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STUDIES OF BASIC MECHANISMS INFLUENCING SOLAR-CELL
EFFICIENCY FOR TERRESTRIAL APPLICATIONS

MASTER

Work Performed Under Contract No. EY-76-S-05-5134

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Solar Energy

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PROGRESS REPORT

I. Papers and Reports Resulting from Support of this Contract

Since the start of contract support in June 1976, our work has led to 27 papers and reports. These are listed below in chronological order.

1. M.P. Godlewski, H.W. Brandhorst, Jr., F.A. Lindholm, and C.T. Sah, "Experimental Investigation of the Diffused Layer of a 0.1 ohm-cm Silicon Solar Cell," Symposia of the 1976 Device Research Conference and the 1976 Electronic Materials Conference, Salt Lake City, Utah, June 23, 1976.
2. F.A. Lindholm and C.T. Sah, "Studies of Basic Mechanisms Influencing Solar Cell Efficiency for Terrestrial Applications," Proc. National Solar Photovoltaic Program Review Meeting, session III, paper 7, Orono, ME, 1976.
3. F.A. Lindholm, A. Neugroschel, and C.T. Sah, "Basic Mechanisms Governing Solar-Cells Efficiency," Proc. Int. Solar Energy Society, Vol. 6, pp. 120-129, Winnipeg, Manitoba, Canada, Aug. 1976.
4. F.A. Lindholm and C.T. Sah, "Normal Modes of pn Junction Devices for Material-Parameter Determination," J. Appl. Phys., Vol. 47, pp. 4203-4205, Sep. 1976.
5. F.A. Lindholm, C.T. Sah, A. Neugroschel, M.P. Godlewski, and H.W. Brandhorst, "Methodology for Experimental Determination of Gap Shrinkage and Lifetimes in Emitter and Base of pn Junction Solar Cells," Record of Twelfth Photovoltaic Specialists Conf., paper 1.1, pp. 1-9, Nov. 1976.
6. F.A. Lindholm, J.G. Fossum, and E.L. Burgess, "Basic Corrections to Solar Cell Performance Required by Inapplicability of Superposition," Record of Twelfth Photovoltaic Specialists Conf., paper 1.6, pp. 33-40, Nov. 1976.
7. C.T. Sah and F.A. Lindholm, "Characteristics of Solar Cells on Granular Semiconductors," Record of Twelfth Photovoltaic Specialists Conf., paper 2.5, pp. 93-96, Nov. 1976.
8. F.A. Lindholm, A. Neugroschel, and C.T. Sah, "Junction Modeling for Solar Cells--Theory and Experiment," Tech. Digest 1976 Int. Electron Devices Meeting, 76CH1151-OED, pp. 61-65, Dec. 1976 (invited paper).

9. F.A. Lindholm, C.T. Sah, and J.G. Fossum, "Fundamental Considerations for Improving the Efficiency of Junction Silicon Solar Cells," Proc. National Solar Photovoltaic Program Review Meeting, session III, paper 1, San Diego, Calif., Jan. 1977.
10. F.A. Lindholm and C.T. Sah, "Fundamental Electronic Mechanisms Limiting the Performance of Solar Cells," IEEE Trans. Electron Devices, Vol. ED-24, pp. 299-305, April 1977.
11. C.T. Sah and F.A. Lindholm, "Carrier Generation, Recombination, Trapping and Transport in Semiconductors with Position-Dependent Composition," IEEE Trans. Electron Devices, Vol. ED-24, pp. 358-363, April 1977.
12. J.G. Fossum and F.A. Lindholm, "The Dependence of Open-Circuit Voltage on Illumination Level in p-n-Junction Solar Cells," IEEE Trans. on Electron Devices, Vol. ED-24, pp. 325-330, April 1977.
13. F.A. Lindholm, A. Neugroschel, C.T. Sah, M.P. Godlewski, and H.W. Brandhorst, Jr., "Methodology for the Experimental Determination of Gap Shrinkage and Lifetimes in the Emitter and Base of p-n Junction Solar Cells and Other p-n Junction Devices," IEEE Trans. Electron Devices, Vol. ED-24, pp. 402-410, April 1977.
14. A. Neugroschel, F.A. Lindholm, and C.T. Sah, "A Method for Determining the Emitter and Base Lifetimes in p-n-Junction Diodes," IEEE Trans. Electron Devices, Vol. ED-24, pp. 662-671, June 1977.
15. M.P. Godlewski, H.W. Brandhorst, Jr., F.A. Lindholm, and C.T. Sah, "Experimental Investigation of Excess Charge and Time Constant of Minority Carriers in the Diffused Layer of 0.1 ohm-cm Silicon Solar Cell," Int. J. Electronic Materials, Vol. 6, No. 3, pp. 373-382, 1977.
16. F.A. Lindholm, J.G. Fossum, and E.L. Burgess, "Application of the Superposition Principle to Solar-Cell Analysis," IEEE Trans. Electron Devices, accepted 8/77.
17. F.A. Lindholm, C.T. Sah, and J.G. Fossum, "Studies of Basic Mechanisms Influencing Solar Cell Efficiency for Terrestrial Applications," Proc. National Solar Photovoltaic Program Review Meeting, Washington, D.C., March 1977.
18. F.A. Lindholm, A. Neugroschel, and C.T. Sah, "Measurement of Material Parameters that Limit the Open-Circuit Voltage in P-N-Junction Silicon Solar Cells," NASA-Lewis Research Center High Efficiency and Radiation Damage Silicon Solar Cell Meeting, April 1977.
19. J.G. Fossum, E.L. Burgess, and F.A. Lindholm, "The Design of Silicon Solar Cells for Concentration Systems," Digest of the ERDA Photovoltaic Concentrator Systems Workshop, May 24, 1977 (invited paper).
20. C.T. Sah, F.A. Lindholm and J.G. Fossum, "A High-Low Junction Emitter Structure for Improving Silicon Solar Cell Efficiency," IEEE Trans. Electron Devices, accepted 8 July 1977 for publication, to appear Jan. 1978.

21. J.G. Fossum, F.A. Lindholm, E.L. Burgess, "Silicon Solar Cell Designs Based on Physical Behavior in Concentrated Sunlight," Solid-State Electronics, accepted August 1977.
22. J.G. Fossum, F.A. Lindholm, and C.T. Sah, "Physics Underlying Improvements in Efficiency of High-Low-Junction Emitter Solar Cells," 1977 Int. Electron Devices Meeting, accepted August 1977.
23. P.J. Chen, S.C. Pao, A. Neugroschel, and F.A. Lindholm, "Measurement of Series Resistance in P-N-Junction Diodes and Solar Cells," IEEE Trans. Electron Devices, accepted September 1977, to appear 3/78.
24. A. Neugroschel, P.J. Chen, S.C. Pao, and F.A. Lindholm, "Diffusion Length and Lifetime Determination in P-N Junction Solar Cells and Diodes by Capacitance Measurements," IEEE Trans. Electron Devices, submitted 8/77, accepted 10/77.
25. F.A. Lindholm, A. Neugroschel, J.G. Fossum, and C.T. Sah, "Design of HLE Junction Silicon Solar Cells," 1978 Photovoltaic Specialists Conf., submitted 11/77.
26. A. Neugroschel, P.J. Chen, S.C. Pao, and F.A. Lindholm, "Forward-biased Capacitance Measurements for Determining the Lifetime in the Emitter and Base Regions of p-n Junction Solar Cells," 1978 Photovoltaic Specialists Conf., submitted 11/77.
27. F.A. Lindholm, A. Neugroschel, C.T. Sah, and J.G. Fossum, "Studies of Basic Mechanisms Influencing Solar Cell Efficiency for Terrestrial Applications," Proc. Nat. Solar Photovoltaic Program Review Meeting, Golden, CO, 10/77.

