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Current driven vortex-antivortex pair breaking and vortex explosion in the Bi_2Te_3/FeTe interfacial superconductor

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ABSTRACT

We investigated the dissipative regime of the Bi_2Te_3/FeTe topological insulator-chalcogenide interface superconductor at temperatures well below the Berezinski-Kosterlitz-Thouless transition. We observe a transition in the current-resistance and temperature-resistance curves that quantitatively agrees with the Likharev vortex-explosion phenomenon. In the limit of low temperatures and high current densities, we were able to demonstrate the regime of complete vortex-antivortex dissociation arising from current driven vortex-antivortex pair breaking.

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1. Introduction

A principal cause of dissipation and resistance within the superconducting state is the motion of flux vortices. In thin film samples, vortices parallel to the film plane do not contribute significantly to the dissipation because of very strong intrinsic pinning. Thus dissipation arises principally from vortices perpendicular to the film plane. In the absence of an applied magnetic field, in thin samples, vortices perpendicular to the sample plane can be generated spontaneously by thermal fluctuations through two main routes: (1) the unbinding of virtual vortex-antivortex pairs generated in the interior of the sample and (2) unbinding of single vortices spontaneously generated at the sample edge from their image antivortices just outside the edge.

The first scenario, which requires the film to be sufficiently thin as to be in the two-dimensional limit ($\xi < d$, where ξ is the superconducting coherence length and d is the film thickness), corresponds to the well known BKT (Berezinski-Kosterlitz-Thouless) state [1–8] that appears above a temperature T_{BKT} where one has a plasma of thermally unbound vortices of both polarities. Besides temperature, vortex-antivortex pairs can also be unbound by the Lorentz force of an applied transport current.

The second scenario, the edge nucleation of single vortices as proposed recently by Gurevich and Vinokur (GV) [9], can become a dominant source of dissipation under certain conditions (e.g., somewhat outside the 2D limit $\xi > d$ and for $T < T_{BKT}$) for which the BKT dissipation is suppressed. As shown previously [10], the GV edge nucleation process is in turn facilitated when parallel vortex segments are precluded by the Likharev vortex explosion phenomenon [11]. The gist of the Likharev phenomenon is that a stable vortex core can exist inside a film along the direction parallel to the film only if there is a minimum thickness $d \geq 4.4\xi(T)$. As one or both dimensions transverse to the vortex core are progressively reduced, the circulating supercurrents around the core become squeezed leading to an increase in the local current density. This increases current induced pair breaking, which suppresses the order parameter leading to an increase in coherence length. This causes the vortex to expand and further squeeze the circulating supercurrents. This self feeding process causes the vortex core to explode below some critical dimension $4.4\xi(T)$. Conversely if the film thickness is fixed (which is usually the case) with increasing temperature the vortex will explode at a certain vortex-explosion temperature T_v which satisfies $\xi(T_v) > d/4.4$. Our previous work on thin molybdenum-germanium (MoGe) films [10] provided the first experimental confirmation of this prediction.

In this work we studied the current-resistance and temperature-resistance curves in the Bi_2Te_3/FeTe interface superconductor. In the limit of low temperatures ($T \ll T_{BKT}$) and high pulsed current densities j (but with $j \ll j_d$ the depairing current density), we are able to reach the condition that corresponds to the unbinding of the entire population of vortex-antivortex pairs (similar to when $T > T_{BKT}$). We also observed at low currents, the drop in dissipation related to the Likharev vortex explosion. As found in our earlier work, the explosion is sensitive to the conditions of the measurement, and gets washed out by noise, magnetic

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field, and higher levels of measuring current. To our knowledge this is one of only two experiments that have shown evidence of the Likharev vortex explosion, a phenomenon that was theoretically predicted more than thirty years ago. The measurement also sheds light on the thickness of the superconducting layer. The interface of the Bi_2Te_3/FeTe heterostructure represents the first realization of superconductivity at the interface between a topological insulator (Bi_2Te_3) and an iron-chalcogenide (FeTe). Many questions remain as to the origin and nature of superconductivity at the interface, since neither system is a superconductor by itself [12]. One of the crucial questions is regarding the thickness of the interface that carries the superconductivity. In their work, He et al. observed certain signatures of the BKT transition and a square-root temperature dependence of the parallel upper-critical-field, which allowed them to conclude that the 2D superconductivity resides in a $d = 7$ nm thick interface layer. The present work provides independent information indicating that the superconducting layer is indeed 7–8 nm thick.

2. Experimental details

The sample was synthesized by a VG-V80H MBE system, and consist of a ZnSe buffer layer (50 nm) deposited on a GaAs (001) semi-insulating substrate, followed by a deposition of 220 nm thick FeTe, which is then capped with a 20 nm thick Bi_2Te_3 layer (This thickness comprises 20 QLs, i.e., quintuple layers. The Bi_2Te_3 unit cell consists of 3 QLs bonded by van der Waals forces along the [0001] direction.) Upper-critical-field measurements [12] indicate that the superconductivity occurs within a 7 nm thick interfacial layer, which is much thinner than both the FeTe and Bi_2Te_3 layers.

The present work utilized projection photolithography followed by argon-ion milling to pattern a microbridge with lateral dimensions of width $w = 11.5$ μm and length $l = 285\mu$m. The onset T_c (defined as the intersection of the extrapolation of the normal-state portion and the extrapolation of the steep transition portion of the $R(T)$ curve) was 11.7 K. Further details about sample preparation are provided elsewhere [12].

