudinal detector structures. The bias voltage polarity is indicated by the (+) and (-) symbols.

quantum efficiency, specifically for wavelengths longer than 6500 angstroms, where the incident photons will penetrate deeply enough to generate charge in the low-resistivity substrate region (Janesick et al. 1987). The majority of this charge will recombine due to the short minority carrier lifetime in this region, although some charge will diffuse into the epitaxial layer. A solution to this problem which also yields a stable near-infrared quantum efficiency is to flood the CCD with near-infrared light prior to each exposure.

Injection Efficiency. If a hybrid architecture is used, then another quantum efficiency becomes involved, that of the injection efficiency associated with the input circuit to the focal plane array. This is a result of the charge being injected into the device and its corresponding efficiency effects. The injection efficiency is a function of the transconductance, g_m , and can be expressed as

$$\eta_{inj} = \frac{g_m R_D}{1 + g_m R_D} \quad (5.18)$$

where R_D is the shunting resistor of the detector (Bluzer and Jensen, 1987).

Note that Equation 5.18 is for zero spatial frequency. It is used in the computer program because the frequency dependent equations rely heavily on the various capacitances associated with any particular input circuit and are beyond the scope and direction of this thesis. However,

the interested reader can consult Felix, et al. (1980) and Bluzer and Stehlik (1978) for additional information on frequency dependent injection efficiencies.

The input transconductance for a PV detector is given by (Nelson, 1977)

$$g_m = \mu C_{ox} \left(\frac{W}{L} \right) \left(\frac{kT}{q} \right) \left[\left[1 + 2I_{CCD} (q/kT)^2 / \left(\frac{\mu C_{ox} W}{L} \right) \right]^{1/2} - 1 \right] \quad (5.19)$$

where μ is the field effect mobility, C_{ox} is the oxide capacitance, and k is Boltzmann's constant. Additionally, T is the temperature, q is the electronic charge, W is the input gate width, L is the input gate length, and I_{CCD} is the dc current flow into the gate. Figure 37 depicts the equivalent circuit (shown as a direct injection) used for the above equation (Iwasa, 1977).

For the subthreshold current regime defined by

$$I_{CCD} \ll \frac{W \mu C_{ox}}{2 L} \left(\frac{kT}{q} \right)^2 \quad (5.20)$$

where all parameters are as defined for Equation 5.19, the transconductance will reduce to

$$g_m = \frac{q I_{CCD}}{k T} \quad (5.21)$$

where

$$I_{CCD} = I_{\phi} + I_{SAT} \quad , \quad (5.22)$$

Figure 37. An equivalent circuit for a direct injection hybrid input. (Iwasa, 1977).

$$I_{\phi} = q \eta_b A_D \quad , \quad (5.23)$$

$$I_{SAT} = \frac{k T}{q R_O} \quad . \quad (5.24)$$

Here, R_O is the zero bias diode resistance (typically about 20 Megohms), η is the quantum efficiency, ϕ_b is the background photon flux, and A_D is the photosensitive area (Iwasa, 1977).

It follows then that the condition $I_{\phi} \gg I_{SAT}$ assures a high percentage signal injection. It is also known as the background infrared limited condition (or BLIP), which means that there is 100% signal injection, a linearity of the photoresponse (between I_{CCD} and ϕ_b), and a channel uniformity which is independent of the variations in R_O . The computer simulation presented herein assumes a BLIP condition, and therefore, Equations 5.21 to 5.24 will be used. The effect of both injection efficiency and quantum efficiency may be combined to define the overall quantum efficiency by the relation

$$\eta = \eta * \eta_{inj} \quad (5.25)$$

and this is the relation which is used for the FPA quantum efficiency. For a monolithic FPA architecture, η_{inj} is taken to be equal to 1.

Computer Model General Equations

The computer model as described herein will use the equations described so far in the following procedures. The symbology used in the following equations will be the same as

for those symbols used previously. Appendix A is to be referred to for the units involved by the different parameters.

Dark Current

Since a CCD operates by controlling depletion volumes, there is continual generation of hole-electron pairs due to the thermal vibration of the detector's lattice structure (Barbe and Campana, 1977). Minority carriers tend to flow to the point of minimum potential where they are collected. The source of these carriers is usually called dark current, and it forms the bulk of the charge transfer process.

There are three components of dark current, namely, thermal generation at the silicon dioxide (SiO_2) interface, thermal generation in the depleted volume, and thermal generation in the neutral bulk within a diffusion length of the interface (Kim, 1979). The other source of carrier generation is from the background photon flux; this will not be included as part of the dark current analysis, but it is still a valid carrier source.

Dark Current Limitations

The dark current imposes three limitations on the operating characteristics of a CCD; they are finite storage time, fixed pattern noise, and temporal noise. The noise limitations will be discussed in a subsequent section on

noise. The finite length of time required to fill a well is called the storage (or store) time T_S , and it is given by

$$T_S = \frac{qN_{Full}}{J_D} \quad (5.26)$$

where q is the electron charge, N_{Full} is the full well density of carriers, and J_D is the dark current density. Typical values for the storage time are in the range of 0.1 - 10 seconds (Steckl, 1976). Long storage times are obtainable by reducing the number of bulk generation centers, by reducing the number of surface states, and by reducing the temperature (Kim, 1979).

The storage time is also affected by carrier lifetime which is controlled by both bulk and surface recombination. The bulk generation centers, which are usually gold impurities in silicon, as well as the surface states, depend very critically on the fabrication process and the material. Therefore, a long storage time can only be obtained by selecting a good material and by careful fabrication. The storage time will be used by the computer model in order to define an upper limit for the user-defined integration time.

Another problem in imaging applications of charge-coupled devices is dark current non-uniformity. However, if care is taken during the fabrication process, the output signal will be relatively uniform over the entire device except for a few very large current spikes (Kim, 1979). The

cause of this non-uniformity is the non-uniform distribution of the bulk generation centers mentioned previously.

Frequency limitations. The low frequency limit of a CCD can be estimated by comparing the charge accumulated from dark current with the saturation charge. If a CCD is clocked continuously at a constant frequency f , the output signal due to dark current is (Sze, 1981)

$$Q_{\text{dark}} = \frac{A_d J_{\text{dark}}^M}{p f} \quad (5.27)$$

where A_d is the area of the electrode, J_{dark} is the dark current density, M is the number of electrodes, and p is the number of phases.

The low frequency degradation of the frequency is due to the buildup of dark current in the charge packets, which distort the signal charge. At very high frequencies, transfer efficiency falls rapidly because there is not enough time for complete charge transfer (Sze, 1981). To improve the low frequency response, one must reduce all the dark components (which will be discussed in the following paragraphs) by having a long minority lifetime, large diffusion length, and low surface recombination velocity.

To extend the high frequency performance, one can reduce the gate electrode length, maximize surface mobility by using electrons instead of holes in the charge packet, and minimize electrode spacings. The electrode spacings and

lengths can be changed by the program user, and the program assumes electrons instead of holes are the charge carriers.

Dark Current Expressions

The expressions for the different components of the dark current are given below (Kim, 1979). The thermal generation at the interface, J_s , is given by

$$J_s = \frac{q n_i S_0}{2} \quad (5.28)$$

where q is the electron charge, n_i is the intrinsic carrier concentration, and S_0 is the surface recombination velocity and has been introduced to allow for the semiconductor-insulator interface conditions. The surface recombination velocity, S_0 , is given by the expression $S_0 = (\sigma v_{th} \pi k T N_{ss})$ where v_{th} is the thermal velocity, k is Boltzmann's constant, T is the operating temperature, σ is the capture cross sectional area, and N_{ss} is the density of the surface states.

The depletion region thermal generation, J_G , is given by

$$J_G = \frac{q n_i x_d(t)}{2 \tau_n} \quad , \quad (5.29)$$

where q is the electron charge, n_i is the intrinsic carrier concentration, $x_d(t)$ is the depletion region depth as a function of time, and τ_n is the minority carrier lifetime.

The thermal generation due to the bulk, J_b , is given by

$$J_b = \frac{qn_i^2 L_D}{N_a \tau_n}, \quad (5.30)$$

where q is the electron charge, n_i is the intrinsic carrier concentration, N_a is the doping concentration, and τ_n is the minority carrier lifetime. L_d is the diffusion length which is given by $L_d = (D_n \tau_n)^{1/2}$, where D_n is the diffusion constant given by the Einstein relation $D_n = \mu (kT/q)$.

As the states that contribute to thermal generation are near the center of the forbidden gap, the temperature dependence of the dark current is

$$J_{\text{dark}} \sim \exp(-E_g/2kT) \quad (5.31)$$

where E_g is the energy gap. Thus, the dark current is a strong function of temperature, decreasing by a factor of 2 for every 10 degree C increase in temperature. A plot of dark current versus temperature is shown in Figure 38 for a typical device. The actual numerical values will differ for different devices.

Figure 38. Actual monitor screen display of a Plot of dark current versus temperature.

Computer Model Dark Current

The total dark current is given by the sum of the three components defined above. Thus, the total dark current to fill up a well is given by

$$J_{\text{dark}} = J_G + J_S + J_b \quad . \quad (5.32)$$

In the computer program's dark current procedure, N_{Full} (see Equation 5.26) is also calculated and displayed on the screen.

Noise Analysis

There are a number of noise sources that limit the sensitivity of a system using a CCD focal plane. There are noises associated with the scene photon flux, noises related to the array itself, and noises related to the output pre-amplifier. As is the case with any system, the best possible performance is obtained when the noise is caused by the randomness of the photons arriving at the detector. All sources of noise are assumed to obey Poisson statistics and are averaged as the root mean square with units given in rms electrons.

