

## Anisotropic Electrical Properties of Amorphous Germanium

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The electrical conductivity of amorphous Ge films ranging in thickness between 240 Å and 6 μm was measured both in the plane and in the transverse directions. A marked anisotropy in both the resistivity and its temperature dependence was observed below 0.4 μm. There are also marked differences in electrical properties between films deposited at 300°K and kept at 77°K, which are related to the structure of the films.

Galeener has recently interpreted<sup>1,2</sup> an anomalous structure in the uv dielectric constants of 1000-Å amorphous evaporated films in terms of cracklike voids. These cracks (10 Å wide, 100 Å long) have been observed in high-resolution electron micrographs by Donovan and Heinemann.<sup>3</sup> On the other hand, a small-angle x-ray scattering study by Cargill<sup>4</sup> on 7-μm-thick films is consistent with rodlike low-density regions (22 and 46 Å in the film plane, 2200 Å normal to the film plane). Finally, Clark and Burke,<sup>5</sup> who measured the electrical properties of amorphous Ge films both in the plane and the transverse directions, reported no anisotropy for films ranging in thickness between 4 and 0.4 μm.

In a sense, it was not surprising that Clarke and Burke<sup>5</sup> found no anisotropy in the electrical properties, as the thinnest of their films (0.4 μm) was appreciably thicker than the reported scale of the internal defect structure.<sup>1-4</sup> The main objective of the present study was to extend the transverse measurements to thinner films (240 Å). Furthermore, this study includes a new type of amorphous Ge film, namely, films deposited and kept at 77°K until measured. All films, regardless of the temperature of deposition or degree of anneal, had a low-field resistivity of the form

$$\rho = \rho_0 \exp[(T_0/T)^{1/4}]. \quad (1)$$

This equation was first derived by Mott<sup>6</sup> and recently recast by Ambegoakar, Halperin, and Langer<sup>7</sup> in terms of percolation theory. The temperature  $T_0$  in Eq. (1) is given as<sup>7</sup>  $16\alpha^3|N(E_F)|$ , where  $\alpha$  is the coefficient of exponential decay of localized states and  $N(E_F)$  is the density of states at the Fermi level. If the material is inhomogeneous on a semimacroscopic scale (regions large compared to tunneling distances), then formula (1) gives a local resistivity,  $T_0$  and  $\rho_0$  being functions of position. Films deposited at 77°K were found to have lower resistivities (lower  $T_0$ ) than

films deposited at 300°K. The transverse electrical resistivity was lower than the planar resistivity for films thinner than 0.4 μm, this anisotropy increasing with decreasing film thickness.

The films were deposited on sapphire and glass substrates by getter sputtering<sup>8</sup> from an arc-melted Ge target<sup>9</sup> with a resistivity of 60 Ω cm. The rates of deposition varied between 2 and 8 Å/sec. For the transverse electrical resistance measurements, the Ge films were deposited between two narrow orthogonal electrodes with a cross-sectional area of  $3.6 \times 10^{-4}$  cm<sup>2</sup>. This geometry allowed four-probe resistance measurements which eliminated the necessity for electrode resistance corrections.<sup>5</sup> Furthermore, the deposition of both electrodes and Ge films at 77°K without either breaking the vacuum or raising the temperature eliminated both the formation of crystalline Ge and the formation of an oxide barrier, the presence of which requires huge corrections to the data.<sup>5</sup> Consequently, all the data presented here do not require correction, thus allowing the study of much thinner films. All resistance measurements planar and transverse are low-field measurements<sup>10</sup> and were obtained with electric fields smaller than  $10^2$  V/cm.

