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Saturation of the internal photoemission effect in forward biased silicon junctions

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The behavior of the far-infrared laser-induced negative photoeffect in silicon homojunctions as a function of irradiation intensities is reported. A rate equation model treating this effect as a laser-heated hot-carrier internal photoemission is presented. The model predictions are compared to experimental results measured at 80 K, showing good agreement. [S0163-1829(96)01632-3]

I. INTRODUCTION

It is known that semiconductor junctions irradiated by pulsed CO_2 lasers ($\lambda \approx 10.6\ \mu$m) produce voltages that are opposite in sign (negative) to the normal (positive) photovoltaic effect.[1–3] In previous papers,[4,5] we report evidence of two independent contributions to the induced negative photovoltages. The first contribution is intrinsically bias independent and its origin lies in a modification in the transport parameters of hot carriers with respect to their room-temperature values. The second contribution is caused by the internal photoemission of hot carriers that are directly photoexcited by the laser light above the junction barrier. As the barrier height is lowered by forward bias, this internal photoemission becomes strongly bias dependent. In this paper, we will refer to this second contribution as the internal photoemission effect or IPE. We reported the bias dependence of the IPE (Ref. 4) using moderate intensity laser light. At low irradiances the induced photovoltage is almost linear with the light intensity and shows no saturation. The theoretical treatment of this effect considered only the absorption of laser light and neglected stimulated emission and excited-state populations.[4] It is thought, however, that larger light intensities could possibly produce a saturation of the intraband transition. Due to the rapid spontaneous emission of optical phonons, the hot-carrier plasma would not be able to overcome the Debye temperature, thus producing a saturation behavior in the generated photovoltage.

In the present work, we study the dependence of the IPE on the laser-light intensity. The effects of stimulated emission and the saturation of carrier temperature have been included in our theoretical model.

II. EXPERIMENTAL SETUP

As in our previous paper,[4] in order to separate the two contributions to the negative photovoltage, we have used the transmission of electrical pulses across the junction. These electrical pulses were synthesized with a pulse generator having the same temporal profile as the laser-pulse shape. This synthesizer was capacitively coupled to the biased junction in order to isolate the bias potential. A single transverse mode (TEM_{00}) CO_2 laser was used to excite the photoeffect in the junction. An electro-optic pulse-shaping system allowed us to obtain a 30-ns-wide optical pulse from the normally several microseconds wide laser pulse, and a beam integrator was used to get a more homogeneous transverse profile.

Samples of the excitation pulse were taken by a fast (5-ns rise time) $Hg_xCd_{1-x}Te$ photodetector operated at 80 K. A two-channel fast digitizer (2-G sample per second) was used to simultaneously record the input and output pulses, both in the electrical measurements as well as in the optical excitation. All circuit elements were connected with 50-Ω impedance coaxial cables.

A Si photodiode with P^+/N structure and P^+ doping of about $2\times10^{18}\ cm^{-3}$, the Siemens BPW21, was used to induce the negative photoeffect. The junction was placed inside a Dewar cryostat at either room or liquid-N_2 temperature. A set of CaF_2 absorbers was used to control the excitation light intensity. To avoid progressive heating in the junction, all measurements were carried out in a single pulse mode.

III. EXPERIMENTAL RESULTS

The measurements of the negative photoeffect taken at a lattice temperature of $T_L = 80$ K as a function of the light intensity are shown in Fig. 1(a), that is, the raw measurements taken at 1.00-V and zero bias. The zero-bias plot provides the behavior of the bias-independent negative effect. This plot is then extrapolated to a 1.00-V bias using the previously measured electrical characteristic of the junction,[4] and the extrapolated values are subtracted from the raw measurements taken at 1.00-V bias, thus the intensity dependence of the IPE is determined. The extrapolated values and the resulting IPE are plotted in Fig. 1(b). As was expected, the internal photoemission is saturated at high intensities.

