Peak effect in single crystal MgB$_2$ superconductor for $H \parallel c$-axis

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We have studied the phase diagram of MgB$_2$ superconductor using a single crystal for $H \parallel c$-axis. For the first time we report the existence of peak effect in the screening current in MgB$_2$ single crystal for $H \parallel c$-axis. In the magnetic field regime $10 < H < 13.5$ kOe the local fundamental diamagnetic moment displays a very narrow diamagnetic step, with a temperature width of the same size as the zero dc-magnetic field transition. For higher field this step is transformed to a peak which is related with the peak effect in the screening current. Finally, for $H < 10$ kOe the diamagnetic step is transformed to a gradual transition. Our findings for the vortex matter phase diagram for the MgB$_2$ are closely related with theoretical predictions concerning the vortex matter phase diagram of a type II superconductor in the presence of weak point disorder.

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The recent discovery [1] that MgB$_2$ compound is a superconductor with remarkably high transition temperature $T_c \sim 39$ K has generated extensive scientific research (for a review see Ref. [2]). MgB$_2$ is an anisotropic 2 1 3 4 8 type II superconductor with a sample dependent anisotropic constant $\gamma = H_{c2}^{q}/H_{c2}$, taking values [1 1 11 12 13 14 15 16] into interval $2 \leq \gamma \leq 6$. The absence of weak link problem [16] in polycrystalline MgB$_2$ samples gives expectations for its using in practical applications. Furthermore, the intermediate $T_c$ of MgB$_2$, in comparison with high-$T_c$ and low-$T_c$ conventional superconductors, makes significant the experimental exploration of its vortex matter phase diagram, considering MgB$_2$ as a model physical system where both thermal fluctuations and disorder must be treated on an equal footing. In addition, the MgB$_2$ gives us the opportunity for experimental verification of theoretically proposed issues, like the melting transition of the vortex matter, the Bragg and amorphous vortex phases [17].

In this paper, we report a detailed study of the vortex matter phase diagram for $H \parallel c$-axis. In the magnetic field regime $10 < H < 13.5$ kOe the local fundamental diamagnetic moment displays a very narrow diamagnetic step, with a temperature width of the same size as the zero dc-magnetic field superconducting transition. For higher fields this step is transformed to peak which is related with the peak effect. Finally, for $H < 10$ kOe the diamagnetic step is transformed to a gradual transition. Our findings for the vortex matter phase diagram for the MgB$_2$ are closely related with the theoretical ideas proposed recently [18 19 20 21 22 23 24 25]

MgB$_2$ single crystals have been grown under high pressure in the quasiternary Mg-MgB$_2$-BN system at a pressure of 4-6 GPa and temperature 1400-1700$^\circ$C for 5-60 mins, in a BN container, using a cubic-anvil press (TRY Engineering). The present experiments were performed on a small (250 $\times$ 250 $\times$ 40 $\mu$m$^3$) MgB$_2$ single crystal using as magnetic induction sensor a GaAsIn Hall sensor with an active area of $50 \times 50$ $\mu$m$^2$, superimposing ac ($H_{ac} = H_o \sin(2\pi ft)$, $f = 0.8$ Hz) and dc magnetic fields parallel to the crystal’s c-axis ($H_{dc} \parallel H_{ac} \parallel c$). The real and imaginary part ($V = V'' + iV''$) of the modulated Hall voltage, which is proportional to the local magnetic induction ($V \propto B_z$), in the surface of the crystal, was measured by means of two lockin amplifiers. Measurements were performed as a function of temperature (isofield measurements) and also as a function of the applied field (isothermal measurements). As cryogenic environment and for the dc-field production a 10 T OXFORD cryostat has been used. Besides the superior sample quality, one of the most important aspects of our measurements is the sample’s microscopic size, restricting to a minimum any residual inhomogeneities.

Measurements of local magnetic induction in zero dc-magnetic field for $H_o = 1.4$ Oe, display a $T_c = 38.3$ K with a transition width (defined at the levels 10% and 90% of the real part of $B'$) $\Delta T \approx 0.16$ K, indicating a high quality single crystal. Fig. [3(a)] shows the real and imaginary parts of the local fundamental susceptibility ($\chi' = V''/H_o - 1$, $\chi'' = V''/H_o - 1$) as function of temperature, measured under a dc magnetic field of $H_{dc} = 15$ kOe for ac-field $H_o = 3.9$ Oe. The measurements have been taken during cooling and heating. As temperature decreases both $\chi'$ and $\chi''$ traces remain zero. Right below a temperature, which is denoted by $T_{on}$, both real and imaginary parts form a peak, with a peak-width roughly 0.5 K. Moreover, the characteristic points of the peak, the onset temperature $T_{on}$, the location of the peak, $T_p$, and $T_{on}$ do not depend on the amplitude of the ac-field. The same holds and for the other dc-fields where the peak effect is present (vide infra). As temperature further decreases both $\chi'$ and $\chi''$ exhibit the characteristic functional form of a superconducting sample, which supports a screening current, increasing monotonically.
more distorted near $H_{c2}$. It adjusts to increase pinning energy and thus has a higher critical current. Consequently, Larkin and Ovchinnikov interpreted the peak effect based on the hypothesis that the elastic moduli of the vortex lattice suddenly soft while going from local to nonlocal elasticity. Recently the onset of the peak effect has been associated with the proliferation of dislocations in the flux-line lattice [18, 19, 20, 21, 22, 23].

