Subgap and Above-Gap Differential Resistance Anomalies in Superconductor–Normal-Metal Microjunctions

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We present the results of differential resistance (dV/dI) measurement on high-transmittance Nb-Ag (or Al) microjunctions. At low bias, dV/dI has the conventional Blonder-Tinkham-Klapwijk double-dip structure *plus* a sharp single dip at zero bias. This zero-bias anomaly is completely suppressed by a modification in interface. It is insensitive to magnetic field. We relate it to the electron phase-coherence effect in the proximity of superconducting gap potential Δ. Above Δ/e, dV/dI exhibits an anomalous peak, whose position is found to be proportional to $\Delta(T, H)$.

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Superconductor–normal-metal (S-N) contacts exhibit nonlinear electron transport behavior because of the mismatched quasiparticle excitation spectra. Until recently, most of the non-Ohmic properties seemed to be accounted for by the theory of Blonder, Tinkham, and Klapwijk (BTK) [1]. Central to the I-V characteristics of S-N contacts is the Andreev reflection (AR) [2], which converts normal current to supercurrent. At the interface, an incident electron from N with subgap energy is retroflected into a hole, while the missing charge of $2e$ propagates into S as a Cooper pair carrying away the excess current. In a completely transmissive contact, the differential resistance [$R_d(V) = dV/dI$] below the gap voltage (Δ/e) becomes half of the normal resistance (R_N) because of AR. As the barrier strength is increased, normal reflection becomes appreciable, causing the zero-bias resistance, $R_d(0)$, to increase. A typical R_d vs V curve shows a double-dip structure at $\pm\Delta/e$, which has become the hallmark of the BTK behavior.

Recently, highly anomalous phenomena have emerged from a new class of heterojunctions involving contacts between superconductor and semiconductor (Sm). In particular, a *single* large zero-bias resistance dip, referred to as zero-bias anomaly (ZBA), was observed in some S-Sm-S junctions [3,4] and S-Sm contacts [5], which is different from the usual BTK behavior. In addition, a resistance peak above R_N was observed at bias voltages much higher than the gap voltage [4]. Various mechanisms [4–8] from phase-coherent transport to proximity effect were proposed to explain these observations.

There appears to be a consensus that S-Sm structures are prone to exhibit novel transport behavior. Interesting as these structures are for their wide range of carrier density and mobility, the inherent strong scattering at the S-Sm interface due to the Schottky barrier makes it difficult, though not impossible, to achieve high transmittance. To avoid this complication and to investigate the general nature of the anomalous transport, we have fabricated thin-film based *single* S-N microjunctions. In this Letter, we will present the result of dV/dI measurements on these junctions. Surprisingly, *both* the subgap and above-gap anomalies appear in our S-N contacts, which are much simpler in structure than the S-Sm and S-Sm-S contacts and are also different from the usual S-N configuration. More importantly, we are able to observe a transition from the BTK behavior to non-BTK behavior, i.e., ZBA, by adjusting the structure of the S-N contact, thus identifying the source of the ZBA. In addition, we have observed, for the first time, a novel magnetic field dependence for the ZBA. We have also characterized the above-gap anomaly, which is directly related to the superconducting gap, with both changing temperature (T) and magnetic field (H).

Figure 1 shows a scanning electron mircoscope micrograph and a schematic of a typical S-N junction. Distinctive from the commonly used planar or point contacts, our junctions are formed near the edge of a Nb film. Such a geometry offers some advantages crucial to our study. For example, the N electrode can be easily

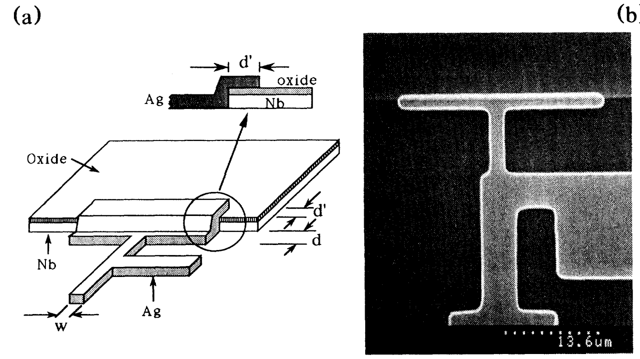

FIG. 1. (a) Schematic views of an overlayered junction. (Not to scale.) (b) Micrograph of a bare junction with $w = 2$ μm, $d = 1$ μm, and $d' = 0.5$ μm.

