# Quasiparticle Interference Effects in a Ballistic Superconductor-Semiconductor-Superconductor Josephson Junction

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We have studied transport properties in a superconductor-semiconductor-superconductor junction formed by two superconducting Nb electrodes and a two-dimensional electron gas in an InAs/AlSb heterostructure in the ballistic regime on the basis of $I$-$V$ measurements. We observe sharp spikes in the differential resistance at temperatures below 2.5 K which can be explained by quasiparticle interference effects, which are related to Andreev bound states. [S0031-9007(98)06969-5]

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Coherent tunneling of Cooper pairs through an insulating barrier between two superconductors as predicted by Josephson in 1962 [1] is one of the most impressive manifestations of the macroscopic coherence of the BCS superconducting state. While in a Josephson junction with an insulating layer between the superconducting electrodes most of the transport phenomena can be explained by (simple) tunneling of Cooper pairs and quasiparticles (QPs), the situation is far more complicated with a normal conducting layer of finite thickness (SNS), formed by a metal or a degenerate semiconductor, instead.

So far different models have been discussed in the literature to describe the transport mechanisms in these junctions. One of them relies on the superconducting proximity effect, where it is assumed that Cooper pairs penetrate into the normal conductor. If the coherence length $\xi$ exceeds the electrode spacing $L$, a supercurrent can flow through the normal conductor [2] or the semiconductor [3].

Another description is based on the Andreev reflection [4] of QPs at the interfaces between the normal conductor and the superconductors. Because of the energy gap of the superconductor, QPs cannot enter the superconductor as long as their energy $E$ above the Fermi level $E_F$ is smaller than the gap energy $\Delta_0$. Nevertheless, a Cooper pair can be formed in connection with a second QP of energy $-E$ (below $E_F$), where a phase-conjugated hole with opposite momentum is left behind [5]. Sequential Andreev cycles can explain the transfer of Cooper pairs; that means the flow of a supercurrent through the junction [6], as well as subgap structures in the $I$-$V$ characteristics at voltages equal to integer fractions of $2\Delta_0$, caused by multiple Andreev reflections (MAR) [7].

When QPs cross the normal region ballistically without loosing their phase, reflection at the boundaries to the superconductors causes interferences of their wave functions. This means that the QPs' energies $E$ are quantized in discrete values, the energies of which also depend on the interface barrier strength $Z$ and the superconducting phase difference of the boundaries [8,9], which is constant as long as no voltage drop appears across the junction. Nevertheless, even for a finite voltage drop $V \neq 0$, interference effects are expected, which modify the $I$-$V$ characteristics.

In this paper, we report current-voltage and differential resistance measurements of a superconductor-semiconductor-superconductor junction where the coherent coupling between the two superconductors is achieved via a two-dimensional electron gas (2DEG) in an InAs/AlSb quantum well structure. Reproducibly and well correlated with the device dimensions we observe pronounced spikes which according to their spectral position, magnetic field, and temperature dependences cannot be explained by well known effects like Fiske steps, flux-flow oscillations, parasitic series connection of junctions, etc. Instead, our data provide strong support for quasiparticle interference effects as an explanation of the observed structures [10].

We have used MBE-grown InAs/AlSb quantum well structures with a 2DEG in InAs as the normal conductor, with mobilities and carrier densities of 20 000 $\mathrm{cm^2/V\,s}$ and $4.7 \times 10^{12}\ \mathrm{cm^{-2}}$, respectively. Different electrode spacings $L$ of nominal 100, 200, 300, and 400 nm were prepared via a negative electron-lithographic process and selective isotropic wet chemical etching of the GaSb cap layer and the upper AlSb barrier. Next, the samples were cleaned by a low-power Ar sputtering just before the deposition of 60 nm thick niobium films. According to [14], this geometry, where the upper barrier of the 2DEG is replaced by the niobium layer, reduces the effective interface barrier due to the cumulative Andreev reflection probability. Finally, the same resist mask is used a second time for a lift-off process. The width of all of the junctions is 20 $\mu$m.

We have measured current-voltage characteristics, using a high-resolution digital current source, as well as

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the differential resistance $dV/dI$ with a standard lock-in technique for different temperatures and magnetic field strengths applied perpendicular to the sample surface. Special care was taken to maintain any sharp subgap structure using a modest low-pass filter, low measurement speed, and a small stepwidth of the current source.

