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DEPLETION LAYER EFFECTS IN THE OPEN-CIRCUIT-VOLTAGE-DECAY LIFETIME MEASUREMENT

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Abstract—There is a renewal of interest in open circuit voltage decay as a technique for determining the base region minority carrier lifetime in semiconductor diodes. Although the existing theory of open circuit voltage decay provides a substantial foundation for interpreting the experimental data, major features of the decay curves of real silicon diodes cannot be satisfactorily explained unless depletion layer effects are taken into account. Theoretical decay curves are calculated to show the effects of depletion layer capacitance and recombination current on the otherwise ideal open circuit voltage decay. From these and from experimental decay curves, it is shown that each of these depletion layer effects is significant only below a threshold junction voltage that depends upon material parameters of the device.

NOTATION

- a p^+ layer width
- C depletion layer capacitance per unit area
- C_{diff} diffusion capacitance per unit area
- D_p minority carrier diffusivity
- g excess minority carrier generation rate
- J net current density
- J_{gen} depletion layer generation current density
- J_L light-generated current density
- J_{rec} depletion layer recombination current density
- k Boltzmann's constant
- L_p minority carrier diffusion length
- n_i intrinsic carrier density
- n_n base region majority carrier density
- n_p emitter region minority carrier density
- n_{p0} thermal equilibrium emitter region minority carrier density
- N total number of photons per unit area
- N_D base region doping density
- p_n base region minority carrier density
- p_{n0} thermal equilibrium base region minority carrier density
- q magnitude of the electronic charge
- Q_n excess base region minority carrier charge per unit area
- Q_{n0} base reference charge per unit area
- t time
- T temperature
- V junction voltage (positive for p^+n-junction forward biased)
- V_0 diffusion potential (positive for p^+n-junction)
- $w(x)$ $\exp(x)\,\mathrm{erfc}(\sqrt{x})$
- W depletion layer width
- x distance
- α optical absorption constant
- δ delta function
- ϵ semiconductor permittivity
- Δp_n excess base region minority carrier density
- τ_{eff} effective decay time
- τ_n emitter region minority carrier lifetime
- τ_p base region minority carrier lifetime
- τ_0 depletion layer minority carrier lifetime
- ϕ photon flux density
- ϕ_0 constant photon flux density

1. INTRODUCTION

The purpose of the open circuit voltage decay measurement is to determine the average recombination time of excess minority charge carriers (the minority carrier lifetime) within the quasi-neutral base region of a semiconductor diode. The method as first proposed in 1955[1] was based on the decay of the open circuit voltage following rapid termination of a forward current pulse. Mahan *et al.*[2] have shown that the current pulse can be conveniently replaced with an abruptly terminated light source. In both cases, the minority carrier lifetime is determined from the observed voltage decay waveform that follows termination of the excitation.

There has recently been a renewal of interest in such transient measurements of minority carrier lifetime as applied to photovoltaic devices[2–6]. However, previous analyses do not account for the full range of behavior observed for either the photo- or the forward current-induced open circuit voltage decay. The purpose of this paper is to show the effects of phenomena associated with the base region depletion layer (charge storage and depletion layer recombination) that have not been included in previous calculations of the decay behavior, but must be considered to complete the theoretical analysis.

2. PREVIOUS THEORETICAL INVESTIGATIONS

The first published analysis of an open circuit voltage decay lifetime measurement in a pn-junction was based on a lumped parameter model[1]. The hole density at the junction in the n-type (base) region of a p^+n diode was assumed to be

$$p_n(t) = p_{n0} \exp[qV(t)/kT], \tag{1}$$

where p_{n0} is the hole density under thermal equilibrium conditions, $V(t)$ is the instantaneous junction voltage, and the other symbols have their usual meanings. It was also assumed that the excess minority carrier concentration decays exponentially (independent of position) following termination of excitation:

$$p_n(t) = \Delta p_n(0) \exp(-t/\tau_p) + p_{n0}. \tag{2}$$

The open circuit voltage then decays according to the following expression:

$$V(t) = (kT/q) \ln\{1 + [\exp(qV(0)/kT) - 1] \exp(-t/\tau_p)\} \tag{3a}$$

which reduces to the familiar linear decay for $V(t) \gg kT/q$:

$$V(t) \approx V(0) - kTt/q\tau_p. \quad (3b)$$

It was then suggested that with this equation the minority carrier lifetime may be found from the slope of the measured decay curve.

