Temperature dependence of carrier mobility in Si wafers measured by infrared photocarrier radiometry

Jerias Batista,[a] Andreas Mandelis, and Derrick Shaughnessy
Center for Advanced Diffusion-Wave Technologies (CADIFT), Department of Mechanical and Industrial Engineering, University of Toronto, Toronto M5S 3G8, Canada

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A recently introduced infrared photocarrier radiometry technique has been used to determine the temperature dependence of carrier mobility in Si wafers. In addition, its potential to determine simultaneously the carrier lifetime, diffusion coefficient, and surface recombination velocity is reported. This noncontact, nonintrusive, and all-optical technique relies on the detection of infrared radiation from harmonically excited free carriers (pure electronic diffusion-wave detection). Using a multiparameter fitting to a complete theory, the results showed that the lifetime increases with temperature, the diffusion coefficient decreases [$D(T) \sim T^{-1.5}$], and the temperature dependence of carrier mobility is $\mu(T) = (1.06 \pm 0.07) \times 10^9 \times T^{-2.49 \pm 0.01}$ cm^2/V s. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1582376]

Laser-induced infrared photocarrier radiometry (PCR) has recently been introduced as a powerful carrier-density-wave diagnostic technique for noncontact characterization of transport properties in semiconductors.[1] It was derived from the well-known infrared photothermal radiometry (PTR), a technique extensively used in semiconductor analysis.[2–6] Both techniques rely on the measure of infrared radiation from an optically excited region of the sample. When a semiconductor is optically excited by an intensity modulated laser beam with photon energy $h\nu$ greater than the fundamental energy gap E_g, absorption will occur, and a net amount of free carriers will be generated, in addition to the existing intrinsic carrier density. According to the principle of conservation of energy,[4] the radiation absorbed by the sample is exactly balanced by the radiation it emits (Kirchhoff's law). Therefore, the increase in carrier density above the intrinsic level will lead to a corresponding increase in the free carrier absorption coefficient and a subsequent increase in the emission of radiation.[7] This is the *carrier plasma contribution* to the PTR signal. During the deexcitation processes free carriers will diffuse in the conduction or valence-band edge through distances equal to their respective ac diffusion lengths $L_i(\omega) = L_i/(1+i\omega\tau)^{1/2}$, where $L_i = (D_i\tau_i)^{1/2}$ is the dc diffusion length, and then recombine directly across the band gap or into impurities and/or defect states within it. Here, D_i stands for diffusion coefficient, τ_i is the carrier lifetime, and $i=n$ (electron) or $i=p$ (hole). For an indirect gap material, such as silicon, the dominant process takes place through nonradiative energy conversion accompanied by phonon emission. As a result, the increase in sample temperature leads to an additional increase in infrared emission in accordance with Planck's radiation law. This second source of radiation is known as the *thermal contribution* to PTR. In PCR, the thermal contribution to the infrared emission is completely blocked by the judicious spectral matching of the detector bandwidth to the carrier plasma recombination-induced infrared emission spectrum in a semiconductor ("spectral matching").

In this letter, we report the application of infrared PCR as a noncontact technique to measure the temperature dependence of carrier mobility in industrial silicon wafers. In addition, the ability of the technique to measure carrier lifetime as well as surface recombination velocity is reported.

Carrier mobility (μ) is an important phenomenological parameter for describing the operation of semiconductor devices such as metal–oxide–semiconductor field-effect transistors and solar cells. It is one of the basic input parameters for expressing electrical current in devices. In addition, the determination of doping level in wafers requires a knowledge of carrier mobility. Several techniques have been used in determining carrier mobilities in semiconductors.[8] However, they all require samples specially prepared or, when this is not the case, they require electrical contacts for signal acquisition. In this work, we report the results of carrier mobility using an all-optical, nondestructive, and noncontacting diagnostic methodology.