These 27 papers fall into the following categories: 12 in refereed research journals, 8 in International Conference Proceedings (2 invited), 7 in governmental review and workshop meetings (6 ERDA, 1 NASA, 1 invited).

II. Brief Description of Progress

The research has three related general objectives that provide basic support to the needs of the national photovoltaic program. The first is to identify, determine and describe basic mechanisms that control and limit solar-cell efficiency, innovating the measurement techniques needed to do this. The second is to develop mathematical models of various degrees of complexity that enable the inclusion of these mechanisms in the engineering design of solar cells. The third is to use the under-

standing gained of the basic mechanisms to improve cell design and to innovate changes in cell structure that will both increase the power conversion efficiency and define the maximum efficiency expected from a given material technology.

By basic mechanisms we mean mechanisms that dominate in a given cell structure in determining transport, recombination, and generation of electrons and holes in semiconductor material of which the cell is made; in large measure, these mechanisms determine the solar conversion efficiency. Thus our research focusses on the mechanisms that control the electronic parameters, such as lifetime and effective band gap, that characterize the transport, recombination and generation processes. It focusses also on the basic mechanisms by which such design variables as injection level, doping profile, and device structure influence these processes.

In addition to identifying and experimentally determining the basic mechanisms, we seek also to exploit the better understanding obtained of the basic mechanisms in order to improve solar-cell design and to innovate changes in cell structure that will increase the power conversion efficiency. That such improvements can result from studies of the basic mechanisms is indicated by the research findings made during this period of D.O.E. support that are reported below.

The progress achieved in the research is as follows.

A. Detailed Theoretical Study of the Basic Mechanisms

At the beginning of the research period, we recognized that no comprehensive, concise summary existed of the many mechanisms that could control the electronic parameters characterizing transport, recombination, and generation. Thus, as the first step, we developed such a summary

from a theoretical viewpoint [2,10,11; see Sec. I for references].

In outline form, the mechanisms can be grouped as follows:

- (a) distorted energy bands in highly-doped material, such as in the emitter of a p-n junction solar cell;
- (b) bulk, surface, and grain-boundary recombination;
- (c) spatial dependencies of (1) and (2) above resulting from the space variation of the chemical composition, both in the longitudinal and transverse (areal inhomogeneity) directions.

The majority of our effort in this theoretical study concentrated on the basic mechanisms in single-crystal semiconductors. But the study dealt also with granular semiconductors [7], yielding a simple model for characterizing the recombination current at a grain boundary in a solar cell. The model contains one parameter: the surface recombination velocity at the grain-boundary plane. Its use allowed a quantitative comparison to be made of polycrystalline silicon solar cells deposited on graphite substrates and on metallurgical grade substrates, and of diffused and epitaxial solar cells on EFG ribbon substrates. The model also enabled an estimate to be made of the minimum grain size needed for an efficient solar cell.

The review of the basic mechanisms limiting the efficiency of single-crystal semiconductors served as an effective first step in the research in that it led to the following research findings that support objectives of the national photovoltaic program:

- (a) the development of new measurement techniques for determining the effective lifetime, diffusion length, and energy gap

shrinkage in all regions of the solar cell, including degenerately doped regions such as the surface layer in a p-n junction cell;

- (b) a methodology based on the results of these measurement techniques that enables the determination and mathematical characterization of the basic mechanisms controlling the effective lifetime, diffusion length, and energy gap shrinkage in the various regions of the solar cell;
- (c) innovations, based on the understanding gained of the basic mechanisms, of new device design theories and new structures that improve the solar power conversion efficiency for single-crystal silicon cells under one-sun and multiple-sun levels of illumination and lead toward a more accurate estimate of the maximum designable efficiency possible from single-crystal silicon cells.

A brief description of these research findings appears below.

Details are given in the references of Sec. I of this Progress Report.

B. Experimental Methods for Determining Basic Mechanisms

Although the detailed theoretical study of Sec. II-A was informative and necessary as a first step in the research, theoretical considerations alone fall short of determining the basic mechanisms that control and limit the solar conversion efficiency. Theoretical considerations alone fail to answer the question: which of the many mechanisms that can occur in semiconductor materials limit the efficiency of a particular solar cell made from a particular semiconductor material? As the next step in our research, therefore, we developed methods based on experiment that would

disclose the dominant mechanisms and determine the relevant material parameters, as described in Sec. B-2 below.

In developing the measurement techniques, we applied the methods exclusively to p-n junction solar cells made of single-crystal silicon, although it is probable that the methods can be adapted to cells made of thin-film noncrystalline material as well. We chose to emphasize cells made of single-crystal silicon for several reasons. First single-crystal silicon was a convenient choice for experimentation; second, issues about single-crystal silicon cells remain unresolved that keep the efficiencies seen in laboratory and manufactured cells suboptimal, that is, well below the efficiency that is possible. Third, a recent study (B. Carbajal of Texas Instruments, ERDA Review Meeting, 1977) has concluded that an AM1 cell efficiency of no less than 16% is needed to absorb the module encapsulation costs and meet the D.O.E. goal of \$2/Watt flat-plate photovoltaic modules by 1982 and the goal of \$0.50/Watt by 1986. Thus, according to the conclusions of Carbajal's study, to be cost effective, thin-film cells, whatever material they are made of, must have efficiencies about equal to these seen in the best single-crystal silicon cells manufactured today. This suggests that the same basic mechanisms limiting and controlling the efficiencies of silicon single-crystal cells of today will also be among the basic mechanisms that limit the performance of useful noncrystalline thin-film cells of tomorrow. Therefore, basic studies of single-crystal silicon cells such as ours, which aim to support the innovation of designs and structures that improve efficiency and establish upper bounds on efficiency, provide basic support also to the development of thin-film cells having high enough efficiency to meet the D.O.E. cost goals of 1982 and 1986.

1. METHODS FOR DETERMINING THE BASIC MECHANISMS IN THE HIGHLY-DOPED EMITTER REGION [1,4,5,8,13,15,18,24 of Sec. I]

OVERVIEW: We have considered one of the most important unresolved issues about single-crystal silicon cells: that the maximum open-circuit voltage and hence the maximum solar energy conversion efficiency seen at one sun in fabricated silicon cells is about 25% less than the maximum value predicted by traditional theory. The discrepancy is even larger for cells operating under concentrated sunlight. Many theoretical speculations have been made about the origin of this discrepancy. We began by noting that the measured open-circuit voltage V_{OC} in low-resistivity (about 0.1 ohm/cm) or back-surface-field (BSF) cells gives evidence that the recombination current in the highly-doped emitter region of the solar cell is four or five orders of magnitude larger than traditional theory predicts. This high emitter recombination current limits the conversion efficiency about 25% (for AM1) below the efficiency that otherwise would result in low efficiency resistivity or BSF cells. From our theoretical review of the basic mechanisms controlling efficiency, energy-band distortion (energy-gap shrinkage) and high recombination rates (low lifetime) in the emitter suggest themselves as the probable reasons for the discrepancy.

