Finite Bias Anomaly in the Subgap Conductance of Superconductor-GaAs Junctions

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We measure the subgap conductance across a superconductor-GaAs junction at low temperature. Below $T = 4$ K we observe a zero bias conductance peak. For the first time, we observe that at even lower temperatures ($T \leq 0.8$ K), the conductance peak is shifted to a finite voltage. Application of a magnetic field restores a zero bias conductance peak. This is consistent with theoretical predictions for superconducting-semiconducting junctions in the regime where the contact conductance is larger than the coherent semiconductor conductance. [S0031-9007(97)03966-5]

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Mesoscopic aspects of the Andreev reflection have been discovered recently, after the pioneering work of Kastalsky *et al.* [1]. In superconductor-semiconductor (S-Sm) junctions, where the normal transparency per channel t_{NS} of the interface is small, the coherent backscattering of carriers to the junction due to disorder in the normal part induces the so-called "reflectionless tunneling" [2]; the constructive interference between an electron and an Andreev reflected hole, diffusing on time-conjugated trajectories, which return many times at the interface, gives rise to a high zero bias subgap conductance [zero-bias anomaly (ZBA)]. This ZBA is now well explained and have been observed in few superconductor-semiconductor junctions [1,3–5]. In these junctions, a small t_{NS} results either from the presence of a Schottky barrier at interface, or from the mismatch between Fermi velocities. S-Sm contacts are very different from superconductor–insulator–normal-metal (S-I-N) contact where the insulating tunnel barrier is an oxide. The transparency of oxide barriers are always very small as compared to the transparency of Schottky barriers. The main disadvantage in S-Sm contacts comes from a poorly controlled technology, and unavoidable disorder near the interface, produced by annealing or surface cleaning processes. This disorder can have two major implications. First, the normal resistance near the S-Sm interface is large (low mobility and low density of carriers in Sm). This explains why the reflectionless tunneling is mainly seen in S-Sm junctions, because it supposes strong backscattering to the interface ($t_{NS} \simeq t_N$, the normal coherent region transparency per channel). Second, it implies departure from the ideal S-I-N interface, by weakening of the superconductivity near the interface, by increasing pair-breaking processes, or by producing structural inhomogeneities. For instance, the Blonder-Tinkham-Klapwijk (BTK) theory [6] does not describe the I-V characteristics, except if very large pair-breaking rates are supposed.

Here we report a crossover from a ZBA to a finite bias anomaly (FBA) by decreasing the temperature in a S-Sm junction. The low temperature FBA could have two explanations, depending on the effect of the disorder. The first one is understood in the framework of models [7–10], which suppose that the semiconductor is indeed very disordered near the (relatively transparent) superconducting interface, i.e., $t_{NS} \geq t_N$. In that case the crossover to a high temperature ZBA is due to finite temperature smearing of the Fermi distribution and possibly to increasing dephasing processes. The FBA appears at energies or voltages comparable to the Thouless energy of the normal part [11].

A second explanation is based on the assumption that FBA anomalies could be due to anomalies of $G(V)$ characteristics of some superconductive shunts or weak links in series with the junction. The annealing procedure could introduce weakly coupled superconducting islands or inhomogeneities near the interface. Few FBA appears in the literature for various S-Sm junctions including S-Sm-S geometries [5,12]. These anomalies appear often as fine, nonsymmetric structures at large bias, but also at small bias [13]. Increasing temperature or magnetic field tends to shrink such FBA to zero bias as the critical supercurrent in the weak links decreases, which mimics aspects of the reflectionless tunneling. Here we develop interpretation in terms of the mesoscopic proximity effect.

The samples are based on a 200 nm thick molecular-beam epitaxy (MBE) grown GaAs:Si layer doped at 5×10^{23} m^{-3}. After defining a mesa by chemical etching, AuGeNi contacts are deposited and annealed at 450 °C. The layout is shown in Fig. 1. The structures are made by electron beam lithography and lift-off processes. A 100 nm thick superconducting Sn-Pb alloy ($T_c \simeq 6$ K), covered with a 50 nm thick Cu layer, is deposited and moderately annealed (330 °C) in order to reduce the Schottky barrier. However, the Schottky barrier is not completely removed and we observe a characteristic asymetry in the I-V curve, related to the nonsymmetric profile of the barrier (see inset of Fig. 1). The surface of the Schottky contact is 25 μm^2 with an overlap distance $L = 1$ μm. In a third step, an Au gate is deposited at 0.5 μm from interface. The sample can be visualized by an S-Sm junction where the junction is an annealed planar Schottky barrier and the resistance of the Sm part

