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Citation: Appl. Phys. Lett. **49**, 791 (1986); doi: 10.1063/1.97548
View online: http://dx.doi.org/10.1063/1.97548
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v49/i13
Published by the American Institute of Physics.

Steady-state photocarrier grating technique for diffusion length measurement in photoconductive insulators

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(Received 3 April 1986; accepted for publication 4 August 1986)

A new simple technique for the determination of the diffusion length in photoconductive insulators is presented. A steady-state photocarrier grating is created by two interfering laser beams, and the magnitude of the secondary photocurrent perpendicular to the grating fringes is measured. The measurement is then repeated when the two beams are incoherent. From a determination of the two photocurrents as a function of grating period the diffusion length of the photocarriers can be obtained. The method can yield accurate results to 5% of the laser wavelength.

Interference of two light beams has been widely used for measuring the excess carrier diffusion length in semiconductors,[1] and in particular in amorphous hydrogenated silicon.[2,3] In these experiments the interference pattern produces a periodic change in the refractive index and the absorption coefficient of the investigated material. The diffusion length is then obtained from the intensity of the light which is diffracted from these gratings, measured as a function of time and grating period. In this letter we propose an alternative technique for measuring the diffusion length which also involves a grating produced by the interfering light beams but which does not involve diffraction effects. Instead it is merely necessary to measure the steady-state photocurrent perpendicular to the direction of the grating fringes. The suggested technique has the merit of being free from any thermal grating effects which may contribute to the diffracted light intensity,[1] but obviously not to the photocurrent. In our technique the photocarrier gratings have a small modulation depth and can therefore be regarded as a perturbation of a uniform illumination. A linear mathematical treatment is therefore justified even for materials having a nonlinear response to light intensity.

Two interfering beams of intensities I_1 and I_2 form a sinusoidally varying light intensity pattern:

$$I(x) = (I_1 + I_2)\left[1 + \gamma_0 \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} \cos\left(\frac{2\pi x}{\Lambda}\right)\right]. \quad (1)$$

In Eq. (1) $\Lambda = \lambda/[2\sin(\delta/2)]$ is the grating period, λ the light wavelength, δ the angle between the two beams, and x the coordinate perpendicular to the intersect between the two beams. γ_0 is a factor between zero and unity by which the fringe visibility is reduced because of partial coherence between the beams, light scattering, and mechanical vibration averaged over some time constant.

In general, the photocurrent in the sample will be dominated by one of the carriers and its concentration N will not be uniform because the generation rate G is proportional to the light intensity given by Eq. (1). In the absence of a strong electric field the diffusion equation is

$$D\frac{d^2N}{dx^2} - R(N) + G = 0. \quad (2)$$

In this equation R is the recombination rate and D is an effective diffusion constant. At first glance Eq. (2) is identical with the diffusion equation for the minority carriers in an extrinsic semiconductor.[4] Since, however, both electrons and holes diffuse together and trapping of both carriers must be taken into account D can be a complicated function of material parameters and even light intensity. The exact value of D need not, however, concern us here since we shall be interested only in the diffusion length L which contains the product of D and τ, where τ is a suitably defined lifetime. In order to define τ we first note that the recombination rate is generally concentration dependent, which leads to a steady-state photoconductivity PC of the form $\mathrm{PC} \propto G^{\alpha}$, with α in the range from 0.5 to 1.[5] Since the carrier concentration N is proportional to PC and since in the steady state, under uniform illumination $R = G$, one obtains

$$R = cN^{1/\alpha} \equiv N/\tau(N), \quad (3)$$

where c is a constant. Equation (3) defines $\tau(N)$, the concentration-dependent lifetime.

In the present context the generation rate G consists of a uniform part G_0 and a sinusoidally varying part $g(x)$ which is small if $I_1 \gg I_2$. A perturbation technique can then be used to solve for the first-order variation in the excess carrier concentration $n(x)$:

$$\alpha D\frac{d^2n}{dx^2} - \frac{n}{\tau(N_0)} + \alpha g = 0, \quad (4)$$

where N_0 is the density of carriers due to the uniform generation G_0. Comparing Eq. (4) with the ordinary linear diffusion equation we find that the diffusion length L is carrier concentration dependent and equal to

$$L = \sqrt{\alpha D\tau(N_0)}. \quad (5)$$

Since the photoconductivity σ is proportional to $N = N_0 + n(x)$, solution of Eq. (4) yields

$$\sigma(x) = \sigma(I_1 + I_2)[1 + A\cos(2\pi x/\Lambda)], \quad (6)$$

where $\sigma(I_1 + I_2)$ is the PC due to the uniform part of Eq. (1). The photocarrier grating amplitude A is found to be

$$A = 2\alpha\gamma_0\gamma\sqrt{I_1 I_2}/(I_1 + I_2), \quad (7)$$

with

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$$\gamma = \frac{1}{1 + (2\pi L/\Lambda)^2} . \quad (8)$$

The grating amplitude is detected by measuring the secondary photocurrent perpendicular to the grating fringes. The average resistivity in this direction is obtained by integrating the resistivity over one grating period and dividing by the grating spacing. Neglecting the dark resistivity, the resulting "grating conductivity" σ_g is

$$\sigma_g = \Lambda \Big/ \int_0^{\Lambda} \frac{dx}{\sigma(x)} = \sigma(I_1 + I_2)\sqrt{1 - A^2} . \quad (9)$$

In order to demonstrate the steady-state photocarrier grating effect we first point out that for the case of an ideal grating, linear dependence of photocurrent on excitation, and no carrier diffusion, i.e., $\gamma_0 = \alpha = \gamma = 1$, inserting (7) into (9) yields

$$\sigma_g = \sigma(I_1) - \sigma(I_2) . \quad (10)$$

Here $\sigma(I_1)$ and $\sigma(I_2)$ are the PC due to I_1 and I_2 separately. In a material having a linear dependence of PC on the light intensity an incoherent beam I_2 added to I_1, results in an increase of the total photoconductivity from a value of $\sigma(I_1)$ to $\sigma(I_1) + \sigma(I_2)$. The striking result of Eq. (10), on the other hand, is that in such a material and no diffusion a coherent beam I_2 superimposed on I_1, reduces the PC by exactly the same $\sigma(I_2)$ to a value of $\sigma(I_1) - \sigma(I_2)$.

