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A comparative study on field, temperature, and strain dependences of the critical current for doped and undoped MgB₂ wires based on the percolation model

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A comparative study on field, temperature, and strain dependences of the critical current for doped and undoped MgB₂ wires based on the percolation model

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Field, temperature, and strain dependences of the critical current for a SiC doped multifilamentary *in situ* MgB₂ wire have been studied. Measurement results were compared with that of the undoped wire, and the origin of the difference in the critical current is discussed. The critical current can be calculated with the percolation model considering the effect of anisotropy. The temperature dependence of the fitting parameters, the upper critical field along the *ab*-plane, and *c*-axis is compared with the dirty-limit two-gap theory. To assess the validity of the fitting parameters, resistive transition has been measured especially to extract the upper critical field directly. It is shown that even the resistive broadening can be well explained by a simple parallel path model using the fitting parameters obtained from the critical current analysis. © 2009 American Institute of Physics. [doi:10.1063/1.3224862]

I. INTRODUCTION

It is now rather well established that transport properties of MgB₂ such as resistivity or the critical current are strongly affected by connectivity. Especially for polycrystalline samples, pores or oxide layers are usually claimed for the cause of reduction in grain connectivity. In an early review of Rowell,¹ reported resistivity for a variety of samples was studied and at least for a relatively clean limit case, a simple empirical formula was proposed for the estimation of connectivity. A bit more sophisticated study on connectivity has been carried out by Yamamoto *et al.*² recently. They incorporated percolation theory to relate resistivity with packing factor variation taking into account porosity and the portion of oxide layers. For a rough estimation of residual resistivity, the effect of anisotropy was also considered. Even though MgB₂ is less anisotropic compared with cuprate superconductors it is still anisotropic. When the applied field is below the upper critical field along the *c*-axis (B_{c2}^c), every grain within a polycrystalline sample may carry an electrical current. But as the field is increased above B_{c2}^c , the portion of grains participating electrical transport gradually decreases and will reduce to zero above the upper critical field along the *ab*-plane (B_{c2}^{ab}). We definitely need to consider the connectivity caused by the anisotropy of MgB₂, especially for granular samples below the transition temperature at field above the upper critical field along the *c*-axis.

An attempt to calculate the critical current of polycrystalline MgB₂ taking into account the percolative nature of transport due to anisotropy was reported by Eisterer *et al.*³ Anisotropic Ginzburg–Landau theory is assumed for the angular dependence of the upper critical field. The Kramer grain boundary pinning model and percolation theory are adapted. The critical current of several bulks and wires whether they were irradiated or not can be explained by four fitting parameters, the upper critical field along the *ab*-plane (B_{c2}^{ab}), the anisotropy parameter (γ), the pinning force maximum (F_m), and the percolation threshold (p_c).³ The relevance of fitting parameters such as the anisotropy parameter with reported results is discussed in their work. We recently reported that the critical current of a carbon doped sample also can be understood by the percolation model proposed by Kim *et al.*⁴ The percolation model enables a quantitative analysis on the effect of doping. The increase in the critical current by doping was closely related with the increase in the upper critical field and the decrease in the anisotropy parameter. The pinning force maximum was lowered and seems to be a reason for the reduction in the critical current at low field by doping.⁵ However, the effect of reduced effective cross-sectional area by porosity also needs to be considered.⁶ The strain dependence of the critical current for an undoped MgB₂ wire was also studied and can be analyzed by the same percolation model.⁵ It was argued that the linear strain dependence of the critical current for the undoped sample is mainly related to a variation in the anisotropy parameter. In this work, we study the effect of doping and applied strain

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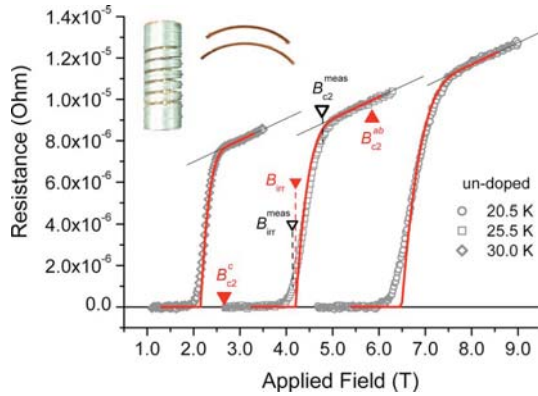


FIG. 1. (Color online) The resistive transition measurements at various temperatures for the undoped sample. The thick lines are calculated with the parallel path model using the fitting results for the critical current. (Inset) Left side: sample attached on a spiral. Right side: microscope image after removal from the spiral. The Monel sheath was partially grinded.

together and compared with the previous results. The temperature dependence of the upper critical field is compared with a recent dirty-limit two-gap theory.^{7,8} The validity of the fitting parameters is argued with a simple model on resistive transition. The overall effectiveness of the percolation model will be discussed.