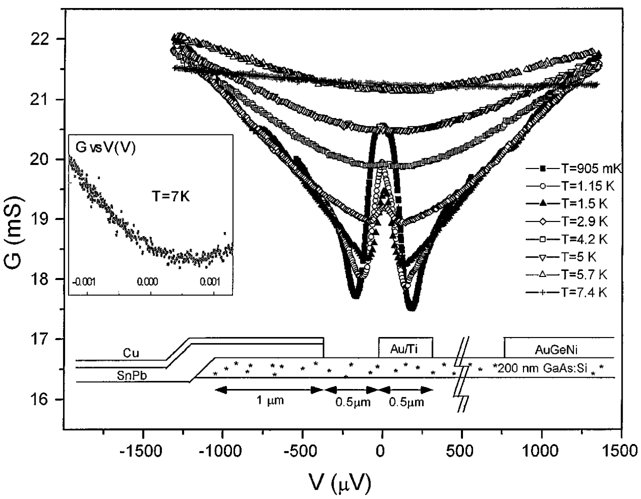

FIG. 1. $G = \frac{\delta I}{\delta V}$ versus V for various temperatures between $T = 7.4$ K and $T = 905$ mK. The data have been corrected by the estimated resistance in series (60 Ω). Note the appearance of the "reflectionless tunneling" zero bias conductance peak when T decreases. Inset: $G(V)$ at $T = 7$ K in an enlarged scale. The polarity is arbitrary. Note the rectifying behavior of the Schottky junction. Lower inset: Cross section of the sample.

is modulated by the gate. Here, we consider only the situation at zero gate voltage.

The sample is measured using an ac lock-in technique (ac measuring currents $\simeq$ 50 nA). The voltage is probed between a gold contact sputtered on Sn-Pb/Cu layer and a AuGeNi contact at 8 μm from the S-Sm interface. Thus the voltage drop is over the superconducting wire, the junction, and the semiconducting layer in series, which consists of 5 squares in parallel and has a resistance of 60 Ω. In all the presented curves we have subtracted this resistance. Measured values for the specific normal resistance of our junction (interface resistance *in series with* the annealed Sm layer resistance) is roughly 10^{-5} Ω cm^2 (40 Ω for a 25 μm^2 contact surface). This is typical for alloyed metallic contacts on GaAs doped at this level (5×10^{23} m^{-3}) [14]. Nevertheless, some samples show much higher specific resistance.

The parameters of our initial GaAs:Si layer are listed below: $D \simeq 5 \times 10^{-3}$ m^2 s^{-1}, the elastic mean free path is $\ell \simeq 35$ nm, $k_F\ell \simeq 8.5$, and the sheet resistance is 296 Ω at $T = 4$ K. The phase coherent length is determined by a separate weak localization experiment: $L_\phi(\mu\text{m}) \simeq 0.94T^{-1/2}$ for $T > 0.9$ K and saturates at 1.2 μm below 0.8 K. The thermal length $L_T = \sqrt{\frac{\hbar D}{k_B T}}$ reaches 1.1 μm at $T = 0.03$ K. It is known that the annealing produces alloying and diffusion of tin inside the GaAs below the SnPb layer. This reduces the Schottky barrier, but also increases the disorder in the semiconductor. It has been shown that the normal side of the thin Schottky barrier in tin alloy contacts on GaAs consists of a degenerate and heavily compensated GaAs [14]. As a result $k_F\ell$ is reduced from its initial value of 8.5. Because $k_F\ell \simeq \pi$ (Ioffe-Regel criterion), the alloyed semiconductor is close to the metal-insulator transition. The square resistance in the semiconductor under the SnPb film R^*_{square} is much larger than for the initial layer. This is confirmed in a separate conductance measurement, where a large square of the GaAs film covered with 6 μm width alloy strips separated by 6 μm is increased up to 20% by annealing at 450 °C (the increase under the annealed strips is of course much larger, but difficult to evaluate precisely). Knowing that a cube of size L_ϕ has a conductance of $\frac{e^2}{h}$ at the metal-insulator transition, we estimate that $R^*_{\text{square}} \simeq \frac{h}{e^2} \times \frac{L_\phi}{W}$, where L_ϕ is the phase-breaking length and W the thickness of the layer. Near the metal-insulator transition, L_ϕ is of the order of 130 nm in GaAs:Si [15], such that $R^*_{\text{square}} \simeq 17$ kΩ for $W = 200$ nm, and the Thouless energy is large: $E_C = \frac{\hbar D}{L_\phi^2} \simeq k_B \times 0.8$ K. Note that near the transition large sample-to-sample dispersion in resistances is attempted.

