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Pinning regimes in the vortex solid and crossover between them in single crystals of $2H\text{-}NbSe_2$

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Abstract

We report on the ac susceptibility and the dc magnetization response measurements in the $B_{dc}||ab$ orientation, in weakly pinned single crystals of $2H\text{-}NbSe_2$. We have found evidence for a crossover-like feature between different pinning regimes in the vortex solid that is not associated with the peak effect phenomenon. Instead this crossover feature is associated with novel history dependent response. Such behavior is contrary to a theoretically proposed scenario that the crossover between weak to strong pinning regimes in the vortex state is associated with the peak effect phenomenon. In the field (B)–temperature (T) phase diagram we trace the crossover boundary between the different pinning regimes in the vortex solid which differentiates its location from that of the peak effect phenomenon in these crystals.

Keywords: Superconductivity; $2H\text{-}NbSe_2$; Vortex pinning; Crossover in pinning regimes

1. Introduction

The perennial tussle between elasticity of the vortex lattice and pinning produces different phases of vortex matter [1] in superconductors. Understanding the effective pinning strength in the different phases of vortex matter is a fundamental as well as technologically relevant issue. In recent times a theory [2] analyzing the '*crossover*' between two distinct pinning strength regimes, viz., the weakly collective [3] and the strong pinning regime [4], in the vortex matter has been presented. The theory [2] proposes that the ubiquitous peak effect phenomenon [5], which is an order–disorder transition [5] in the vortex state, is coincident with the crossover in pinning strength. In this paper we report our experimental results on the search for the crossover in pinning strength and its relation to the peak effect phenomenon.

2. Measurements and discussion

We have measured, using a commercial SQUID and VSM, the ac and dc magnetization response in different single crystals of $2H\text{-}NbSe_2$ (which we label as crystals #1 and #2). Both the crystals possess very weak pinning ($J_c \sim 500$ A/cm^2 at 100 G of dc field) and have average dimensions of $1.5 \times 1.5 \times 0.1$ mm^3 with $T_c(0) \approx 7.2$ K and $T_c(0) \approx 7.1$ K for crystals #1 and #2, respectively. To minimize demagnetization effects we have performed the measurements in $B_{dc}||ab$ orientation. We investigate the behavior of the dissipation (χ'') response in the superconductor via ac susceptibility measurement. In Fig. 1 we identify three distinct regions in the $\chi''(T)$ behavior. In region 1, the high dissipation response can be understood on the basis of the critical state model viz., the complete penetration of h_{ac} to the sample center (screening currents induced by $h_{ac} > J_c(T)$). The high dissipation regime should have continued to higher T, however, in the cross shaded region 2, we observe a substantial drop in the χ'' response. The cross shaded region 2, where the dissipation response drops substantially is bounded within two arrows, with the onset

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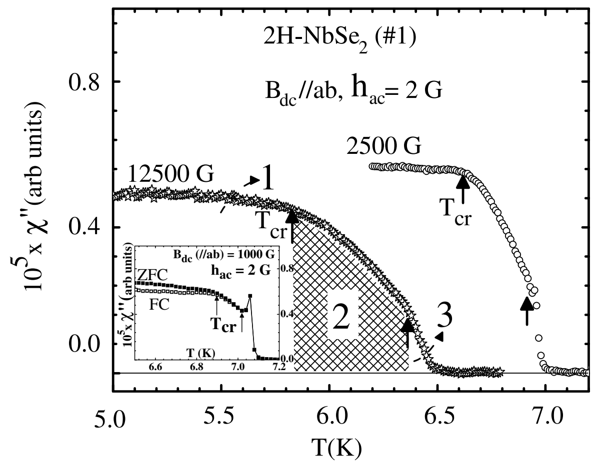

Fig. 1. $\chi''(T)$ response at different magnetic fields. Inset shows the history dependence in $\chi''(T)$ response at 1000 G across T_{cr}.