Various theoretical models exist that 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 of the Shockley differential equations 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 theoretical model over another.

The methods we have developed in our D.O.E. contract research provide such experimental justifications. In the methods, effective lifetimes and energy gap shrinkages present in 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 (Fig. 1) 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 minority-carrier charge storage (related to the energy gap shrinkage) in the emitter. For the most part, the novelty of the methods we have developed 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.

The relevance of the methods to the engineering design of p-n solar cells is that they can be used to discover and describe the fundamental electronic mechanisms influencing solar-cell efficiency, and to provide physics-based mathematical models that incorporate these mechanisms into solar-cell design. The methods yield the minority-carrier charge storage Q_E and Q_B in the emitter and base and the lifetimes τ_E and τ_B in the emitter and base (see Fig. 1). 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 emitter and minority-carrier charge storage and lifetimes. Computer solution of the Shockley differential equations (modified as disclosed by our theoretical study described in Sec. A) permits a study of physical models of any degree of complexity, containing

Fig. 1 .The excess minority-carrier charges Q_E and Q_B in the quasi-neutral (unshaded) emitter and base regions of the cell: $Q_E = \int P(x)dx$ and $Q_B = \int N(x)dx$. The cross-hatched layer represents the junction space-charge region (SCR);

various combinations of the fundamental electronic mechanisms that could influence the solar-cell efficiency. As is indicated in Fig. 2, comparison of the results of experiments with those of computer simulation then discloses the dominant fundamental mechanisms (Auger vs. SHR recombination, for example) at work in a given cell structure. The ability to determine these mechanisms enables us to study their relation to the fabrication processes used in solar-cell manufacturing, which leads toward a systematic improvement of cell efficiency. As Sec. C describes, it leads also toward the improvement of cell designs and the innovation of changes in cell structure that likely will yield the highest power conversion efficiencies possible for silicon solar cells.

DETAILS (references here refer to those listed in Sec. I of this Progress Report)

As was described above, we have developed methods that enable, for the first time, the experimental determination of the recombination lifetime in the quasi-neutral emitter and base of a p-n junction solar cell and the minority carrier charge storage (and hence the energy gap shrinkage) in the quasi-neutral emitter. The methods integrate experiment with theory in such a way that the quantitative analysis of the measurements is rigorously based on the underlying device physics. The presentation to follow begins with the elements of the theory underlying the measured quantities and then proceeds to a discussion of the measurement techniques.

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

FIG. 2 FLOW CHART INDICATING THE METHOD USED TO DETERMINE THE BASIC MECHANISMS CONTROLLING THE CONVERSION EFFICIENCY OF A GIVEN SOLAR CELL. A SET OF PHYSICAL MODELS IS ASSUMED THAT ENCOMPASSES ALL OF THE VARIOUS BASIC MECHANISMS THAT COULD DOMINATE IN DETERMINING THE ELECTRICAL CHARACTERISTICS OF THE CELL. FOR EACH OF THESE PHYSICAL MODELS WE COMPUTE SUCH ASPECTS OF THE ELECTRICAL CHARACTERISTICS AS THE MINORITY CARRIER CHARGE STORAGE (Q_E AND Q_B) AND THE PHENOMENOLOGICAL LIFETIMES (τ_E AND τ_B) IN THE QUASI-NEUTRAL BASE AND EMITTER REGIONS. THESE COMPUTATIONS WE THEN COMPARE WITH THE VALUES OF Q_E, Q_B, τ_E , AND τ_B OBSERVED EXPERIMENTALLY, USING THE EXPERIMENTALLY-BASED METHODS DETERMINED IN OUR CONTRACT RESEARCH. AGREEMENT BETWEEN THE CALCULATED AND EXPERIMENTAL VALUES OF Q 'S AND τ 'S, INCLUDING THEIR TEMPERATURE AND BIAS DEPENDENCE, THEN DISCLOSES THE BASIC MECHANISMS (AUGER VS. SRH RECOMBINATION, ONE BAND-NARROWING MODEL VS. ANOTHER, ETC.) DOMINANT FOR THE CELL STRUCTURE UNDER STUDY. THE CALCULATION OF Q_E, Q_B, τ_E AND τ_B IS DONE BY COMPUTER SOLUTION OF THE MODIFIED SHOCKLEY EQUATIONS.

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

In addition, as will be seen, the model must describe both the electrical characteristics resulting from static and transient (or sinusoidal) excitation.

Our model [4,13] is 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:

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

and

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

Here Δ is a measure of the minority-carrier charge storage (and energy 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:

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

and

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

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 parameters δV_{OC} , τ_{QN} , I_{QNO} , Q_{EO} , and Q_{BO} appearing in Eqs. (1)-(4) are defined below.

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 (Fig. 1). Thus, [4-13] I_{QNO} is the saturation current of the dark current-voltage characteristics,

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

due to recombination in the quasi-neutral regions. Similarly, τ_{QN} is the relaxation time of the quasi-neutral regions [4,13]. 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_{OCqn}^B would result. The difference,

$$\delta V_{OC} = V_{OCqn}^B - V_{OCqn} \quad (6)$$

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:

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

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

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

$$Q_{BO} = q n_i^2 L_B / N_{BB} \quad (9)$$

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 [13]

$$Q_{EO}^0 \approx q n_i^2 W_E \{N(W_E) \ln[N_{MAX}/N(W_E)]\}^{-1} \quad (10)$$

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 [10,11]

$$\Delta E_G = kT \ln(Q_{EO}/Q_{EO}^0) = kT \ln(\Delta/\Delta^0) \quad (11)$$

where $\Delta^0 = Q_{EO}^0/Q_{BO}$.

There are seven parameters in Eqs. (1)-(4): τ_E , τ_B , τ_{QN} , I_{QNO} , δV_{OC} , Q_{DO} , 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 .

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 [13] 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 [13]. Here we outline some possible methods.

Base τ_B and Q_{BO}

For high-quality silicon solar cells, the X-ray generated [13] short-circuit photocurrent originates mainly within the base region. By combining this with several other measurements [13], one can determine the base lifetime τ_B and the related charge Q_{BO} . Alternatively, transient-capacitance methods [13] 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 [13].

The key to accurate determination of τ_{QN} is similar to that of I_{QN} . The electrical response is a mix coming from the quasi-neutral and the space-charge regions. To determine τ_{QN} , one must separate the components so that the one from the quasi-neutral regions is disclosed. As is discussed in Sec. B-2(b) below, this can be done by measuring the real and imaginary parts of the forward-biased admittance at both low and high frequency. In certain cases, the open-circuit voltage decay method can be used if the temperature is raised enough to assure dominance of the quasi-neutral regions in producing the transient response. But, in general, our measurements [24,26] show that open-circuit voltage decay is an unreliable method for determining τ_{QN} , even though other workers continue to use it, in papers published as recently as in December 1977.

The clarification on this subject intended to be offered by our studies constitutes an example of the basic support to the national photovoltaic program.

