Study of Vortex DynamicsinV$_{0.001}$NbSe$_2$ Superconductor

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Abstract: Largesingle crystals of $V_{0.001}NbSe_2$ superconductor were synthesized using chemical vapour transport method. The vortex dynamics of thiscompoundisevaluated in terms of critical current density (J_c) and pinning force density (F_p) characteristics. J_c shows a remarkably high value which indicates the presence of collective pinning of vortices. The superconducting transition temperature is suppressed to lower value in $V_{0.001}NbSe_2$. The normalized pinning force response with reduced magnetic field follows the Dew Hugh's and Kramer's law, indicating the presence of both surface pinning and point pinning centers in this material.

INTRODUCTION

Two dimensional superconductors now emerge as one of the most attracting class of materials because of its diverse intriguing properties [1]. Among them, $NbSe_2$, a 2D transitional metal dichalcogenides (TMDs) low transition temperature (T_c) superconductors, provide a promising material platform for investigating various richly correlated electronic phases [2, 3].$NbSe_2$ consists of one Nb layer sandwiched between two Se layershave been investigated enormously both in theoreticaland experimental condense matter physicsowing to its essentially anisotropic properties [4]. Until now, many elements i.e. Fe, Cu, Sn, Mn, Co, Te, and Cr have been incorporated into the octahedral position of the Van de Waals gap between two NbSe layers, which results suppression of superconductivity in $NbSe_2$[5-10]. Besides that, the coexistence of superconductivity and ferromagnetism has been also reported in hydrazine treated $NbSe_2$[11]. It is demonstrated that hydrazine treated $NbSe_2$ leads to the modification of Nb-Se interaction and results short range ferromagnetism with $T_c \sim 6.8$ K. These results are significant for understanding mechanism behind the superconductivity of anisotropic, layered low T_c as well as high T_c materials. This could shed new light on promising pathways to increase the T_c values and novel phases into the vortex dynamics of superconductor.

Here we study the effect of V atoms on T_c and vortex dynamics of $NbSe_2$ through magnetization measurement to improve the practical applicability of low T_c superconductor. We have estimated critical current density (J_c) and pinning force density (F_p) to give better insight into the microscopic origin of the pinning mechanism in $V_{0.001}NbSe_2$.

EXPERIMENTAL DETAILS

To grow large single crystal of $V_{0.001}NbSe_2$, chemical vapour transport method is used. High purity starting material Nb (99.8%), Se (99.999%), and V (99.99%) were weighed in proper stiochiometric ratio and well-grounded to make circular pellets of 1.3 cm diameter. The pellets were then sealed into an evacuated (5 X 10^{-5} Torr) quartz tube and heated in a two zone furnace. The size of the crystal are 2X3X0.1 mm^3. The obtained samples were characterized by Rigaku Smartlab powder X-ray diffractometer with Cu K_α radiation at room temperature. Magnetic properties were measured using a Physical properties measurement system (PPMS-VSM) (Quantum Design) at ambient condition.

RESULTS AND DISCUSSIONS

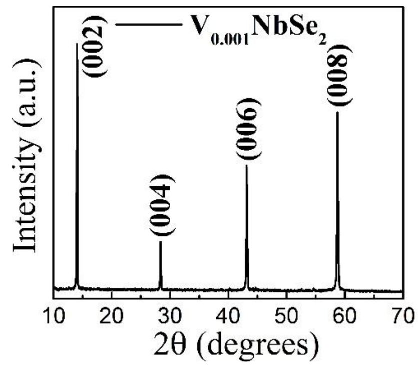

Figure 1. Xrd pattern of $V_{0.001}NbSe_2$.

The X-ray diffraction pattern of $V_{0.001}NbSe_2$is presented in Fig. 1. This shows hexagonal phase with space group 194-P63/mmc which isconfirmed from JCPDS card no. 01-070-5612.The presence of (00*l*) planesconfirm the formation of single crystalof $V_{0.001}NbSe_2$.

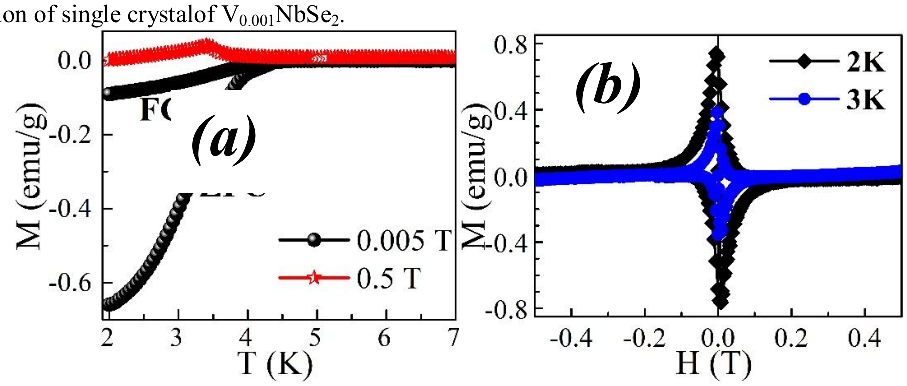

Figure. 2.(*a*) Temperature dependence of magnetization curvesin $V_{0.001}NbSe_2$ under 0.005 T and 0.5 T for FC and ZFC measurements (*b*)Isothermal hysteresis loops (M-H) of $V_{0.001}NbSe_2$ at 2K and 3K.

