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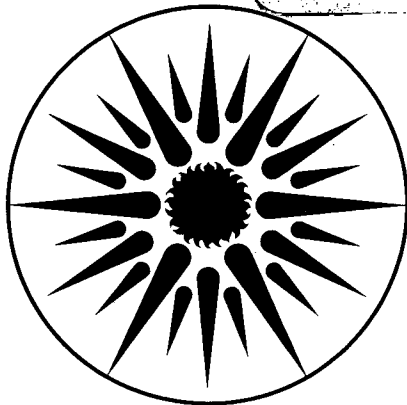
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SPATIALLY-RESOLVED INVESTIGATION OF TRANSPORT IN SEMICONDUCTORS: A PHOTOTHERMAL DEFLECTION APPROACH

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The unique ability of photothermal deflection spectroscopy¹ to probe the local index of refraction of matter is exploited to investigate, in a spatially-resolved manner, thermal and electronic transport in semiconductors. An added advantage of this approach is that it is contactless; hence, it obviates the classical problems associated with electrodes and contacts.

The basic premise of the technique is the use of the heat associated with non-radiative processes (e.g., recombination of carriers) to deflect a focussed laser probe beam (sub-gap energy) propagating *through* the semiconductor. The deflection of the probe beam is caused by a change in the refractive index of the sample which is in turn governed by carrier diffusion and recombination.

Various photoacoustic detection schemes have been proposed for measuring transport parameters in semiconductors.⁽²⁻⁴⁾ However, for these approaches the acoustic response was due either to the sample surface temperature (gas-cell experiment) or to the integrated deformation of the entire sample (piezoelectric detection). Hence neither approach yields spatially-resolved information. Our approach is significantly different since we employ a local probe beam which enables us to directly investigate transport anywhere within or at the surface/interface of the semiconductor under investigation. To calculate the temperature and the carrier distributions throughout the sample, we consider the case shown in Fig. (1). The deflection of the probe beam located at distance x from the illuminated sample surface is given by:

$$\theta(x,t) = \frac{l}{n} \frac{\partial n(x,t)}{\partial x}$$

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where $\frac{\partial n(x,t)}{\partial x}$ is given by:

$$\frac{\partial n(x,t)}{\partial x} = \frac{\partial n}{\partial T} \frac{\partial T(x,t)}{\partial x} + \frac{\partial n}{\partial N} \frac{\partial N(x,t)}{\partial x}$$

where l is the interaction length of the probe beam and the probed area, ($l \gg x$, and is much larger than thermal and carrier diffusion lengths), n is the average index of refraction, $T(x,t)$ and $N(x,t)$ are the time-dependent temperature and the minority carrier density distribution, respectively. $\frac{\partial n}{\partial N}$, which is mainly due to free carrier generation, depends strongly on the probe beam wavelength, whereas $\frac{\partial n}{\partial T}$ is weakly wavelength dependent.

We have shown that the gradient of the minority carrier density distribution can be written as:

$$N(x,t) = \text{Re} \left[\frac{-\phi_0}{h\nu D \left(\frac{s}{D} + \sigma \right)} e^{-x\sigma} e^{j\omega t} \right] \quad (1)$$

where D is the minority carrier diffusion, s is the surface recombination velocity, ϕ_0 is the light flux, $h\nu$ is the photon energy, τ is the minority carrier lifetime, $\sigma =$

$\sqrt{\frac{1 + j\omega\tau}{\tau D}}$, while the temperature gradient is given by:

$$\begin{aligned} \frac{dT}{dx}(x,t) = \text{Re} & \left\{ \frac{\phi_0 E_G \sigma e^{-x\sigma} e^{j\omega t}}{h\nu\tau D k \left(\frac{s}{D} + \sigma \right) \left(\frac{1}{\tau D} + j \left(\frac{\omega}{D} - \frac{\omega}{D_{th}} \right) \right)} \right. \\ & \left[\frac{\phi_0 E_G \sigma}{h\nu\tau D k \left(\frac{s}{D} + \sigma \right) \left(\frac{1}{\tau D} + j \left(\frac{\omega}{D} - \frac{\omega}{D_{th}} \right) \right)} + \right. \\ & \left. \left. \frac{\phi_0 E_G s}{h\nu D k \left(\frac{s}{D} + \sigma \right)} + \frac{(h\nu - E_G) \phi_0}{h\nu k} \right] e^{-x} \sqrt{\frac{j\omega}{D_{th}}} e^{j\omega t} \right\} \quad (2) \end{aligned}$$

where D_{th} is the thermal diffusivity, k is the thermal conductivity, E_G is the semiconductor gap energy.

