RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 37, NUMBER 17 15 JUNE 1988-I

Anisotropic drift mobility in hydrogenated amorphous silicon

M. A. Parker and E. A. Schiff
Department of Physics, Syracuse University, Syracuse, New York 13244-1130
(Received 28 March 1988)

The dependence upon the electric field direction of the electron photocarrier transient drift mobility was measured in amorphous hydrogenated silicon (*a*-Si:H) using transient photocurrent and time-of-flight spectroscopy. In contrast with the frequent assumption of microscopically isotropic transport in noncrystalline materials, the measurements indicate that the electron drift mobility is anisotropic in *a*-Si:H. The ratio of axial measurements (along the growth axis) and planar measurements (parallel to the surface) can exceed an order of magnitude. Certain problems with previous transport-based characterizations of *a*-Si:H may be resolved by anisotropic mobility effects.

The experiment presented in this Rapid Communication shows that the electron transient drift mobility in hydrogenated amorphous silicon (*a*-Si:H) is profoundly anisotropic at sufficiently long times. Essentially, all previous work involving electrical transport in *a*-Si:H implicitly assumes *isotropy,*[1] and our result is thus a major modification in the understanding of transport in this material. Anisotropy also resolves at least one of the apparent contradictions between models for the electronic properties of this material derived from drift mobility measurements in different experimental geometries.[2-4] Finally, the enormous transport literature for *a*-Si:H plays an important role in the formulation of concepts (in particular, the mobility edge) to describe electrical transport in noncrystalline materials,[1] and anisotropy of transport in *a*-Si:H will need to be incorporated.

The *transient drift mobility* is the proportionality between the spatially averaged drift velocity $\langle v(t)\rangle$ of an excess carrier distribution generated as an impulse at $t=0$ and the electric field F inducing the drift:

$$\langle v(t)\rangle = \mu(t)F . \tag{1}$$

The time dependence of $\langle v(t)\rangle$ is often termed "dispersion," and can result from the interaction of mobile carriers with localized states (multiple trapping)[5] or from other mechanisms.[6] In our experiments, we first computed an electron photocarrier drift mobility for both axial external fields (parallel to the thin-film growth axis) and planar fields (parallel to the interfaces) from the measured transient photocurrent response to uniformly absorbed optical impulses in a uniform external electric field. We then confirmed the drift-mobility interpretation by detecting time-of-flight[5] effects for the larger external fields.

Our experiments are the first, to our knowledge, to experimentally check the isotropy of the transient drift mobility in a thin-film semiconductor. The results are essentially isotropic at short times, but become quite anisotropic at long times. They are not incompatible with previous photoconductivity experiments in *a*-Si:H, and indeed they account naturally for the "geometry problem" for electron mobility-lifetime products[3] in *a*-Si:H: that is, the several orders of magnitude between the electron mobility-lifetime products for axial and planar fields. Although anisotropy is reasonable given the known microstructures of *a*-Si:H, our data are not an obvious consequence of the previously reported structures.[7] We shall speculate further on the origins of our observed anisotropy at the conclusion of this paper.

We now show our anisotropic transient drift mobility estimates and then discuss the evidence supporting them. Figure 1 shows our estimates of the electron planar drift mobility (field parallel to the surface) and the axial drift mobility (field parallel to the growth axis) at room temperature for one sample of undoped *a*-Si:H. Similar axial $\mu(t)$ measurements have been interpreted as due to weakly dispersive transport involving electron multiple trapping[5] in the band tail at short times, followed by *deep trapping* by dangling-bond defects.[8] Similar planar $\mu(t)$ measurements have been interpreted in terms of multiple trapping involving the dangling-bond defects.[9] Integration of $\mu(t)$ yields a mobility-lifetime product;[2] for our data, we find after integration to 10 μs that $\mu\tau_{\text{planar}}=18$ and $\mu\tau_{\text{axial}}=0.8(\times 10^{-8}\ \text{cm}^2/\text{V})$. The ratio is reasonably

