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Hydrostatic pressure induced transition from δT_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 (δT_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)

Magnesium diboride (MgB_2) is a promising superconducting material which can replace conventional low critical temperature (T_c) superconductors in practical applications, due to its relatively high T_c of 39 K, strongly linked grains, rich multiple band structure, low fabrication cost, and especially, its high critical current density (J_c) values of 10^5–10^6 A cm^{-2} [1–9]. Numerous studies have been carried out in order to understand the vortex-pinning mechanisms in more detail, which have led to real progress regarding the improvement of J_c. There are two predominant mechanisms, δT_c pinning, which is associated with spatial fluctuations of the T_c, and $\delta\ell$ pinning, associated with charge carrier mean free path (ℓ) fluctuations [10–14].

Very recently, our team have found that hydrostatic pressure is a most effective approach to enhance J_c significantly in iron based superconductors, as the pressure can induce more point pinning centres and also affect the pinning mechanism [15]. Therefore, it is natural to investigate the impact of hydrostatic pressure on J_c and flux pinning mechanisms in MgB_2. Previous studies have shown that pressure of 1 GPa can reduce T_c, but only by less than 2 K in MgB_2 [37]. This is a very insignificant reduction as compared to the other approaches (i.e. chemical doping and irradiation) which are mainly used for J_c enhancement [16]. For instance, chemical doping can significantly enhance J_c in MgB_2, but with a considerable degradation of T_c; carbon doping can reduce T_c from 39 K to nearly as low as 10 K, for carbon content up to 20% [17–22]. Similarly, the irradiation method can improve J_c in MgB_2, but it reduces T_c values significantly (by more than 20 K in some cases) [23–27]. Correspondingly, the chemical doping and irradiation methods can also change the nature of the pinning mechanism in MgB_2 [24, 28–30]. The determination of J_c and the flux pinning mechanism under hydrostatic pressure is also an important step to probe the mechanism of superconductivity in more detail in MgB_2. It is very interesting to know whether hydrostatic pressure can increase the pinning and J_c at both low and high fields.

In this work, we report our study on pressure effects on T_c, J_c, and the flux pinning mechanism in MgB_2. Hydrostatic pressure can induce a transition from the regime where pinning is controlled by spatial variation in the critical transition temperature (δT_c) to the regime controlled by spatial variation in the mean free path ($\delta\ell$). In addition, T_c and low field J_c are slightly reduced, although the J_c drops more quickly at high

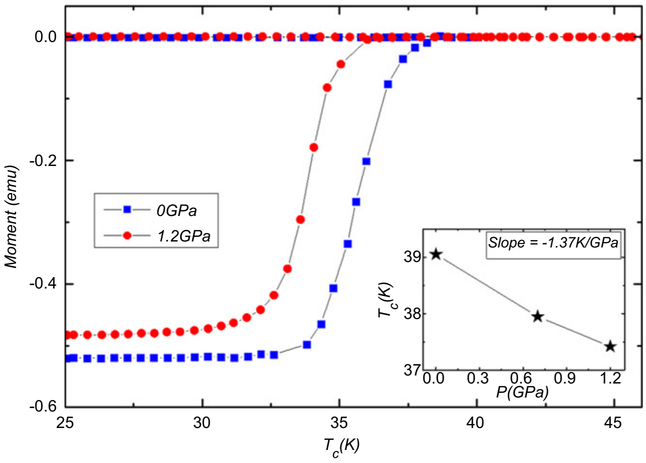

Figure 1. Temperature dependence of magnetic moment under different applied pressures in both ZFC and FC runs. The inset shows the pressure dependence of the T_c for MgB_2. T_c is found to decrease with a slope of $dT_c/dP = -1.37$ K GPa^{-1}.

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 $3 \times 2 \times 1$ 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 (γ) under pressure can be interrelated through a mathematical relation as in [31]

$$\Delta T_c^{/}(P) + \Delta V^{/} + \Delta\gamma^{/} = 0, \tag{1}$$

where

$$\Delta T_c^{/}(P) = \left[\frac{T_c(P) - T_c(0)}{T_c(0)}\right],$$

$$\Delta V^{/} = \left[\frac{V(P) - V(0)}{V(0)}\right] \text{ and}$$

$$\Delta\gamma^{/} = \left[\frac{\gamma(P) - \gamma(0)}{\gamma(0)}\right].$$

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 $P \approx 1.2$ 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):

$$\Delta\gamma^{/} = \left[\frac{\gamma(P) - \gamma(0)}{\gamma(0)}\right] \approx 0.036. \tag{2}$$