II. EXPERIMENTAL

In our previous work, field, temperature, and strain dependences of the critical current for an undoped commercial Hyper Tech multifilamentary *in situ* wire were reported.⁵ Here, detailed critical current measurements have been carried out for a SiC doped multifilamentary wire. The doped wire was fabricated by the same way as for the undoped wire except carbon doping. It has a Monel sheath and within the sheath seven filaments are bundled together. It was heat treated by the same way as before, 30 min at 650 °C. Detailed measurement procedures using a variable temperature Walter spiral probe for the transport critical current measurement by four-probe method were reported elsewhere.⁹

The measured field dependence of the critical current is analyzed with the percolation model. As a way to check the validity of the fitting parameters such as the upper critical field, resistive transition measurement was also carried out. Usually, the upper critical field is determined from the onset of resistive broadening. The sample used for the critical current measurements was carefully removed from the spiral (inset of Fig. 1). The Monel sheath was partially grinded until the filament core appeared. Resistive broadening was measured using Quantum Design physical property measurement system with an applied current of 100 mA. The current was supplied with a Keithley 220 current source, and the voltage was measured by a 2182 A nanovoltmeter.

III. RESULTS AND DISCUSSION

The field and temperature dependences of the critical current for the doped sample compared with the undoped sample are shown in Fig. 2. At 4.2 K, the critical current for the doped sample at high field is much higher than that for

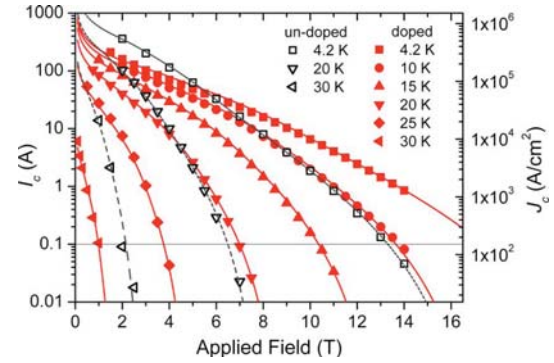


FIG. 2. (Color online) The field dependence of the critical current at various temperatures for the undoped (open symbols) and doped samples (solid symbols). The lines are calculated with the percolation model.

the undoped sample. As we increased the temperature, the critical current for both samples was comparable with each other even at a field near the irreversibility field, for example, at 20 K. Near the transition temperature, at 30 K, the critical current for the doped sample is lower than that for the undoped sample at all fields. Whether doped or not, the critical current of both samples can be described by the percolation model. All lines in Fig. 2 were calculated with the model proposed by Eisterer *et al.*³ and are in good agreement with the measured data. The fitting parameters used are shown in Figs. 3 and 4. As was argued in our previous work,⁴ there is a clear increase in the upper critical field and there is a decrease in the anisotropy parameter by doping. On the other hand, the pinning force maximum is significantly lowered by doping at all temperatures. A temperature independent percolation threshold of 0.26 was used, the same as it was for the undoped sample.

As can be seen in Fig. 3, there are clear upward curvatures in the temperature dependence of the upper critical fields parallel to the *ab*-plane B_{c2}^{ab} , whether doped or not. The positive curvature is usually argued as related with the two-band nature of MgB₂, for example, as was reported by Gurevich *et al.*⁸ All lines in Fig. 3 are calculated with Eq. (1), based on the dirty-limit two-gap theory.

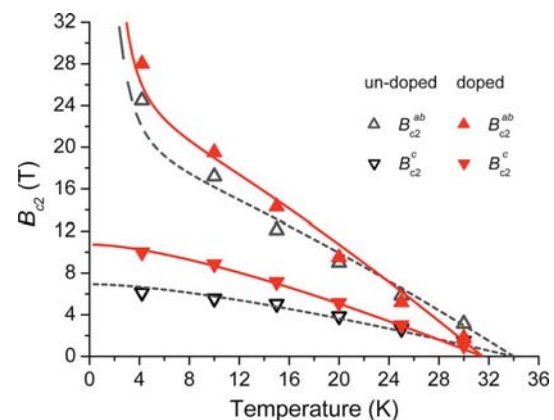


FIG. 3. (Color online) The upper critical field along the *ab*-plane and the *c*-axis for the undoped and doped MgB₂ wires obtained from the fitting of the critical current. The lines are calculated with the dirty-limit two-gap theory.