IV. THEORETICAL MODEL

A plasma of hot carriers at a local thermal equilibrium temperature T_c, which is higher than the lattice temperature T_L, is produced by rapid-heating induced by the laser

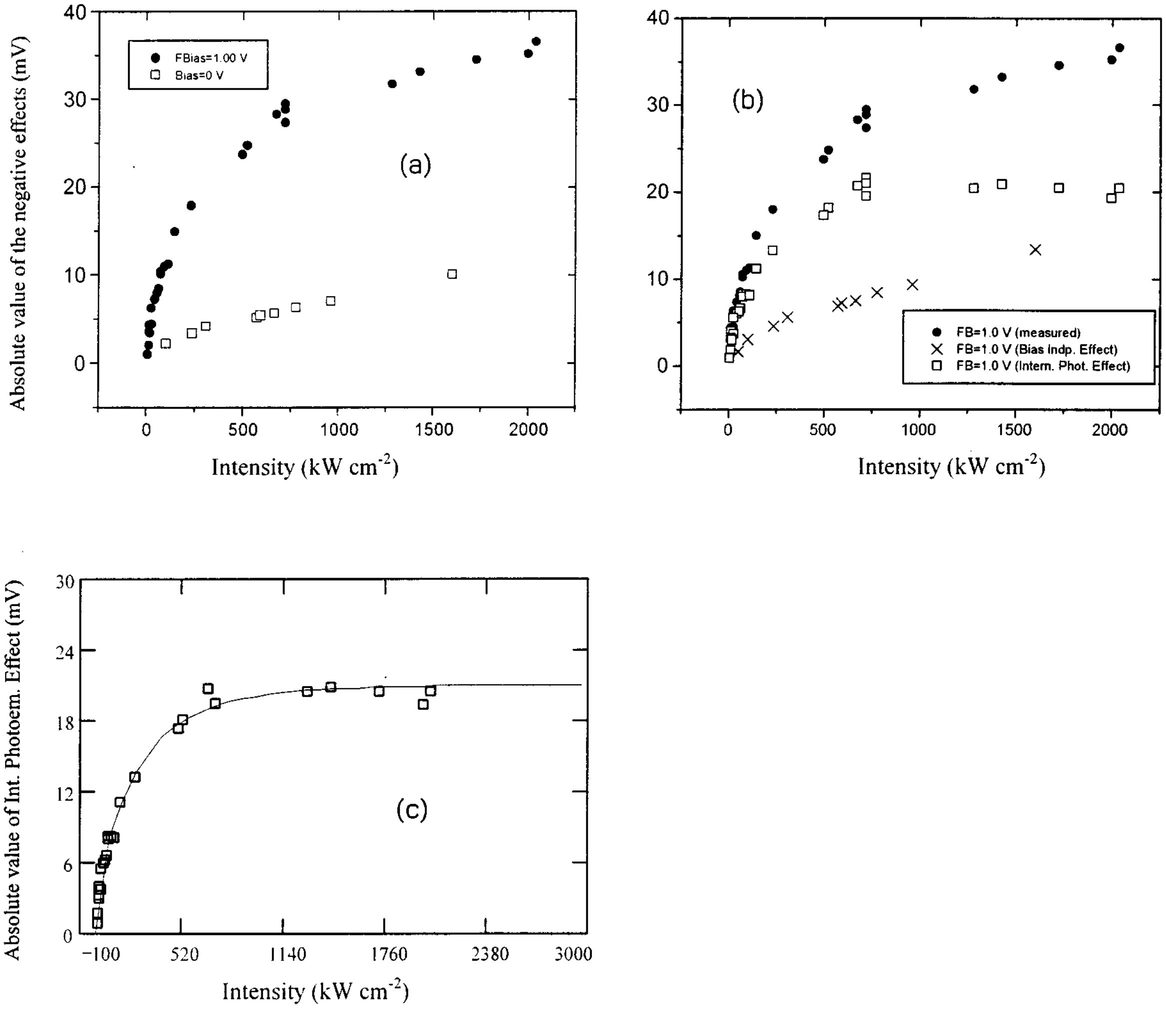

FIG. 1. Absolute value of negative effects as a function of irradiation intensities by $T_L = 80$ K (a) measured at two bias voltages: (●) a forward bias of 1.00 V and (☐) zero bias. (b) For a forward bias of 1.00 V: (●) the measurements of the induced photovoltage (including both effects), (X) the calculated majority-carrier effect, and (☐) the IPE resulting from the subtraction of the other two data sets. (c) Theoretical fit to the IPE shown in (b) (☐) by Eq. (19); the fit parameters are $I_0 = 80$ kW cm^{-2}, $C = 1.44$, and $I_S = 5.8$ kW cm^{-2}.

light.[4,5] This heating enhances the population of carriers near the top of the junction barrier that can be directly photoexcited to levels above the barrier.

Assuming a nondegenerate carrier plasma, the density of carriers on the fringe, with an energy level that is below the barrier, but enough to be photoexcited above the barrier, is given by[4] [see Fig. 2(a)]

$$n_{10} = n\frac{2}{\sqrt{\pi}}\int_{a(V_B)}^{b(V_B)} x^{1/2}e^{-x}dx = n\frac{2}{\sqrt{\pi}}\left\{\gamma\left[\frac{3}{2}, b(V_B)\right] - \gamma\left[\frac{3}{2}, a(V_B)\right]\right\}, \tag{1}$$

where

$$a(V_B) = \begin{cases} \dfrac{q(V_0 - V_B) - h\nu}{KT_c} & \text{if } q(V_0 - V_B) > h\nu \\ 0 \quad \text{if } q(V_0 - V_B) \leqslant h\nu, \end{cases} \tag{2}$$