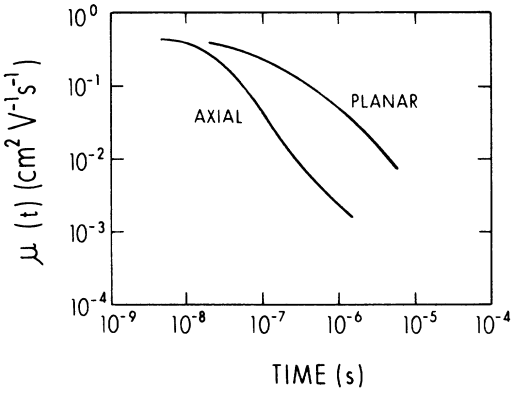

FIG. 1. The anisotropy of the transient drift mobility $\mu(t)$ is shown by the difference between the axial (electric field perpendicular to surface) and planar transient drift mobilities for the same *a*-Si:H specimen and photoexcitation conditions. The drift mobility was computed from the transient photocurrent measured at low electric field.

consistent with previously reported axial/planar ratios obtained using steady-state techniques [corresponding to integration of $\mu(t)$ to infinity] for $\mu\tau_{\text{planar}}$.[2-4]

The transient drift mobilities in Fig. 1 were computed using the following relation equating the power dissipation of charge Q of photocarriers drifting in an external electric field F and the power supplied by the external bias voltage V_b for photocurrent $I(t,F)$:

$$I(t,F)V_b = Q\langle v(t,F)\rangle F . \tag{2}$$

Since our experiments used illumination uniformly absorbed between the electrodes, both electrons and holes can in principle contribute to the photocurrent. We identify our drift mobilities with electrons; for the axial drift mobility, this identification was confirmed using conventional measurements with surface-absorbed illumination. We define a *mobility-normalized photocurrent* $\mu^*(t,F)$ by the relation

$$\mu^*(t,F) = I(t,F)V_b/(QF^2) . \tag{3}$$

This mobility-normalized photocurrent is identical to the transient drift mobility for times prior to the onset of photocarrier sweep out ($t < t_T$). The transit time t_T (as detected in time-of-flight experiments) may be estimated by equating the time integral of the drift velocity and an appropriate fraction of the interelectrode spacing d. For illumination uniformly absorbed between the electrodes we write

$$d/4 = F\int_0^{t_T}\mu(\tau)d\tau . \tag{4}$$

An anisotropic transient drift mobility is sufficiently surprising that we undertook to confirm it using time-of-flight measurements and Eq. (4). This procedure is intended to rule out other photocurrent mechanisms (arising perhaps from contact injection or other specimen inhomogeneities) which cannot be interpreted as simple photocarrier drift. In the following, we give the experimental details of our measurements and demonstrate that the two approaches to measuring the drift mobility are equivalent for our specimens.

The a-Si:H specimens used for these experiments had both *biplanar* (sandwich cells to measure axial drift mobilities) and *coplanar* (gap cells to measure planar drift mobilities) electrode configurations and were prepared in the following manner. The bottom member of the biplanar electrode set and both interdigital coplanar electrodes were first evaporated onto Corning 7059 glass substrates; the interdigital set had 25-μm interelectrode gaps. A 3.7-μm-thick film was then deposited in a 13.56-MHz glow-discharge reactor with pure silane at a substrate temperature of 250 °C; the growth rate was 0.33 μm/h. Next, a 1-μm layer of polyimide insulation was spun onto the virgin surface to reduce contact carrier injection and passivate the free surface of the specimen. The top semitransparent biplanar electrode was then evaporated onto the polyimide; the overlap area was 3 mm^2. In independent experiments on axial drift mobilities, we found essentially no difference between measurements on a-Si:H grown on evaporated Cr and a-Si:H grown at the same time on the uncoated substrates.

The measurements presented here were performed on a specimen which was *light soaked* for several hours prior to the transient photocurrent measurements; we arranged for the material between both sets of electrodes to receive the same illumination intensity. Light soaking increases the density of localized states in a-Si:H (the Staebler-Wronski[10] effect); for the specimen in Fig. 1 it also decreases (by tenfold) the photocurrents originating from the built-in interfacial fields (as measured in the absence of an external field) that would otherwise perturb the transient drift mobility at small times. Measurements were made in several specimens and in both annealed and light-soaked states; similar anisotropy was found in all specimens and states.