Fig. 2 shows the real part of the local magnetic moment near the peak regime for $H_{dc} = 23$ kOe, for various ac fields, during cooling and heating. In the particular magnetic field for $H_o = 1.7$ Oe the measurement shows a strong hysteretic behavior for $T < T_p$. This hysteretic behavior reduces as the amplitude of ac-field increases [28]. Indeed, in the measurement for $H_o = 5.7$
Oe the hysteric behavior is negligible. In addition, the width of the peak now is $\sim 1$ K in comparison with the width observed for $H_{dc} = 15$ kOe. More importantly, the peak is more obvious as the amplitude of ac-field increases. The peak effect has also been observed in isothermal measurements, as Fig. (b) illustrates. The observed thermomagnetic history dependence of the ac-response is not compatible with the conventional critical-state model. This model treats the critical current, $J_c$, as a single valued function of the magnetic induction $B$ and temperature $T$, while our measurements indicate that $J_c$ depends on the measuring path in the regime $T < T_p$. The observed behavior can be understood as follows: as we expose the system to an applied dc-field followed by cooling, through the $H_{c2}$-line, the topological defects remain as temperature decreases (the field cooling disordered phase is simply supercooled from the phase existing above $T_p$). In other words, the field cooling state yields a disordered vortex glass phase. During heating this disordered state becomes more order with consequent lower critical current in comparison with the field cooling one. The observation of the peak effect, with negligible thermomagnetic history effects, for large amplitude of the ac-field, may be related with the unblocking of the vortices from their pinned meta-stable configuration. The ac-field triggers a transition into the stable low pinning state which does not change on subsequent larger ac-field measurements.

More interestingly, detailed measurements in the regime $8 \leq H < 15$ kOe revealed that the peak effect has been transformed to a very narrow diamagnetic step with a temperature width of similar size (or less) as the zero dc-field transition. Moreover, for fields $H_{dc} \leq 10$ kOe (see Fig. 3) the diamagnetic step at the onset of the transition becomes a gradual transition (see Fig. 3). Our findings concerning the diamagnetic step in $m'$ are in accordance with the magneto-resistance results of Eltsev et al. [2], where an extremely sharp drop in the magnetoresistance has been observed, in the same magnetic field regime. Our observations resemble the vortex flux lines lattice melting transition observed in YBa$_2$Cu$_3$O$_{7-\delta}$ [24] near critical points. Based on this analogy it is plausible that in this regime the transition concerns a first order transition of the vortex lattice. Below and above the low ($H_{c1P}$) and upper ($H_{c2P}$) boundaries of this regime the transition is transformed to a second order.

Based on the local measurements a phase diagram for MgB$_2$ has been constructed. In Fig. 3 plotted are the onset points of the appearance of diamagnetic local moment that coincide with the end point of peak effect. If the pinning of the vortex lattice starts exactly below the upper critical field these points correspond to the upper critical field $H_{c2}$ of MgB$_2$. In transport measurements the $H_{c2}$ line is determined by the onset of the magneto-resistance drop [22]. The locus of these points is distinctly different from our $H_{irr}$, but most probably the onset of non-ohmic behavior [8] has to do with surface superconductivity.

As illustrated in Fig. 4, for $T > T_c/2$, the $H_{irr}$ line displays a positive curvature, while for $T < T_c/2$ it displays a negative curvature and approaches zero temperature with nearly zero slope at $H_{irr}(0) \approx 29$ kOe. The experimental points can be reproduced very well using the empirical formula $H_{irr}(T) = 29[1-(T/T_c)^2]^{1.45}$. Included are also the points where the peak is located, as well as the onset. The region at which the peak effect occurs, occupies a small fraction of the region of the mixed state, located slightly below the $H_{irr}(T)$ line. In the regime between 10 and 15 kOe the peak effect is transformed to a very narrow diamagnetic step and finally, for lower fields the transition becomes gradual.

It is widely accepted that the vortex phase diagram in the presence of weak point disorder consists of three generic phases, the vortex liquid, the high field amorphous vortex glass and the low field, low temperature Bragg glass [7]. These phases are governed by the three basic energies: the energy of thermal fluctuations, pin-
melting transition with two critical points.

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FIG. 4: The phase diagram of vortex matter of MgB$_2$ compound for \( H \parallel c \)-axis. Presented are the onset point, \( T_a \), (open circles), the peak temperature, \( T_p \), (solid circles), and the irreversibility points, \( T_{irr} \), (open squares). The solid line through \((T, H_{irr})\)-points is a plot of the empirical formula \( H_{irr}(T) = 29(1 - (T/T_c)^2)^{1.45} \). The \( H_{ucp} \) and \( H_{lcp} \) are the points where the peak effect and the diamagnetic step disappear respectively.

In summary, we experimentally estimated the vortex matter phase diagram for MgB$_2$ single crystal superconductor for \( H \parallel c \)-axis. We found that in a narrow temperature (or field) regime a peak in the screening current exists. The three distinct behaviors of the onset of the diamagnetic local moment resemble the picture of the melting transition with two critical points.

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