$$b(V_B) = \frac{q(V_0 - V_B)}{KT_c}, \tag{3}$$

and

$$n = 2\left(\frac{2\pi m_e^* KT_c}{h^2}\right)^{3/2} \exp\left(-\frac{E_c - E_F}{KT_c}\right). \tag{4}$$

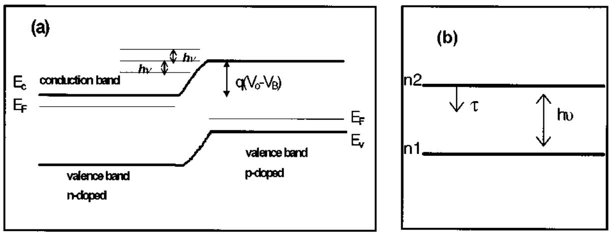

FIG. 2. (a) Diagram of internal photoemission scheme. (b) Nondegenerate plasma statistics allows the grouping the carriers in two discrete levels.

Here, m_e^* represents the electronic effective mass, E_F and E_c, respectively, the pseudo-Fermi level of hot-carrier plasma and the conduction-band energy, q is the electronic charge, and V_B and V_0 are, respectively, the bias and transition voltage of the junction. The coefficient n [Eq. (4)] can be identified as the total density of carriers in the band and $\gamma(\alpha,x)$ is the incomplete gamma function.

Those directly excited carriers, that already have an energy level greater than the barrier, have a density of carriers given by

$$n_{20}=n\frac{2}{\sqrt{\pi}}\int_{c(V_B)}^{d(V_B)}x^{1/2}e^{-x}dx=n\frac{2}{\sqrt{\pi}}\left\{\gamma\left[\frac{3}{2},d(V_B)\right]-\gamma\left[\frac{3}{2},c(V_B)\right]\right\}, \tag{5}$$

where

$$c(V_B)=\begin{cases}\dfrac{q(V_0-V_B)}{KT_c} & \text{if } q(V_0-V_B)>h\nu\\ \dfrac{h\nu}{KT_c} & \text{if } q(V_0-V_B)\leqslant h\nu,\end{cases} \tag{6}$$

$$d(V_B)=\frac{q(V_0-V_B)+h\nu}{KT_c}. \tag{7}$$

Since the plasma statistics have been assumed to be nondegenerate, we may group the carriers lying in both fringes in two discrete levels separated by the energy $h\nu$ of the laser photons [Fig. 2(b)].