The laser impulse had a wavelength of 682 nm and was of 4-ns duration. The bias voltage was pulsed to provide an effectively uniform field[11] distribution. Q was determined from the collected charge Q_{CC} measured by integrating the high-field photocurrents to times beyond the transit time;[12,13] inspection of Fig. 1 shows that the difference between the planar and axial $\mu(t)$ cannot originate in a simple scaling factor as might be the case if incorrect estimates for Q or other parameters were employed.

Figure 2 shows the families of *mobility-normalized transient photocurrents* $\mu^*(t,F)$ for both geometries as parametrized by the applied field in units of kV/cm; both families cover the same time scale and the same range of applied fields. Note that these families have the appearance expected for a time-of-flight experiment: As the field is increased successive curves depart from a common asymptote at earlier times due to the earlier onset of sweep-out effects. The same value of the photogenerated charge Q was used to compute $\mu^*(t,F)$ for each member of the family; this procedure assumes that photogenera-

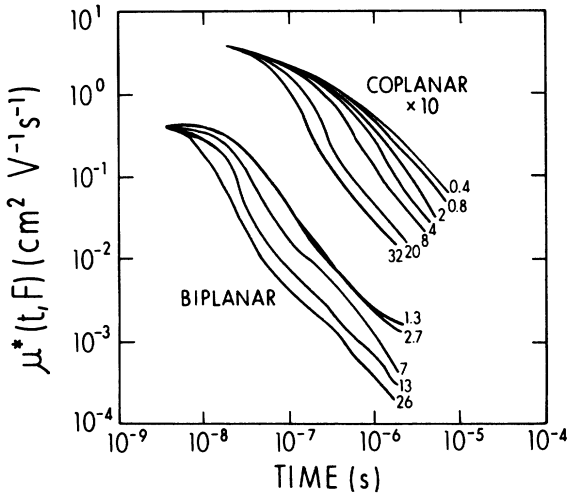

FIG. 2. Biplanar and coplanar electrode mobility-normalized photocurrent transients $\mu^*(t,F)$ as measured using uniformly absorbed impulse photoexcitation; the transients are parametrized by the externally applied electric field F (in units of kV/cm). At low fields, $\mu^*(t,F)$ becomes identical with the transient drift mobility $\mu(t)$; at high fields, the carriers are collected by one of the electrodes as shown by the undercutting of successive curves.

tion is not electric field assisted in *a*-Si:H near room temperature in agreement with our own measurements and previous work.[5] We also ascertained that the transient photocurrents were measured in the low-intensity, linear photocurrent response regime.

We can now demonstrate that the drift-mobility interpretation of our transient photocurrents (Fig. 1) is consistent with transit-time observations (Fig. 2). We adopt as the experimental transit time t_T the measured time at which the mobility-normalized transient photocurrent $\mu^*(t,T)$ falls to $\mu(t)/2$ due to sweep out. We predict t_T from Eq. (4). Figure 3 shows the measured time versus the predicted time for both geometries in samples of differing Staebler-Wronski states and temperatures (150 and 300 K). The agreement between the predicted transit time and the measured time shows that the transient drift mobility $\mu(t)$ (for each geometry) predicts t_T over several decades. We conclude that the drift-mobility interpretation is correct for each geometry.

The origin of the anisotropic drift mobility in *a*-Si:H is quite unclear. Specimen stratification does not explain our measurements.[14] Some speculations may be offered based on previous interpretations of the results for each geometry independently. The drift mobility becomes substantially anisotropic following the cutoff in the axial drift mobility usually identified with deep trapping of electrons by dangling-bond defects. Multiple trapping appears to apply to each geometry separately (although with different parameters).[5,9] These facts suggest the presence of two transport channels: an isotropic short-time channel characterizing the bulk of the material, and an anisotropic long-time channel associated with some microstructure to which the dangling-bond defects are attached.

As mentioned in the Introduction, microscopic isotropy of transport is implicitly assumed in essentially all transport-based characterizations of thin-film semiconductors. Examples include the space-charge spectroscopies[15] as well as photoconductivity. In *a*-Si:H there are significant discrepancies between models obtained from differing spectroscopies; it is possible that transport anisotropy may furnish an explanation for some of these problems.

