probability D depends, have been discussed in Ref. 10. In this paper we consider D to be a function only of $E_{||}$. In general, it also depends on the energy variable ϵ and on the self-energy $\sum_B(\epsilon)$ of the electrons in the "barrier" region. The "quasi-particle-dispersion" behavior illustrated in Fig. 1 results from taking $Z(-eV)\equiv 1$, $D=$const, and using the collective-mode induced behavior of $\zeta(-eV)$ as reflected in the phase-space restrictions in the sum over $\mathbf{k}_{||}$ to determine the conductance.[6,10] The "quasiparticle-renormalization" behavior results when the behavior of $Z(-eV)$ is evaluated for a $V_q\propto q^{-2}$ electron–collective-mode vertex.[5,11,12] The resulting symmetric structure in dI/dV about zero bias is broadened, but not obliterated, by dispersion in the excitation spectrum of the collective modes.[5] From Fig. 1 it is evident that the existence of a resonancelike structure near $|eV|\cong\hbar\omega_0$ in d^2I/dV^2 which is antisymmetric about zero bias is neither a necessary nor a sufficient condition for the association of this structure with the mechanism of inelastic tunneling. The only general feature of the line shapes predicted by existing formulations of the transfer-Hamiltonian model[10] is the distinction between an abrupt increase in the total (zero-temperature) conductance at the threshold bias for an inelastic tunneling channel and various cusplike behaviors in the elastic conductance at the threshold bias for a loss process described by the electrode (or barrier) self-energy.[10,13] In the experimental data reported by both Tsui[1] and by Duke *et al.*[5] the distinction between the types of behavior shown in panels 1 and 3 of Fig. 1 cannot be made. The tentative identification of the observed structure as a bulk self-energy effect was made by Duke *et al.*[5] via its comparison with a line-shape calculation embodying essentially one adjustable parameter as well as via the correlation of the tunneling resonance with the IR reflectivity.

Summarizing, our considerations suggest that (a) doping-dependent resonances in d^2I/dV^2 cannot be identified with either bulk or surface plasmons until a direct (e.g., Raman-scattering or IR-reflectivity) measurement of the bulk plasmon energy is performed to determine the effective local value of the impurity concentration, and (b) regardless of the association of these resonances with bulk or surface plasmons, any interpretation based on their symmetry about zero bias is not unique. Some perspective concerning these plasmon effects is provided by the observation that the reported resonance structure[1,5] is quite weak and can be seen only in second-derivative measurements. This situation is in contrast to that in the case of superconductors[10] and in the case of phonon-induced self-energy effects in covalent semiconductors.[6,10] Therefore, ambiguities currently exist in both the experimental data and their theoretical interpretation which merit further clarification.

[10] C. B. Duke, *Tunneling in Solids* (Academic Press Inc., New York, 1969), Sec. 20.
[11] G. D. Mahan and C. B. Duke, Phys. Rev. **149**, 705 (1966).
[12] B. I. Lundqvist, Physik Kondensierten Materie **6**, 193 (1967); **6**, 206 (1967); **7**, 117 (1968).
[13] L. D. Landau and E. M. Lifschitz, *Quantum Mechanics* (Addison-Wesley Publishing Co., Reading, Mass., 1965), 2nd ed., Chap. 18.

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Surface-Plasmon Excitation by Tunneling Electrons in GaAs-Pb Tunnel Junctions

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Carrier-concentration-dependent structure in curves of d^2I/dV^2 versus bias in n-type GaAs-Pb tunnel junctions is compared with the bulk-plasmon and surface-plasmon energies of the GaAs sample. The bulk-plasmon energy is determined directly from infrared-reflectivity measurements. The conclusion is consistent with the previous suggestion that this structure can be interpreted as due to excitation of surface plasmons in the GaAs electrode by tunneling electrons.

RECENT observation of carrier-concentration-dependent broad structure in curves of d^2I/dV^2 versus voltage in n-type GaAs-metal tunnel junctions[1,2] has been interpreted as resulting from emission of surface plasmons in the GaAs electrode by tunneling electrons.[1,3] Such structure has been observed in both bias directions and can be related to an increase in conductance at bias voltage equivalent to the surface-plasmon excitation threshold energy. In Ref. 1, the observed threshold energy was contrasted to that expected from the bulk volume plasmon energy,

[1] D. C. Tsui, Phys. Rev. Letters **22**, 293 (1969).
[2] C. B. Duke, M. J. Rice, and F. Steinrisser, Phys. Rev. **181**, 733 (1969).
[3] K. L. Ngai, E. N. Economou, and M. H. Cohen, Phys. Rev. Letters **22**, 1375(1969).

$\omega_p = [4\pi n e^2/(m^* \epsilon_\infty)]^{1/2}$, using values of the electron concentration n obtained from sample suppliers. Duke[4] has suggested that such electron concentrations may be unreliable.

