PHYSICAL REVIEW VOLUME 186, NUMBER 2 10 OCTOBER 1969

Comments and Addenda

The Comments and Addenda section is for short communications which are not of such urgency as to justify publication in Physical Review Letters *and are not appropriate for regular articles. It includes only the following types of communications: (1) comments on papers previously published in* The Physical Review *or* Physical Review Letters; *(2) addenda to papers previously published in* The Physical Review *or* Physical Review Letters, *in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section may be accompanied by a brief abstract for information retrieval purposes. Accepted manuscripts will follow the same publication schedule as articles in this journal, and galleys will be sent to authors.*

Plasmon Excitation by Electron Tunneling

C. B. Duke*

General Electric Research and Development Center, Schenectady, New York 12301

(Received 28 February 1969)

In a recent paper, Tsui interprets broad doping-dependent resonances in d^2I/dV^2 for metal contacts on n-type GaAs as being caused by the mechanism of inelastic tunneling associated with the excitation of surface plasmons in the GaAs electrode. His interpretation and data are compared with those of Duke, Rice, and Steinrisser. These authors measured the doping of the GaAs by infrared reflectivity. Substantial reductions in the effective value of the density of the dopant found from these measurements (relative to the value quoted by the supplier) require a change in the interpretation of similar resonance structure in d^2I/dV^2 from one in terms of surface plasmons into one in terms of bulk plasmons. Also, the momentum dependence of the electronic self-energy due to the electron-plasmon interaction has the consequence that a barrier-excitation interpretation of the resonance structure is not unique. An interpretation in terms of self-energy effects may be equally satisfactory.

IN a recent paper,[1] Tsui reports the observation of a broad doping-dependent resonance in the d^2I/dV^2 characteristic of lead contacts on n-type GaAs. He (a) associates this resonance with surface plasmons in the GaAs electrode, and (b) suggests that the mechanism responsible for this resonance is inelastic electron tunneling[2–4] via plasmon emission. A prior observation (and detailed interpretation) of similar data[5] led to the identification of such resonances with self-energy effects[4–6] in the GaAs electrode. In this paper, the origin of the discrepancy is discussed.

In order to identify a broad resonance, such as that observed by Duke *et al.*[5] and by Tsui,[1] with a plasmon energy, three quantities must be known precisely: (a) the doping of the semiconductor in the region of the metal contact, (b) the line shape of the resonance, and (c) its position relative to the ($\mathbf{k}=0$) bulk plasmon energy. In his paper, Tsui[1] discusses neither the accuracy with which his doping is known nor the magnitude of local variations within a sample. Duke *et al.*[5] performed an independent measurement of the impurity concentration by correlating the plasma minimum in the (room-temperature) infrared (IR) reflectivity (measured on the samples used in the tunneling experiments) directly with the (helium-temperature) observed resonance in d^2I/dV^2. Since the local fluctuations in the doping level of bars cut from a presumably uniform sample can be large (~50%), an independent establishment of the $\mathbf{k}=0$ plasmon energy was regarded by Duke *et al.*[5] as a significant prerequisite of a reliable experimental determination of the plasmon energy scale (corrected for plasmon–LO-phonon interactions when necessary[7]). For example, the sample labeled $n=6.2\times10^{18}$ in Fig. 7 of the paper by Duke *et al.* was obtained from a bar labeled $n=9.3\times10^{18}$ by the manufacturer.[8] The observed structure d^2I/dV^2 reported in Ref. 5 for this sample is almost identical to that observed by Tsui[1] in his sample labeled $n=9.5\times10^{18}$ cm^{-3}. Therefore, if Duke *et al.*[5] has used the manufacturer's value of the doping, they also would have interpreted their observations in terms of a "surface plasmon." An identical conclusion is true for the $n=4.2\times10^{18}$ sample described in Ref. 5 which was labeled as $n=5.4\times10^{18}$ by the manufacturer.[8] Tsui subsequently has reported preliminary measurements[9a]

---

* Present address: Department of Physics, University of Illinois, Urbana, Ill. 61801.

[1] D. C. Tsui, Phys. Rev. Letters **22**, 293 (1969).

[2] N. Holonyak, Jr., I. A. Lesk, R. N. Hall, J. J. Tiemann, and H. Ehrenreich, Phys. Rev. Letters **3**, 167 (1959).

[3] R. C. Jaklevic and J. Lambe, Phys. Rev. Letters **17**, 1139 (1966).

[4] C. B. Duke, S. D. Silverstein and A. J. Bennett, Phys. Rev. Letters **19**, 312 (1967); Phys. Rev. **176**, 969 (1968).

[5] C. B. Duke, M. J. Rice, and F. Steinrisser, Phys. Rev. **181**, 733 (1969).

[6] L. C. Davis and C. B. Duke, Solid State Commun. **6**, 193 (1968).

[7] C. G. Olson and D. W. Lynch, Phys. Rev. **177**, 1231 (1969).

[8] The sample was obtained from the Monsanto Co.

[9] (a) D. C. Tsui, Bull. Am. Phys. Soc. **14**, 414 (1969); (b) D. C. Tsui and A. S. Barker, following paper, Phys. Rev. **186**, 590 (1969); (c) K. L. Ngai, E. N. Economou, and M. H. Cohen, Phys. Rev. Letters **22**, 1375 (1969).

of the IR reflectivity of his samples, which indicate that the manufacturers's values of the impurity concentration, given in his paper, are accurate. However, this point seems to deserve further consideration.

Note added in proof. A detailed report of these measurements is given in the following paper.[9b] There seems to be no significant correction to the supplier's values of the doping in Tsui's samples.