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

$$\begin{aligned} \Delta E_{Gmin} &= kT \ln(\Delta_{min} / \Delta^0) \\ &\approx kT \ln\{[\Delta_{min} L_B / W_E] \ln[N_{MAX} / N(W_E)]\} \end{aligned} \quad (12)$$

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

We estimate that our accuracy of measurements is such that $\Delta_{\min} \approx 0.2$, i.e., that we can measure Q_{EO} if it is one-fifth of Q_{BO} or larger. As indicated in Eq. (9), Q_{BO} decreases with increasing base doping concentration N_{BB} because both the diffusion length L_B and n_i^2/N_{BB} decrease as N_{BB} increases. For a typical N^+-P silicon junction solar cell of 0.1 ohm-cm base resistivity ($N_{BB} = 5 \times 10^{17} \text{ cm}^{-3}$), we estimate that Δ will be several times $\Delta_{\min} = 0.2$. Thus, the measurement methods described here can be expected to apply to cells having base resistivities of 0.1 ohm-cm or lower, as our experimental results [13,14] have indicated.

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 $\Delta_{\min}$, 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.

EXAMPLES

The methods have been applied to a variety of p-n structures. One type [14] 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.

Another type of p-n structure studied [13] 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 an effective gap shrinkage of 140 mV (corresponding to $\Delta \approx 0.4$).

Various other diffused N^+-P and P^+-N structures of our fabrication are now being studied to determine the minority carrier charge Q_{EO} stored in the emitter and the phenomenological lifetime τ_E of the emitter, as well as the material parameters of the base. Parallel theoretical studies are in progress that enable use of the procedure of Fig. 2, by which the basic mechanisms (Auger and SRH recombination, various models for gap shrinkage) that produce the measured values of Q_E , τ_E , and other parameters can be determined.

2. METHOD FOR DIFFUSION LENGTH AND LIFETIME DETERMINATION IN THE BASE REGION

OVERVIEW

The new method we have developed determines the value and the temperature dependence of the minority-carrier diffusion length and lifetime in the base region of p-n junction solar cells and diodes. The method applies to devices after the p-n junction is formed, and thus includes the influence of the junction fabrication on the diffusion length and lifetime. The method requires only forward-biased capacitance measurements at the device terminals. It combines the dependencies of the low-frequency and high-frequency capacitance on forward bias in such a way as to yield the component of the capacitance associated with the minority carriers in the quasi-neutral base region. From this quasi-neutral-base capacitance the minority carrier diffusion length and lifetime are then deduced. The accuracy of this method is estimated to be $\pm 5\%$ based on the accuracy of the capacitance bridges and of the measured temperature. To illustrate the method and its accuracy, it is applied to a set of silicon p-n junction diodes having base doping concentrations ranging from about 10^{14} to 10^{18} cm^{-3} , and the values of the diffusion

lengths determined by the capacitance method are compared with those obtained using the current response to X-ray excitation. Excellent agreement is seen. In contrast, the open-circuit-voltage-decay method yields values of the diffusion length that differ appreciably from those determined by the capacitance and X-ray methods. The reasons for the relative inaccuracy of the open-circuit-voltage-decay method applied to silicon devices are discussed. The practical limitations of the capacitance method were determined, and an extension of the method is proposed that makes it applicable to devices having highly doped base regions and surface (emitter) layers. In such devices, the capacitance of the quasi-neutral emitter region can contribute appreciably to the total forward-biased capacitance, and the method can yield information about the material properties of the degenerately doped surface layer. The material properties determined are the phenomenological emitter lifetime and a measure of the energy band-gap narrowing in the emitter.

DETAILS (see end of this section for references)

One of the material parameters that most influences the performance of a p-n junction solar cell or diode is the minority carrier diffusion length L of the base (or substrate) region. The diffusion length limits the collection efficiency and power conversion efficiency achievable in a solar cell, and it controls the current-voltage characteristic in a long-base (non-illuminated) diode.

Many methods exist for the measurement of L . Of these, the ones of most relevance to p-n junction device studies yield the value of L in a solar cell or diode after the junction is formed so that the influence on L of the process used to fabricate the junction is included. Existing measurement methods applicable to this problem [1-5] involve various trade-offs between accuracy and convenience.

The purpose here is to describe a new method for measuring L , which is accurate and requires only straightforward capacitance measurements made at the device terminals. The accuracy results because the measurements required employ very accurate capacitance bridges. The accuracy is demonstrated by showing that the values of L yielded by this capacitance method agree well with those obtained by use of the X-ray method described by Rosenzweig [1]. In contrast, the results determined by the capacitance method disagree sharply with those determined from open-circuit-voltage decay [4], for reasons that are discussed.

Theoretical Grounds for the Method

Consider a p^+-n junction diode or solar cell with no illumination applied; analogous results hold for n^+-p devices. The minority-carrier diffusion length, $L_p = \sqrt{D_p \tau_p}$, in the n -type base influences the small-signal capacitance C_{QNB} and conductance G_{QNB} of the quasi-neutral base region according to [6],

$$C_{QNB} = \frac{q}{kT} \frac{A q n_i^2 L_p}{2 N_{DD}} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (1)$$

$$G_{QNB} = \frac{q}{kT} \frac{A q n_i^2 D_p}{N_{DD} L_p} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right], \quad (2)$$

for an applied sinusoidal signal whose period greatly exceeds the base lifetime τ_p . The above results hold for a one-dimensional model of a device having a uniformly doped base and operating under low-injection conditions. To determine the minority carrier diffusivity D_p , one first finds the base doping concentration N_{DD} from the measured reverse-biased capacitance vs. voltage characteristic, then uses published data [7] to find the mobility, μ_p , and finally employs the Einstein ratio, $D_p = (kT/q)\mu_p$. The undefined symbols appearing in (1) and (2) have their usual meanings.

If either C_{QNB} or G_{QNB} could be determined from measurements, (1) or (2) would then yield L_p , which is the desired quantity. But the capacitance C and conductance G measured at the terminals contain components in addition to C_{QNB} and G_{QNB} [8-11]:

$$C = C_I + C_S + C_{SC} + C_{QNE} + C_{QNB} \quad (3)$$

$$G = G_S + G_{SC} + G_{QNE} + G_{QNB} \quad (4)$$

under low-injection conditions. In (3) and (4) the subscript S refers to the surface region, SC to the junction space-charge region, and QNE and QNB to the quasi-neutral emitter and base regions respectively.

The capacitance C_I is the capacitance due to the ionized impurities in the junction space-charge region and C_{SC} is that due to the mobile holes and electrons in that region [8]. From the viewpoint expressed in (1)-(4), the problem of determining L_p becomes the problem of extracting C_{QNB} from the measured C vs. V characteristic or of extracting G_{QNB} from the measured G vs. V characteristic.

The surface components C_S and G_S are negligible in devices having low concentrations of surface states and of charge in the oxide over the surface. If necessary, the surface components can be greatly reduced by applying a bias voltage to an MOS guard ring located over the metallurgical p-n junction. Thus, in (3) and (4), we can neglect C_S and G_S .