All samples prepared show critical currents up to 100 $\mu$A and normal resistances of 2 to 3.5 $\Omega$. When a magnetic field is applied, the critical current follows a Fraunhofer pattern as a function of the phase difference $\Delta\phi$, as can be seen in Fig. 1 as an example for a sample with $L = 200$ nm. The periodicity corresponds to one flux quanta inside the junction taking into account a penetration depth of about 50 nm and a flux enhancement of a factor of 2.5 due to flux focusing within this planar geometry. The observed pattern indicates that the current density and hence the electrode spacing show very good uniformity along the width of the junction. Thus only a small inhomogeneous broadening of Andreev bound states (ABS) or similar resonance effects caused by QPs' wave-function interference should be expected.

The differential resistances $dV/dI$ at temperatures above 2.5 K reveal the well-known subgap structures caused by MAR, observed by many other groups before (e.g., [15], and references therein). A comparison of the measurements with calculations based on the OBTK model [7] yields good agreement, if values of $Z \approx 0.5$ for the interface barrier strength and $\Delta_0 \approx 1$ meV are assumed. This comparably low value of $Z$ shows that the interfaces are cleaned properly and that a good transparency is achieved. In conformity with [16], our fitted values of $\Delta_0$ are smaller than expected from the measured transition temperature of the Nb of 8.7 K, which indicates induced superconductivity in the 2DEG.

At temperatures below 2.5 K, some additional structures in the $dV/dI$ curves appear. This is shown, for example, in Fig. 2a for a sample with $L = 100$ nm, where the differential resistance is plotted versus the voltage drop. The broad structures found symmetrical to $V = 0$ are a signature of the aforementioned multiple Andreev reflections. Superimposed on the multiple Andreev reflection background again symmetrical to $V = 0$ we observe sharp spikes. With increasing electrode spacings $L$, we find an increasing number of spikes as shown in the inset of Fig. 1. The spikes are pronounced at voltages below $2\Delta_0/e$ and decay for higher voltages, as depicted in Fig. 3a for a structure with electrode spacing of $L = 400$ nm. This systematic trend is consistently observed for all the samples. In addition, depending on the temperature, all the spikes are roughly equidistant with respect to their spectral position in contrast to the subgap structures caused by MAR. Altogether, this can be explained by QPs' interference effects, where the number of longitudinal modes as well as their spectral distance would show the similar scaling. We thus conclude at this point, that the sharp spikes are caused by the boundaries of the superconducting energy gaps and the resulting interference of QPs' wave functions.

Following [17], resonance with an ABS leads to a reduction of the Andreev-reflection probability. Similary, in our junctions resonance suppresses the reduction of the resistance and a spike in $dV/dI$ can be formed.

However, following the Josephson relation $\langle \frac{d}{dt}\phi \rangle \hbar / 2e = V$ a voltage drop results in an increase of the phase difference between the two superconductors. Since the ABS' energies depend on this phase difference, they no longer will be constant, and in fact may be smeared out, unless the temporal integral over the dependent values of voltage, phase, and ABS does result in a zero average effect. A precise calculation of the $I$-$V$ curves should also take into account the classical transit time given by $t_{\mathrm{tr}} = L/v_F$ ($L$ electrode spacing, $v_F$ Fermi velocity in

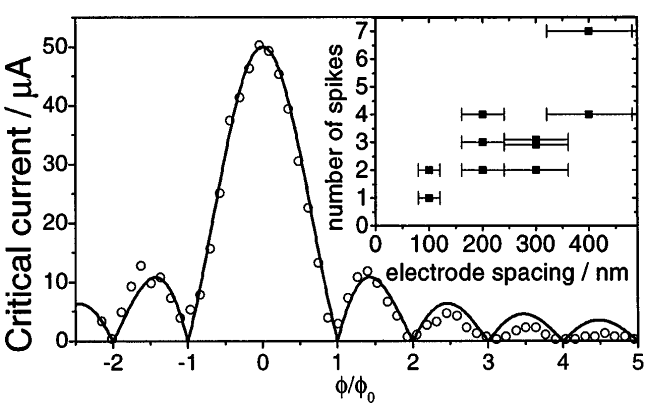


FIG. 1. Measured critical current (circles) and a theoretical Fraunhofer pattern (line) versus magnetic flux for a sample with $L = 200$ nm at a temperature of 1.25 K. Inset: The number of observed spikes without a magnetic field versus the electrode spacing for all prepared samples; the error bars correspond to 20% deviations of the nominal electrode spacing.