This indicates that the anisotropy of MgB_2 is increased by applying pressure, i.e., $\gamma(P) > \gamma(0)$. Therefore, the coherence length (ξ) at $P = 1.2$ GPa is reduced as compared to its value at $P = 0$ GPa $\left[\text{i.e., } (\xi)_P < (\xi)_0\right]$. The density of states in Bardeen–Cooper–Schrieffer-like superconductors such as MgB_2 is expressed as

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

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

$$N_n(E_F) \propto V E_F^{1/2} \propto V k_F^2, \tag{4}$$

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

$$k_F = \frac{2m\Delta\xi}{\hbar}. \tag{5}$$

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

$$N_s(E) \propto V\xi. \tag{6}$$

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 ξ. $(\xi)_P < (\xi)_0$ leads to a comparison regarding the density of states at $P = 1.2$ GPa and $P = 0$ GPa

$$\text{i.e. } \left[N_s(E)\right]_P < \left[N_s(E)\right]_0, \tag{7}$$

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

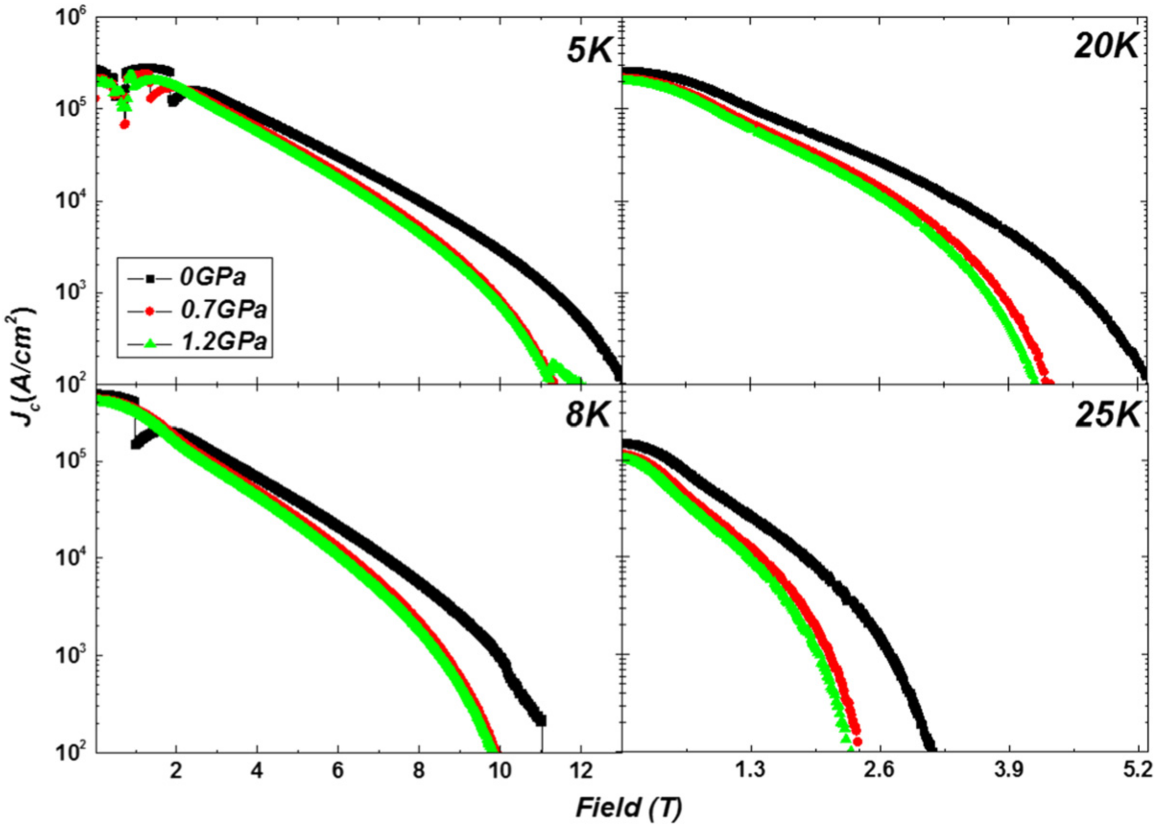

Figure 2. Field dependence of J_c under different pressures measured at 5, 8, 20, and 25 K.