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patterned into different shapes and dimensions suitable for observing mesoscopic electron coherence effects in the proximity of a superconducting gap potential. Two types of junctions were fabricated, one with a 120-nm-thick oxide (Nb_2O_5) layer on the top surface of the Nb film, and the other with a bare Nb surface causing the S-N contact to cover both the edge and a portion of the top surface of the Nb film. This variety in the interface turned out to be essential for clarifying the ZBA. In addition to the interface, the junctions are characterized by three geometrical parameters, the width (w) of the N lead, the distance (d) from the injection point to the interface, and the width (d') of the S-N overlap on the Nb top surface. The oxide layer effectively makes d'=0. On one Si chip (3×3 mm^2), there are twenty different junctions with w, d, and d' ranging from about 0.6 to 2.5 μm. The total contact width is always 28 μm. The thicknesses of the films are 230–350 nm. The films were deposited by e-beam evaporation and patterned by optical lithography. We always used Nb as the S electrode, while both Ag and Al were employed as the N electrode, which yield qualitatively the same behavior. The I-V curve and dV/dI were measured simultaneously at various T and H with the phase-sensitive-detection technique.

We have measured over fifty junctions and observed universal behaviors among *all* samples. Without exception, the differential resistance of the junctions without the oxide layer (bare junction) can be represented by Fig. 2(a), and those with the oxide layer (overlayered junction) by Fig. 2(b). These data are highly anomalous in both the subgap and above-gap regions. Different junctions may differ in the details of some features; the general behaviors, nevertheless, are universal as follows: (1) In the subgap region, dV/dI of the bare junctions [Fig. 2(a)] consists of two components well resolved at low T

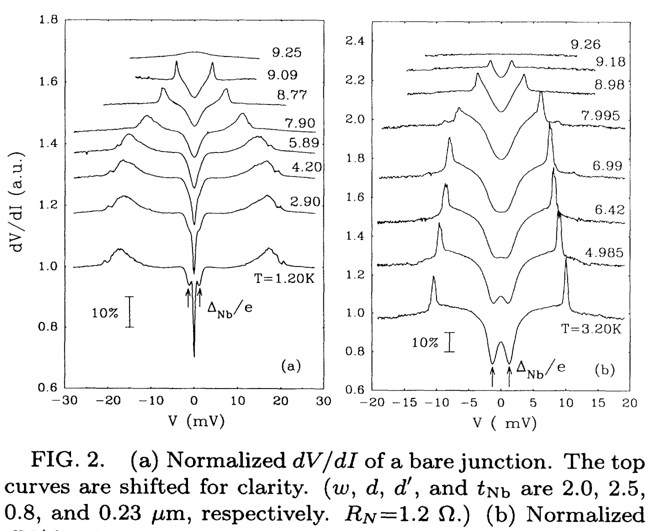

FIG. 2. (a) Normalized dV/dI of a bare junction. The top curves are shifted for clarity. (w, d, d', and t_{Nb} are 2.0, 2.5, 0.8, and 0.23 μm, respectively. R_N=1.2 Ω.) (b) Normalized dV/dI of an overlayered junction. (w, d, and t_{Nb} are 1.0, 2.5, and 0.33 μm, respectively. R_N=2.1 Ω.)

—a sharp single dip at zero bias and a component with double dips at $\pm\Delta_{Nb}/e$. As T is increased, these two components gradually collapse and merge into a broad dip. (2) In the overlayered junctions [Fig. 2(b)], the zero-bias dip does not exist; only the double-dip structure is observed. (3) In the above-gap region, both types of junctions exhibit a dV/dI peak above R_N, and its position always follows the same T and H dependence. All these features disappear above T_c, and therefore are due to superconductivity. It is important to be reminded that these novel behaviors are observed in S-N junctions much different from other Sm-based junctions.