The rate equation for the population of the higher level is

$$\frac{dn_2}{dt}=-(n_2-n_1)\frac{\sigma}{h\nu}I_i-\frac{1}{\tau}(n_2-n_{20}), \tag{8}$$

where

$$I_i=(1-R)I, \tag{9}$$

where I is the intensity of the laser light, R the reflection coefficient, τ the decay time between the two levels, and σ the radiative cross section for stimulated processes. If τ is short ($\approx 10^{-9}$ s) as compared with the typical evolution time of laser light (30×10^{-9} s), we may use the adiabatic approximation:

$$(n_2-n_1)\frac{\sigma}{h\nu}I_i+\frac{1}{\tau}(n_2-n_{20})\approx 0, \tag{10}$$

and

$$\Delta n_2=n_2-n_{20}\approx-(n_1-n_{10}). \tag{11}$$

Substituting Eq. (11) in Eq. (10), we have

$$\Delta n_2=\frac{(n_{10}-n_{20})}{2}\frac{I_i}{I_i+\dfrac{h\nu}{2\sigma\tau}}, \tag{12}$$

here, the saturation intensity is given by

$$I_s=\frac{h\nu}{2\sigma\tau}. \tag{13}$$

From Eq. (1) and Eq. (5), we have

$$\frac{n_{10}-n_{20}}{2}=\frac{n}{\sqrt{\pi}}\left[\gamma\left(\frac{3}{2},b\right)-\gamma\left(\frac{3}{2},a\right)-\gamma\left(\frac{3}{2},d\right)+\gamma\left(\frac{3}{2},c\right)\right], \tag{14}$$

where a, b, c, and d are given by Eqs. (2), (3), (6), and (7), respectively, and are all functions of V_B and of the carrier temperature T_c. Previously a relationship between T_c and the laser intensity was derived assuming an equilibrium between radiation absorption and acoustic-phonon emission,[6]

$$T_c=T_L\left(1+\frac{I}{I_0}\right). \tag{15}$$

However, due to the rapid spontaneous optical-phonon emission process, the carrier temperature T_c should not be higher than the Debye temperature T_D. Thus, to produce a ‘‘soft’’ saturation of T_c towards T_D at high light intensities, we have modified Eq. (15) to the form

$$T_c=T_L\frac{\left(1+\dfrac{I}{I_0}\right)}{\left(1+\dfrac{T_L}{T_D}\dfrac{I}{I_0}\right)}. \tag{16}$$

Using Eqs. (14) and (16) in Eq. (12), we obtain Δn_2, which is the part of the carrier population that has been removed from the local thermal equilibrium due to direct excitation by laser radiation. This excess of excited carriers above the junction barrier produces a diffusion open-circuit potential in the junction, which using the Einstein relationship, $D/\mu=KT_c/q$, (where D is the diffusion coefficient and μ the carrier mobility) is given by

$$\Delta V=\frac{KT_c}{q}\frac{\Delta n_2}{n}. \tag{17}$$

Using Eqs. (12) and Eq. (14), Eq. (17) becomes

$$\Delta V=\frac{KT_c}{q\sqrt{\pi}}\left[\gamma\left(\frac{3}{2},b\right)-\gamma\left(\frac{3}{2},a\right)-\gamma\left(\frac{3}{2},d\right)+\gamma\left(\frac{3}{2},c\right)\right]\frac{I_i}{I_i+I_S}. \tag{18}$$

It is very interesting to note here that the generated potential is not explicitly dependent on the carrier density n, contrary to what could be normally expected.

