THE OPTICAL TRANSFER FUNCTION OF SILICON SOLAR CELLS: THEORY AND EXPERIMENT

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ABSTRACT

Silicon solar cells have traditionally been used for conversion of direct sunlight to energy. These cells can also be used as low rate optical detectors. The internal resistances and capacitances, however, limit the usable bandwidth. Under forward bias conditions, diodes exhibit, in addition to the depletion layer capacitance, a diffusion capacitance caused by the rearrangement of minority carriers. A similar process occurs in solar cells when photons are absorbed and electron-hole pairs are produced. This paper presents a method successfully used by the authors to determine this unknown term as a function of background illumination.

INTRODUCTION

Economic considerations have always been important in communication systems, and in this light several firms have begun to consider cheap, readily available solar cells in lieu of more costly photodetectors for low data rate applications. Mallette[1,2] has developed an accurate circuit model for a solar cell (Figure 1). The cell can be enclosed in a light-tight environment and treated as any other encapsulated diode. Series, shunt, and dynamic resistances (R_S, R_{SH}, r) and junction capacitance (C_J) can be measured (or calculated from measurements) using standard techniques.[2,3,4,5] An additional capacitance, diffusion capacitance, is present when the cell is exposed to illumination. Diffusion capacitance is shown to be a function of diode voltage, which is related to background illumination by the spectral responsivity constant. This paper presents one method of determining the diffusion capacitance for various solar cells.

THEORY

The theoretical aspects of modeling solar cells are discussed in Reference 2. The two primary bandwidth-limiting components are the diffusion capacitance and the junction capacitance. The most variable and rarely measured capacitance is diffusion capacitance, which is explained in detail below.

Diffusion Capacitance

In a semiconductor material, light of a specific frequency* will excite an electron (up) into the conduction band for n-type materials (Figure 2). Conversely, for p-type materials, the photon will excite a hole (down) into the valence band. In the diode, the electron-hole pairs are generated in three regions:

1) p region - Free electrons will diffuse to the junction area and drift to the n-region.

2) n region - Free holes will diffuse to the junction and drift to the p-region.

3) Transition region (junction) - Holes and electrons will drift to the p and n regions respectively.

In each case, it is the minority carrier that is moving and generating a (light-induced) current in the reverse direction (with respect to the diode). The movement of minority carriers creates a current I_λ that is the basis for the photoelectric effect first noticed by Bequerel in 1839. This current is divided between the diode and the output loop, which is composed of the series resistance R_S and the load impedance Z_L. See Figure 1.

The addition of these photo-induced electron-hole pairs causes a significant change in the concentration of minority carriers in the bulk region on either side of the transition region. Before the minority carriers reach the transition region and drift to the opposite side, the diffusion of minority carriers results in buildup of charge distribution. This buildup of minority carriers on either side of the transition region constitutes a diffusion capacitance proportional to the light striking the semiconductor surface. This capacitance is the factor we wish todetermine to complete the ac model of the solar cell.

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* Photon of energy equal to $h\nu$ and greater than the ionization energy.

The diffusion capacitance C_d is classically modeled to be proportional to the diode current I_D, the current at the terminals of the cell. Many authors use an approximation for diffusion capacitance that is not valid when the cell is operated in the photovoltaic (unbiased) mode. The correct solution in farads has been shown to be:[1]

$$C_d = \frac{q I_o \tau_p}{nkT} \exp\left(qV_D/nkt\right) \tag{1}$$

where q = electron charge (1.602×10^{-19}C)

I_o = reverse saturation current

τ_p = lifetime of minority holes in n-region

n = charge carrier density

k = Boltzmann's Constant (1.381×10^{-23} J/°K)

T = temperature in degrees Kelvin

V_D = diode voltage

For a given temperature, the coefficient of the exponential term in Equation 1 is a constant that we choose to call k_d.

The derivation of Equation 1 considers only the n region, because the p region of the semiconductor material under consideration was heavily doped compared to the n region. This implies that the diode current is composed almost entirely of holes moving from the n side to the p side.