The infrared PCR technique used here has already been applied to depth profilometry and imaging of deep subsurface electronic defects.[1] In Ref. 1, the authors presented a complete theory for PCR along with experimental evidence of its potential for semiconductor characterization. Spectral matching is instrumentally achieved by replacing the HgCdTe detector (spectral bandwidth between 2–12 μm) used in PTR by an InGaAs detector, which has a spectral bandwidth of 0.8–1.8 μm. This narrow spectral window ensures the Planck-mediated thermal infrared emission band be completely excluded from the detection range, while encompassing almost the entire emission band from the free carriers, found to be below 3 μm.[4]

The details of PCR instrumentation setup were described elsewhere.[1] An Ar^+ ion laser (λ=514.5 nm), emitting 15 mW on the sample surface, was used as an excitation source. In principle, any laser with super-band-gap photon energy could be used for exciting carriers, since the kinetics of the

[a]On leave from: Departmento de Física, Universidade Federal do Maranhão; Av. dos Portugueses, s/n, 65085-580 São Luis, MA, Brazil; electronic mail: jbatista@ufma.br

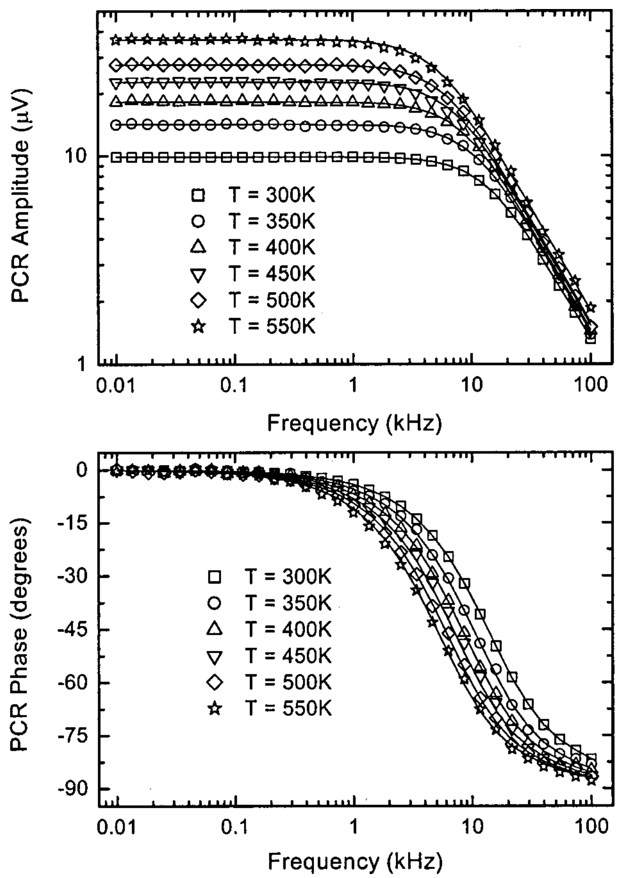

FIG. 1. (a) PCR amplitudes and (b) phase frequency responses at different temperatures. Only six of the twelve data sets are shown. The symbols represent experimental data points, while the lines are the best fitting to data. Laser power: 15 mW and beam size: 1.34 mm.

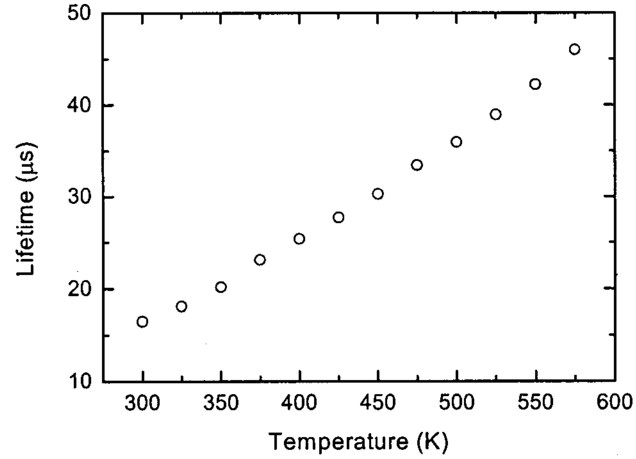

FIG. 2. Lifetime temperature dependence obtained by simultaneously fitting amplitude and phase frequency responses of Fig. 1.

diffusion–recombination processes following the absorption does not depend on the perturbation itself, but rather on the material properties. The modulation frequency range used was 10 Hz–100 kHz. It is worthwhile to point out that it is not necessary to be concerned with the lower-frequency limit at which the strength of the thermal emissions becomes significant relative to the plasma emissions, since the InGaAs detector is insensitive to any heating due to phonon emission. The laser beam diameter was measured to be 1.34 mm using the PTR response to a reference sample of known thermal properties. Temperature ramps were introduced by a heater/temperature controller with the entire process controlled by computer.

