The critical current density of SiC-doped MgB_2 as determined from the Campbell penetration depth using the tunnel-diode resonator technique

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The tunnel-diode resonator (TDR) technique for accurate measurements of the magnetic penetration depth is used to measure the London and Campbell penetration depths of polycrystalline SiC doped (10wt.%) MgB_2. The Campbell length was used to investigate the field and temperature dependence of the critical current density. The as determined critical current density provides values as high as 6×10^6 A/cm^2 at 4.2K, 1T, which is higher than values estimated by Bean method.

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1. Introduction

The Campbell method is an AC magnetic field inductive method, which is valuable for the investigation of the response of the vortex matter in purely elastic (linear) regime. The method is able to provide both the critical current density of superconductor and the relationship between the force on and the displacement of the flux lines [1,2]. In this method, the penetration of a small AC field in the presence of the vortices is explored. The quantity which depicts the penetration is known as Campbell pinning penetration depth λ_C or simply the Campbell length. In a certain way, it is similar to the London penetration length which depicts the Meissner state [1,3-5]. The Campbell length is extracted from the shift of the resonance frequency of an LC circuit when the sample, in mixed state, is inserted in the primary coil. Small changes of the AC field amplitude do not influence the current density, which is assumed to be constant.

Technically, a DC magnetic field H_e and a small AC field $h_0\cos\omega t$, either parallel [6-9] or perpendicular to each other, are applied on the sample. The magnetic response of the sample is sensed by a pick-up coil surrounding the sample which allows the calculation of the total magnetic flux Φ penetrating the sample [10-12]. From the dependence of Φ on h_0, Campbell length can be further obtained as: $\lambda_C = \frac{1}{k\mu_0}\frac{\partial\Phi}{\partial h_0}$ [13], where k is a geometrical parameter. Once λ_C obtained, its derivative vs h_0 provides the critical current density J_c [1, 14,15] as:

$$J_c = \frac{1}{\mu_0}\left(\frac{\partial\lambda}{\partial h_0}\right)^{-1} \tag{1}$$

In this work, we use the Campbell penetration length to investigate the critical state properties of SiC-doped MgB_2 superconductor as a function of applied field and temperature. The magnetic penetration length is measured by detecting the shift of the resonance frequency of LC system as a result of the change of sample properties inside the primary coil using the tunnel-diode resonator (TDR) technique. The shift is related in a simply way to the Campbell penetration depth and, further to the critical current density.

2. Experimental

2.1. The principles of the penetration depth measurements by TDR technique

The experimental set-up consists of a tunnel-diode driven resonator, a self-resonant LC circuit, designed in agreement with the data from literature [16,17]. The detector consists of a pick-up coil and a reference coil that are connected to LC circuit. The tunnel diode is set in the region of negative differential resistance in order to provide power only for the compensation of the dissipated energy so that the resonance of the LC circuit should be maintained. When the sample is placed in the pick-up coil, the inductance L of the coil changes to $L+\Delta L$ and the resonance frequency shifts as:

$$f_0 + \Delta f = \frac{1}{2\pi\sqrt{(L+\Delta L)C}}, \tag{2}$$

where C is the effective capacitance of the TDR circuit. For $L << \Delta L$, Eq. (2) leads to $\frac{\Delta f}{f} = -\frac{\Delta L}{L}$. Since the relative variation of the inductance is related to the magnetization of the sample as $\frac{\Delta L}{L} = \chi \frac{V_S}{V_C}$, with V_S and V_C are the volume of the sample and empty coil, respectively, and χ is the magnetic susceptibility of the sample. Based on this relationship, the dependence between the frequency shift and the penetration depth λ for a superconducting cylindrical sample of radius $R >> \lambda$ reads [18]:

$$\Delta f(T) = -G\left(1-\frac{\lambda}{R}\right), \tag{3}$$

where G is a calibration constant, $G = \frac{f_0 V_s}{2V_C(1-N)}$, with N the demagnetization factor, which is determined from the full frequency change by physically pulling the sample out of the coil [16]. In this experiment, the magnetic field H_{ext}, which consists of a DC magnetic field H_e and a small AC field $h_0\cos\omega t$, is provided by PPMS (Quantum Design) system and is applied with both components parallel to the axis of the cylindrical sample with geometrical radius R. As the temperature changes, the penetration depth changes at low temperatures as:

$$\Delta\lambda(T) = \delta f(T)\left(\frac{R}{G}\right) \tag{4}$$

With $\Delta\lambda(T) = \lambda(T) - \lambda(T_{min})$.

