# Vortex matter in NbN/AlN superconducting multilayers

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**Abstract**

The vortex matter (VM) in NbN/AlN multilayers (ML) is investigated by transport measurements in fields applied parallel and perpendicular to the layers. Similarly to HTS, the irreversibility line (IL) shifts to lower temperatures with increasing anisotropy. The resistivity of the higher anisotropy ML scales with the normal component of the field, suggesting the presence of a 2D VM above the IL. The activation energy of the less anisotropic sample scales with the number of the superconducting layers, in agreement with 3D VM. The resitivity and IV characteristic are compared with the Bose-glass theory.

*Key words:* multilayer; vortex matter; irreversibility line

The vortex matter in high-$T_c$ superconductors (HTS) is subject to the competing roles of dimensionality, thermal fluctuations, and quenched disorder [1]. Due to the interplay of these physical parameters and to their complex crystal chemistry, the nature of the vortex matter in HTS remains incompletely understood. One way to address this problem is to use artificial low-$T_c$ superconducting multilayers as a model system for HTS. The advantage of this method is that one parameter, namely the anisotropy, can be systematically and independently controlled by changing the thickness of the layers.

In this work, we report studies of the in-plane properties of low-$T_c$ superconducting NbN/AlN multilayers. These systems are ideal for investigating the role of anisotropy in disordered layered superconductors because of their strong pinning properties [2]. Consequently, in contrast to the previously studied weak pinning low-$T_c$ multilayers [3] and HTS, the effects of thermal depinning, which can make the melting and decoupling transitions unobservable, are reduced.

High quality NbN/AlN multilayers were fabricated using reactive dc-magnetron sputter deposition as described elsewhere [4]. The multilayers are referred to as X/Y, where X and Y respectively represents the NbN and AlN layer thicknesses, in nm. Each multilayer has an initial NbN layer in contact with the substrate, followed by 10 AlN/NbN bilayers. Samples were deposited onto silica substrates. The films were patterned into the usual four-point configuration in order to measure the in-plane resistance. Tracks were 500 $\mu$m $\times$ 50 $\mu$m. The contact pads were made using conductive silver paint. Resistance was measured as a function of temperature in fields up to 7 Tesla applied parallel or perpendicular to the layers. The orientation of the sample can be controlled to better than $0.1^o$. An ac current source was used at a frequency of 72 Hz and the voltage measured with lock-in amplifiers.

The coherence lengths along and across the layers, and the anisotropy ratio of the samples are obtained from an analysis of the upper critical field for perpendicular and parallel orientations of magnetic field, as reported in reference [2]. The irreversibility lines, defined close to the limit of the sensitivity of the measured resistivity, are found to shift to lower temperatures with increasing anisotropy of the multilayers [2]. To study the effects of dimensionality, thermal and quenched disorders, the angular dependence of the resistivity above

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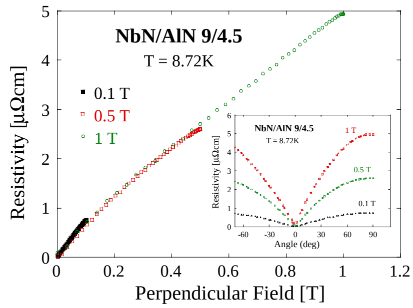


Fig. 1. The resistivity of sample 9/4.5 as a function of the angle $\theta$ of the magnetic field B with respect to film surface for B equal to 0.1, 0.5 and 1T (inset). These curves collapse into one single curve when plotted against the perpendicular field component $B\sin\theta$.

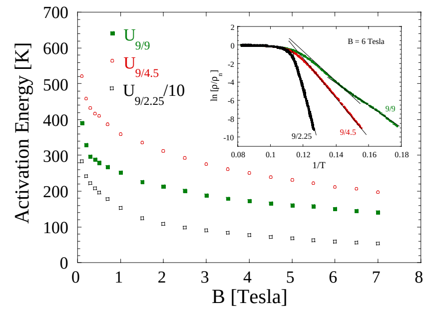


Fig. 2. Activation energy as a function of applied magnetic field. The activation energy for sample 9/2.25 is divided by the number of the superconducting layers (11).The inset shows normalised resistivity of the samples as a function of 1/T plotted in Arrhenius fashion for an applied field of 6 T. The lines are linear fits.

the irreversibility line, activation energies, and Bose-glass scaling of the resistivity and current-voltage characteristics are investigated.

Figure 1 shows the resistivity versus angle for sample 9/4.5 for applied fields of 0.1, 0.5 and 1 T. A replot of the same data as a function of the normal component of the magnetic field makes these curves to collapse into one single curve. Same behaviour is observed for sample 9/9. Thus the vortices are two dimensional, i.e. 2D pancakes, in these samples. This is in agreement with the decoupling field $B_{2D}$ estimations (i.e. the field needed to decouple the pancake vortices across the layers) for samples 9/4.5 and 9/9 [2]. Similar kind of data was observed in BSCCO single crystals [5].

The pinning energy $U_p$, which opposes the thermal activation motion of the vortices, can be estimated from plotting $\ln[\rho]$ versus $1/T$ in different magnetic fields. Inset of Figure 2 shows these Arrhenius graphs at 6 Tesla for samples 9/2.25, 9/4.5 and 9/9. It is clear that the resistivity is thermally activated, i.e. $\rho \propto \exp -U/kT$ , over several orders of magnitude of the normal state resistivity $\rho_n$. The activation energies versus applied field are shown in the main figure. It is noticed that the activation energy $U$ for sample 9/2.25 is about one order of magnitude larger than that of 9/4.5 and 9/9. However, by dividing $U_{9/2.25}$ by the number of the superconducting layers in the sample, i.e. 11, $U_{9/2.25}/11$ falls within the range of the others. This result suggests that the pancakes are coupled through the layers, and are thermally activated as 3D vortex lines. This is again in agreement with $B_{2D}$ calculation for 9/2.25 [2]. The pinning energy of a vortex pinned along its length is $U_p = B_c{}^2/2\mu_0 \times \xi_{ab}{}^2 d$, where $d$ is the film thickness [6]. Using the values for our samples, we obtain $U_p(0) = 1950$ K for sample 9/2.25, assuming that d=9×11=99 nm. This is in good agreement with the experimental data. It is also noticed that the activation energies of samples 9/4.5 and 9/9 are almost identical. This leads us to conclude that the vortices are 2D in both samples, in agreement with the previous section.

It is well know that NbN is a strong and correlated pinning system (due to columnar grain boundaries) [7]. The resistivity and IV characteristics were compared with the prediction of Bose-glass theory (BG), valid for correlated disorder. However, only the resistivity is found to scale with BG formulas. These results are inconsistent with BG, which is supposed to apply only to 3D vortex matter.

In summary, the vortex state in NbN/AlN multilayers is investigated by transport measurements in fields applied parallel and perpendicular to the layers. The resistivity of the higher anisotropy multilayers scales with the normal component of the field, suggesting the presence of pancake vortices above the irreversibility line. The activation energy of the less anisotropic sample scales with the number of the superconducting layers, in agreement with 3D flux-lines. However, the data is found to be inconsistent with Bose-glass theory predictions.

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