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FERMI VELOCITY OF SILVER FROM PROXIMITY EFFECT TUNNELLING (*)

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Résumé. — Nous avons mesuré les caractéristiques tunnel d'une série de diodes tunnel Al-oxyde- $(\text{Ag}_{1-x}\text{Er}_x)\text{Pb}$, l'épaisseur du métal normal variant de 500 Å à 3 000 Å et des champs magnétiques parallèles de 0 à 1 000 gauss. La variation de la dérivée seconde (d^2V/dI^2) met en évidence la distribution des phonons dans le plomb superposée aux effets d'interférence des électrons et une structure apparaissant aux fréquences des phonons dans l'argent. L'application d'un champ magnétique inférieur au champ critique du sandwich permet d'atténuer la structure due aux phonons de l'argent, tandis que l'introduction d'impuretés réduit les effets d'interférence tout en n'ayant que peu d'action sur le spectre de phonons de l'argent. Nous pouvons ainsi séparer les deux contributions de la caractéristique tunnel. La théorie de McMillan et Rowell nous permet de déterminer V_F . En comparant les courbes expérimentales avec la théorie, on s'aperçoit que le terme d'interférence fait apparaître la variation du libre parcours moyen avec la fréquence, effet dû à l'émission de phonons, et permet ainsi une nouvelle méthode de mesure du couplage électron-phonon dans le métal normal.

Abstract. — We have measured the tunneling characteristics of a series of Al-oxide- $(\text{Ag}_{1-x}\text{Er}_x)\text{Pb}$ proximity effect sandwiches for normal metal thicknesses ranging from 500 Å to 3 000 Å and parallel magnetic fields of 0-1 000 gauss. Second derivative characteristics (d^2V/dI^2) reveal the Pb phonon structure through electron interference effects and also reveal structure at the Ag phonon frequencies. Application of a magnetic field less than the critical field of the sandwich reduces the Ag phonon structure. Introduction of impurities reduces the interference effects with little effect on the Ag phonon structure. We are thus able to separate the two contributions to the tunnelling characteristics. Comparison with the theory of McMillan and Rowell then allows determination of V_F . Comparison of the theoretical and experimental curves for the interference term shows a frequency dependent mean free path from phonon emission and allows an independent measure of the electron-phonon coupling in the normal metal.

When one tunnels into a normal metal backed by a superconductor, the density of states one obtains is significantly different from the one obtained by tunnelling into a superconductor. The second derivative characteristics of an N-I-S sandwich show *dips* at energies, shifted by the gap, corresponding to the Van Hove singularities in the phonon density of states of S [1]. In the second derivative signal of an N-I-N-S sandwich, however, this phonon structure is modified by an oscillatory function which depends on the thickness of the normal metal, its Fermi velocity, and the applied bias voltage [2]. This oscillatory function is a result of an electron interference phenomenon. Most strikingly, for small normal metal thicknesses (~ 500 Å) those dips appear as peaks. In addition the frequency dependent pair potential in N, induced

by the proximity effect, produces structure at energies, shifted by the gap, corresponding to the Van Hove singularities in the phonon density of states of the normal metal. In previous papers [3, 4] it has been shown that those two phenomena contribute to the tunnelling density of states and that the application of a parallel magnetic field quenches the N phonon structure by eliminating the pair potential in N. We have used this effect to measure the Fermi velocity in Ag by comparing our results with the McMillan and Rowell model [2]. In addition we have observed that the introduction of impurities in N significantly reduces the Pb structure by reducing the electron interference phenomenon in N, but does not substantially alter the structure at the Ag phonon energies.

The electron interference phenomenon can be explained if one notes that an electron propagating in N is back-scattered into a hole at the NS interface due to Andreev scattering [5]. The hole is assumed to

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be specularly scattered at the tunnelling barrier, and propagates back until it is scattered again into an electron at the NS interface. The two electron-like parts of the wave function can then interfere. Thus the spatial discontinuity of the pair potential at the interface gives rise to an oscillatory function in the expression for the density of states, just as in a normal metal a spatial variation of the scattering potential creates the Friedel oscillations in the charge density. The difference, however, is that whereas the characteristic length for the Friedel oscillation is $1/k_F$ ($\sim 3 \text{ \AA}$), here it is a function of energy ω . Since the electron (with k slightly greater than k_F) is scattered into a hole (with k slightly less than k_F) at the N-S interface the interference effect will depend on the difference in the wave vectors of the two particles which is $\omega/\hbar V_F$. For the range of energies studied ($30 \text{ meV} - \omega_{\text{gap}}$) the characteristic length of the oscillation varies from $\sim 100 \text{ \AA}$ to several microns [1].

