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Point-contact spectroscopy in Al/In heterojunctions

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Point-contact spectra have been measured on Al/In heterocontacts. The amplitude of the Al contribution to the spectra is found to be reduced compared to that of In. The amplitude of the highest-energy Al peak near 36 mV is also reduced compared to the Al peak near 20.5 mV. These results qualitatively support the intrinsic potential-step model of Baranger *et al.* Other potential explanations are also considered.

Since its discovery by Yanson,[1] point-contact spectroscopy (PCS) has been used for many metals to obtain information about the electron-phonon interaction or the interaction between electrons and other elementary excitations. Most of these studies[2,3] have been made on homocontacts between the same materials. Relatively fewer have been made on heterocontacts.[4-6] These latter studies generally have been reported as consistent with simple additivity of the spectra from the two different metals comprising the heterocontact, with probably the clearest case being Cu/Au.[4] Batrak and Yanson,[5] on the other hand, reported more complex behavior in needle-anvil point contacts of Cu/Zn, in which the relative contributions to the spectra from the two metals depended upon the contact resistance and upon which metal was the needle. For contact resistances below about 1 Ω the two contributions were simply additive; for resistances somewhat larger than 1 Ω the contribution from the needle tended to be bigger than that from the anvil, and for an 11-Ω contact in which Zn was the anvil they found the Zn contribution to be dominant. Batrak and Yanson[5] and Schekhter and Kulik[6] attributed the PCS asymmetries for resistances greater than 1 Ω mainly to contact asymmetries, which produced different effective volumes for phonon generation in the two metals. Schekhter and Kulik examined PCS in heterojunctions theoretically, and concluded that—everything else being equal—one would expect a smaller contribution to the PCS spectra from the metal with larger Fermi momentum p_F and Fermi velocity v_F, due to the smaller relative phase volume of nonequilibrium occupied states in that metal, and to reflection of part of the electron trajectories at the metal interface.

Recently, Baranger, MacDonald, and Leavens,[7] calculated realistic PCS for alkali-metal heterocontacts, and found that the heterocontact PCS could differ strikingly from the sum of the two homocontact PCS. They found that the contribution from the larger-bandwidth metal could be very much smaller than in a homocontact junction, and that the part of spectrum due to scattering by $2k_F$ phonons was relatively enhanced. These effects originate from the intrinsic potential barrier between the two materials, which excludes scattering through angles less than a minimum angle from contributing to the PCS for the larger-bandwidth metal, and also relatively enhances the contribution of very large angle scattering. The minimum scattering angle Θ_c is given by

$$\sin(\Theta_c/2)=k_c/k_{F1}=\frac{[2m(E_{F1}-E_{F2})]^{1/2}}{\hbar k_{F1}} . \quad (1)$$

Here E_{F1} and E_{F2} are the Fermi energies of the wider and narrower bandwidth metals, respectively, k_c and k_F are the critical and Fermi wave vectors, m is the electron mass, and $\hbar$ is Planck's constant divided by 2π. If scattering events involving angles less than Θ_c contribute significantly to the homocontact spectrum of metal 1, its heterocontact spectrum will be reduced relative to that of metal 2. The approximate additivity reported in previous studies means that large angle scattering must have predominated in those metals. Indeed, in Cu/Au the additivity is clear only for the large peak due to scattering by transverse phonons. Such scattering is known to be dominated by large angle umklapp processes.[4]

Baranger *et al.*[7] suggested the Al/In heterocontact as a fruitful system for experimental work, because the Fermi surfaces are relatively simple, and the values of k_F are quite different. In addition, the energy ranges of the two-phonon spectra are well separated; the highest-energy peak of In is about 13 mV, while the lowest-energy peak of Al is near 20 mV. In this Rapid Communication, we report point-contact experiments on Al/In heterocontacts and compare the results with the theory of Baranger *et al.*

The experiments were made with a needle-anvil pressure-type contact. The aluminium was a zone-refined single crystal with a residual resistivity ratio of about 25000, and the indium was a 6-9 grade single crystal of a residual resistivity ratio larger than 20000. The anvils were cut from single crystal ingots by spark erosion, and chemically polished by an acid polishing procedure which yielded visibly flat surfaces. The needles were also formed by spark erosion. After chemical polishing, the needles were cemented to 0.2-mm-diam silver wires with pure In solder. Springlike behavior of the silver wire produced a stable contact. Both the anvil and needle were electro-

chemically polished just before measurement. The remainder of the experimental method is the same as reported previously.[8]

In Fig. 1, we show spectra for homocontact junctions Al/Al and In/In which were prepared as carefully as possible in the same manner as the Al/In heterocontact. In the In/In homocontact spectra, we observed two peaks, near 5.5 and 13 mV, respectively, and a shoulder near 10.5 mV. The highest-energy edge of the spectra is at about 16 mV. These values agree satisfactorily with previous results.[2,3,9] The background signal at high energies (i.e., ≥ 20 mV) is large, probably indicating deformation of the soft In in the point-contact region. Such deformation probably also explains why our peaks are not as sharp as the sharpest previously reported.[9] In the Al/Al spectra, we found two large peaks, near 21 and 36 mV, respectively, and a small peak near 31 mV. The highest-energy edge was estimated to be 42 mV. These values are also consistent with previous results.[2,3] The Al background signal is smaller than that in In, which is consistent with the greater hardness of Al. We have measured under many different conditions, and we generally obtained comparable signal heights in Al/Al and In/In as in Fig. 1, provided that we compare the spectra for nearly the same contact resistance and the same modulation amplitude. This is also consistent with previous results.[3]