The conductance G_{QNE} has the same dependence on forward-bias V as that given in (2) for G_{QNB} , whereas G_{SC} is proportional to $[\exp(qV/mkT) - 1]$, in which $1 < m \leq 2$ for large enough V [10]. Because both components plot as straight lines in the $\ln(G)$ - V plane for large enough V , a simple construction technique [12,13] can be used to determine $G_{QN} = G_{QNE} + G_{QNB}$. But, as experiments [12,13] including those described in Section III show, G_{QNE} can be comparable to G_{QNB} or larger than G_{QNB} in many p-n junction devices of interest. Thus,

except in special cases, one cannot determine C_{QNB} , and hence L_p , from the conductance data.

The construction technique referred to above does not apply to the capacitance data because, as theory confirms [8,9], $C_I + C_{SC}$ will not plot as a straight line on the $\ln(C)$ vs. V plane, whereas C_{QNE} and C_{QNB} are both proportional to $[\exp(qV/kT) - 1]$ and do plot as straight lines on this plane for large enough V .

The key to the extraction of C_{QNB} , and hence to the determination of L_p , from the C-V data lies in making capacitance measurements at relatively high as well as at low frequencies. At low frequencies, the mobile carriers in all regions of the device respond to the signal, and (3) describes the measured low-frequency capacitance. But, at a higher frequency, the minority carriers in the base region cannot follow the signal, and C_{QNB} will contribute negligibly to the total capacitance [6]. The mobile carriers associated with C_I and C_{SC} can respond to the signal and contribute to the measured capacitance if the period of the signal is long compared with both the dielectric relaxation time of the semiconductor and the transit time across the junction space-charge region. Thus, by subtracting the low-frequency capacitance from this higher-frequency capacitance, one obtains a capacitance associated with the quasi-neutral regions. This capacitance is C_{QNB} if the phenomenological lifetime τ_E of the emitter [12-14] is much shorter than τ_p , and if the signal frequency f is chosen so that $\tau_E \ll \frac{1}{f} \ll \tau_p$, as is illustrated qualitatively in Fig. 1. If, on the other hand, $\tau_E \approx \tau_p$, or if $\frac{1}{f} \ll \tau_E, \tau_p$, this subtraction yields the capacitance, $C_{QNE} + C_{QNB}$, which reduces to C_{QNB} for the commonly occurring case that $C_{QNE} \ll C_{QNB}$. Thus, as will be discussed and illustrated in the following sections, the method yields C_{QNB} and, hence, from (1), the value of L_p .

Fig. 1 Qualitative illustration of the forward-biased capacitance dependence on frequency for a device for which the base minority-carrier lifetime τ_p greatly exceeds the phenomenological minority-carrier lifetime τ_E of the emitter.

This method works because C_{QNB} decreases with frequency. It cannot be adapted to the conductance data because G_{QNB} increases with frequency [6].

Illustrative Example

To explore the utility of the method, we fabricated a set of circular p^+-n junction diodes having various base doping concentrations between $1.4 \times 10^{14} \text{ cm}^{-3}$ and $6.5 \times 10^{17} \text{ cm}^{-3}$. Each diode was circular with an area of $4.5 \times 10^{-3} \text{ cm}^2$. Three separate runs were made: runs #1 and #3 at 950°C and run #2 at 1000°C . Runs #1 and #2 employed phosphorous gettering from the back face to getter metallic impurities from the substrate. In Table I, we list the surface concentration N_s and the junction depth x_j measured on the various diodes.

Figure 2 shows representative data: the measured $\ln(G)$ and $\ln(C)$ dependencies on qV/kT for diode #1-2 from run #1 having a base doping concentration $N_{DD} = 1.25 \times 10^{15} \text{ cm}^{-3}$. The data were taken at 299°K and 376°K . The low-frequency capacitance and conductance, C_{LF} and G_{LF} , were measured at 3 kHz using a Wayne-Kerr B224 bridge. The level of the ac signal was kept below 5 millivolts. For over 3 decades G_{LF} is nearly a straight line having a reciprocal slope of about 1.05 at 299°K and about 1.01 at 376°K . To determine G_{QN} , the component of the conductance from the quasi-neutral regions, which has unity reciprocal slope, we used the construction technique [12,13] referred to earlier, and found that $G_{QN} = G_{QNB} + G_{QNE} = 250 \mu\text{mho}$ at $V = 0.45\text{V}$ and $T = 299^\circ\text{K}$. For $V \leq 0.3$ Volts, and $T = 299^\circ\text{K}$ and $V \leq 0.1$ Volts and $T = 376^\circ\text{K}$ the measured capacitance shows only a slight dependence on V , implying that, in this range of voltage, C_I and (to a lesser degree) C_{SC} dominate in determining C . At higher values of V , C_{QN} becomes important, and the reciprocal slope gets as small

Fig. 2 See caption on following page

Fig. 2 Measured conductance and capacitance vs. forward-bias V for diode #1-2 ($N_{DD} = 1.25 \times 10^{15} \text{ cm}^{-3}$).

(a) $T = 376^\circ\text{K}$;

(b) $T = 299^\circ\text{K}$.

The insert shows the capacitance characteristic for diode #1-4 ($N_{DD} = 8 \times 10^{16} \text{ cm}^{-3}$), demonstrating the increased importance of C_{SC} and emphasizing the value of the subtraction called for in Eq. (5) for determining C_{QNB} . In the figure, --- stands for the components from the quasi-neutral regions ($m=1$) and -.-.- stands for $G_{SC} + G_S$.

Table I Device make-up (N_{DD} , N_S , and x_j) and the diffusion length at 299°K determined by three methods: L_{pC} by capacitance measurements, L_{pG} by conductance measurements, and L_{pX} by X-ray measurements.

Device No.	Base doping $N_{DD}(\text{cm}^{-3})$	Emitter surface concentration $N_S(\text{cm}^{-3})$	Junction depth $x_j(\mu\text{m})$	$L_{pC}(\mu\text{m})$	$L_{pX}(\mu\text{m})$	$L_{pG}(\mu\text{m})$
1-1	1.4×10^{14}	4×10^{19}	0.59	97	96	97
1-2	1.25×10^{15}	4×10^{19}	0.52	80	84	80
1-3	1.15×10^{16}	4×10^{19}	0.46	34	35	34
1-4	8×10^{16}	4×10^{19}	0.40	28	31	15
1-5	6.5×10^{17}	4×10^{19}	0.32	15	15	1.3
2-3	1.15×10^{16}	1.5×10^{19}	0.8	25	27	31
3-2	9.5×10^{14}	2.5×10^{19}	0.9	21	24	26

as about 1.1. To determine C_{QN} , we proceeded as described in the preceding section of this paper. Using a Wayne-Kerr B801B bridge, we measured the capacitance C_{HF} at a higher frequency, 10 MHz for the diode studied in Fig. 1, and obtained C_{QN} from

$$\begin{aligned} C_{QN} &= C_{LF} - C_{HF} \\ &= C_{QNB} \quad \text{if } \tau_E \ll \tau_p \\ &= C_{QNE} + C_{QNB} \quad \text{if } \tau_E \sim \tau_p \end{aligned} \quad (5)$$

For the diode in question, $C_{QN} = 550$ pf at 0.45 Volts and $T = 299^\circ\text{K}$. In Fig. 1 note that the subtraction indicated in (5) yields for $\ln(C_{QN})$ versus qV/kT a straight line having unity reciprocal slope. This result provides a consistency check on the validity of the method. Another consistency check, discussed below, can also be made using the value of the base lifetime τ_p inferred from C_{QN} .