Junction Capacitance

For a specified bias voltage, there exists an equilibrium p-n junction depletion region in which the sole charges are bound ionized donors or acceptors. Mobile holes and electrons tend to be swept out by the high electric field existing in the space charge region. The width of the depletion region increases for an increased reverse bias. This bias increases the number of bound donors or acceptors that are not neutralized by mobile electrons and holes, and thus increases the fixed charge on either side of the junction; and vice versa for forward bias. The junction capacitance is defined as the incremental charge increase dq of fixed, unneutralized donors or acceptors per incremental voltage change dv and is given in Equation 2 below.

EXPERIMENT

Incident light on a cell will induce a current I_λ from the current generator. We measured the diffusion capacitance using the equipment described below. The argon laser-variable beamsplitter combination provided an adjustable source of “background” illumination for the solar cell, and the incident light generated a time invariant current I_λ and a voltage V_D across r and R_{SH}. This exact voltage cannot be observed unless the current in R_S is zero, which is the case when the cell is open circuited, or nearly open circuited as when connected to an oscilloscope. This dc voltage V_D is observable directly on an oscilloscope and will vary with incident light power P_{INC}. The relationship between the current and the incident power is the spectral responsivity constant R_V, at the frequency of the light, and can be determined from this simple measurement.

The ir laser was used to generate an impulse (500 ns triangular pulse) of light sufficiently low in amplitude that it would not significantly perturb the background illumination. If the background illumination is not changed significantly, the diode voltage will be approximately constant, and the impulse can be used to determine the small-signal parameters of the model .

The open circuit output voltage of the cell caused by the impingement of light from both lasers can be represented by a one-sided decaying exponential, superimposed on a dc bias. A darkened solar cell can be treated as a diode, and its dynamic resistance and junction capacitance can be measured by standard techniques.[2,3,4,5] They are of the form:

$$r = R_1 \exp (V_D/V_T) \text{ ohms} \tag{2}$$

$$C_j = k_j/(V_{BI}-V_D)^\gamma \text{ farads}$$

where R_1, $V_T = (kT/q)$, k_j, V_{BI}, and γ are constants[1,3,4,5] associated with the particular diode. V_{BI} is the built-in junction potential. The exponent γ is a constant that is a function of the junction doping. An exponent of 0.5 indicates the transition is fairly abrupt, as opposed to a linearly graded junction where the exponent may be 0.33.

Circuit analysis of Figure 1 and the above equations directly give the decay time constant in seconds of the exponential as:

$$\tau = \left[\frac{R_1 \exp (V_D/V_T)}{1 + \frac{R_1}{R_{SH}} \exp(-V_D/V_T)} \right] \left[\frac{k_j}{(V_{BI} - V_D)^\gamma} + k_d \exp (V_D/V_T) \right] \tag{3}$$

Careful examination of Equation 3 identifies k_d as the only unknown constant for a given value of dc diode voltage V_D. Plotting τ versus V_D shows that the time constant decreases when the diode voltage (or background illuminations increases. Figure 3 shows a measured set of points and a fitted curve for a one square cm silicon cell. As can be seen in Figure 3, time constant changes by over an order of magnitude for a normal[1] operating range could wreak havoc in many forms of digital signal processing. The purpose of this paper is to acquaint the reader with possible problems that might arise and to show how to predict their effect on the system.

Should the duration of the pulse of the light be a significant portion of the product $R_T C_T$ (we used 4 percent maximum), the pulse waveform and the exponential response must be convolved to obtain the true decay time constant.

EQUIPMENT

The layout of test equipment setup is shown in Figure 4, and Figure 5 is a photograph of the equipment used to measure the time constant τ. Figure 5 shows from left to right: the Ar-ion laser,[2] mirror, variable beamsplitter, screen cage with cell mounted on aluminum block inside the cage, 50 percent mirror, ir laser,[3] and part of the Ar-ion laser power supply. The oscilloscope is not shown in this photograph. The beams of the two lasers coimpinged on the face of the cell after passing through a double convex lens used to defocus the two beams of light. The intensity of the ir pulse of light must be kept at a level sufficiently low to not cause a significant change in the amplitude of the background illumination.

