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Drift-mobility measurements in amorphous semiconductors using traveling-wave method

H. Fritzsche and K.-J. Chen
James Franck Institute, The University of Chicago, Chicago, Illinois 60637
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We report the first detailed measurements of the drift mobility of n-type and p-type doped glow-discharge amorphous silicon using the traveling-wave technique. The results agree well with time-of-flight measurements even though the latter were carried out on nearly intrinsic samples.

We report here measurements of the drift mobilities and tail state distributions in glow-discharge amorphous silicon (a-Si:H) using the traveling-wave method. This new technique which was first introduced by Adler, Janes, Hunsinger, and Datta[1] is very useful because it complements and extends the applicability of the time-of-flight (TOF) method.[2] The traveling-wave technique measures the drift mobility as well as the sign of the dominant charge carriers under thermal equilibrium conditions. Since no excess charges are injected, semiconducting materials can be measured which would be unsuitable for the TOF method because of drift range limitations due to deep trapping. Moreover, it appears important to test the validity of the interpretation of the TOF results because of a recent claim[3] that they underestimate the mobilities by several orders of magnitude. This claim is based on interpretation of photocurrent transients using reverse recovery techniques.

Adler *et al.*[1] placed a thin semiconductor film a short distance above a piezoelectric crystal in the fringe electric field of a surface-acoustic Rayleigh wave. The traveling electric wave produces in the direction of its propagation a dc acoustoelectric short-circuit current or open-circuit voltage in the semiconductor film which can be measured by placing two electrode strips separated by L across the film. The acoustoelectric voltage is proportional to the mobility of the majority carriers. First, we shall outline the theory of the traveling-wave method.

Following Blotekjaer[4] we use the quasistatic approximation and derive the electric field from a scalar potential: $\vec{E} = -\vec{\nabla}\phi$. When the diffusion term can be neglected in the transport equation, i.e., when the carrier diffusion length during the dielectric relaxation time and during a wave period $1/\nu$ is less than the wavelength λ, then there is no bulk space charge produced by the traveling fringe field so that $\nabla^2\phi = 0$. The absence of a bulk space-charge wave in the fringe field geometry requires an interpretation of the observed acoustoelectric voltage which differs somewhat from that given by Adler *et al.*[1]

Choosing the z axis along the direction of wave propagation and the y axis normal to the surface of the piezoelectric crystal we write the solution of the Laplace equation in the semiconductor as

$$\phi = \phi_0[A\cosh k(y-h) - B\sinh k(y-h)]\exp i(\omega t - kz) \ . \tag{1}$$

With the proper boundary conditions at the air and substrate interfaces we find

$$A = [\cosh(kh) + \epsilon^*(B/A)\sinh(kh)]^{-1} \ , \tag{2}$$

$$B/A = (\epsilon_s + \epsilon^* kd)/(\epsilon^* + \epsilon_s kd) \ , \tag{3}$$

$$\epsilon^* = \epsilon - i4\pi\sigma/\omega \ . \tag{4}$$

We assumed that the substrate is thick (500 μm) and the semiconductor film is thin (1 μm) compared with the wavelength ($\lambda = 180$ μm). Here ϵ, σ, and d are the dielectric constant, conductivity, and thickness of the semiconductor, h is its separation from the surface of the piezoelectric crystal, and ϵ_s is the dielectric constant of the insulating substrate. ϕ_0 is the potential at the piezoelectric surface which is given by the Rayleigh wave power.[5] The y component of the electric field produces a current in the semiconductor normal to its surface. This, in turn, produces surface charge waves which are given by the current continuity equation

$$\delta_1 = -i\frac{\sigma}{\omega}\frac{\partial\phi}{\partial y}\bigg|_{y=h} \ , \quad \delta_2 = i\frac{\sigma}{\omega}\frac{\partial\phi}{\partial y}\bigg|_{y=h+d} \ , \tag{5}$$

where the subscripts 1 and 2 refer to the semiconductor surfaces at $y = h$ and $y = h + d$, respectively. By multiplying the surface charges with the carrier mobility μ and the z component of the electric field we obtain two surface currents whose time averages are

