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Short-length-scale conductivity enhancement in a superlattice

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We have used far-infrared absorption to probe the optical conductivity of metallic GaAs:Si sheets imbedded in GaAs by molecular-beam epitaxy. An enhancement of the conductivity is observed at short-length scales which we attribute to localization and Coulomb-interaction effects. However, the spectra do not appear to be quantitatively described by existing theories for long-length scales.

It is well known that disorder inhibits electron conduction in metals, and eventually leads to a metal-insulator transition in a number of experimental systems.[1-3] These effects have been understood in part on the basis of the scaling theory of localization and of the effect of the electron-electron interactions.[4] Mott has suggested[5] that disorder may, in fact, enhance the conductivity at short-length scales. His suggestion arises from the view that the spatial reduction of the electron wave function in some regions in the disordered metal must lead to a pileup in other regions. This pileup would imply an enhanced conductivity if the system is probed at these length scales, which lie between the coherence length and the elastic mean free path.

Another way to see the possibility of a conductivity enhancement is to consider the sum rule for the total optical conductivity.[6] A conductivity suppression compared to the Boltzmann result at low frequencies (long-length scales) necessitates an enhancement at higher frequencies (shorter-length scales). However, this consideration does not determine the frequency range at which the enhancement will occur.

To search for this enhancement, we have studied the conductivity of an *n-i-n-i* structure (alternating *n*-type and insulating GaAs heterostructure[7]). The use of this type of sample enables us to tailor both the density and mean free path, and make the frequency scale accessible to our far-infrared absorption apparatus. A sample thickness small enough for near-optimum transmitted intensity could also be conveniently obtained. We were able to probe a frequency range, $0.13 < \omega\tau < 3$, well below and above the elastic scattering rate $1/\tau$. Studies of this range have not proved possible, as yet, in electron layers in metal-oxide-semiconductor field-effect transistors (MOSFET's[8]) and are rare in bulk metals,[9] where interband transitions usually interfere with a simple analysis. With our device we were able to obtain a scattering rate significantly higher than that for a bulk metal doped to the same average density[10] because in the heterostructure the electron motion is directly in plane with the sheets of dopant. This low mobility allows a detailed study of the intermediate frequency range of interest. The careful studies of MOSFET's by Wilson *et al.*[8] showed that good fits to the usual Drude behavior were found for $\omega\tau > 1$ in relatively high-mobility devices in which the electrons are weakly localized.

Our main result is illustrated in Fig. 1 which shows the enhancement of the conductivity at short-length scales. The range of lengths shown is from about 150 to 500 Å, or 1.5–5 times the Bohr radius of an isolated Si donor in GaAs. The quantity α plotted on the y axis is given by

$$\alpha = [\ln(I_0/I)]/d \ , \tag{1}$$

where I is the transmitted intensity through the sample and I_0 is the intensity through a reference crystal of GaAs of the same material as the substrate on which the sample was grown. The thickness of the absorbing layer $d = 1.28$ microns is measured by a deposit thickness monitor during the sample growth. The variation of α is approximately the same as that of the absorption coefficient, but differs because of the reflectivity.

The length L plotted on the x axis is the distance scale over which an electron diffuses within a period of the incident radiation field. Values of L are given by the diffusion coefficient of the sample D and the optical frequency ω using the diffusion formula[11]

$$L = (D/\omega)^{1/2} \ . \tag{2}$$

The far-infrared light comes to the sample from a Michelson interferometer and, after passing through, is detected by a bolometer operating near a temperature of 300 mK. Since the direction of incidence is perpendicular to the doped