Open circuit voltage decay in real semiconductor diodes is a much more complex process than the above analysis suggests. Indeed, in the previous reference it was recognized that minority carriers on both sides of the junction must be considered and that their decay behavior is more accurately represented by the solution of the one-dimensional continuity equation with appropriate boundary conditions. The *coupling* of the excess minority carrier densities on either side of the junction means that p_n and n_p (the minority carrier density in the p^+ layer) cannot return to their equilibrium values independently, but are in fact related in the following way[7]:

$$p_n(t)/p_{n0} = n_p(t)/n_{p0} = \exp[qV(t)/kT]. \quad (4)$$

The open circuit voltage decays, according to the lumped model with coupling considered, with an *effective* decay time[8]:

$$V(t) \approx V(0) - kTt/q\tau_{eff}, \quad (5)$$

where

$$\tau_{eff} = (n_p + p_n)/[(n_p/\tau_n) + (p_n/\tau_p)]. \quad (6)$$

Carrier diffusion is included in the analysis (returning to the case of the one-sided p^+n junction) by considering the one-dimensional continuity equation, which is

$$\partial p_n(x,t)/\partial t = D_p \partial^2 p_n(x,t)/\partial x^2 - [p_n(x,t) - p_{n0}]/\tau_p + g(x,t) \quad (7)$$

where D_p is the hole diffusivity and $g(x, t)$ is the excess hole generation rate. Solutions of the continuity equation have been found and the resulting open circuit voltage decay characteristics obtained for several modes of excitation with the following boundary conditions assumed:

$$\partial p_n(x,t)/\partial x \Big|_{x=0} = 0 \quad (8a)$$

$$\lim_{x\to\infty} p_n(x,t) = p_{n0}. \quad (8b)$$

The first boundary condition implies that the diode is open-circuited during the decay, and the second, that the n-region width is much greater than the minority carrier diffusion length.

In each case considered the junction voltage and the minority carrier density at the edge of the depletion layers were assumed to be functionally related as follows:

$$p_n(x,t)\Big|_{x=0} = p_{n0}\{\exp[qV(t)/kT]\}. \quad (9)$$

In their original paper, Lederhandler and Giacoletto gave solutions to eqn (7) by North[1] for decay following instantaneous termination of a forward current. The initial minority carrier distribution was assumed to be that of the steady-state forward bias condition:

$$p_n(x,t)\Big|_{t=0} = p_{n0}\{1 + [\exp(qV(0)/kT) - 1]\exp(-x/L_p)\}. \quad (10)$$

The open circuit voltage decays according to the following expression:

$$V(t) = (kT/q)\ln\{1 + [\exp(qV(0)/kT) - 1](1 - \operatorname{erf}\sqrt{t/\tau_p})\}, \quad (11a)$$

which reduces to

$$V(t) \approx V(0) + (kT/q)\ln[\operatorname{erfc}\sqrt{t/\tau_p}] \quad (11b)$$

for $V(t) \gg kT/q$. There is a rapid initial drop in the open circuit voltage, but for t greater than a few τ_p, the decay is approximately linear with time. If the average decay rate during the latter part were used to calculate the lifetime according to eqn (3b), an error of at most a few per cent would occur.

