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Thermodynamic Evidence for Reentrant Peak Effect in a Clean Single Crystal of 2H-$NbSe_2$ and the Effect of Disorder and Thermomagnetic History on it

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New results in 2H-$NbSe_2$ system confirm the thermodynamic nature of reentrant characteristic of PE curve in very clean samples and show that disorder shrinks the (H,T) region of vortex solid phase. All thermomagnetic history effects cease at a Peak Effect boundary which we identify with onset of pinned vortex liquid state.

Nelson [1] had proposed existence of reentrant characteristic (i.e., turnaround) in the melting curve of an ideal flux line lattice (FLL). The samples, howsoever pure, have residual disorder (pins) and depinning of FLL in them takes place in the same region of (H,T) space, where melting of FLL is expected. In a weakly pinned system, an anomalous peak in J_c (i.e., peak effect (PE)) is observed at the edge of depinning transformation. Ghosh *et al* [2] discovered that in a clean crystal of 2H-$NbSe_2$, PE curve determined from in-phase ac susceptibility (χ') data has a reentrant characteristic at H < 150 Oe. The broadening and ultimate disappearance of PE at lower fields (H < 50 Oe) was argued [2] to be a consequence of crossover to a disordered glassy state. In order to further explore the correspondence between PE and collapse of elastic moduli of FLL at the melting transition, it is useful (i) to confirm the reentrant characteristic of PE via thermodynamic measurements and (ii) to investigate the effect of disorder and thermomagnetic history on it. We have done these via measurements in different crystals, viz., those of Ghosh *et al* [2, 3] and Henderson *et al* [4].

The ac susceptibility measurements are not considered strictly thermodynamic in nature, therefore, we examined the reentrant characteristic of PE curve in the clean crystals [2, 3] of 2H-$NbSe_2$ via checking its dependence on the amplitude of ac field and via identification of fingerprints of double crossover of reentrant PE curve in isothermal dc magnetisation hysteresis data. We find that the PE temperatures are indeed independent of amplitude of ac field at different dc fields in all the crystals we examined (data not shown here). This suggests that PE curve (inclusive of its reentrant characteristic) in a given crystal would not undergo any significant change in a thermodynamic measurement. In one of the crystals which showed reentrant behaviour, we recorded dc magnetisation hysteresis loops at close temperature intervals near the turnaround of PE curve. From these data, one could compute the pinning force vs H at different T. These curves have a double hump character. At a given T, the hump at higher H identifies PE on the upper branch of PE curve, whereas occurrence of PE on the lower branch can be confirmed by location of (lower) field value at which pinning force at a given T exceeds that at a neighbouring lower temperature value (see Fig.3 of [5]).

Henderson *et al* [4] recently reported metastability and history dependence in transport $J_c(H,T)$ in a doped crystal of 2H-$NbSe_2$. In Fig.1 we show $\chi'(T)$ data at 5 kOe (|| c) in a similar crystal of 2H-$NbSe_2$ for both zero field cooled (ZFC) and FC states. In ZFC state, a sharp drop in $\chi'(T)$ data is observed at the onset of PE (marked T_m), followed by another sharp drop at T_p, after which χ' rises rapidly. In FC case, χ'

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is more diamagnetic well below PE region thereby confirming [4] more strongly pinned nature of the FC state. Significantly, thermomagnetic history effects disappear at T_p, where FC and ZFC curves merge.

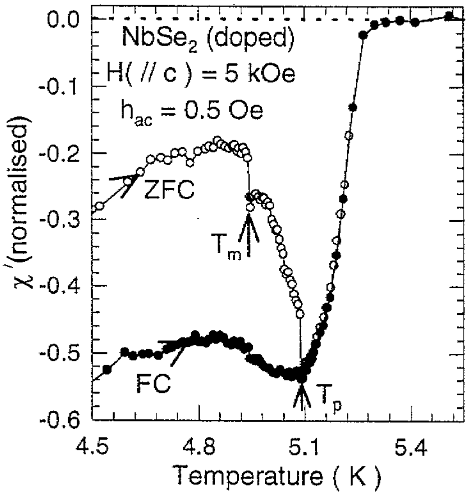

Figure 1: $\chi'(T)$ in doped 2H-$NbSe_2$ at 5 kOe for two states with different magnetic histories.

