Mixed-State Dissipation in Zero Temperature Limit in MgB$_2$ Thin Films

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We have studied mixed-state dissipation in epitaxial MgB$_2$ thin films by measurements of resistive transition, current-voltage characteristics, Hall effect, and point-contact tunnelling spectrum. We found that unlike single gap superconductors with negligible vortex quantum fluctuations in which vortices are frozen at $T = 0$ K, finite zero-temperature dissipation due to vortex motion exists in MgB$_2$ over a wide magnetic field range. This dissipation was found to be associated with proliferation of quasiparticles from the $\pi$-band of MgB$_2$. The result shows that the vortex fluctuations are enhanced by two-band superconductivity in MgB$_2$ and we suggest that the vortex quantum fluctuation is a possible cause of the non-vanishing zero-temperature dissipation.

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Anomalous properties of vortex matter have been observed or predicted in MgB$_2$ in association with two-gap superconductivity. In MgB$_2$ there are 3-dimensional (3D) $\pi$ bands (the energy gap $\sim$ 2 meV) and 2-dimensional (2D) $\sigma$ bands (the energy gap $\sim$ 7 meV) [6, 7]. The coherence length in the $\sigma$ band is smaller than that in the $\pi$ band in particular in the $c$ direction [8]. Thus the vortices in MgB$_2$ are 3D-like and large with the $\pi$ gap [1] and 2D-like with smaller cores if the $\pi$-band superconductivity is suppressed. It has been observed that the resistive transition width increases monotonically with increasing magnetic field in MgB$_2$ [8, 10, 11, 12], or equivalently the magnetic field transition width $\Delta H_c(T) = H_{c2}(T) - H_{irr}(T)$ increases monotonically with decreasing temperature [13]. In a type-II superconductor, $\Delta H_c(T)$ should vanish at $T = 0$ K because thermal activation of flux motion disappears, and consequently there should be no mixed-state dissipation at $T = 0$ K [14], unless strong quantum vortex fluctuations exist [13]. In this paper we present results from high quality epitaxial MgB$_2$ thin films, which show that the monotonic broadening of the resistive transition leads to non-vanishing mixed-state dissipation in the zero temperature limit and at sufficiently high magnetic field that suppresses the $\pi$ band superfluidity density. $\Delta H_c(T)$ is over 7 T at $T = 0$ K. Under the high field, the vortex system changes from 3D-like to 2D-like with smaller vortex cores, and the spread of the $\pi$-band quasiparticles reduces the entropy difference inside and outside of the $\sigma$ band-dominated vortex cores, enhancing vortex fluctuations in MgB$_2$. We suggest that vortex quantum fluctuation is a possible cause for the zero-temperature dissipation, made observable in MgB$_2$ by the two-gap superconductivity.

The MgB$_2$ thin films used in this study were grown by the hybrid physical-chemical-vapor deposition technique [10] on (0001) 4H-SiC substrate. They are epitaxial with the $c$ axis normal to the film surface. The films, with a thickness of about 100 nm, were patterned into bridges with a width of 20 $\mu$m for the resistive measurement, and into Hall bars with a width of 0.4 mm for Hall and point-contact tunnelling measurements. All measurements were made on an Oxford cryogenic Maglab-Exa-12 system with magnetic field up to 12 T. In this paper, results obtained from one MgB$_2$ thin film are presented, but similar effect was also observed in other films.

In Fig. 1(a) we present the temperature dependence of resistivity measured with the magnetic field normal to the film surface. At zero field, the onset transition temperature is 40.74 K with a width $\Delta T_c \sim 0.46$ K (determined with 1% - 99%($\rho_n$), and the normal state residual resistivity $\rho_n$ is about 2.4 $\mu\Omega$cm. When the magnetic field increases, $T_c$ decreases and the transition is broadened monotonically. At fields above 5.2 T, zero resistivity is not achieved at any temperature, suggesting a non-vanishing dissipation in the zero-temperature limit. In Fig. 1(b) we present the field dependence of resistivity at various temperatures. Instead of becoming narrower when temperature approaches zero as in single gap superconductors with negligible vortex quantum fluctuations [14], the transition width $\Delta H_c(T)$ increases monotonically when the temperature is decreased down to 1.7 K, the lowest temperature in our measurements. A zero temperature resistivity at different fields is extracted by using a linear fit to the data between 1.7 K and 3 K, which is plotted as open circles in Fig. 1(b). The extracted data at $T = 0$ K show finite resistivity over a broad magnetic field range (> 7 T). To make sure that the finite dissipation at $T = 0$ K is an equilibrium state property and not the result of a large driving force due to measurement current, we measured $I - V$ curves at
broad transition over 7 T is observed at different temperatures under a field of T. Itive transitions at various magnetic fields (right to left): 0, 11, 12 T. Above about 5.2 T zero resistivity is not reached in the zero-temperature limit. (b) Magnetic field dependence of resistivity at temperatures of (right to left) 0, 2, 4, 8, 12, 16, 20, 25, 30, 35 K. The T = 0 K data were extracted from the data between T = 1.7 K and T = 3 K using a linear fit. A broad transition over 7 T is observed at T = 0 K.