2. 2. Measurement of λ(T).

The TDR technique provides precise measurements of the variation of the penetration depth from Eq.(3) due to the accurate possibility to determine the frequency shift. However, the total magnetic penetration depth has always two contributions; one is the London penetration depth λ_L and one is the vortex penetration depth. The latter reduces to Campbell length λ_C at low temperatures and frequencies below the vortex oscillation frequency. Consequently, the total magnetic penetration depth is given by [19]

$$\lambda^2 = \lambda_L^2 + \lambda_C^2 \tag{5}$$

The London penetration depth $\lambda_L(T)$ can be extracted from the penetration data measured in zero magnetic field. Actually, if the absolute value of London penetration depth at zero Kelvin is known $\lambda_L(T = 0) = \lambda(T = 0, H = 0)$, then $\lambda(T_{min})$ is shifted to $\lambda_L(0)$ and $\Delta\lambda$ can be standardized as $\lambda(T)$. Meanwhile, the calibrated penetration length in the presence of the DC magnetic field $\lambda(T, H)$ can be achieved by shifting $\Delta\lambda$ in the normal state ($T >> T_c$) to the same value as $\lambda(T, H = 0)$. The determination of $\lambda(0)$ itself is still a difficult problem and several methods have been developed [19]. At the normal state, the penetration depth converts to the electromagnetic skin depth limit.

2.3. Critical current extraction from Campbell penetration depth

When the AC field ic applied, the Campbell contribution, λ_C, rapidly dominates the London depth, leading to [20]

$$\lambda_C^2 = \frac{B^2}{\mu_0 \alpha} \tag{6}$$

where α_L is the Labusch parameter:

$$\alpha_L = \frac{J_c B}{c r_p} \tag{7}$$

where r_p is the radius of the pinning potential. With equations (6), and (7), the Campbell critical current can be derived as

$$J_c = \frac{c r_p B}{\mu_0 \lambda_C^2} \tag{8}$$

2.4. Experimental data

Polycrystalline samples of carbon doped MgB_2·via SiC (10wt.%) were prepared by a modified spark plasma sintering (SPS-3.20-MK-V) method [21] from MgB_2 (Alpha Aesar, average particle size of 0.1μm) and 10wt% SiC powder (Alpha Aesar, 99.5%). The powders were loaded into a graphite die of 2.0 cm diameter, heated with a rate of 100°C min^{-1} up to the 1050°C, where it was sintered for 5 minutes in vacuum (30–40 Pa) under a uniaxial pressure of 50 MPa, and finally cooled down to room temperature with the system. The zero-field transition temperature of our samples was $T_c \approx 36$ K. A slab of 1.0×2.0×10.0 mm^3 was cut from sample and placed into the cryostat for the measurements. A DC magnetic field, up to 9 T, was applied parallel to the AC field (~5mT, $f \approx 1$ kHz), both parallel to the longest face of the sample. The magnetic penetration depths were measured by TDR technique as discussed in above.

First, we determined $\lambda_L(T)$ from the data taken in zero field. In our measurement, it was quenched by applying a negligible small field H_e = 0.5 mT, which cannot affect our analysis in mixed state which. The absolute value of London penetration depth for MgB_2, at zero Kelvin was taken $\lambda_L(0)$ = 100 nm [22]. Fig. 1 shows the temperature dependence of the magnetic penetration depth λ for different applied field measured upon warming, after the sample was cooled down in zero field and the target field was applied at low temperature. Therefore all our data are measured in zero field cooled regime.

From the penetration depth in zero field, which provides $\lambda_L(T)$ and the data taken in applied DC-field $\lambda(T,H)$, we obtained the Campbell length $\lambda_C(T)$ via Eq.(5). The temperature and field dependence of $\lambda_C(T)$ is shown in the Fig. 2. The decrease of λ_C, which is noticed at high temperatures, is due to the transition from superconducting to normal state. Finally, we shall mention that the noise in TDR might be due to the frequency shift, but, because this is not field dependent and is reproducible, it can be subtracted as a background offset.