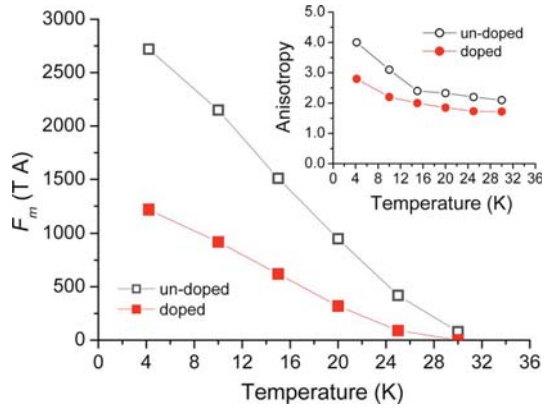


FIG. 4. (Color online) The pinning force maximum as a function of temperature obtained from the fitting of the critical current. (Inset) The temperature dependence of the anisotropy parameter for both the undoped and doped samples.

$$2w[\ln t + u(b/t)][\ln t + u(\eta b/t)] + \lambda_2[\ln t + u(\eta b/t)] + \lambda_1[\ln t + u(b/t)] = 0. \quad (1)$$

Here, t is the reduced temperature T/T_c and b is defined as $\hbar H_{c2} D_\sigma / 2 \phi_0 k_B T_c$. D_σ is σ band diffusivity and ϕ_0 is the flux quantum. The function $u(x)$ is defined as $u(x) = \psi(1/2 + x) - \psi(1/2)$, where $\psi(x)$ is the digamma function. η is a ratio of the π band and σ band diffusivity, D_π/D_σ . w and $\lambda_{1,2}$ can be obtained from the electron-phonon coupling constant λ_{mn} and the Coulomb pseudopotential matrix μ_{mn} .⁸ The electron-phonon coupling constant and the Coulomb pseudopotential can vary upon doping. According to a model calculation based on the two-band Eliashberg theory for MgB_2 ,¹⁰ the Coulomb pseudopotential is a slowly decreasing almost linear function as the content of carbon increases. Even within the dirty-limit two-gap theory, interband scattering can affect the transition temperature and the upper critical field.^{7,8} However, the variation of the transition temperature due to doping is relatively small (about 2.4 K) for the sample studied in this work. In this case, the variation of λ_{mn} or μ_{mn} by doping and the effect of interband scattering can be neglected⁸ and are not considered here for simplicity. The best fits are obtained with the diffusivities listed in Table I. The π band is much dirtier than the σ band, especially along the ab -plane. In our case, carbon doping increases the π band scattering a bit more than the σ band scattering, consistent with the report of Angst *et al.*¹¹ On the other hand, the opposite result was reported by Sologubenko *et al.*¹² from thermal conductivity measurements.

The upper critical fields discussed in the previous paragraph are fitting parameters and not measured data. A usual way determining the upper critical field is to measure it from

TABLE I. The diffusivities used for the calculation of the upper critical field with the dirty-limit two-gap theory, Eq. (1), shown in Fig. 3.

	D_σ^{ab} (m ² /s)	D_π^{ab} (m ² /s)	D_σ^c (m ² /s)	D_π^c (m ² /s)
Undoped	1.5×10^{-4}	4.3×10^{-6}	4.0×10^{-4}	1.2×10^{-4}
Doped	1.15×10^{-4}	2.8×10^{-6}	2.4×10^{-4}	0.7×10^{-4}

