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Photovoltaic effect of 10.6-μm radiation on hot carriers in silicon P^+-N junctions

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The highly nonlinear photovoltaic effect induced in silicon junctions by 10.6-μm laser pulses is theoretically studied through a hot-carrier-plasma model. Acoustic-phonon scattering is assumed to be the dominant energy relaxation mechanism during the hot-carrier thermalization. A simple relationship between the laser excitation intensity peak and the current response peak has been derived and is shown to fit the experimental results well.

I. INTRODUCTION

As is well known, a complex voltaic response is obtained when semiconductor junctions are illuminated by laser light. However, if the photon energy $h\nu$ is less than half the forbidden-band energy E_G, no photovoltaic response is to be expected. This is the case of the 10.6-μm photons ($\simeq 0.12$ eV), as compared to the silicon forbidden-band energy. In previous papers we reported the measurement of a highly nonlinear photovoltaic response to pulsed 10.6-μm laser radiation in silicon junctions.[1-3] More recent experiments indicate that this photovoltaic response is a hot-carrier effect.[3] Particularly revealing is the extreme sensitivity of the effect to the lattice temperature.[3] A hot-carrier-based model is described and fitted to the experimental measurements. In the last section, we discuss the accordance between the model predictions and the experimental features, as well as the model's range of application.

II. EXPERIMENTAL SETUP

The experimental setup has been previously described,[1-3] so only a brief outline is given, pointing out the most significant features. The laser was a high-intensity transversely excited atmospheric (TEA) model.[4,5] Nitrogen was not present in the laser mixture, in order to have a short pulse width of 60 ns corresponding to the gain switch peak. The light fluence was controlled by variable attenuators and a transmitting photon-drag detector.

The photodiode was linked to a digital transient register, the sensitivity was 1 mV, with a vertical resolution of 8 bits, 2 Gs per second, a maximum of 32 000 points in the horizontal record, and 50 Ω input impedance. The whole measurement system was inside a Faraday cage to avoid radio-frequency stray noise.

The P^+-N silicon junction has an active area of 6 mm^2, a maximum B doping of 2×10^{18} cm^{-3} on the surface, and a trap-assisted Auger recombination time $\tau_{\text{Auger}} \leq 5$ ns.

III. EXPERIMENTAL RESULTS

The photoresponse was measured in the photovoltaic and reverse-biased photoconductive mode. A detailed description of the experimental results in silicon junctions can be found in Refs. 1–3. As in the ordinary photovoltaic effect, the photoresponse narrows in the reverse-biased photoconductive mode, as compared to the photovoltaic one. Also, a significant delay ($\simeq 40$ ns) between the photocurrent and the light pulse may be observed. A plot of the peak voltage of the photoresponse in the photoconductive mode ($V_{\text{bias}} = -9.6$ V) versus laser intensity is shown in Fig. 1.

IV. THEORETICAL APPROACH

The irradiation of semiconductor materials with powerful laser light pulses has been studied for many years. When the energy $h\nu_0$ of the laser photons is

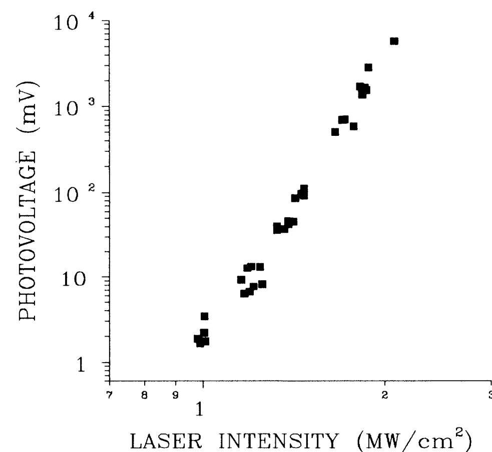

FIG. 1. Laser-induced peak photovoltage vs laser peak excitation intensity in the photoconductive mode (voltage reverse bias $= -9.6$ V).