The cryostat was a Cryomech PT405 pulsed-tube closed-cycle refrigerator that went down to about 3.7 K. All measurements are conducted in zero magnetic field. The majority of the electrical transport measurements used continuous dc currents in the standard four-probe current-direction-reversed configuration with the voltage measured by a Keithley model 2182A nanovoltmeter. The variable current curves used a programmable Hewlett Packard 5532A dc power supply. The single fixed low-current temperature-resistance curve used a battery-based current source to reduce noise to a minimum. The dc technique is generally better suited for small-signal measurements, where it provides a better signal-to-noise ratio. The large-signal data were measured with a pulsed technique to reduce sample heating. These pulsed measurements used in-house built pulsed current sources, preamplifier circuitry, and a LeCroy model 9314A digital storage oscilloscope. The pulse durations were in the 0.1–5 μs range with a pulse repetition frequency of $\sim$ 1 Hz (duty cycles of $\sim$ 1 part per 10^6). This reduces Joule heating of the sample to the mK range, as was ascertained by a direct measurement of the thermal resistance $\Delta T/\Delta P \approx 0.4$ K/W using the method devised in our previous work [13]. About 100 pulses were averaged to improve the signal-to-noise ratio. Further details of the pulsed measurement techniques have been published in previous review articles [14–16].

3. Results and discussion

Fig. 1(a) shows the extended $R(I)$ (resistance-vs-current) response, with the lower portion measured using continuous dc currents and the higher portion measured using fast pulsed signals.

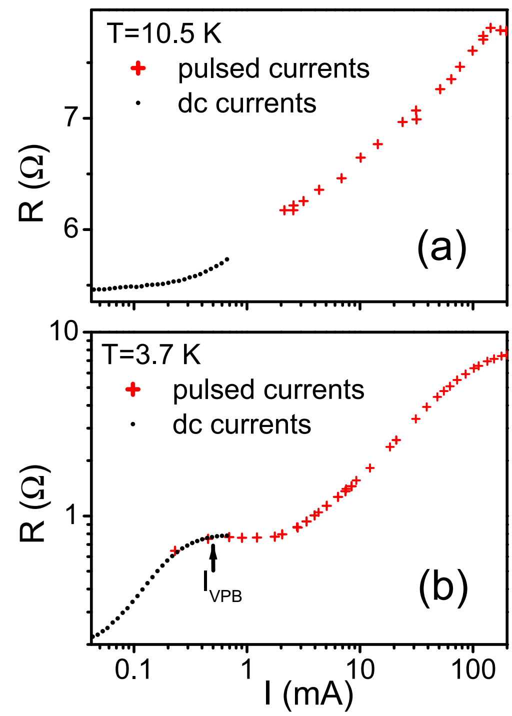

Fig. 1. (a) $R \neq 0$ as $I \to 0$ for $T > T_{BKT}$. (b) $R \to 0$ as $I \to 0$ for $T < T_{BKT}$; however, increasing I above the threshold of $I_{VPB} \approx 0.5$ mA (arrow) restores an Ohmic $R \neq 0$ plateau due to the breaking of vortex-antivortex pairs by the Lorentz force of the current. We define this I_{VPB} as the "vortex-pair-breaking current".

The temperature for these data is T=10.5 K, which is above T_{BKT}. On the left of the graph, notice that the resistance plateaus to a finite value as $I \to 0$, indicative of an Ohmic response. This is expected because of the plasma of unbound vortices and antivortices that exists in thermal equilibrium above T_{BKT}, even in the absence of the driving force of a current. Fig. 1(b) shows similar curves at $T = 3.7$ K $\ll T_{BKT}$. In this case $R \to 0$ as $I \to 0$, instead of reaching an Ohmic plateau, indicating that the vortex-antivortex pairs become bound and non-dissipative as the separating force of the current vanishes, since purely thermal dissociation vanishes for $T < T_{BKT}$. Tracing this $R(I)$ curve from lowest to highest I, the resistance rises with increasing I and momentarily saturates to a constant value in the middle of the graph above $I \approx 0.5$ mA. In anticipation that this plateau corresponds to the condition when most of the vortex-antivortex pair population has become unbound from the force of the current, we will call this quantity $I_{VPB} \approx 0.5$ mA, the "vortex-pair-breaking current". We obtain an estimate of I_{VPB} by starting with the inter-vortex potential [17,18]

$$U = \frac{d}{2\pi\mu_0}\left(\frac{\Phi_0}{4\pi\lambda}\right)^2\left(\ln\frac{|\vec{r}-\vec{r}'|}{\xi} - \ln\frac{w}{\xi}\right), \quad (1)$$

where λ is the magnetic penetration depth and $\Phi_0 = h/2e$ is the flux quantum. The current density exerts a constant force $jd\Phi_0$ on the vortex, adding a potential $-jd\Phi_0 r$ to Eq. (1). Defining the dimensionless interaction $u = \frac{Ud}{\pi\mu_0}\left(\frac{\Phi_0}{4\pi\lambda}\right)^2$, and the dimensionless length $x = |\vec{r}-\vec{r}'|/\xi$, and including a factor $x/(x+\xi)$ as a cutoff of the vortex-antivortex interaction at distances of the order of the coherence length, we can express the interaction as

$$u = \frac{1}{2}\left(\frac{x}{x+1}\right)\left(\ln\frac{x}{\ell}\right) - kx, \quad (2)$$

where $\ell = w/\xi$ and $k = j\xi\pi\mu_0(4\pi\lambda)^2/\Phi_0$. For $k = 0$, this has a single minimum at $x = 0.718$ (i.e., for $|\vec{r}-\vec{r}'| < \xi$), which

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