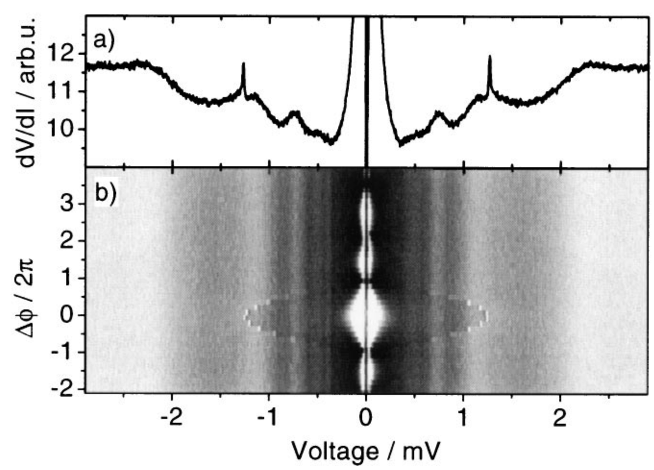


FIG. 2. Sample with $L = 100$ nm at a temperature of 1.25 K. (a) Differential resistance $dV/dI$ for zero magnetic field as a function of voltage. (b) Gray-scale plot of the differential resistance $dV/dI$ as a function of voltage and magnetic field-induced phase shift $\Delta\phi$. White means high resistance.

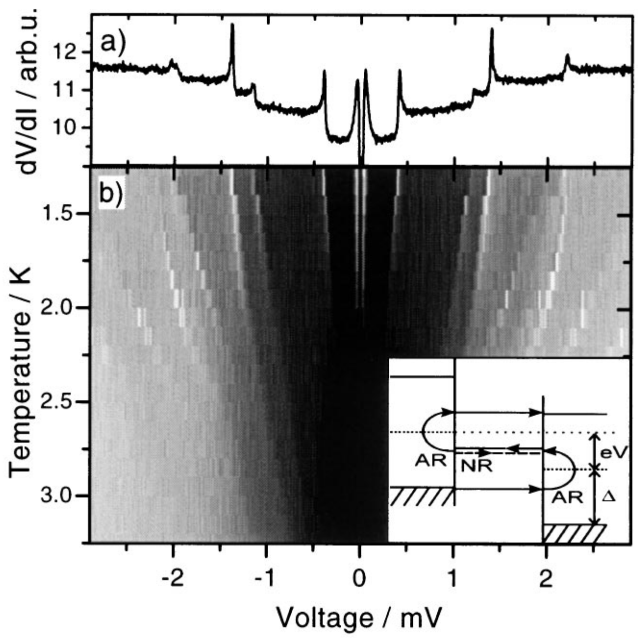


FIG. 3. Sample with $L = 400$ nm for zero magnetic field. (a) Differential resistance $dV/dI$ for a temperature of 1.25 K. (b) Gray-scale plot of the differential resistance $dV/dI$ as a function of voltage and temperature. White means high resistance. Inset: An injected electron can undergo Andreev reflections (straight line) or normal reflections (dashed), so that a "standing wave" can be formed even for $V \neq 0$.

the normal conductor) and its relation to the temporal dependence of the above variables. A simple calculation of this transit time, neglecting time for the Andreev reflection process itself, gives about 56 fs for $L = 100$ nm and the measured carrier concentrations of $4.7 \times 10^{12}$ cm$^{-2}$ corresponding to a Fermi wave vector of $5.4 \times 10^{6}$ cm$^{-1}$ ($m* = 0.035 \times m_0$), which can be compared with the Josephson period given by $h/2$ eV. This shows that for a voltage drop of 1 mV the ratio of Josephson period to transit time is about 40, so that the phase can be considered as quasistatic [18].

