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Determination of the lower critical field $H_{c1}(T)$ in FeSe single crystals by magnetization measurements

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ABSTRACT

In a recent work, Abdel-Hafiez et al. [1] we have determined the temperature dependence of the lower critical field $H_{c1}(T)$ of a FeSe single crystal under static magnetic fields H parallel to the crystallographic c axis. The temperature dependence of the first vortex penetration field has been experimentally obtained by two independent methods and the corresponding $H_{c1}(T)$ was deduced by taking into account demagnetization factors. In general, the first vortex penetration field may not reflect the true $H_{c1}(T)$ due to the presence of surface barriers. In this work we show that magnetic hysteresis loops are very symmetric close to the critical temperature T_c = 9 K evidencing the absence of surface barriers and thus validating the previously reported determination of $H_{c1}(T)$ and the main observations that the superconducting energy gap in FeSe is nodeless.

1. Introduction

At low applied magnetic fields H, a bulk type-II superconductor can expel the magnetic field from its interior by means of screening supercurrents running typically in a submicron layer of width λ from the sample's borders [2,3]. As H increases, the kinetic energy of the superelectrons increases until at a certain field $H_{c1}(T)$ it becomes favorable to allow quantum units of flux to penetrate into the superconductor thus relaxing the magnetc pressure. Eventually, at an even higher field, H_{c2}, the vortex core of neighboring vortices overlap, and the sample reestablishes the normal metallic behavior. This description of the magnetic response of a superconductor holds within the thermodynamic limit, i.e. large volumes and homogeneous fields, but requires some revision if we include geometrical details of the sample through demagnetization factors and surface boundary effects. Indeed, in case of perfectly flat surface boundaries, it has been shown that the entrance of vortices can be delayed up to the thermodynamic critical field [4] $H_C = \sqrt{H_{C1}H_{C2}} \ll H_{C1}$ and moreover the ultimate vestige of superconductivity can be found at fields surpassing by almost 70% the upper critical field H_{c2} [5]. In other words, surface effects can severely modify the overall behavior of the superconducting state.

The determination of H_{c1} is of primary importance since it allows one to extract the magnetic penetration depth λ fundamental parameter characterizing the superconducting condensate and carrying information about the underlying pairing mechanism. A popular approach to measure H_{c1} consists of measuring the magnetization M as a function of H and then identify the deviation of the linear Meissner response which would correspond to the vortex penetration. This technique implicitly relies on the assumption that no surface barriers are present, thus assuring that H_{c1} coincides with vortex penetration.

Although $s^{\pm}$-pairing has been suggested for Fe-based superconductors, the pairing mechanism of superconductivity in these materials remains one of the most important open questions [6–10]. In a recent work, Abdel-Hafiez et al. [1] determined H_{c1} in FeSe single crystal from the onset of either the trapped moment or the nonlinear $M(H)$ response. This analysis and the main conclusion of that work, i.e. that FeSe has a nodeless superconducting gap, remain partially uncertain unless evidence of absence of surface barrier in this particular crystal is brought up. In this work, it is

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precisely this issue that we address and, we demonstrate that the fact that magnetization loops exhibit no asymmetries with respect to $M = 0$, strongly suggests that surface barriers are of little relevance showing that first vortex penetration occurs at H_{c1} [11].

2. Experimental

Magnetic susceptibilities were performed on a FeSe single crystal of rectangular shape rectangular with short dimension single crystal, which has lateral dimensions $a \times b \times c = 1.05 \pm 0.08 \times 1.25 \pm 0.1 \times 0.02 \pm 0.1$ mm^3 and a mass of 1.2 mg. The investigated plate-like FeSe crystal grown was grown in an evacuated quartz ampoule using the $AlCl_3KCl$ flux technique with a constant temperature gradient of 5 °C/cm along the ampoule length temperature of the hot end was kept at 427 °C, temperature of the cold end was about 380 °C. The phase purity of the resulting crystal was checked with X-ray diffraction [12]. Magnetization measurements were performed using a superconducting quantum interference device magnetometer (MPMS-XL5) from Quantum Design.