One n-type silicon wafer with resistivity $\rho = 10–15$ Ω cm, $N \sim 8 \times 10^{14}$ cm^{-3}, and a 980 Å thermally grown SiO_2 layer was studied. The wafer thickness ℓ was 530 μm.

Figure 1 shows the PCR experimental amplitude and phase frequency responses at different temperatures. The measured temperature range was 300–575 K, given a regular step of 25 K. For the sake of clarity, however, only six of the twelve data sets are shown in Fig. 1. The results of the best multiparameter fitting using the theory presented in Ref. 1 are also shown in Fig. 1. There is very good agreement between theory and experimental data for all temperatures. The typical cumulative fitting error for both amplitude and phase channels for each curve was about 1.8%. With one frequency scan (typical duration of about 10 min), it is possible to simultaneously obtain the carrier lifetime, diffusion coefficient, and surface velocity. The inherent instrumental component of the signal was removed by introducing an indirect normalization method. It was based on the fact that in the high-frequency regime both HgCdTe and InGaAs detectors monitor the same electronic processes.[1] Therefore, the instrumental normalization of the PCR signal could be performed by mathematically extracting the electronic component of the PTR signal from a good quality wafer and then adjusting the PCR signal to that component. All curves shown in Fig. 1 were normalized by the same transfer function obtained by this method.

As can be seen in Fig. 1, the PCR amplitude increases with temperature. There are two phenomena contributing to this behavior. The first one follows the Shockley–Read–Hall theory,[9,10] which assumes that the thermally excited carrier density partially neutralizes existing ionized impurities by increasing the occupation of empty energy states. Therefore, the photoinjected density of free carriers increases, consequently increasing the plasma recombination emission. This is directly associated with an increase of free carrier lifetime, as shown in Fig. 2. Previous measurements using conventional photothermal infrared radiometry led to the same conclusions.[5] The second contribution accounts for increasing of scattering mechanisms with temperature, which results in a decrease of carrier diffusivity, as shown in Fig. 3. The symbols represent experimental values and the line is the result of data fitting using a polynomial function of the form: $D(T) = a \times T^b$. The value obtained for the exponent b ($b = -1.49 \pm 0.01$) is in excellent agreement with that reported in literature,[5] where the diffusivity is found to have the following dependence on temperature: $D(T) \sim T^{-1.5}$. Lower diffusion coefficients amount to a higher probability of a carrier to remain within the PCR detection area before the deexcitation processes. A decreasing front surface recombination velocity with increasing temperature was observed: From 166 cm/s at 300 K to values less than 5 cm/s when the temperature approaches 575 K. This result was expected, since recombination velocity is inversely proportional to surface recombination lifetime. The PCR signal was not sensitive to changes in the back surface recombination velocity because the wafer is electronically thick ($L \ll \ell$) for all values of the carrier-wave diffusion length. The maximum value

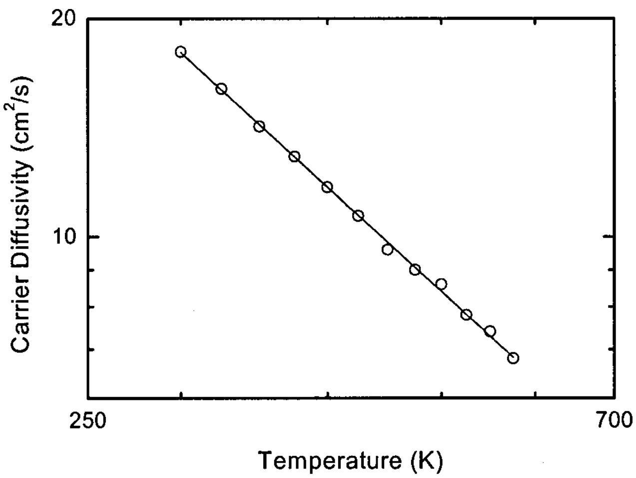

FIG. 3. Temperature dependence of ambipolar diffusion coefficient obtained by simultaneously fitting amplitude and phase frequency responses of Fig. 1. The symbols represent experimental values, while the line is the best fitting using the function $D(T)=a\times T^b$, where $a=(8.75\pm0.73)\times10^4$ and $b=-1.49\pm0.01$.

for L was about 177 μm at 10 Hz, much smaller than the wafer thickness ($\ell=530$ μm).

