Evidence for localization effects in compensated semiconductors

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We report measurements of the low-temperature conductivity of Ge crystals doped with Sb as a function of net donor density and of compensation. With increasing compensation the conductivity-versus-density curve broadens toward the curve predicted by the scaling theories of localization.

We consider a series of samples composed of a crystalline Ge lattice and a small number of randomly arranged impurity atoms. The dominant impurities are Sb donors and there are also significant numbers of acceptors, but the net donor concentration n is sufficient that the samples have finite conductivity in the limit of zero temperature $\sigma(0)$, and are therefore metals. Studies[1] of Si:P with negligible acceptor concentration show a remarkably sharp curve for $\sigma(0)$ vs n compared to an estimate based on the scaling theory of localization.[2–4] This theory does not consider Coulomb interactions.[5,6] Application of the Kubo-Greenwood formulation[7] predicts a discontinuous transition for $\sigma(0)$ less than Mott's minimum metallic conductivity (Ref. 8) $\sigma_{\min}$ (under certain circumstances), but, for $\sigma(0) > \sigma_{\min}$, a broader curve than observed.[9]

It seems possible that inclusion of Coulomb interactions might provide a better description of the observed $\sigma(0)$ vs n curve. We have investigated this hypothesis by comparing the $\sigma(0)$ curve of compensated samples with the uncompensated case. By adding compensation, we expect to add scattering centers to the random potential with a fixed number of mobile donor electrons involved in the Coulomb interactions. We find that added compensation lowers $\sigma(0)$, producing a broader $\sigma(0)$ vs n curve. Results at increasing values of compensation suggest a trend toward the estimate of the scaling theories of localization.

Figure 1 shows the low-temperature conductivity σ_{LT} for a number of samples of Ge:Sb as a function of net donor concentration n. The samples were selected from a large number of crystals to obtain groups with similar values of compensation. Different symbols are used for samples with given compensation K_0, where K_0 is estimated experimentally and is related to the donor and acceptor densities, n_D and n_A, according to $K_0 = n_A/n_D$. We define n as $n_D - n_A$. The value of σ_{LT} is determined from the conductivity extrapolated[10] to $T = 0$ K for $K_0 \lesssim 5\%$ and from the conductivity at $T \approx 1.5$ K for samples with larger K_0 where the temperature variation of the conductivity is less.

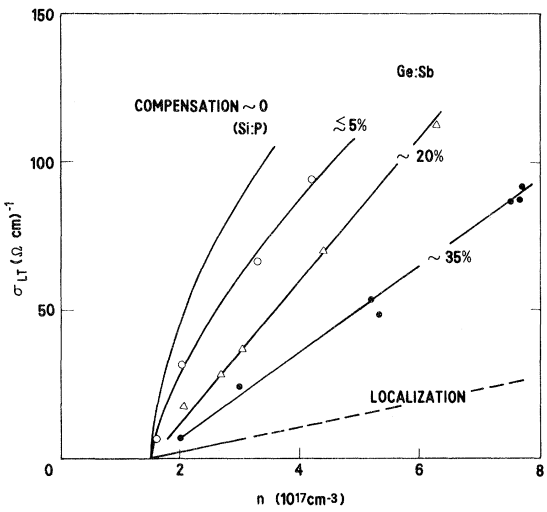

FIG. 1. Low-temperature conductivity σ_{LT}, as a function of net Sb concentration in compensated Ge. Starting from the scaled behavior of Si:P, the trend of the four upper experimental curves shows that with increasing compensation K_0, the results tend toward a prediction of the scaling theories of localization. The results correspond to temperatures T and fitted curves $\sigma_{LT} = A\sigma_{\min}(n/n_c - 1)^{\nu}$ with the values: $(K_0, T, A, \nu) = (\sim 0\%, \to 0$ K, 13, 0.55), $(\lesssim 5\%, \to 0$ K, $9 \pm 2, 0.7 \pm 0.2)$, $(\sim 20\%, 1.5$ K, $5.5 \pm 2, \lesssim 1)$, $(\sim 35\%, 1.5$ K, $3.3 \pm 1, \sim 1)$. The scaling theory of localization curve shown has parameters $(T, A, \nu) = (0$ K, 1, 1), and all curves use $n_c = 1.55 \times 10^{17}$ cm^{-3}. The uncertainties are approximately $\pm 10\%$ in n, $\pm 5\%$ in σ_{LT}, and $\pm 5\%$ in K_0.

The corrections for the zero T limit will involve some change in the shape of the curves for $K_0 > 5\%$, but will not change the general trend as a function of K_0. According to Mott's estimate,[8] the minimum metallic conductivity for Ge:Sb should be $\sigma_{\min} \sim 7\,(\Omega\ \mathrm{cm})^{-1}$. Since the data shown in Fig. 1 all have $\sigma_{LT} > \sigma_{\min}$, they do not bear directly on the question of the existence of $\sigma_{\min}$. We have measured a sample with $n = 1.4 \times 10^{17}\ \mathrm{cm}^{-3}$ and $K_0 \lesssim 5\%$ down to $T \lesssim 50$ mK and find it to be an insulator.

The densities used in Fig. 1 are determined from measurements of the Hall coefficient at room temperature in a magnetic field $H \approx 7$ kOe. We have not used the room T resistivity ρ_{RT} method[11] of determining n because the compensation is sufficient to increase ρ_{RT} significantly. We assume that relative values of n are reasonably well determined from the Hall coefficient, although the absolute values may be slightly low as is the case[11] in uncompensated Si:P. Some of the data in Fig. 1 have been previously published by Sasaki and coworkers.[12–15] Since these older and our new measurements give consistent results, we have used different symbols to indicate approximate values of K_0 and have not differentiated among sources of the results.