Dhariwal and Vasu[9] have analyzed the decay behavior of a p^+n diode following excitation by a monochromatic light pulse. The continuity equation was solved assuming the boundary conditions given by eqns (8a, b) and a generation rate of the form

$$g(x,t) = \phi(t)\alpha\exp[-\alpha(x+a)]. \quad (12)$$

α is the optical absorption constant, a is the thickness of the p^+ layer plus the n-type base region depletion layer width, and $\phi(t)$ is the time-dependent photon flux density entering the device. The limiting case of $\phi(t) = N\delta(t)$ was solved, where $\delta(t)$ is a delta-function at $t = 0$ and N is the total number of photons per unit area contained in the pulse. This results in an initial minority carrier distribution within the base region given by

$$p_n(x,t)\Big|_{t=0} = N\alpha\exp[-\alpha(x+a)]. \quad (13)$$

The result was that the excess minority carrier density at the junction boundary exhibits an exponential decay that is modulated by an additional time-dependent function. The open circuit voltage decays as follows:

$$V(t) = (kT/q)\ln\{1 + [\exp(qV(0)/kT) - 1] \times w(\alpha^2 L_p^2 t/\tau_p)\exp(-t/\tau_p)\}, \quad (14a)$$

where

$$w(x) = \exp(x)\,\mathrm{erfc}(\sqrt{x}) \tag{14b}$$

and L_p is the minority carrier diffusion length. For $V(t) \gg kT/q$,

$$V(t) \approx V(0) - (kTt/q\tau_p) + kT/q \ln[w(\alpha^2 L_p{}^2 t/\tau_p)]. \tag{15}$$

The decay behavior is basically that of eqn (3b), with an additional term depending on the ratio $\alpha^2 L_p{}^2 t/\tau_p$. The additional term is a relatively slowly varying function of time for $\alpha^2 L_p{}^2 t$ greater than a few τ_p. The spectral output of broadband pulsed light sources such as commercial stroboscopes is such that this condition can be readily attained with many silicon diodes. (If the light pulse contains photons of different wavelengths, the last term in eqn (15) is replaced by a sum of terms corresponding to each wavelength contained in the pulse and weighted according to the spectral content of the pulse.) In many real cases, the minority carrier lifetime may be determined from the observed decay behavior assuming eqn (3b) holds.

Jain[6] has recently considered a related case where the photo-voltage decay is from steady state such that

$$\phi(t) = \begin{cases} \phi_0 & t < 0 \\ 0 & t \geq 0 \end{cases}. \tag{16}$$

The initial minority carrier distribution for this case is

$$p_n(x,t)\Big|_{t=0} = \alpha\phi_0\tau_p \exp(-\alpha a)[\alpha^2 L_p{}^2 - 1]^{-1} \times \{\alpha L_p \exp(-x/L_p) - \exp(-\alpha x)\} + p_{no}. \tag{17}$$

Assuming the spatial boundary conditions given by eqns (8a, b), the open circuit voltage decays according to

$$V(t) = (kT/q) \ln\{1 + [\exp(qV(0)/kT) - 1][\alpha L_p - 1]^{-1} \times [\alpha L_p w(t/\tau_p) - w(\alpha^2 L_p{}^2 t/\tau_p)] \exp(-t/\tau_p)\}. \tag{18}$$

For $V(t) \gg kT/q$,

$$V(t) \approx V(0) - kTt/q\tau_p + (kT/q) \times \ln\{[\alpha L_p w(t/\tau_p) - w(\alpha^2 L_p{}^2 t/\tau_p)]/[\alpha L_p - 1]\}. \tag{19}$$

The decay behavior approaches that of the forward current-induced open circuit voltage decay (eqn 11b) for $\alpha L_p \gg 1$ and that of the previously considered photo-induced decay following a delta-pulse (eqn 15) for $\alpha L_p \ll 1$. Jain[6] points out that for long times (t greater than a few τ_p) the decay is linear with time and therefore the slope of the linear part of the decay curve can be used with eqn (3b) to estimate the minority carrier lifetime, in many cases with an accuracy of a few percent.

All four models depend on a quasistatic approximation[8, 10], which is that the junction voltage and the minority carrier density at the edge of the depletion layer are functionally related under transient conditions as they are in steady state:

$$V(t) = (kT/q) \ln[p_n(0,t)/p_{no}]. \tag{20}$$

The above relation holds only under low-injection conditions, defined by $p_n(0,t) \ll n_n$, where n_n is the free electron concentration in the n-type region. Numerical solutions[11] indicate that when $p_n(0,t)$ exceeds the base doping level then

$$V(t) \approx (2kT/q) \ln[p_n(0,t)/n_i] \tag{21}$$

where n_i is the intrinsic carrier density. Assuming a constant lifetime, the open circuit voltage decay rate according to the lumped parameter model is $-2kT/q\tau_p$, twice the rate under the low injection conditions. The high injection lifetime may be different, however, due to a significant change in the occupancy of recombination centers or the increased probability of bimolecular recombination.

