Type-II superconductivity related phenomena at point contacts with indium

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Abstract. We have investigated superconducting indium break junctions at large bias current. Most of the contacts showed up to three additional anomalies that can be attributed to the thermodynamic critical field $B_{th} = 29$ mT, as well as to the lower and upper critical field $B_{c1}$ and $B_{c2}$ of the deformed indium at the contact. $B_{th}$ fits well the expected self-magnetic field for contact diameters derived from the Sharvin formula for ballistic contacts. According to the conventional understanding vortex rings are created at the contact when the self-magnetic field exceeds $B_{c1}$. We suggest that this concept can not be applied here because our contacts (1–30 nm diameter) are much smaller than the superconducting coherence length ($\sim 100$ nm) which defines the diameter of the vortex core. We discuss possible beam-narrowing mechanisms.

1. Introduction
An electrical current $I$ through a point contact of diameter $d$ generates a large magnetic field in a small volume element with a maximum of $B_{sf} = \mu_0 I / \pi d$ at the circumference of the constriction. In case of contacts with a superconductor this self-magnetic field can be larger than the critical field and suppress superconductivity near the contact, see the review [1]. Especially interesting are type II superconductors for which one can expect vortex rings to appear at the lower critical field $B_{c1}$ when the contacts are large and the superconducting coherence length $\xi \ll d$ [2, 3].

Contacts with classical type I superconductors are more difficult to treat [4, 5, 6]. Preparing the contact by mechanical means (like cutting, sawing, squeezing) creates defects that shorten the electron mean free path $l$, and thus the coherence length, so that near the contact the material can become a type II superconductor. Such contacts with indium, for example, have coherence lengths of $\xi \geq 100$ nm but typically $d \approx 1–30$ nm. A conventional vortex ring with one flux quantum can then not exist at the smallest circumference. Therefore an alternative explanation for the observed $B_{c1}$-anomaly has to be found.

2. Experimental
We have investigated indium break junctions at a base temperature of $T = 0.1$ K. The samples were fabricated by cutting a groove into a bulk indium wire ($1–2$ mm diameter, residual resistance ratio $\sim 1600$) and breaking it at low temperature. The spectra were measured with standard current biasing. We have chosen indium because it is a rather soft metal to ensure a low pressure or stress exerted at the contact. All contacts had a superconducting energy gap, derived from the Andreev reflection anomaly, $2\Delta_0 = 1.06(2)$ meV which agrees very well with
the BCS prediction for $T_c = 3.40$ K. The contact diameter (1 – 30 nm) was set mechanically and fine-adjusted with a piezo tube.

3. Results

Figures 1 and 2 show the differential resistance $dV/dI$ spectrum as well as the $V(I)$ voltage-current characteristic of one typical indium contact with normal resistance $R_N = 1.25 \, \Omega$. Besides the Josephson and Andreev-reflection anomalies up to three extra features appear as a resistance increase, which could be interpreted as a successive reduction of the excess current $I_{ex} = I_{SC} - I_N$. We denote them as $I_{c1}$, $I_{ih}$, and $I_{c2}$. The anomalies shift systematically along the $I$ axis when the contact diameter or $R_N$ is changed. They are surprisingly narrow, indicating homogeneous conditions, both for the field and the material properties in that part of the sample that is affected.

**Figure 1.** Differential resistance spectra of a typical contact with $R_N = 1.25 \, \Omega$ and the position of the three extra anomalies. The inset enlarges the $I_{ih}$ anomaly.

**Figure 2.** $I(V)$ of the same contact in the normal (N) and the superconducting (SC) state. (a) $I_{ex}$ versus voltage. (b) one branch of $I_{ex}$ and the three extra anomalies.

Figure 3 shows the position of the additional anomalies as function of normal resistance $R_N$. Already here we can exclude several possible explanations. i) These extra anomalies are not related to the Josephson effect because only at very small $R_N \approx 1 \, \Omega$ do they overlap with the critical supercurrent $I_0$. ii) They are not connected with Andreev reflection because they are not fixed to the superconducting energy gap. iii) The current density at those anomalies is between one and two orders of magnitude larger than the depairing current density of [8] $j_{pair} = 4B_{th}/3\sqrt{\mu_0} \lambda_L$, of which we do not see any experimental evidence. Here $\lambda_L \approx 125 \, \text{nm}$ is the London penetration depth. iv) Local heating, or heating the whole sample due to its finite thermal coupling, will matter at very large currents. The power required to reach $B_{th}$ at the contact is about $5 \, \mu\text{W}$. This might heat up the sample to 1 K in the worst case, estimated using the thermal coupling measured near $T_c$.