3. Results and discussions

The main panel of Fig. 1 presents the temperature dependence of the isothermal magnetization M at $H = 100$ Oe parallel to c. The zero-field cooled (ZFC) data above the superconducting transition temperature T_c displays a larger susceptibility and diamagnetic-like temperature dependence of the magnetic susceptibility as that observed in [13], which indicates the itinerant nature of electronic states of Fe at the Fermi energy. The inset shows the temperature dependence of the magnetic susceptibility measured by following ZFC and field-cooled (FC) procedures in an external field of 1 Oe applied along c The ZFC data show a sharp diamagnetic signal, thus confirming bulk superconductivity in FeSe single crystal. The magnetic susceptibility exhibits a superconducting transition with an onset transition temperature $T = 9.4$ K.

Fig. 2(a) presents the field dependence of the critical current density J_c at various temperatures up to 40 kOe for H parallel c and H parallel ab (see the inset of Fig. 2(a)). For H parallel c, the magnetic irreversibility presents a second peak at $T = 2$ K. Whereas no second peak is observed for H parallel ab.

From the magnetization hysteresis loops $M(H)$ as recently reported in [1], we calculate the J_c of both orientation by using the critical state model with the assumption of field-independent J_c.

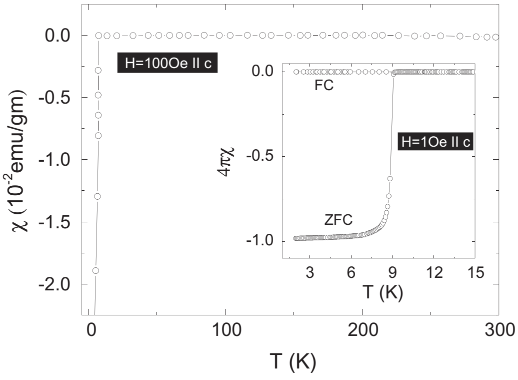

Fig. 1. The main panel shows the temperature dependence of the isothermal magnetization M vs. T measured with the field parallel to both c axis of 1 kOe. The inset presents the temperature dependence of the magnetic susceptibility after demagnetization correction in an external field of 1 Oe applied along c following ZFC and FC protocols for FeSe single crystals.

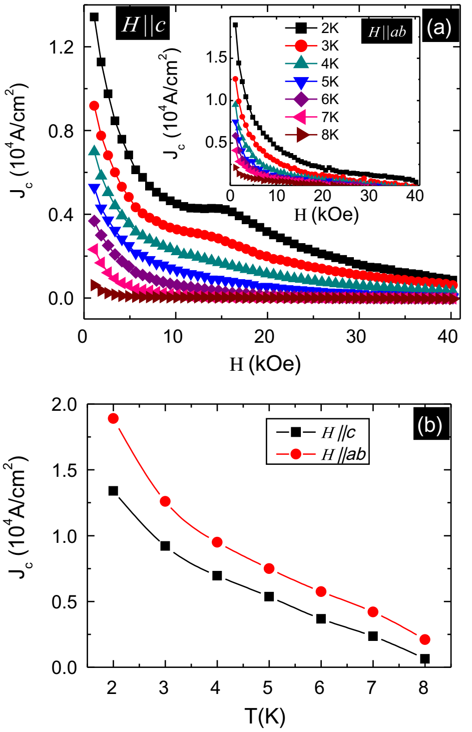

Fig. 2. (a) The critical current density J_c at various temperatures up to 40 kOe for H parallel c. The inset presents the J_c values for H parallel ab. (b) Temperature dependence of the critical current density J_c values at $H = 0$ of both orientation for the FeSe single crystal. The line is a guide to the eyes.