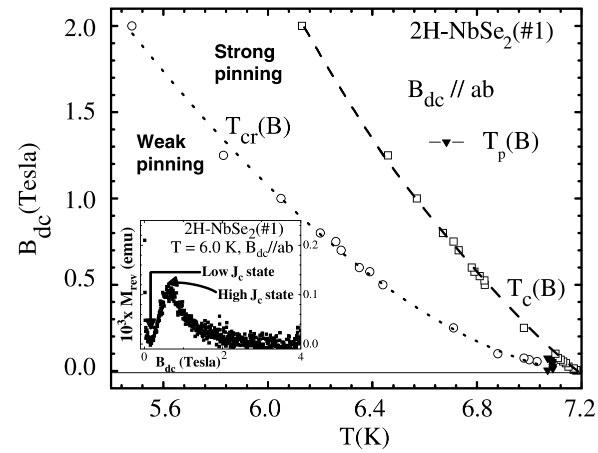

Fig. 2. B–T phase diagram demarcating weak and strong pinning crossover boundary. Inset shows the novel history dependent magnetization response in M_{rev} across the pinning crossover.

position being marked with an arrow labeled as T_{cr}. The nomenclature for T_{cr} will become clear in subsequent discussions. Via in phase ac susceptibility (χ') measurements in these crystals, we have ascertained that the peak effect phenomenon occurs in these samples only below 1000 G and well above T_{cr}. In the region 3, we observe the χ'' response tends to increase (onset of reversibility) before collapsing to zero ($T_c(B)$). Inset of Fig. 1, also shows that, the state of vortex matter quenched from above T_{cr} viz., FC state, exhibits lower dissipation (more strongly pinned) in comparison to the zero field cooled (ZFC) state, implying a strong pinning regime above T_{cr}. (We have confirmed all the above behavior in crystal #2, data not shown here.)

In the B–T phase diagram of Fig. 2 we show the location of $T_{cr}(B)$, the $T_p(B)$ line which shows the location of the peak effect phenomenon and $T_c(B)$ line which demarcates the superconducting to normal boundary. The $T_{cr}(B)$ line denotes the crossover boundary between weak and strong pinning, across which the dissipation (χ'') response drops rapidly (viz., region 2 in Fig. 1). Based on the requirement that strong pinning regime appears when the pinning energy dominates over the elastic energy of the vortex lattice, G. Blatter et al. [2] proposed the relationship, pinning force (f_p) $\sim$ Labusch force (f_{Lab}) $= (\varepsilon_0\xi/a_0)$, where $\varepsilon_0 = (\phi_0/4\pi\lambda)^2$ is the energy scale for the vortex line tension, ξ is the coherence length, ϕ_0 is the flux quantum associated with a vortex, λ is the penetration depth and a_0 is the inter vortex spacing ($a_0 \propto B^{0.5}$). The above relation is best satisfied for a situation pertaining to a softening of the elastic moduli of the vortex lattice. At the crossover in pinning we have from the above criterion, $a_0 \approx \varepsilon_0\xi f_p^{-1}$. At $B = B_{cr}$ and far away from T_c, if we use a temperature dependence of the type $f_p \sim f_{p0}(1-t)^{\beta}$, where $t = T/T_c(0)$ and $\beta > 0$, then we obtain a relation $B_{cr}(T) \propto (1-t)^{2\beta}$. Using the form derived for $B_{cr}(T)$, we obtain a good fit to the data (cf. dotted line in Fig. 2 through the $T_{cr}(B)$ data) with $2\beta \sim 1.66 \pm 0.03$. Across the weak to strong pinning crossover (viz., $B_{cr}(T)$, equivalent to $T_{cr}(B)$) line we report anomalous history dependent behavior. We observed a bump-like feature on the reverse leg of the magnetization hysteresis loop (M_{rev}) at fixed T (cf. inset of Fig. 2). It should be noted that this bump-like feature is absent on the forward leg of the hysteresis loop [6]. This anomalous history dependence in the magnetization, we believe, is associated with the crossover in pinning. Upon reversing the field from above B_{cr}, there is a quenching of the strongly pinned state with high J_c down to low fields. Upon further reduction in field the vortex state transforms into a low pinning state with low J_c across the peak of the bump in M_{rev} (as shown in the inset of Fig. 2).

In conclusion we have observed a crossover in pinning in the static vortex state which occurs perhaps due to softening of the elastic moduli of the vortex lattice well prior to the peak effect [6]. Across the crossover regime we observe interesting history dependent features. We have also derived the curvature of the pinning strength crossover boundary.

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