FIG. 2: (Color online) I – V characteristics (R = V/I) at different temperatures under a field of μ0H = 6T. At the lowest temperature T = 1.7 K, the resistivity is finite in the zero current limit indicating an equilibrium state property.

FIG. 3: (Color online) Correlation between ρxx and ρxy measured at different magnetic fields. The two solid lines indicate the slope β = 2. Inset (a) The field dependence of β determined in the region ρxx ≤ 1/3ρn. Inset (b) Dependence of β on the upper limit of T during fitting.

different magnetic fields and an example is shown in Fig. 2 for μ0H = 6 T. It is clear that finite dissipation in the low temperature limit at fields above 5.2 T is obtained in the zero current limit.

It is necessary to determine the nature of the zero-temperature dissipation at high fields (μ0H ≥ 5.2 T). It has been pointed out by Vinokur et al. [17] that there is a general scaling law for dissipations due to vortex motion: ρxy = Aρxxβ with β close to 2, where ρxy and ρxx are Hall and longitudinal resistivity, respectively, and A is a field dependent parameter. In Fig. 3, we show the relationship between ρxy and ρxx during the resistive transition in a log-log plot for various fields. The decreasing ρxx value in a curve corresponds to decreasing temperature. A scaling relationship with β = 2 was found for all the fields, indicating that the nature of the dissipation in the MgB2 film is vortex motion. The fitted β value in the low temperature region (ρxx ≤ 1/3ρn, where ρn is the normal state resistivity) is plotted against the field and shown in the inset (a), and β = 2.0 ± 0.1 is obtained. A typical example for fitting with upper T → 0 is shown in inset (b) for μ0H = 6 T. It shows that β is close to 2 at low temperatures but deviates slightly from 2 at around 10 K. It suggests that in the zero temperature limit the dissipation arises from vortex motion. Above ρxx ~ 1/3ρn (about 15 K for 6 T), the contribution of the quasiparticle scattering cannot be neglected. Similar result has been reported by Kang et al. [18].

In the earlier reports of transition broadening in polycrystalline MgB2 samples [10, 11], there is a possibility that it may be caused by the different upper critical fields for H||c and H||ab as the orientations of the grains are random. The single crystal-like epitaxial MgB2 films used in this work allow measurements for H||c and H||ab separately. In Fig. 4, the upper critical field
FIG. 4: (Color online) The vortex phase diagram determined using different criterions/techniques. The fields at which the \( \pi \)-band gap feature in the point-contact tunnelling spectra disappears are also shown as open squares.

and the irreversibility field for the MgB\(_2\) film are shown for both \( H||c \) and \( H||ab \). The values for \( H_{\text{c2}} \) and \( H_{\text{irr}} \) are determined using the criteria of \( \rho_{xx} = 99\% \rho_n \) and \( \rho_{xx} = 1 \times 10^{-7} \Omega \text{cm} \), respectively. The figure shows a monotonic increase of \( \Delta H_c(T) \) with decreasing temperature and a large \( \Delta H_c(T) \) over 7 T at \( T = 0 \) K for \( H||c \). The \( \Delta H_c(T) \) at \( T = 0 \) K observed here is much larger than those in the previous reports of vortex quantum fluctuations \([12, 19]\). The figure also shows that percentage-wise the broadening of \( \Delta H_c(T) \) is much larger for \( H||c \) than for \( H||ab \). The critical field from the tunnelling spectrum (see Fig. 5 and related text) is also presented.

Using point-contact spectroscopy, we have found a strong correlation between the non-vanishing zero temperature dissipation and the suppression of the \( \pi \)-band superfluid density and subsequently the proliferation of the quasiparticles from the \( \pi \)-band. In Fig. 5(a), the point-contact tunnelling spectra at 2 K with the tip along the \( c \) axis are shown. The sharp Andreev reflection peaks in the zero field spectrum correspond to the \( \pi \)-band gap and the slight shoulders correspond to the \( \sigma \)-band gap. By fitting the spectra to the extended BTK model \([20]\) using a linear combination of the two contributions from the \( \pi \) band and \( \sigma \) band, we found that the zero-field value is 2 mV for the \( \pi \) gap and 6.65 mV for the \( \sigma \) gap, in good agreement with previous experimental results \([21, 22]\). The dominant contribution to the spectra is from the \( \pi \)-band, with a ratio of the \( \sigma \)-band to \( \pi \)-band contributions of 0.075, indicating a well-defined \( c \)-axis injection of quasiparticles in the tunnelling measurement. The \( \pi \)-band Andreev reflection peaks decay rapidly with increasing field and disappear completely at about 6.5 T. This field is close to the field above which zero resistivity is not obtained at \( T = 0 \) K. In fact, as shown in Fig. 4, the field where the Andreev peaks from the \( \pi \)-band is completely suppressed overlaps with the temperature dependence of the magnetic field when \( \rho_{xx} = 10\% \rho_n \).