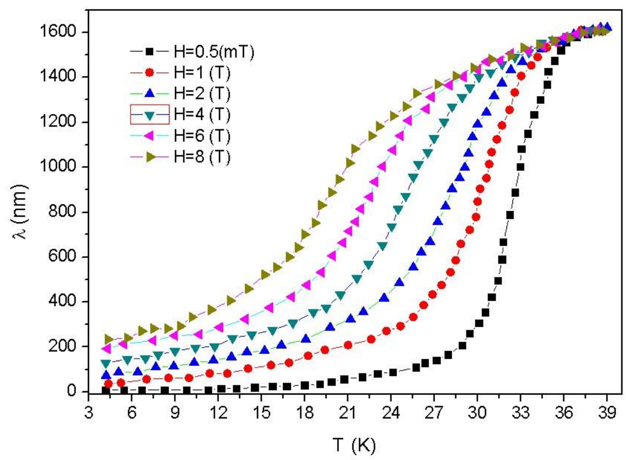

Fig. 1. Temperature dependence of the magnetic penetration length λ as measured in applied fields up to 8 T.

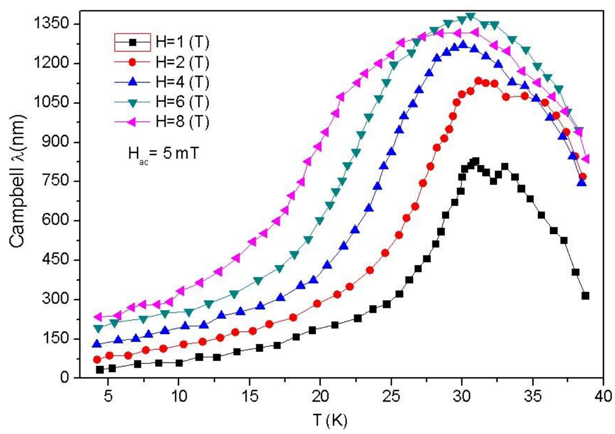

Fig. 2. (Color online) Temperature dependence of the Campbell length λC as measured in applied fields up to 8 T extracted from the data of Fig. 1.

The critical current density was extracted from the Campbell penetration depth using Eq.(8). In this equation we took the radius of the pinning potential r_p equal to the coherence length, specifically, r_p = 7 nm [23]. The temperature dependence of the critical current density J_c as measured in different applied fields is shown in the Fig. 3. When the superconductor is in normal state, Eq.(8) is no more valid. Therefore, the data in Fig. 3 must be discarded for $T > T_c(H)$.

The value of the critical current density in superconductors as obtained from Campbell method is usually overestimated. Actually, the critical current density, as measured from irreversible magnetization (Bean method), is affected by the relaxation of the magnetization during the measurement time whereas in Campbell method, the critical current density correspond to zero pinning potential $U(J_c) = 0$.

Although in this inductive method several steps are necessary in order to extract the critical current density, it has the advantage to provide more information on the pinning potential [1]. We mention here: the relationship between the pinning force and the displacement of flux line, the discrimination between the global and local critical current densities [10] and grain connectivity in superconductor [24].

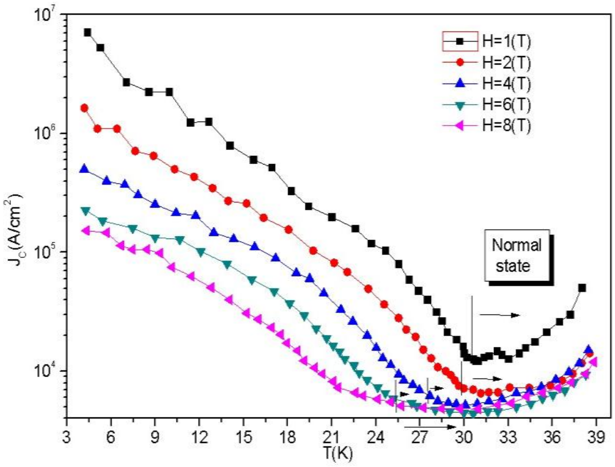

Fig. 3. Temperature dependence of the critical density of the SiC doped MgB_2·(10wt.% SiC) measured at different applied fields. Data were extracted from the Campbell length (Fig. 2). Vertical bars mark the critical temperatures. At higher temperatures the samples are in normal state.

4. Conclusion

In this work, we estimated the critical current density of a polycrystalline SiC doped (10wt.%) MgB_2 from the Campbell penetration length. We used a home build system based on a TDR technique systems run on the platform of PPMS equipment to determine the magnetic penetration depth from which we separated the Campbell depth. This quantity was further used for the extraction of the critical current density and its field and temperature dependence. The value of the critical current density is about 6×10^6 A/cm^2 at 4.2K in 1T applied field. It seems to be an overestimated value compared to the values obtained from the irreversible magnetization, but in fact this is a value which is not influenced by the relaxation of the magnetization, hence, of the currents, which influences the Bean method.

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