The oscillatory function should depend on four times the thickness of the normal metal and the difference in the hole and electron wave vectors with energy $\hbar\omega$. In addition the double scattering at the NS interface should give rise to a term proportional to Δ_{Pb}^2 . Thus, assuming no induced pair potential in the normal metal, one gets the expression for the normalized density of states given by McMillan and Rowell [2]

$$N(\omega) = 1 + \text{Re} \left\{ \frac{\Delta_{\text{Pb}}^2(\omega)}{2\omega^2} \tau^2 F \left[\frac{4d\omega}{\hbar V_F} \right] \right\} \quad (1)$$

where

$$F(y) = \int_1^\infty \exp(ixy) \frac{dx}{x^2},$$

Δ_{Pb} is the pair potential in S, V_F the Fermi velocity, d the thickness of the normal metal, and τ the transmission coefficient. V_F occurs in this expression as the ratio of the change in wave vector from k_F to the change in energy from ε_F . We are thus measuring V_F directly rather than as an energy derivative of the area of an orbit as in cyclotron resonance. This is one of the few ways of directly obtaining V_F .

The tunnelling junctions were prepared in a vacuum of $1-2 \times 10^{-5}$ torr at room temperature. The junction was made by evaporating $3000 \text{ \AA} \pm 500 \text{ \AA}$ of Al and edge masking with $\sim 700 \text{ \AA}$ of SiO_2 . The film was then put into a humid oven at 100°C for 10-30 min in order to form the tunnelling barrier. The Ag film was then evaporated with thickness ranging from 500 to $3000 \text{ \AA}$ followed by $3000 \pm 500 \text{ \AA}$ of Pb. The thickness was measured with a quartz crystal thickness monitor which was calibrated with an optical interferometer. The overall thickness accuracy was $\sim 5\%$. Interestingly enough the time between the Ag and Pb evaporations was unimportant. Even opening the system to air before the Pb evaporation did not alter the data. The normal state resistances of the junc-

FIG. 1. — Tunnelling characteristics of an Al-I-Ag-Pb junction : a) Calculated tunnelling characteristics for this junction from the model of Rowell and McMillan [2]. Magnified curves have been displaced for clarity. b) In a parallel field of 700 gauss, ($H_c = 830$ gauss), c) In zero field.

tions were between 10-1 000 Ω with a cross section of $\sim 1 \text{ mm}^2$. The gaps (Ω_N) were measured from the I vs. V curves using the McMillan and Rowell construction [1]. Our data was taken between 1.1 and 1.4 K.

The second harmonic signals were taken by applying an ac modulation current of 1 019 Hz. We measured the voltage using a lock-in amplifier at the primary frequency for dV/dI and the second harmonic frequency for d^2V/dI^2 . The apparatus was similar to the one used by J. C. Adler *et al.* [6]. For the second harmonic signal the modulation was 1 mV with the bias voltage set at 10 mV.

Figure 1c shows the results obtained for an Al-Ox-Ag-Pb tunnel junction with the thickness of the normal metal being 900 Å. Thicknesses of 100 Å, 200 Å, 400 Å, and 600 Å have been investigated previously [3, 4]. The Pb structure that one obtains for an Al-Ox-Pb sandwich appears as dips around 6 mV and 10 mV [1]. For an Al-Ox-Ag-Pb sandwich, however, the structures may appear as dips or peaks depending on the value of the oscillatory function. This complicated lead structure has been observed by Rowell and McMillan [2] and by Nédellec [7]. Studies with different thicknesses of the normal metal show that the structure is quite sensitive, especially at high bias voltages, to the thickness of the normal metal. The normal metal phonon structure around 20 mV was decreased in amplitude but did not change shape as the thickness of the normal metal was increased. This indicates that the normal metal phonon structure is a function of the induced pair potential only.

Figure 1a shows the calculated value for the second harmonic signal, for the same thickness of the normal metal, using the McMillan expression for the density of states, eq. (1). We see the two major discrepancies between figure 1a and 1c. The normal phonon structure around 20 mV is not present in the theory. This is simply due to the fact that the McMillan model assumes no induced pair potential in the normal metal. In addition we see a sharp peak at 3.2 mV which is not present in the theoretical curve. This peak comes from a dip at 1.4 mV (the Pb gap) in the first derivative and has also been observed by S. M. Freake [8]. It is believed to be due to the fact that the wave function tends to have a larger amplitude in the region where the density of states is highest.

Figure 1b shows the same sample as figure 1a but in a parallel magnetic field of 700 gauss (the critical field of this N-S sandwich is ~ 830 gauss). We see that qualitatively the results agree much better with the theoretical predictions. The 3.2 mV peak is gone and the normal phonon structure is sharply reduced due to the quenching of the induced pair potential. Note that the structure due to the geometrical resonance is much less affected at this field.

We see from the McMillan expression for the density of states that the frequency dependence of the first and second derivative signal depends on the thickness

FIG. 2. — Second derivative signal for Al-I-Ag-Pb junction for Ag thickness of 600 Å in 600 gauss and 900 gauss.