To calculate the diffusion length L_p of the base region, we assume that the minority carrier charge storage in the base greatly exceeds that in the emitter, and, hence, that $C_{QNE} \ll C_{QNB}$. For the particular diode under study, these assumptions are likely to hold for three reasons:

(a) the low surface concentration N_s tends to limit the size of the energy-gap shrinkage effects [12,15,16] in the emitter; (b) the low doping concentration N_{DD} of the base implies a large minority carrier charge storage in the base so that the base recombination current dominates over the emitter recombination current despite the energy-gap shrinkage in the emitter; (c) the thinness of the emitter region tends to limit the amount of minority-carrier charge it can store.

The subtraction called for in (5) yields $C_{QN} \approx C_{QNB} = 550\text{pF}$ at 0.45 Volts and 299°K . Then, from (1), the minority carrier diffusion

length of the base obtained from the capacitance method is $L_{pC} = 80\mu\text{m}$. To assess the accuracy of this result, we also determined the diffusion length by the X-ray method described by Rosenzweig [1], which is accurate within about $\pm 5\%$ [1], and found $L_{pX} = 84\mu\text{m}$. The standard devices used for the X-ray measurements were calibrated by a method using electron-beam excitation [1,2]: The good agreement between L_{pC} and L_{pX} tends to confirm the utility and accuracy of the capacitance method.

Having obtained L_{pC} , we can now make a second self-consistency check. In our development of the capacitance method, we have assumed that the minority carriers of the base region would respond to the low-frequency signal of 3 kHz (whose period is 333 μsec) but would be unable to follow the signal of frequency 10 MHz (whose period is 0.1 μsec). The diffusion length $L_{pC} = 80\mu\text{m}$ deduced by the capacitance method corresponds to a base lifetime τ_p of about 5 μsec , which is consistent with these assumptions.

For some devices, the emitter recombination current will be much less than the base recombination current, so that $G_{QNE} \ll G_{QNB}$ and L_p can be deduced from (2) using only the low-frequency conductance data. This is true for the diode #1-2 under consideration. If one assumes $G_{QNE} \ll G_{QNB}$ and substitutes $G_{QNB} = G_{QN} = 250\mu\text{mho}$ (0.45V, 299°K) into (2), one obtains $L_{pC} = 80\mu\text{m}$, which agrees well with the values obtained by the capacitance and X-ray methods.

But the conductance method fails whenever the emitter recombination current contributes significantly to the current-voltage characteristic, as can be expected to occur in diodes having higher base doping concentrations and consequently lower minority-carrier charge storage in the base. This point is illustrated in Fig. 3. For diodes having base doping concentrations above 10^{16} cm^{-3} , L_{pG} differs from L_{pC} and L_{pX} by a factor of two or more. The capacitance and the X-ray methods

Fig. 3 Diffusion length L determined by capacitance, conductance, and X-ray methods versus base doping concentration N_{DD}^P .

give results in excellent agreement for all base doping concentrations, however, which illustrates the accuracy and applicability of the capacitance method. The diffusion lengths L_{pC} , L_{pG} and L_{pX} for the seven diodes measured are listed in Table I.

Equations (1) and (2) for L_n are based on a one-dimensional model of a diode. In such a model, the minority carriers diffuse only in the direction normal to the semiconductor surface. But in a real diode, they diffuse transversely as well. The resulting fringing effects, described recently by Grimbergen [17], must be included in interpreting the capacitance, conductance, and X-ray-current data. The fringing effects are slight in the devices studied here, but we have accounted for them [18].

Comparison with the Open-Circuit-Voltage-Decay-Method: Determination of the base lifetime τ_p by the open-circuit-voltage-decay (OCVD) method [4] is a commonly used approach. The OCVD method is attractive because it involves the measurement of only a single transient, which can be rapidly done.

To examine the applicability of OCVD to silicon devices, we consider first its theoretical basis. In the theoretical development of the OCVD response, one finds the open-circuit response of a diode following the sudden removal of forward bias by solving the continuity equation for the minority carriers in the base. Under low-injection conditions, the open-circuit voltage decays linearly with time, to a close approximation, and measurement of the slope of this straight-line decay suffices to determine τ_p . This result applies if the minority carriers in the base dominate in determining the response, as was the case for the germanium diodes considered in the original OCVD study [4]. But if the carriers

associated with the junction space-charge region or with the quasi-neutral emitter contribute appreciably to the response, then the OCVD method is applicable.

The junction space-charge region contributes to the measured capacitance and conductance characteristics of Fig. 2, as evidenced by the non-unity slopes of these characteristics, particularly of the capacitance characteristic. At 299°K, the slopes come nearest to unity in the voltage range, 0.45 Volts $\leq V \leq$ 0.52 Volts. For this range the minority hole concentration in the base is in low injection. Figure 4 displays the corresponding OCVD response, taken at 299°K and beginning at $V \approx 0.5$ Volts. Note that this response fails to exhibit a simple linear decay. Thus, as one could anticipate from the nonideality of conductance and capacitance characteristics, the OCVD method for determining τ_p is inapplicable for this diode at 299°K. A coarse estimate of τ_p can be inferred from the OCVD response, however, by fitting a straight line to the response and measuring its slope. This yields τ_p (OCVD) ≈ 8 sec, which differs by nearly a factor of two from the value, $\tau_p \approx 4.4 \mu\text{sec}$, corresponding to $L_{pC} = 80 \mu\text{m}$ determined by the capacitance method and corroborated by the X-ray method and by the calculation [6], $\tau_p = 2 C_{QN}/G_{QN}$. For comparison, the straight-line decay corresponding to $\tau_p \approx 4.4 \mu\text{sec}$ is plotted on Fig. 4.

According to theory, the quasi-neutral capacitance and conductance increase more rapidly with temperature than do the components from the junction space-charge region. Thus one might expect the capacitance and conductance characteristics to have slopes that more closely approach unity as the temperature is raised. This is confirmed by the data of Fig. 2 measured at 376°K, where the closest approach to unity slope occurs in the voltage range, 0.25 Volts $< V <$ 0.32 Volts. In this range, which corresponds to low-injection levels of the minority holes in the base,

the conductance almost shows an ideal slope of unity, and the capacitance shows a reciprocal slope of 1.07. As Fig. 4 indicates, however, even these slight departures from the ideal characteristics are enough to produce an OCVD response that again fails to exhibit a simple linear decay. The fitting of a straight line to the OCVD response at 376°K results in the estimate, τ_p (OCVD) $\approx$ 9 μ sec, which differs considerably from the value, $\tau_p = 7$ μ sec, corresponding to $L_{pC} = 80 \mu\text{m}$ at 376°K determined by the capacitance method and corroborated by the calculation [6], $\tau_p = 2 C_{QN}/G_{QN}$.

Figures 2 and 4 plot the data for a single device: #1-2 of Table I. Similar deviations from the ideal capacitance and conductance characteristics and the ideal (linear) OCVD response were seen for all of the silicon diodes of Table I. This suggests that the OCVD method for determining τ_p is questionable for silicon devices, although one might expect its accuracy to increase as temperature is raised. The capacitance method avoids the inaccuracies resulting from the nonideality of the characteristics by combining low-frequency and high-frequency data in accordance with (5).