The temperature dependence of the resistance measured in the plane of the film for films deposited at 300°K and higher is shown in Fig. 1. The data are well fitted by relation (1) with  $T_0 \approx 3 \times 10^8$  °K and a room-temperature resistivity  $\rho_{RT}$  on the order of a few hundred ohm centimeters; this is to be compared with films evaporated at 300°K, which yield  $T_0 = 10^8$  °K and  $\rho_{RT} = 100$  Ω cm<sup>11</sup> or  $T_0 = 7.2 \times 10^7$  °K and  $\rho_{RT} = 40$  Ω cm.<sup>12</sup> Electron micrographs<sup>13</sup> of the sputtered films show a structure similar to the one reported by Donovan and Heinemann<sup>3</sup> but on a finer scale: The cracklike voids in a 100-Å film surround islands about 40 Å in diameter. The high resistivity of the sputtered films could be the result of

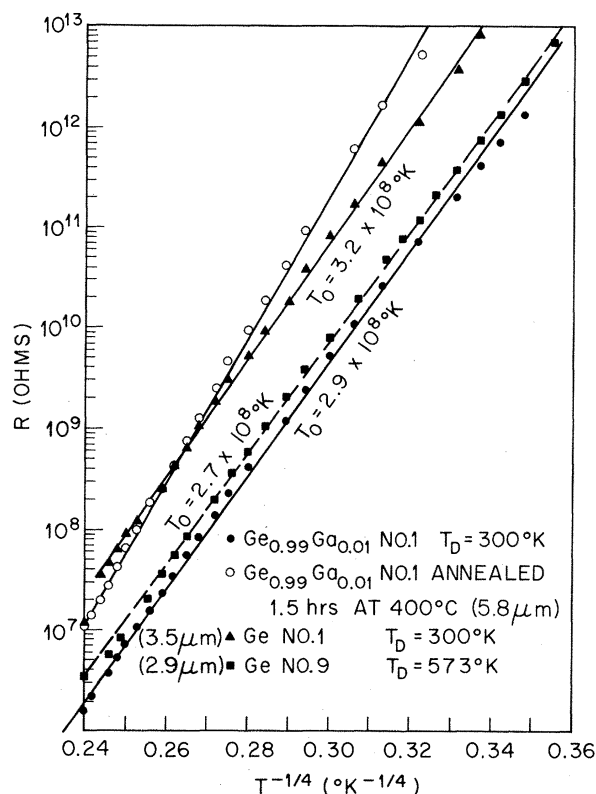


FIG. 1. Temperature dependence of the planar resistance for films deposited at and above 300°K.  $\text{Ge}_{0.99}\text{Ga}_{0.01}$  sample No. 1,  $d=5.8 \mu\text{m}$ ,  $\rho_{RT}=600 \Omega \text{ cm}$ ; Ge sample No. 1,  $d=3.5 \mu\text{m}$ ,  $\rho_{RT}=1500 \Omega \text{ cm}$ ; Ge sample No. 9,  $d=2.86 \mu\text{m}$ ,  $\rho_{RT}=600 \Omega \text{ cm}$ .

the higher density of voids. Furthermore, the higher density of voids may occur at the expense of the number of localized states, thus increasing  $T_0$ . This point is somewhat confirmed by the fact that annealing in general (see, for example,  $\text{Ge}_{0.99}\text{Ga}_{0.01}$  sample No. 1 in Fig. 1) results in a higher  $T_0$ .

We shall now turn our attention to films deposited at 77°K. The electron micrographs of such films taken after they were warmed up to room temperature are very similar to those taken on a film deposited at room temperature. Consequently, a film deposited at 77°K and brought back to 300°K certainly has the same type and density of cracklike voids as that of a film deposited at 300°K. The room-temperature x-ray diffraction of a film deposited at 300°K is in excellent agreement with electron diffraction as reported by others<sup>3</sup>: There are two broad peaks, the [111] being very close to the crystalline value, while there is a broad peak at  $d=1.85 \text{ \AA}$  which replaces Ge [220] and Ge [311]. The x-ray diffraction taken at 77°K