Noise Due To Photons

This noise is due to the random fluctuations in the arrival rate of photons incident on the detector. Since this process is stochastic with Poisson statistics determining the photon arrival times, the noise is equal to the square root of the average number of photons. Photon noise manifests

itself as shot noise in the device. The photoconductive gain (G) is equal to two for photoconductors because of the generation and recombination of charge carriers, and $G = 1$ for photovoltaic (PV) detectors where recombination is not present. The expression for the photon noise, n_{ph} , is given by the following (Dereniak and Crowe, 1984)

$$n_{ph} = [2G^2 \eta E_p A_d \tau_i]^{1/2} \quad (5.33)$$

where G is the photoconductive gain ($G=1$ for PV), η is the quantum efficiency, E_p is the photon irradiance input, A_d is the active pixel area, and τ_i is the integration time.

Noise Due To The Input

This noise is the random injection of charge from a diffusion into a potential well, and is often called Fat Zero noise when a Fat Zero is put in electrically. It is also associated with transferring charge onto a capacitor (the charge coupled device technology) and is often called kTC noise. This is the thermal noise of a resistor in parallel with a capacitor (Beynon and Lamb, 1980). The number of noise electrons is inversely related to the square of the electron charge (Dereniak and Crowe, 1984) and is given by

$$n_{in} = \left[\frac{kTC_{in}}{q^2} \right]^{1/2} \quad (5.34)$$

where k is Boltzmann's constant, T is the operating temperature, C_{in} is the input oxide capacitance, q is the electron charge, and n_{in} is the input noise.

Noise Due To Transfer Inefficiency

The transfer inefficiency noise is associated with the random amount of charge lost by a signal upon a transfer including the amount of charge introduced to a signal upon entering a well. If N is the total number of carriers in the signal packet, then, on the average, ϵN will be left behind at each transfer (Barbe, 1980; Thornber, 1974). There will be fluctuations about this mean with a mean squared value of $2 \epsilon N$. The factor of 2 is introduced because of the shot noise introduced once for entering and once for leaving the potential well. Both the signal carriers, N_s , and the background carriers, N_{FZ} , will fluctuate because of this mechanism. The expression for the transfer noise is given by (Lee and Patel, 1980)

$$n_{ti} = [2 \epsilon M (N_s + N_{FZ})]^{1/2} \quad (5.35)$$

where n_{ti} is the trapping inefficiency noise, ϵ is the transfer inefficiency, M is the number of gate transfers, N_{FZ} is the number of Fat Zero background carriers, and N_s is the number of signal charge carriers.

Noise Due To Trapping

The trapping noise arises from random trapping and emission from interface states or bulk states. This expression is derived from the Shockley-Read-Hall equation for the fractional rate of emission of trapped carriers from a given interface energy state (Dereniak and Crowe, 1984). Even in the complete charge transfer model, there are other limitations on the charge transfer efficiency caused by trapping. The trap states exist on both surface-channel and buried-channel devices; however, the density of states, N_{ss} , in the surface channel is about two orders of magnitude higher than the buried channel devices.

Fast interface state noise is present in surface channel CCD's during transfer, and bulk state noise is present in buried channel devices (Lee and Patel, 1980). The rate of filling these traps depends on the population in the conduction band, and the rate of decay of the trap state depends on the energy difference between the conduction band and the trap level. There is a net charge pile up since the trapping states will fill faster than they empty. The expression for the trapping noise, n_{tr} , is given by (Dereniak and Crowe, 1984)

$$n_{tr} = [MkTA_d N_{ss} \ln 2]^{1/2} \quad (5.36)$$

where M is the number of gate transfers, k is Boltzmann's constant, A_d is the active pixel area, N_{ss} is the fast surface state density, and T is the operating temperature.

One way to reduce this loss is by the introduction of a Fat Zero that keeps the fast interface states continuously filled so that no traps are empty to capture charge from the signal packet (Broderson, Buss, and Tasch, Jr., 1975). A diagram depicting what the Fat Zero operation does is shown in Figure 39.

Another way to reduce this noise is by using a buried channel rather than a surface channel device. In this case, the charge is transported in the bulk rather than at the surface and interaction with the surface states is avoided which suppresses the noise source. The trapping effects due to the bulk traps are quite different from those due to interface traps as the bulk states occur at discrete energy levels with defined characteristic emission times. Thus, the effect of bulk state trapping is strongly dependent on the clock frequency (Lee and Patel, 1980). For a single level trap characterized by the trap emission time τ_e , the bulk state noise is given by (Lee and Patel, 1980)

$$N_B = 2 V_S N_t \exp(-T_C/p) [1 - \exp(-T_C/p)]^{1/2} \quad (5.37)$$

where V_S is the volume occupied by the charge per gate, N_t is the density of bulk traps, T_C is the clock period, and p is

Figure 39. The introduction of Fat Zero into a well. (a) Potential well with Fat Zero. (b) Potential well with Fat Zero and signal charge, thus causing a greater number of surface traps to be exposed.

the number of phases. The effects of bulk trapping are reduced as the signal level decreases, and at low temperatures it can be considerably reduced as the emission time constant, τ_e , increases exponentially to become much longer than the clock frequency. Thus, the device can be operated at the minimum noise. The computer program will only calculate the surface channel trapping noise since buried channel devices are not included in this work.

Noise Due To Dark Current

The dark current noise is that associated with thermally generated carriers to bring the well into thermal equilibrium. Since the generation process is random and obeys Poisson statistics, there is temporal noise which is the square root of the mean. The dark current itself is not completely uniform throughout the device, and the effect of this nonuniformity is to impose a fixed pattern of noise on the signal (Barbe and Campana, 1977). Since the dark current is a strong function of temperature, the temporal dark current noise and the fixed pattern noise can be reduced by cooling. The expression for the dark current noise, n_d , is given by (Dereniak and Crowe, 1984)

$$n_d = \left[\frac{J_d \tau_i A_d}{q} \right]^{1/2} \quad (5.38)$$

where J_d is the dark current density, τ_i is the integration time, A_d is the pixel area, and q is the electron charge.

Noise Due To Floating Diffusion

Floating diffusion noise, also called reset noise, is the thermal noise of the MOSFET channel resistance in parallel with the floating diffusion capacitance. In the floating diffusion type of readout, the charge packet is transferred to a floating diffusion, which is connected to a gate of an output MOSFET. Basically, the charge packet is dumped onto a capacitor to produce an output voltage. The noise is again the kTC type of noise discussed previously (Milton, 1980). The expression used for the floating diffusion noise, n_{fd} , is given by (Dereniak and Crowe, 1984)

$$n_{fd} = \left[\frac{k T C_O}{q^2} \right]^{1/2} \quad (5.39)$$

where k is Boltzmann's constant, T is the temperature, C_O is the output capacitance, and q is the electron charge.

A technique known as correlated double sampling, (CDS), can be used to suppress the reset noise as well as resetting shift levels. This technique will also smooth low-frequency noises such as 60 Hz noise (Dereniak and Crowe, 1984). In the computer model presented herein, CDS will not be considered. It is left to the user to decide whether or not to use CDS outside of this program.

Noise Due To The Preamplifier

Besides the KTC noise mentioned previously for an output circuit, which can be removed by correlated double sampling, there still is some noise remaining, and it is called the preamplifier noise. The preamplifier noise is associated with a MOSFET of a given transconductance, and the expression used here has been derived by Jordan and Jordan (1965). The expression for the preamplifier noise, n_p , is given by

$$n_p = \left[\frac{C_o^2}{q^2} \frac{8kT \Delta f}{3 g_m} \right]^{1/2} \quad (5.40)$$

where C_o is the output capacitance, k is Boltzmann's constant, T is the operating temperature, Δf is the electrical bandwidth, g_m is the transconductance of the preamplifier, and q is the electron charge.

Partition Noise

Partition noise is the noise associated with the channel length, L , dependence on the reset noise. It is associated with the carrier partition in the reset MOS channel. From a reset noise (i.e. floating diffusion noise) measurement experiment, it has been inferred that reset noise consists of two parts; the sensing capacitance (C_s) dependent part and the effective reset channel length (L) dependent part (Teranishi and Mutoh, 1986).

Conventional reset noise theory, where the Johnson noise in the reset MOS channel is regarded as the only noise source, agrees with the C_g dependent part of measured reset noise. However, it cannot explain the L dependent part. Teranishi and Mutoh (1986) proposed that, in addition to Johnson noise, partition noise is found to be a noise source in CCD signal detection. They found the noise, n_{PN} , to be of the form

$$n_{PN} = \left[\frac{2}{\pi^2} \frac{kTWLC_{ch}}{q^2} \right]^{1/2} \quad (5.41)$$

where k is Boltzmann's constant, T is the temperature, W is the effective reset channel width, L is the channel length, C_{ch} is the channel capacitance, and q is the electron charge.

It is notable that the partition noise has a "kTC" form like Johnson noise. However, the partition noise is generated under a nonequilibrium partitioning process, while the Johnson noise is generated under equilibrium. Therefore, the partition noise can be distinguished from the Johnson noise only by experiment (Teranishi and Mutoh, 1986). Even so, it will be included in the computer model as an overall contributor to the total noise.

Other Noises

The other output circuit that is often used, which is also included in this computer model, is the floating gate amplifier. The noise associated with it is thermal noise of

the resistance through which the floating gate is reset. However, if the floating gate is reset once each frame time by an MOS transistor, the reset noise will be below the bandpass and can be removed by filtering (Carnes and Kosonocky, 1972). Hence, floating gate noise will not be considered as a noise contributor in this program.

Another possible candidate for a CCD noise source is $1/f$ noise, a generic term used to describe noise with a $\sqrt{1/f}$ power spectrum. This noise is closely associated with trapped charges. However, since it is assumed that there is complete charge transfer, the trapped charge is part of the signal charge itself and there is no amplification or gain mechanism. Thus, the $1/f$ mechanism should be absent in CCD's (Carnes and Kosonocky, 1972).

