

Lifetime measurements in semiconductors by infrared absorption due to pulsed optical excitation

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A new contactless technique for determination of excess carrier lifetime in semiconductors is demonstrated. The technique involves measuring the change in the transmitted intensity of a continuous probe beam ($h\nu < E_g$) as a function of time through a semiconductor sample after switching off the excitation from a pulsed pump beam ($h\nu_p > E_g$). The technique has been applied to silicon samples having different doping densities. The measured lifetime values in the range of 0.5–200 μ s on both *n*-type and *p*-type silicon samples by this new technique agree well with the values obtained by the traditional photoconductive decay method.

The excess carrier lifetime is an important parameter as it characterizes the quality of the semiconductor material and affects the performance of the electron devices fabricated from it. The standard photoconductive technique for lifetime measurement needs attachment of electrical contacts to the sample. However, for many applications it is necessary to know the lifetime of excess carriers in the starting material prior to device processing and fabrication. Hence, contactless techniques are desirable.

The contactless techniques for excess carrier lifetime measurement reported in the literature so far include measurement of the change in intensity¹⁻⁴ or the deflection⁵ of a probe beam transmitted through a semiconductor sample due to the steady-state distribution of photogenerated excess carriers resulting from a pump beam with photon energy $h\nu_p$ greater than the semiconductor energy gap E_g . The probe beam photon energy $h\nu$ is less than E_g .

A new contactless technique for determination of excess carrier lifetime in semiconductors is reported here. The contactless techniques¹⁻⁵ mentioned above depend on the steady-state distribution of excess carriers due to the pump beam. The technique reported here differs from the others in that it measures the transient changes in the transmitted probe beam ($h\nu < E_g$) intensity after the pump beam pulse ($h\nu_p > E_g$) is shut off. The transient measurements reflect the excess carrier recombination process and hence is more direct in interpretation of results.

For a semiconductor sample, if surface recombination is negligible and if the product of the diffusion length and the absorption coefficient at the pump beam wavelength is much greater than unity, then the fractional change in the transmission of the probe beam ($\Delta I/I$) due to the steady-state excess carrier distribution is given by²

$$\Delta I/I = -(1 - R_\lambda)v_\lambda\sigma Q_p\tau, \quad (1)$$

where R_λ is the reflectivity, v_λ is the quantum yield, Q_p is the photon flux at the pump frequency, σ is the effective

cross section for carrier absorption at the probe frequency, and τ is the excess carrier lifetime. From Eq. (1), τ can be obtained provided the values of R_λ , v_λ , and σ for the material are known. However, for many materials these parameters frequently are not readily available.

If a pulsed pump beam irradiates the front surface ($x = 0$) of a uniformly doped semiconductor wafer, the continuity equation for the excess carrier density δ after the removal of the pulse is given by

$$\frac{\partial \delta}{\partial t} = D \frac{\partial^2 \delta}{\partial x^2} - \frac{\delta}{\tau}, \quad (2)$$

where D is the ambipolar diffusion coefficient and τ is the excess carrier lifetime. The solution of this equation for negligible surface recombination and for a high value for the absorption coefficient at the pump frequency is given by⁶

$$\delta(x,t) = \frac{\delta_0}{\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt} - \frac{t}{\tau}\right), \quad (3)$$

where δ_0 is the surface density of photogenerated carriers injected by a single pulse of the pump beam. In the presence of the pump beam the total absorption coefficient α for the probe beam will increase by $\Delta\alpha$ given by

$$\Delta\alpha = \sigma\delta(x,t). \quad (4)$$

The fractional change in the transmitted probe beam intensity $\Delta I/I$ can be expressed as

$$\frac{\Delta I}{I} \approx -\sigma \int_0^d \delta(x,t) dx \quad (5)$$

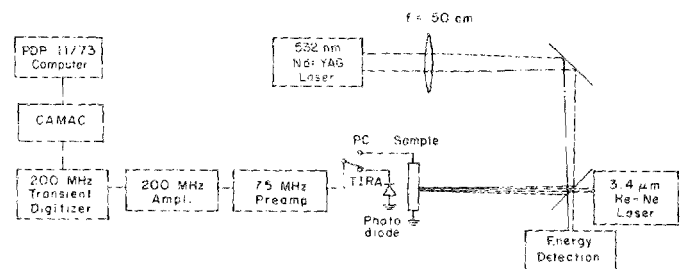


FIG. 1. Schematic of the experimental apparatus.