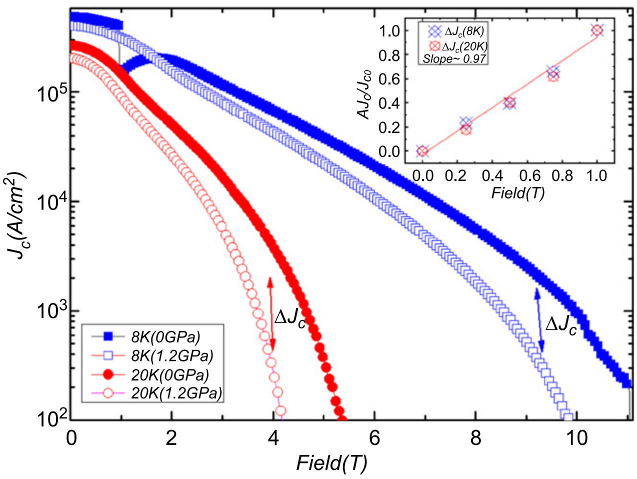

Figure 3. Comparison of J_c at two pressures (0 and 1.2 GPa) for 8 and 20 K curves. The inset shows the plot of $\Delta J_c/J_{c0}$ versus field, illustrating the trend towards the suppression of J_c with increasing field, nearly at a same rate of $\sim -0.97\ T^{-1}$ for 8 and 20 K.

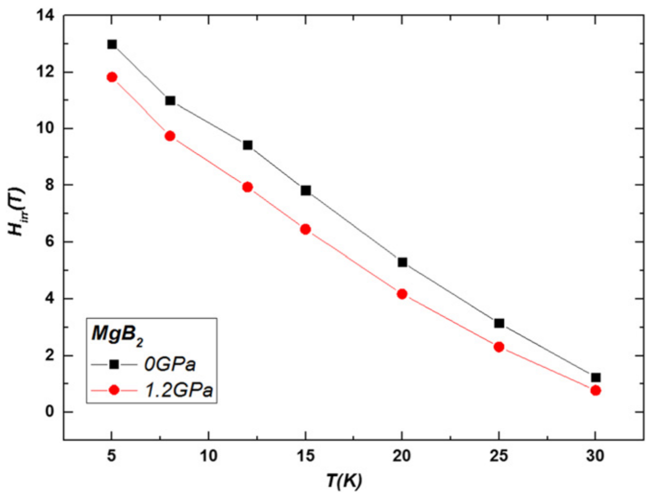

Figure 4. H_{irr} as a function of temperature.

pressure. The inset shows normalized ΔJ_c (i.e., $\Delta J_c = J_c^P - J_c^o$) 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 μ is the slope of the fitted line and its value depends on the magnetic field [35–37]. The exponent μ 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.

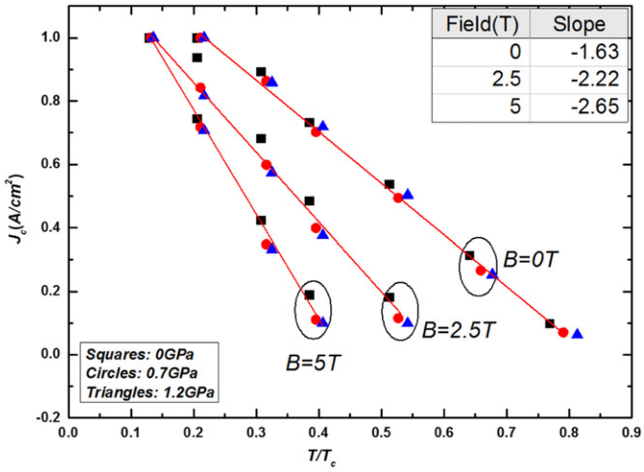

Figure 5. J_c as a function of reduced temperature ($\tau = 1 - T/T_c$) at 0, 2.5, and 5 T for pressures of 0, 0.7, and 1.2 GPa. The solid lines are fitted well to the data according to the power law in the framework of Ginzburg–Landau theory.