In contrast, $1/f$ noise is present in MOSFET's, and it would contribute to the overall noise if they are used at the output of a CCD (Martinson, Gaffney, and Mayer, 1977). For the MOSFET, the frequency spectrum of the coupling noise current has a $1/f$ part and a white spectrum part, which is the afore mentioned preamplifier noise. For very weak injected currents, the $1/f$ part is practically negligible (Felix et al. 1980). However, for poor injection efficiency, MOSFET $1/f$ noise can be a serious problem (Chow et al. 1982).

There is considerable $1/f$ noise present in the best of devices, and the "main goal of the future will be to design an output transistor that operates fully buried to

reduce the $1/f$ noise component" (Janesick et al. 1987). Because of the preceding discussion, the computer program will consider the $1/f$ noise contribution as part of the preamplifier noise and $1/f$ will not be treated any further than that.

Other noises that are present in devices (i.e. CCD) but will not be used in the model are a number of luminescent noises including clocking, diffusion, pinch-off, and blemish luminescence (Janesick et al. 1987). Clocking luminescence results simply from the action of clocking the gates, and it adds noise in the same fashion as an optically injected fat zero. Diffusion luminescence is related to the n-p diffusions used in the input-output structure of the CCD. It can be eliminated by reducing or inhibiting the bias voltage during the integration period.

Pinch-off luminescence is associated with the channel of the CCD output MOSFET. It can add significantly to the $1/f$ noise, but it can be reduced by careful bias of the MOSFET to yield the highest transconductance and lowest $1/f$ noise level. Blemish luminescence is the most serious of the luminescence problems. It is related to a single pixel that, in some extreme cases, can saturate the entire CCD in a few seconds. The problem is typically related to a low impedance between clock gates within the pixel, but it can be reduced by the appropriate clock phasing during the integration and readout cycles.

Computer Model Noise Analysis

Since all sources of the noise contributors are taken as Poisson statistics, they may be averaged as the root mean square to get a total noise value of the focal plane array. The total noise for the focal plane array in one integration time period is given by

$$n_T = \left[n_{ph}^2 + n_{in}^2 + n_{ti}^2 + n_{tr}^2 + n_d^2 + n_{fd}^2 + n_p^2 + n_{PN}^2 \right]^{1/2} \quad (5.42)$$

where n_T is the total number of rms noise electrons. The noise procedure in the computer program makes use of the values specified in the architecture set up routine. The program also performs a truncation on the results of the square root function in order to ensure that the program will print the number of noise electrons as a whole number rather than as a fraction. The program will also check to see if a floating gate output is selected, which will then set the floating diffusion noise to zero.

Spatial Charge Movement

The "spatial charge movement" of this computer model consists mainly of looking at the time constants used to describe a focal plane array in order to give an estimate for how long the injected charge takes to make a complete charge transfer. The dynamics of charge transfer are governed by the continuity equation and Poisson's equation with the appropriate boundary conditions. In general, both drift and

diffusion contribute to charge transfer, but drift processes dominate.

Drift current is caused either by the electrical field due to a nonuniform distribution of electrons under two electrodes at the same potential or by a field due to the potential differences between electrodes. These processes are called self-induced drift and fringe-field drift respectively (Barbe and Campana, 1977). The detailed solution of these equations for real device structures requires numerical calculations (Mohsen et al. 1973).

As noted earlier, that the three mechanisms involved in the free charge transfer process are thermal diffusion, self-induced drift, and fringing field drift (Boyle and Smith, 1970). Each of these has a time constant associated with it. The composite sum of these three mechanisms yields t_4 , the time required to transfer 99.99% of the charge (Steckl, 1976). Another important parameter is the charge-up time (t_c), since it represents the length of time the device can store before reaching saturation and, thus, establishes the minimum frequency of operation (Steckl, 1985).

Self-induced Drift

As a rule, self-induced drift accounts for about 95% of the charge transfer and is caused by the mutual repulsion of like charges. It is electrostatic in nature (Carnes, Kosonocky, and Ramberg, 1971). Consider the ideal two electrode charge coupled device as shown in Figure 40.

Figure 40. The ideal two electrode charge-coupled device, biased for charge transfer between 1 and 2.

During the charge transfer process, the electron concentration under the first electrode, capacitor 1, will not be uniform but will decrease as one travels along the length of the electrode's surface. This change in the electron concentration will induce an electric field because the surface potential is a function of the charge stored at the surface as well as the gate voltage applied to the electrode. This induced field is called the self-induced drift and is in such a direction as to push the electrons towards the second electrode, capacitor 2 (Kim, 1979).

The expression for self-induced-drift charge density as a function of time is the following asymptotic expression (Carnes, Kosonocky, and Ramberg, 1972):

$$\frac{N_S(t)}{N_S(0)} = \frac{t_{SI}}{t + t_{SI}} \quad (5.43)$$

where $N_S(0)$ is the charge density at the initialization transfer, and t_{SI} is the self-induced time constant. The self-induced time constant is given by (Carnes, Kosonocky, and Ramberg, 1972)

$$t_{SI} = \frac{2 L^2 C_{ox}}{\pi \mu q N_S(0)} \quad (5.44)$$

where L is the interelectrode spacing, C_{ox} is the oxide capacitance, μ is the mobility, and q is the electron charge.

Thermal Drift

When the requirement for the transfer efficiency is high, there should be a very small amount of electron concentration under the first electrode during the final stage of the transfer process. The transfer process due to the self-induced field is then no longer the dominant charge transfer mechanism, because the effective diffusion coefficient is now smaller than the thermal diffusion constant. The total charge under the storage electrode decreases exponentially with time, and the thermal time constant, t_{TH} , is given by (Kim, 1979)

$$t_{TH} = \frac{4 L^2}{\pi^2 D_n} \quad (5.45)$$

where L is the interelectrode spacing. The thermal diffusion constant, D_n , is related to the mobility, μ , by Einstein's relationship $D_n = \mu (kT/q)$, where k is Boltzmann's constant, T is the operating temperature, and q is the electron charge.

It can clearly be seen in Figure 40 that the self-induced field transfers the charge during the initial stage of the charge transfer process when the charge density is relatively large. During the final stage when the charge density is small, the charge transfer is due to the thermal diffusion. If the amount of initial stored charge is small, the self-induced field is also small, and thermal diffusion then becomes the dominant charge transfer mechanism.

Fringing Field Drift

It has been assumed, so far, that the surface potential under the first electrode is flat in the absence of electrons. Then, as the size of the electrode becomes smaller, the surface potential under the first electrode is affected by the voltages applied to the adjacent electrodes due to the two-dimensional coupling of the electrostatic potential. This results in a surface electric field even in the absence of mobile charge at the interface, and this is termed the 'fringe field' (Kim, 1979).

Since the fringing field is present even at very low charge concentrations, the last bit of the signal charge will be transferred by the fringing field rather than by thermal diffusion. The magnitude of the fringing field is a function of the oxide thickness t_{ox} , electrode length L , substrate doping N_A , and gate voltages V_g . The expression for the fringe field drift time constant is given by (Sequin and Tompsett, 1975)

$$t_{FF} = \frac{L}{2 \mu E_Y^{min}} \quad (5.46)$$

$$\text{and } E_Y^{min} = 6.5 \frac{t_{ox} V_g}{L^2} \left| \frac{\frac{5 X_d}{L}}{\frac{5 X_d}{L} + 1} \right|^4 \quad (5.47)$$

where X_d is the depletion depth and μ is the mobility. It is noted that the fringing field is larger for a thicker oxide,

a greater clock swing, and a smaller electrode length (i.e. pixel size). In comparison to surface channel devices, the fringing field is higher in buried channel devices (Kosonocky, 1974).

t₄ Time Constant

The t₄ time constant is a convenient figure of merit and is the time required for the transfer of 99.99% of the charge. It is the composite sum of all of the other previously described charge transfer mechanisms. This time constant is given by (Steckl, 1976)

$$t_4 = \frac{L^2 q}{10 \mu k T} \ln \left[10^5 \frac{k T / q}{|\phi_{sf} - \phi_{s0}|} \right] \quad (5.48)$$

where μ is the effective minority carrier mobility, L is the electrode length (i.e. pixel size), k is Boltzmann's constant, and T is the operating temperature. Also, q is the electron charge, ϕ_{sf} is the full well potential, and ϕ_{s0} is the empty well potential. In order to have a fast and efficient transfer process or a small t_4 , semiconductors with large μ and a CCD design with narrow gates are indicated. It is in this area where narrow bandgap semiconductors with a small effective mass (e.g. InSb) could have significant advantages resulting in possibly very high transfer efficiency (Steckl, 1976).

Charge Up Time Constant

The charge up time constant, t_c , is another critical parameter in the operation of a CCD since it represents the length of time the device can store charge before reaching saturation and, thus, establishes the frequency of operation (Steckl, 1976). The charge up time constant was derived by finding the time-dependent solution for t_c after combining the equation for relating the semiconductor surface potential to the applied voltage and the equation for the rate of change of the charge in the inversion layer (Steckl, 1985). It is given by

$$t_c = \frac{2}{\alpha} (|\phi_{s0}|^{1/2} - |\phi_{sf}|^{1/2}) + \frac{2}{\alpha^2} (\frac{\beta\alpha}{2} - \gamma) \ln \left[\frac{\gamma + \alpha |\phi_{s0}|^{1/2}}{\gamma + \alpha |\phi_{sf}|^{1/2}} \right] \quad (5.49)$$

where

$$\alpha = \frac{q n_i}{2 \tau_n C_{ox}} \left[\frac{2 k_s \epsilon_0}{q N_A} \right]^{1/2} \quad (V^{1/2} \text{sec}^{-1}) \quad (5.50)$$

$$\beta = \frac{\left[2 q k_s \epsilon_0 N_A \right]^{1/2}}{C_{ox}} \quad (V^{1/2}) \quad (5.51)$$

$$\gamma = \frac{(J_G + J_S + J_D)}{C_{ox}} \quad (V \text{ sec}^{-1}) \quad (5.52)$$

and C_{ox} is the oxide thickness. In addition, n_i is the intrinsic carrier concentration, τ_n is the carrier lifetime, k_s is the relative dielectric constant of the semiconductor, ϵ_0 is the permittivity constant in a vacuum, N_A is the doping

concentration, and q is the electron charge. Also, J_G is the depletion current density, J_S is the surface current density, J_D is the dark current density, ϕ_{sf} is the full well potential, and ϕ_{s0} is the empty well potential.