To summarize this review of open circuit voltage decay theory, theoretical models have been developed based on a lumped parameter analysis and for three additional cases where the one-dimensional continuity equation was solved to include the effects of the initial minority carrier distribution and subsequent redistribution by diffusion. The three additional cases were for decay from steady state following instantaneous termination of a forward current, decay following a monochromatic light pulse described by a delta function at $t = 0$, and decay from steady state following instantaneous termination of monochromatic photoexcitation. We have given the solutions for one-sided p^+n-junctions where the quasi-neutral base region is much wider than the minority carrier diffusion length and for which carrier trapping is insignificant. In all these cases, the open circuit voltage decays linearly with time for times greater than a few τ_p, as predicted by the original lumped-parameter analysis of Lederhandler and Giacoletto[1]. This important result suggests that such lumped-parameter models are useful for providing a semi-quantitative and perhaps more transparent model of the decay behavior.

3. DEPLETION LAYER EFFECTS

The material in the previous section provides a substantial theoretical foundation for interpreting the open circuit voltage decay curves of silicon diodes, for which the minority carrier lifetime can be much longer than the turn-off time of the excitation source and for which trapping does not complicate the recombination kinetics. However, there are some aspects of the decay behavior of certain silicon devices that cannot adequately be explained by the previous models.

Some experimental open circuit voltage decay curves that we have obtained over the course of several years' investigation of the technique are shown in Fig. 1. These are representative of types of decay behavior that we have frequently observed. Figure 1(a) is a room temperature photovoltage decay curve for an EG & G silicon

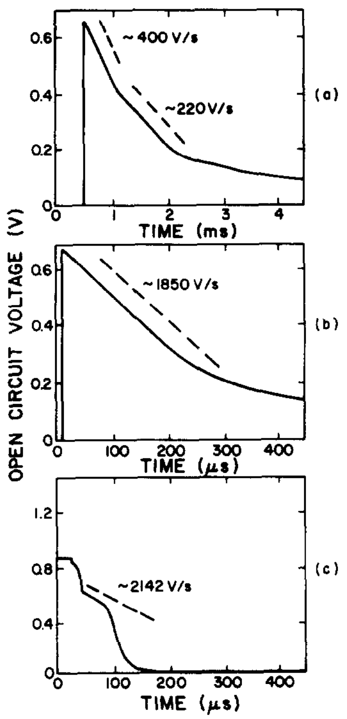

Fig. 1. Experimental open circuit voltage decay: (a) photovoltage decay curve for a commercial silicon photodiode; (b) photovoltage decay curve for a diffused silicon p^+n-junction; (c) forward current-induced open circuit voltage decay curve for a commercial silicon solar cell.

photodiode (model UV-100B) using a General Radio model 1542-B stroboscope as the light source. This device exhibits the high- and low-injection behavior discussed previously. From the high- and low-injection decay rates as indicated on the figure, our estimates of the base region minority carrier lifetime are 125 and 114 μs, respectively, which are close enough to be considered reasonably consistent with each other and are also consistent with the device's excellent long-wavelength photoresponse. This device provides a near-ideal example of the decay behavior as given in the previous section, although the slow tail on the decay below ~0.2V is not predicted. A slow tail on the decay curve is more pronounced in Fig. 1(b), which is a 0°C photovoltage decay curve for a p^+n-junction made on a 10 Ω-cm wafer. Here the decay rate decreases drastically below ~0.3V. Figure 1(c) is a room-temperature forward current-induced decay curve for a commercial silicon solar cell (manufactured by Solarex Corporation). The initial drop from 0.9 to 0.6V is associated with the series resistance of the device. Next is a brief linear decay segment; from the decay rate given, we estimate a lifetime of 12 μS. Then the decay is accelerated, but this probably does not represent minority carrier recombination within the quasi-neutral base region. The lifetime ($\sim 1\ \mu$S) calculated from this accelerated decay rate would be too small to be consistent with the solar cell's observed photoresponse.

