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# Search for Anisotropic Electrical Properties in Amorphous Germanium*

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Low-field and high-field resistivity in amorphous Ge were measured in both the planer and transverse directions on the same samples, whose thickness ranged from 0.4 to 4 $\mu$m. No anisotropy was found, suggesting that the voids recently described by Galeener may not play a significant role in these transport processes.

In recent papers, Galeener[1,2] showed that some of the structure in the optical constants of amorphous Ge may be ascribed to slitlike voids, whose normals are randomly aligned in the plane of the film. The presence of such voids has recently been confirmed in an electron microscopy study by Donovan and Heinemann[3] and in a small-angle x-ray scattering study by Cargill.[4] The volume fraction of the voids is estimated by Galeener[1] to be about 5% and their thickness about 5–10 Å for films deposited at room temperature. The void structure is not present in films deposited at temperatures above 160°C.[5]

It has been suggested[1,3] that the void structure should affect the electrical properties of amorphous Ge, possibly leading to an anisotropy in properties measured parallel and perpendicular to the plane of the film. While Galeener[6] predicts that anisotropy in the low-frequency dielectric constant should produce an anisotropy in conductivity of less than 5%, there is the possibility of a larger effect if the voids act as effective barriers.

It is well known that the low-field conductivity of unannealed $a$-Ge has the form

$$\sigma = \sigma_0 \exp[-(T_0/T)^{1/4}]. \quad (1)$$

This relation was first proposed by Mott[7] and has recently been reviewed by Ambegaokar, Halperin, and Langer.[8] A high-field effect is observed for fields greater than $10^4$ V/cm and temperatures less than 77 K. Morgan and Walley[9] have extensively studied this effect and conclude that their results correspond well to a modified Poole-Frenkel theory developed by Hill.[10] It thus becomes important to ascertain whether the void structure has a significant effect upon electron transport, because the theories described above apply to an essentially homogeneous model with atomic-sized defects.

By examining the results of earlier work (e.g., Morgan and Walley[9] and Walley and Jonscher[11]), it is possible to conclude that there is no striking anisotropy in either the low-field or high-field transport. It appears that no study has specifically examined this question, however, particularly by searching for anisotropy in the *same sample*.

The $a$-Ge in this study was prepared in an ion-pumped system by electron-beam evaporation onto quartz substrates held close to room temperature. The system base pressure was in the $10^{-9}$-Torr range, and the ambient pressure during deposition was in the $10^{-7}$-Torr range. The source to substrate distance was 19 cm, and the deposition rate was 50–75 Å/sec. Using appropriate masking, electrodes were deposited to permit measurement of low- and high-field conductivity both parallel and perpendicular to the plane of the film. The thickness of the $a$-Ge

ranged from 0.4 to 4 $\mu$m.

Considerable difficulty was encountered due to the formation of small crystallites in the "sandwich" region of the samples, an effect first reported by Bosnell and Voisey.[12] In the present study, it was observed that $a$-Ge deposited onto Au, Al, or Cr at room temperature almost invariably contained a small crystalline region whose size was estimated from electrical measurements to be 1–10 $\mu$m in diameter. The problem was finally circumvented by working strictly with Al electrodes and growing a thin (about 10 Å) layer of oxide on the Al before depositing the $a$-Ge. The tunnel resistance of the oxide has been well characterized in a recent study by Smith and Clark[13] so that it was a straightforward matter to correct for this additional resistance in the transverse resistivity ($\rho_\perp$) measurement. It is interesting to note that depositing the top Al electrode onto freshly deposited $a$-Ge causes no difficulties, suggesting that the crystallization occurs during growth of the $a$-Ge.

Samples of $a$-Ge prepared under the same conditions as described above were supplied to Cargill as part of his small-angle x-ray scattering studies.[4] These samples showed anisotropic small-angle scattering qualitatively consistent with Galeener's model.

Figure 1 shows low-field resistivity versus temperature for a typical sample, measured both in the planar ($\rho_\parallel$) and transverse ($\rho_\perp$) directions. The estimated absolute uncertainty in the resistivity is indicated. This uncertainty is primarily due to limitations in defining the pattern geometry and errors in measuring sample dimensions. The room-temperature resistivity of all samples is about 75 $\Omega$ cm. The points in the figure represent a rough correction to $\rho_\perp$ for the additional series resistance of the oxide plus electrodes. For all samples studied, $\rho_\perp = \rho_\parallel$ within the experimental uncertainties indicated.

Figure 2 shows the high-field effect at 77 K measured in both the planar and transverse directions (the electrode spacing for the planar measurement was about 0.1 mm). The deviation from the Poole-Frenkel-type behavior at high fields is presumably due to sample heating. The high-field effect is found to be the same in both directions, again within the experimental uncertainty indicated.