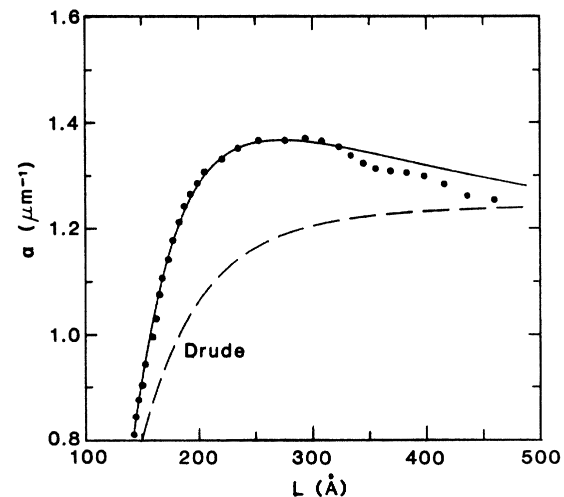

FIG. 1. The approximate absorption coefficient α as a function of length scale L for a heterostructure (*n-i-n-i*) device of GaAs with highly doped Si sheets separated by undoped layers. The structure is designed to enhance the scattering rate and tailor the absorption parameters to the far-infrared measuring capabilities. The values of α differ from the absorption coefficient because of reflectivity, but the reflectivity correction is included in the theoretical curves. The values of L are calculated from the measuring frequency and the diffusion coefficient. The solid circles are data; the solid curve is a fit including corrections to the Drude (dashed) curve based on localization and Coulomb intereactions.

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sheets the average electron motion is parallel to the plane. The data are initially recorded as an interferogram as a function of the position of the movable mirror in the interferometer and are then Fourier transformed to obtain the intensity as a function of frequency.

The sample was grown by molecular-beam epitaxy as part of a series of samples composed of alternating layers of undoped GaAs and GaAs:Si. In the sample used in Fig. 1, there were undoped layers 53 Å thick separating GaAs:Si layers 11 Å thick with the structure repeated 200 times. Since this layer separation is less than the Si-donor Bohr radius of 100 Å, we expect the sample to be three dimensional and have analyzed our results accordingly. The donor and electron density in the sample n was estimated two ways: with the Hall effect and with the Schubnikov–de Haas oscillations at a temperature of 4.2 K. The Hall effect gave $n = 4.8\times10^{17}$ cm^{-3}, and the oscillations gave 3.8 in the same units. In the analysis of the spectra discussed below we used the value 4×10^{17}. An important feature of this density estimate is that it indicates the sample to be a good metal since n is 40 times the critical density[12] of the metal-insulator transition which we estimate to be at 10^{16} cm^{-3}. Since the sample is metallic, we have used a Drude fit at short-length scales (high frequencies), shown in Fig. 2 and discussed below, to evaluate the average time between collisions τ. We find $1/\tau = 78$ cm^{-1}. Using these values, we can determine the diffusion coefficient using

$$D = l^2/3\tau \ . \tag{3}$$

Here, the mean free path l is obtained using the standard free-electron formula and the accepted effective mass for an electron in GaAs of 0.0665 times the free-electron mass. The result is $l = 270$ Å, again indicating the sample is a good metal, since compared to the Fermi wave vector $\mathbf{k}_F$ we have $k_F l = 6.2$. The resulting D is 35.7 cm^2/s.

The dashed line in Fig. 1 is the Drude prediction for the frequency dependence of α (including the reflectivity correction).[13] This curve is one term in the solid line fit to the data, also shown, and represents the behavior assumed to occur in the absence of localization and Coulomb interactions. It is with respect to this curve that the suppression of conduction occurs at longer-length scales than those investigated here—a region that has been extensively studied elsewhere.[1-4] The enhancement over the Drude conductivity at short scales is clearly seen in Fig. 1. The drude contribution α_D is calculated including both the reflectivity and the absorption due to the conductivity σ_D,

$$\sigma_D = \sigma(0)/(1+\omega^2\tau^2) \ , \tag{4}$$

where the Boltzmann conductivity $\sigma(0) = ne^2\tau/m^*$, and τ is obtained from the fitting procedure.

The second contribution to α is of a form that we have assumed in the absence of a proper theory in the length-scale range of interest. It is composed by assuming it to have the correct limiting form[4,14,15] ($\omega^{1/2}$) for $\omega\tau \ll 1$ and that it not modify the form of the Drude curve in the opposite limit. Both localization and Coulomb interactions have a behavior in the small $\omega\tau$ limit of the form $\omega^{1/2}$, and together predict the correction to σ of

$$\sigma' = -c\sigma(0)(\mathbf{k}_F l)^{-2}(\omega\tau)^{1/2} \ , \tag{5}$$

where the theoretical constant c is 2.24 (with 1.84 from a noninteracting perturbation calculation of localization and the rest from Coulomb interactions, assuming only Hartree contributions). We have inserted a Gaussian factor with range of order τ to reduce σ' to zero for $\omega\tau \gg 1$,

$$\sigma'' = \sigma'' \exp(-1.7\omega^2\tau^2) \ . \tag{6}$$

We calculate the dielectric constant consistently from $\sigma_D + \sigma''$ using the Kramers-Kronig relation and put both into the reflectivity and absorption to obtain α.

