Doppler shift in Andreev reflection from a moving superconducting condensate in Nb/InAs Josephson junctions

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We study narrow ballistic Josephson weak links in an InAs quantum wells contacted by Nb electrodes and find a dramatic magnetic-field suppression of the Andreev reflection amplitude, which occurs even for in-plane field orientation with essentially no magnetic flux through the junction. Our observations demonstrate the presence of a Doppler shift in the energy of the Andreev levels, which results from diamagnetic screening currents in the hybrid Nb/InAs banks. The data for conductance, excess, and critical currents can be consistently explained in terms of the sample geometry and the McMillan energy, characterizing the transparency of the Nb/InAs interface.

In recent years a detailed microscopic understanding of the proximity effect has emerged. There is now agreement that in highly transparent Josephson junctions formed by a metallic weak link in good contact with two superconducting (SC) banks the supercurrent is carried by Andreev bound states (ABSs).¹ These come in pairs corresponding to the opposite directions of Cooper-pair transfer mediated by multiple Andreev reflection (MAR) at the SC/metal interfaces provided that the acquired quasiparticle phase is a multiple of \(2\pi\).² At currents exceeding the critical current \(I_c(T, B)\) MAR between the SC banks manifests itself in the current-voltage characteristics as subharmonic gap structures at voltages \(eV_n=2\Delta/n\), where \(\Delta\) is the SC energy gap and \(n=1,2,\ldots\). At higher voltage \(eV>2\Delta, \Delta/V\) becomes linear with an excess current \(I_{\text{scr}}=I(V)\equiv G_N V\) determined by a single Andreev reflection (AR) probability \(|a(\varepsilon)|^2\) \((G_N\) is the normal-state conductance\)).³⁴

Weak links formed by a two-dimensional (2D) electron gas (2DEG) in semiconductor quantum wells⁵ are of particular interest because here the ballistic transport can be studied. In very high magnetic field perpendicular to the 2DEG, theory⁶ and experiments⁷⁺⁸ have demonstrated Andreev transport via edge states. Indirect evidence for a strong magnetic-field effect on AR was experimentally found in antidot billiards.⁹ The case of parallel field, with respect to the 2DEG, is equally intriguing: as ideally no magnetic flux threads the 2DEG, one may naively expect the Josephson current to survive up to the critical fields of the SC leads. This is not the case, but the underlying mechanism of the supercurrent suppression is still unclear. This question, also relevant for other 2D hybrid systems,¹⁰ is among the issues this Rapid Communication focuses on.

In this Rapid Communication, Nb/InAs Josephson junctions of different width are studied in a four-terminal lead configuration within the 2DEG. This allows us to separately determine the transparencies of the InAs weak link and Nb/InAs interfaces and identify an additional energy scale in the electronic spectrum of the hybrid SC terminals. We observe a very strong suppression of both the AR probability and supercurrent in weak magnetic fields of 4 and 100 mT for perpendicular and parallel orientations, respectively. This unexpectedly rapid decay can be traced back to diamagnetic supercurrents in Nb, which break the time-reversal symmetry of Andreev reflection.

The samples were prepared from a heterostructure containing an InAs quantum well with thickness \(d_1=15\) nm and mean free path around \(3.7\) µm, confined between two AlGaSb layers. The electron density was \(7.8\times 10^{15}\) m⁻², resulting in a Fermi wavelength \(\lambda_F=2\pi/k_F=28\) nm. First, a constriction of width \(W\) with a four-terminal \((4t)\) lead structure provides the optimal description of the experimental data. The black curve is the standard Fraunhofer pattern fitting the data for sample No. 3 with width \(W=2\) µm.

FIG. 1. (Color online) (a) Scanning electron micrograph of sample No. 3 with width \(W=2\) µm and length \(L=0.6\) µm. Regions with InAs two-dimensional electron gas are shown in yellow. Etched regions are light gray. The horizontal dark gray stripes are \(1098-0121/2009/80(22)/220507(4)\) ©2009 The American Physical Society

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ture [shown in yellow in Fig. 1(a)] was patterned using electron-beam lithography (EBL) and etched by reactive ion etching in a SiCl₄ plasma. In a second EBL step two Nb stripes were deposited onto the InAs [horizontal gray bars in Fig. 1(a)] after removal of the top AlGaSb layer and in situ Ar-ion cleaning of the InAs surface. The Nb stripes have a width $W_0=1$ μm and a thickness $d_2=35$ nm; their distance $L=600$ nm defines the length $L$ of the junction. This results in a Thouless energy of $e^2t_0=\hbar v_F/L=0.8$ meV=Δ for all samples, $v_F$ being the Fermi velocity in the normal metal. We have prepared four samples on two chips in the same batch. The chips contained junctions with $W=0.5$ and 1 μm (denoted as No. 1 and No. 2a), and $W=1$ and 2 μm (denoted No. 2b and No. 3), respectively.