In a junction, there are two kinds of carriers with similar transport properties and, the generated potential will be the summation of both contributions, each one given by Eq. (18). If both of the contributions are independent, then there are too many independent parameters to fit. Thus, we make the assumption that the ratio of the contribution from each carrier type will remain the same, and this is accounted for by including a proportionality constant C in Eq. (18).

$$\Delta V = C\frac{KT_c}{q\sqrt{\pi}}\left[\gamma\left(\frac{3}{2},b\right)-\gamma\left(\frac{3}{2},a\right)-\gamma\left(\frac{3}{2},d\right)+\gamma\left(\frac{3}{2},c\right)\right]\frac{I_i}{I_i+I_S}. \tag{19}$$

This constant C will also be reduced because the experimental measurements were taken on a closed circuit and not on an open circuit system.

We then fit our theoretical model to our experimental data using Eqs. (16) and (19). In the fit, we used the values $q=e=1.602\times10^{-19}C$, $R=0.2$, $V_0=1.10$ V (transition potential at 80 K in our photodiode), $h\nu=0.118$ eV ($\lambda=10.6$ μm), and $T_D=625$ K (Debye temperature for silicon). We used I_0, I_S, and C as the fitting parameters. The fitted experimental data were taken as bias $V_B=1.0$ V. Reasonable fits were obtained with the fitting parameters inside the intervals $I_0=[70-100]$ kW cm^{-2}, $C=[1.43-1.5]$, and $I_S=[5-11]$ kW cm^{-2}. When I_s is below 5 kW cm^{-2}, it has no effect on the fit result, indicating that the saturation due to the Debye temperature limitations is more important than the saturation due to the population equilibrium between the two levels (I_S). The case corresponding to $I_0=80$ kW cm^{-2}, $C=1.44$, and $I_S=5.8$ kW cm^{-2} is shown in Fig. 1(c).

V. DISCUSSION AND CONCLUSIONS

The values for the parameters produced by fitting our theoretical and the experimental results are reasonable physically. The parameter I_0 is given by[4]

$$I_0=\frac{32V^2q}{3\pi\mu\sigma(1-R)},$$

where V is the sound velocity in the junction material.

The value of this parameter, with $T_L=300$ K, was experimentally determined to be $I_0=2.7$ MW cm^{-2}.[4] Assuming that σ, the radiative cross section, is only slightly dependent on the temperature,[3] the main temperature dependence in I_0 comes from μ, the carrier mobility. In silicon, the mobility is generally proportional to T^{-i} with $i=2.5$ for electrons and $i=2.7$ holes.[7] The value for I_0 at $T_L=80$ K is thus,

$$I_0(T_L=80\ \text{K})\approx I_0(T_L=300\ \text{K})\left(\tfrac{80}{300}\right)^{2.6}=87\ \text{kW cm}^{-2},$$

in good agreement with the range of goods fits $I_0=(70\text{–}100)$ kW cm^{-2}. [The fitted value was $I_0=80$ kW cm^{-2} in Fig. 1(c).]

With the fitted value of $I_S=5.8$ kW cm^{-2} and the optical cross-section value[3] $\sigma\approx2.7\times10^{-16}$ cm^2, the relaxation time from Eq. (13) is then $\tau\approx6\times10^{-9}$ s, which is a reasonable value at 80 K. The fitted value of $C=1.44$, after compensating for the 50-Ω input impedance of the transient digitizer, is equivalent to $C\approx2$ measured in an open circuit. This would indicate electron and hole contributions that are almost equal.

In conclusion, we have measured the radiation intensity dependence of the laser-induced negative potential in Si homojunctions. We have separated this effect in two different contributions, a bias independent effect and the strongly bias-dependent IPE. The experimental measurement of the IPE exhibited a strong saturation with radiation intensity. We advanced a theoretical model of this IPE. Interestingly, the model indicates no explicit dependence of the IPE on the doping in either side of the junction. The model shows good agreement with the experimental results and is capable of producing quantitative predictions.

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