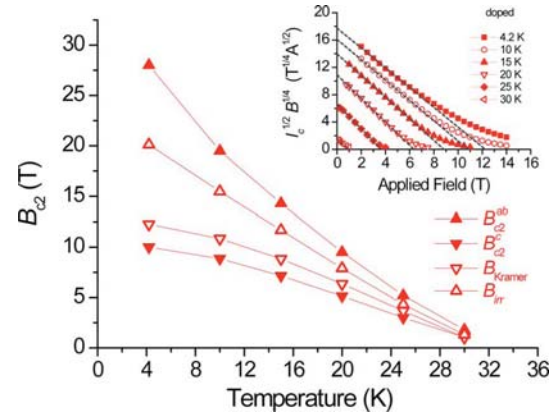


FIG. 5. (Color online) The temperature dependence of the upper critical field along the ab -plane and the c -axis, the irreversibility, and the Kramer field for the doped sample. (Inset) Kramer plots for the doped sample. The Kramer field is extrapolated from the linear fitting for the low field region (dotted lines).

resistive broadening. Resistive transition measurements for the undoped sample are shown in Fig. 1. The upper critical field is defined as a field at which 90% of normal state resistance at the onset is observed (B_{c2}^{meas}) and the irreversibility field as a field where 10% normal state resistance is observed ($B_{\text{irr}}^{\text{meas}}$). The measured upper critical field and the irreversibility field at 25.5 K are presented in Fig. 1 as open triangles.

Quite interestingly, the resistive transition can be well reproduced by a simple parallel path model. It was assumed that if the applied current (represented as a horizontal line in Fig. 2) exceeds the critical current, the residual current (a difference between the applied and critical currents) flows partially through normal MgB_2 grains or along the sheath. Thereby resistivity gradually develops along these parallel resistive paths. The thick solid lines in Fig. 1 were calculated with the parallel path model using the critical current calculated by the percolation model. The resistance of resistive paths is approximated as a linear function of temperature extended from the onset as shown in Fig. 1 as thin solid lines. There is a slight difference in temperature between the resistive measurements and the calculated lines. The resistive broadening measured at 25.5 K, for example, quite well coincides with the thick solid line calculated with the fitting results for the critical current measurements at 25 K. The critical current measurements had been carried out with the variable temperature Walter spiral probe as noted, and there can be a slight difference in temperature sensor calibration. Also, for the critical current measurements, the effect of sensor magnetoresistance was considered whereas for the resistive measurements it was not and can be another possible reason for the observed slight difference in temperature. As the applied current exceeds the critical current, the calculated resistivity sharply increases whereas there are tails at the offset in the measured data. The difference at the offset might be related with flux flow resistivity. However, the irreversibility defined from the critical current measurements with a criterion of 100 A/cm², B_{irr} (solid triangle in the middle of resistive transition shown in Fig. 1), is comparable with the measured irreversibility field $B_{\text{irr}}^{\text{meas}}$. We argue that

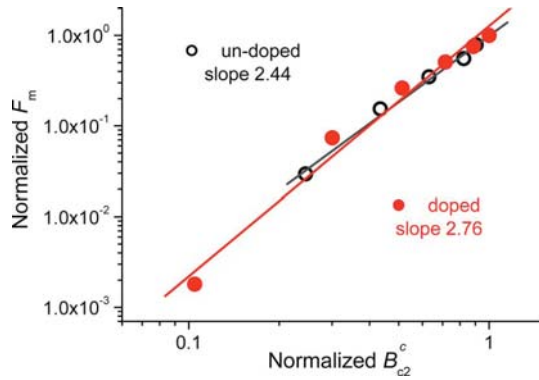


FIG. 6. (Color online) Correlation between the normalized pinning force maximum and the normalized upper critical field along the c -axis.

the fitting parameters obtained are relevant not only for the critical current analysis but also for the assessment of the resistive broadening. At least for polycrystalline samples of MgB_2 , the usual method for the determination of the upper critical field can underestimate the actual upper critical field.

If there are correlations among the fitting parameters, the uncertainty in the determination of the fitting procedure would diminish, and the fitting parameters, such as the upper critical field, might be directly extracted from the analysis of resistive broadening. In our previous work,⁵ some interesting correlations were reported and the same correlations work for the doped sample as well. As shown in Fig. 5, the upper critical field along the ab -plane and the c -axis are proportional to the irreversibility field B_{irr} and the Kramer field B_{Kramer} , respectively. The Kramer field is defined as an intercept of a linear fitting in the low field region (dotted lines in the inset of Fig. 5) of the Kramer plot. It is also observed that the normalized pinning force maximum, $F_m/F_m(4.2\text{ K})$, is almost proportional to $[B_{c2}^c/B_{c2}^c(4.2\text{ K})]^{2.5}$, consistent with the grain boundary pinning model, the Kramer model,¹³ as can be seen in Fig. 6.