Figure 1(b) shows the two-terminal $(2t)$ resistance of samples No. 1, No. 2a, and No. 3 measured through the Nb stripes vs temperature $T$. The resistance drops at the transition temperature of the Nb stripes around 8.3 K and again between 2 and 3 K, where the constriction becomes superconducting. In Fig. 1(c) we plot the $2t$ resistance measured across the Nb stripes and the $4t$ resistance measured within the InAs layer at $T=10$ K as a function of $W$. The $4t$-resistance scales as $1/W$, obeying the ballistic Landauer-Büttiker formula:

$$G_N = \frac{2e^2}{h} \sum_n T_n = \frac{2e^2 k_F W}{\pi} \langle T \rangle,$$

where $\langle T \rangle$ is the average channel transparency. From the slope of $G_N(W)$ we extract $\langle T \rangle = 0.8$. The $2t$ resistance at 10 K is also proportional to $1/W$, however, with an offset caused by the normal-state resistance of the Nb stripes and the Nb/InAs-interface resistance. Finally, we show in Fig. 1(d) the interference pattern of the junctions in a transversal magnetic field. For the widest junction the critical current $I_c(B)$ exhibits the expected Fraunhofer pattern. For the narrower ones the order maxima are suppressed, and in the 0.5 μm-wide device $I_c(B)$ resembles more a Gaussian rather than a Fraunhofer pattern. This will be addressed below.

Information about the spectral distribution of ABS is contained in the $T$ dependence of the supercurrent. In Fig. 2 we present the critical current $I_c$ at $B=0$ as a function of temperature for different widths $W=0.5, 1,$ and 2 μm of the InAs constriction. With decreasing temperature $I_c(T)$ initially increases and then saturates at $T\approx 1$ K. The solid lines are fits based on the approach of Grajcar et al. who adapted the scattering theory for the Josephson current to 2D ballistic proximity structures. Two parameters were used in these fits: the average normal-state transmission probability $\langle T \rangle$ and the McMillan energy $\Gamma_{McM}=\tau_{SN}\hbar v_F/2d_N$, which is the Thouless energy of the InAs quantum well multiplied by the Nb/InAs interface transparency $\tau_{SN}$. $\Gamma_{McM}$ determines the strength of the proximity-induced superconducting correlations in the InAs regions underneath the Nb film, which act as effective superconducting terminals described by the Green’s functions of the McMillan model. Clearly, the smaller $\tau_{SN}$, the weaker the proximity effect. Because $\langle T \rangle$ influences mainly the saturation value of $I_c(T\to 0)$, while $\Gamma_{McM}$ determines the decay of $I_c$ with $T$, these two parameters can be extracted independently from the measured $I_c(T)$.

The fit parameters are given in the inset of Fig. 2. The values of $\langle T \rangle$ scatter by $\pm 5\%$ around 0.9, which is slightly higher but still close to $\langle T \rangle = 0.8$ estimated independently from $4t$ resistance [Eq. (1)]. The values of $\Gamma_{McM}$ scatter by $\pm 15\%$ around 0.9 meV. From this, we find $\tau_{SN} = 0.06$ which is much smaller than $\langle T \rangle$. The high mobility of the InAs-quantum well provides the high transparency of the constriction, while the comparatively low Nb/InAs interface transparency is sufficient to transform the Nb/InAs-bilayer into an effective superconductor with the additional energy scale $\Gamma_{McM}$ (see also inset in Fig. 5).

Having all sample parameters fixed, we now turn to the main topic of our study, i.e., the magnetic field dependence of Andreev reflection. First, we examine $IV$ and $dl/dV$ char-
characteristics. Figure 3 shows the differential conductance $dI/dV$ of sample No. 2a ($W=1 \text{ m}\mu$) for different values of perpendicular field $B_{\perp}$. At $B_{\perp}=0$ subharmonic gap structures (see arrows) appear at integer fractions $V_n=2\Delta_{Nb}/ne$ of $2\Delta_{Nb}$. The location of the steps vs $1/n$, plotted in the inset of Fig. 3, agrees very well with the value of $\Delta_{Nb}=1.35$ meV. The $n=1$ step appears at lower voltage as predicted in Ref. 16. A tiny perpendicular field of 4 mT washes out these features, vanishing completely at 10 mT. Also, the enhancement of $dI/dV$ at low bias is suppressed. It is known$^{2,11}$ that the subharmonic gap structure and low bias enhancement of $dI/dV$ originate from multiple AR at finite $V$. The large number of steps independently confirms the high AR probability $|a|^2$ expected from the high values of $\langle \gamma \rangle$. The rapid smearing of these steps thus indicates a surprisingly strong magnetic field dependence of $|a|^2$.