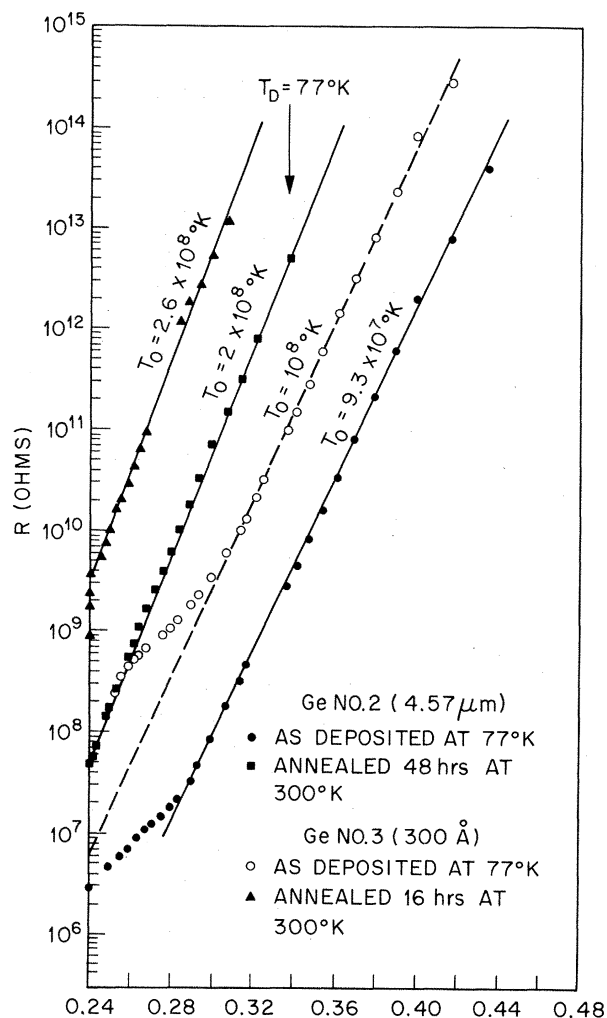


FIG. 2. Temperature dependence of the planar resistance for films deposited at 77°K showing the effect of room-temperature annealing. Ge sample No. 2,  $\rho_{\text{extr } RT}=57 \Omega \text{ cm}$ ; Ge sample No. 3,  $\rho_{\text{extr } RT}=14.4 \Omega \text{ cm}$ .

on a film deposited and kept at 77°K displays an even more distorted amorphous structure as shown by the smaller intensity over background of the peaks and a displacement of the peaks to lower angles (higher  $d$  values) which indicates a still lower density.

The temperature dependence of the planar resistance for films deposited and kept at 77°K is shown in Fig. 2. The data were obtained in the following manner: The films were cooled from 77 to 4.2°K, and the resistance was measured while they warmed up. As shown in Fig. 2 the data of the films deposited below 120°K are very well fitted by relation (1) with  $T_0 \approx 10^8 \text{ °K}$  which is appreciably lower than the value of  $T_0$  for room-temperature-deposited films. The films

anneal around 120°K as shown by the deviation from the low-temperature data towards higher resistance. If one extrapolates the low-temperature data to room temperature, one obtains a  $\rho_{\text{extr RT}}$  on the order of a few tens of ohm centimeters, which is lower than the value for room-temperature-deposited films. However, after an anneal at room temperature the films progressively regain the values of the parameters characteristic of a room-temperature-deposited film ( $T_0 \approx 3 \times 10^8$ °K and  $\rho_{\text{RT}}$  on the order of a few hundred ohm centimeters). If one combines this electrical behavior with the structural information obtained from electron and x-ray diffractions, the following picture emerges. One may postulate that films deposited at 77°K possibly have low-density regions,<sup>4</sup> but not voids. The x-ray diffraction at 77°K suggests a more distorted structure where atoms would be frozen in during deposition, thus leading to a greater density of localized states (thus lower  $T_0$ ) but where adatom mobilities<sup>1</sup> would be too low for crack formation. Upon annealing two things happen simultaneously: Localized states are annealed out, thus increasing  $T_0$ , and cracks are opened up, thus increasing the resistivity. As the properties, both structural and electrical, of a film deposited at 77°K and annealed at 300°K are identical to those of a room-temperature-deposited film, we shall concentrate on 77°K-deposited films for the transverse measurements (where such a method allows the study of much thinner films).