PROCEDURE

The cell is connected to the oscilloscope and is illuminated by the two lasers. Note that the oscilloscope will give us two signals, or pieces of information: 1) the dc level (V_D) at which the cell is operating and 2) superimposed on this dc level, the response to the impulse of light, represented as a one-sided decaying exponential (Figure 6). Measurement of the dc level and of the decay time constant τ uniquely determines k_d. The decay time constant can be measured by any of several methods. Since these methods rely on graphic interpretation, we recommend that several values of τ be determined for several values of

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[1] "Normal" for our situation meant variations from a moonless night to a cloudless noon in Baja.

[2] A 750 mW Argon-ion laser manufactured by Control Laser, Inc., of Orlando, Florida.

[3] An ir laser manufactured by Electromagnetic Sciences, Inc., of Atlanta, Georgia. Output pulse is approximately triangular, of 0.5 μsec duration, operating at a wavelength of 9043 Å.

dc diode voltage V_D. From these τ-V_D pairs, a set of k_d's can be calculated and an average value can be selected.

Figures 6 and 7 were taken with identical test setups, oscilloscope settings, and camera settings.[4] The one difference is that Figure 7 was taken with background illumination (from the Ar-ion laser sufficient to generate a 100 mV voltage at the output of the cell), whereas Figure 6 was taken without background illumination.

The background illumination causes two phenomena. 1) It causes addition of noise, some of which is 60 Hz modulation by the background source. 2) It causes τ to decrease as background illumination is increased. This pattern is illustrated by Figure 7 and quantified by Equation 3.

SUMMARY

When solar cells are operated in the photovoltaic mode, two capacitance terms need to be determined to completely model the solar cell. Knowing these capacitance terms will allow you to predict the solar cells' response to a pulse of light.

In our experiment, both the junction and the diffusion capacitance terms varied with background illumination. A technique for calculating the diffusion capacitance term through two lasers was used. One of the two lasers was used as a source of controlled background illumination, the other as a source of impulses of light. Their beams coimpinged on, and uniformly illuminated, the cell. A series of measurements were taken, and the unknown constant k_d was then found. Our experimental findings supported our theory that the decay time constant is inversely proportional to incident light intensity.

ACKNOWLEDGEMENT

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[4] Oscilloscope sync to internal, 1 mV/div vertical, 50 µsec/div horizontal, and input coupling to ac. Photograph was taken with Kodak TX-135 of f stop 1.8, 1/30 second shutter speed.

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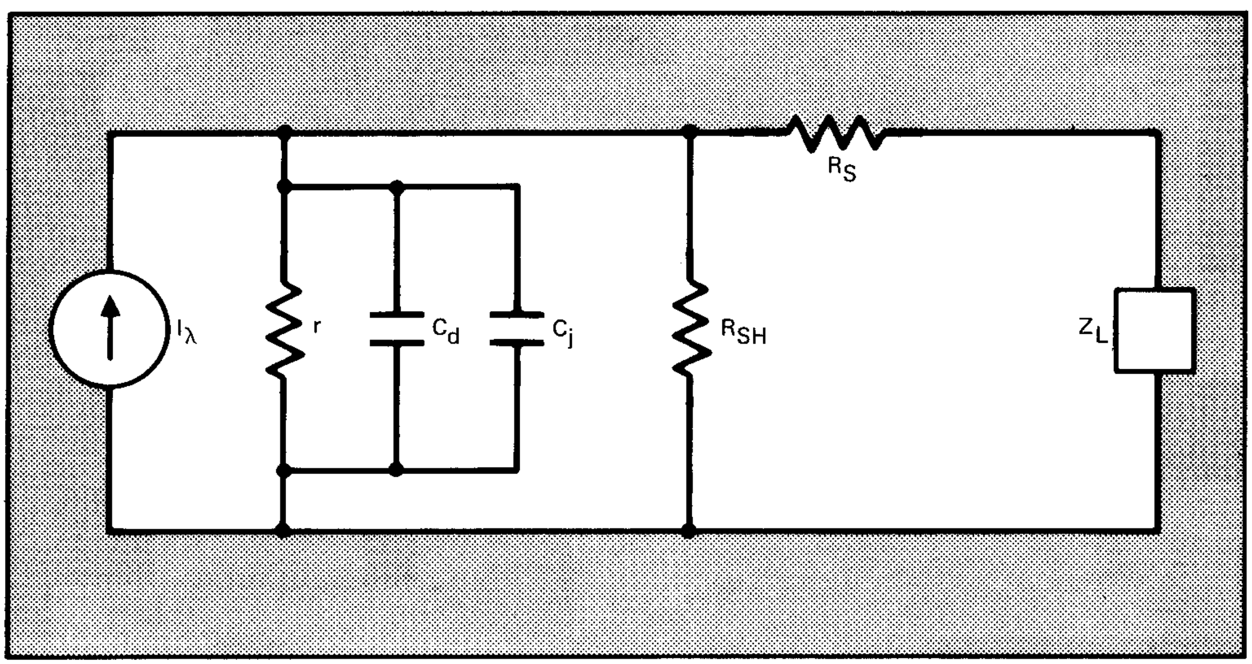