$$J_c = \frac{20\Delta M}{a(1-a/3b)} \tag{1}$$

where $\Delta M = M_{dn} - M_{up}$, M_{dn} and M_{up} are the magnetization measured with decreasing and increasing applied field, respectively, a (cm) and b (cm) are sample widths ($a < b$). The unit of ΔM is in electromagnetic unit per cubic centimeter and the calculated J_c is in Ampere per square centimeter. We obtain $J_c(2\text{ K}) \sim 1.34 \times 10^4$ A/cm^2 for H parallel c and $J_c(2\text{ K}) \sim 1.8 \times 10^4$ A/cm^2 for H parallel ab. These values are lower than those reported in Ba-122, 1111, 11, and the 111 systems [14–17] and higher than those observed in $K_{0.64}Fe_{1.44}Se_2$ [18]. Fig. 2(b) summarizes the temperature dependence of the J_c value at $H = 0$ for both orientation and one can clearly see a strong temperature dependence of J_c at $H = 0$.

One may argue that the nominal H_{c1} values obtained with our experiment either by the trapped moment M_t or nonlinear $M(H)$ response in FeSe studies in [1] may not reflect the true H_{c1} but the flux entry field because of the Bean–Livingston surface barrier [11]. However, it is clear that the influence of surface barrier is not important in our investigated single crystal since: (i) the magnetic hysteresis loops are very symmetric close to T_c, see Fig. 3 as well as the lower and upper inset for 8.5 and 9 K, respectively. (ii) an extremely small and unreasonable H_{c1} will be obtained when following the scenario of the Bean–Livingston surface barrier: $H_C = \frac{kH_{C1}}{\ln k}$ assuming $k \sim 72.3$. Therefore, if the surface barrier should be taken into account, the true H_{c1} would be much smaller than the one studied in [1]. (iii) the lower critical field has been obtained on a high quality single crystal. Therefore, due to the latter reasons the Bean–Livingston barrier is not important in our present sample. It is worth mentioning that recently, multiple Andreev reflections spectroscopy [12] and angle-resolved photoemission spectroscopy (ARPES) [19] as well as specific-heat measurements [20] also gave

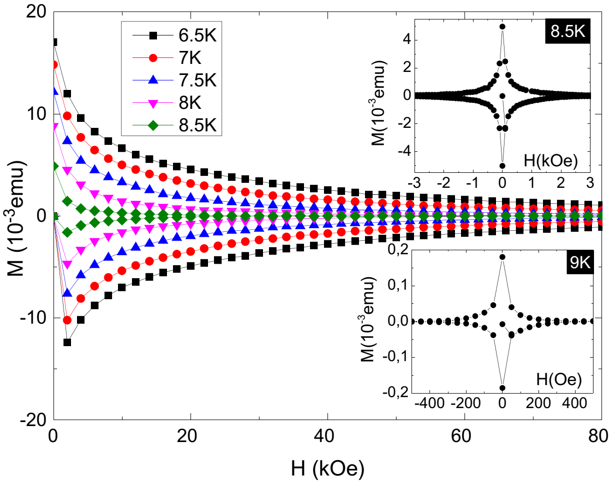

Fig. 3. Magnetic field dependence of magnetization in FeSe single crystal at different temperatures ranging from 6.5, 7, 7.5, to 8.5 K. The lower and upper inset shows the full magnetic hysteresis loops of 8.5 and 9 K, respectively.

results consistent with the good quality of our investigated single crystal.

4. Summary

In conclusion, we have measured the *M*–*H* curve of a high-quality FeSe single crystal close to T_c and found out that the magnetic hysteresis loops are symmetric. We calculated the critical current density of both orientation and the values are found to be J_c (2 K) $\sim$1.34 $\times$ 10^4 A/cm^2 for *H* parallel *c* and J_c (2 K) $\sim$1.8 $\times$ 10^4 A/cm^2 for *H* parallel *ab*.

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