Figure 1 shows the differential conductance of the sample $G = \frac{\delta I}{\delta V}$ versus V for various temperatures above $T = 0.9$ K. G shows a dip below $V \simeq 1.7$ meV, at temperatures lower than the superconducting transition of the Cu/Sn-Pb alloy (around 6 K). This dip becomes more pronounced as the temperature decreases, as expected qualitatively by the BTK formula [6].

Below 4.2 K, G exhibits a maximum for $V = 0$, as also observed in Ref. [1]. This is not seen in higher resistive samples. We note that the conductance peak is well developed, such that the zero bias conductance is less but comparable to the normal conductance at large bias. This indicates that the normal coherent conductance at $T \simeq 1$ K is comparable to the normal conductance of the junction [16]. We observe that the reflectionless tunneling at $T \simeq 1$ K is suppressed only for magnetic fields of about 150 mT, which corresponds to a magnetic length of 160 nm (see inset of Fig. 3). This is consistent with our estimation for L_ϕ. Thus, results above 0.9 K confirm our estimation of a large Thouless energy combined with a high coherent resistance (small $k_F\ell$). Moreover, this makes the appearance of a finite bias anomaly at moderate voltages and temperatures possible.

The new observation is the shift to finite voltage of the conductance peak shown in Fig. 2, when the temperature decreases further (a superimposed conductance anomaly appears also due to weak links in the superconducting films [13]). We note that the FBA and the ZBA have the same width. Figure 3 shows how the conductance dip at small bias is progressively filled up when magnetic field is applied; the ZBA is recovered for $H \simeq 280$ mT. On Fig. 4, one sees that zero bias conductance is maximum at $T_{\text{max}} \simeq 800$ mK, and decreases at lower temperature. Moreover, at the lowest temperature, the conductance is maximum at a bias given by $eV \simeq 1.5 k_B T_{\text{max}}$. The factor 1.5 could be due to the underestimation of the substracted incoherent resistance (60 Ohms) in series with the coherent S-N junction.

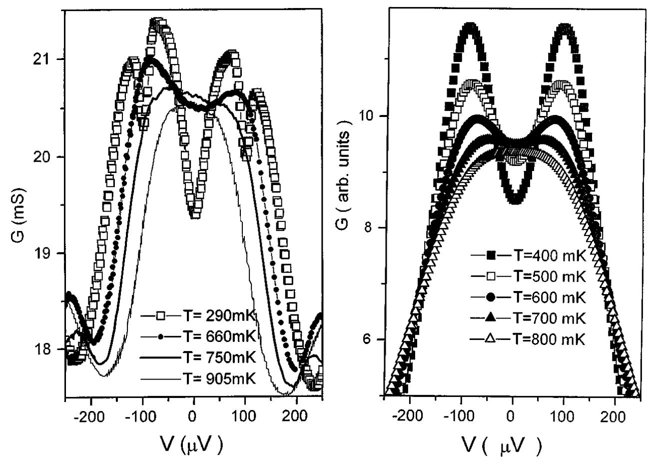

FIG. 2. (a) G versus V for various temperatures below 905 mK. G is no more sensitive to temperature below $T \simeq 200$ mK. Note the shift from a zero bias anomaly to a finite bias anomaly by decreasing T. The width of the peak is basically not affected by the temperature. The anomaly at $V \simeq 100\ \mu$V is explained in the text [13]. (b) G versus V at various temperatures for the two barriers model considered in the text ($t_{ns} = 0.4$, $t_n = 0.1$, distance between barriers $= 0.15\ \mu$m). The temperature is introduced only by thermal smearing of the Fermi distribution (L_ϕ infinite).