Figure 1. AC Model of a Solar Cell.

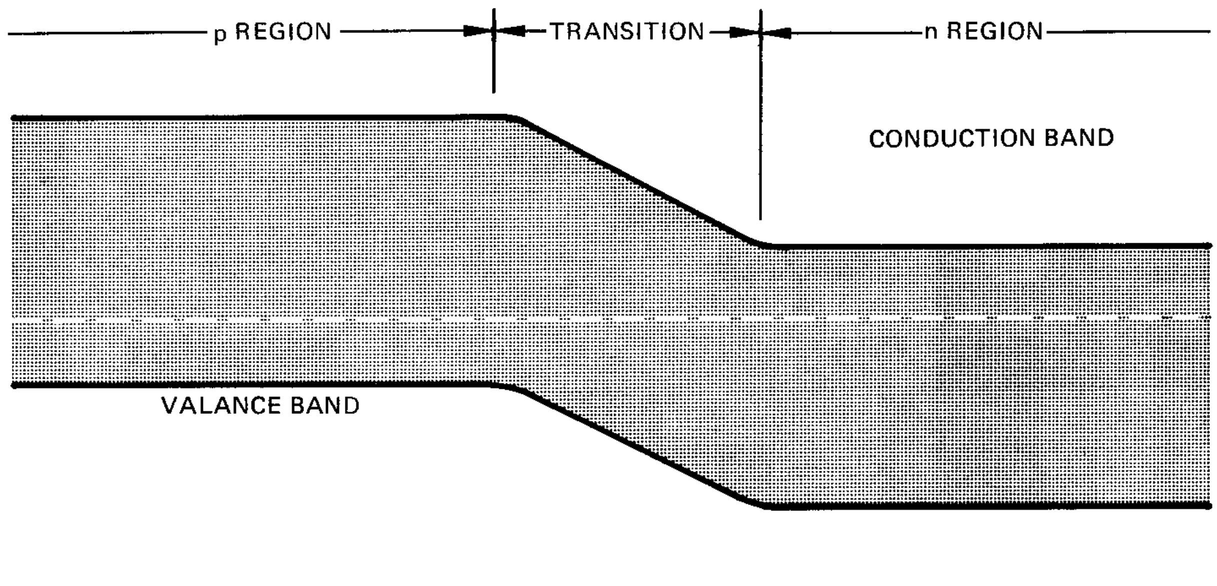

Figure 2. Conduction Valence Band of a P-N Junction.

