On the reversible magnetization in MgB$_2$ superconductor

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ABSTRACT. The equilibrium magnetization $M_{eq}(T,H)$ 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 $M_{eq}(T,H)$ behavior closely follows Landau behavior $M_{eq}(T,H)\sim \ln(H_c/H)$ in the intermediate field range $H_c<\text{H}<H_{c2}$.

1. 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 $\kappa$ can then be used to evaluate other superconducting parameters; such as the upper critical field $H_{c2}(T)$, the penetration depth $\lambda(T)$ and the coherence length $\xi(T)$ 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 $\kappa$ 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 $T_c$ [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) strips 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 980 °C for two hours. The tube was water-quenched 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 Han-Clem model for the equilibrium magnetization of Ti-based single crystals has revealed a strong increase in Gl. parameter $\kappa$ 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 Beams 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:

$$\int M_{eq}dH = -\frac{\chi}{8\pi},$$

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 hysteresis 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 $T \leq 30K$, the figure clearly shows that $H_{irr}$ is about 6 times larger than $H_c$. 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 $T_c$ 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, $G=\frac{T_c}{H_c}{\gamma}(0)\xi^2\gamma(0)\xi^2}/2$, where $\gamma$ is the anisotropy factor.

![Figure 2](image.png)

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 $M_{eq}=\frac{Me}{2} \ln (\frac{\eta}{H_c/H})$ where $\eta=1$ [12]. The $H_{c2}$ and $H_c$ data are represented in Fig. 3 vs. $(1-t)^\alpha$. The figure shows that the two lines are nearly parallel reflecting similar temperature dependence. The linear fit yields $H_{c2}(0)=3.55T$ and $\alpha=1.44$. The ratio $H_{c2}(0)/H_c(0)$ is used to evaluate $\xi(0)$ =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 $dH_c/dT$ at $T_c(\sim39K)$ is about -220 Oe/K and $\alpha=1.55$ deviating from $\alpha=1$ expected from the two fluid model.

The ratio $H_c/T_c=140$ is about half the ratio obtained for the classic Nb superconductor. Using the electronic specific heat coefficient $\gamma$=2.53 mJ/K$^2$, we obtain for the ratio $\gamma(T_c)/H_c^2$=1.30, a much larger value than what the BCS theory predicts ($\approx 0.17$) 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 $T_c$ and the ratios of $H_{oi}/T_c$ are different than the behavior expected from BCS theory seen in the classic type-II $Nb$ superconductor.

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References


احترم السلوك العكسي للمغناطيسية في مادة MgB₂

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المستخلص: استخدمنا في هذا البحث معدل المغناطيسية المستقرة (Mₚ) لتصنيف
اعتماد المجال المغناطيسي الحرج Hᵣ على درجة الحرارة. وجدنا أنه يمكن تمييز
المغناطيسية المكوسية (Mₚ) باستخدام مجال الحرج Hᵣ، وعلى وجه الخصوص
تماشت منحنى ملأ مسكة سلوكاً موحداً في مدى حراري واسع في (30 K).
لكنا نبين هذه التغييرات والتوصيفات بالسلوك المتوقع من خلال
انموذج "وولدن" وذلك في منطقة المجال المغناطيسي الوسطي.