Temperature dependence of the electron drift mobility in doped and undoped amorphous silicon

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We have measured the temperature dependence of the drift mobility of electrons in undoped and phosphorus-doped amorphous-silicon samples by the time-of-flight technique between 300 and 30 K. The drift mobility is nondispersive and thermally activated for both doped and undoped samples up to 200 K. Below 200 K the drift mobility becomes dispersive and, below 140 K, it becomes too small to be measured and remains so down to 30 K. In particular, we do not see the upturn in drift mobility below 100 K as observed by Cloude *et al.* [Philos. Mag. B **54**, L113 (1986)]. This suggests that the low-temperature transport is critically dependent on details of the distribution of states in the band tails.

I. INTRODUCTION

The drift mobility in amorphous semiconductors is an important measurement as it explores the tail states near the mobility edge. In amorphous silicon the temperature dependence of the drift mobility has been extensively investigated by many workers.[1–4] These studies have established that in undoped amorphous silicon (*a*-Si) the electron drift mobility is thermally activated in the regime of multiple trapping. Recently, Cloude *et al.*[5] reported a new regime of transport at low temperature. They found that below 100 K, the drift mobility increased and was almost as large as the room-temperature mobility below 50 K. They attribute this mobility to hopping in the localized states.

The charge collection efficiency in this regime of transport will be a measure of the electrons "lost" to deeper states and is hence expected to give us insight into the thermalization process. This provided the motivation for this work.

In this paper, we have investigated the temperature dependence of the drift mobility using the time-of-flight (TOF) technique for both undoped and doped samples. The ability to carry out these measurements on doped samples is important as we can reduce the loss of electrons to deep states by moving the dark Fermi level closer to the mobility edge.

II. EXPERIMENT

The samples used in this study were made by the dc discharge of silane at a pressure of 200 mTorr and a substrate temperature of 230 °C. The power density was 30 mW/cm^2. Doping was achieved by the addition of phosphine to silane. Table I lists some details of the samples used.

We will now discuss the precautions to be taken for measuring TOF in doped samples. The samples used in the study were gold Schottky barriers on amorphous silicon with n^+-type back Ohmic contact. The samples were excited by a pulsed Nd:YAG (where YAG denotes yttrium aluminum garnet) laser with a frequency doubler. The wavelength of the light is 532 nm. The absorption coefficient α for green light is 6×10^4 cm^{-1}. Some experiments were also carried out using blue light ($\lambda=355$ nm). The results for blue and green light were identical. Table I lists details of the samples used in this study. The laser pulse was typically 30 ns wide.

A voltage pulse was applied across the sample prior to the arrival of the laser pulse. It is necessary to ensure that the applied field is uniform across the thickness of the sample.[6] For undoped samples, this requirement is easily met as the dielectric relaxation time is of the order of a millisecond at room temperature and the applied voltage pulse is shorter than this time. For doped samples the maximum pulse width was determined as follows: The capacitance was measured as a function of frequency and temperature. At any given temperature above a certain frequency f_0, the capacitance becomes constant and equal to the parallel plate capacitance. This occurs when the occupation of the localized states at the Fermi level cannot follow the applied frequency. In such a case the charge will appear at the two electrodes and give rise to a constant electric field. This implies that for a voltage pulse of width $t_0 < 1/2\pi f_0$, the field will be constant in the specimen. In our experiments we chose $t_0 < 1/4\pi f_0$ so that this condition is strictly satisfied. The laser pulse generates electron-hole pairs which are separated and drift in the electric field. Care was taken to see that the generated charge carriers gave rise to negligible space charge effects, and that the collected charge was proportional to the light intensity. For the undoped sample, the collected charge was 50 pC. For doped samples, the amount of light had to be reduced by about an order of magnitude as compared to that used for undoped samples in order to avoid saturation effects.

TABLE I. Some of the properties of the samples.