Computer Model Time Constants

The time constant procedure in the focal plane array computer model simulation program uses the values calculated by the previous dark current procedure. The necessary parameters, as chosen in the architecture set-up program, are also utilized to calculate all of the time constants just discussed. The computer screen will then display these results with the unit of seconds. An additional time constant displayed is the storage (or stare) time as defined previously in the dark current analysis section.

Modulation Transfer Function

The Modulation Transfer Function (MTF) describes the rolloff of imager response with increasing spatial frequency, and it is an important measure of the quality of the conversion of an image to its electrical form. It is analagous to an electrical circuit transfer function which describes the ratio of output and input signal modulations as a function of frequency. It can be measured by applying an image which has a sinusoidal intensity pattern to the sensor. The electrical output signal amplitude is measured for sinusoidal optical patterns with constant amplitude and

various periods (or spatial frequencies). The variation of the output electrical signal amplitude with spatial frequency is the MTF. The overall MTF of the chip is composed of three factors: (1) the loss of frequency response due to the geometry of the integrating cell, MTF_C , (2) the loss of frequency response due to the transfer inefficiency, MTF_T , and (3) the loss of frequency response due to the diffusion of charge between photon absorption and photon collection, MTF_D . In general, MTF_T and MTF_D are dependent on the wavelength of the incident radiation. Again, this spectral dependence will be ignored in this work.

Integration cell MTF

The integration cell MTF is given by the Fourier transform of the basic integration cell. For a rectangular cell of length Δz repeated with periodicity p in a given frame, the integration cell MTF is given by (Barbe and Campana, 1977)

$$MTF_C = \frac{\sin\left(\frac{\pi}{2} \frac{f}{f_n} \frac{\Delta z}{p}\right)}{\left(\frac{\pi}{2} \frac{f}{f_n} \frac{\Delta z}{p}\right)} \quad (5.53)$$

where $f_n = 1/(2p)$ is the folding frequency, also known as the cutoff spatial frequency response of the array (also referred to as the Nyquist frequency), and f is the scene spatial frequency. In this expression, Δz is used to denote the dimension of an integrating cell in either the x or y

direction, and p is the periodicity in either the x or y direction, respectively, and is also the same as the pixel's center to center spacing in its respective direction. As is shown in Figure 41, $\Delta x = p$ and $\Delta y = 2p$ for the frame transfer (and full frame transfer) chip, $\Delta x = p/2$ and $\Delta y = p$ for the interline transfer chip, and $\Delta x = \Delta y = p$ for the CID chip. Note that there is a separate MTF_{cell} in each direction, horizontal (x) and vertical (y), each made with the appropriate substitutions. Figure 42 gives the integration cell MTF versus normalized spatial frequency.

Transfer MTF

During the transfer of a sampled sinusoid along a focal plane array, a fraction of the charge ϵ is lost from each of the samples at each transfer, and this charge is added to trailing samples. The effect of this dispersion effect is given by (Barbe and Campana, 1977)

$$MTF_T = \exp(-M \epsilon (1 - \cos(\pi \frac{f}{f_N}))) \quad (5.54)$$

where M is the number of transfers that the charge undergoes, and ϵ is the transfer inefficiency. Again, f is the scene spatial frequency, and f_N is the folding frequency.

Table 4 gives the maximum number of transfers (i.e. worst case) required to read out the array beginning with the first cell, or the one located farthest from the output cell. The number of transfers in the x -direction is the same for

Figure 41. Schematic diagrams showing the integrating cells for (a) CCD frame transfer, (b) CCD interline transfer, and (c) CID arrays.

Figure 42. Integration MTF versus normalized spatial frequency for various integrating cell dimensions. Those shown include the cell dimensions equal to the cell spacing ($\Delta z = p$), and equal to half the cell spacing ($\Delta z = (1/2)p$) (Barbe, 1975).

TABLE 4. NUMBER OF TRANSFERS

	Frame Transfer	Interline Transfer
At video rate	$n_{\phi} N_X$	$n_{\phi} N_X$
At line rate	$n_{\phi} N_Y$	$n_{\phi} N_Y$
At intermediate rate	$n_{\phi} N_Y$	--

TOTAL	$n_{\phi} (N_X + 2N_Y)$	$n_{\phi} (N_X + N_Y)$
-------	-------------------------	------------------------

where n_{ϕ} = number of phases, and also

$$(N_X)_{FT} = (N_X)_{IT}$$

$$(N_Y)_{FT} = (N_Y)_{IT} + n_{\phi} N_Y$$

both frame transfer and interline transfer arrays. Thus, the horizontal (or x) MTF_T will be the same for both types of transfer arrays. The vertical (or y) MTF_T for the frame transfer (and full frame transfer) is less than that for the interline transfer as given by the above equation. Figure 43 shows the transfer MTF versus normalized spatial frequency where the ne product is the varying parameter. Figure 44 also shows how the charge transfer appears to vary as discussed earlier under charge transfer efficiency. Note that there is a symmetry about the curves, which has been explained by Sequin (1973), which yields the maximum frequency carried in a field at $f_n/2$, and that the minimum frequency that can be carried in a field occurs when $f = 0$ and $f = f_n$. The transfer inefficiency will thus have a maximum detrimental effect at the folding frequency, and no effect at zero frequency where the MTF is unity (Nelson and Waters, 1973).

Diffusion MTF

If photons are absorbed entirely within the depletion regions, then we can assume 100% collection efficiency. However, this computer model simulation will not make that assumption. Instead, it is assumed that the photons are absorbed away from the depletion region resulting in charge configurations that spread as they diffuse toward the depletion region with a resulting decrease in MTF (Seib, 1974; Kolodny and Kidron, 1982). If photons are absorbed at a

Figure 43. Transfer MTF versus normalized spatial frequency. The varying parameter is the $n\epsilon$ product, where n is the number of transfers and ϵ is the transfer inefficiency (Barbe, 1975).

Figure 44. The size of successive charge packets in the output of a charge transfer device for different values of transfer inefficiency product $n\epsilon$.

distance d from the depletion regions and if the diffusion length in the silicon substrate layer is L_0 (and is the same as L_D), the diffusion MTF is given by (Barbe and Campana, 1977)

$$MTF_D = \frac{\cosh(d/L_0)}{\cosh(d/L)} \quad (5.55)$$

where $L^{-2} = L_0^{-2} + (2\pi f)^2$. Figure 45 shows the diffusion MTF versus normalized spatial frequency with d as the varying parameter.

MTF and FPA Response

The MTF component that most greatly affects the focal plane array's response is the integration cell MTF, which is determined entirely by the geometry of the cell, $\Delta z/p$. Conversely, the transfer MTF and diffusion MTF depend strongly on the spectral wavelength, trapping state densities, the thickness of the substrate for thinned CCD's, and the epi thickness for CID's. Furthermore, these factors only modify the primary frequency response which is determined by the integration MTF (Barbe and Campana, 1977). As in any real sampled data system with non-zero integration elements, the MTF decreases as the signal frequency approaches the folding frequency (Nelson and Waters, 1973). The MTF can be improved with a decreased active layer thickness, but the quantum efficiency also decreases as the active layer thickness is reduced (Cheung, 1981).

Figure 45. Diffusion MTF versus normalized spatial frequency. ($p = 1.2$ mils is assumed) (Barbe, 1975).

Aliasing versus MTF. Aliasing occurs when frequencies higher than the folding limit [$f_n = 1/(2p)$] appear in the passband ($-f_n \leq f \leq f_n$) as lower frequency components caused by an overlapping of the spectra of the sampled irradiance response. It has been suggested that since CCD's sample the image plane and are, therefore, subject to aliasing, the spatial frequency response beyond the sampling limit is a major design consideration. Also, since response beyond that limit only serves to introduce spurious signals into the passband, this response should be eliminated by filtering the scene before sampling (Barbe and White, 1973). However, this cannot be done perfectly in practice, and some response to the frequencies within the passband must be sacrificed if the spurious response is to be avoided. Thus, in the design of focal plane arrays and sampling imagers there is a tradeoff to be made between the adversity of aliasing and the inevitable loss in image sharpness incurred in reducing the aliasing.

Several authors (Schade, 1973; Legault, 1973; Sequin, 1973) have offered guidelines for making this tradeoff. However, it should be stressed that all three of these criteria are strictly arbitrary and each requires a considerable amount of prefiltering. The Legault criterion (Legault, 1973) requires that at least 95% of the prefiltered scene's energy be within the folding limit. The Sequin criterion (Sequin, 1973) states that the best tradeoff occurs when the

aliased response equals one-half of the true response at the folding frequency. The Schade criterion (Schade, 1973) requires the MTF at the folding frequency to be less than or equal to 0.15.

Computer Model Total MTF

For the purposes of this computer model, it is assumed that no aliasing occurs and that the sampling frequency is exactly twice the folding frequency ($f = 1/p$). In the horizontal (x) direction the total MTF is given by

$$MTF_{TOTALx} = MTF_C * MTF_T * MTF_D \quad (5.56)$$

The diffusion MTF will also affect the vertical (y) direction since the diffusion process is omnidirectional (Barbe, 1987). Therefore, the total MTF in the vertical (y) direction is

$$MTF_{TOTALy} = MTF_C * MTF_T * MTF_D \quad (5.57)$$

Thus, the MTF of a focal plane array consists of two separable parts, the horizontal MTF and the vertical MTF. The computer monitor screen will display both values as well as the individual values for the MTF.