Let us discuss now the origin of the crossover between a low temperature FBA to a high temperature ZBA. First, a zero temperature FBA is predicted in various cases either by Green's function [7–9], or by scattering matrix approaches [10]. The main ingredient is a smaller conductance for the normal part of the junction than for the S-N interface itself. The FBA is shown to be closely related to a dip in the density-of-states around the Fermi level, whose extension is comparable to the Thouless energy in the normal part [8]. This situation has been considered in S-I-N (I being either a clean tuned barrier or a disordered insulator) [8–10] or in S-I-N'-I-N systems (N' being ballistic or diffusive) [7,17]. For instance, a FBA at few times the Thouless energy has been derived in quasi-one-dimensional S-I-N junction by Yip [9]. He obtains that the subgap conductance exhibits a finite bias peak instead of a zero bias peak when the normal conductance of the barrier G_B is larger than the normal conductance of the coherent disordered wire G_{wire}. More precisely, this finite voltage $V_{\max}$ is given by $eV_{\max} \simeq \frac{G_B}{G_{\mathrm{wire}}} \times E_c$ [9] for G_B larger (but not too much) than G_{wire}. $E_c = \frac{\hbar D}{L^2}$ is the Thouless energy of the wire of length L. Our system exhibits strong similarities with the results of Ref. [9]. As suggested above, we estimate $eE_c \simeq 70\ \mu$eV and $L_\phi \simeq 130$ nm. The conductance maximum takes place at bias comparable to this Thouless energy (see Fig. 2).

From the scattering matrix approach, Marmokos *et al.* [10] observe numerically the shift from a zero bias conductance peak in quasi-one-dimensional S-I-N junctions with a resistive interface, to a finite bias conductance peak at few times the Thouless energy for an ideal interface. In [18], it is suggested that the FBA can be viewed as a manifestation of the smeared Andreev levels, closest to the Fermi surface. To get more insight in this, we have performed numerical simulations for the simplest case of a double barrier system in the one channel case. The starting point is the scattering matrix approach, with explicit introduction of the energy dependence for transmission and reflection coefficients [10]. A first barrier of transparency $t_{NS} = 0.4$ is located at the S-N interface and a second barrier of transparency $t_N = 0.1$ is placed at a distance $L = 0.15\ \mu$m from the interface in the normal (ballistic) part. $t_N = 0.1 \simeq \frac{\ell}{L_\phi}$, taking into account our estimation of L_ϕ and the Ioffe-Regel criterion.

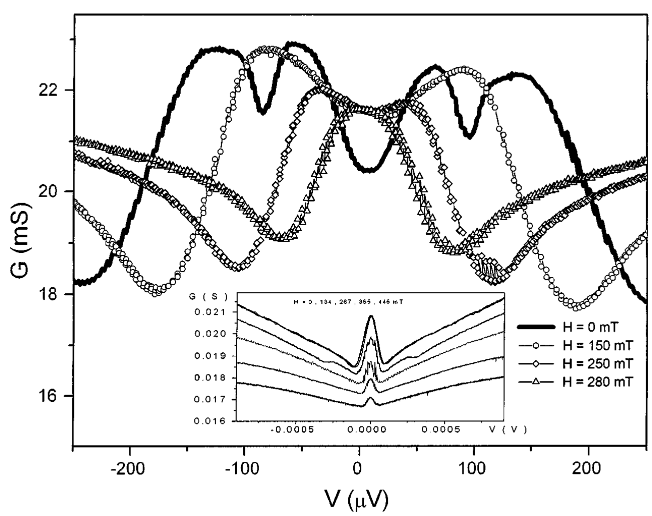

FIG. 3. G versus V at $T = 30$ mK for various magnetic fields. Increasing the magnetic field is similar to increasing the temperature: the zero bias conductance peak is restored at intermediate magnetic fields. Inset: $\frac{\delta I}{\delta V}$ versus V for various magnetic fields at $T = 1.26$ K. The curves have been shifted for clarity.