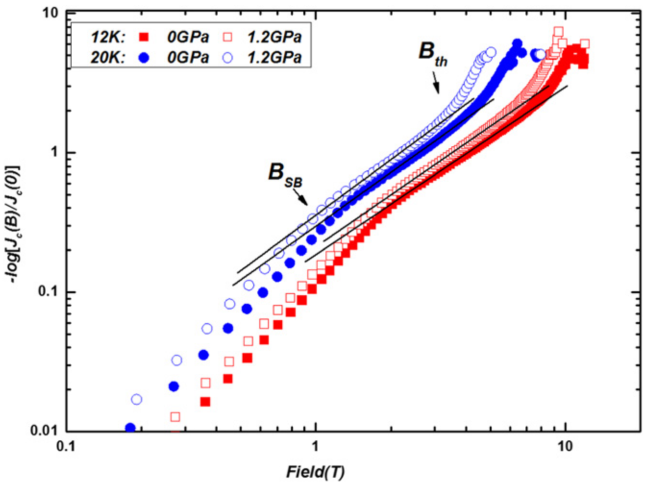

Figure 6. Double logarithmic plot of $-\log[J_c(B)/J_c(0)]$ as a function of field at 12 and 20 K.

A double logarithmic plot of $-\log[J_c(B)/J_c(0)]$ 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,

$$B_{SB} \propto J_{sv} B_{c2} \tag{8}$$

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}), $J_c(B)$ follows an exponential law

$$J_c(B) \approx J_c(0) \exp\left\{-\left(B/B_0\right)^{3/2}\right\}, \tag{9}$$

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

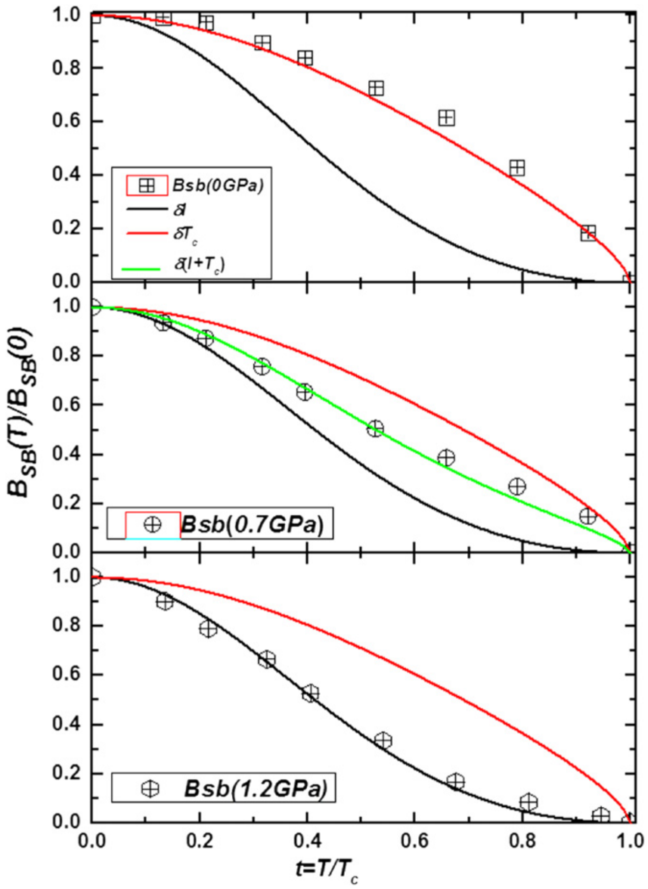

Figure 7. Plots of $B_{sb}(T)/B_{sb}(0)$ versus T/T_c at different pressures (0, 0.7. and 1.2 GPa). The red fitted line is for δT_c pinning, the black fitted line is for $\delta\ell$ pinning, and the green fitted line is for mixed $\delta(T_c + \ell)$ pinning.

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

$$B_{SB}(T) = B_{SB}(0)\left(\frac{1 - t^2}{1 + t^2}\right)^{\nu}, \tag{10}$$

where $\nu = 2/3$ and 2 for δT_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),

$$J_{sv} \approx \left(1 - t^2\right)^{7/6}\left(1 + t^2\right)^{5/6}: \text{ for } \delta T_c \tag{11}$$

$$\text{and } J_{sv} \approx \left(1 - t^2\right)^{5/2}\left(1 + t^2\right)^{-1/2}: \text{ for } \delta\ell. \tag{12}$$

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 δT_c. We found that hydrostatic pressure can induce the transition from the δT_c to the $\delta\ell$

pinning mechanism. The δT_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 (ℓ) of the carriers, and therefore, pressure can enhance $\delta\ell$ 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 δT_c to the $\delta\ell$ 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

Competing financial interests: The authors declare no competing financial interests.

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