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On the reversible magnetization in MgB_2 superconductor

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ABSTRACT. The equilibrium magnetization $Meq\ (T,H)$ in MgB_2 has been used to obtain the thermodynamic critical field H_c and its variations with temperature. The M_{eq}/H_c vs. H/H_c curves has been found to follow closely a universal behavior over a wide temperature range (4-37K). In addition, at a given temperature, the $Meq\ (T,H)$ behavior closely follows London behavior $Meq\ (T,H) \sim ln(H_{c2}/H)$ in the intermediate field range $H_{c1}<H<H_{c2}$.

I. Introduction

The discovery of superconductivity in MgB_2 [1] has stimulated considerable interest in this binary intermetallic compound [2]. Shortly after the discovery, Boron-isotope effect has pointed out the importance of phonon frequencies [3]. Moreover, thermodynamic properties, transport measurements and the phonon density of states strongly suggest that MgB_2 is likely to be a phonon-mediated s-wave superconductor [4,5].

The thermodynamic critical field H_c is one of the fundamental parameters for superconductors. Its temperature behavior is very important in determining various superconducting properties and material specific parameters that can be compared with the prediction of theoretical values, like BCS theory for example [6,7]. The H_c values and the Ginzburg-Landau (GL) parameter κ can then be used to evaluate other superconducting parameters; such as the upper critical field H_{c2}(T), the penetration depth λ(T) and the coherence length ξ(T) among many other properties [6].

Traditionally, the field has been evaluated using the area under the reversible magnetization [6,7]. Moreover, Hao-Clem model has been successfully used to evaluate H_c and κ for several high temperature superconductors. Recently however, Heon-Jung *et al.* analysis of the equilibrium magnetization suggested that Hao-Clem model introduces an anomalous increase of the upper critical field H_{c2} near Tc [9,11].

Recently, Willemin *et al.* have used a small transverse *ac* field to 'shake' the vortex lattice out of the non-equilibrium to the equilibrium configuration. They found that the equilibrium magnetization is close to the average value of the ascending and descending magnetization obtained from the hysteresis loop [8]. It has also been recently pointed out by Landau and Ott that the obtained equilibrium magnetization curves derived from magnetization data obtained below the irreversibility line do not really represent M_{eq} [9].

In this study, we use Bean's model to evaluate the equilibrium magnetization in MgB_2 and use it to evaluate H_c over a wide range of field and temperature [10,11]. We also use London model to obtain related thermodynamic parameters, and compare the properties of MgB_2 with Nb, the classic type-II superconductor.

II. Experimental Technique

Solid state reaction has been used to prepare MgB_2 sample used in this study. Shiny Mg (99% purity) stripes and B (99.5% purity) coarse powder were mixed in stoichiometric ratio MgB_2. The mixture was wrapped in Ta-sheet and sealed under Ar-gas in stainless steel tube. The assembly was annealed under Ar-gas flow at 950 °C for two hours. The tube was water-queuched to room temperature.

Magnetization measurements were performed on a computer controlled PAR-4500 vibrating sample magnetometer. The magnetic moment was calibrated using standard Ni-sample. The temperature was monitored using calibrated carbon-glass resistor.

III. Results and discussion

Recent analysis based on Hao-Clem model for the equilibrium magnetization of Tl-based single crystals has revealed a strong increase in GL parameter κ with increasing temperature [9,11]. This increase is not compensated by the drop in H_c, and will result in an anomalous increase of the upper critical field H_{c2} near Tc, unlike what is commonly observed. The increase in H_{c2} is not confined near Tc, but extends well below Tc where fluctuations have minimum effects. To overcome this difficulty, we use the Beans model to obtain the equilibrium magnetization and use it to evaluate the free energy curves by evaluating the area under the equilibrium magnetization $M_{eq} = (M_1+M_2)/2$, we have:

$$\int M_{eq} dH = -(H_c)^2/8\pi, \qquad (1)$$

Where M_1 and M_2 are the descending and ascending branches of the hysteresis loop.

In figure 1 we present the hysteresis loop and the equilibrium magnetization at 4K. The inset of figure 1 shows the linear fit of the equilibrium magnetization to London model near the upper critical field H_{c2}.

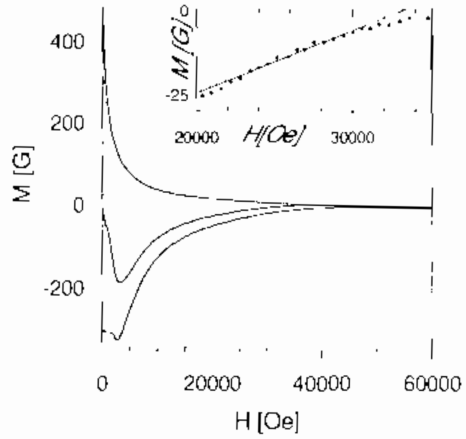

Fig. 1. Hysteresis loops and the equilibrium magnetization at 4K. The inset is the equilibrium magnetization fit to London model.

The hysteresis loops at various temperatures have been in the temperature range 4-40K. The bifurcation point of the hyteresis loop is used to obtain the irreversibility fields H_{irr} at the corresponding temperature. Moreover, these loops were used to evaluate the equilibrium magnetization which is then used according to equation 1 to obtain H_c.

