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Rectification effects in superconducting triangles

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A superconducting microtriangle is proposed to be used as a field-dependent diode. A dc voltage generated by the triangle induced by an applied ac drive is observed close to the superconducting/normal phase boundary. This effect is due to the superposition of the asymmetric screening currents in the triangle and the ac drive. The sign of the dc voltage is an alternating function of the applied magnetic field that reflects switching of the direction of the screening currents in the structure. *© 2006 American Institute of Physics*. [DOI: 10.1063/1.2349834]

When a superconducting condensate is confined on a length scale of the order of the coherence length ξ or of the penetration depth λ, the superconducting properties are strongly changed. Topology and geometry-dependent critical parameters have been observed in superconducting microstructures.[1–3]

In individual structures the direction of the screening current is an oscillatory function with respect to the magnetic field due to the fluxoid quantization.[4] For asymmetric superconducting loops, Dubonos *et al.* have shown that the persistent currents induced by a magnetic flux $\Phi \neq \Phi_0$ through the loops can be detected by applying an ac drive and measuring a dc response.[5] The observed dc voltage oscillates with the magnetic field like the persistent current in a loop. The rectification is the result of the superposition of the external current and the persistent current. In the absence of external current, it has been predicted that a small dc signal may persist due to fluctuations of the order parameter induced by thermal noise.[6]

There have been recently several studies focused on voltage rectifiers and vortex ratchets where vortices move in the preferential direction in an ac driven current, leading to a net dc voltage. These ratchets have either an asymmetric pinning potential as origin[7–10] or an asymmetric edge barrier.[11] Ratchet effects in superconductors can be used to decrease the noise caused by trapped flux in superconducting devices by reducing the vortex density using ratchet effects with an ac drive.[12] In superconductors without spatial asymmetry it is also possible to control the vortex motion by applying a time-asymmetric drive.[13] By varying the asymmetry of the drive we can increase or decrease the vortex density at the center of the superconductor.

In this letter we report observations of voltage oscillations $V(H)$ in a superconducting triangle that reflect the oscillatory behavior of the screening currents in superconducting individual structures.

Figure 1 shows an atomic force microscopy (AFM) micrograph of the superconducting triangle obtained by thermal evaporation of an Al film of 43 nm thickness. The structure was obtained by evaporation through an e-beam patterned resist mask and lift-off technique. The sample consists of an equilateral triangle with an area of $S=2.25\ \mu\text{m}^2$. The wedge shaped current and voltage contacts are positioned in the middle of the sides of the triangle.

The rectifier effect is studied by measuring the dc voltage response with a dc nanovoltmeter for an applied ac with frequencies from 100 Hz to 100 kHz. No frequency dependency has been detected in this range. The measured dc voltage is the result of the integration of the ac response of the superconducting triangle over typically 40 periods. In order to avoid ac generation in the structure by high frequency noise signal, solder-in Pi filters were used with a cutoff frequency above 1 MHz. An ac drive causes a dc response in the superconducting triangle, due to the observed diode effect, which makes this system very sensitive to electromagnetic noise caused by the measurement equipment.

The measured dc voltage $V_{dc}(H)$ is shown in Fig. 2 as a function of the applied magnetic field for different applied acs and temperatures. A nonzero dc voltage is observed showing the presence of a diode effect. This measured dc voltage is antisymmetric in field and shows different sign reversals for increasing fields and/or different temperatures. From simultaneous measurements of the ac voltage it has been observed that the diode effect is always observed at the onset of the resistive state.

The origin of this alternating positive-negative diode effect can be found in the screening currents flowing in the triangle as a consequence of the quantization effects.[4] This is shown in Fig. 2(c) where the screening currents are schematically presented. It is clear from the picture that, since the current contacts are far from the geometric middle of the

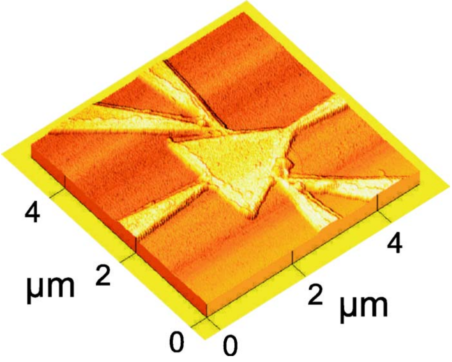

FIG. 1. (Color online) AFM micrograph of the superconducting equilateral Al triangle of 2.25 μm^2 with wedge shaped current and voltage contacts with an opening angle $\Gamma=15°$. The Hall contacts were not used in this study.

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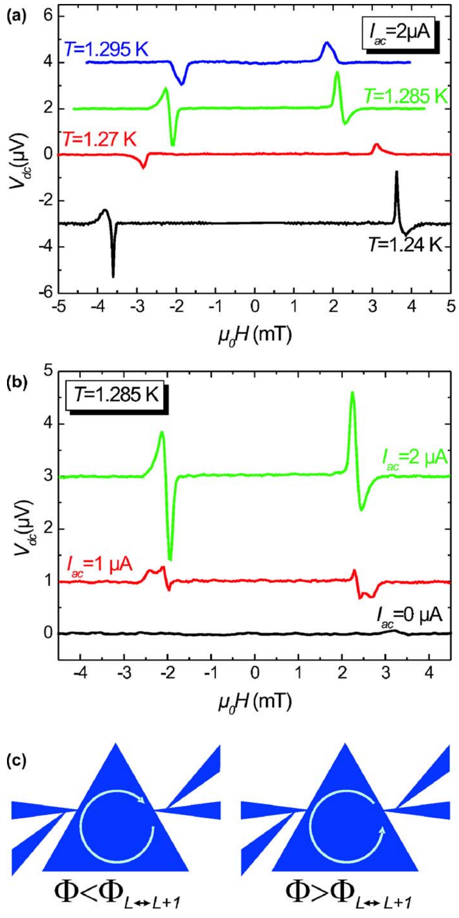