Sensitivity

The sensitivity of the focal plane array is concerned with how the device will respond to various changes to any of its input parameters as well as how the array responds in a general sense. Another term often used to describe the

sensitivity equations used is 'figure of merit'. The figure of merit for a focal plane array should at least take into account the filling efficiency of the array, spatial resolution limits, modulation transfer function, quantum efficiency, and integration time (or bandwidth) in order for it to be universally accepted. The responsivity of the array, the noise equivalent flux, and the voltage out of the focal plane array will be considered. The conversion gain of the output preamplifier will also be addressed. Other reference 'figures of merit' include the detectivity of the device, D^* , and the cutoff wavelength λ_c .

Responsivity

The responsivity of a focal plane array is found by multiplying the responsivity for zero spatial frequency by the MTF in the two orthogonal directions, thereby getting two expressions for spectral array photon responsivity, one in the horizontal (x) direction and one in the vertical (y) direction. The responsivity of the array for zero spatial frequency is given by (Dereniak and Crowe, 1984; Barbe, 1975)

$$R_p^{\text{array}} = \Delta x \Delta y \tau_{\text{int}} \eta q(\text{CG}) \quad (5.58)$$

where Δx is the pixel length in the x-direction, Δy is the pixel length in the y-direction, τ_{int} is the integration time, η is the quantum efficiency, q is the electron charge, and CG is the conversion gain.

The conversion gain relates the voltage produced on a capacitor for a single electron and is typically about 0.16 microvolts per electron. The equation for this relationship is

$$CG = \Delta V = \frac{\Delta Q}{C_{out}} * \frac{g_m R_L}{1 + g_m R_L} \quad (5.59)$$

where ΔQ is the charge at the output, C_{out} is the output capacitance of the preamplifier circuit, g_m is the transconductance of the on-chip preamplifier, and R_L is the load resistance of the preamplifier.

The charge at the output is obtained by multiplying the overall FPA charge transfer efficiency by the number of carriers. For the computer model, the number of carriers is found by subtracting the number of Fat Zero electrons from the maximum number of electrons, N_{max} (Equation 5.11). The output transconductance is given by (McCarthy, 1982)

$$g_m = \frac{Z}{L} * \mu C_{out} * \text{abs}(V_{sd}) \quad (5.60)$$

where Z/L is the gate width-to-length ratio, C_{out} is the output capacitance, V_{sd} is the applied MOSFET source-to-drain voltage, and μ is the mobility. The output capacitance is given by (McCarthy, 1982)

$$C_{out} = \left[\frac{1}{\frac{t_{out}}{k_o \epsilon_0} + \frac{X_d}{k_s \epsilon_0}} \right] \quad (5.61)$$

where t_{out} is the substrate thickness of the output preamplifier, X_d is the depletion depth of the preamplifier (Equation 5.14), k_o is the oxide dielectric constant, k_s is the semiconductor dielectric constant, and ϵ_0 is the permittivity of free space.

Since a scene can be transformed into Fourier components in the spatial frequency domain, the response of imaging chips as a function of spatial frequency is important (Barbe and Campana, 1979). The proper figure of merit for the response of an imaging is, therefore, the product of the chip response at zero spatial frequency and all of the MTF factors that affect frequency response as discussed in the previous section on the modulation transfer function. The equation is given by the following

$$R_{array}(f) = R_p^{array}(0) \prod_i (MTF)_i \quad (5.62)$$

where $\prod$ is the product of the MTF formats. This computer simulation program will calculate the following:

$$R_{array-x} = R_p^{array} * MTF_{total-x} \quad (5.63)$$

and

$$R_{array-y} = R_p^{array} * MTF_{total-y} \quad (5.64)$$

where the MTF values are those given by the equations in the previous MTF section.

Noise Equivalent Photon Flux

The noise equivalent photon flux (NEQF) is the photon irradiance flux on the array that would give a signal-to-noise ratio of 1, and it is defined by the following expression (Dereniak and Crowe, 1979)

$$\text{NEQF} = \frac{\text{noise}}{R_p^{\text{array}}} \quad (5.65)$$

where $\text{noise} = \Delta n_T^2(\text{CG})$ and n_T is the total noise as added in quadrature and given in the previous section on noise, and CG is the conversion gain. Again, this value for NEQF is for zero spatial frequency and it must be normalized by the MTF of the array. In the case of background limited infrared photodetector (BLIP) operation, the expression can be rewritten as

$$\text{NEQF} = G \left[\frac{2 E_p}{\Delta x \Delta y \tau_{\text{int}} \eta} \right]^{1/2} \quad (5.66)$$

where G is the photoconductive gain ($G=1$ for PV), and E_p is the input photon irradiance, Δx is the pixel length in the x direction, Δy is the pixel length in the y direction, τ_{int} is the integration time, and η is the quantum efficiency. For the model expressions two expressions are used:

$$\text{NEQF}_x = \text{NEQF} * \text{MTF}_{\text{total-x}} \quad (5.67)$$

and

$$\text{NEQF}_y = \text{NEQF} * \text{MTF}_{\text{total-y}} \quad (5.68)$$

where the MTF values are given by the expressions in the previous section on MTF.

Voltage Out

The output voltage of the device of a pixel, when only monochromatic irradiance is considered (as is done here in this program), can be found with the following expression as given by Dereniak and Crowe (1984)

$$V_{out} = E_p * R_p^{array} \quad (5.69)$$

where E_p is the input photon irradiance, and the responsivity is as given previously in this section.

Other Figures of Merit

Other figures of merit that were mentioned are termed reference since they serve only as indications about the suitability of any particular detector to an imaging application. One such reference is that of the cutoff wavelength, λ_c . It is given by the following definition

$$\lambda_c = \frac{1.24}{E_g} \quad (5.70)$$

where E_g is the energy bandgap (Marsh et al, 1981).

The other reference is the detectivity, D^* , of the detector and it is given by the following expression

$$D^* = \frac{\lambda}{h c} \left[\frac{\eta}{2 Q_B} \right]^{1/2} \quad (5.71)$$

where λ is the wavelength of interest, h is Planck's constant, c is the speed of light, and Q_B is the background flux density (Dereniak and Crowe, 1984).

Computer Model Sensitivity

The simulation model calculates the responsivities, the NEQF, the voltage out, and the D^* values as defined above, and displays them on the screen. This information gives the user the necessary data to make decisions based upon the desired application of the focal plane array.

CHAPTER 6

COMPUTER SCREEN OUTPUT PLOTS

The analysis of the focal plane array architecture can also be graphically viewed by the use of plots. This was first described in Chapter 3, reference Figure 22. Any of the choices in any order from the 'Plot Variables' submenu may be selected for viewing. Each choice performs a complete analysis, the same as all analysis submenus use for displaying the numerical results, with the appropriate substitutions for each particular range. It is important that a complete analysis be performed because of the interdependence among many equations with the same variables. The temperature dependence of many parameters is one major example of this interrelation. Others include the integration time and the input photon irradiance.

Temperature Dependence

The temperature at which a focal plane array is operated affects many of its characteristics. As previously stated in Chapter 4, the electron mobility, the oxide relative dielectric constant, and the intrinsic carrier concentration are affected by temperature. The carrier concentration is the most dependent while the others are relatively stable over temperature. Few references explained

in detail the exact dependence on temperature for the mobility and dielectric constant parameters.

Most focal plane arrays are operated at only specific temperatures. The temperature is 300 degrees Kelvin for silicon, and 77 degrees Kelvin for the other materials. However, it may be possible to obtain an optimum FPA performance by varying the temperature a few degrees. The capability to observe the predicted performance is given by this program.

One such temperature dependent parameter is the dark current. The relationship between these two was previously given by the approximate Equation 5.31. The actual dependence on temperature depends on the equations given for the carrier concentration (Tables 1 to 3), and the surface recombination velocity. An actual screen printout of the plot for the default device was previously shown in Figure 38. This showed that for every 10 degree change in temperature, the dark current changed by a factor of about 2.

The integration time (or stare time) to a full well is also temperature related, and this relationship was previously given by the approximate Equation 5.26. An actual screen printout for the default device of this plot is shown in Figure 46. There is an inverse exponential correspondence between the stare time and increasing temperature. This indicates that at lower temperatures, it will take a longer time to fill a potential well.

FIGURE 46. Actual screen printout of the plot for Stare Time versus Temperature. This is for the program's default device. The units of time are in seconds, and the temperature units are degrees K.

The relationship between the charge up time and temperature was previously given by Equations 5.49 to 5.52. An actual printout of the screen display of this plot for the default device is shown in Figure 47. Here the correspondence between the two parameters is inversely linear. In other words, it will take longer to charge up the potential well at lower temperatures.

The total noise associated with a device is another parameter that varies with temperature. There is a direct linear relationship between the two, and this is shown by an actual printout of the plot of the two in Figure 48. If the noise becomes too great, it will be very difficult to determine the actual signal level. Thus, from this point of view it is desirable to operate the FPA at as low of a temperature as is physically possible.

Integration Time Dependence

The integration time is the time that the device detector is allowed to gather input information before being clocked through the FPA to the output. There is a limit on the integration time though, and it is the time to fill up a potential well. Because once the well is full, a longer dwell time is not necessary since no additional information (or electrons) may be gathered. The two major items that the integration time affects are the noise and the voltage out.

The total noise has a direct linear dependence on the integration time. The plot of this for the default device is

FIGURE 47. Actual screen printout of the plot for Charge-Up Time versus Temperature. This plot is for the default device, and the units are seconds versus degrees Kelvin.