The double-dip structure in dV/dI in the overlayered junctions is typical of the BTK behavior. This allows us to obtain some fundamental parameters by applying the BTK model to our data. One of them is a dimensionless number, $Z = V_0/\hbar v_F$, specifying the strength of the interface potential barrier, $V_0\delta(x)$. In the BTK theory, the current through an S-N contact is [1]

$$I = \frac{1+Z^2}{eR_N}\int_{-\infty}^{\infty}[f_0(E-eV)-f_0(E)] \times[1+A(E)-B(E)]dE, \qquad (1)$$

where f_0 is the Fermi distribution function, and $A(E)$ and $B(E)$, listed in Table II of Ref. [1], are the AR and normal reflection probability, respectively. Using Eq. (1), one can fit the dV/dI vs V data by choosing an appropriate Z. As a consistency check, Z can also be obtained by analyzing the T dependence of the zero bias $(dV/dI)_{V=0}$. From both fittings, we obtained a consistent $Z = 0.5$ for the overlayered junction in Fig. 2(b). In the framework of the BTK model, a junction with such a low Z is highly transmissive, corresponding to a transmission coefficient of 80% $[(1+Z^2)^{-1}]$ in the normal state. At zero bias, the AR probability is estimated to be 45%, which is very high, indicating that the S-N contact is of high quality.

One of the important results of this study is the evolution from the BTK behavior to a non-BTK ZBA as we increase the S-N contact area on the Nb top surface in the bare junctions. The ZBA gradually becomes dominant at the expense of the diminished BTK component as shown in Fig. 2(a). We have observed a systematic increase of the ZBA with d', from a tiny dip when $d' \approx 0$ to more than 30% of R_N when $d' \approx 1$ μm. To our knowledge, this is the first time that the ZBA is so clearly resolved from the "normal" BTK behavior. We can also unambiguously identify the top contact area as the cause for the ZBA.

A ZBA has been observed in S-Sm [5] and S-Sm-S junctions [3, 4] much different from our single S-N junction. In one study [5], the resistance dip was attributed to a proximity effect induced pair current across the Schottky interface barrier. It was found that the anomaly can be easily suppressed by a mere H of 18 mT. This mechanism is not responsible for our ZBA, which is not sensitive to H (see discussion later). In another study [4], the ZBA was interpreted in terms of AR, modified by multiple electron reflections in the Sm quantum well. Such a process leads to a high cumulative AR probability, giving rise to a sharp dip in dV/dI at zero bias.

Various theoretical models for ZBA have been proposed, ranging from ordinary proximity effect [8] to more radical mesoscopic effects [6,7]. These models are not necessarily opposed to each other, but may be complimentary to each other. van Wees *et al.* [6] investigated phase-coherent transport near the interface, and found that the constructive quantum interference due to phase conjugation between multiply reflected electrons and AR holes results in a resistance dip. Like the model based on proximity effect, it also predicts easy suppression of the effect by a small H.

We have measured dV/dI vs V in different H [Fig. 3(a)] and the H dependence of the zero-bias resistance as shown in Fig. 3(b). Also shown is the H dependence of the resistance of the Nb film, providing H_{c2} at various T [Fig. 3(c)]. The results in Fig. 3 are astonishing and anomalous. The ZBA is very robust against H, persisting up to a field of almost 2 T. This observation excludes the mechanism based on proximity effect, and also jeopardizes the applicability of the model of van Wees *et al.*, according to which the effective critical field H_c^{eff} to suppress the zero-bias anomaly is Φ_0/Al_e^2 (A is of the order of 10 depending on the electron mean free path l_e). Using l_e=1800 Å for our Ag film, $H_c^{\mathrm{eff}} \simeq$0.01 T, which is much smaller than what we observed.

In addition to the strength of the ZBA against H, there also exist two zero-bias $(dV/dI)_{V=0}$ plateaus at intermediate H and high H. The plateaus are insensitive to T (for $T \leq$4.2 K). The first plateau begins at a field H' smaller than H_{c2} but ends at H_{c2} above which Nb starts to become normal. A careful examination reveals that H' corresponds to the field at which Nb becomes gapless while remaining superconducting (see discussions later). This indicates that Δ_{Nb} is the main parameter affecting the ZBA. The second plateau begins at the field where Nb becomes completely normal. It is therefore associated with the normal resistance of the S-N contact and portions of the Nb and Ag leads.