FIG. 2. (Color online) Measured $V_{dc}(H)$ voltage as a function of the applied magnetic field (a) for different temperatures with an applied ac with amplitude of 2 μA and (b) for different currents at a temperature $T=1.285$ K. acs with a frequency of 1 kHz have been used for the measurements. (c) Scheme of the screening currents in the superconducting triangle. The screening currents are flowing in the clockwise direction for positive fields below the transition of vorticity $L\rightarrow L\pm1$ and counterclockwise for fields above the transition.

triangle, the applied current will flow mainly via the upper part of the triangle. When the screening currents are flowing in the clockwise direction the screening currents will compensate a negative applied current (i.e., flowing from right to left). For positive applied magnetic fields, the currents flowing in the clockwise direction will be the strongest just below the fields where the change of vorticity $L\rightarrow L\pm1$ occurs. When the magnetic field is increased, a new vortex enters the triangle, resulting in a screening current flowing in the opposite direction.

Screening currents flowing in the same direction as the applied current in the upper part of the triangle will result in a higher current density than for opposite applied currents. The triangle will go faster out of the superconducting state than when compensated giving rise to a nonzero averaged voltage over one period. A positive observed voltage means that the screening currents are flowing clockwise and that the positive applied currents will push the superconductor out of the superconducting state faster than negative applied currents. The measured mean dc voltage is a result of a sign-dependent critical current.

In Fig. 2(a) positive voltage is observed for the highest temperature at a positive applied magnetic field. This voltage becomes negative for negative magnetic fields reflecting the direction of the screening currents for a vorticity $L=0$. When decreasing the temperature the resistive region moves towards higher magnetic fields and the sign of the measured voltage changes for $H>0$ from positive to negative value each time the vorticity changes. This happens close to the theoretical value of 2.06 mT for the transition $L=0\rightarrow1$ and of 3.57 mT for the next change of vorticity $L=1\rightarrow2$.[2] However, the change of sign occurs always at magnetic fields slightly higher than the theoretical predictions. The presence of an applied current is most probably the reason of this slight shift[14] since for very low currents a good agreement is found for the theoretical and experimental positions of the peaks at the superconducting-normal phase boundary.[15]

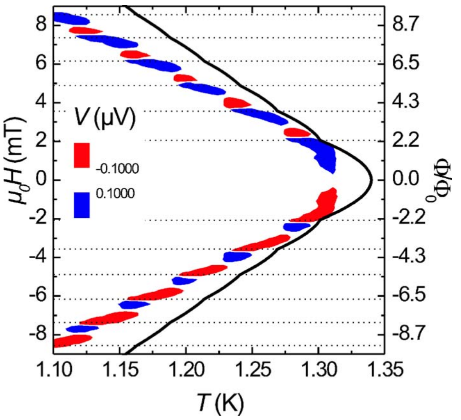

FIG. 3. (Color online) Phase diagram showing the rectified voltage $V_{dc}(H,T)$ as a function of the magnetic field and the temperature. An ac of 2 μA with a frequency of 1 kHz was used. The colors represent the regions where a dc voltage larger than 100 nV has been measured, in blue (dark gray) for positive voltage and in red (light gray) for negative voltage. The theoretical phase boundary is represented by the thick line (Ref. 2). A coherence length of $\xi(0)=110$ nm and a critical temperature $T_{c0}=1.34$ K were used (Ref. 15). The calculated magnetic fields where the change of vorticity $L\rightarrow L\pm1$ occurs at the phase boundary are given by dashed lines.

When changing the amplitude of the applied ac drive [see Fig. 2(b)] the same change of sign for the dc voltage is observed. The features are shifted towards lower temperatures when increasing currents. For zero applied currents no rectification is observed showing that no large noise signal is passing through the structure since our measurements are not frequency dependent at least for low frequencies.

The temperature dependence of the diode effect is shown in Fig. 3 where the sign of the rectified voltage is shown as a function of the applied temperature and magnetic field. From this graph it is clearly seen that the rectification effects are present for all vorticities. A change of sign occurs at the change of vorticity $L\rightarrow L\pm1$ (given in the graph by dashed lines) and in between two changes. At the change of vorticity the change of sign is very abrupt reflecting a sudden change of direction for the screening currents. In the middle of two dashed lines the transition is smooth since there the screening currents evolve gradually from counterclockwise to clockwise direction for increasing magnetic field.

The rectification is observed below the phase boundary obtained for a low applied current of 0.1 μA (Refs. 15 and 16) and is always starting at the onset of the resistive state.

It is interesting to note that the alternating positive and negative change of sign is measured up to high vorticities. When a vortex enters the triangle this changes drastically the scheme of the supercurrent with current flowing in one direction around the vortex core and in the other direction at the edge.[17] Since our data show alternating dc voltage up to high vorticity (up to $L=12$) the applied currents will flow via the upper edge of the triangle since the order parameter is the strongest there.

In summary we have studied a superconducting asymmetric structure where the screening currents are responsible for a rectification effect of the applied ac signal into a dc signal. The screening currents compensate the positive (or negative) part of the applied current and are added to the negative (or positive) part. This polarity-dependent compensation gives rise to a net dc voltage when averaged over a full period of the applied ac drive which sign is an alternating function of the magnetic field. The observed rectification effect makes it possible to use the investigated system as a diode.

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