The characterization of the superconducting properties of $V_{0.001}NbSe_2$have been done by temperature dependent magnetization measurement with the magnetic field of H=0.005T and 0.5 T as shown in Fig. 2 (*a*) following zero field cooling (ZFC) and field cooling (FC) process. The magnetization curves show a sharp drop at low temperature indicating the onset of superconductivity. The superconducting transition temperature, T_c, estimated at the point of deviation of ZFC curve from zero magnetization value, is about 4.6 K for $V_{0.001}NbSe_2$. This result implies that the superconductivity is suppressed in $V_{0.001}NbSe_2$ compare to $NbSe_2$, which follows Fe_xNbSe_2 and Cr_xNbSe_2 as reported to our previous paper [6, 7]. The reason behind the reduction of T_c in $V_{0.001}NbSe_2$ may be due to the depletion of density of electronic states at Fermi energy level [5].

Further, the isothermal hysteresis loops (M-H) for $V_{0.001}NbSe_2$ at 2 K and 3 K are represented in Fig. 2 (*b*).The M-H curves reveal the irreversible asymmetric behaviour indicating the dominating Bean-Livingstone (B-L) surface barrier effect. Following the M-H curves, intergrain J_c is calculated from Bean model [12, 13] using the following equation:

$$J_c = \frac{20\,\Delta M}{b[1-(b/3a)]}, \qquad a > b \qquad (1)$$

Where ΔM is the width of the M-H hysteresis loop and *a*, and *b* are the sample dimensions. However, Fig. 3 (*a*) shows the J_c curves of $V_{0.001}NbSe_2$ that are estimated from eq. 1 at 2 K and 3 K temperatures.The determined value of $J_{c,\ max}$ at 2K is about 3 X 10^5 A/m^2 for $V_{0.001}NbSe_2$ andafter that J_c decreases monotonically with increasing magnetic field. This infers the collective creep of magnetic flux lines in the vortex lattice of $V_{0.001}NbSe_2$.

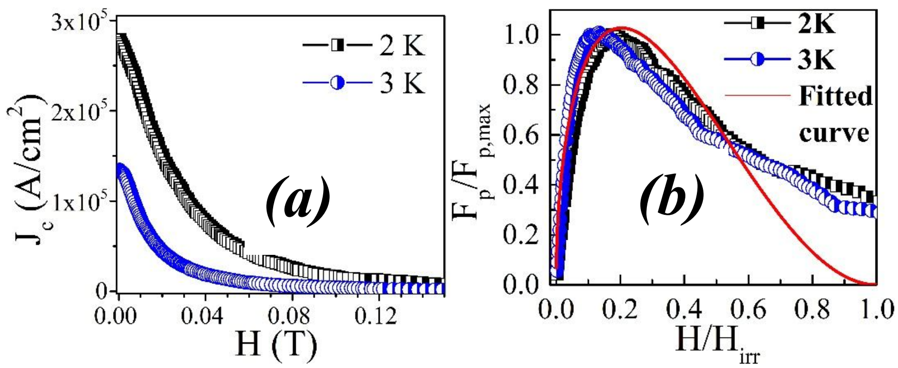

Figure 3. (*a*) Magnetic field dependence of critical current density (J_c) for $V_{0.001}NbSe_2$ at 2K and 3K (*b*) Normalized flux pinning force f_p= $F_p/F_{p, max}$shown as a function of reduced field H/H_{irr} at 2K and 3K temperatures.

Moreover, such a high value of J_c in $V_{0.001}NbSe_2$ indicates the weak pinning phenomena due to the presence of V impurities. Depending on the size of the material and direction of magnetic field, the magnetization factor can be evaluated using the formula [14],

$$N = 1 - tanh\sqrt{0.36b/a}, \tag{2}$$

Where *a* and*b* are the width and thickness of the sample. Here the estimated demagnetization factor for $V_{0.001}NbSe_2$ is 0.68, which is almost similar with Cu_xNbSe_2 as reported by Luo et. al [5]. Further, the pinning mechanism is investigated using Kramer's scaling law and Dew Hugh's scaling law of pinning force density. F_p was evaluated using the equation,

$$F_p = \mu_0 H \times J_c, \tag{3}$$

Fig. 3 (*b*) shows the normalized pinning force density (f_p= $F_p/F_{p, max}$)as a function of reduced field (h = H/H_{irr}) at 2K. To elucidate the contribution of the different pinning centers in the F_p, Dew-Hughes proposed a scaling rule $f(h) \propto h^p(1-h)^q$[15].According to the Due-Hughes model, p = 0.5 and q=2 reveal the surface pinning mechanism and p=1 and q=2 definethe point pinning mechanism. In order to shed light on the geometry of pinning center in these samples, the normalized pinning force is fitted here using the following equation,

$$f(h)= a\, h^{0.5}\, (1-h)^2+bh\, (1-h)^2 \tag{4}$$

where*a* and *b* are the fitting parameters. The normalized F_p curves are well fitted with eq. (4) as shown in Fig. 3 (*b*). The fitting parameters indicates the surface pinning dominates over the point pinning mechanism.The V impurities act here as point pinning centers. Dew Hughes also proposed that h_{max} =0.33 and 0.2 correspond to the point core pinning and surface pinning, respectively. Thus, h_{max} =0.2 in the $V_{0.001}NbSe_2$ indicates toward the surface core pinning mechanism as the dominating pinning centers. There is also a clear deviation of f_p vs h curves from the fitted plot at higher magnetic fields, which refers the onset of the flux creep phenomenon.

CONCLUSION

The pinning mechanism and the $J_c$characteristic are investigated intensely by studying the magnetization properties of $NbSe_2$ single crystal. V atom depresses the superconductivity but J_c is improved at low magnetic field due to the point pinning centers. The maximum of the reduced field (h_{max}) is observed at 0.2, indicating the surface pinning mechanism as dominating one.Both surface and point pinning take participate to the pinning mechanismof$V_{0.001}NbSe_2$.

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