The temperature dependence of the transverse resistance as a function of temperature for films deposited and kept at 77°K is shown in Fig. 3. If one compares these data with the planar measurements of Fig. 2, one concludes there is a marked anisotropy, which is revealed in two ways for films thinner than 4000 Å. First of all,  $T_0$  decreases smoothly from  $6 \times 10^7$ °K to  $2.5 \times 10^7$ °K as the film thickness decreases from 4000 to 240 Å, as compared with  $T_0 = 10^8$ °K for the planar measurements. Furthermore,  $\rho_{\text{extr RT}}$  is now a few ohm centimeters as compared with a few tens of ohm centimeters for the planar measurements. The annealing behavior which starts at 120°K is very similar to that observed in the planar geometry, but is shown in greater detail in Fig. 3. The data obtained for Pb-Ge-Pb sample No. 7 by heating it up to 120°K was retraced exactly upon cooling, which demonstrates that the curves are reversible if the annealing temperature is not exceeded. Successively greater degrees of annealing have

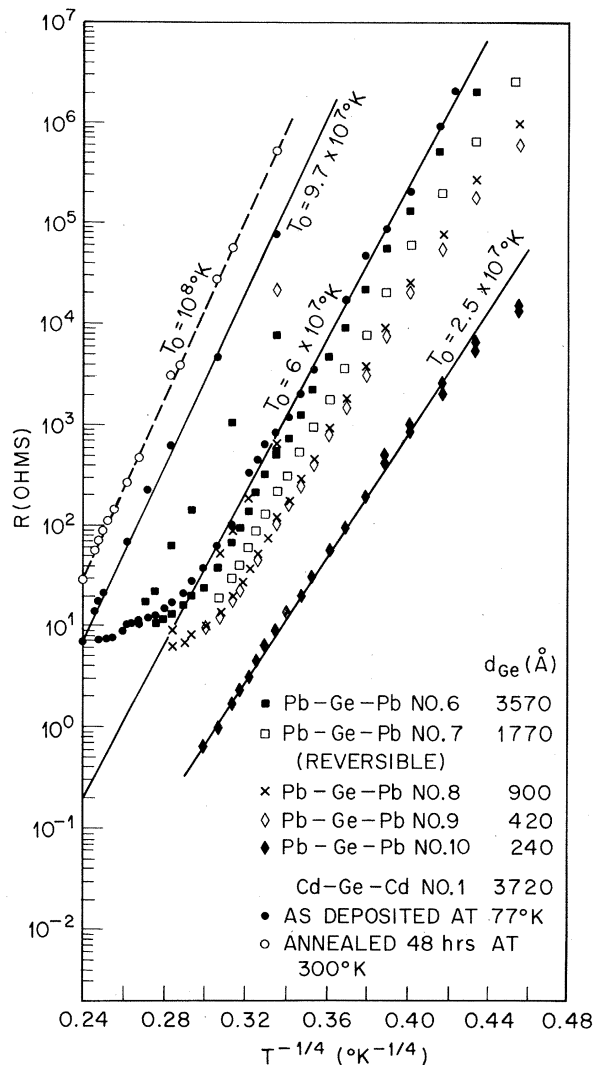


FIG. 3. Temperature dependence of the transverse resistance for films deposited at 77°K showing the effect of room-temperature annealing. The  $\rho_{\text{extr RT}}$  for the six samples are, respectively, for No. 6, 1.3  $\Omega$  cm; No. 7, 1.2  $\Omega$  cm; No. 8, 2.2  $\Omega$  cm; No. 9, 4.3  $\Omega$  cm; No. 10, 1.35  $\Omega$  cm; and No. 1, 1.9  $\Omega$  cm. The two sets of data for samples No. 1, No. 6, and No. 9 were obtained as follows: The lower-resistance data were measured on the sample as deposited at 77°K, while the higher-resistance data were measured by cooling from the highest temperature of anneal (e.g., 300°K for No. 1).