This observation is further substantiated by the behavior of the excess current $I_{exc}^2$ obtained by integrating $dI/dV-G_N$ (see Fig. 3) over voltage. Since $I_{exc}$ results from a single AR at $V>2\Delta_{Nb}$, it is more robust than MAR whose amplitude is $\approx |a|^{27}$. Figure 4 shows $I_{exc}$ on a logarithmic scale for both field orientations. It is suppressed to $\approx 50\%$ at $B_{\parallel}=30$ mT and $B_{\perp}=300$ mT as indicated by the vertical dotted lines. The field $B_{\parallel}$ exceeds $B_{\perp}$ by an order of magnitude but is still a factor of five smaller than needed for an appreciable reduction in the gap $\Delta_{Nb}(B)$ as follows from the pair-breaking theory$^{18}$ (right dotted line in Fig. 4).

We attribute the behavior of $I_{exc}(B)$ to the magnetic field suppression of the Andreev reflection at the InAs proximity regions underneath the Nb films. In the presence of the external field $B=\nabla \times A(r)$, the SC order parameter acquires an inhomogeneous phase, $\gamma(r)=-2\pi k_0^{\parallel} \int_0^{r} A(r')dr'$, whose gradient $k_0^{\parallel}=\nabla \gamma$ induces diamagnetic currents in the entire Nb/InAs structure, including the InAs proximity layer [see, Figs. 4(b) and 4(c)]. If $k_i$ and $k_f$ denote the wave vectors of initial and final quasi-particle states in the AR-process momentum conservation requires $k_i+k_f=k_0^{\parallel}$. Since the Cooperpairs absorbed by the moving SC condensate have moment-

FIG. 4. (Color online) (a) Measured excess current of sample No. 2a versus perpendicular (O) and parallel (●) magnetic field. The solid lines result from our model including the Doppler shift $\varepsilon_D(k_0^\parallel)$ (see text) and the dashed line shows $I_{exc}$ due to the suppression of $\Delta_{Nb}(B)$ only (Ref. 18). [b] and [c] One of the Nb/InAs terminals in parallel and perpendicular fields. Red arrows indicate the SC order-parameter phase gradient, $k_0^\parallel=\nabla \gamma$, with $k_0^\parallel=-\pi/W \times \Phi/\Phi_0$ determined by the magnetic flux $\Phi$ through the bilayer for given field orientation.

FIG. 5. Critical current vs $B$ for sample No. 1 at small angles $\alpha$ between B and 2DEG. The lines are theoretical fits (see text). The inset shows the double peak structure of $|a(\varepsilon)|^2$ characteristic of hybrid SC and its suppression by $B_{\perp}$.
the perfectly parallel field there is the phase gradient due to the vector potential [Fig. 4(b)] that induces a Doppler energy shift of the ABS. When it becomes comparable to $I_{\text{MCM}}$, counterpropagating ABS overlap in energy, and their contributions to $I_C$ gradually cancel. Similar to $I_{\text{exc}}$, the suppression of $I_C$ occurs at $\sim 100$ mT. In Fig. 5 we plot $I_C(B)$ for sample No. 1 for several almost parallel field orientations. The small perpendicular component of $B$ still leads to a Fraunhofer-like minimum in $I_C$, which allows a precise determination of the angle $\alpha$ between $B$ and the junction plane. This can be described by $I_C(B) = I_0(\alpha) \sin(\pi B_{\perp}/\Phi_0)/(\pi B_{\perp}/\Phi_0)$, where $B_{\perp} = B \sin \alpha$, $B_{\parallel} = B \cos \alpha$, and $\alpha$ is the junction area. Unlike the standard Fraunhofer pattern, in which we express the AR amplitude $a$ in terms of the McMillan’s Green’s functions with the Doppler shift in the InAs proximity layers, the dependence $I_C(B_{\perp})$ makes the Fraunhofer-like oscillations decay much faster than the usual $1/B_{\perp}$ law, which is clearly seen in Fig. 5. For $\alpha \approx 1.3^\circ$ no minimum is detected, while it is still observed for a wider sample No. 2a on the same chip (not shown). The curve for $\alpha \approx 0$ resulted from a careful maximization of $I_C$ at fixed field, since in this case, evidently, no Fraunhofer minimum can be observed anymore. The fits (solid lines in Fig. 5) are obtained by varying the effective thickness of the Nb/InAs bilayer, $d_{\text{eff}}$. We find $d_{\text{eff}} = d_s + d_L = 50$ nm for sample No. 2a (not shown) in agreement with the geometry, while for sample No. 1 $d_{\text{eff}} \approx 25$ nm. The reason for this discrepancy is unclear, since the excess current data in Fig. 4 agree very well. The deviation of the data for $\alpha \approx 0$ from the theoretical $B_{\parallel} = 0$ curve is probably due to a weak perpendicular stray field of the Nb electrodes.

In conclusion, we have studied the IV characteristics and critical current of ballistic Nb/InAs Josephson junctions in parallel and perpendicular magnetic fields. The observed field dependence is much stronger than anticipated from standard models and can be traced back to the Doppler shift of Andreev levels due to diamagnetic supercurrents in hybrid Nb/InAs contacts. Several different aspects of the proximity effect are consistently and nearly quantitatively described by our theoretical model.

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