The carrier diffusion coefficient is a key parameter for mobility determination. It is assumed that the carrier transport in wafers under intensity modulated optical excitation is predominantly by diffusion. In the relatively low injection level regime, the carrier transport can be described by Boltzmann statistics and hence the mobility is related to the carrier diffusion coefficient by the Einstein relation $D=(kT/q)\mu$, where k is the Boltzmann constant, T is the absolute temperature, and q is the elementary charge. Therefore, if the diffusion coefficient is known at different temperatures, the temperature dependence of carrier mobility can be determined. Figure 4 shows the temperature dependence of the experimental carrier mobility (symbols) along with the best fitting (full line) using the same polynomial function as used for carrier diffusivity. Note that the values of mobility were appropriately normalized by their corresponding thermal voltages (kT/q). The temperature dependence of carrier mobility obtained could be expressed as

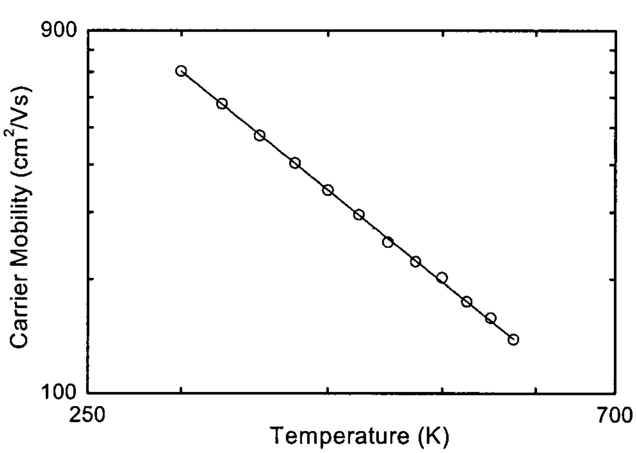

FIG. 4. Temperature dependence of conductivity mobility calculated from the ambipolar diffusion coefficients of the Fig. 3. The symbols represent experimental values, while the line is the best fitting using the function $\mu(T)=a\times T^b$, where $a=(1.06\pm0.07)\times10^9$ and $b=-2.49\pm0.01$.

$$\mu(T)=(1.06\pm0.07)\times10^9\times T^{-2.49\pm0.01}\ \mathrm{cm^2/V\,s}.$$

A similar result $[\mu_n(T)=(2.1\pm0.2)\times10^9\times T^{-2.5\pm0.1}$ cm^2/V s and $\mu_p(T)=(2.3\pm0.1)\times10^9\times T^{-2.7\pm0.1}$ cm^2/V s] was reported previously[11,12] using the Hall effect for determining the mobility of electrons and holes in Si, respectively. In a different study,[13] a semiempirical model was proposed and applied to several sets of data from literature, and values in between 2.2 and 2.4 were found for the constant b, the temperature power for mobility in Si samples.

The mobility of carriers in nonpolar semiconductors are determined by interactions with the acoustical vibrations of the lattice as well as by scattering by ionized impurities or other defects. The temperature dependence of mobility predicted by the deformation potential theory[14] is $\sim T^{-3/2}$. However, as mentioned above, experimentally measured dependencies differ from this value of $(-3/2)$. Reasons for this discrepancy include: (a) contributions from other scattering mechanisms may be present (for example, at temperatures above 100 K, the contribution of optical phonon scattering becomes considerable, which lowers the value of the mobility); and (b) the nonparabolicity, the distortion of equienergy surfaces as well as the effect of split-off subband holes may also contribute.[15]

Based on the experimental evidence shown here, there are excellent prospects for the PCR technique as a diagnostic technology in semiconductor process quality control. Its local monitoring nature surpasses the present available techniques for measuring carrier mobility (for example, conventional conductivity mobility, Hall effect, magnetoresistance mobility, and drift mobility). Besides, there are distinct advantages of PCR stemming from its fully noncontacting, nondestructive, and nonintrusive character. PCR may become an important tool toward device fabrication improvement, as it can monitor local values of carrier mobilities and other transport properties at several intermediate stages of device fabrication.

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