Discussion

The capacitance method for determining L_p and τ_p involves measuring the dependence of the capacitance on forward bias at two frequencies: a frequency f_L low enough that $1/f_L \gg \tau_p$, and a frequency f_H high enough that $1/f_H \ll \tau_p$. Because τ_p is unknown at the outset, an order of magnitude estimate of τ_p is needed. The validity of this estimate can be checked experimentally. If it is valid, small changes in frequency about f_L and f_H will produce no changes in the capacitance measured. Once the low-frequency and higher-frequency capacitances are measured,

Fig. 4 OCVD response for diode #1-2 at 299°K and 376°K. Dashed lines correspond to the lifetime τ_p determined by the capacitance method.

they are subtracted as indicated in (5) to give the quasi-neutral capacitance C_{QN} . The resulting dependence of $\ln(C_{QN})$ on qV/kT must be a straight line of slope unity, which provides a convenient self-consistency check on the validity of the results. For diodes for which $C_{QNE} \ll C_{QNB}$, which often occurs, the quasi-neutral base capacitance C_{QNB} is thus determined. Combining C_{QNB} with (1) then determines L_p and τ_p .

The inequality, $C_{QNE} \ll C_{QNB}$, holds for the diodes of Table I because the surface doping concentration is low ($N_S \sim 10^{19} \text{ cm}^{-3}$) and the emitter junction is thin ($x_j \sim 1 \mu\text{m}$). These conditions make the total number of dopant atoms in the emitter small. That $C_{QNE} \ll C_{QNB}$ for these devices is substantiated by the demonstration that $L_{pC} = L_{pX}$. But if a given device has a large number of dopant atoms in the emitter, then C_{QNE} can be large because of band-narrowing effects [12,15,16]. If, in addition, the device has a large doping concentration in the base, which from (1) implies a small value of C_{QNB} , then $C_{QNE} \approx C_{QNB}$. For such a device, the diffusion length of the base can be determined by the X-ray method and the method described in this paper can be adapted to enable the determination of the minority-carrier charge Q_E stored in the emitter and the phenomenological lifetime τ_E of the emitter. From the values of Q_E and τ_E thus determined one can deduce information about the band-narrowing and recombination mechanisms in the highly doped emitter [12]. The details of such studies for p-n junction solar cells, diodes and bipolar transistors will be published elsewhere [19].

There are several practical limitations that define the scope of applicability of the capacitance method. First, the value of f_H required by the device under study must fall within the capabilities of the

capacitance bridges available. This tends to limit the maximum area of the device being measured, but does not impose a fundamental limitation on the applicability of the capacitance method. Bridges having upper frequency limits of 100 MHz and an accuracy of about 2% are available for the required measurements provided small-area test structures are used. For example, the Wayne-Kerr B801 B bridge can measure capacitances smaller than 250 pF, and the Boonton 33A-1, which has the advantage of an internal bias supply, can be used for measuring capacitances smaller than 30 pF above 50 MHz and larger capacitance values below 50 MHz. For large-area devices, for example, 2 cm x 2 cm solar cells, such bridges as the Wayne-Kerr B601 and B602 can be used. These bridges have upper frequency limits of 5 and 10 MHz, respectively, and an accuracy of about 1%. These bridges are suitable unless the base lifetime is smaller than about 1 μ sec, which would require that f_H exceeds 10 MHz.

As a second limitation of the method, we note that the neutral base capacitance must contribute appreciably to the total capacitance being measured. Thus, the method may not apply to devices having very small diffusion lengths, although L_p as small as about 15 μ m was determined for some of the devices listed in Table I.

Third, the method determines L_p for low injection only. Adapting the method to enable the determination of L_p for high injection may be difficult because the capacitance peaks and then decreases following the onset of high injection [9,20].

Finally (1) and (2) and hence the method in the form presented here, apply only if the thickness of the base region W_B greatly exceeds L_p so that the surface recombination velocity S of the back face will not affect C_{QNB} . But, the method can be extended in a straightforward

way by use of conventional diode theory [3,6,21] to make it applicable to devices for which $L_p \ll W_B$, provided the value of S can be estimated. If a back-surface field (high-low junction) is present, S can be estimated [22]; in the absence of a back-surface field, the estimate $S = \infty$ can be used.

These limitations are not severe and the capacitance method applies to a wide range of silicon devices, as the results given in Section III demonstrates. The capacitance method has the advantage of being accurate and of requiring only straightforward electrical measurements at the terminal using inexpensive equipment. It also enables the easy determination of the dependence of diffusion length and lifetime on temperature.

The accuracy of low-frequency capacitance bridges, such as Wayne-Kerr B224, is about $\pm 0.1\%$ and the accuracy of available high-frequency bridges is about $\pm 2\%$. If the temperature during measurement is controlled within $\pm 0.1^\circ\text{K}$, which will introduce an error in n_i^2 less than 2%, the overall accuracy of the method is estimated to be about $\pm 5\%$.

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3. VARIOUS OTHER METHODS (references cited appear in Sec. 1)

The study of the basic mechanisms in the highly-doped emitter, which is outlined in Section II-B-1, requires careful scrutiny of the adequacy of various techniques for determining both the static and dynamic characteristics of solar-cell test structures, and it requires also careful design of the structures themselves [13,14,24]. The analysis of the experimental data must be based on the physics underlying the operation of the cell, and each parameter must be determined as accurately as possible. We have developed various computer programs that aid the determination of such parameters as the base doping concentration, the dark saturation current, and the defect energy levels and their fundamental kinetic parameters. To assure a proper interpretation of the data, the series resistance must be determined accurately; and we have developed a new method for determining series resistance based on measuring admittance versus frequency and forward bias [23]. The new method offers advantages over earlier methods [23].

C. Improvements of Silicon Solar Cell Design [19-22 of Sec. I]

OVERVIEW (references refer to those listed in Sec. I)

As was stated earlier, one of the objectives of our research is improving solar-cell design and innovating new solar-cell structures based on the understanding gained of the basic mechanisms governing cell performance. During the period of contract support, after first developing a detailed understanding of the relevant device physics, we evolved three different silicon solar cell structures that are designed to yield substantial improvements for one-sun and for concentrated-sunlight applications. These designs are projected to yield conversion efficiencies of about 20%

for illumination levels in the 25-100 sun range. These projected efficiencies are based on pertinent device physics, exact numerical solutions of the basic Shockley differential equations, and experimental results.

Of the three proposed cell designs, the selection of the most practical one will follow from cost and technology considerations. None of the designs involve significant departures from the conventional silicon solar cell structure. This fact, in conjunction with the alternatives provided by three different cell designs, encourages an optimistic outlook for the achievement soon of silicon solar cells having 20% efficiencies in concentrated sunlight. Careful refinement of the design of one of the structures may yield 20% efficiency at AM1.

The projected figure of 20% for 25-100 suns should not be construed as the maximum efficiency achievable in silicon. Rather, it is the predicted efficiency of three cell designs that appear to be technologically achievable now. These designs evolved from our work on the basic mechanisms governing cell operation. One of the structures [20,22], which is new, evolved from our work on the basic mechanisms [1-5,8-11,13-15,17,18] occurring in the highly-doped emitter region of p-n junction silicon solar cells. The other two designs [20,21] evolved from our studies of the basic mechanisms [6,12,16] occurring in the base region.