FIG. 3. — Second derivative signal for Al-I-Ag-Pb junction for Ag thickness of 1 500 Å in 420 gauss and 900 gauss.

of the normal metal and the Fermi velocity. A simple way to measure the Fermi velocity is to look at the positions of certain peaks and dips (shown as a , b , c in Fig. 2 and Fig. 3) of the d^2V/dI^2 curve in a magnetic field (so as to quench the pair potential in the normal metal) and compare with the computed values for different Fermi velocities. Going from figure 2 to figure 3 one can see the change in position of the peaks

and dips at points marked *a*, *b* and *c* due to the change in thickness.

Figure 4 shows the measured and computed position for four film thicknesses and three different Fermi velocities. The thickness dependence of the oscillatory function is clearly greater at higher bias voltages. We obtain good agreement between the theory and experiment for $V_F = (1.4 \pm 0.07) \times 10^8$ cm/s, where the uncertainty in V_F is primarily determined by the accuracy with which we can determine the thickness of the normal metal.

FIG. 4. — Position as a function of thickness of different peaks and dips of the second harmonic signals for an Al-I-Ag-Pb film.

It is worth emphasizing that all of the data used in figure 4 comes from samples placed in a parallel magnetic field (less than H_c) and has been reproduced on at least two tunnel junctions prepared at different times for each thickness. An interesting point is that V_F is obtained from the frequency (energy) dependence of d^2V/dI^2 and is rather insensitive to the amplitude of this structure. We have investigated this last point by doping the normal metal with impurities to reduce the amplitude of the interference effect. The frequency dependence in these doped junctions remains unchanged.

Rowell and McMillan [2] have shown that silver film deposited on glass has a preferred crystal orientation, with a [110] axis perpendicular to the substrate; we therefore expect our experiment to measure the Fermi velocity in the [110] direction. Our determination of V_F is rather close to the free electron value, 1.39×10^8 cm/s [9]. We are also in good agreement with de Haas-Van Alphen measurements [10, 11] which give Fermi velocities along [110] of 1.34 and 1.46×10^8 cm/s, respectively. Rowell and McMillan have used the same technique and obtained a value of $V_F = 1.1 \times 10^8$ cm/s. We note that their measure-

ments were taken in zero magnetic field. As seen in figure 1, the application of a magnetic field reduces the effect of the normal metal pair potential and considerably changes the tunnelling characteristics.

The McMillan model, in addition to assuming no induced pair potential in the normal metal, supposes the electron mean free path to be larger than four times the thickness of the normal film so that the interference effect can take place. Comparison of our data with the theoretical prediction, as in figure 1, indicates a frequency dependent disagreement in the amplitudes of the signals. The observed signals are increasingly reduced above the bias voltages corresponding to the normal metal phonons. We believe that this is due to the energy dependent mean free path due to phonon emission [12]. A preliminary value of the electron-phonon coupling constant (λ) of 0.1 is sufficient to account for the magnitude of the observed effects. The finite mean free path due to impurities and film defects has been investigated theoretically by Wolfram [13] by adding an imaginary part to the wave vector and has been included in the expression for the density of states by Nédélec [7, 14] in the Tomasch geometry [15] and in the McMillan and Rowell geometry [1]. It should also be noted that the amplitude of the signals is sensitive to the type of scattering at the interface: specular or diffuse.

If indeed the Pb phonon structure is due to an interference of the electron wave function in the normal film, then one should be able to reduce this effect by putting impurities in the Ag film, thus

FIG. 5. — Second harmonic signal of an Al-Ox-AgEr-Pb tunnel junction. a) 0% Er in Ag. b) 0.2% Er in Ag. c) ~1% Er in Ag.

reducing the mean free path. Impurities should have a lesser effect on the Ag phonon structure since that depends on the induced pair potential, which will be only slightly depressed for the thin normal films used in this study. Figures 5a, b and c show second derivative signals of an Al-Ox-AgEr-Pb sandwich. The erbium concentrations were 0 %, 0.2 % and ~ 1 %, respectively. Figure 5b shows that 0.2 % of Er impurities significantly reduces the amplitude of the Pb phonon structure with little effect on the Ag phonons. Figure 5c shows an even more drastic effect with ~ 1 % of impurities in Ag. It should be noted that the induced gap is also reduced (and thus the Ag structure) since in the dirty limit the coherence length is proportional to the square root of the mean free path. We have observed similar effects on doping

with non-magnetic impurities such as In but we are more confident in the impurity concentration obtained in the AgEr films where an identical procedure has been used to produce films for EPR work.

In summary we have seen that proximity effect tunnelling allows us to study the electron-phonon interaction in N and in S separately. The effect of an applied magnetic field smaller than the critical field of the sandwich reduces the pair potential at the phonon frequencies of the normal metal by reducing the induced gap with little effect on the pair potential in S. The effect of impurities in N reduces the interference effect in N and thus the S phonon structure but has a lesser effect on the N phonon structure. Use of the McMillan model then allows us to directly measure the Fermi velocity in the normal metal.

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