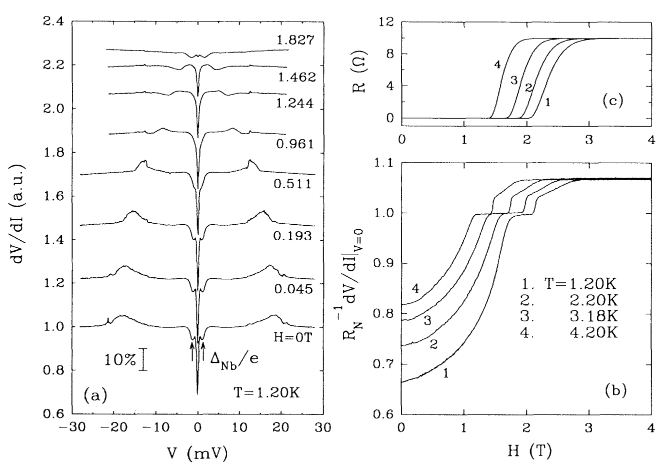

FIG. 3. (a) Normalized dV/dI of the same junction shown in Fig. 2(a) in different parallel magnetic fields. (b) Zero-bias resistance as a function of $H_{\parallel}$ at several temperatures. (c) Superconducting transitions of the Nb film under the same conditions.

Recently, in a more rigorous and general approach, Beenakker [7] developed a quantum transport theory for mesoscopic S-N junctions, incorporating both AR and quantum interference effect. In mesoscopic *disordered* junctions, the size of the junction is comparable to the phase-coherence length l_ϕ in N, but much larger than the elastic mean free path l_e. It was found that the S-N interface becomes *reflectionless* at zero bias despite the presence of a potential barrier (i.e., $Z > 0$), due to the phase coherence and AR. This leads to a zero-bias resistance reduction. This model differs from that of van Wees *et al.* in that the latter requires deterministic elastic scatterings to achieve constructive quantum interference between electrons and AR holes. Furthermore, Beenakker also claimed that the ZBA is *insensitive* to H, which is consistent with our experimental results. Using a phase relaxation time (τ_ϕ) of 5×10^{-11} s and $l_\phi = \sqrt{D\tau_\phi}$, where $D = v_F l_e/3$ is the diffusion constant, we obtain a l_ϕ of 3.5 μm for our Ag film at 1.2 K. Therefore, it is expected that mesoscopic effect plays an important role in our S-N junctions. The H dependence of the ZBA, a crucial test for theory, supports Beenakker's model. The observed transition from the BTK to non-BTK behavior as the top contact area is increased can now be understood as follows: In the bare junctions, the upper surface of the Ag film causes effective electron "confinement" in the top contact region. The Ag surface greatly reduces the probability of normally reflected electrons drifting back to the reservoir and increases the probability of coherent multiple reflections. Multiple reflections drastically enhance the total probability of AR, especially at zero bias, resulting in the ZBA. It is not clear whether the ZBA reported in Ref. [4] is of the same origin as ours. It is noted that the electron transport in the Sm quantum well in Ref. [4] is ballistic, while in our N electrode it is diffusive. Unfortunately, the H dependence of the ZBA is not available in Ref. [4] for comparison. The lowest T in our measurement is 1.2 K. The trend in $R_d(0)$ vs T shows that the ZBA should further increase at even lower T. A measurement at lowest possible T would be very useful in that the data could be more directly compared with various theoretical calculations.

We now turn our attention to the second anomaly in Fig. 2, i.e., the above-gap resistance peak. This peak, existing in every junction, can be sharp or broad. Its position, V_d, varies from slightly above the gap to an order of magnitude higher, but is not any harmonic of Δ_{Nb}. We note that V_d contains a tiny contribution ($< 5\%$) from

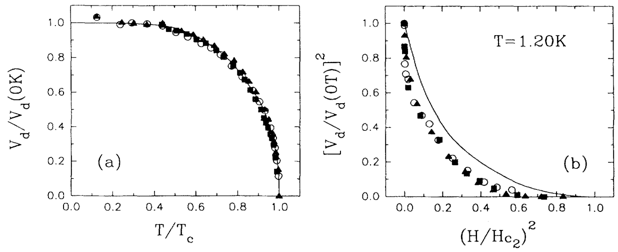

FIG. 4. (a) The T dependence of the normalized peak voltages for three junctions with V_d(0 K)=3.5, 10.0, and 17.0 mV. The solid curve is $\Delta(T)$. (b) The square of the normalized peak voltages as a function of the square of the reduced magnetic field. Results for both $H_{\parallel}$ (squares and triangles) and $H_{\perp}$ (circles) are displayed. The solid curve obtained from Ref. [9] represents the theoretical H dependence of the gap in the dirty limit.