The evolution of the three designs proceeded as indicated in Flow Chart 1. We considered first the elementary p^+-n and n^+-p junction structures. For concentrated-sunlight applications, the p^+-n structure is the better of the two because the Debye voltage induced in the base region adds to the voltage across the junction space-charge region rather

FLOW CHART 1: ILLUSTRATING THE EVOLUTION OF THREE DEVICE STRUCTURES PROPOSED TO YIELD EFFICIENCIES GREATER THAN 20% FOR LEVELS OF ILLUMINATION IN THE RANGE OF 25 TO 100 SUNS.

than subtracting from it [12]. But both structures suffer the degrading effects of Ohmic drops in the base region, which reduce the fill factor (FF), thereby limiting the achievable efficiency to about 16% in the 25 to 100 sun range of illumination.

To overcome these degrading effects, one can follow two different approaches, as illustrated in Flow Chart 1. In the first of these approaches, one adds a high-low (H-L) junction in the base region, forming the so-called back-surface-field (BSF) cell. This structure, in either p^+-n-n^+ or an n^+-p-p^+ form, increases FF by increasing the conductivity modulation of the base. BSF cells were introduced about five years ago, but the design of these cells was suboptimal because no theory existed that adequately described the device physics of the structure, particularly in concentrated sunlight. We have developed the basic elements of such a theory [21 and unpublished]. This theory projects that efficiencies of about 20% are probable for either the n^+-p-p^+ or p^+-n-n^+ structures, in the 25 to 100 sun range of illumination. This figure is higher than was thought possible previously, and, indeed, is higher than the efficiency cited as the ERDA (DOE) goal for 1986. The main technological requirement for achieving 20% efficiency is that the base diffusion length must exceed the base thickness by at least a factor of three. Examples exist to indicate that this requirement can be met for both the p^+-n-n^+ and n^+-p-p^+ structures though its satisfaction may prove to be easier for one of these structures than for the other. These technological considerations and the availability of alternatives become especially important for cells that are to be produced on a manufacturing line, which is the ultimate objective in the national solar photovoltaic program.

As was noted, the projected efficiencies of 20% for 25-100 suns substantially exceed the D.O.E. goals of 1986. But we caution again that 20% should not be construed to be our projection of the maximum efficiency obtainable from silicon. Although our new design theory for the BSF cell structure advances understanding, it nonetheless yields suboptimal designs because of the uncertainties in present knowledge about the basic physics governing the transport and recombination of holes and electrons in the heavily doped layers that constitute the emitter region and the H layer of the H-L junction of the back surface field. The studies described earlier in Section II-B-1 seek to remove these uncertainties and enable the development of a design theory that can yield optimum BSF cells for a given temperature and level of illumination.

In the second of the approaches indicated in Flow Chart 1, one increases the conductivity of the base region and thereby improves the fill factor FF simply by increasing the doping concentration N_{BB} of the base region. In an n^+p cell, for example, the efficiency of the cell increases with increasing N_{BB} until N_{BB} reaches about 10^{17} cm^{-3} ; for N_{BB} much greater than 10^{17} cm^{-3} , the diffusion length in the base region, the short-circuit current, and the efficiency all decrease. Our analytic theoretical development, supported by exact numerical solutions of the device-physics differential equations and by pertinent experiments, shows that the efficiency of this n^+p structure reaches a maximum value of about 17% for 25 to 100 suns. Our studies have demonstrated why this limiting value of efficiency is reached. The value of FF no longer limits the efficiency obtainable because the high value of N_{BB} greatly diminishes the contribution of the base to the series resistance, even though the base stays in the low-injection condition for levels of illumination as high as

100 suns. The short-circuit current does not degrade the efficiency severely provided N_{BB} is not much greater than 10^{17} cm^{-3} . Rather, the culprit is the open-circuit voltage V_{OC} , which the heavy doping mechanisms in the emitter region degrade by producing a dark emitter recombination current so large that it dominates in determining the value of the open-circuit voltage. This conclusion stems from our theoretical studies based on exact numerical solutions of the relevant differential equations and also from direct experimental evidence obtained in the research of the Florida program (the experimental procedure used to obtain this evidence is detailed in ref. [14] of Sec. I).

As the next attempt toward improving the solar cell efficiency, therefore, we consider reducing the dark emitter recombination current by reducing the doping concentration in the thin emitter to the order of $10^{19} \text{ (cm}^{-3}\text{)}$, thereby decreasing the magnitude of the degrading basic mechanisms (band narrowing and lower lifetime) that accompany heavy doping concentrations. Our preliminary experiments at Florida (unpublished) show that this can be done: that reducing the emitter doping concentration can decrease by more than an order of magnitude the dark emitter recombination current and thus can lead to considerably larger values of the open-circuit voltage than were obtained previously. But the consequent values of the emitter sheet conductance results in values of series resistance so high as to produce intolerably small values of the fill factor.

To overcome this problem, we have proposed a new device structure (due to the researchers in the University of Florida program, C.T. Sah and J.G. Fossum in collaboration). In this structure, the low value of the emitter doping concentration is retained to reduce the emitter dark saturation current well below that in a conventional

n^+ -p structure; but a region (the n region in a n^+ -n-p structure) of low doping concentration (for example, $5 \times 10^{16} \text{ cm}^{-3}$) is added which is thick enough to have a low enough sheet conductivity to retain a large value of the fill factor. This device structure we have called the H-L Emitter Solar Cell [20,22,25] because a high-low junction exists in the emitter region.

(See Flow Chart 1.) The basic H-L emitter structure has many variations, a number of which we have already made at Florida and Sandia. For example, the H-L junction can be formed by diffusion into an epitaxial p-n junction, by double diffusions into a p (or n) substrate and by ion implantation into an epitaxial p-n junction through a thin oxide. Additional variations on the basic structure evolve from including or excluding a back-surface-field (and varying the base resistivity appropriately). Some of these variations of the H-L structure are illustrated in Fig. 1. Within any single type of the H-L structure indicated in Fig. 1, there are many variations resulting from the details of the fabrication procedures used to form the junction, to getter defect centers, to improve the surface recombination velocity, etc. Measurements just made on some of the resulting devices (which we emphasize are far from being optimized to yield best possible performance) indicate a 7% increase in open-circuit voltage over the conventional counterparts and a 15% increase in short-circuit current). We project on theoretical grounds considerably better performance than this, leading to an efficiency of about 20% for levels of illumination between 25 to 100 suns and about 18% for AM1.

Our early experimental results encourage optimism about the usefulness to the national solar photovoltaic program of this new structure (the H-L emitter structure). But we emphasize that experimental studies involving many variations in the details of the fabrication procedures

Fig 1: Illustrating variations of the H-L emitter solar cell structure proposed in the Florida (Sandia) research program. Additional variations under consideration result from designing a grid of metal at the back as well as at the front face to reduce the recombination current associated with the back-surface field and, perhaps, to allow light to be usefully incident on both faces. Various other structures associated with the details of forming the H-L junction in the emitter are also under study but are not shown.

must continue to determine whether the projected efficiencies can be achieved (or exceeded). Refinements of the theory underlying the projections and the device design also are needed.