

Ambipolar drift-length measurement in amorphous hydrogenated silicon using the steady-state photocarrier grating technique

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The steady-state photocarrier grating technique, which yields the ambipolar diffusion length in photoconductive insulators, can also yield the ambipolar drift length if the measurements are carried out as a function of electric field. This characteristic length in turn gives a lower bound on the experimental value of the minority-carrier drift length. From measurements of both the diffusion and drift length on the same sample of amorphous hydrogenated silicon it is found that the ratio between the ambipolar diffusion coefficient and the ambipolar mobility is equal to about twice the classical Einstein value.

Ambipolar transport measurements are frequently carried out in semiconductors in order to obtain information about the behavior of excess carriers, such as those produced by light, which move under the influence of a concentration gradient and/or an electric field.¹ If the sole driving force for the carriers is a concentration gradient the experiments yield a parameter called the ambipolar diffusion length L_d . If, on the other hand, the main motive force is an electric field, one obtains the ambipolar drift length L_e . Under certain circumstances, such as in doped crystalline semiconductors, L_e and L_d are simply the minority-carrier diffusion length and drift length, respectively, and are thus related through the Einstein relation. Under other circumstances, as for a near-intrinsic crystalline material, the Einstein relation does not hold since L_e then approaches zero.¹ In the case of amorphous semiconductors, as typified by hydrogenated amorphous silicon (*a*-Si:H), the relation between these two characteristic lengths cannot be predicted *a priori* since the transport and recombination behavior of excess carriers in such materials are not sufficiently well understood. It is therefore not clear whether undoped material can be treated as an intrinsic semiconductor, and for this reason a separate determination of the ambipolar diffusion length and the ambipolar drift length is of interest. From the point of view of device physics a knowledge of L_e *per se* is not of interest but rather the separate values of the electron and hole drift length are desired.² A determination of L_e will, nevertheless, yield the minority-carrier drift length if undoped *a*-Si:H behaves like an extrinsic material and will at least yield a lower limit for the drift length of the minority carriers if it behaves like an intrinsic material.

We have recently demonstrated a new, simple technique for measuring L_d called the steady-state photocarrier grating (SSPG) technique. In the theory underlying the technique³ and in the subsequent more detailed description of experimental results⁴ the assumption was made that the electric field employed in carrying out the measurements is negligible so that carriers move only due to a concentration gradient. In this paper we show that by carrying out the experiment as a function of the electric field both the ambipolar diffusion length and the ambipolar drift length

of carriers can be determined in the same sample.

The SSPG technique for determining the ambipolar diffusion length in a photoconductive insulator has been described elsewhere.^{3,4} Briefly, the technique consists of measuring the ac component of the photocurrent in a sample illuminated by two light beams, one of which is chopped and much weaker than the other, when the two beams are coherent and when they are incoherent. In the former case the interference of the beams results in a sinusoidally varying concentration of photocarriers. One can show that the ac component of the photocurrent in this case is smaller than for the case in which the two beams are incoherent. Because the concentration of carriers is not uniform, diffusion takes place and tends to smear out the photocarrier grating. This blurring process depends on the grating period and its effect can be seen as a reduction of the difference in the ac component of the photocurrents for the coherent and incoherent cases. By measuring this difference at some known grating period the ambipolar diffusion length can be calculated.³

When the effect of an electric field is included and no space charges exist, the ambipolar continuity equation for the steady-state photocarrier concentration is given by

$$D\nabla^2 n + \mu E \nabla n + G - R = 0, \quad (1)$$

where n is the photocarrier concentration, D and μ are the ambipolar diffusion constant and ambipolar mobility of the photocarriers, respectively, E is the electric field, R the recombination rate, and G the generation rate. The ambipolar transport parameters D and μ may both be complicated functions of the electron and hole transport parameters and even the light intensity,^{5,6} due to the requirement of charge neutrality which couples the motion of electrons and holes. Since the derivation of their explicit expressions in *a*-Si:H is beyond the scope of this article we confine the present discussion to the measurement of the ambipolar drift and diffusion lengths with no further elaboration on the exact nature of D and μ .

The generation rate G is composed of two parts, a large uniform generation rate G_0 and a small nonuniform part created by the interference of the two nonequal beams.

Thus, G is given by

$$G = G_0 + G_1 \cos \left(\frac{2\pi}{\Lambda} x \right), \quad (2)$$

where $G_1 \ll G_0$, Λ is the grating period, and x is the coordinate perpendicular to the grating fringes. We define a lifetime τ by the rate of change of the recombination rate R at the background concentration n_0 , as follows:

$$\tau^{-1} = \left. \frac{dR}{dn} \right|_{n_0}. \quad (3)$$

Solving Eq. (1) and using (2) and (3) the photocarrier concentration is found to be

$$n = n_0 + \gamma G_1 \tau \cos \left(\frac{2\pi}{\Lambda} x + \phi \right). \quad (4)$$

In Eq. (4) n_0 is the carrier concentration generated by G_0 , ϕ is a phase factor, and γ is the fraction by which diffusion and drift reduce the photocarrier grating amplitude and is given by

$$\gamma = \left| 1 - iE\mu\tau \frac{2\pi}{\Lambda} + D\tau \left(\frac{2\pi}{\Lambda} \right)^2 \right|^{-1}. \quad (5)$$