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greater than that of the forbidden band E_g, an optical pumping takes place and the population of carriers can be strongly enhanced by the production of electron-hole pairs. Assuming parabolic bands, the photoexcited carriers are created with an excess of energy given by

$$\Delta E_e = (h\nu_0 - E_g)[1 + (m_e/m_h)]^{-1} ,\\ \Delta E_h = (h\nu_0 - E_g) - \Delta E_e . \tag{1}$$

When the laser photons have an energy $h\nu \ll E_g$, there is no electron-hole production, and intraband free-carrier absorption takes place. In this case, the carrier excess energy per photon absorption is the total photon energy

$$\Delta E_c = h\nu . \tag{2}$$

If the carrier population is higher than $\simeq 10^{18}$ cm^{-3}, the carriers (electrons and holes) become thermalized at a temperature $T_e = T_h = T_c$ greater than the lattice temperature T_L, giving rise to a hot-carrier thermalized plasma.[6-11] At such carrier densities, the rate of energy relaxation by intercarrier collisions dominates the energy relaxation by phonon emission, and thus a thermalized distribution $f_{T_c}(\varepsilon)$ is established due to the fact that the energy exchange between carriers proceeds faster than that between carriers and the lattice. In times of order 10^{-14}–10^{-13} s, the electrons and holes attain the thermal distribution characterized by temperatures $T_e = T_h = T_c$. At the same time, for these high carrier densities $n,p \geq 10^{18}$ cm^{-3}, the Auger recombination and its inverse process of electron-hole pair production by impact ionization are the dominant recombination-generation mechanisms.[8,12,13] If the laser intensity pulse does not vary appreciably in times of order τ_{Auger} (Auger recombination time), the Auger processes change the number of electrons and holes to bring the n,p densities into accordance with the plasma temperature variations.[8] Thus, the n and p densities will be the same as the equilibrium density in the intrinsic semiconductor, at a lattice temperature equal to T_c. Thus, an extra number of electron-hole pairs should be generated by impact ionization during the laser-pulse illumination (Fig. 2).

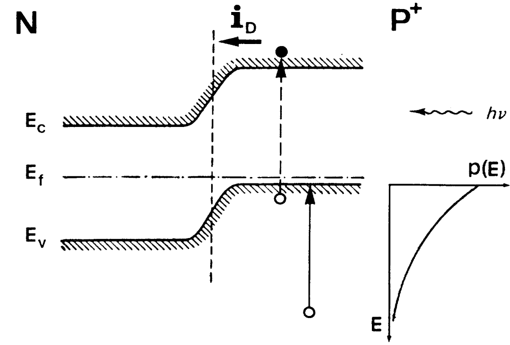

FIG. 2. Band diagram showing the generation of minority carrier in the hot-carrier plasma through the impact ionization process. $p(E)$, hot-hole plasma energy distribution in the P^+ region; i_D, minority diffusion current; E_c, conduction band; E_f, Fermi level; and E_v, valence band.

We shall now consider the case of a P^+-N abrupt junction with shallow impurities. The excess of minority carriers created in the P^+ region, where the free-carrier absorption is strong, should give rise to the measured photocurrent.

Dynamical equilibrium in the hot-carrier plasma is obtained when energy balance occurs.[6,11] In the present model, we assume that the main energy losses are due to acoustical-phonon scattering. If the light intensity attenuation within the highly doped surface region and the light reflected on the rear surface are neglected, the rate of radiation energy absorption per carrier is

$$\left[\frac{dE}{dt}\right]_{\text{ra}} = I(1-R)\sigma(T_c) . \tag{3}$$

I is the laser intensity, R the surface reflectivity, and σ the free-carrier absorption cross section at the carrier temperature T_c. In the relaxation time approximation and in the short-wavelength limit $\omega\tau \gg 1$ ($\tau \equiv$ relaxation time), the free-carrier cross section is[14]

$$\sigma = \frac{e^3}{n\epsilon_0 c\omega^2 m^2 \mu} , \tag{4}$$

where n is the real refraction index, m the effective carrier mass, ω the angular light frequency, and μ the carrier mobility.

During hot-carrier thermalized plasma formation and transient time, the change in the lattice temperature T_L is neglected. When there is dominant scattering by acoustical phonons then[15]

$$\mu(T_c) = \mu_0(T_L)\left[\frac{T_L}{T_c}\right]^{1/2} . \tag{5}$$

Thus, with (4) and (5) we get

$$\sigma(T_c) = \sigma(T_L)\left[\frac{T_c}{T_L}\right]^{1/2} \tag{6}$$

and, finally, the energy absorption rate per carrier is obtained by

$$\left[\frac{dE}{dt}\right]_{\text{ra}} = I(1-R)\sigma(T_L)\left[\frac{T_c}{T_L}\right]^{1/2} . \tag{7}$$

On the other hand, the rate of energy losses by acoustical-phonon processes is[15]

$$\left[\frac{dE}{dt}\right]_{\text{ap}} = \frac{32v^2 e}{3\pi\mu_0}\left[\frac{T_c}{T_L}\right]^{1/2}\left[\frac{T_c}{T_L} - 1\right] , \tag{8}$$

where v is the velocity of sound in the material and μ_0 is the carrier mobility by acoustical-phonon scattering at thermal equilibrium, when the laser fluence is zero.