To check this point, we have measured the carrier concentration of the material described in Ref. 1 using the Hall effect. The measurements were made at 300 and 4.2°K on samples adjacent to the tunneling samples. We find that the plasmon energy reported in Ref. 1 is accurate to better than 10%.

We have also made infrared-reflectivity measurements to determine directly the bulk plasmon energy of the GaAs sample. In the remainder of this paper, a comparison of the observed tunneling excitation threshold energy is made with these optical measurements. The conclusion is consistent with the previous suggestion that the observed broad structure in d^2I/dV^2-versus-bias curves can be interpreted as resulting from excitation of surface plasmons in the GaAs electrode by tunneling electrons.

The infrared-reflectivity measurements are made at 300 and 78°K using a double-pass prism spectrometer and standard techniques.[5] The focused light beam covers an area 0.5×4 mm of the sample surface. Various spots on the sample surface of about 6×6 mm yield a difference of 3 meV in the energy position of the plasmon in the optical spectra. However, care has been taken to fabricate the tunnel junctions on the same spots of the sample on which the reflectivity measurements have been made (the tunnel junction has an area of 0.5×0.5 mm). The accuracy of the reflectivity data is better than 2%. It should be pointed out that the infrared-reflectivity spectra are temperature-dependent. As the sample cools down from 300 to 78°K, the plasmon shifts up in energy by 3.5 meV (~4% change). In the following paragraph, the data measured at 78°K are used to compare with the tunneling results which are obtained at 4.2°K.

Figure 1 shows the d^2I/dV^2-versus-bias curve of an n-type GaAs-Pb tunnel junction at 4.2°K. The GaAs sample is cut from the same bulk slice as the second sample listed in Table I of Ref. 1. Hall-effect measurements give a carrier concentration of $6.3 \pm 0.5 \times 10^{18}/\text{cm}^3$ at 4.2°K (carrier concentration from the supplier is $6.5 \times 10^{18}/\text{cm}^3$). The tunnel junction is fabricated by the method previously described[6] on the same spot of the sample on which the infrared reflectivity spectra have been measured. The dielectric function ϵ deduced from a two-oscillator fit to the reflectivity spectra at 78°K shows a bulk plasmon with energy $\omega_p = 94.5 \pm 1.0$ meV and width 5 meV.[5] This energy is shown in Fig. 1. The surface-plasmon energy given by $\omega_{sp} = \omega_p/\sqrt{2} = 67$ meV is also shown. It is evident from the figure that this surface-plasmon energy is in agreement with the observed excitation-threshold energy.

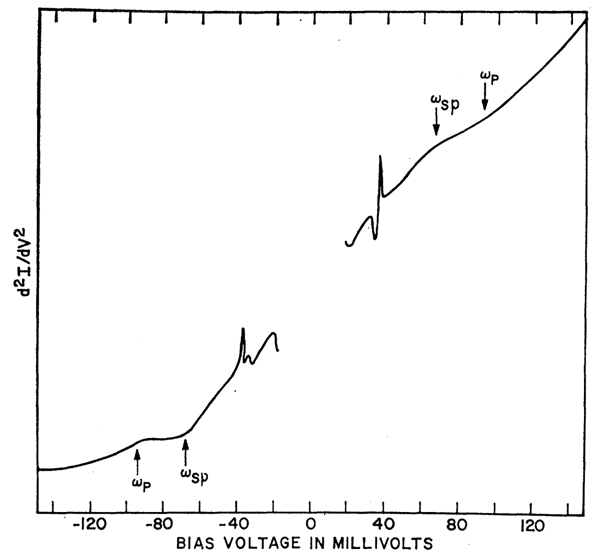

FIG. 1. d^2I/dV^2 signal from n-type GaAs ($n = 6.3 \times 10^{18}/\text{cm}^3$)-Pb tunnel junction at 4.2°K. The bias voltage, whose sign refers to that of the Pb electrode, is measured from the superconducting Pb energy gap. ω_p is the bulk plasmon energy of the GaAs electrode determined optically at 78°K. ω_{sp} is given by $\omega_p/\sqrt{2}$.

It would be desirable to measure infrared-reflectivity spectra at 4.2°K to make a better comparison with the tunneling results. We expect, however, a shift of the optically observed plasmon energy of less than 2% on further cooling from 78 to 4.2°K. Such a shift would not alter the consistency of the interpretation.

[4] C. B. Duke, preceding paper, Phys. Rev. **186**, 588 (1969).

[5] A. S. Barker, Jr., in *Optical Properties and Electronic Structure of Metals and Alloys*, edited by F. Abelès (North-Holland Publishing Co., Amsterdam, 1966). The reflectivity data are adequately fitted by considering the interaction of a quasifree electron plasma with the long-wavelength optical phonons of pure GaAs. The pole in $1/\epsilon$ near the reflectivity minimum gives the bulk plasmon energy and width.

[6] D. C. Tsui, Phys. Rev. Letters **21**, 994 (1968).