Sample	Activation energy (eV)	Thickness (μm)	$T_{\text{substrate}}$ (°C)
Undoped	0.9	5.5	230
100 ppm PH_3 doped	0.3	2.0	230

The mobility was calculated from a plot of $1/t_{tr}$ versus applied V where t_{tr} the transit time is defined as time taken for 50% charge collection. In the results reported here, we ensured that the mobility is independent of the applied electric field.

To record the current transients we used an Ortec 474 amplifier whose output was fed to a transient recorder. The data were transferred to a computer and integration of the current transient done in software to get the charge. In another technique we also directly recorded the charge transient.[6] (Here the current was fed to an integrating capacitor which was kept shorted till a few microseconds before the arrival of the laser pulse. By this time the displacement current due to the application of the voltage pulse had disappeared. The capacitor was shorted again before the end of the voltage pulse.) The smallest detectable signal is determined by leakage currents as well as the noise. For instance, we find that for the undoped samples (which have low leakage) the charge transient offers better sensitivity. For the doped samples, which are leaky even at low temperatures, the current transient gives us better sensitivity.

III. RESULTS

The solid points in Fig. 1 show the drift mobility μ for undoped amorphous silicon. The dc conductivity activation energy ΔE for this sample is 0.9 eV. We see that μ is thermally activated with an activation energy of 0.16 eV. This is in agreement with the results reported by other authors.[1,2] Below 200 K, the transport becomes dispersive. Experiments by Cloude *et al.*[5] showed that the drift mobility began to increase again below 100 K. The drift mobility in this regime was also seen to depend on the intensity of the excitation pulse. In our samples the drift mobility is too small to be measurable below 140 K and continues to be so down to the lowest temperature (30 K). We have also investigated the effects of excitation light intensity on the mobility and we do not see any visible effect of the light intensity on the drift mobility. We hence conclude that we do not see the upturn in the drift mobility at low temperature as reported by Cloude *et al.*[5] in our samples. We now examine various possibilities which can contribute to the masking of the time-of-flight signal at low temperatures.

If the upturn in mobility at low temperatures is due to hopping in the tail states, there must exist a thermalization bottleneck to prevent loss of carriers to deep states at low temperatures.[7] If we lose carriers to deep levels at low temperature, then we may not be able to see the TOF signal due to electrons hopping in the tail states. To rule out this possibility we have carried out TOF measurements on a sample doped with 100 vpm of phosphine. The dc activation energy in the dark was 0.3 eV for this sample. This implies that thermalization cannot occur below 0.3 eV from the mobility edge for this sample.

The circles in Fig. 1 show the drift mobility as a function of reciprocal temperature for the doped sample. We see that the drift mobility is thermally activated and the activation energy is 0.11 eV. Below 200 K the transport becomes dispersive. The TOF signal also becomes small

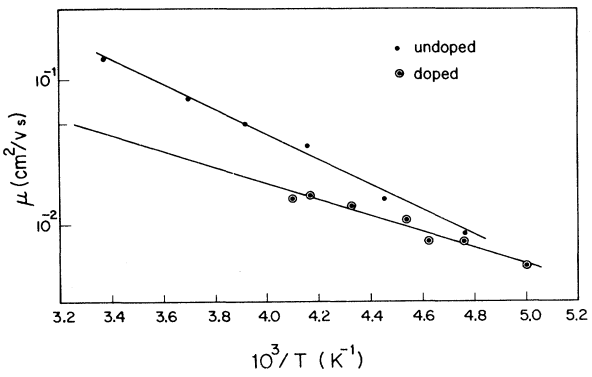

FIG. 1. A plot of the drift mobility vs $1/T$ for phosphorus-doped and undoped amorphous-silicon samples.

and continues to remain so down to 30 K. Since we do not see the upturn in the drift mobility even in the doped sample, it is reasonable to conclude that deep trapping is not responsible for no upturn in the drift mobility at low temperature being seen.

