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ELECTRONIC TRANSPORT IN AMORPHOUS SILICON FILMS

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Drift mobility and conductivity measurements were made between 290 and 85°K on amorphous silicon specimens prepared by glow-discharge decomposition of silane. The results suggest that excess electrons drift in the extended states with a mobility of about 10 $cm^2 sec^{-1} V^{-1}$. At lower temperatures, phonon-assisted hopping occurs through localized states occupying a range of 0.2 eV below the extended states. Conductivity results also suggest hopping transport near the Fermi energy.

During recent years a model of the electronic structure of amorphous materials has evolved, largely through the work of Mott,[1-4] Davis and Shaw,[5] Cohen, Fritzsche, and Ovshinsky,[6] and Cohen.[7,8] Although its general features appear to be in agreement with experimental evidence, there still exists a serious lack of experimental information whereby some of the more detailed predictions could be tested, particularly those connected with electronic transport properties.

In the following, we should like to report drift mobility measurements in amorphous silicon which, in conjunction with conductivity measurements on the same specimens, allowed us to make a number of meaningful deductions about electronic states and the transport mechanism.

The specimens used in the present work consisted essentially of an amorphous silicon film, about 1 μm thick, sandwiched between two evaporated aluminium electrodes. The amorphous layer was produced by an electrodeless rf glow discharge in silane gas at a substrate temperature of about 200°C. As shown by the work of Chittick, Alexander, and Sterling[9] and Chittick,[10] a distinctive feature of specimens prepared by this technique is their high resistivity, appreciably larger than that of specimens prepared by vacuum evaporation[11] or sputtering.[12]

In the drift mobility measurements, we used pulsed electron-beam excitation (10-nsec pulses, 6-keV electrons) to generate excess carriers near the top electrode. The transit of electrons could be observed in a pulsed applied field, synchronized to the excitation. So far, no hole signals have been detected. Further details of this experimental technique can be found in the work of Spear.[13] Conductivity measurements were carried out with steady fields of up to 40 kV cm^{-1}. Specimens were Ohmic in this range, but some asymmetry was apparent on field reversal.

The five specimens so far investigated[14] led to results showing the same general features. Except at temperatures below 200°K, the reproducibility was good. The following discussion

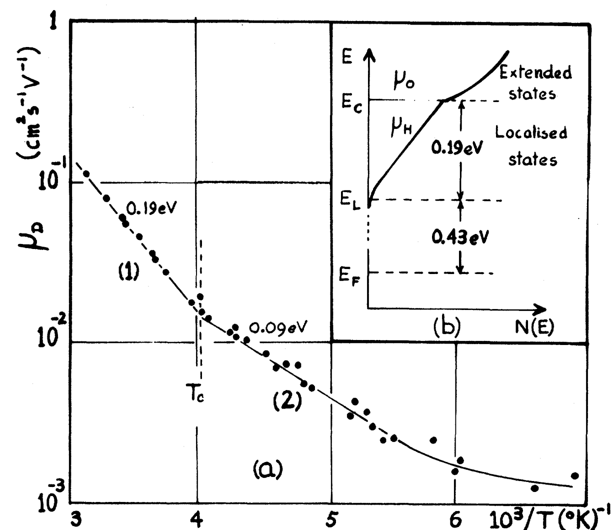

FIG. 1. (a) Temperature dependence of the electron drift mobility μ_D in an amorphous silicon film, 1.3 μm thick. (b) Model of the electronic-state distribution in an amorphous solid. The linear distribution of localized states has been chosen for illustration and does not necessarily follow from the results described.

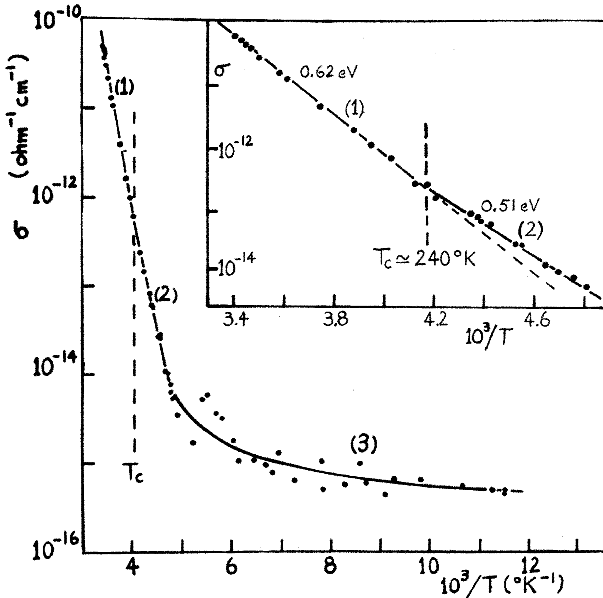

FIG. 2. Temperature dependence of the electrical conductivity σ for the same specimen as in Fig. 1 (a). The inset gives a more detialed plot of results near temperature T_c, showing the change of gradient.

