Title
INVESTIGATION OF NONRADIATIVE RECOMBINATION IN SMEICONDUCTORS BY PHOTOTHERMAL DISPLACEMENT SPECTROSCOPY

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Abstract

The dynamics of nonradiative recombination processes are investigated by measuring the thermal expansion and subsequent displacement of a sample surface caused by the absorption of a modulated laser beam.

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Nonradiative recombination processes in semiconductors have attracted much interest due to their fundamental role in determining electronic properties, and because of their impact on device performance and in material processing (Laser annealing etc.). Despite this importance, only limited data are available, mostly due to a lack of experimental tools. Several papers report on distinct differences in the photoacoustic response of samples with short and long nonradiative lifetimes [1-3], and theoretical models have been developed which attempt to account for the observed effects [3-5]. A problem is the complicated frequency dependence of the photoacoustic response, even in the absence of finite recombination effects. As Sablikov and Sandomirskii [5] point out, the baseline for determining the kinetics of nonradiative transitions is difficult to establish; yet it is of vital importance for such application.

We present a noncontact method for studying the dynamics of nonradiative recombination which is based on the photothermal displacement effect [6]. The heat released during the nonradiative recombination raises the sample temperature and causes it to expand. In the photothermal displacement experiment the resulting displacement of the sample surface is measured with a Michelson interferometer. The frequency (or time) dependence of the signal is directly related to the kinetics of the nonradiative processes. As will be shown below, the frequency dependence of the signal, without any

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finite recombination effects, i.e., the baseline of the experiment, is simple and predictable, so that the analysis of the data is straightforward. The experimental set-up is shown in Figure 1. By adjusting the optical path difference between the two arms to points A or B, the interferometer will serve as a sensitive detector for the displacement δ of the sample surface. The sensitivity is best at frequencies above 10 kHz and approaches 3×10^{-5}Å. A detailed theoretical analysis of the photothermal displacement has been given in Ref. 6. A simplified one dimensional model can be applied to the present case. If the modulated pump beam power is completely absorbed in the sample we can write the resulting thermal expansion δ:

$$\delta = \frac{\xi}{Q \cdot \rho} \times (1 - R) \times \int P(t)\,dt \qquad (1)$$

where ξ - thermal expansion coefficient; Q - heat capacity; R - reflectivity; ρ - mass density. For a modulated power $P = P_0 e^{j\omega t}$ + c.c. the resulting amplitude of the modulated displacement is given by:

$$\delta = \frac{\xi}{Q \cdot \rho} \times (1 - R) \times \frac{1}{j\omega} \times P_o + c.c. \qquad (2)$$

Thus, a $1/\omega$-dependence for the signal strength and a phase of -90° establishes the baseline for this thermal method.

This behavior was verified on a variety of materials. In all cases the signal approaches the $1/\omega$-dependence and the -90° phase angle above some frequency which depends on the specific material properties. Figure 2 shows results from the two extreme cases (low vs. high thermal conductivity). The straight lines indicate the $1/\omega$-dependence and the phase of -90°. In both cases, Eq. (2) is verified for the signal and the phase. However, for the copper sample, this behavior is approached at much higher frequencies due to the higher thermal conductivity. The absolute value of the displacement in the $1/\omega$-regime agrees with the predicted value given by equation (2) within 30%.

The usefulness of the method to evaluate nonradiative lifetimes is demonstrated in Figure 3 The left part shows data obtained on a mechanically polished Si-surface, which generally exhibit high surface recombination velocities. The data shown in the right part have been measured on the same surface after chemical etching to reduce the surface recombination velocity. The experimental results clearly reflect the surface treatment. The data can be fitted to an exponential relaxation with lifetimes of 2.6 μs for the mechanically polished and 18 μs for the chemically polished case.

In conclusion, we have shown that the photothermal displacement effect exhibits a highly predictable and simple frequency dependence which makes it suitable for studying nonradiative recombination processes.

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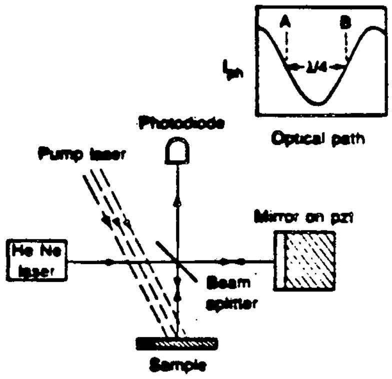

Figure 1: Experimental set-up for detecting the photothermal displacement.

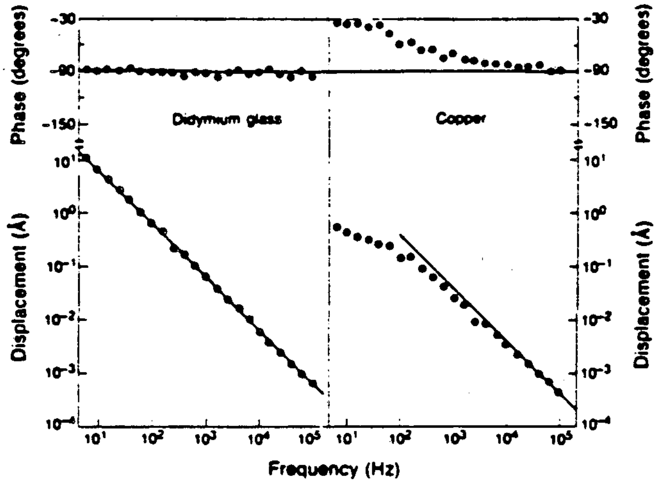

Figure 2: Magnitude and phase of the displacement for a copper and didymium samples.

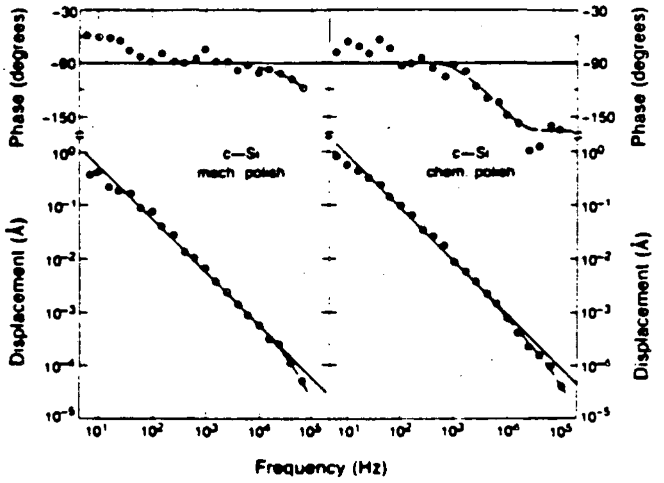

Figure 3: Photothermal displacement obtained on differently prepared surfaces of p-type crystalline silicon.

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