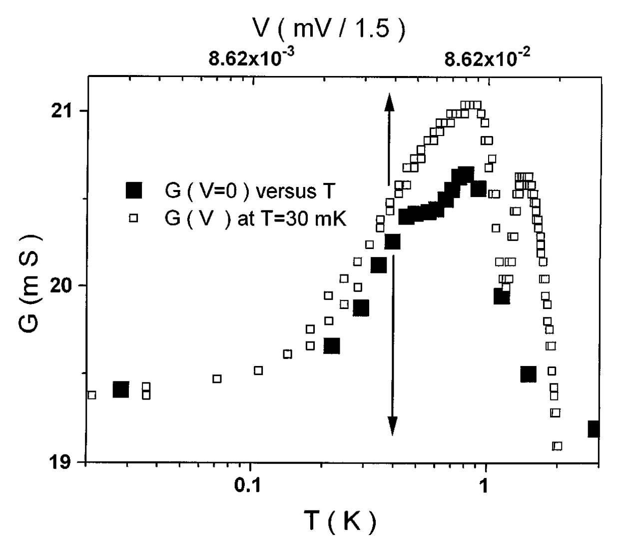

FIG. 4. $G(V = 0)$ as a function of temperature and $G(V)$ at $T = 30$ mK. The conductance is maximum at finite temperature and finite bias; to adjust the maxima, the bias has been divided by a factor of 1.5.

The chosen values of t_{NS} and t_N give a low specific contact resistance $R_b \simeq 10^{-6}\ \Omega\,\text{cm}^2$ (depending on k_F) and a high resistance per square for the semiconductor under SnPb film. These values give [19] a total normal resistance of the junction R_{tot} of few ten's of Ω in good agreement with experiment.

Without any averaging over L, very sharp resonances exist at finite bias, which are unambiguously due to Andreev levels [for $t_{NS} = 1$ the positions of the resonances are given by $eV_i = \hbar \frac{\pi v_F}{2L}(i + 1/2)$ and are just the Rowell-McMillan oscillations [20]]. Then we randomize the phases by averaging the conductance over $0.15\ \mu\text{m} - \frac{\lambda_F}{4} \leq L \leq 0.15\ \mu\text{m} + \frac{\lambda_F}{4}$ (the Fermi velocity is taken to $v_F = 1.5 \times 10^5\ \text{m}\,\text{s}^{-1}$). The results are plotted on Fig. 2(b). We obtain an FBA as the first smeared Andreev resonance. Its position in bias is approximately given by the mean inverse dwell time ($\frac{\hbar v_F t_N}{eL} \simeq 66\ \mu\text{V}$) for carriers in this double barrier system [17], which is the analog of the Thouless energy in a disordered S-N system. With this oversimplified model we recover qualitative conclusions, obtained for diffusive systems by more elaborate theories.

Now the question is to understand how finite temperature or magnetic field effects restore a ZBA. In scattering matrices approaches, temperature is introduced by the integration over the Fermi distribution. As seen in our numerical simulation, this produces a broadening and a smearing out of the conductance peak, as the temperature exceeds $eV_{\max}/k_B$. In Green's function approaches, on the other hand, dephasing effects are introduced as phenomenological pair-breaking rates, for instance, a spin scattering rate γ in Ref. [9] or an inelastic time. Qualitatively, the FBA is turned to a ZBA when the pair-breaking rate exceeds the characteristic energy of the FBA. Magnetic field and temperature are pair breakers, which explains why a ZBA is restored when the magnetic length becomes comparable to L_ϕ or when temperature exceeds $eV_{\max}/k_B$. Again, the crossover from a FBA to a ZBA is accompanied by a broadening of the conductance peak in bias.

Nevertheless, in our experimental data, the ZBA at high temperature is not substantially broadened in bias as compared to the FBA at lower temperature. Also, a magnetic field does not broaden the finite bias peak but rather shrinks it into a ZBA. We have no clear explanation, but we know from simulation that a small increase of t_N to $t_N \simeq t_{NS} = 0.4$ gives a ZBA of whatever is the temperature. In highly disordered semiconductors, the conductivity increases significantly with temperature (below $T \simeq 4$ K).

In conclusion, we suggest that in our annealed junction, the resistance at the residual Schottky interfacial barrier is smaller at very low temperature than the resistance of the alloyed semiconductor below the junction. Our experiment shows for the first time that the zero bias anomaly caused by reflectionless tunneling is shifted to a finite bias at very low temperature and in zero magnetic field. The typical bias is comparable to the Thouless energy of the highly disordered semiconductor [21].

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