Hydrostatic pressure induced transition from $\delta T_c$ to $\delta \ell$ pinning mechanism in MgB$_2$

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Abstract

The impact of hydrostatic pressure up to 1.2 GPa on the critical current density ($J_c$) and the nature of the pinning mechanism in MgB$_2$ have been investigated within the framework of the collective theory. We found that the hydrostatic pressure can induce a transition from the regime where pinning is controlled by spatial variation in the critical transition temperature ($\delta T_c$) to the regime controlled by spatial variation in the mean free path ($\delta \ell$). Furthermore, critical temperature ($T_c$) and low field $J_c$ are slightly reduced, although the $J_c$ drops more quickly at high fields than at ambient pressure. We found that the pressure raises the anisotropy and reduces the coherence length, resulting in weak interaction of the vortex cores with the pinning centres. Moreover, the hydrostatic pressure can reduce the density of states [$N_s(E)$], which, in turn, leads to a reduction in the $T_c$ from 39.7 K at $P=0$ GPa to 37.7 K at $P=1.2$ GPa.

Keywords: superconductors, critical current density, hydrostatic pressure, pinning mechanism

(Some figures may appear in colour only in the online journal)
fields than at ambient pressure. We found that the pressure increases the anisotropy and reduces the coherence length, resulting in weak interaction of the vortex cores with the pinning centres.

The MgB$_2$ bulk sample used in the present work was prepared by the diffusion method. Firstly, crystalline boron powders (99.999%) with particle size of 0.2–2.4 μm were pressed into pellets. They were then put into iron tubes filled with Mg powder (325 mesh, 99%), and the iron tubes were sealed at both ends. Allowing for the loss of Mg during sintering, the atomic ratio between Mg and B was 1.2:2. The sample was sintered at 800 °C for 10 h in a quartz tube under flowing high purity argon gas. Then, the sample was furnace cooled to room temperature. The size of bar shaped sample used for measurements is 3 × 2 × 1 mm$^3$. The temperature dependence of the magnetic moments and the $M$–$H$ loops at different temperatures and pressures were performed on Quantum Design Physical Property Measurement System (PPMS 14T) by using vibrating sample magnetometer. We used a Quantum Design High Pressure Cell with Daphne 7373 oil as a pressure transmission medium to apply hydrostatic pressure on a sample. The $J_c$ was calculated by using the Bean approximation.

The zero-field-cooling (ZFC) and field-cooling (FC) curves at different applied pressures are plotted in figure 1. The $T_c$ drops from 39.7 K at $P=0$ GPa to 37.7 K at $P=1.2$ GPa, with a pressure coefficient of $-1.37$ K GPa$^{-1}$, as can be seen in the inset of figure 1. It is well known that $T_c$, the unit cell volume ($V$), and the anisotropy ($\gamma$) under pressure can be interrelated through a mathematical relation as in [31]

$$\Delta T_c'(P) + \Delta V' + \Delta \gamma' = 0, \quad (1)$$

where

$$\Delta T_c'(P) = \left[ T_c(P) - T_c(0) \right]/T_c(0),$$

$$\Delta V' = \left[ V(P) - V(0) \right]/V(0)$$

and

$$\Delta \gamma' = \left[ \gamma(P) - \gamma(0) \right]/\gamma(0).$$

The $\Delta V'$ found for MgB$_2$ is 0.0065, as the pressure can reduce the unit cell volume of MgB$_2$ from 29.0391 Å$^3$ at $P=0$ GPa to 28.8494 Å$^3$ at $P=1.2$ GPa [32]. A similar value for $\Delta V'$ can also be obtained from $\Delta V' = -\Delta P/B$, where $B$ is the bulk modulus of the material [31]. We found $\Delta T_c'(P) = 0.042$ from figure 1. By using $\Delta V'$ and $\Delta T_c'(P)$, we can obtain from equation (1):

$$\Delta \gamma' = \left[ \gamma(P) - \gamma(0) \right]/\gamma(0) \approx 0.036. \quad (2)$$

This indicates that the anisotropy of MgB$_2$ is increased by applying pressure, i.e., $\gamma(P) > \gamma(0)$.

It is important to mention that pressure has no significant impact on the unit cell volume of MgB$_2$ up to $P=1.2$ GPa. Therefore, the density of states in Bardeen–Cooper–Schrieffer-like superconductors such as MgB$_2$ is expressed as

$$N_s(E) = N_s(0) \left[ \frac{E}{\sqrt{E^2 - \Delta^2}} \right], \quad (3)$$

where $N_s(E)$ is the density of states at the Fermi level in the normal state and $\Delta$ is the superconductivity gap. Therefore, $N_s(E) \propto N_s(0)$ and

$$N_s(0) \propto VE_F^{1/2} \propto V k_F^2, \quad (4)$$

where $V$ is the total volume and $k_F$ is the Fermi wave vector [33, 34].

Combining equations (3), (4), and (5), we obtain

$$N_s(E) \propto V k_F^2. \quad (6)$$

It is important to mention that pressure has no significant impact on the unit cell volume of MgB$_2$ up to $P=1.2$ GPa. Therefore, the density of states is mainly dependent on $\xi$, $\xi < \xi_0$ leads to a comparison regarding the density of states at $P=1.2$ GPa and $P=0$ GPa

i.e. $[N_s(E)]_0 < [N_s(E)]_0$, \quad (7)

given that hydrostatic pressure can decrease the density of states in MgB$_2$ and therefore contributes to a reduction in $T_c$.