The H_c and H_{irr} values are shown in figure 2. At T≤ 30K, the figure clearly shows that H_{irr} is about 6 times larger that H_c. Both fields start off with parallel slopes and then gradually decrease. Above 30K, H_c decreases at a much faster rate than H_{irr}, reaching about 7% of H_{irr} at 37K. The rapid reduction in H_c near Tc may signify the importance of fluctuation effects. While H_{irr} reflects pinning strength, changes in pinning mechanism may not be cause in the rapid reduction in H_c. However, fluctuation effects in MgB_2 deserves a closer look, as one need to evaluate the fundamental parameter that determines the strength of the thermal fluctuations, namely, the Ginzburg number, Gi=$[Tc\ /\ H_c^{2}(0)\ \gamma^3(0)\xi]^2/2$, where γ is the anisotropy factor.

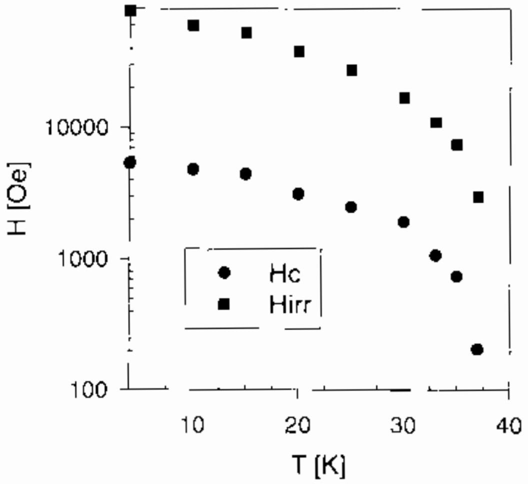

Fig. 2. Variations of the irreversibility field (H_{irr}) and the thermodynamic critical field (H_c) with temperature.

The upper critical field H_{c2} has been evaluated by fitting the equilibrium magnetization with London theory using Meq=$-Mo\ ln\ (\eta\ H_{c2}/H)$ where η ~1 [12]. The H_{c2} and H_c data are represented in Fig. 3 vs. $(1-t^2)^\alpha$. The figure shows that the two lines are nearly parallel reflecting similar temperature dependenee. The linear fit yields $H_{c2}(0)$ =3.55T and $\alpha\approx1.44$. The ratio $H_{c2}(0)/\ H_c(0)$ is used to evaluate $\kappa(0)$ =4.5 which is in close agreement with published values for GL parameter.

The fitted H_c data yield: $H_c(0)$ =0.558T and $d\ H_c\ /dT$ at $Tc(\sim39K)$ is about -220 Oe/K and $\alpha\approx1.55$ deviating from $\alpha\approx1$ expected from the two fluid model.

The ratio $H_c/Tc\approx140$ is about half the ratio obtained for the classic *Nb* superconductor. Using the electronic specific heat coefficient $\gamma\approx2.53$ mJ/K^2, we obtain for the ratio $\gamma(Tc/H_0)^2\approx1.30$, a much larger value than what the BCS theory predicts (≈0.17) for conventional superconductors [6,7].

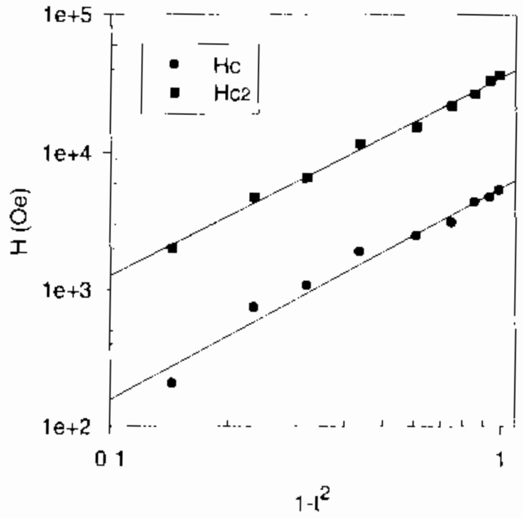

Fig. 3. Scaling of the thermodynamic critical field H_c and the upper critical field H_{c2} with 1-t^2.

IV. Conclusion

We have extended the region in which we commonly evaluate H_c beyond the thermodynamic reversibility region using Bean's Model. For these materials, the thermodynamic critical field provides a very useful parameter and can be evaluated over a sufficiently wide range of temperatures. Both the slope of the thermodynamic critical field curve at *Tc* and the ratios of *Ho/Tc* are different than the behavior expected from BCS theory seen in the classic type-II *Nb* superconductor,

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حول السلوك العكوسي للمغناطيسية في مادة MgB_2 مفرطة التوصيل

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المستخلص. استخدمنا في هذا البحث معدل المغناطيسية المستقرة (M_{eq}) لتوصيف اعتماد المجال المغناطيسي الحرج H_c على درجة الحرارة. وجدنا أنه يمكن معايرة المغناطيسية العكوسية (M_{eq}) باستخدام المجال الحرج H_c. وعلى وجه الخصوص تطابقت منحنيات M_{eq}/H_c vs. H/H_c وسلكت سلوكاً موحداً في مدى حراري واسع (4 - 37 K). كما قمنا بمقارنة هذه التغيرات والتوصيفات بالسلوك المتوقع من خلال أنموذج "لوندن" وذلك في منطقة المجال المغناطيسي الوسطي.