A voltage drop also results in an increase in energy of a QP for each Andreev reflection. This does not only change the shape of their wave functions from plane waves to Airy functions, but also modifies the condition of resonance with a *constant* energy of an ABS. For intermediate interface barrier strengths $Z$, where both processes of normal and Andreev reflection have a nonvanishing probability, normal reflection can rewind the energy and phase difference picked up during former Andreev reflections, as depicted in the inset of Fig. 3b. In this case the Josephson junction behaves similar to a normal-metal-insulator-normal-metal-superconductor (NINS) structure, where the formation of quasibound Andreev levels has been described theoretically [19,20]. Therefore, a significant amount of QPs can return to the same energy and position where they started from, forming a kind of "standing wave" for those voltages drops which satisfy the condition for constructive interference. Thus the conductivity via MAR is reduced, resulting in spikes in the differential resistance [17,21].

To further confirm our interpretation, we have studied the dependence of the energy and intensity of these sharp spikes on temperature and magnetic field strength. In Fig. 3b, the differential resistance and the spectral positions of the spikes versus temperature is shown, where the gray scale reflects the value of the differential resistance with white corresponding to the largest and black to the lowest values. As the temperature is increased from 1.25 to 2.5 K, the spikes shift to lower energies and lose strength. Above this temperature, where their spectral spacing is about equal to the thermal energy $k_B T$, the spikes are no longer observable. This behavior should be expected for interferences of QPs' wave functions, which can be "smeared thermally." The spikes' shift is neither correlated to the temperature dependence of the critical current, which can still be observed at higher temperatures, nor to the temperature dependence of the superconducting energy gap, which is almost constant in this temperature range. Nevertheless, in a simple model of a cavity formed by the energy gaps of the superconducting electrodes, no shift of the levels to lower energies with increasing temperature is expected. But taking into account the temperature dependence of the proximity effect, where a superconducting gap can be induced into the 2DEG at low temperatures [16], the cavity's effective size is increased with increasing temperature. This results in a shift of the longitudinal modes to lower energies as seen in our measurements, which again supports the explanation by QPs' interference effects [23].

The spectral positions of the sharp spikes versus magnetic field-induced phase shifts are shown in the gray-scale plot of Fig. 2b for the sample with electrode spacing of $L = 100$ nm. The sharp spikes shift with increasing magnetic field strength towards $V = 0$ and eventually collapse to $V = 0$ at magnetic field strengths corresponding to a phase difference along the width of $\Delta\phi = 2\pi$. At these values for $\Delta\phi$, the critical current is suppressed, which is in agreement with the predicted shift of ABS [24,25] for phase differences between the two confining superconducting electrodes. In samples with a larger number of spikes the same behavior is observed (not shown); the spikes also shift towards $V = 0$ for phase differences of $2\pi$ or multiples of $2\pi$. At higher magnetic field strength corresponding to phase differences of more than about 10 times $\pi$, no spikes can be seen in any of the junctions, and the remaining broad structures in the differential resistance are due to MAR. It has been shown that a small magnetic field can reduce an induced superconducting gap [26], so the modulation of the spikes spectral position with the phase difference is superimposed by a change of the effective cavity size similar to the case with increasing temperature.

While our measurements and estimations support the existence of interference effects, it would be a task for forthcoming theories to treat this problem quantitatively. In the high damping limit, which applies for most of the studied SNS junctions, the voltage drop can oscillate with significant amplitude with the Josephson frequency. Present theories can predict $I$-$V$ curves as well as the density of ABS for different interface barrier strength, phase differences, and material properties [9,27], but voltage oscillations and the reduced dimensionality of a two-dimensional electron gas must be taken into account to obtain the complete description of the transport properties in such junctions.

We have performed a systematic study of the current-voltage characteristics of superconductor-semiconductor-superconductor Josephson junctions with low interface barriers carrying a homogeneous supercurrent in the ballistic regime. We have observed sharp spikes in the $dV/dI$ curves and have measured their dependence on magnetic field, temperature, and electrode spacings. Their spectral positions as well as the number of spikes in dependence on electrode spacing strongly support the explanation due to resonance modes of interfering QPs' wave functions. These resonances, which are a more general kind of Andreev bound states, can be observed in the $I$-$V$ characteristics due to a combination of normal and Andreev reflection. In addition, the temperature dependence of the spikes' spectral position indicates that a superconducting energy gap is induced into the 2DEG. While all this gives a qualitative explanation, it is obvious that the results presented here require and will stimulate further experimental and theoretical work in order to obtain a complete understanding of the very fundamental problem addressed here.

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