At low frequencies, the second term of the right-hand side of Eq. (2) dominates, hence the signal exhibits a thermal wave-like dependence. At high frequencies ($\omega\tau \gg 1$), since $D \ll D_{th}$ by typically an order of magnitude, the free carrier contribution dominates through Eq. (1) which is related to the free carrier-induced index of refraction variation; and/or through the first term in the right-hand side of Eq. (2) which is associated with the heat released in the crystal when carrier recombination takes place. For the intermediate frequencies, there is a complex interaction which is highly sensitive to the carrier lifetime and surface recombination.

The experimental set-up is shown in Fig. (1). The sample used for our experiment was a p-doped Si ($\rho \sim 6\Omega \text{ cm}$ - 3×10^{15} carriers/cm³). One face of the crystal was mechanically polished and the surface was treated with methanol to minimize surface recombination.

Fig. (2) shows the results obtained when the polished methanol-treated face of the Si crystal was illuminated (with 2.4 eV photons) and the carrier transport was probed by a 1.15 μ HeNe beam at increasing distances from the face, detected by a position sensor. The regimes predicted by the theory are evident and the agreement with the theory is excellent for both the signal and phase. The experimental values deduced for D_{th} and D agreed exactly with literature values. In reasonable agreement were s , τ and dn/dN , which were taken as adjustable parameters. Illuminating the unpolished face gave results that could be fitted with the same parameter set, except, as expected, with an appropriately larger value for s , (Fig. 3). It should be emphasized that no input parameters need be known *a priori*. We have also investigated the effect of the pump beam intensity and probed the free carrier contribution with the use of 3.39 μ probe beam.

In conclusion, we have presented a novel method for the study of transport in semiconductors. It yields spatially-resolved, *in situ* information; requires *no* contacts; and is easy to implement.

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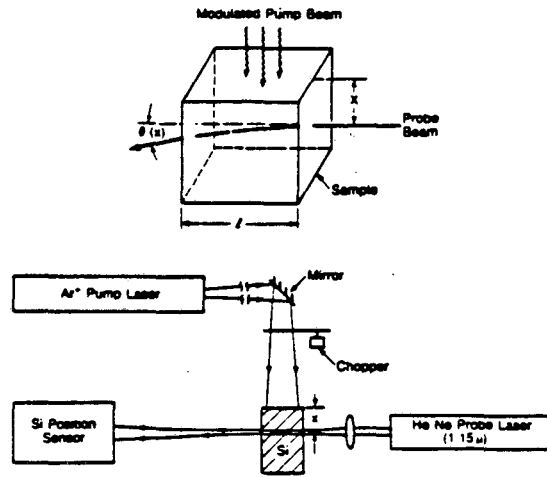


Fig. (1)

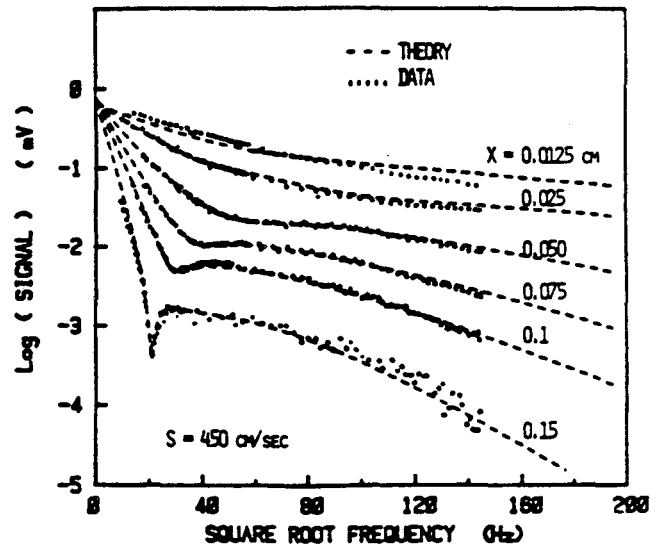


Fig. (2A)