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TABLE I. Resistivity and thickness of silicon samples used in the experiment.

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Type	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Resistivity (Ω cm)	0.02	0.15	1.3	4.0	5.4	18	0.57	1.7	12.5	13	69	230	400
Thickness (μ m)	200	260	170	410	250	200	250	240	190	230	1380	1400	6×10^4

for the low pump-beam intensity condition

$$\sigma \int_0^d \delta(x,t) dx \ll 1,$$

where d is the thickness of the sample. If the thickness of the sample is much greater than the ambipolar diffusion length L , the integral limit in Eq. (5) can be replaced from 0 to ∞ . Combining Eqs. (3) and (5) gives

$$\Delta I(t) = -I\delta_0\sigma \exp(-t/\tau). \quad (6)$$

Equation (6) shows that the transmission recovery curve $\Delta I(t)$ is an exponential function of time t . Hence, by this technique the observation of $\Delta I(t)$ after a pump beam pulse is shut off enables the lifetime to be determined directly.

The experimental setup is shown in Fig. 1. A Spectra Physics 120S-2 He-Ne laser of 2 mW intensity at 3.4 μ m wavelength was used as a probe beam. It illuminated the sample over a 3-mm² area defined by a hole. A Quantal YAG laser with a 10-Hz repetition rate running on its second harmonic at 532 nm wavelength with a full width at half-maximum (FWHM) value of 18 ns was slightly focused through the same aperture onto the sample. The focus was positioned 2 cm behind the sample. The intensity of the YAG laser was measured by a calibrated joulemeter. An Oriel InAs IR photodiode with a peak response wavelength of 3.5 μ m and a time constant of 50 ns was located behind the sample to measure the changes in the transmitted intensity of the He-Ne laser due to the changes in the number of free carriers caused by the YAG laser pulse. The signal from the photodiode was amplified and fed into a LeCroy 8828B 200-MHz transient digitizer and stored in a PDP 11/73 computer. The circuit used allowed switching from the transmission to the photoconductivity measurement without moving the sample or any other part of the alignment.

The resistivity and thickness values of the silicon samples used in this paper are listed in Table I. The samples were polished by using a Buehler 67-1509 polisher and etched in

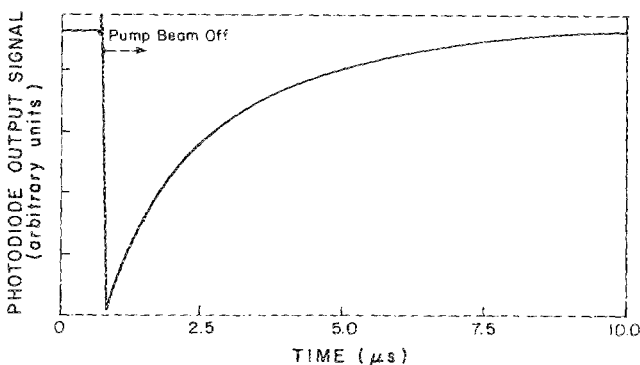


FIG. 2. Typical photodiode output curve.

CP4-a solution. Ohmic contacts were made on some of the samples for photoconductivity measurement by depositing Al or Ni for *p*- or *n*-type silicon, respectively. The resistivity was measured with a Veeco FPP-100 four-point probe.

