JUNCTION MODELING FOR SOLAR CELLS--
THEORY AND EXPERIMENT*

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ABSTRACT

This paper describes methods that enable us to experimentally determine the recombination lifetimes in the emitter and base of a p-n-junction solar cell and the energy-gap shrinkage in the emitter for the first time. The methods integrate experiment with theory such that the quantitative analysis of the measurements is rigorously based on the underlying device physics.

I. INTRODUCTION

This paper describes methods for determining material parameters needed in a mathematical analysis of the electrical characteristics of p-n-junction solar cells. The methods thus furnish information useful to solar-cell design. They provide quantitative procedures to remove certain discrepancies between theory and experiment that were previously unexplained.

As one example of such a discrepancy, the maximum solar energy conversion efficiency seen in fabricated silicon cells is about 25% less than the maximum value predicted by traditional theory (1). Many speculations have been made on the origin of this discrepancy. In these speculations, attention has focused on the highly-doped emitter region of the solar cell. Energy-band distortion (energy-gap shrinkage) and high recombination rates (low lifetime) in the emitter have been suggested as probable reasons for the discrepancy (2).

Various theoretical models have been proposed to describe the gap shrinkage and the carrier lifetime in the emitter. Solar cell performance based on these models has been calculated in various ways, including the use of detailed computer solutions (3) of the Shockley differential equations (4) for a p-n junction. But no explanation of the discrepancy has yet been generally accepted because no experimental justifications have existed to support one speculation over another.

The methods to be described in this paper are aimed to provide such experimental justifications. In the methods, the material parameters of a solar-cell structure are determined after the p-n junction is formed. Special care is taken to separate the contributions to the solar-cell characteristics from the three regions of the device: the quasi-neutral emitter, the quasi-neutral base, and the bulk and surface space-charge regions. This separation enables us to determine the effective recombination lifetimes in the quasi-neutral emitter and base regions and the effective energy-gap shrinkage in the emitter.

The novelty of the methods presented here lies not in the various measurements that are taken. Rather, it lies in the careful and critical application of the underlying device physics to the quantitative analysis of the experimental data.

II. THEORY

To provide a basis for determining material parameters of the emitter and base, the model used to describe the p-n-junction diode must be general enough

(a) to apply to any impurity doping profile of a p-n junction, and

(b) to apply in the presence of position-dependent lifetimes and gap shrinkage in the emitter.

In addition, as will be seen, the model must describe both the static and the transient electrical characteristics.

Recently such a model was proposed (5,6), based on a charge-control analysis of a p-n diode. The model gives two relations for a dark diode that are useful in material-parameter determination:

$$\Delta = Q_{EO}/Q_{BO} = (\tau_{QN} I_{QNO}/Q_{BO}) - 1 \qquad (1)$$

and

$$\tau_B/\tau_E = (1/\Delta)[(\tau_B/\tau_{QN})(\Delta+1) - 1] \quad . \qquad (2)$$

Here Δ is a measure of the gap shrinkage in the emitter and τ_B/τ_E is the ratio of the base to the emitter lifetime. If measurements of the open-circuit current of the illuminated diode are taken, two more relations, independent from Eqs. (1) and (2), can be obtained:

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$$\Delta = \frac{\exp(q\delta V_{OC}/kT)}{\tau_B/\tau_{QN}} - 1 \qquad (3)$$

and

$$\tau_B/\tau_E = 1/\Delta[\exp(q\delta V_{OC}/kT) - 1] \ . \qquad (4)$$

Because Eqs. (3) and (4) are independent of Eqs. (1) and (2), Δ and τ_B/τ_E can be determined in two different ways to check for consistency.

The model that yields Eqs. (1) through (4) describes the contribution to the electrical characteristics that comes from the quasi-neutral emitter and base regions. Thus, I_{QNO} is the saturation current of the dark current-voltage characteristics,

$$I = I_{QNO}[\exp(qV/kT) - 1] \ , \qquad (5)$$

due to recombination in the quasi-neutral regions. Similarly, τ_{QN} is the relaxation time of the quasi-neutral regions (5). This relaxation time determines the natural (force-free) behavior when the device is perturbed by an applied force, such as an impulse current or a voltage step. If the dark current-voltage characteristics are given by Eq. (5), then the illuminated diode would show an open-circuit voltage V_{OCqn}. If only the quasi-neutral base region contributed to the dark current, then an open-circuit voltage V^B_{OCqn} would result. The difference,

$$\delta V_{OC} = V^B_{OCqn} - V_{OCqn} \qquad (6)$$

appears in Eqs. (3) and (4). The coefficients Q_{EO} and Q_{BO} describe the excess minority carrier charges, Q_E and Q_B, stored in the quasi-neutral emitter and base regions:

$$Q_E = Q_{EO}[\exp(qV/kT) - 1] \ , \qquad (7)$$

$$Q_B = Q_{BO}[\exp(qV/kT) - 1] \ . \qquad (8)$$

If the base doping concentration N_{BB} and the base lifetime τ_B are both independent of position, then

$$Q_{BO} = qn_i^2 L_B/N_{BB} \qquad (9)$$

where L_B is the minority-carrier diffusion length of the base.