The fit in the range of data shown in Fig. 1 is sensitive to the constant c entering σ'', while the fitting at large ω is sensitive to the scattering time and density. We find a value of $c = 0.9$, which is considerably larger than the theoretical estimate of $c = 0.06$. This discrepancy is somewhat surprising since we expected the theory to be relatively firm for a

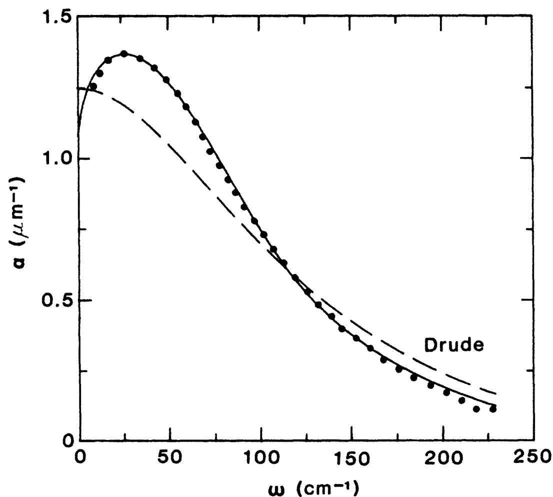

FIG. 2. The approximate absorption coefficient α as a function of measuring frequency ω. This fit of the solid line (discussed in the text) to the data at relatively high ω (along with the measured electron density) determines the diffusion coefficient and the Drude curve, both used in the analysis for Fig. 1.

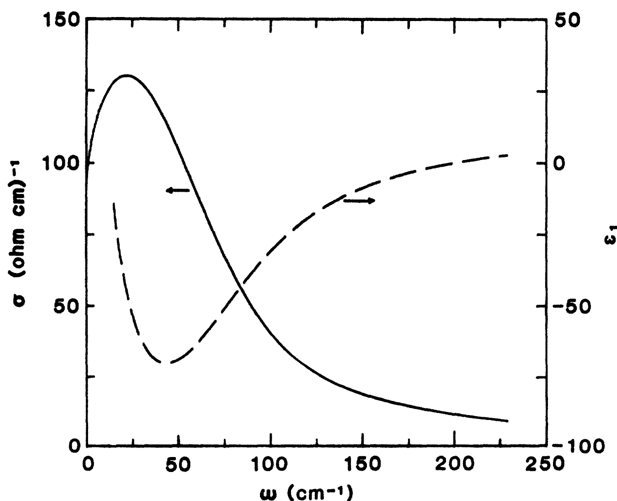

FIG. 3. The conductivity and dielectric constant determined by the fitting to the data as discussed in the text and shown in Figs. 1 and 2.

sample with $k_F l \sim 6$, even though we are investigating relatively short-length scales. The experimental determination of c should be accurate to within a factor of 2 (and probably much better), independent of the high ω cutoff procedure used. Similar discrepancies have also been seen in the temperature dependence of the conductivity of Ge:Sb crystals[16] and amorphous Si:Nb alloys,[17] but in these cases both the values of $k_F l$ and the discrepancies are smaller.

Figure 2 shows the approximate absorption coefficient α as a function of measuring frequency in wave numbers over the entire range that we have measured. The points are the measured values and the solid curve is the fit discussed above and partly shown (at low frequencies) in Fig. 1. The main result illustrated by this figure is the good fit obtained at high ω, from which we obtain the scattering time τ discussed above and the Drude curve shown in Fig. 1.

The conductivity σ and dielectric constant ϵ that were used to make the fits in Figs. 1 and 2 are shown in Fig. 3 as a function of ω. Based on our analysis presented above we suggest that qualitatively the peak in σ at low ω arises as follows. At low frequency the conductivity is suppressed due to localization and Coulomb interaction effects; this effect dies out as ω increases, leading to an enhanced conductivity. At still higher ω, $\sigma(\omega)$ decreases in the usual Drude fashion. The dielectric constant reflects this behavior through the Kramers-Kronig relation.

In conclusion, we find an enhancement of the conductivity at short-length scales in a relatively clean disordered metal. We expect this enhancement to be a universal feature of disordered systems.

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[1]See, e.g., the article by R. F. Milligan, T. F. Rosenbaum, R. N. Bhatt, and G. A. Thomas, in *Electron-Electron Interactions in Disordered Systems,* edited by A. L. Efros and M. Pollak (Elsevier, Amsterdam, 1985), p. 231.

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