The dynamical equilibrium condition is

$$\left[\frac{dE}{dt}\right]_{\text{ra}} = \left[\frac{dE}{dt}\right]_{\text{ap}} . \tag{9}$$

With (7), (8), and (9) we get

$$\frac{T_c}{T_L}=1+\frac{I}{I_0}\ , \tag{10}$$

$$I_0=\frac{32v^2 e}{3\pi\mu_0(1-R)\sigma(T_L)}\ . \tag{11}$$

Equation (10) is a simple relationship between the laser intensity I and the hot-carrier plasma temperature T_c.

According to the analysis done at the beginning of this section, and since $\tau_{\text{Auger}} \ll \tau_{\text{laser}}=60$ ns, the carrier densities in the hot plasma are (nondegenerate case)

$$n(T_c)=N_C(T_c)\exp[(E_F-E_C)/kT_c]\ , \tag{12}$$

$$p(T_c)=N_V(T_c)\exp[(E_V-E_F)/kT_c]\ , \tag{13}$$

$$N_C(T)=2\left[\frac{2\pi m_e kT}{h^2}\right]^{3/2}\ , \tag{14}$$

$$N_V(T)=2\left[\frac{2\pi m_h kT}{h^2}\right]^{3/2}\ , \tag{15}$$

then

$$\frac{N_C(T_c)}{N_C(T_L)}=\frac{N_V(T_c)}{N_V(T_L)}=\left[\frac{T_c}{T_L}\right]^{3/2}\ . \tag{16}$$

Employing (12), (13), and (16) and calling $E_G=E_C-E_V$, we obtain

$$n(T_c)p(T_c)=N_C(T_L)N_V(T_L)\left[\frac{T_c}{T_L}\right]^3\exp(-E_G/kT_c)\ . \tag{17}$$

If N_A is the doping density on the P^+ side of the junction, and taking into account the condition for charge neutrality under the supposition of fully ionized impurities, we get

$$N_A=p(T_c)-n(T_c)=p(T_L)-n(T_L)\ . \tag{18}$$

But $n \ll p$ and we can take $p(T_c)\simeq p(T_L)$ in (17), obtaining an electron-pair concentration of

$$C_{e\text{-}h}(T_c)=n(T_c)=\frac{N_C(T_L)N_V(T_L)}{p(T_L)}\left[\frac{T_c}{T_L}\right]^3 \times\exp(-E_G/kT_c)\ . \tag{19}$$

The change in the concentration of minority carriers gives rise to a diffusion current towards the junction, as in a conventional photovoltaic effect. This current would be

$$i_D \propto D(T_c)[C_{e\text{-}h}(T_c)-C_{e\text{-}h}(T_L)]\ , \tag{20}$$

where $D(T_c)$ is the diffusion coefficient. Using the Einstein relation $D(T)=kT\mu(T)/e$ with Eq. (5), we have

$$\frac{D(T_c)}{D(T_L)}=\left[\frac{T_c}{T_L}\right]^{1/2}\ . \tag{21}$$

Joining Eqs. (19), (20), and (21), we get

$$i_D \propto \left[\frac{T_c}{T_L}\right]^{1/2} D(T_L)\frac{N_C(T_L)N_V(T_L)}{p(T_L)} \times\left[\left[\frac{T_c}{T_L}\right]^3\exp(-E_G/kT_c)-\exp(-E_G/kT_L)\right]\ . \tag{22}$$

By neglecting the second exponential ($T_c > T_L$), the following approximation is reached:

$$i_D \propto i_0(T_L)\left[\frac{T_c}{T_L}\right]^{7/2}\exp\left[-\frac{E_G}{kT_L}\left[\frac{T_c}{T_L}\right]^{-1}\right]\ . \tag{23}$$

Using Eq. (10), we have the photocurrent as a function of the laser intensity and taking into account the logarithm in (23), we obtain

$$\ln\left[\frac{i_D}{(1+I/I_0)^{7/2}}\right]=\ln[i_0(T_L)]-\frac{E_G}{kT_L}(1+I/I_0)^{-1} +\text{constant term}\ . \tag{24}$$

If we plot $\Psi\equiv\ln[i_D/(1+I/I_0)^{7/2}]$ as a function of $\xi\equiv(1+I/I_0)^{-1}$, we get a straight line whose slope must be E_G/kT_L. Figure 3 shows the experimental data of the photocurrent peak for the photoconductive mode ($V_{\text{bias}}=-9.6$ V) in the silicon P^+-N junction, fitted by expression (24). The fitted experimental data correspond to the exciting peak radiation intensities between 1 and 2 MW/cm^2. We take $kT_L=0.0252$ eV and $E_G=1.12$ eV. The best fit shown in Fig. 3 is obtained for $I_0=2.7$ MW/cm^{-2}.