The center anomaly of this specific contact is rather small and could be resolved only at small $R_N$. At the larger resistances we replace it by the geometrical average of the lower and the upper anomaly $I_{ih} = \sqrt{I_{c1} I_{c2}}$, as expected from the relation $B_{ih} = \sqrt{B_{c1} B_{c2}}$ of the critical fields of a type II superconductor [8]. It fits perfectly the thermodynamical critical field $B_{th} = 29 \, \text{mT}$ if we derive the diameter from the Wexler formula [9], which is the sum of the Maxwell and the
Sharvin resistance

\[ R_N \approx \frac{\rho_0}{d} + \frac{8R_K}{(dk_F)^2} \]  

(1)

Here \( \rho_0 = 2 \mu \Omega \text{cm} \) is the estimated residual resistivity of the contacts in Figs. 1 - 3 in the normal state which corresponds to \( l = 25 \text{ nm} \), and \( k_F = 1.51 \cdot 10^{10} \text{ m}^{-1} \) is the Fermi wave number of indium [7]. There is a perfect agreement in the ballistic regime, verifying Sharvin's resistance formula against the Maxwell equations of electrodynamics. The lower and the upper anomaly at \( I_{c1} \) and \( I_{c2} \) represent then the lower \( (B_{c1}) \) and the upper \( (B_{c2}) \) critical field of the contacts.

By changing the contact diameter gently and in small steps we could reproduce these curves by repeatedly increasing and decreasing the resistance. After opening the contact and closing it again the center anomalies remained at their original positions, but the lower and the upper anomalies changed, as expected for a changing stress at the contact. The relative size of the different anomalies also varied from sample to sample.

Figure 3. Position of the extra anomalies. The thick solid line shows the current at which the self-magnetic field equals \( B_{th} \) of ballistic junctions. The thin solid line takes into account enhanced electron scattering at the contact with a mean free path of \( l = 25 \text{ nm} \) (in the bulk electrode \( l \approx 20 \mu \text{m} \)). The clean-limit critical current \( I_{th} \) overlaps with the extra anomalies only at the smallest \( R_N \). Also indicated is the current density \( j_{th} = A I_{th}/\pi d^2 \) at the center anomaly as well as the depairing current \( j_{pair} \) and current density \( j_{pair} \) in the ballistic limit.

4. Discussion

If we assume that the current flows either homogeneously through the sample or through a surface sheet, then the maximum magnetic field is reached at the contact itself. It falls off rapidly along the constriction. That means only a tiny region of the contact, with dimensions of the contact diameter, should be affected by the self-field. Since vortices are the essential ingredient of type II superconductivity – their appearance marks the lower critical field – the \( I_{c1} \)-anomaly should indicate the existence of one or more vortices near the contact. However, a vortex ring can not exist at the contact itself because \( d \ll \xi \). On the other hand, the \( I_{th} \) anomaly must origin from the bulk type I material since the contact region itself is of type II. This requires a rather homogenous self-magnetic field which extends far into the bulk electrodes.

To solve this dilemma one would have to assume a narrow electron beam through the contact. Beam narrowing is well-known as the so-called Z-pinch in large electrical current sparks and discharges [10, 11]. However, in our case the attractive Lorentz force seems to be too small because the cyclotron radius \( mv_F/eb_{th} \approx 0.35 \text{ mm} \) is much larger than the electron mean free path. An alternative beam-narrowing mechanism is described by the Knudsen cosine-law which
predicts that the flow through a ballistic contact has a preferred forward direction within a distance of the electron mean free path. However, taking the Knudsen cosine-law into account to calculate the magnetic field distribution around the contact, we find that the magnetic field strength drops rather rapidly both with axial as well as with radial distance from the contact, as shown in Fig. 4. This rules out the existence of vortices near the contact.

5. Conclusions

Our experimental data would be consistent with beam narrowing at ballistic contacts between two superconductors, but the most promising mechanisms fail to explain the required narrow electron beam. In contrast to typical situations where the field is applied outside of the sample, one should also consider that due to ballistic electron transport through the contact the self-magnetic field is generated inside the superconductor. Another notable fact is the extreme inhomogeneity of the field varying within \( \pm B_{sf} \) in a very small volume element. The contacts presented here can have field gradients of up to \( dB/dr = 2B_{sf}/d \approx 10^8 \text{T/m} \) at temperatures of around 1 K. How this might effect the current flow through the constriction is yet unknown.

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