FIGURE 48. Actual screen printout of the plot for Total Noise versus Temperature. This is for the default device, and the temperature units are in degrees K. The noise units are in rms electrons.

depicted in Figure 49 by an actual screen printout. This is a logical consequence because of the noise due to photons, and this exact relationship was previously given by Equation 5.33. Obviously, the total noise will increase as the integration time is increased.

Similarly, the voltage output of the device is a direct linear relationship with the integration time as previously given by Equations 5.58 and 5.69. The actual screen printout of the plot of voltage out versus integration time for the default device is shown in Figure 50. However, note that the voltage out will be limited by the on-chip preamplifier. Therefore, a long integration time will not necessarily be the optimum solution because the total noise will still be increasing even at a saturated output.

Input Irradiance Dependence

The overall input to output relationship with all other parameters being constant is the bottom line evaluator of a focal plane array design. Its importance has not been overlooked, though, as the actual makeup and construction of the device as previously discussed has equal importance. Figure 51 shows a plot of the voltage out versus input irradiance for the default device. Again, notice that the output will be limited by the preamplifier.

FIGURE 49. Actual screen printout of the plot for Total Noise versus Integration Time. This plot is for the default device. Noise units are in rms electrons, and time is in seconds.

FIGURE 50. Actual screen printout of the plot for Voltage Out versus Integration Time. This is for the default device. Units are in seconds for the time and volts for the voltage out.

FIGURE 51. Actual screen printout of the plot for Voltage Out versus Input Photon Irradiance. This is for the default device, with units of volts for the voltage out. The irradiance is in units of photons per second per centimeter squared.

Summary of Plots

The plots that are available from the computer model presented herein enable the user to quickly view some of the various parameters and their relationships to others.

Although there is more numerical information given at each analysis submenu, the plots offer valuable insight into the FPA's predicted performance. From these plots, the user can analyze which parameters can be modified in order to design for the optimum performance of a focal plane array.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The work performed for this thesis involved extensive research to locate the most widely known and valid equations for charge transfer devices. This provided the basis with which to develop a computer model simulation to predict the performance of the design of a focal plane array using a personal computer. The computer program is complex and intertwined between all aspects of the architecture and the analysis. It provides the ability to graphically view some simplified architecture representations, and graphically plot some of the parameters versus other variables. A major feature of the program is that the graphical representations are not absolutely necessary, as all of the graphical information can be obtained numerically in the analysis portion of the program. This numerical information is only for one particular set of values, but how this information varies can be determined by varying the parameters and noting the results. However, the graphical information simplifies the analysis by the user.

Conclusions

From all of the research work, it was apparent that there has been a lot of effort devoted to the operation, testing, and evaluation of focal plane arrays and charge

transfer devices. There have been numerous conferences devoted solely to charge-coupled devices, specifically from 1973 until 1979. After that time, other organizations such as the Society of Photooptical Instrumentation Engineers (SPIE) have hosted many conferences for the presentation of related research and development. There is still a great deal of information that is needed for this thesis that was unavailable. For example, the temperature dependence on some of the parameters was either presented at one temperature only, or it was presented in a graphical form without an equation of the curve, nor could an equation of the curve be deduced from the information given. Some examples of parameters where this was the case are the density of surface states, the mobility of the charge carriers, and the minority carrier lifetime to name a few.

Recommendations

In some chapters, references were made to some of the other types of detectors, namely the Schottky barrier and the switched FET readout structures. Both of these should be included in future generations of this computer model. Another recommendation is to add more materials for the simulation's architecture such as lead telluride (PbTe) and gallium arsenide (GaAs). The latter of which has become one of the most recently researched compound for switched FET focal plane arrays.

Further recommendations are to include buried channel devices and the spectral dependence of the parameters that are affected by spectral changes in the input radiation. The buried channel device inclusion would involve adding the appropriate equations as found in the previously noted references, and it would also necessitate a change in the menu structure, particularly the architecture portion, to include a choice of buried or surface channel technology. The spectral dependence would yield a more detailed and precise analysis.

The highest recommendation, though, is for the program code to be upgraded to the recent release of Borland International's Turbo Pascal version 4.0. This upgrade will eliminate the use of chained files by providing library units that are resident in memory. This will also speed up the program's execution time significantly. Because of the use of units and elimination of chained files, version 4.0 will also provide the capability to include a greater number of choices to be available in the 'Plot Variables' submenu.

The version 4.0 upgrade will also eliminate the need to recompile because of different graphics cards in the many computer systems available for use. This is due to an internal graphics card checking procedure that is currently not available. Also, the executable source code will no longer be a command (.COM) file, but will be the more widely recognized .EXE file. Additionally, version 4.0 allows the

program code to exceed 64K of code, enabling more memory to be available to the program, up to the memory limit of the personal computer. In most cases, this limit will be up to 640 Kbytes of RAM. The upgrade of this program from the current version 3.0 to the new version 4.0 is currently in progress, but is not available before the completion of this work. An updated Owner's Manual and Operating Guide will also be available at that time. Completion of the upgrade will occur by September, 1988.

APPENDIX A

Symbols, Nomenclature and Units

A_d	Area of pixel element (cm^2)
c	Speed of light ($2.99792438(10^{10}) \text{ cm sec}^{-1}$)
C_D	Depletion layer capacitance (F)
C_{FD}	Floating diffusion capacitance (F)
C_{FG}	Floating gate capacitance (F)
C_{ins}	Insulator capacitance (F)
C_o	Output capacitance (F)
C_{ox}	Oxide capacitance (F cm^{-2})
C_p	Parasitic capacitance (F)
CG	Conversion gain (V/e^-)
CTE	Charge transfer efficiency
d	Distance from depletion area (cm)
D_n	Diffusion constant ($\text{cm}^2 \text{ sec}^{-1}$)
D^*	Normalized detectivity ($\text{W}^{-1} \text{ Hz}^{1/2} \text{ cm}$)
E_g	Energy gap (electron volts (eV))
E_p	Photon flux density irradiance ($\text{photons sec}^{-1} \text{ cm}^{-2}$)
f_c	Clock frequency (Hz)

f_n	Nyquist frequency (folding frequency - cycles/mm)
f_s	Signal frequency (cycles/mm)
G	Photoconductive gain
g_m	CCD transconductance (mho)
h	Planck's constant ($6.626176(10^{-34}) \text{ W sec}^{-1}$)
I	Total detector current (A)
I_{SAT}	Diode reverse saturation current (A)
I_ϕ	Photo-generated current (A)
J_b	Bulk current density (A cm^{-2})
J_B	Background current density (A cm^{-2})
J_D	Dark current density (A cm^{-2})
J_G	Depletion current density (A cm^{-2})
J_s	Surface current density (A cm^{-2})
k	Boltzmann's constant ($1.380662(10^{-23}) \text{ J K}^{-1}$)
k_o	Oxide relative dielectric constant
k_s	Semiconductor relative dielectric constant
L	Gate width (cm) (a.k.a. ΔY)
L_D	Diffusion length (cm)
M	Number of gate transfers
MTF	Modulation transfer function (a.c. gain)
N	Noise

N_A	Substrate acceptor doping density (cm^{-3})
N_{max}	Maximum number of charge carriers (cm^{-2})
N_C	Number of signal carriers (cm^{-3}) (a.k.a. N_S)
N_{ss}	Density of surface states ($\text{cm}^{-2}\text{eV}^{-1}$)
n_i	Intrinsic carrier concentration (cm^{-3})
ΔN_1	Number of lost carriers in first packet
ΔN	Maximum number of carriers (a.k.a. N_{max})
NEQF	Noise equivalent quanta flux ($\text{q sec}^{-1}\text{cm}^{-2}$)
p	Periodicity (cm)
p_C	Number of clock phases
Q_B	Background photon flux density ($\text{cm}^{-2}\text{sec}^{-1}$)
q	Electronic charge (1.6×10^{-19} C)
R_p^{array}	Spectral array responsivity ($\text{V q}^{-1}\text{sec}^{-1}\text{cm}^{-2}$)
R_D	Detector resistance (ohms)
R_L	Load resistance (ohms)
R_O	Zero bias diode resistance (ohms)
S	Signal
S_0	Surface recombination velocity (cm sec^{-1})
T	Temperature (degrees K)
t	Time (sec)
t_C	Charge up time constant (sec)

t_{ff}	Fringe field time constant (sec)
t_o	Oxide thickness (angstroms) (a.k.a. t_{ox})
t_{si}	Self induced time constant (sec)
t_4	t4 time constant (sec)
V_B	Bias voltage (V)
V_D	Drain voltage (V)
V_{DD}	Output amplifier drain supply voltage (V)
V_{FB}	Flatband voltage (V)
ΔV_{FD}	Output voltage of floating diffusion (V)
ΔV_{FG}	Output voltage of floating gate (V)
V_g	Applied gate voltage (V)
V_{out}	Output voltage (V)
V_{ref}	Reference voltage (V)
V_{SCR}	Shift control register voltage (V)
v_{th}	Thermal electron velocity ($cm\ sec^{-1}$)
W	Gate width (cm) (a.k.a. ΔX)
x	Mole fraction of Cadmium in $Hg_{1-x}Cd_xTe$ eqns. only
ΔX	Pixel width (cm)
x_d	Depletion layer thickness (cm)
ΔY	Pixel height (cm)
Δf	Bandwidth (Hz)

ϵ	Transfer inefficiency
ϵ_0	Permittivity ($8.854(10^{-14})$ F cm $^{-1}$)
η	Quantum efficiency
η_{inj}	Injection efficiency
μ	Mobility of carriers (cm sec $^{-1}$ V $^{-1}$)
σ	Capture cross sectional area (cm 2)
τ_1	Integration time (sec)
τ_n	Minority carrier lifetime (sec)
ϕ_{sf}	Full well maximum potential (V)
ϕ_{s0}	Empty well minimum potential (V)
ϕ_x	$\phi_1, \phi_2, \phi_3, \phi_4, \phi_T$ - clock phases
λ_c	Cutoff wavelength (microns (μm))