The strain dependence of the critical current at 20 K within reversible strain limit is shown in Fig. 7. It is also linear for the doped sample and can be written as $I_c(\varepsilon)$

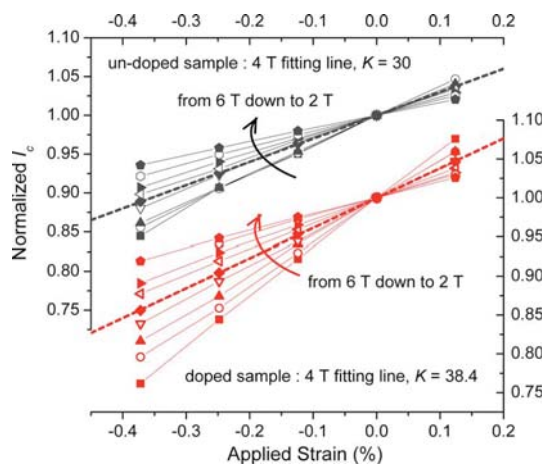


FIG. 7. (Color online) The strain dependence of the critical current for the doped and undoped samples at 20 K. The dotted lines are linear fitting results.

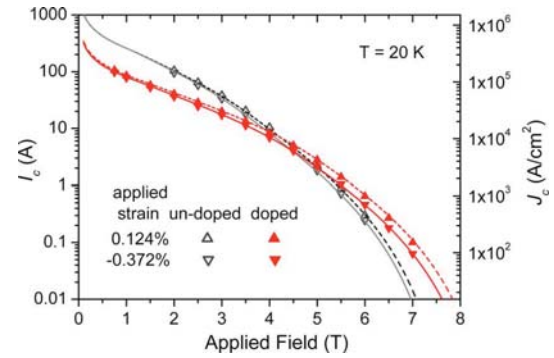


FIG. 8. (Color online) The field dependence of the critical current with different applied strains for both the doped and undoped MgB_2 wires. The lines are calculated with the percolation model.

$=I_c(0)[1+K\varepsilon]$ as reported,¹⁴ where K is a constant of proportionality. The critical current for the doped sample is much more strongly affected by the external longitudinal strain compared with that for the undoped sample as can be clearly seen both in Figs. 7 and 8. The strain dependency coefficient K at 20 K, 4 T, is 38.4 for the doped sample whereas it is 30 for the undoped sample. The solid and dotted lines in Fig. 8 calculated with the percolation model are in agreement with the field dependence of the critical current at different strains for the doped sample as well. Compared with the undoped sample, not only the anisotropy parameter but also the upper critical field and the pinning force maximum varied by the applied strain as listed in Table II, which seems to be a major cause for the observed strong strain dependence for the doped sample.

IV. CONCLUSIONS

In summary, a comparative study on the field, temperature, and strain dependences of the critical current for doped and undoped MgB_2 wires has been carried out. The critical current can be analyzed with the percolation model where the effect of anisotropy is considered. The temperature dependence of the upper critical field along the ab -plane obtained from the fitting for both wires shows an upward curvature. It was argued from the analysis using the dirty-limit two-gap theory that the π band is much dirtier than the σ band, and the π band scattering increases a bit more by the carbon doping and that is a cause for the increase in the upper critical field and the reduction in the anisotropy parameter. The resistive broadenings also can be understood reasonably with the simple parallel resistive path model using

TABLE II. The fitting parameters used for the calculation of the critical current density shown in Fig. 8, with the percolation model.

	ε_a (%)	B_{c2}^c (T)	F_m (TA)	γ
Undoped	-0.372	9.0	950	2.43
	0.124	9.0	950	2.33
Doped	-0.372	9.4	300	1.91
	0.124	9.52	325	1.83

the fitting results of the percolation model for the critical current, which suggest that usual determination of the upper critical field might underestimate the actual upper critical field. We observed the same correlation among the fitting parameters for both wires such as $F_m/F_m(4.2\text{ K}) \propto [B_{c2}^c/B_{c2}^c(4.2\text{ K})]^{2.5}$, which might reduce the uncertainty in the determination of the fitting parameters using the percolation model. The strain dependency of the critical current for the doped sample is much stronger than that for the undoped. It was argued that not only the anisotropy parameter but also the upper critical field and the pinning force maximum vary by the applied strain for the doped sample from the percolation model analysis.

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