We continue now by describing the experimental procedure for obtaining the diffusion length from the grating effect. The weak excitation beam I_2 is chopped and the resulting "in-phase" photocurrent is measured by a lock-in amplifier in the presence of the coherent beam I_1. Thus, the obtained reading is proportional to $\sigma_g - \sigma(I_1)$. Now the coherent beam I_1 is replaced by a beam which is incoherent with I_2 but has the same intensity I_1, and the measurement is repeated. The obtained signal is now proportional to $\sigma(I_1 + I_2) - \sigma(I_1)$. We denote the ratio between these two signals by β

$$\beta = [\sigma_g - \sigma(I_1)]/[\sigma(I_1 + I_2) - \sigma(I_1)] . \quad (11)$$

Note that in the above ratio the denominator is the PC due to I_2 with an incoherent bias illumination of intensity I_1, while the numerator is the PC due to the same light beam I_2 but with a coherent bias illumination. For the case of no diffusion, linear PC, and ideal grating one finds using Eq. (10) that $\beta = -1$. In the general case, using the power law intensity dependence of PC and Eq. (9), we obtain

$$\beta = [(1 + \theta)^{\alpha}\sqrt{1 - A^2} - 1]/[(1 + \theta)^{\alpha} - 1] , \quad (12)$$

where $\theta = I_2/I_1$. Substituting A from Eq. (7), and using the fact that I_2 is chosen to be much smaller than I_1, the following relation is obtained:

$$\beta = 1 - 2\alpha\gamma_0^2\,\gamma^2 . \quad (13)$$

Finally, using Eq. (8) and solving for the diffusion length yields

$$L = (\Lambda/2\pi)[\alpha^{1/2}\gamma_0\sqrt{2/(1 - \beta)} - 1]^{1/2} . \quad (14)$$

Figure 1 is a plot of β as a function of L/Λ for several reasonable values of the parameter $\phi = \alpha\gamma_0^2$. We first note that β is close to unity for L much longer than the grating period. This is the case in which the carrier diffusion completely blurs the grating and the signal is the same whether I_1 and I_2 do interfere and create a grating or not. At the other extreme, if the diffusion length is much shorter than the grating period, the carrier grating will sustain and β becomes negative. This means that due to the carrier grating the total photocurrent with I_2 on is less than with I_2 off, and the lowest value of β is -1 for the ideal case which has been discussed above. The plots shown in Fig. 1 can now be used to determine L from the measured value of β. Assuming that $\gamma_0 = 1$ and having measured α independently, an upper limit for L is obtained using the curve corresponding to the parameter $\phi = \alpha$. The grating "quality factor" γ_0 may be estimated by measuring β for grating spacings well beyond the diffusion length, and comparing the results to the plots given in Fig. 1. From these plots it is also evident that to obtain an accurate measurement of L, the grating period has to be set to a value which yields values of β ranging between 0.2 and 0.8. In this range β is sensitive to the ratio L/Λ while some uncertainty about the exact value of ϕ will not cause a serious error in the corresponding L. Since the shortest obtainable Λ is $\lambda/2$ and the lowest limit for an accurate determination of L is about 0.1Λ, the shortest L accurately measurable with this method is about $\lambda/20$.

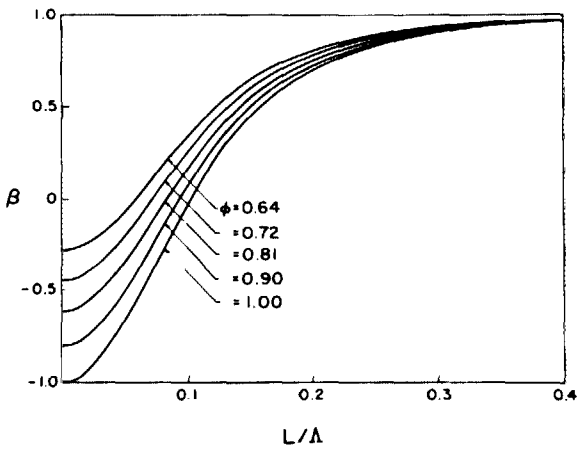

FIG. 1. Ratio β vs the diffusion length normalized by the grating period, for different values of $\phi(\phi = \alpha\gamma_0^2)$.

Preliminary data have been obtained on hydrogenated amorphous silicon samples which confirm the usefulness and accuracy of the technique. These will be given elsewhere[6] together with the experimental details. As an example, for a sample with a photoconductivity of 2×10^{-4} $(\Omega\,\mathrm{cm})^{-1}$ at one sun illumination, we find an ambipolar diffusion length of 1030 Å with an accuracy of 5%. These results are comparable with typical values for L obtained by more conventional techniques like the surface photovoltage method[7–9] and the photoelectromagnetic effect.[10]

This work was supported by the Solar Energy Research Institute, U. S. Department of Energy, and the Technion, Israel Institute of Technology.

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