been experienced by samples No. 8 ( $T_{\text{max}} = 153$ °K), No. 6 ( $T_{\text{max}} = 193$ °K), and No. 1 ( $T_{\text{max}} = 300$ °K). One notices again that  $T_0$  and  $\rho_{\text{extr RT}}$  increase upon annealing. In the case of Cd-Ge-Cd sample No. 1 the room-temperature anneal increased  $T_0$  to  $10^8$ °K and  $\rho_{\text{RT}}$  to 67  $\Omega$  cm, upon reaching room temperature, and 285  $\Omega$  cm, 48 h later; this is still somewhat below the planar measurements on

such a film (Fig. 2). Clark and Burke<sup>5</sup> could not have detected the small anisotropy of a 4000-Å film with the accuracy of their measurements. The anisotropy disappears around 5000 Å as revealed by transverse measurements on a Pb-Ge-Pb sandwich deposited at room temperature which yielded identical parameters [ $T_0 = 2.4 \times 10^8$  °K and  $\rho_{RT} = 550$  Ω cm] to those in the planar measurements. The conductivity anisotropy in the thinner films is consistent with inhomogeneities on a semimacroscopic scale in the plane of the film, extending up to several thousand angstroms perpendicular to the plane. An electrical current transverse to the film can take advantage of regions with lower  $T_0$  and lower resistivity while a current in the plane of the film may be forced to traverse a network of barriers of higher  $T_0$  and resistivity. It is also obvious from Fig. 3 that these results are independent of the electrodes: Cd and Pb are shown in Fig. 3 but Mg and Ag yielded similar results. The resistance values for the 240 Å are somewhat low. This could be because every attempt to go below 240 Å resulted in shorts, suggesting that a 240-Å film has an uneven thickness as a result of its microstructure.

The electron micrographs as well as data on films deposited at intermediate temperatures along with further data on the present films will

be published in a more complete paper. I would like to thank B. L. Halperin for many valuable discussions and J. H. Wellendorf for his able technical assistance.

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<sup>9</sup>I am indebted to D. Dorsi for arc melting the target.

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<sup>13</sup>I am indebted to Miss A. Staudinger for the electron micrographs.

## Evidence for Interactions in Magnetically Doped Tunnel Junctions

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Tunnel junctions with high concentrations of magnetic atoms at the tunnel barrier show a characteristic conductance quite different from the  $G \approx \ln(|eV| + kT)$  which is shown by low-concentration junctions. The conductance as a function of voltage has a narrow minimum which gets deeper as the temperature is lowered. This is the behavior which is expected to result from interactions making the exchange scattering processes inoperative at low voltages and temperatures.

It is now well established that magnetic moments in a tunnel barrier can give rise to an extra conductance  $G$  which peaks at zero bias  $V$ .<sup>1-5</sup> The tunneling electrons are exchange scattered by the same interaction which gives rise to the Kondo effect in dilute alloys. If the concentration of magnetic atoms is low then the Anderson-Appelbaum<sup>6,7</sup> behavior is found in which the conductance varies logarithmically in temperature and voltage.<sup>8</sup> However, at very high concentrations a completely different behavior occurs.

The conductance peak does not appear and there is a broad conductance minimum instead, which is independent of magnetic field.<sup>9</sup> We have been looking at intermediate concentrations to chart the disappearance of the conductance peak which we thought could be due to interactions between the magnetic moments.<sup>10</sup> Here we present data which confirm this view, and suggest that much greater care must be taken in the future to ensure that interaction effects are not dominating the behavior of the conductance at low tempera-