Two aspects of the experimental line shape are used by Tsui[1] in his interpretation of his data: (a) the identification of the plasmon energy with a particular inflection point in d^2I/dV^2, and (b) the use of its roughly antisymmetrical shape about zero bias to identify the interaction mechanism as inelastic tunneling. Duke *et al.*[5] give an analysis of the line shape associated with the modification of the electron propagators in GaAs due to the electrons's interactions with (bulk) plasmons. One of their results is the conclusion that the dispersion and perhaps the damping of the plasmons play major roles in determining the tunneling line shapes. In particular, the dispersion leads to the predictions that the observed structure for a self-energy effect is broad and that the minimum in d^2I/dV^2 is associated with $\hbar\omega_p(q_0)$, where q_0 is an appropriate maximum plasmon wavelength, rather than $\hbar\omega_p(k=0)=(4\pi ne^2\hbar^2/m^*\epsilon)^{1/2}$. The "half-width" of the resonance structure referred to by Tsui[1] also is determined primarily by plasmon dispersion. This fact can explain his observation of "no systematic dependence of this half-width on the electron mobility of the sample." Tsui attributes this observation to "the nonideal boundary between the electron plasma and the tunneling barrier."

Note added in proof. Similar conclusions have been reached subsequently by Ngai *et al.*[9c] who presented a detailed calculation of the inelastic plasmon emission lineshape. Their line shapes look much better than those calculated by Duke *et al.*[5] However, Ngai *et al.*[9c] permitted themselves the luxeries of five adjustable parameters (γ, α, k_{c2}, d, and ϕ_{eff}) and an arbitrary background subtraction procedure. Duke *et al.*[5] used only two parameters (Γ and α). They determined Γ from the IR spectroscopy analysis of Olson and Lynch[7] and α from the random-phase approximation (RPA) analysis of (bulk) plasmons.

Finally, Duke *et al.*[5] demonstrated that, if the electron–collective-mode vertex is a rapidly varying function of momentum transfer, then an antisymmetric structure about zero bias in d^2I/dV^2 is a consequence of electronic self-energy effects due to electron-plasmon interactions in the electrode, as well as of barrier-excitation mechanisms. The qualitative features of the conductance associated with electron interactions with (dispersionless) bosons of energy $\hbar\omega_0$ are shown in Fig. 1. The sharp increases in conductance, symmetrical about zero bias, associated with inelastic tunneling are well known[3,4] to be caused by the availability of new tunneling channels. The self-energy effects may be illustrated by using the transfer-Hamiltonian model to write the tunnel conductance of a metal-semiconductor contact as

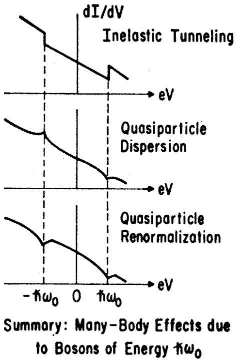

FIG. 1. Summary of three qualitatively distinct consequences of the interaction of a tunneling electron with a single "dispersionless" collective mode at zero temperature. The top panel describes the consequences of inelastic excitation of such a mode as discussed in detail in Ref. 4. The bottom two panels describe the consequences of self-energy effects in a single electrode in the limits that (a) the electronic self-energy depends only on the ϵ variable—"quasiparticle dispersion," and (b) the electronic self-energy depends strongly on the momentum variable $\mathbf{k}$, because of a q^{-2} momentum-transfer dependence of the electron–collective-mode vertex—"quasiparticle renormalization."

$$\frac{dI}{dV}=\frac{2e^2A}{\pi h}\int_{-\zeta}^{\infty}d\xi_{\mathbf{k}}\,\mathrm{Im}G^R(\xi_{\mathbf{k}},\,-eV)\times\int\frac{d^2\mathbf{k}_{||}}{(2\pi)^2}D(\mathbf{k}_{||},\epsilon\equiv0)\,,\quad(1a)$$

$$[G^R(\xi_{\mathbf{k}},\epsilon)]^{-1}=\epsilon-\xi_{\mathbf{k}}-\Sigma^R(\xi_{\mathbf{k}},\epsilon)\,,\quad(1b)$$

$$\xi_{\mathbf{k}}=\hbar^2k^2/2m^*-\zeta\,,\quad(1c)$$

$$\zeta=\hbar^2(3\pi^2n)^{2/3}/2m^*\,,\quad(1d)$$

in which A is the area of the junction, ζ is the Fermi degeneracy of the semiconductor, and a free-electron model has been used for the metal. In the quasiparticle approximation,

$$\mathrm{Im}G^R(\xi_k,\epsilon)=\pi Z(\epsilon)\delta[\xi_k-\xi(\epsilon)]\,,\quad(2a)$$

$$\epsilon-\xi(\epsilon)-\mathrm{Re}\Sigma[\xi(\epsilon),\epsilon]=0\,,\quad(2b)$$

$$Z(\epsilon)=\left(1+\frac{\partial}{\partial\xi_k}\mathrm{Re}\Sigma\,|\,\xi_k,\epsilon|\right)^{-1}=\xi(\epsilon)\,.\quad(2c)$$

Inserting Eqs. (2) into Eqs. (1) gives

$$\frac{dI}{dV}=\frac{2e^2A\rho_{||}}{h}Z(-eV)\times\int_0^{\zeta+\xi(-eV)}dE_{||}D(E_{||}),\quad(3a)$$

$$\rho_{||}=m^*/2\pi\hbar^2\,.\quad(3b)$$

Some technical difficulties, associated with the selection of the variables on which the barrier penetration 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 $Z(-eV)\equiv 1$, $D=\text{const}$, 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.

PHYSICAL REVIEW VOLUME 186, NUMBER 2 10 OCTOBER 1969

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

D. C. Tsui and A. S. Barker, Jr.
Bell Telephone Laboratories, Murray Hill, New Jersey, 07974

(Received 20 June 1969)

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).