The slow tail on the decay curve of Fig. 1(b) and the acceleration during the latter stage of the decay in Fig. 1(c) cannot be adequately explained with any of the theoretical models of the previous section. These phenomena may be explained however, by considering physical processes associated with the depletion layer: the depletion layer capacitance effect and the depletion layer recombination current. Several authors indicate that they are aware of these phenomena[1, 4, 6, 7, 12] but we know of no substantial theoretical models where these effects are included. We return to a lumped parameter analysis because the problem appears to be intractable otherwise. The lumped parameter analysis at least illustrates the general features of the decay behavior, when these physical processes are operative.

(a) *Depletion layer capacitance*

A lumped-parameter analysis of open circuit voltage decay including the effect of charge storage in the depletion layer is based on the following expression for the net current density J:

$$J(t) = -J_L + Q_n(t)/\tau_p + \mathrm{d}Q_n(t)/\mathrm{d}t + C\,\mathrm{d}V(t)/\mathrm{d}t \tag{22}$$

where J_L is the light-generated current density, $Q_n(t)$ is the total excess minority carrier charge in the quasi-neutral base region per unit area. $Q_n(t)/\tau_p$ thus represents the minority carrier diffusion current density of an ideal diode. During open circuit voltage decay, $J = J_L = 0$ and the decay behavior is found from the solution of the following equation:

$$0 = Q_n(t)/\tau_p + \mathrm{d}Q_n(t)/\mathrm{d}t + C\,\mathrm{d}V(t)/\mathrm{d}t. \tag{23}$$

$Q_n(t)$ and C, based on the depletion layer approximation for an abrupt junction[11] and assuming the quasistatic approximation holds, are

$$Q_n(t) = Q_{no}[\exp(qV(t)/kT) - 1] \tag{24}$$

and

$$C = [q \in N_D/2(V_0 - V(t))]^{1/2} \tag{25}$$

where the base reference charge is

$$Q_{no} = q\sqrt{(D_p\tau_p)}(n_i^2/N_D). \tag{26}$$

The symbols are not previously defined are ϵ, the semiconductor permitivity; N_D, the base region doping density; and V_0, the diffusion potential.

Equation (23) may be rewritten as follows using eqn (24):

$$0 = Q_n(t)/\tau_p + (\mathrm{d}Q_n(t)/\mathrm{d}t)[1 + (kTC/q)/(Q_n(t) + Q_{no})]. \tag{27}$$

Thus the depletion layer capacitance can significantly affect the decay behavior whenever

$$C \gtrsim (q/kT)[Q_n(t) + Q_{no}]. \tag{28}$$

The r.h.s. of this equation has been called the *diffusion* capacitance (per unit area). For the purpose of illustration, we calculate and plot in Fig. 2 the depletion layer and diffusion capacitances assuming some realistic p^+n silicon diode parameters (base resistivity of $\sim 1\,\Omega$-cm; emitter doping density of $10^{19}\,\text{cm}^{-3}$): $kT/q = 0.026$V; $D_p = 20\,\text{cm}^2/\text{S}$; $N_D = 10^{16}\,\text{cm}^{-3}$; $\tau_p = 1\,\mu$S; $n_i = 10^{10}\,\text{cm}^{-3}$; $V_0 = 0.93$V[11]; and $\epsilon = 11.8 \times 8.86 \times 10^{-14}$ F/cm. It is apparent from Fig. 2 that the ideal decay behavior will be observed for this device so long as $V(t) > 0.47$V, but below that point, the depletion layer capacitance will control the decay. A calculated decay curve illustrating the depletion layer capacitance effect is shown in Fig. 3, obtained via a simple numerical integration of eqn (27) and using eqn (20) with $p_n(0, t)/p_{no} = Q_n(t)/Q_{no}$. For the numerical integration we have assumed a constant depletion layer capacitance such that the transition occurs for $V(t) \sim 0.38$V (for $CkT/q = 4 \times 10^6 Q_{no}$) and an initial Q_n of 10^{10} Q_{no} to give an initial voltage of 0.6V. The ideal decay curve (for $C = 0$) is also shown for comparison.