From the suppression of the Andreev reflection peaks we have estimated the quasiparticle density of state (DOS), \( S_{qp} \), as a function of the applied field. All the spectra were first normalized by the conductance at 10 mV. Then \( S_{qp}(H) \) was calculated using a relation \( S_{qp}(H) = I(0) - I(H) \), where \( I(H) \) is the integrated area under the spectrum between \( \pm 10 mV \), which is roughly proportional to the superfluid density \([21]\), and \( I(0) = 2.85 \). The result is presented in Fig. 5(b) for field up to 2 T, as the error of calculation becomes too large at high fields. It shows that the quasiparticle DOS increases rapidly and reaches about 67% of the maximum value (maximum \( S_{qp} = 2.85 \) at 6.5 T) at 2 T. Also plotted in Fig. 5(b) is the normalized zero-bias conductance (ZBC) from the STM measurement by Eskildsen \textit{et al.} taken in the superconducting region between two vortices \([1]\), which was shown to be consistent with the DOS determined from the specific heat measurement \([23]\). The calculated \( S_{qp}(H) \) and the normalized ZBC from the STM measurement overlap remarkably well. The fact that \( S_{qp}(H) \) reaches only 67% rather than near 90% as in the STM measurement may be due to the normal cores of vortices, which also contribute to the conductance in the point-contact tunneling measurement. The result clearly shows that the depression of the \( \pi \)-band Andreev peaks is accompanied by a rapid increase of the quasiparticle DOS in the MgB\(_2\) film.

Based on the results presented above, we can conclude that the broadening of the resistive transition and the zero-temperature dissipation in high magnetic field are the results of enhanced vortex fluctuations in MgB\(_2\) due to two-band superconductivity. In MgB\(_2\) the in-plane
coherence length is about 51 nm for the $\pi$ band and 13 nm for the $\sigma$ band [4]. In the $c$ direction, the coherence length of the $\sigma$ band is 1/17 of that of the $\pi$ band [5]. At low magnetic field, the effective in-plane coherence length and thus the vortex core size is dominated mainly by the $\pi$-band gap, and the vortices are thick, 3D and continuous. When the magnetic field is large enough to suppress the $\pi$-band gap, the superfluid in MgB$_2$ is predominantly from the $\sigma$-band and the vortices become 2D and pancake-like, and the vortex core size shrinks. In addition, the $\pi$-band quasiparticles are widespread in MgB$_2$ [1], which reduces the entropy difference inside and outside of the vortex core leading to smaller pinning energy at high field as reported in the literature [12, 24]. These effects cause strong vortex fluctuations in MgB$_2$ in high fields. When $H||c$, the broadening is less pronounced because the vortices are always continuous. For practical applications, dopant and defect need to be introduced into MgB$_2$, which increases interband and intraband scattering, lowers anisotropy, and enhances vortex pinning [12, 24, 25].

Although the field-induced broadening of the resistive transition above 5 K was interpreted as the result of thermally activated flux motion [12], while it is known that the thermally activated flux motion should be absent at $T = 0$ K. A possible explanation for the zero-temperature dissipation is the vortex quantum fluctuation, or the zero-point motion of vortices. Traditionally, strong quantum fluctuations occur in 2D vortex systems with large sheet resistance and small coherence length, that is, the ratio $\rho_n/\xi$ needs to be large [12, 19]. For the MgB$_2$ samples studied here, $\rho_n$ is small. However, unlike single-gap $s$-wave superconductors where quasiparticles are confined within the vortex cores at $T = 0$ K, in MgB$_2$ the $\pi$-band quasiparticles are both inside and outside of the vortex cores [1], which could have the same effect as disorder in single-gap superconductors which enhance vortex quantum fluctuation [12]. On the other hand, quasiparticles in the superconductor could increase vortex viscosity which is detrimental to quantum fluctuation. However, compared to the cuprate superconductor, a 2D vortex system with weak pinning suggested for strong vortex quantum fluctuation [12], the vortex viscosity characterized by the Bardeen-Stephen coefficient $\eta \propto \rho_n \xi^2$ in MgB$_2$ is comparable as the smaller $\rho_n$ is balanced by the larger $\xi$. It is possible that the two-band nature makes MgB$_2$ a suitable system to observe vortex quantum fluctuation.

In summary, a non-vanishing mixed state dissipation has been observed in MgB$_2$ thin films at $T = 0$ K when the magnetic field is high enough to suppress the $\pi$-band gap. Hall effect measurement confirms that the zero-temperature dissipation is induced by vortex motion. Point-contact tunneling spectroscopy indicates that it is associated with the proliferation of quasiparticles from the $\pi$ band. The transition from a $\pi$ band-dominated 3D vortex system to a $\sigma$ band-dominated 2D vortex system at high field and the reduction of pinning energy due to the spread of $\pi$-band quasiparticles inside and outside of the vortex core cause enhanced vortex fluctuations in MgB$_2$. Vortex quantum fluctuation is a possible mechanism for the dissipation at $T = 0$ K.

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