But I_0 is predicted by Eq. (11), where such silicon physical constant values as carrier mobility, surface reflectivity, light-absorption cross section, and sound propagation velocity appear. These values have been taken from current literature. Thus, $\sigma=3\times10^{-16}$ cm^2 was

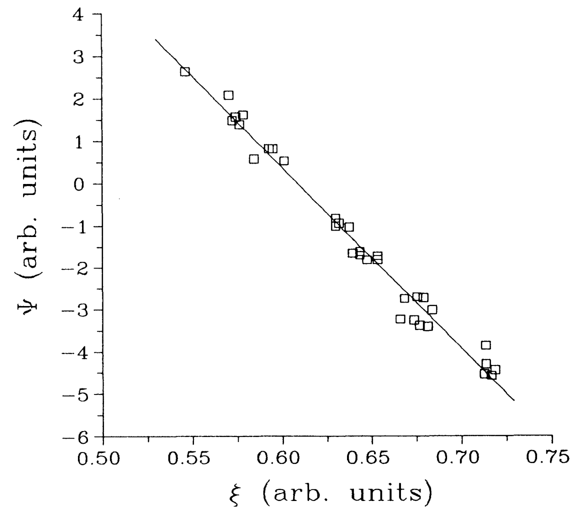

FIG. 3. Linear fit of Ψ vs ξ according to Eq. (24) (see text for explanation).

taken from the absorption data.[12] The sound velocity[16] is $v=9\times10^5$ cm s^{-1}, the acoustic mobility[12] $\mu_0=500$ cm^2/V s, and $R=0.2$. The predicted value according to expression (11) is then $I_0=3.7$ MW/cm^2. This value is in good agreement with that obtained from the fit previously described. The observed difference between the two values of I_0 is probably due to the accumulative effect of several uncertainties affecting the experimental measurements, the values of the constants taken from current literature, and also to the simplifying hypothesis introduced in the model, which shall be discussed later. Thus, the very nonlinear character of the effect makes it very difficult to get accurate experimental measurements. Any slight spatial inhomogeneity or uncontrolled temporal instability produces great fluctuations in the photocurrent, which introduces dispersion and lack of reproducibility in the measurements.

V. DISCUSSION AND CONCLUSIONS

In the previous sections, we have described a model of a hot-carrier photovoltaic effect, whose main hypotheses are the following: (1) Under infrared (10.6 μm) pulsed laser excitation, the semiconductor free carriers become excited by intraband transitions; (2) the laser excited carriers are assumed to be instantaneously thermalized and diffused; (3) a hot-carrier plasma is in thermal equilibrium at a temperature higher than the lattice temperature; (4) the dominant energy losses are produced by acoustic-phonon scattering, and (5) the lattice temperature does not change during irradiation and the hot-carrier thermalized plasma formation process.

The first hypothesis deals with the absorption of infrared radiation by semiconductor free carriers, a well-known phenomenon. The second hypothesis is reasonable if the intercarrier scattering is the dominant process. The higher the carrier density, the more accurately the second and the third hypotheses are fulfilled, as was discussed previously.

The carrier scattering in Si at room temperature occurs predominantly by acoustic phonons, even though a significant contribution can exist from optical phonons.[17] As a first-order approximation, the situation in nonpolar semiconductors such as Si in the case of moderate laser light intensities, is such that only acoustic phonons are important, because not many electrons in the electron distribution have sufficient energy to interact with optical phonons. The average carrier energy is lower than the optical-phonon energy, i.e, the carrier temperature T_c is lower than the Debye temperature. Thus, the fourth hypothesis imposes an upper limit on the hot-carrier-plasma temperature. When T_c is greater than the Debye temperature T_D, the spontaneous emission of optical phonons becomes the dominant loss energy scattering process and Eq. (10) fails (the temperature growth tends to saturate). In our experimental results, reasonably well fitted by (24), the highest peak laser intensity corresponds to a carrier temperature $T_c\simeq500$ K, which is still below the silicon Debye temperature[18] $T_D\simeq730$ K.