The effect of stored charge in the depletion layer is to slow down the decay in the latter stages, starting when the junction voltage falls to that value at which the depletion layer capacitance is comparable to the diffusion capacitance. The threshold voltage depends on the values of the various material parameters entering eqns (25) and (26). For the device whose decay curve is shown in Fig. 1(b), it is possible to determine the minority carrier lifetime from the linear part of the decay that precedes the onset of the depletion layer capacitance effect, as the calculated curves in Fig. 3 suggest.

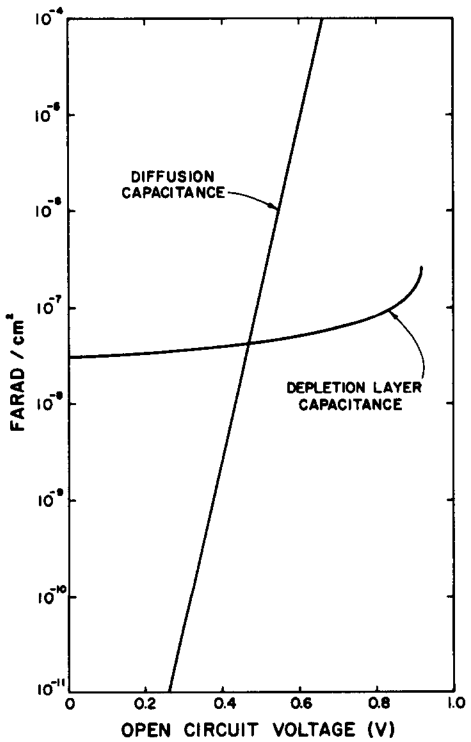

Fig. 2. Calculated depletion layer and diffusion capacitances for material parameters given in the text.

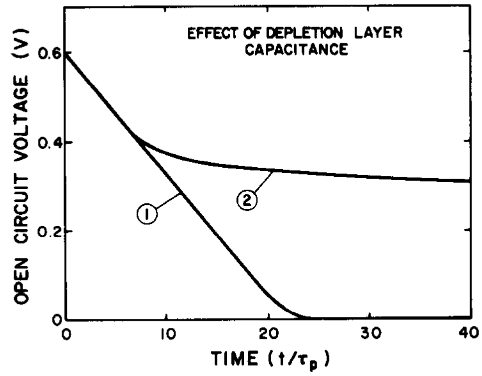

Fig. 3. Calculated open circuit voltage decay curves comparing (1) the ideal decay behavior to (2) decay behavior including the effects of depletion layer capacitance.

The depletion layer capacitance effect also accounts for the slow tail on the decay curve shown in Fig. 1(a), though it sets in at a lower level.

Dhariwal *et al.*[4] found an analytic solution to eqn (23) making approximations valid for $V(t) \ll kT/q$. Unfortunately, this voltage range is not of practical interest. Neugroshel *et al.*[12] briefly discussed the effect of depletion layer capacitance in relation to decay curves they obtained that did not exhibit a simple linear decay, but they did not develop a model for the observed behavior. To our knowledge, this is the extent of previous theoretical treatments of the effect of depletion layer capacitance on the decay.

(b) *Depletion layer recombination current*

The governing equation for the decay behavior when the depletion layer recombination current density J_{rec} is included and the depletion layer capacitance is neglected is

$$0 = Q_n(t)/\tau_p + \mathrm{d}Q_n(t)/\mathrm{d}t + J_{rec}. \tag{29}$$

For the purpose of illustrating the effect of this forward current component we make the common assumption that the recombination rate is constant throughout the depletion layer[11] such that

$$J_{rec}(t) = J_{gen}[\exp(qV(t)/2kT) - 1] \tag{30}$$

where

$$J_{gen} = qn_iWA/\tau_0. \tag{31}$$

W is the depletion layer width and τ_0 is the minority carrier lifetime within the depletion layer. Using eqns (24) and (30), eqn (29) can be rewritten as follows:

$$0 = Q_n(t)/\tau_p + \mathrm{d}Q_n(t)/\mathrm{d}t + J_{gen}\{[(Q_n(t)/Q_{no}) + 1]^{1/2} - 1\}. \tag{32}$$