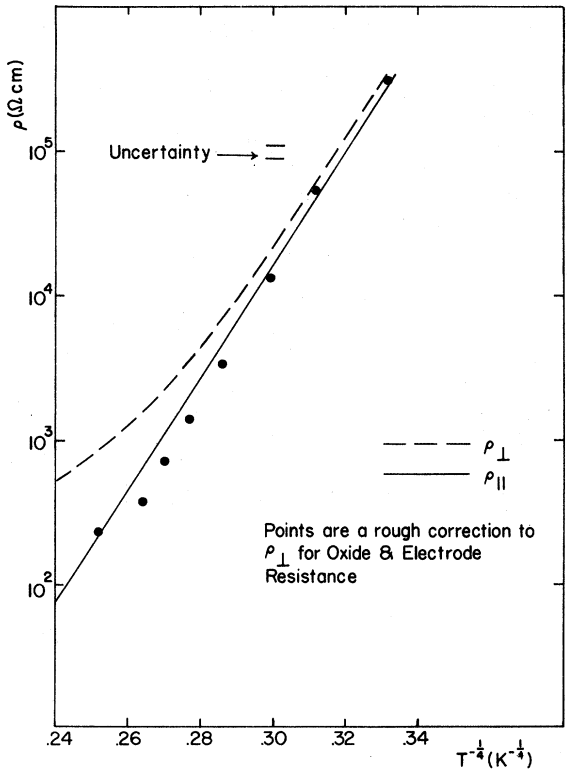


FIG. 1. Transverse and planar low-field resistivity of an amorphous germanium film 2.7 $\mu$m thick.

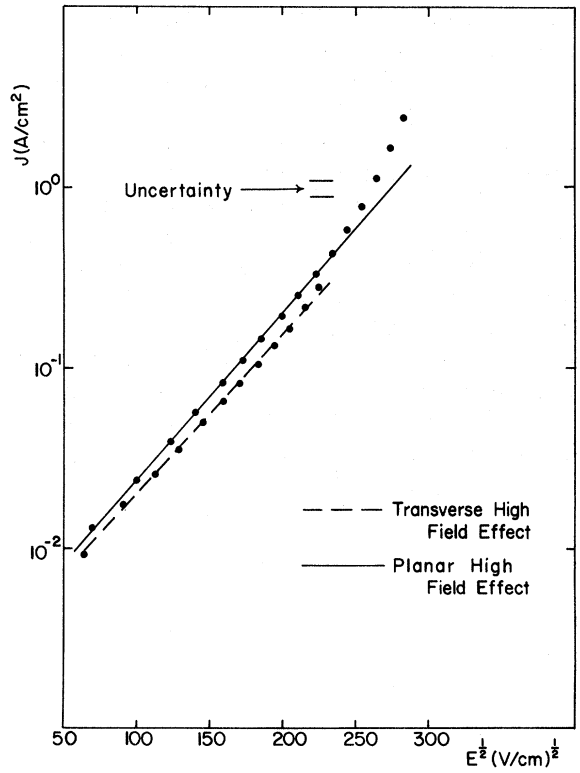


FIG. 2. Transverse and planar high-field effect at 77 K for an amorphous germanium film 1.2 $\mu$m thick.

Because of the difficulties with contacts, the thinnest film from which reliable transverse data could be obtained was about 0.4 $\mu$m. In addition, we studied the planar low-field resistivity of a film 100 Å thick because very thin films might be expected to be more sensitive to the void structure. The low-field resistivity of this film showed the same $T^{-1/4}$ behavior and agreed well with resistivity of the thicker samples. Since we obtained no transverse data on this sample, however, we draw no conclusions concerning anisotropy in very thin films.

The main conclusion of this study, therefore, is that if the voids are affecting transport in films thicker than 0.4 $\mu$m, they are doing so in an isotropic manner. The voids are so anisotropic structurally, however, that one would not expect them to influence the transport isotropically. Furthermore, annealing should decrease the void concentration (although in Galeener's study[5] the films were *deposited* at higher temperatures, not *annealed*). If the voids are influencing the low-field transport, possibly by creating barriers, annealing of the films should increase the conductivity, rather than decrease it as actually occurs. One concludes, therefore, that

$$(1/l)\mu_0 < (1/t)\mu_{\text{barrier}}, \quad (2)$$

where $\mu_0$ is the low-field mobility (due presumably to some form of hopping transport), $l$ is some average spacing between voids, and $t$ is some average void thickness.

One can attempt to estimate the effect of the voids by calculating the tunnel resistance for a 5–10-Å vacuum layer between two regions of $a$-Ge of thickness 100 Å. The tunnel resistance is so sensitive to thickness, however, that the results are inconclusive [Eq. (2) is satisfied for a 5-Å barrier but not for a 10-Å barrier].

The void structure may play a more important role in the photoconductivity. This effect (at photon energies of about 1 eV and above) presumably is due to electrons in extended states. In this case, one may very well have

$$(1/l)\mu_{\text{extended}} > (1/t)\mu_{\text{barrier}} \quad (3)$$

so that a large void concentration may limit the photoconductivity, but not necessarily the low-field conductivity. Films produced in this study show a very small photoeffect as prepared, but the photoconductivity increases upon annealing at 150°C. The details of this study will be presented in a later paper, but the annealing result is at least consistent with the barrier hypothesis. Fischer and Donovan[14] similarly found that a film grown at 300°C showed increased photoconductivity over films grown at room temperature, although their room-temperature films also exhibited considerable photoconductivity.

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