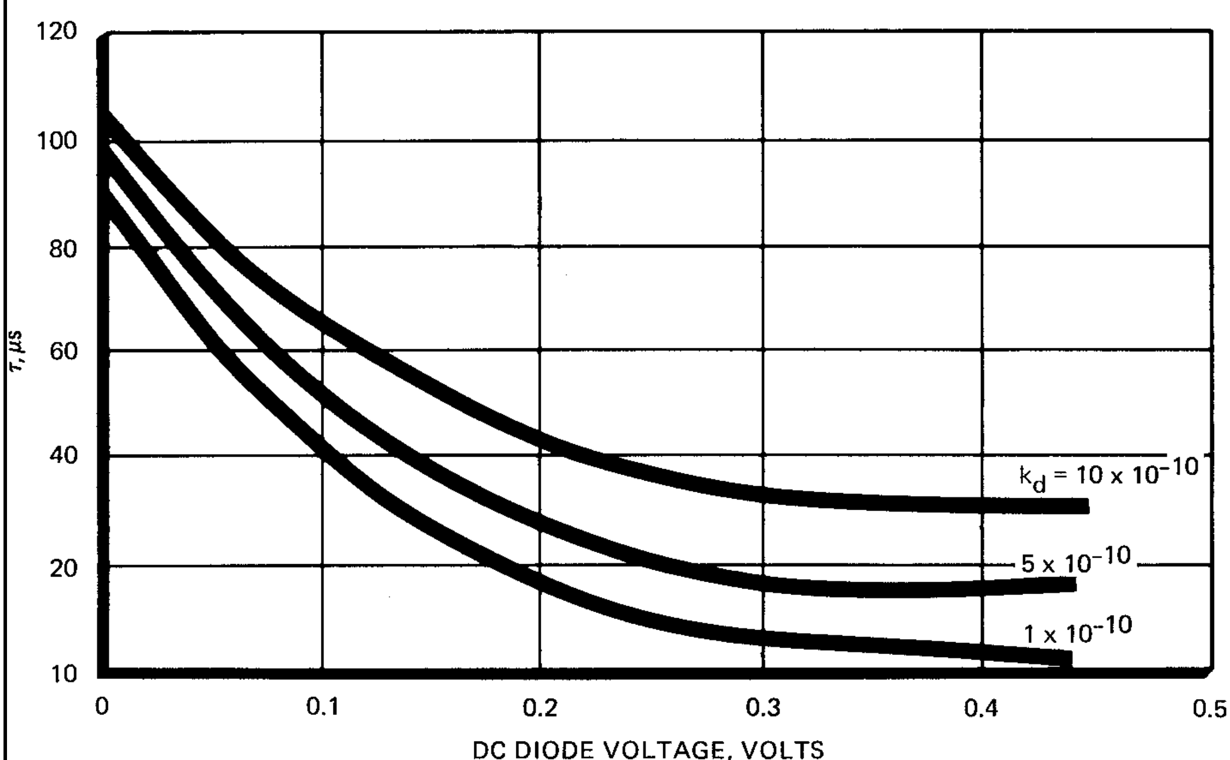

Figure 3. Variation of Open Circuit With DC Diode Voltage.

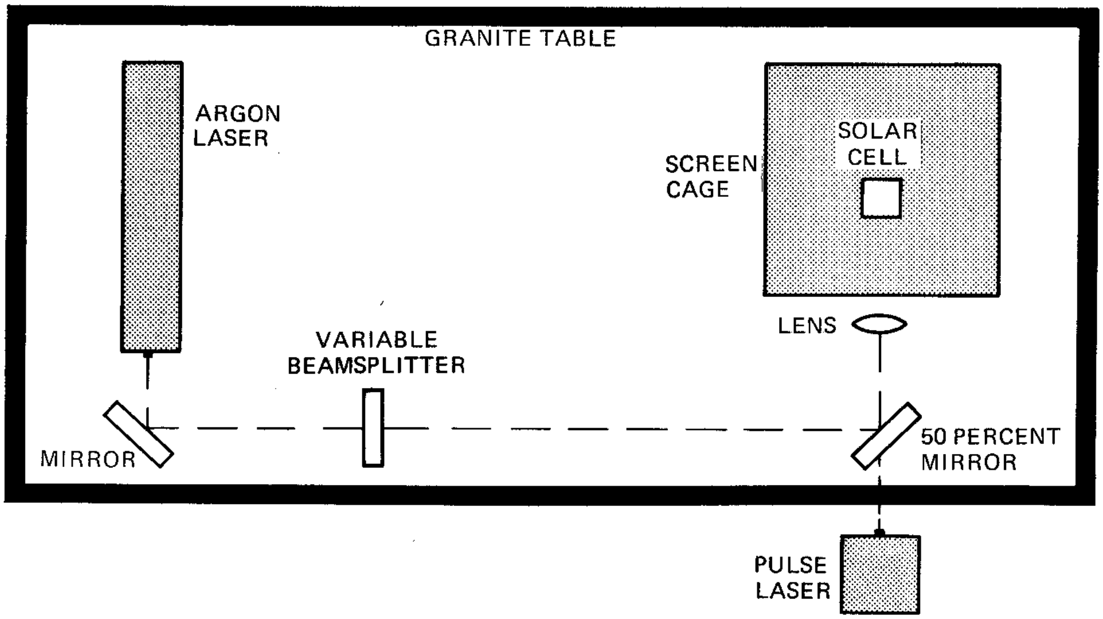

Figure 4. Layout of Equipment Used for Testing Variation of τ With Background Illumination.