Cloude and Spear[8] have argued that the quantum efficiency for photogeneration (η) at low temperature is limited by geminate recombination and η decreases at low temperatures to about 0.1. If η is very small then this will result in a reduction of the total charge transitting the specimen. The resultant loss in sensitivity may prevent the detection of the hopping transport regime. If η is limited by geminate recombination then it is expected that the geminate pairs will dissociate at high electric fields causing η to increase. We have studied the charge collection efficiency and the drift mobility as a function of the applied electric field up to a field of 1.5×10^5 V/cm. We find that at 150 K the charge collection efficiency is close to unity for an applied field of 6×10^4 V/cm for a 5-μm-thick sample. This result is in agreement with recent results of other workers.[9,10] We find that even at large fields (up to 1.5×10^5 V/cm) the drift mobility is too small to be measured below 140 K. We hence discount the possibility that a small value of η is responsible for our inability to observe the upturn in the drift mobility in our sample.

It is possible from our experiments to arrive at an upper limit for the drift mobility at low temperature in our sample. We decreased the excitation intensity to determine the smallest detectable signal. In the case of the undoped sample at room temperature the signal was easily detectable even after the excitation intensity was reduced by a factor of 100 for an applied field of 2×10^4 V/cm. This has the following implication. If the transient at low temperature was 100 times longer (than at room temperature) we would still have detected the signal as the instantaneous current at low temperature would be smaller only by a factor of 100, assuming the same collection efficiency as at room temperature. This enables us to put an upper limit of 2×10^{-3} cm^2/V sec on the mobility at low temperature in our sample. In fact at higher bias values the CV product is higher and enables us to use higher levels of illumination. We hence estimate our lim-

it for the detection of the mobility to be $<10^{-3}$ cm^2/V sec in our sample. Recent experiments to determine the drift mobility at low temperature in a-Si by the traveling-wave method also appear to result in similar limits.[11]

IV. DISCUSSION

A. $T>200$ K

In this temperature range we find that the mobility μ is thermally activated with well-defined activation energies (ΔE_d) for both doped and undoped samples and given by

$$\mu=\mu_{00}\exp-(\Delta E_d/kT)\cdots . \quad (1)$$

When excess electrons are introduced in the material they thermalize by capture and reemission processes. If the density of states falls off rapidly at lower energies, the thermalization process will slow down below an energy E_t. Thus, over the time scale of our measurement, the carriers are unable to thermalize below the energy E_t. We define ΔE_d in Eq. (1) to be the depth of E_t from the mobility edge E_c.[7] The preexponential factor μ_{00} in Eq. (1) is given by $\mu_{00}=g(E_c)\mu_0/g(E_t)$, where μ_0 is the mobility in the extended states and $g(E_c)$ and $g(E_t)$ the density of states at energy E_c and E_t, respectively. We see from Fig. 1 that μ_{00} for doped samples is smaller than that for the undoped samples by a factor of 40. If we assume $\mu_0 g(E_c)$ to be unaffected by doping, then $g(E_t)$ for doped samples must be larger by a factor of 40 than that for undoped samples. However, the transition from nondispersive to dispersive transport takes place at 200 K for both doped and undoped samples. This suggests that the tail widths are similar in both samples. This implies that μ_{00} must be smaller in the doped samples as compared to the undoped samples.

It is not difficult to understand the origin of a smaller value for μ_{00} for doped samples. Doping produces potential fluctuations arising from Coulomb barriers. The electron has to surmount this barrier for transport to take place. This can give rise to a reduced value for μ_{00}. These results are in agreement with recent results obtained from a combination of charge sweep-out techniques and dc conductivity measurements in doped a-Si.[12] We have measured the drift mobility in undoped a-Si for electric fields up to 2×10^5 V/cm. We find the drift mobility to be independent of the electric field in the regime of nondispersive transport.[13]

B. $T<200$ K

We do not see the upturn in the drift mobility below 100 K as reported by Cloude *et al.*[5] We estimate the mobility at low temperatures to be less than 10^{-3} cm^2/V sec for the undoped samples. The reason for not seeing the upturn in the mobility is unlikely to be due to deep trapping resulting in extremely low charge collection efficiencies as we do not see the upturn in mobility even in doped samples. A possible reason for the difference between our results and those of Cloude *et al.*[5] could be that the upturn in drift mobility is very sensitive to the distribution of gap states in the band tails.

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