APPENDIX B

ARCHITECTURE/ANALYSIS MENU HIERARCHY

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MENU_ITEM(1100,'Mono','Monolithic Architecture');
  MENU_OPEN_LEVEL('Modify Monolithic Parameters');
  MENU_ITEM(1116,'Layout','Physical Layout');
    MENU_OPEN_LEVEL('Select Physical Layout');
    MENU_ITEM(1118,'Number','Pixel Numbers');
      MENU_OPEN_LEVEL('Select number of pixels');
      MENU_ITEM(1119,'# of X','# of X');
      MENU_ITEM(1120,'# of Y','# of Y');
      MENU_CLOSE_LEVEL;
    MENU_ITEM(1121,'Spacing','X- and Y- spacing');
      MENU_OPEN_LEVEL('Select pixel-to-pixel spacing');
      MENU_ITEM(1122,'X-X','X to X spacing');
      MENU_ITEM(1123,'Y-Y','Y to Y spacing');
      MENU_CLOSE_LEVEL;
    MENU_ITEM(1124,'Area','Pixel Active Area');
      MENU_OPEN_LEVEL('Select Active pixel dimensions');
      MENU_ITEM(1125,'dX','Width of Pixel X');
      MENU_ITEM(1126,'dY','Height of Pixel Y');
      MENU_CLOSE_LEVEL;
    MENU_CLOSE_LEVEL;
  MENU_ITEM(1136,'Pixel','Pixel Type');
    MENU_OPEN_LEVEL('Select Pixel Type');
    MENU_ITEM(1137,'MIS','MIS');
    MENU_ITEM(1138,'PV','Photo-Voltaic');
      MENU_OPEN_LEVEL('Select PV parameters');
      MENU_ITEM(1139,'Nd','Nd-donor doping conc. ');
      MENU_ITEM(1140,'Vappl','Voltage applied');
      MENU_ITEM(1141,'InZ/L','Input width/length ratio');
      MENU_CLOSE_LEVEL;
    MENU_CLOSE_LEVEL;
  MENU_ITEM(1150,'Config','Configuration');
    MENU_OPEN_LEVEL('Select CCD addressing layout');
    MENU_ITEM(1151,'FF','Frame/Field');
    MENU_ITEM(1152,'IntLin','Inter-Line');
    MENU_ITEM(1153,'Full','Full Frame');
    MENU_CLOSE_LEVEL;
  MENU_ITEM(1105,'Matl','Material Type');
    MENU_OPEN_LEVEL('Select Material Type');
    MENU_ITEM(1106,'Si','Silicon');
      MENU_OPEN_LEVEL('Select doping concentration');
      MENU_ITEM(1111,'Silicon Na','Si_Na');
      MENU_CLOSE_LEVEL;

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MENU_ITEM(1107,'InSb','InSb');
  MENU_OPEN_LEVEL('Select InSb parameters');
  MENU_ITEM(1109,'InSb Na','InSb_Na');
  MENU_ITEM(1160,'p- n-type','p- or n-type');
  MENU_CLOSE_LEVEL;
MENU_ITEM(1108,'HgCdTe','HgCdTe');
  MENU_OPEN_LEVEL('Select HgCdTe parameters');
  MENU_ITEM(1110,'MCT Na','HgCdTe_Na');
  MENU_ITEM(1127,'mol Cd','molar Cd');
  MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1142,'R/O','R/O Type');
  MENU_OPEN_LEVEL('Select Readout Type');
  MENU_ITEM(1145,'CCD','CCD');
    MENU_OPEN_LEVEL('Select CCD readout parameters');
    MENU_ITEM(1117,'Read','Read Noise');
    MENU_ITEM(1130,'Thick','Ins R/O Thickness');
    MENU_ITEM(1129,'FatZ','Fat Zero');
      MENU_OPEN_LEVEL('Fat zero choice');
      MENU_ITEM(1132,'FatZ','Number of electrons');
      MENU_ITEM(1135,'%Full','Percent of full well');
    MENU_CLOSE_LEVEL;
    MENU_ITEM(1133,'Clocks','Clock Phases');
  MENU_CLOSE_LEVEL;
MENU_ITEM(1146,'CID','CID');
  MENU_OPEN_LEVEL('Select CID readout parameters');
  MENU_ITEM(1117,'Read','Read Noise');
  MENU_ITEM(1130,'Thick','Ins R/O Thickness');
  MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1147,'Preamp','Preamplifier');
  MENU_OPEN_LEVEL('Select Pre-Amplifier');
  MENU_ITEM(1148,'FD','Floating Diffusion');
    MENU_OPEN_LEVEL('Select FD parameters');
    MENU_ITEM(1112,'Z/L','Width/length ratio');
    MENU_ITEM(1113,'Nd','Preamp Nd-donor doping');
    MENU_ITEM(1114,'Vsd','Source/drain Voltage');
    MENU_ITEM(1115,'Rl','Preamp load resistor');
    MENU_ITEM(1131,'Thick','Oxide thickness');
    MENU_ITEM(1143,'Vrst','Reset voltage');
  MENU_CLOSE_LEVEL;
MENU_ITEM(1149,'FG','Floating Gate');
  MENU_OPEN_LEVEL('Select FG parameters');
  MENU_ITEM(1112,'Z/L','Width/length ratio');
  MENU_ITEM(1113,'Nd','Preamp Nd-donor doping');
  MENU_ITEM(1114,'Vsd','Source/drain Voltage');
  MENU_ITEM(1115,'Rl','Preamp load resistor');
  MENU_ITEM(1131,'Thick','Oxide thickness');
  MENU_ITEM(1144,'Vref','Reference voltage');
  MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;

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MENU_ITEM(1200, 'Hybrid', 'Hybrid Architecture');
MENU_OPEN_LEVEL('Modify Hybrid Parameters');
MENU_ITEM(1116, 'Layout', 'Physical Layout');
MENU_OPEN_LEVEL('Select Physical Layout');
MENU_ITEM(1118, 'Number', 'Pixel Numbers');
MENU_OPEN_LEVEL('Select number of pixels');
MENU_ITEM(1119, '# of X', '# of X');
MENU_ITEM(1120, '# of Y', '# of Y');
MENU_CLOSE_LEVEL;
MENU_ITEM(1121, 'Spacing', 'X- and Y- spacing');
MENU_OPEN_LEVEL('Select pixel-to-pixel spacing');
MENU_ITEM(1122, 'X-X', 'X to X spacing');
MENU_ITEM(1123, 'Y-Y', 'Y to Y spacing');
MENU_CLOSE_LEVEL;
MENU_ITEM(1124, 'Area', 'Pixel Active Area');
MENU_OPEN_LEVEL('Select Active pixel dimensions');
MENU_ITEM(1125, 'dX', 'Width of Pixel X');
MENU_ITEM(1126, 'dY', 'Height of Pixel Y');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1210, 'DetMat1', 'Detector Material');
MENU_OPEN_LEVEL('Select Detector Material');
MENU_ITEM(1211, 'InSb', 'InSb');
MENU_OPEN_LEVEL('Select InSb parameters');
MENU_ITEM(1109, 'InSb Na', 'InSb_Na');
MENU_ITEM(1160, 'p- n-type', 'p- or n-type');
MENU_CLOSE_LEVEL;
MENU_ITEM(1214, 'HgCdTe', 'HgCdTe');
MENU_OPEN_LEVEL('Select HgCdTe parameters');
MENU_ITEM(1110, 'MCT Na', 'HgCdTe_Na');
MENU_ITEM(1127, 'mol Cd', 'molar Cd');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1216, 'ReadMat1', 'Readout Material');
MENU_OPEN_LEVEL('Select Readout Material');
MENU_ITEM(1217, 'Si', 'Silicon');
MENU_OPEN_LEVEL('Select Doping Concentration');
MENU_ITEM(1111, 'Si Na', 'Si_Na');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1220, 'Preamp', 'Preamplifier');
MENU_OPEN_LEVEL('Select Pre-Amplifier');
MENU_ITEM(1221, 'FD', 'Floating Diffusion');
MENU_OPEN_LEVEL('Select FD parameters');
MENU_ITEM(1112, 'Z/L', 'Width/length ratio');
MENU_ITEM(1113, 'Nd', 'Preamp Nd-donor doping');
MENU_ITEM(1114, 'Vsd', 'Source/drain Voltage');
MENU_ITEM(1115, 'Rl', 'Preamp load resistor');
MENU_ITEM(1131, 'Thick', 'Oxide thickness');
MENU_ITEM(1143, 'Vrst', 'Reset voltage');
MENU_CLOSE_LEVEL;