$$I_1 = \sigma(\mu/\omega)k^2 w(B\cdot A)\phi_0^2/2 \ , \tag{6}$$

$$I_2 = -I_1 + \sigma(\mu/v_s)wdk^2(|A|^2 + |B|^2)\phi_0^2/2 \ , \tag{7}$$

where v_s is the wave velocity and w is the width in the x direction of the semiconductor film and of the Rayleigh wave. $(B\cdot A)$ is the dot product of the complex amplitudes A and B. Dividing the net current $I_1 + I_2$ by the conductance of the semiconductor we obtain the dc open-circuit acoustoelectric voltage

$$V_{ae} = \pm(\mu/v_s)Lk^2(|A|^2 + |B|^2)\phi_0^2/2 \ , \tag{8}$$

where the sign is that of the dominant charge carrier. L is the separation of the electrodes. The attenuation coefficients $|A|^2$, $|B|^2$, and $A\cdot B$ can be calculated from Eqs. (2)–(4).

We now turn to the interpretation of the mobility μ. Only a fraction δ_f/δ of the carriers in the charge wave is in transport states which are characterized by a microscopic mobility μ_0. Hence the mobility in Eqs. (6)–(8) is a drift mobility $\mu = \mu_0\delta_f/\delta$. The remaining fraction $1 - \delta_f/\delta = \delta_t/\delta$ may be trapped in surface states and in localized bulk states.

In the following we shall neglect surface states and discuss the traveling-wave drift mobility for amorphous semiconductors in terms of the theory of dispersive transport[6,7] and

compare our results reported below with those of the TOF experiments.[2] For simplicity, we consider an n-type semiconductor and assume (i) that tunneling of electrons between localized states is negligible and (ii) that the thermal emission rate from localized states is $\nu_0 \exp(E/kT)$, where E is the energy of the states below the mobility edge E_c. We set $E_c = 0$.

Since only those trapped electrons can be part of the traveling charge wave which equilibrate in a time $t \leq 1/\nu$ we can disregard localized states whose emission rate is less than the traveling-wave frequency or for which $\nu_0 \exp(E/kT) \leq \nu$. This defines the demarkation energy

$$E_d = -kT \ln \nu_0/\nu \ , \tag{9}$$

above which electrons can equilibrate with the conduction band at the measuring frequency. We distinguish two cases depending on the position of the Fermi energy E_F relative to E_d: (i) When $E_F < E_d$ we can set

$$\delta_f/\delta = n_f/(n_f + n_t) \ , \tag{10}$$

since we neglect surface states; n_f is the equilibrium free-electron concentration and n_t is the concentration of trapped electrons in the density of localized states $g(E)$ between E_d and E_c. Comparing Eq. (9) with the corresponding expression of the dispersive transport theory, $E_d = -kT \ln \nu_0 t$, one finds that the traveling-wave mobility is the TOF mobility at $t = 1/\nu$. (ii) When $E_F > E_d$, the traveling charge wave modulates the position of E_F and (neglecting surface states)

$$\delta_f/\delta = \left(\frac{dn_f}{dE_F}\right) \Big/ \left(\frac{dn}{dE_F}\right) \ . \tag{11}$$

We assumed an exponential distribution of localized states in the tail region of the bands: $g(E) = g_0 \exp(E/kT_0)$ for comparing the theoretical predictions with the results of the traveling-wave experiment which will be described now.

Our experimental setup is identical to that of Adler *et al.*[1] We used a y-z cut $LiNbO_3$ crystal plate. The Rayleigh wave of frequency $\nu = 18.2$ MHz was 0.7 cm wide. The wave velocity in the z direction is $v_s = 3.488 \times 10^5$ cm/s. 1-μm-thick a-Si:H films were deposited on Corning 7059 substrates at $T_s = 540$ K in our capacitively coupled glow-discharge reactor. The films having a width $w = 0.7$ cm and length $L = 1$ cm were separated from the $LiNbO_3$ surface by $h = 11$ μm thick Capton spacers. Measurements were carried out in a flow of dry nitrogen after annealing the films at 475 K for 1 h in darkness. We found that V_{ae} is proportional to the Rayleigh wave power P_R and used for most measurements $P_R = 0.22$ W. This corresponds in our geometry to a field amplitude $E_z = k|A|\phi_0 = 760$ V/cm when $\sigma < \epsilon\omega/4\pi$. At larger σ the factor $|A|$ decreases according to Eq. (2)–(4).