will be based on a specimen which was investigated over the largest temperature range, but corresponding results for other layers will be given in the text. Figure 1(a) shows the electron drift mobility and Fig. 2 the conductivity for the same specimen, both plotted against $10^3/T$. The results may be divided into the three temperature regions indicated in the figures. In region 1, extending from a temperature T_c ($\simeq$240°K) towards higher T, the transport mechanism is an activated process with an activation energy of 0.19 eV, and room-temperature mobilities of about 10^{-1} cm^2 sec^{-1} V^{-1} are observed. We should like to suggest the following interpretation: The electrons drift in the extended states, near E_c [Fig. 1(b)]; during the transit they interact with the localized states through trapping and thermal release. The total time a carrier spends in localized states is included in the measured transit time, leading to a trap-controlled drift mobility μ_D, which is related to the mobility μ_0 near the bottom of the extended states by an expression of the form

$$\mu_D = \mu_0 \alpha \exp[-(E_c - E)/kT]. \quad (1)$$

Equation (1) is based the assumption of a local steady-state distribution of excess carriers at all times during transit; this implies that only those localized states can be included which have trapping and release time constants significantly shorter than the measured transit time. In the case of a single level of trapping states at energy E, $\alpha = N_c/N_t$, where N_c denotes the density of states at the bottom of the band and N_t the density of traps. In this form, Eq. (1) has been shown to apply to low-temperature drift-mobility results in single crystals (e.g., CdS,[15] orthorhombic S,[16] or monoclinic Se[17]). In the case of a linear or a uniform distribution of states, it can be shown[18] that μ_D retains the form of Eq. (1), but now $E = E_L$, the energy of the lowest-lying state in the distribution [Fig. 1(b)]; α depends on the form of the distribution. A model suggested by Mott,[18] in which a linearly increasing density of states continues beyond E_c into the region of extended states, gives $\alpha = E_L/kT$. The fit to our data in region 1 by this model leads to $\mu_0 \simeq 10$ cm^2 sec^{-1} V^{-1}; values of μ_0 between 1 and 10 cm^2 sec^{-1} V^{-1} would also be consistent with the other two distributions mentioned. If any one of these three models is applicable, we can conclude that the localized states in thermal equilibrium during transit extend to 0.2 eV below E_c. Measurements on other specimens gave corresponding values of 0.16 and 0.24 eV. Undoubtedly, the predominant part of the distribution lies in this range, but the observed transit pulse shape indicates the presence of deeper-lying states with release times of the order of the transit time, or longer.

The deduced magnitude of μ_0 supports the models of Cohen[7] and of Mott.[3] These suggest a transport mechanism through delocalized states near E_c for which the mean free path is of the order of the interatomic separation a. The transport may be likened to Brownian motion and an approximate upper limit to the mobility is given by[7]

$$\mu_0 \simeq (ea^2/6kT)\nu_{el}, \quad (2)$$

where ν_{el} is a typical electronic frequency (~10^{15} Hz). Equation (2) predicts that $\mu_0 \simeq 5$ cm^2 sec^{-1} V^{-1} at room temperature, not inconsistent with the experimental results.

With decreasing temperature, the probability of thermal release from a localized state becomes rapidly smaller, and eventually hopping by the trapped electron to a neighboring site will become the predominant transport mechanism. It is suggested that this takes place at the temperature $T_c \simeq 240$°K, defined by the marked change in gradient shown in Fig. 1(a). In region 2, the drift mobility is 10^{-2} cm^2 sec^{-1} V^{-1} or less, and we interpret the transport as phonon-assist-

ed hopping between localized states lying in the energy range from E_c to E_L. It is unlikely that the interpretation used for region 1 could be applied here, because a trap-controlled mechanism would normally be expected to lead to a larger, rather than a smaller, gradient with decreasing temperature. Furthermore, the upper limit to the mobility in region 2 (assuming strong overlap) is

$$\mu_H \simeq (ea^2/kT)\nu_{\text{ph}} \exp(-W/kT). \tag{3}$$

With a hopping activation energy of $W = 0.09$ eV, we find a phonon frequency $\nu_{\text{ph}} \gtrsim \times 10^{13}$ Hz, which appears reasonable. In other specimens, T_c lay at higher temperatures, but for three of the samples the same value of $W = 0.01$ eV was found.

Turning now to the conductivity data, we see that the above change in transport mechanism is also reflected in these results. The more detailed plot given in the insert to Fig. 2 shows clearly a change in gradient from 0.62 to 0.51 eV at $T_c \simeq 240$°K, corresponding to the change of 0.10 eV in the activation energy of the mobility at the same temperature. We conclude from the gradient in region 1 (Fig. 2) that the Fermi level (in thermal equilibrium) lies 0.62 eV below E_c. Using this value to estimate the carrier density just above E_c, we find that with the above μ_0, determined from the mobility measurements, a conductivity consistent with the experimental value is obtained.

Finally, there is some evidence from Fig. 2 for a distinct third region below about 200°K. In this temperature range, the number of electrons thermally excited into the localized states between E_c and E_L becomes rapidly smaller (e.g., $n \sim 10^7$ cm^{-3} at 200°K) and it is, therefore, possible that we are observing the hopping transport of electrons through states near the Fermi energy. According to Mott,[3] this should lead to a temperature dependence of the form $\sigma \propto \exp(-B/T^{1/4})$, but it has not been possible to test this relation with any certainty in the restricted temperature range investigated here.

In Fig. 1, on the other hand, we are dealing with injected excess carriers, having a local density during transit very much higher than that of the thermally generated electrons. The mobility results suggest that below 200°K hopping through localized states between E_c and E_L remains the predominant mechanism for excess carriers, but there is some indication of a decrease in W.

In summary, we can say that the present results lend considerable support to current models of the electronic-state distribution in amorphous solids and to suggestions concerning transport mechanisms in these materials. It should, however, be emphasized that the quantitative data deduced refer to specimens prepared by glow-discharge decomposition of silane on to a substrate held at 200°C. Different substrate temperatures and particularly different preparation techniques may lead to widely different state distributions and much remains to be done to correlate these factors with electronic transport and other physical properties.

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