Figure 5. Photograph of Equipment Used for Testing Variation of τ With Background Illumination.

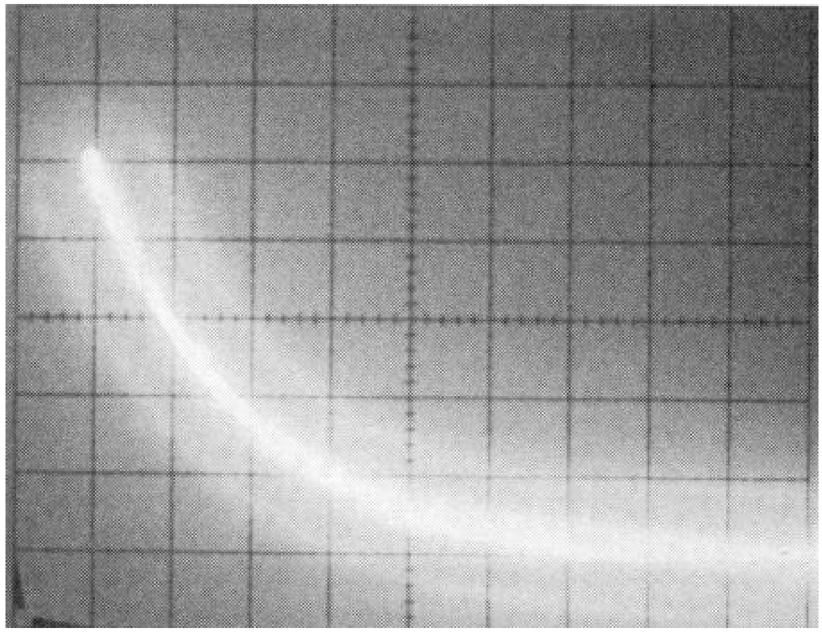

Figure 6. Transient Output of Solar Cell Due to a Pulse of Light,
Without Background Illumination.

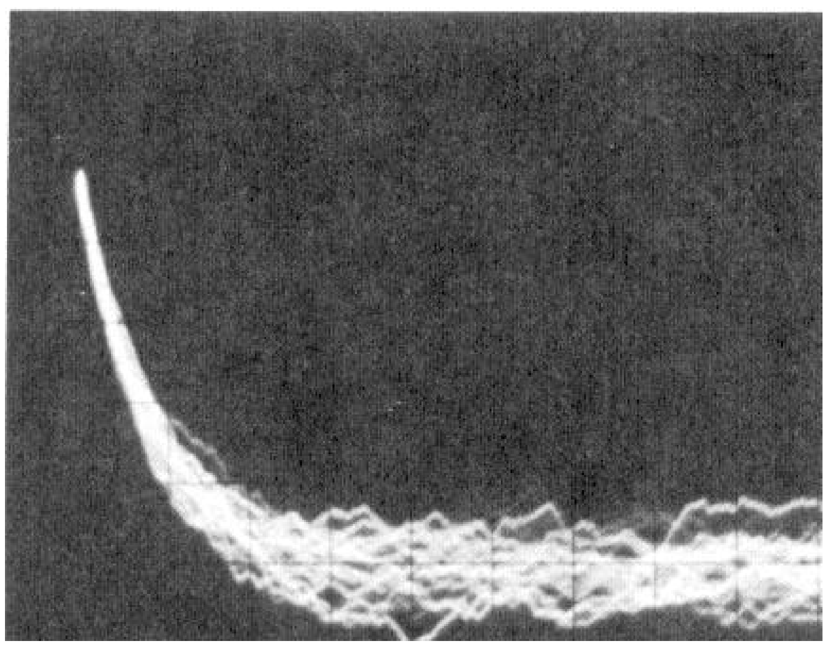

Figure 7. Transient Output of Solar Cell Due to a Pulse of Light,
With Background Illumination
(to Provide a DC Offset of 100 mV).