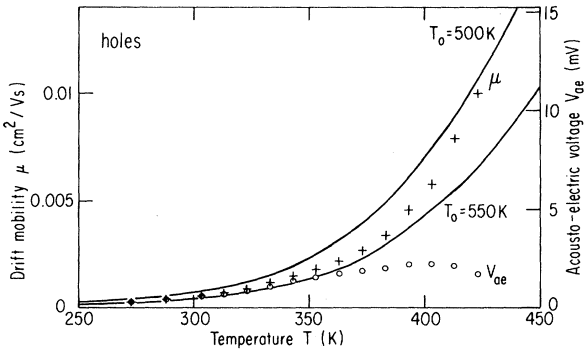

FIG. 1. Acoustoelectric voltage V_{ae} and drift mobility μ of p-type a-Si:H film as a function of temperature. The full lines are calculated hole mobilities for two choices of T_0.

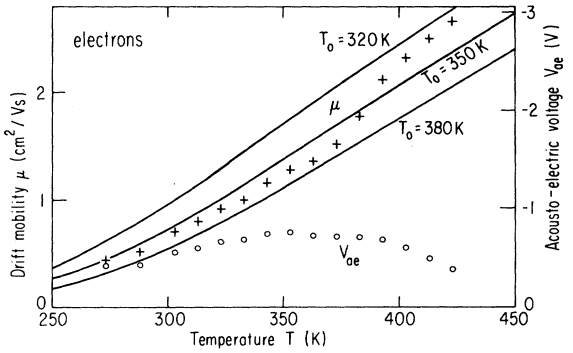

FIG. 2. Same as Fig. 1 for n-type a-Si:H.

Figures 1 and 2 show the dc voltage V_{ae} and the corresponding drift mobilities μ obtained from Eq. (8) for holes and electrons, respectively. The μ and V_{ae} values deviate at higher T because $|A|^2$ and $|B|^2$ depend on σ. The p-type film prepared with a gas doping ratio $[B_2H_6]/[SiH_4] = 1.5 \times 10^{-4}$ had a conductivity activation energy $E_a = 0.37$ eV. The n-type film was prepared with $[PH_3]/[SiH_4] = 3 \times 10^{-4}$ and had $E_a = 0.19$ eV. The solid curves drawn through the mobility data points represent the predictions of the theory described above for several T_0 values, with use of Eq. (11) for the n-type and Eq. (10) for the p-type sample. The latter sample actually falls between the ranges of validity of either Eqs. (10) or (11) since $E_F \simeq E_d$.

Table I lists our fitting parameters next to those obtained by TOF measurements.[2] The agreement is as good as can be expected since samples from different laboratories are being compared. Moreover, the currents giving rise to V_{ae} are close to the surface and interface regions of the semiconductor which may differ in structure from the bulk region which is probed by TOF measurements. In addition, the possible effect of surface states has been neglected. We also note that the TOF samples were nearly intrinsic[2] whereas we studied doped material. Our relatively conduc-

TABLE I. Transport parameters measured by the traveling-wave method and (in parentheses) by the time-of-flight technique (Ref. 2).

	μ_0 (cm^2/V s)	T_0 (K)	ν_0 (10^{12}/s)
Electrons	10 ±1	350 ±20	
	(13)	(312)	(0.46)
Holes	0.25 ±0.05	530 ±20	3
	(0.67)	(500)	(1.6)

tive samples cannot be measured by the TOF method which requires that the dielectric relaxation time is long compared with the transit time.

A fit of μ of the p-type sample with Eq. (11) was less satisfactory but yielded essentially the same μ_0 and T_0 values. Since E_F in our temperature range may be larger than E_a by the statistical shift of E_F we also used $E_F = 0.24$ eV for fitting the μ values of the n-type sample and obtained $\mu_0 \sim 11$ cm^2/V s and $T_0 \sim 350$ K. Note that μ does not depend on ν_0 when $E_F > E_d$. Our agreement with the TOF results suggests (i) that μ_0 and T_0 are not greatly altered by doping and (ii) that the reverse recovery measurements[3] cannot be explained by carrier mobilities which are orders of magnitude larger than those measured here and by the TOF technique. We explore the effect of surface inversion layers on V_{ae} and the mobilities of photoexcited carriers in a more detailed paper.

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