Electronic Transport in Amorphous Silicon Films: Comments

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In a recent letter, LeComber and Spear[1] reported drift mobility and conductivity measurements on films of amorphous silicon. The activation energy of the thermally activated electron drift mobility changed from 0.19 to 0.09 eV below 240 °K. At the same temperature the activation energy of the Ohmic conductivity changed from 0.62 to 0.51 eV. They suggested that a transition occurred from a trap-controlled mobility to a hopping mode of charge transport. The trap-controlled mobility is assumed to arise from the drift of electrons in extended bandlike states while in thermal equilibrium with localized states. Below 240 °K, the transport changes to phonon-assisted hopping of electrons between the localized states.

The purpose of these comments is to present additional arguments, implicit in Fig. 1(b) of LeComber and Spear's Letter,[1] which strongly support their interpretation. A secondary aim is to stress the importance of their combined drift mobility and true Ohmic conductivity measurement as a means of identifying the presence of a hopping mode of charge transport.

It is argued, as by LeComber and Spear[1] in their Letter, that the thermally activated drift mobility of 0.19 eV at high temperatures must represent a trap-controlled drift mobility. Simple arguments show that a two-level trap-controlled mobility can only be invoked if there is an increase in the activation energy on going to lower temperatures. However, the observation of a simultaneous change in slope for both the drift mobility and the Ohmic conductivity means that the drift mobility below 240 °K, which is thermally activated, must be identified as the *conductivity* mobility. This stems from the fact that the activation energy of a *trap-controlled* mobility does not manifest itself in the conductivity.[2] It *must* be concluded, therefore, that this low-temperature thermally activated conductivity mobility involves a phonon-assisted hopping process in which the electrons have no communication with the band of extended states. The change in activation energy for the Ohmic conductivity and drift mobility need not be identical, since it could depend on the distribution function of the localized states.[3] However, the experimental observation is that for amorphous silicon this change is essentially identical. The activation energy of 0.09 eV for the hopping process will be observed in the activation energy of the conductivity. Subtracting this from the activation energy of the conductivity locates the Fermi level 0.42 eV below the localized states. This is the energy controlling the thermal generation of carriers in this temperature range.

Above 240 °K, since the activation energy for the trap-controlled mobility of 0.19 eV will not appear in the conductivity, it is found that the activation energy for the thermal generation of carriers appears to increase by 0.20 eV, from 0.42 to 0.62 eV. This has to be interpreted as a change in the states controlling the conductivity. In other words, the conductivity is now dominated by states lying ~ 0.20 eV above the edge of the localized states which control the low-temperature conductivity. The activation energy of the drift mobility of ~ 0.19 eV identifies these higher-lying states as the edge of the extended states. The total conductivity σ is given by

$$\sigma = e(n_0\mu_0 + n_H\mu_H), \tag{1}$$

where n_0 is the equilibrium dark density of carriers with a conductivity mobility μ_0 in the extended states, and n_H is the equilibrium density of carriers with an activated hopping mobility μ_H in the localized states. At temperatures higher than 240 °K, the free carriers in the extended states dominate the conductivity, while at low temperatures the converse is true.

In principle the transition from a thermally activated drift mobility of 0.19 to 0.09 eV could arise from a hopping mode of transport involving two different states. In the present case, however, the substraction of the activation energy for the mobility from that for the conductivity in the corresponding temperature range shows that the two levels would lie at the same energy above the Fermi level. A rather unlikely situation would have to exist, therefore, in which two hopping mechanisms with different activation energies would occur in states coincident in energy. The weight of evidence therefore favors the observed transition in amorphous Si as occurring between a trap-controlled mobility and a phonon-assisted hopping mobility.

In summary, two facts have been used to reinforce the interpretation made by LeComber and Spear[1] of their measurements on amorphous Si: (a) For a thermally activated hopping mobility, the activation energy must contribute to the activation energy of the Ohmic conductivity, and (b) for a trap-controlled mobility such a contribution will not

occur. The importance of measuring both the drift mobility and the Ohmic conductivity as a function of temperature in order to unambiguously establish the presence of a hopping mode of conduction has been clearly demonstrated by the work of LeComber and Spear.[1]

[1]P. G. LeComber and W. E. Spear, Phys. Rev. Letters 25, 509 (1970).
[2]W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand, New York, 1950), p. 211.
[3]W. E. Spear and P. G. LeComber (private communication).