The sought-after parameters $L_d = \sqrt{D\tau}$ and $L_e = \mu E \tau$ are thus contained in γ which is related to the photocurrents measured as described in Ref. 3. Previously,³ the term involving the electric field E did not appear in our expression for γ since we implicitly assumed that the electric field is very small. Even if E is not small it is not immediately obvious that an electric field should have an effect on these measurements, i.e., that it should blur the carrier grating, since it is not obvious that the ambipolar mobility μ is different from zero. As mentioned above, this would be the case if undoped a -Si:H behaved like a crystalline intrinsic semiconductor. As shown in Fig. 1, however, the material does not behave in this manner. From Fig. 1 we see that γ clearly decreases with E so that the field smears out the grating just as diffusion alone does. We therefore conclude, first of all, that the ambipolar mobility is not zero and that undoped a -Si:H does not behave like an intrinsic crystalline semiconductor.

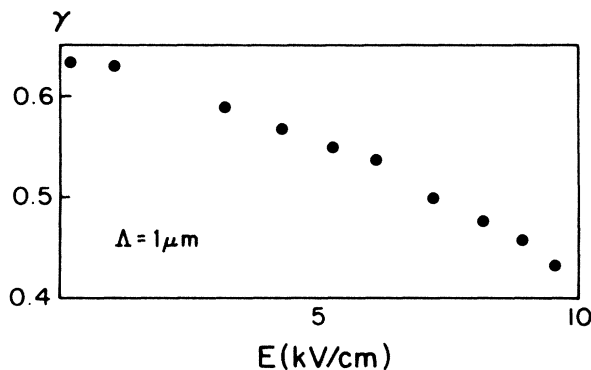


FIG. 1. The normalized grating amplitude factor γ as a function of the electric field for a representative sample of a -Si:H; $\gamma = 1$ for the case of no diffusion or drift of carriers.

We can obtain the ambipolar drift length by defining a zero-field smear factor $\gamma(0)$ as

$$\gamma(0) = \left[1 + D\tau \left(\frac{2\pi}{\Lambda} \right)^2 \right]^{-1}, \quad (6)$$

so that at a finite field γ^2 is given by

$$\gamma^2 = \left[\gamma^{-2}(0) + \left(\frac{2\pi}{\Lambda} L_e \right)^2 \right]^{-1}, \quad (7)$$

and the drift length L_e is given by

$$L_e = \frac{\Lambda}{2\pi} \sqrt{\gamma^{-2} - \gamma^{-2}(0)}. \quad (8)$$

Figure 2 is a plot of the ambipolar drift length for a representative sample prepared by glow-discharge decomposition of silane. The data for graph (a) were obtained for an annealed sample while those for graph (b) were obtained after light soaking for 18 h at a light intensity of 200 mW/cm². The measurements were performed at an illumination intensity of about 10 mW/cm² for the background beam, using a He-Ne laser (632.8 nm). Comparing the drift length at, say, 5 kV/cm we see that in both cases L_e is actually larger than the ambipolar diffusion length. These relatively large values of L_e indicate that care must be taken in measurements of L_d to eliminate even moderate electric fields. Plot (b) shows that light soaking degrades the ambipolar drift length by the same fraction as the square of the ambipolar diffusion length which means that the relation between D and μ remains unchanged as a result of the degradation.

From Fig. 2 the "effective" Einstein relation between the ambipolar diffusion constant and the mobility is found to be $2.2v_T$, where $v_T = 0.026$ V is the thermal voltage. A detailed theory which discusses this relation for the cases of both hopping and extended-state transport has been developed by us and will be given in a separate publication.

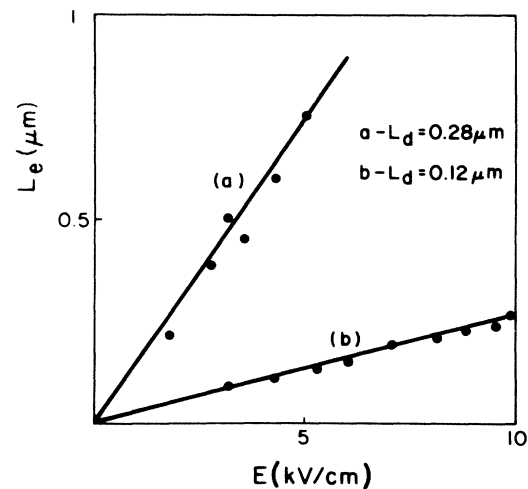


FIG. 2. Ambipolar drift length vs electric field for the same sample as in Fig. 1, (a) before light soaking, (b) after light soaking, as explained in text.

In conclusion, we have demonstrated that the steady-state photocarrier grating technique, when investigated as a function of the electric field, can yield the ambipolar drift length as well as the ambipolar diffusion length of photocarriers from one set of experiments. From the ambipolar drift length a lower limit for the minority-carrier drift length can be obtained. We find that the ratio between the two lengths is larger by a factor 2.2 than the

Einstein relation, a fact which requires additional theoretical explanation.

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