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MENU_ITEM(1222,'FG','Floating Gate');
  MENU_OPEN_LEVEL('Select FG parameters');
  MENU_ITEM(1112,'Z/L','Width/length ratio');
  MENU_ITEM(1113,'Nd','Preamp Nd-donor doping');
  MENU_ITEM(1114,'Vsd','Source/drain Voltage');
  MENU_ITEM(1115,'Rl','Preamp load resistor');
  MENU_ITEM(1131,'Thick','Oxide thickness');
  MENU_ITEM(1144,'Vref','Reference voltage');
  MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1225,'Readout','Readout Type');
  MENU_OPEN_LEVEL('Select Readout Type');
  MENU_ITEM(1227,'CCD','CCD');
  MENU_OPEN_LEVEL('Select CCD readout parameters');
  MENU_ITEM(1117,'Read','Read Noise');
  MENU_ITEM(1130,'Thick','Ins R/O Thickness');
  MENU_ITEM(1129,'FatZ','Fat Zero');
  MENU_OPEN_LEVEL('Fat zero choice');
  MENU_ITEM(1132,'FatZ','Number of electrons');
  MENU_ITEM(1135,'%Full','Percent of full well');
  MENU_CLOSE_LEVEL;
  MENU_ITEM(1133,'Clocks','Clock Phases');
  MENU_CLOSE_LEVEL;
MENU_ITEM(1228,'CID','CID');
  MENU_OPEN_LEVEL('Select CID readout parameters');
  MENU_ITEM(1117,'Read','Read Noise');
  MENU_ITEM(1130,'Thick','Ins R/O Thickness');
  MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(1230,'Input','Input type');
  MENU_OPEN_LEVEL('Select Input Circuit Type');
  MENU_ITEM(1231,'DirInj','Direct Injection');
  MENU_OPEN_LEVEL('Select direct inj. input parameters');
  MENU_ITEM(1139,'Nd','Nd-donor doping conc. ');
  MENU_ITEM(1140,'Vappl','Voltage applied');
  MENU_ITEM(1141,'InZ/L','Input width/length ratio');
  MENU_CLOSE_LEVEL;
MENU_ITEM(1233,'GateMod','Gate Modulation');
  MENU_OPEN_LEVEL('Select gate mod. input parameters');
  MENU_ITEM(1139,'Nd','Nd-donor doping conc. ');
  MENU_ITEM(1140,'Vappl','Voltage applied');
  MENU_ITEM(1141,'InZ/L','Input width/length ratio');
  MENU_CLOSE_LEVEL;
MENU_ITEM(1234,'F/S','Fill/Spill');
  MENU_OPEN_LEVEL('Select Fill/spill input parameters');
  MENU_ITEM(1139,'Nd','Nd-donor doping conc. ');
  MENU_ITEM(1140,'Vappl','Voltage applied');
  MENU_ITEM(1141,'InZ/L','Input width/length ratio');
  MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;

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MENU_ITEM(2000,'Analys','Analysis of FPA');
  MENU_OPEN_LEVEL('Modify Parameters of the Focal Plane
                    Array');
MENU_ITEM(2100,'Current','Dark Current');
  MENU_OPEN_LEVEL('Modify Dark Current parameters');
  MENU_ITEM(2555,'Temp','Temperature');
  MENU_ITEM(1130,'tox','Oxide Thickness');
  MENU_ITEM(2105,'Vg','Gate Voltage');
  MENU_ITEM(2525,'Time','Integration Time');
  MENU_ITEM(1124,'Area','Pixel Active Area');
    MENU_OPEN_LEVEL('Adjust Pixel Active Area');
    MENU_ITEM(1125,'dX','Width of Active Pixel X');
    MENU_ITEM(1126,'dY','Height of Active Pixel Y');
    MENU_CLOSE_LEVEL;
  MENU_CLOSE_LEVEL;
MENU_ITEM(2200,'Spatial','Spatial Charge Movement');
  MENU_OPEN_LEVEL('Modify Spatial Charge Movement');
  MENU_ITEM(2245,'t4','t4 Time Constant');
    MENU_OPEN_LEVEL('Modify t4 parameters');
    MENU_ITEM(2555,'Temp','Temperature');
    MENU_ITEM(2580,'N(c)','Number of Carriers');
    MENU_CLOSE_LEVEL;
  if not Main_data.Architecture.Mono_selected then begin
    MENU_ITEM(2340,'Injeff','Injection Efficiency');
    MENU_OPEN_LEVEL('Modify Injection Efficiency');
    MENU_ITEM(2341,'Rd','Detector Resistance');
    MENU_CLOSE_LEVEL;
  MENU_CLOSE_LEVEL;
  end
else
  MENU_CLOSE_LEVEL;
MENU_ITEM(2300,'Sens','Sensitivity');
  MENU_OPEN_LEVEL('Modify Sensitivity');
  MENU_ITEM(2345,'NEQF','Noise Equivalent Flux');
    MENU_OPEN_LEVEL('Modify NEQF parameters');
    MENU_ITEM(2335,'Phibp','Background Photon Flux');
    MENU_ITEM(2510,'Q-Eff','Quantum Efficiency');
    MENU_ITEM(2525,'Time','Integration Time');
    MENU_ITEM(1124,'Area','Pixel Active Area');
      MENU_OPEN_LEVEL('Adjust Pixel Active Area');
      MENU_ITEM(1125,'dX','Width of Active Pixel X');
      MENU_ITEM(1126,'dY','Height of Active Pixel Y');
      MENU_CLOSE_LEVEL;
    MENU_CLOSE_LEVEL;
  MENU_ITEM(2350,'Rarray','Responsivity');
    MENU_OPEN_LEVEL('Modify Rarray parameters');
    MENU_ITEM(2510,'Q-Eff','Quantum Efficiency');
    MENU_ITEM(2525,'Time','Integration Time');
    MENU_ITEM(1124,'Area','Pixel Active Area');

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MENU_OPEN_LEVEL('Adjust Pixel Active Area');
MENU_ITEM(1125,'dX','Width of Active Pixel X');
MENU_ITEM(1126,'dY','Height of Active Pixel Y');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(2400,'MTF','MTF of Samples');
MENU_OPEN_LEVEL('Modify the Modulation Transfer
Function');
MENU_ITEM(2405,'MTFcell','cell MTF');
MENU_OPEN_LEVEL('Modify cell MTF parameters');
MENU_ITEM(2415,'f','Normalized Spatial Frequency');
MENU_ITEM(2420,'Illum','Illumination-front/back');
MENU_OPEN_LEVEL('Select Illumination');
MENU_ITEM(2421,'Front','Front');
MENU_ITEM(2422,'Back','Back');
MENU_CLOSE_LEVEL;
MENU_ITEM(1125,'dX','Width of Pixel Array X');
MENU_CLOSE_LEVEL;
MENU_ITEM(2425,'MTFepsilon','epsilon MTF');
MENU_OPEN_LEVEL('Modify epsilon MTF parameters');
MENU_ITEM(2415,'f','Normalized Spatial Frequency');
MENU_ITEM(2430,'epsilon','epsilon');
MENU_CLOSE_LEVEL;
MENU_ITEM(2445,'MTFdiff','diffusion MTF');
MENU_OPEN_LEVEL('Modify diffusion MTF parameters');
MENU_ITEM(2450,'l0','Diffusion Length');
MENU_ITEM(2455,'d','Distance from depletion area');
MENU_ITEM(2415,'f','Normalized Spatial Frequency');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(2500,'Noise','Noise');
MENU_OPEN_LEVEL('Select Noise Type');
MENU_ITEM(2503,'Photon','Photon');
MENU_OPEN_LEVEL('Modify Photon Noise Parameters');
MENU_ITEM(2505,'Gain','Photoconductive Gain');
MENU_ITEM(2510,'Q-Eff','Quantum Efficiency');
MENU_ITEM(2515,'Ph-Irr','Photon Irradiance');
MENU_ITEM(2520,'Area','Pixel Active Area');
MENU_OPEN_LEVEL('Adjust Pixel Active Area');
MENU_ITEM(1125,'dX','Width of Active Pixel X');
MENU_ITEM(1126,'dY','Height of Active Pixel Y');
MENU_CLOSE_LEVEL;
MENU_ITEM(2525,'Time','Integration Time');
MENU_CLOSE_LEVEL;
MENU_ITEM(2550,'Input','Input');
MENU_OPEN_LEVEL('Modify Input Noise Parameters');
MENU_ITEM(2555,'Temp','Temperature');
MENU_ITEM(1130,'tox','Oxide Thickness');
MENU_ITEM(2561,'Area','Pixel Area');

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MENU_OPEN_LEVEL('Adjust Pixel Active Area');
MENU_ITEM(1125,'dX','Width of Active Pixel X');
MENU_ITEM(1126,'dY','Height of Active Pixel Y');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(2570,'Transfer','Transfer Inefficiency');
MENU_OPEN_LEVEL('Modify Transfer Inefficiency Noise
Parameters');
MENU_ITEM(2575,'T-Ineff','Transfer Inefficiency');
MENU_CLOSE_LEVEL;
MENU_ITEM(2600,'Trapping','Trapping');
MENU_OPEN_LEVEL('Modify Trapping Noise Parameters');
MENU_ITEM(2605,'N(ss)','Density of Surface States');
MENU_ITEM(2611,'Area','Pixel Active Area');
MENU_OPEN_LEVEL('Adjust Pixel Active Area');
MENU_ITEM(1125,'dX','Width of Active Pixel X');
MENU_ITEM(1126,'dY','Height of Active Pixel Y');
MENU_CLOSE_LEVEL;
MENU_ITEM(2555,'Temp','Temperature');
MENU_CLOSE_LEVEL;
MENU_ITEM(2620,'Dark','Dark Current');
MENU_OPEN_LEVEL('Modify Dark Current Noise
Parameters');
MENU_ITEM(2625,'J(d)','Dark Current Density');
MENU_ITEM(2525,'Time','Integration Time');
MENU_ITEM(2631,'Area','Pixel Active Area');
MENU_OPEN_LEVEL('Adjust Pixel Active Area');
MENU_ITEM(1125,'dX','Width of Active Pixel X');
MENU_ITEM(1126,'dY','Height of Active Pixel Y');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_ITEM(2640,'Float','Floating Diffusion');
MENU_OPEN_LEVEL('Modify Floating Diffusion Noise
Parameters');
MENU_ITEM(2555,'Temp','Temperature');
MENU_ITEM(1130,'tox','Oxide Thickness');
MENU_CLOSE_LEVEL;
MENU_ITEM(2700,'Preamp','Preamplifier');
MENU_OPEN_LEVEL('Modify Preamplifier Noise
Parameters');
MENU_ITEM(2705,'dF','Electrical Bandwidth');
MENU_ITEM(2710,'Gm','Transconductance');
MENU_ITEM(2555,'Temp','Temperature');
MENU_ITEM(1130,'tox','Oxide Thickness');
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;
MENU_CLOSE_LEVEL;

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APPENDIX C

DETAILED PROGRAM FLOW DIAGRAMS

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