The likelihood of the last hypothesis requires a more detailed analysis. The free-carrier absorption cross section in silicon for $\lambda=10.6$ μm is about $\sigma\simeq3\times10^{-16}$ cm^2 and, assuming a doping density of $N_A=10^{18}$ cm^3, the radiation penetration depth is $L_r=1/\sigma N_A=30$ μm. Since the P^+ doping diffusion depth is usually $L_d\simeq0.5$ μm, we may assume that the junction is uniformly illuminated, as in the theoretical approach. Then the energy absorbed per unit area on the highly doped surface layer during the laser pulse width Δt is $\Delta E=(1-R)IN_A\sigma L_d\Delta t$, the surface reflectivity being $R=0.2$, and I being the laser intensity. During irradiation time Δt, this energy is diffused to a depth of the order of the thermal diffusion depth $L_t\simeq2(\kappa\Delta t)^{1/2}$, where we have used the thermal diffusivity[19] $\kappa=0.86$ cm^2/s and $\Delta t=60$ ns. Thus, the temperature rise on the surface will be

$$\Delta T=(1-R)\frac{IN\sigma\Delta t}{C}\frac{L_d}{L_t}\ . \tag{25}$$

The silicon heat capacity[19] is $C=1.66$ J/K cm^{-3}, and the maximum peak laser intensity used in the adjusted range is $I=2$ MW/cm^2. In this case, the highest temperature rise is $\Delta T\simeq2$ K.

The extreme sensitivity shown by the effect on the lattice temperature, perhaps, makes this temperature rise not completely negligible. Nevertheless, the influence of this lattice temperature increase on the fit of (24) is less than 1% on the fitted slope, because of the logarithmic dependence on this expression. On the other hand, the above described thermal increase estimation is probably too pessimistic. Not being degenerate, the hot-carrier plasma could retain a sizable part of the absorbed laser energy, which would be injected into the lattice in a delayed form.

The strong dependence of the photocurrent on the lattice temperature T_L arises from (10) and (23), mainly through the exponential factor $\exp[-E_G/kT_L(1+I/I_0)]$. With the same irradiation intensity at room temperature ($T_L\simeq300$ K), an increase of 50° enhances this factor by nearly two orders of magnitude. Preliminary experiments on this subject confirm this prediction.[3]

In conclusion, we can state that, in spite of the discussed shortcomings, the hot free-carrier photovoltaic model provides consistent physical interpretation of the recently observed infrared laser excited photovoltaic effect, which is in reasonable quantitative agreement with the experimental results.

ACKNOWLEDGMENT

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[1]E. Domínguez Ferrari, F. Encinas Sanz, and J. M. Guerra Pérez, IEEE Phot. Tech. Lett. **1**, 469 (1989).

[2]E. Domínguez Ferrari, F. Encinas Sanz, and J. M. Guerra Pérez, Phys. Rev. B **42**, 11 714 (1990).

[3]F. Encinas Sanz, J. M. Guerra Pérez, and E. Domínguez Ferrari, IEEE J. Quantum Electron. (to be published).

[4]F. Encinas Sanz and J. M. Guerra Pérez, Meas. Sci. Technol. **1**, 1188 (1990).

[5]F. Encinas Sanz and J. M. Guerra Pérez, IEEE J. Quantum Electron. **27**, 891 (1991).

[6]J. Shah, Solid State Electron. **21**, 43 (1978).

[7]J. Shah, J. Phys. (Paris) C **7**, 445 (1981).

[8]Ellen J. Yoffa, Phys. Rev. B **21**, 2415 (1980).

[9]S. A. Lyon, J. Lumin. **35**, 121 (1986).

[10]H. M. Van Driel, in *Interfaces Under Laser Irradiation,* Vol. 134 of *NATO Advanced Study Institute, Series E: Applied Sciences,* edited by L. D. Laude, D. Bäuerle, and M. Wautelet (Martinus Nijhoff, Dordrecht, 1987).

[11]S. E. Esipov and Y. B. Levinson, Adv. Phys. **36**, 331 (1987).

[12]D. K. Schroder, *Semiconductor Material and Device Characterization* (Wiley, New York, 1990).

[13]M. S. Tyagi and R. Van Overstraeten, Solid State Electron. **26**, 577 (1983).

[14]F. J. Blatt, *Physics of Electronic Conduction in Solids* (McGraw-Hill, New York, 1968).

[15]K. Seeger, *Semiconductor Physics. An Introduction* (Springer-Verlag, Berlin, 1985).

[16]H. J. McSkimin and P. Andreatch, Jr., J. Appl. Phys. **35**, 2161 (1964).

[17]S. Wang, *Fundamentals of Semiconductor Theory and Device Physics* (Prentice-Hall, London, 1989).

[18]S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).

[19]R. A. Ghez and R. A. Laff, J. Appl. Phys. **46**, 2103 (1975).