We have solved eqn (32) numerically and calculated $V(t)$, assuming for the purpose of illustration that $Q_n(0)$ is $10^{10}Q_{no}$ and J_{gen} is 270 Q_{no}/τ_p. The value of $Q_n(0)$ chosen gives an initial voltage of 0.6V. The resulting

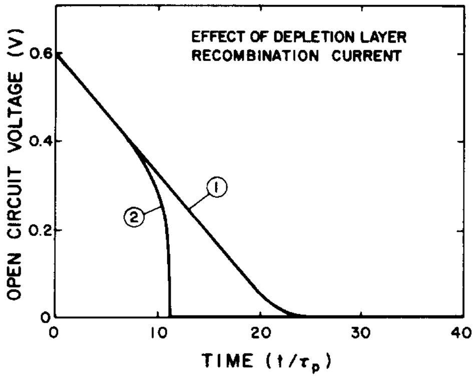

Fig. 4. Calculated open circuit voltage decay curves comparing (1) the ideal decay behavior to (2) decay behavior including the effect of depletion layer recombination current.

photovoltage decay curve is plotted in Fig. 4 together with the ideal curve (for $J_{gen} = 0$). The photovoltage decay follows the ideal case until J_{rec} becomes significant compared to the diffusion current; at this point the decay is accelerated. With the value of J_{gen} selected, this occurs when $V(t) \approx 0.28$V. As for the capacitance effect, the value of the junction voltage for which the effect begins is a function of the material parameters of the device under consideration according eqns (26) and (31).

For the device whose decay curve is shown in Fig. 1(c), forward current-voltage measurements indicate that a depletion layer recombination current dominates at forward bias levels below ~0.4V. However, we are able to estimate the minority carrier lifetime from the linear part of the decay curve above ~0.5V. The slow tail on the decay in Fig. 1(c) below ~0.2V is due to the depletion layer capacitance effect, which is present to some degree in the decay behavior of all the silicon devices we have investigated. There is no tail on the calculated curve of Fig. 4 because a capacitance term was not included in eqn (32). We also note that a simple shunt or leakage resistance would produce an acceleration of the decay similar to that due to the depletion layer recombination current. A leakage resistance in a diode is often an edge effect which can be eliminated by etching or passivating the edges of the device. The depletion layer recombination current, on the other hand, is usually an "intrinsic" property of the device under consideration and cannot be removed by passivation treatments after the junction has been formed.

4. SUMMARY AND CONCLUSIONS

The full theoretical description of the open circuit voltage decay lifetime measurement is quite complex. A precise model of the decay process must include the diffusion of minority carriers starting from some initial spatial distribution that is dependent upon the mode of excitation, and other physical phenomena that can provide sources or sinks for minority carriers such as the depletion layer capacitance, the depletion layer recombination current, and processes occurring in the heavily-doped side of the junction.

For a one-sided, wide base *pn*-junction without significant trapping of the minority carriers, the decay behavior considering both recombination and diffusion (but no depletion region effects) for either forward current- or photo-induced open circuit voltage decay is *basically* that predicted by a simple lumped parameter analysis. It is therefore possible, when a solution of the full continuity equation appears intractable, to turn to a lumped parameter analysis to show, at least qualitatively, the effect on the decay behavior of the depletion layer capacitance and recombination current.

If the open circuit voltage decay method is to be used to determine the base region minority carrier lifetime, the decay must be controlled by minority carrier recombination there. It is convenient if a linear decay is observed because the minority carrier lifetime may then be determined easily from the constant decay rate. The range of the linear part of the decay may often be increased by increasing the initial excitation level, up to the point where high injection occurs. The lower limit of the linear decay range may be expected to be set by depletion layer charge storage or recombination effects, which set in below certain threshold voltages determined by the material parameters of the device.

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