Figure 2 shows the field dependence of $J_c$ at different temperatures (i.e. 5, 8, 20, and 25 K) and pressures (i.e. 0, 0.7, and 1.2 GPa). We found that low field $J_c$ was reduced slightly under pressure. The $J_c$ drops more quickly at high fields, however, as compared to $P=0$ GPa. This is further reflected in figure 3, which shows $J_c$ values at 8 and 20 K under...
pressure. The inset shows normalized $\Delta J_c$ (i.e., $\Delta J_c = J_c^P - J_c^0$) for both 8 K and 20 K, which indicates almost a similar decay trend. We also plotted irreversibility field ($H_{irr}$) as a function of temperature in figure 4, which shows that $H_{irr}$ decreases gradually from nearly 13 to 11.8 T at $T = 5$ K for $P = 1.2$ GPa, which is ascribed to the observed $J_c$ suppression.

$J_c$ as a function of reduced temperature ($\tau = 1 - T/T_c$, where $T$ is the temperature and $T_c$ is the critical temperature) is plotted in figure 5. The temperature dependence of $J_c$ follows a power law description in the form of $J_c \propto \tau^\mu$, where $\mu$ is the slope of the fitted line and its value depends on the magnetic field [35–37]. The exponent $\mu$ in our case is found to be nearly same at different pressures, and its values are 1.63, 2.22, and 2.65 at fields of 0, 2.5, and 5 T, respectively. Different values of exponent $\mu = 1$, 1.7, 2, and 2.5 are also reported for standard yttrium barium copper oxide films [38]. The larger exponent value at high field shows that pressure effects are more significant at high fields as compared to low fields.
A double logarithmic plot of $-\log(Jc(B)/Jc(0))$ as a function of field at 12 and 20 K for $P = 0$ GPa and $P = 1.2$ GPa is plotted in figure 6. This shows deviations at certain fields, denoted as $B_{SB}$ and $B_{th}$. According to the collective theory [10], the region below $B_{SB}$ is the regime where the single-vortex-pinning mechanism governs the vortex lattice in accordance with the following expression,

$$B_{SB} \propto J_{sv} B_{c2}$$

(8)

Where, $J_{sv}$ is the critical current density in the single vortex pinning regime and $B_{c2}$ is the upper critical field. At high fields (above the crossover field $B_{SB}$), $Jc(B)$ follows an exponential law

$$Jc(B) \approx Jc(0) \exp \left\{ -\left(B/B_0\right)^{3/2} \right\},$$

(9)

Where, $B_0$ represents a normalization parameter on the order of $B_{SB}$. It is well known that the deviation observed at $B_{SB}$ is linked to the crossover from the single-vortex-pinning regime to the small-bundle-pinning regime, while the deviation at the thermal crossover field ($B_{th}$) can be connected to large thermal fluctuations [8].

The pinning behaviour can be obtained from the temperature dependence of the crossover field from the single vortex regime [39]. The temperature dependence of the crossover field can be expressed as

$$B_{SB}(T) = B_{SB}(0) \left( 1 - T^2 / T_c^2 \right)^\nu,$$

(10)

where $\nu = 2/3$ and 2 for $\delta T_c$ and $\delta \ell$, respectively.

The above-mentioned equation (10) can be found by inserting the following expressions with $t = T/T_c$ into equation (8),

$$J_{sv} \approx \left( 1 - t^2 \right)^{\gamma/6} \left( 1 + t^2 \right)^{\delta/6}$$

for $\delta T_c$

(11)

and

$$J_{sv} \approx \left( 1 - t^2 \right)^{\delta/2} \left( 1 + t^2 \right)^{-1/2}$$

for $\delta \ell$.

(12)

The crossover fields ($B_{SB}$) for reduced temperature ($T/T_c$) at $P = 0$, 0.7, and 1.2 GPa are plotted in figure 7. The experimental data points for $B_{SB}$ are scaled through equation (10) for $\delta \ell$ and $\delta T_c$. We found that hydrostatic pressure can induce the transition from the $\delta T_c$ to the $\delta \ell$
pinning mechanism. The $\delta T_{c}$ pinning mechanism is dominant in pure MgB$_2$ polycrystalline bulks, thin films, and single crystals [14, 40, 41]. The coherence length is proportional to the mean free path ($\ell$) of the carriers, and therefore, pressure can enhance $\delta T_{c}$ pinning in MgB$_2$. It is noteworthy that $J_{c}$ drops under pressure in MgB$_2$ due to the transition in the flux pinning mechanism.

In summary, the impact of hydrostatic pressure on the $J_{c}$ and the nature of the pinning mechanism in MgB$_2$, based on the collective theory, have been investigated. We found that the hydrostatic pressure can induce a transition from the $\delta T_{c}$ to the $\delta T_{p}$ pinning mechanism. Furthermore, pressure can slightly reduce low field $J_{c}$ and $T_{c}$, although pressure has a more pronounced effect on $J_{c}$ at high fields. Moreover, the pressure can also increase the anisotropy, along with causing reductions in the coherence length and $H_{irr}$, which, in turn, leads to a weak pinning interaction.

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Author contributions

XLW conceived the pressure effects and designed the experiments. BS performed high pressure measurements. XLW and BS analysed the data and wrote the paper. All authors contributed to the discussions of the data and the paper.

Additional information

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