To clarify the effect of gap shrinkage in Eqs. (1)-(4), consider a solar cell in which no gap shrinkage occurs in the emitter. Then, Q_{EO} can be calculated from conventional theory as (7)

$$Q^o_{EO} \simeq qn_i^2 W_E \{N(W_E)\ell n[N_{MAX}/N(W_E)]\}^{-1} \qquad (10)$$

where N_{MAX} is the maximum majority carrier concentration in the emitter and $N(W_E)$ is the majority carrier concentration at the emitter edge of the junction space-charge region. The effective energy gap shrinkage ΔE_G in the emitter is thus (2)

$$\Delta E_G = kT\ell n(Q_{EO}/Q^o_{EO}) = kT\ell n(\Delta/\Delta^o) \qquad (11)$$

where $\Delta^o = Q^o_{EO}/Q_{BO}$.

There are seven parameters in Eqs. (1)-(4): τ_E, τ_B, τ_{QN}, I_{QNO}, δV_{OC}, Q_{BO}, and Q_{EO} (or Δ or ΔE_G). Many of these parameters can be determined experimentally, thereby enabling the determination of ΔE_G, τ_E, and τ_B.

III. MEASUREMENT TECHNIQUES

The use of Eqs. (1)-(4) for device material-parameter determination requires that certain conditions be met in the design of the experiments. As was noted earlier, the recombination and charging current from the quasi-neutral regions must be made to greatly exceed that from the bulk and surface space-charge regions. The concentrations of excess holes and electrons must be limited to a low injection level throughout the quasi-neutral regions. The effects of series resistance must be made negligible.

In the experimental design, two choices are possible. Either the design must assure that all of the above conditions are met, or procedures must be developed to remove unwanted components from the data. For example, consider the requirement of the quasi-neutral-region currents dominating over the space-charge-region current. To satisfy this requirement, the temperature of the device can be raised, which increases the hole and electron charge stored in the quasi-neutral regions more than that in the space-charge regions. To diminish the contribution of the surface recombination current, a voltage of appropriate polarity and magnitude can be applied to an MOS guard-ring to pinch-off the surface channel. As an alternative to these procedures, the space-charge-region current can be removed from the data using a numerical or graphical procedure. In this procedure, the measured current-voltage characteristic is decomposed into components. One first identifies the bulk and surface space-charge-region component (8) and then subtracts it from the measured characteristic to bare the quasi-neutral-region component, which obeys the dependence given in Eq. (5).

The details of measuring the parameters in Eqs. (1)-(4) are treated elsewhere (6,7). Here we outline some possible methods.

3.1 Base τ_B and Q_{BO}

For high-quality silicon solar cells, the X-ray generated (9) short-circuit photocurrent originates mainly within the base region. By combining this with several other measurements (6), one can determine the base lifetime τ_B and the related charge Q_{BO}. Alternatively, transient-capacitance methods (10) provide a technique for determining the lifetime that applies to cells made with solar-grade semiconductors as well as to high-quality silicon cells. The transient-capacitance methods also establish the positional dependence of the lifetime (11).

3.2 Quasi-Neutral-Region Saturation Current I_{QNO}

The parameter I_{QNO} can be obtained either from the static I-V characteristic of a dark diode or from the static I_{SC}-V_{OC} (photo-current versus photo-voltage) characteristic of an illuminated diode. As was discussed earlier, the quasi-neutral-region component of the measured current is enhanced by heating the device, or by applying a voltage to an MOS guard ring; or it is revealed by decomposing the data.

3.3 Quasi-Neutral-Region Relaxation Time τ_{QN}

The response of a p-n diode to any time-varying excitation will contain information about the relaxation time τ_{QN}. Three methods used here to determine τ_{QN} are: junction current recovery (12), open-circuit voltage decay (13), and admittance versus voltage and frequency (14,3(c)). To assure dominance of the quasi-neutral regions, the temperature of the device may need to be raised.

3.4 Other Measurement Techniques

The above measurements involve electrical and optical excitations. Other excitation methods (10) could be used with possible advantages. The list given here is meant to be suggestive, not exhaustive.