The values of K_0 indicated in Fig. 1 were obtained using the Brooks-Herring formula for mobility at $T = 77$ K to obtain $n_D + n_A$, as discussed, for example, by Debye and Conwell,[16] and using the Hall coefficient for n as noted above. Some of the difficulties in using this procedure for metallic samples are discussed by Yamanouchi *et al.*,[17] and by Fritzsche and Cuevas.[18] The relative values of K_0 should be correctly given by this method, but the absolute uncertainty is $\pm 5\%$.

The curves shown in Fig. 1 illustrate the trend in σ_{LT} vs n with increasing K_0. To represent the case of $K_0 = 0$, we have scaled the results[1] in Si:P linearly, using $\sigma_{\min} = 20\ (\Omega\,\mathrm{cm})^{-1}$ and $n_c = 3.74 \times 10^{18}\ \mathrm{cm}^{-3}$ for Si:P, and using $\sigma_{\min} = 7\ (\Omega\,\mathrm{cm})^{-1}$ and $n_c = 1.55 \times 10^{17}\ \mathrm{cm}^{-3}$ for Ge:Sb. Thus, the $K_0 = 0$ curve is given by $\sigma_{LT} = 13\sigma_{\min}(n/n_c - 1)^{0.55}$. The lines through the data for Ge:Sb are best fits for the values of K_0 indicated, using the form

$$\sigma_{LT} = A\sigma_{\min}(n/n_c - 1)^{\nu}\ , \tag{1}$$

with A and ν varied in the fit and n_c fixed. If n_c is used as a parameter, there is very little change in the fits for $K_0 < 5\%$ and $K_0 \sim 35\%$. For $K_0 > 5\%$, $\nu = 1$ is chosen for simplicity since a precise value can be obtained only if K_0 is fixed more accurately than we have done and since, as noted above, the shape of these curves will change between the temperature considered here and the $T = 0$ K limit. Considering these factors, $\nu = 1$ provides a reasonable description of σ_{LT} for $K_0 \sim 35\%$. The experimental values of the fitted parameters in Eq. (1) are given by $(K_0, A, \nu) = (\lesssim 5\%, 9 \pm 2, 0.7 \pm 0.2)$, $(\sim 20\%, 5.5 \pm 2, \sim 1)$, $(\sim 35\%, 3.3 \pm 1, \sim 1)$. For comparison, the lowest line shows the estimate of the scaling theories of localization[2–4] for the zero-temperature conductivity

$$\sigma(0) \sim \sigma_{\min}(n/n_c - 1)\ . \tag{2}$$

This equation uses values of $A = 1$ and $\nu = 1$. These theoretical values are not precise within current analyses and are expected to be reasonable numerical evaluations only for $\sigma(0) << \sigma_{\min}$. However, the region where significant deviations from free-electron theory occur extends up to higher conductivities,[1] including the region we consider here.

The results shown in Fig. 1 indicate a significant broadening of the shape of the conductivity curves with increasing K_0. The behavior clearly moves toward that predicted by localization. We speculate that this trend may be due to a decreasing relative importance of Coulomb interactions[5,6,19] compared to the random potential scattering considered by localization theory.[2–4] However we do not know the effect of compensation on the interactions. In the uncompensated case there is evidence for dominant Coulomb interactions in the temperature[10] and magnetic field[20] dependence of the conductivity. The trend in Fig. 1 for $n >> n_c$ can be understood in terms of the Born approximation even though this model is invalid for $k_F l \lesssim 1$. (Over half of our data has $k_F l < 1$, using $k_F l \sim 0.025\sigma_{LT}/\tilde{n}^{1/3}$, with $\tilde{n}$ in units of $10^{17}\ \mathrm{cm}^{-3}$.) In this model the amount of scattering increases with K_0 at constant n and $\sigma_{LT} \propto 1/n_D + n_A$.

There is additional evidence for the trend in Fig. 1 from the careful and extensive studies of radiation-doped Ge by Fritzsche and Cuevas,[18] and by Sasaki and Yamanouchi.[21] The principal difference between these studies and our work is that we have extended the measurements to lower temperatures. As expected,[22] the lower temperature results change the shape of the σ vs n curves and sharpen the distinction between metals and insulators. In agreement with the previous results,[18,21] we find that the sign of $d\sigma/dT$ at $T \sim 1.5$ K changes from

positive to negative with decreasing density. Fritzsche and Cuevas[23] have noted that this density increases by about a factor of 2 as K_0 increases from $\lesssim 4\%$ to $\sim 40\%$, and have suggested that there may be a corresponding increase in n_c. We define a sample as metallic if it has $\sigma > 0$ in the limit $T \to 0$, independent of the sign of $d\sigma/dT$ near 1 K. As noted above, the fits illustrated in Fig. 1 show no large change in n_c with K_0.

A broad curve for σ_{LT} vs n is observed in amorphous alloys[24,25] that is qualitatively similar to the results shown in Fig. 1 for moderate values of K_0. It may be that, in the alloys, localization effects are relatively more important than for the case of $K_0 = 0$. Also, it may be possible to discuss the effects of annealing in the amorphous alloys in a way analogous to varying compensation. Annealing has been shown to be understandable in terms of a variation of K_0 in radiation-damaged, doped semiconductors.[18,21]

We conclude that the scaling theories of localization provide a better description of compensated than of uncompensated metallic semiconductors with $\sigma(0) > \sigma_{min}$.

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