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Temperature Dependence of Electron Mean Free Paths in Cadmium and Copper*

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A T^{-5} temperature dependence of electron mean free paths is deduced from high-field and open-orbit ultrasonic attenuation data in cadmium and copper.

I. INTRODUCTION

The possibility of a difference between the electron mean free paths for ultrasonic attenuation and electrical resistivity has been discussed by Steinberg[1] and by Bhatia and Moore.[2] Subsequently, low-temperature ultrasonic attenuation experiments in potassium[3] and copper[4] (in the absence of a magnetic field) have yielded mean-free-path values which vary with temperature as T^{-5}, in agreement with the Bloch-Grüneisen theory.[5] In other metals, however, deviations from this theory have been found in both attenuation and resistivity data, and the two experimental techniques sometimes appear to give different results.[6-9] For example, an analysis by Deaton[6] of high-field and open-orbit-resonance data in cadmium indicated temperature dependences for the mean free paths which vary between T^{-3} and T^{-4} (above 3 °K), although the resistivity data appear[10] to follow a T^{-5} law. These results suggested the possibility of a magnetic field effect on the mean free paths,[6] and this question was brought to mind more recently by the $T^{-3.6}$ temperature dependence found for mean free paths in thalluim[8] by magnetoacoustic experiments. We wish to show here that a somewhat more rigorous analysis of Deaton's cadmium data indicates a variation of the mean free paths as T^{-5}, in agreement with the resistivity measurements, and that the same result is obtained when the analysis is applied to similar magnetoacoustic data in copper.

II. THEORY

Our analysis of the low-temperature ultrasonic attenuation data begins with the usual assumption that the mean free path l can be expressed according to Matthiessen's rule,[5]

$$l^{-1} = l_0^{-1} + l_{ph}^{-1}, \tag{1}$$

where l_0 and l_{ph} are the mean free paths for impurity and phonon scattering, respectively. We further assume that at very low temperatures ($T \ll \Theta$)

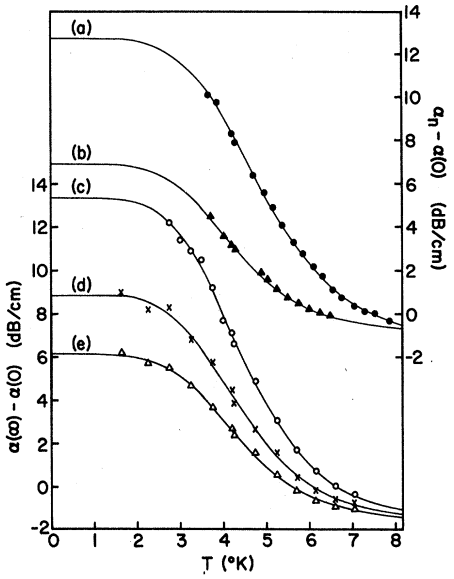

FIG. 1. Least-squares computer fit of ultrasonic attenuation data in cadmium as a function of temperature. The relative open-orbit-resonance height (right-hand scale) is for (a) $f = 72$ MHz with $\vec{q} \| [10\bar{1}0]$ and $\vec{B} \| [\bar{1}2\bar{1}0]$ and for (b) $f = 31$ MHz with $\vec{q} \| [\bar{1}2\bar{1}0]$ and $\vec{B} \| [10\bar{1}0]$. The relative high-field attenuation (left-hand scale) is for $f = 31$ MHz and $\vec{q} \| [\bar{1}2\bar{1}0]$ with (c) $\vec{B} \| [10\bar{1}0]$ and with $\vec{B}$ rotated, (d) 5°, and (e) 10° from $[10\bar{1}0]$ in the $(\bar{1}2\bar{1}0)$ plane.