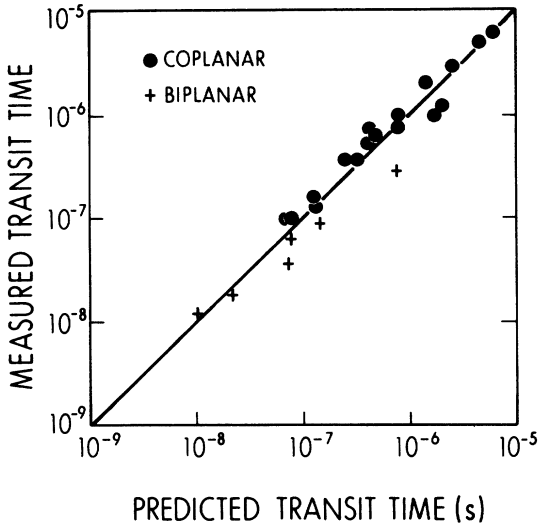

FIG. 3. The measured transit time compared with the predicted time based on transient drift mobility estimates for specimens of differing Staebler-Wronski states and measurement temperatures.

The authors thank R. DeVito and G. Vidali for assistance in preparing the interdigital electrodes. This research was supported by SERI XB-6-06005-2.

[1]A comprehensive review is N. F. Mott, *Conduction in Non-Crystalline Materials* (Oxford University Press, New York, 1987).

[2]E. A. Schiff, Philos. Mag. Lett. **55**, 87 (1987).

[3]M. A. Parker and E. A. Schiff, J. Non-Cryst. Solids (to be published).

[4]K. D. MacKenzie and W. Paul, J. Non-Cryst. Solids (to be published).

[5]T. Tiedje, *The Physics of Hydrogenated Amorphous Silicon II,* edited by J. Joannopoulos and G. Lucovsky (Springer-Verlag, Berlin, 1984), p. 261.

[6]H. Scher and E. W. Montroll, Phys. Rev. B **12**, 2455 (1975).

[7]J. P. Harbison, J. Non-Cryst. Solids **66**, 87 (1984), and references therein.

[8]R. A. Street, Appl. Phys. Lett. **41**, 1060 (1982).

[9]K. A. Conrad and E. A. Schiff, Solid State Commun. **60**, 291 (1986).

[10]*Stability of Amorphous Silicon Alloy Materials and Devices—1987*, AIP Conference Proceedings No. 157, edited by B. L. Stafford and E. Sabisky (American Institute of Physics, New York, 1987).

[11]Interdigital electrodes do not yield strictly uniform electric fields; we used an average electric field in all computations. We investigated the effects of this nonuniformity by studying differing electrode spacings; no significant differences were found.

[12]We used uniformly absorbed illumination for time-of-flight measurements ("distributed time of flight"). The charge Q of photocarriers and the collected charge Q_{CC} (photocurrent integrated to long times) for one photocarrier species are related by $Q=2Q_{CC}[(V_B/d)/F]$. Q_{CC} is thus only half that observed for surface-absorbed illumination for the same Q.

[13]M. A. Parker and E. A. Schiff (unpublished).

[14]*a*-Si:H is potentially stratified along its growth axis due either to deposition or interface effects, and it is natural to inquire whether a specimen with a correspondingly stratified drift mobility could produce the anisotropies reported here. Drift mobilities measured using small drift lengths (cf. Fig. 1) are volume averages of the local (microscopic) drift mobility [Eq. (1)]. *Anisotropy of this average can result only from microscopic anisotropy of the transport process* and not from stratification. Stratification affects drift mobilities estimated from photocarrier sweep out very differently, since the sweep-out time is determined by the average of the *reciprocal* mobility over the photocarrier path. Thus, Fig. 3, which compares these two averages, shows that stratification effects were no larger than the statistical uncertainties in our drift mobility estimates (of order a factor of 2).

[15]J. D. Cohen, *Semiconductors and Semimetals*, edited by J. I. Pankove (Academic, New York, 1984), Vol. 21, Pt. C, p. 9.