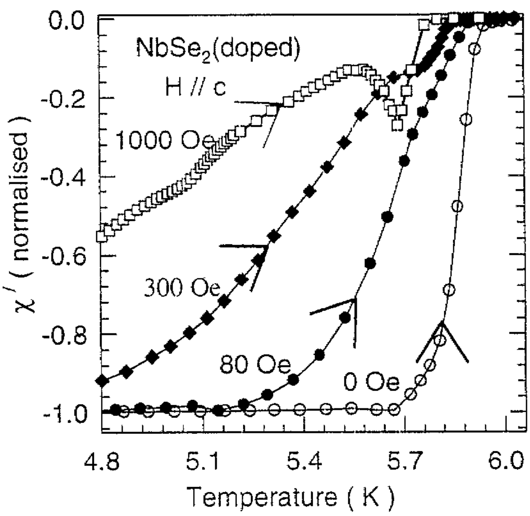

Figure 2: $\chi'(T)$ in 2H-$NbSe_2$ at different H.

Weakly pinned ZFC state exhibits two step structure from T_m to T_p for $H > 1$kOe. Below about 1 kOe, the said structure is unresolved and the depth of anomalous dip in $\chi'(T)$ becomes progressively shallower such that PE is unrecognizable below about 300 Oe (see Fig.2). In the doped 2H-$NbSe_2$, $T_p(H)$ monotonically increases as H decreases down to 300 Oe.

Fig. 3 summarizes the (H,T) phase diagram in the doped crystal obtained from present ac and dc

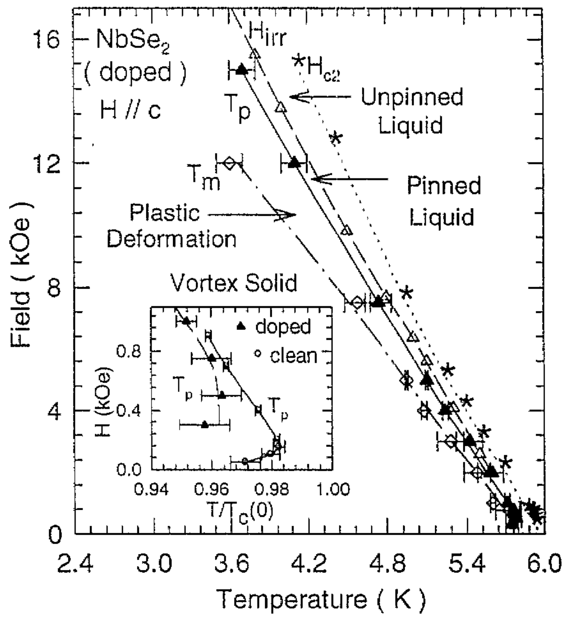

Figure 3: (H,T) diagram in doped 2H-$NbSe_2$ for H||c. Inset shows a comparision of PE (T_p) curves in a clean and a doped samples at low H where reentrant characteristic surfaces in former.

magnetization data and the earlier works of Bhattacharya *et al* [6]. The inset of Fig.3 shows a comparison of PE curves in the doped and clean samples. It is apparent that role of disorder is to shrink the vortex solid phase for both upper and lower branches of PE curve. Increased disorder presumably reduces the correlation length(s) of vortex solid which can therefore melt with weaker thermal fluctuations. The irreversibility line $H_{irr}(T)$ lies above the $T_p(H)$ line where thermomagnetic history effects disappear in $\chi'(T)$ data. Considering that field cooling across $T_p(H)$ creates strongly pinned (more disordered) state, we believe that FC state well below $T_m(H)$ is like a supercooled liquid or glass.

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