the potential drop in the N electrode. Despite variations in this peak, V_d *always* follows the T and H dependence of the gap Δ. In Fig. 4(a) we plot the T dependence of the normalized peak voltages, V_d/V_d(0 K), for three junctions with V_d(0 K)=3.5, 10.0, and 17.0 mV. Amazingly, all data points fall onto the solid curve, which is $\Delta(T)$. Figure 4(b) shows the normalized peak voltages, V_d/V_d(0 T), as functions of the reduced field (H/H_{c2}) for two junctions with V_d(0 T)=9.3 and 17.0 mV under a field parallel to the film plane ($H_{\parallel}$) and a junction with V_d(0 T)=7.2 mV under a perpendicular field ($H_{\perp}$) at 1.2 K. Once again, all data points are well scaled. The solid curve is the theoretical H dependence of the gap in the extreme dirty limit ($l_e \to 0$) [9]. The deviation stems from the finite mean free path in our Nb film [9]. At $T = 1.2$ K, V_d goes to zero at $H_{\parallel}$=1.85 T, implying that $\Delta \to 0$ at the same field. In the same sample, H_{c2}=2 T (see Fig. 3). Therefore between $H_{\parallel}$=1.85 T and 2 T, the Nb film is superconducting but gapless, and within this region the zero-bias resistance exhibits the first plateau (Fig. 3). Unlike the ZBA, the above-gap anomaly is observed in both the overlayered and bare junctions. This is important evidence that the two anomalies are of different origins.

Recently, a similar above-gap anomaly was observed in an S-Sm-S structure [4]. It was suggested that the effect is the result of recapture of AR holes (in the quantum well) by the Nb electrode. This scenario, requiring multiple reflections, cannot be applied to our simple overlayered junctions. We note that the high-bias peak occurs at a current of ~10 mA, corresponding to a current density of j=1×10^6 A/cm^2. Such a large j could be "depairing" near the S-N interface and affect the local contact resistance. It is likely that the above-gap peak occurs at a critical current j_c, which induces an almost discontinuous change in local contact resistance. Even a small variation in the contact resistance could result in a differential resistance (dV/dI) peak. Critical current in a proximity-type S-N contact is closely related to the pair potential. This may be why the peak voltage V_d is proportional to $\Delta(T, H)$.

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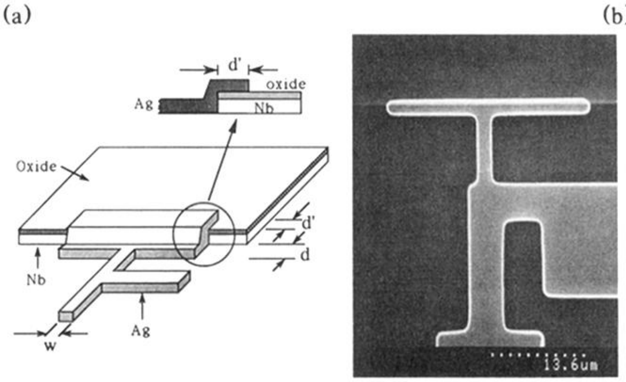
[1] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).
[2] A. F. Andreev, Zh. Eksp. Teor. Fiz. **46**, 1823 (1964) [Sov. Phys. JETP **19**, 1228 (1964)].
[3] A. W. Kleinsasser, T. N. Jackson, D. McInturff, F. Rammo, G. D. Pettit, and J. M. Woodall, Appl. Phys. Lett. **57**, 1811 (1990).
[4] C. Nguyen, H. Kroemer, and E. L. Hu, Phys. Rev. Lett. **69**, 2847 (1992).
[5] A. Kastalsky, A. W. Kleinsasser, L. H. Greene, R. Bhat, F. P. Milliken, and J. P. Harbison, Phys. Rev. Lett. **67**, 3026 (1991).
[6] B. J. van Wees, P. de Vries, P. Magnée, and T. M. Klapwijk, Phys. Rev. Lett. **69**, 510 (1992).
[7] C.W.J. Beenakker, Phys. Rev. B **46**, 12 841 (1992).
[8] A. F. Volkov and T. M. Klapwijk, Phys. Lett. A **168**, 217 (1992).
[9] K. Maki, Prog. Theor. Phys. **31**, 731 (1964); S. Strässler and P. Wyder, Phys. Rev. **158**, 319 (1967).

(a) (b)



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