The lifetime values were taken from the time-resolved transmission recovery curve without the use of any curve-fitting program. Figure 2 shows a typical transmission recovery curve for a 1.7- Ω cm *p*-type silicon sample. The lifetime determined from this curve was 2 μ s. Usually the transmission recovery curve includes a fast rising term at the very beginning, followed by a term with a longer time constant. The lifetime values are obtained from the later part, which starts at approximately 1–3 times the lifetime after the YAG laser pulse irradiation. The change between the values of lifetime taken slightly earlier or later in time from this part is within a range of 10%–20%.

The lifetime versus resistivity results are shown in Fig. 3. The lifetime values shown in this figure are the mean values taken under different YAG laser intensities. The error bar shows the maximum deviation from the mean. In this figure the reference data about lifetime in silicon⁷ are shown by broken lines for comparison purposes.

The pump pulse energy of 0.001–0.05 mJ used in this work corresponds to 9×10^{13} – 4.5×10^{15} photons/cm² at the sample surface. The value of σ at 3.4 μ m probe beam wavelength is about $1\text{--}5 \times 10^{-17}$ cm² (Ref. 7). Hence, the low pump intensity condition $\delta_0\sigma \ll 1$ is satisfied for our experiments. We believe that the nonexponential term in the transmission recovery curve is caused by the higher order modes in the excess carrier decay.⁸ At a sufficiently later stage of the decay the higher order modes will be negligible

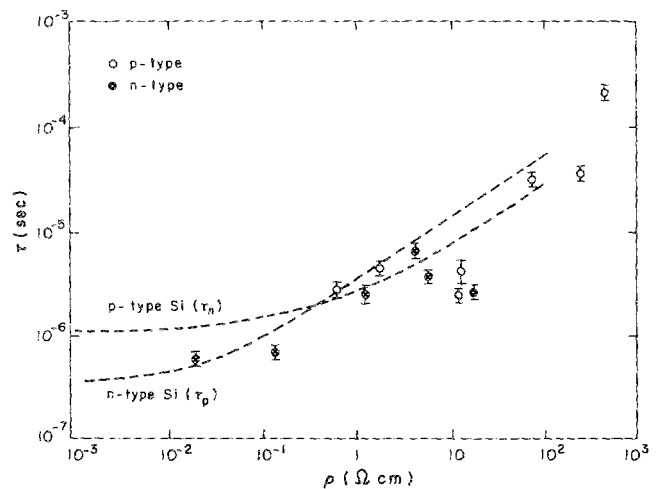


FIG. 3. Experimental results of lifetime vs resistivity for *n*- and *p*-type silicon. The broken lines are after Ref. 7.

TABLE II. Comparison between the measured lifetime values in silicon by the transient infrared absorption (TIRA) and the photoconductivity decay techniques.

Lifetime (μs) \diagdown	Sample No.	1	2	4	5	7	8	9	11
TIRA method		0.60 ± 0.02	0.67 ± 0.05	1.3 ± 0.2	2.5 ± 0.2	2.4 ± 0.2	2.5 ± 0.5	1.7 ± 0.2	30 ± 4
Photoconductive decay method		0.54 ± 0.02	0.74 ± 0.04	1.5 ± 0.3	2.7 ± 0.1	2.6 ± 0.3	2.6 ± 0.5	1.6 ± 0.4	36 ± 6

and the curve becomes exponential from which the effective lifetime τ can be obtained.

For some samples ohmic contacts were made for photoconductivity decay measurement as well. The results are listed in Table II. As seen from this table, the agreement for the measured lifetimes between the two methods is quite good for all these samples.

In summary, we have described a new nondestructive contactless technique for measurement of photogenerated carrier lifetimes in semiconductors that utilizes transient measurements. The results for silicon are in a good agreement with the results from photoconductivity decay measurement. Compared with other steady-state nondestructive measurement techniques, this new method can measure the lifetime directly from the transmission recovery curve without the knowledge of other material parameters. In principle, the new technique can be used for other semiconductors provided appropriate pump beam, probe beam, and related

detector are available. We are currently extending this technique to surfaces with a nonzero surface recombination velocity.

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