In Fig. 2, we show a typical spectrum for an Al/In heterocontact. This spectrum looks rather like that for pure In, except that it also contains a small peak where the lower-energy Al peak is expected. In a few contacts, this Al peak was too small to be seen above the noise. Heterocontact measurements were made in both geometries; Al needle/In anvil and In needle/Al anvil. Unlike the case for CuZn,[5] we did not find any systematic difference between the two geometries, except that a stable contact was relatively hard to obtain when In was the needle. Our results

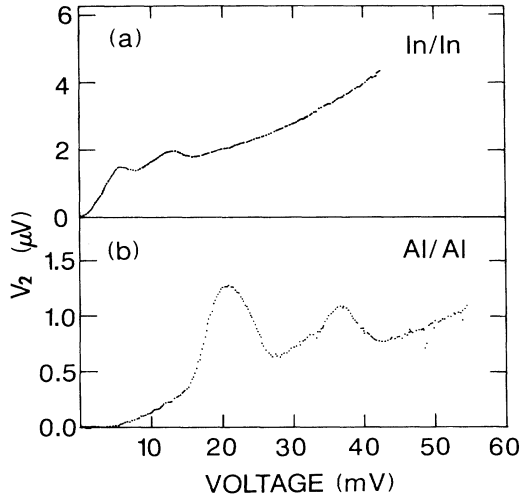

FIG. 1. Typical recorder traces of the second harmonic signal V_2 of (a) In/In, and (b) Al/Al homocontact junctions for similar contact resistances (~ 1 Ω) and modulation amplitudes. The measurement temperature is 4.2 K.

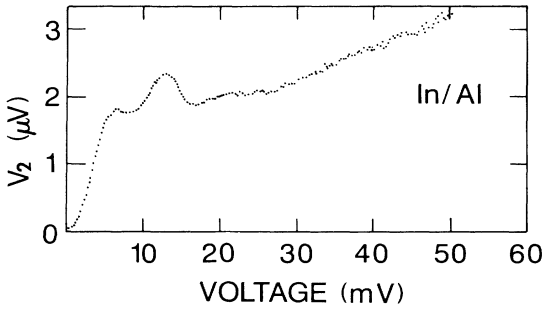

FIG. 2. Typical recorder trace of the second harmonic signal V_2 for an Al/In heterocontact. The contact resistance is about 2 Ω. The contact junction was carefully prepared in the same manner as the homocontact junctions.

also did not show any systematic variation with contact resistance over the range ~ 0.5–10 Ω for which stable contacts could be made.

The Fermi wave numbers of In and Al are 1.51×10^{10} and 1.75×10^{10} m^{-1}, respectively, so that the Baranger *et al.* critical wave number k_c is 0.898×10^{10} m^{-1}. The smallest scattering angle in Al which contributes to the heterocontact spectrum should thus be 62°. With such a large critical angle, the relative weight factor for scattering in Al compared to In increases relatively slowly from zero as the scattering angle increases above 62°; as shown in Fig. 4 of Ref. 7, the weight factor should be only about 0.25 at 80°. This means that we would expect the Al heterocontact spectrum to be greatly reduced compared to the In spectrum, if the homocontact spectrum of Al contains a significant contribution from scattering through angles less than $\sim 80°$–$90°$. The data of Fig. 2 indicate that this must be so, if the Baranger *et al.* model is the primary explanation for the behavior observed.

Baranger *et al.* also calculated a decrease in the height of the highest-energy peak relative to the lower-energy peak if large angle scattering is more important in the low-energy peak than in the high-energy one. Since the effect of large angle scattering is already enhanced in homocontact PCS, we can estimate the relative contributions of large angle scattering to the two peaks in Al by comparing the PCS spectrum for an Al/Al homocontact spectrum with the Eliashberg function $\alpha^2F(\omega)$ computed by Hayman and Carbotte.[10] We find that the relative magnitude of the high-energy peak to the low-energy one in the PCS spectrum is reduced compared to $\alpha^2F(\omega)$. This indicates that the large-angle scattering contribution is smaller for the high-energy peak than for the low-energy one. In agreement with this fact and the prediction of Baranger *et al.*, we see in Fig. 2 that while there is a small Al peak near 21 mV, there is no clear evidence of a peak near 36 mV.

Having shown that our data are qualitatively consistent with the Baranger *et al.* model, we briefly consider two potential alternative explanations for the reduced contribution from Al in Fig. 2. (1) One alternative is an enhanced effective volume for electron scattering in In, relative to that in Al, due to a highly asymmetric point contact. Such

an enhancement could explain both the reduced Al spectrum usually seen, and the occasional absence of this spectrum. However, it seems unlikely that all of our contacts, with both In and Al anvils, and with a wide range of contact resistances, would have such similar asymmetries that the In spectrum is always predominant. On the other hand, occasional asymmetry combined with the Baranger *et al.* effect could explain the occasional absence of the Al peaks. (2) The other alternative would require an unexpected interaction between the electrons in Al and the nonequilibrium phonon distribution that is believed to produce the background signal in PCS spectra.[3,11,12] In homocontacts, it is known from both theory and experiment[3,11,12] that the primary PCS is essentially independent of the size of the background. It seems unlikely that this would be very different in a heterojunction, but perhaps the nonequilibrium phonons produced in one metal (In) could affect the electrons in the other (Al) more than expected. To test this possibility experimentally requires heterocontact PCS with backgrounds of different sizes. Although we investigated a large number of heterocontacts, we always found rather similar background signals compared to the primary In peaks. We were, thus, unable to test this possibility experimentally.

We conclude that our point-contract measurements on Al/In heterocontacts qualitatively support the intrinsic potential step model of Baranger *et al.*[7] A quantitative comparison with this model cannot be made without a detailed calculation for the Al/In heterojunction and some means for estimating the contribution to the spectrum of scattering at a partially disordered interface. The other potential explanations we considered seem less likely.

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