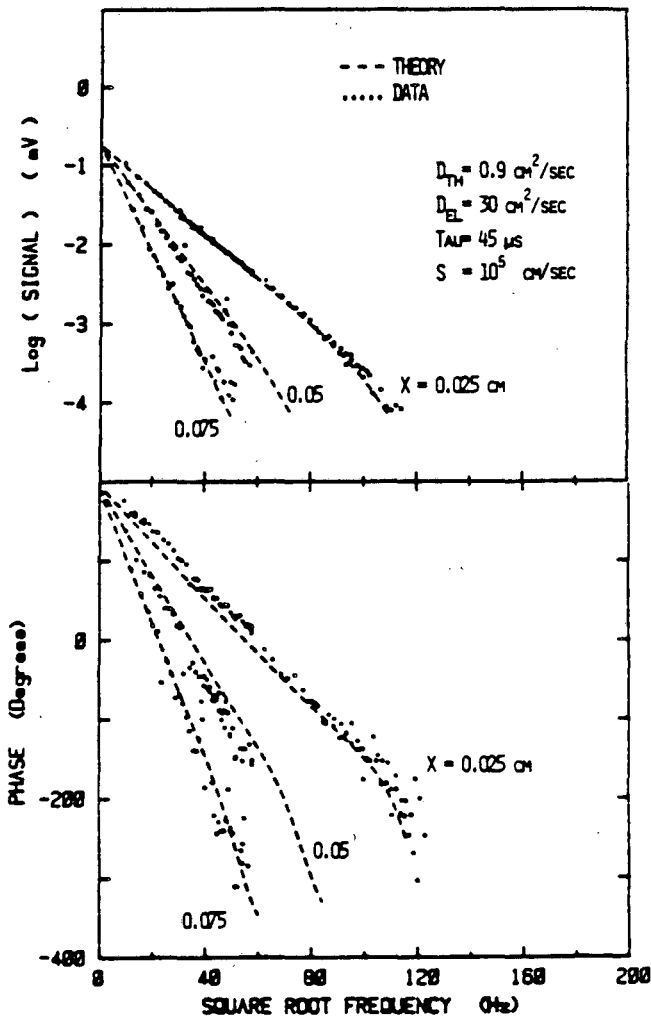


Fig. (3)

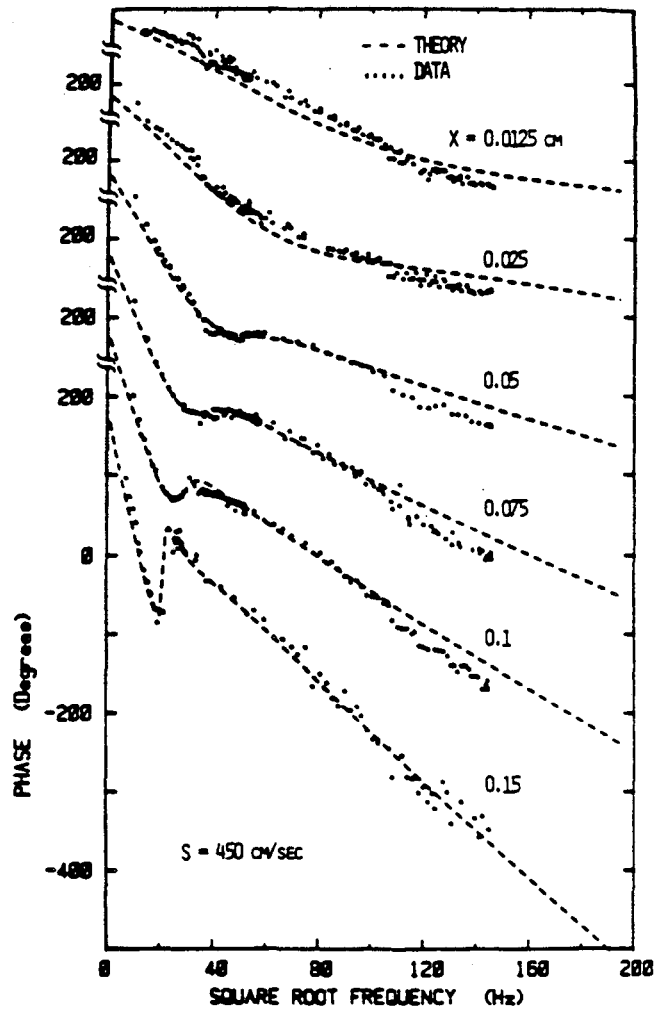


Fig. (2b)

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