3.5 Measurement Sensitivity

The measurement sensitivity of the effective gap shrinkage and emitter lifetime depends on the accuracy with which each of the measured quantities --I_{QNO}, τ_{QN}, τ_B, Q_{BO}, V_{OC}, and I_{SC}--are determined. Let Δ_{min} be the minimum value of Δ obtainable for a given accuracy of the measurements. Then, from Eqs. (10) and (11), the minimum determinable value of the gap shrinkage ΔE_{Gmin} is

$$\begin{aligned}\Delta E_{Gmin} &= kT\ell n(\Delta_{min}/\Delta^\circ) \\ &\simeq kT\ell n\{[\Delta_{min}L_B/W_E]\ell n[N_{MAX}/N(W_E)]\} \qquad (12)\end{aligned}$$

This defines the measurement sensitivity for the emitter gap shrinkage. Combining Eq. (12) with Eqs. (2) or (4) then yields the measurement sensitivity for the emitter lifetime.

3.6 Increasing the Measurement Sensitivity

Equation (12) implies that the measurement sensitivity depends strongly on $\Delta_{min}(L_B/W_E)$. Increasing the accuracy of the measurements will increase Δ_{min}, and thickening the emitter will increase W_E. The diffusion length L_B can be decreased by using a high doping concentration in the base, above about 10^{18} cm^{-3} for silicon solar cells. Alternatively, the diffusion length can be effectively shortened by adding a collector region, making a transistor-like structure. In such structures, an electrical contact can be made to the base. The resulting transistor enables direct measurement of τ_E, which provides an alternate method for determining τ_E and ΔE_G (15).

IV. EXAMPLES

The methods have been applied to two types of p-n structures. The first type (7) consisted of p-on-n silicon diodes fabricated with deep junctions, about 10 μm, to diminish the effective gap shrinkage. The emitter and base lifetimes were determined as a function of the base impurity concentration, which ranged from 10^{14} to 10^{17} cm^{-3}. The results showed that the emitter lifetime is much smaller than the base lifetime only in the diode having the highest base doping concentration. In this diode, the recombination current from the emitter was 65% of the recombination current from the base, demonstrating the significance of the emitter in governing the static current-voltage characteristics.

The second type of p-n structure studied (6) was an n-on-p solar cell having a base resistivity of 0.1 ohm-cm. The thin (0.25 μm) diffused emitter of these structures emphasized the role of energy-gap shrinkage in the emitter. The results showed a base lifetime of 7 μsec, an emitter lifetime of 75 nsec, and a gap shrinkage of 140 mV.

V. SUMMARY

Equations (1)-(4) together with the definition of Eq. (11) express the emitter energy-gap shrinkage and lifetime in terms of measurable parameters. To use these relations for device material-parameter determination, the experimental design and the interpretation of data must be based on the device physics of p-n solar cells. Some specific procedures for accomplishing this are indicated in this paper; details are described elsewhere (6,7).

This paper deals with p-n solar cells whose conversion efficiency depends strongly on recombination and transport processes occurring in the emitter. Examples include cells made on low-resistivity substrates of high-quality, single-crystal silicon. For cells made from amorphous or polycrystalline semiconductors, the recombination processes in the junction space-charge region can play a central role in determining the solar energy conversion efficiency. For such cells, the transient-capacitance methods (10) mentioned earlier can determine the recombination parameters describing the space-charge region.

The methods of this paper are relevant to the engineering design of p-n solar cells. They help to discover and describe the fundamental electronic mechanisms influencing solar-cell efficiency (2), and to provide physics-based mathematical models that incorporate these mechanisms into solar-cell design. The methods yield the gap shrinkage in the emitter and the lifetimes in the emitter and base. If a physical model for the gap shrinkage and the recombination rates is correct, it must predict solar-cell electrical characteristics which are consistent with the experimentally determined values of the gap shrinkage and lifetimes. Computer solution of the Shockley differential equations (3) permits a study of physical models of any degree of complexity, containing various combinations of the fundamental electronic mechanisms (2) that could influence the solar-cell efficiency. Comparison of the results of experiments with those of computer simulation (3) may then disclose the dominant fundamental mechanisms. The ability to determine these mechanisms enables study of their relation to the fabrication processes used in solar-cell manufacturing, which would lead toward a systematic improvement of cell efficiency.

The recombination and transport processes occurring in the emitter of a bipolar junction transistor can limit the achievable maximum current gain and can influence also the frequency and transient response. The methods treated in this paper thus apply not only to p-n solar cells, but also to p-n diodes (7) and to junction transistors (15).

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