Vortex dynamics in disordered niobium films

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Motivation

Vortex matter in type-II superconductors is one of the most intriguing research topics in superconducting physics. Both the VG phase transition and flux lines creep phenomenon have been widely studied in the past, mostly in high temperature superconductors where thermal fluctuations play a crucial role. Evaluation of these subjects is also very interesting in case of ultrathin conventional SC films which can be useful in many applications. In our work, we study the evolution of vortex matter in ultrathin, polycrystalline niobium films with film thickness ranging between 7.4 and 44 nm, using resistance and current-voltage characteristics measurements. We analyze creep behavior using recent strong pinning theory what provides detailed insight into vortex physics. Our findings reveal the existence of two distinct regimes of vortex pinning. One regime, which is due to spatial variations of the mean free path, occurs in thickest film, and the other regime, due to spatial variations of the superconducting transition temperature, arises in thinner films. According to strong pinning analysis, the temperature dependence of the activation barrier energy (a major parameter for describing thermal creep of the vortex system) does not strictly follow existing theoretical predictions, what calls for more theoretical studies of the subject..

Experimental details

- Ultrathin superconducting niobium Nb films of different thickness were deposited using magnetron sputtering and sandwiched between two silicon wafers for protection against oxidation.
- The films were optically patternened with Hall bar-structure mask by means of photolithographic patterning technique.
- Then, samples were etched using ion beam etching teqnique.
- Electric contacts were attached to the contact pads across the current and voltage channels at the surface using indium solder.
- Transport measurement were performed by a standard four-probe measurement method using a quantum design physical property measurement system (PPMS).

Structural Properties (TEM)

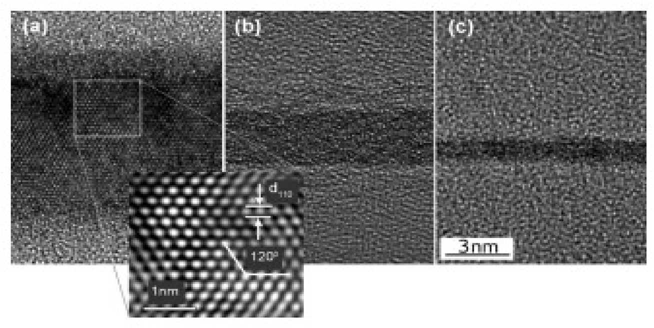

Fig.1 HRTEM images for Si/Nb(d)/Si trilayers, with different Nb thickness.The inset at the bottom shows the enlarged Fourier-filtered part of image (a) indicated by the white square , Ref.[1].

Transport Results

1. Temperature dependence of resistance

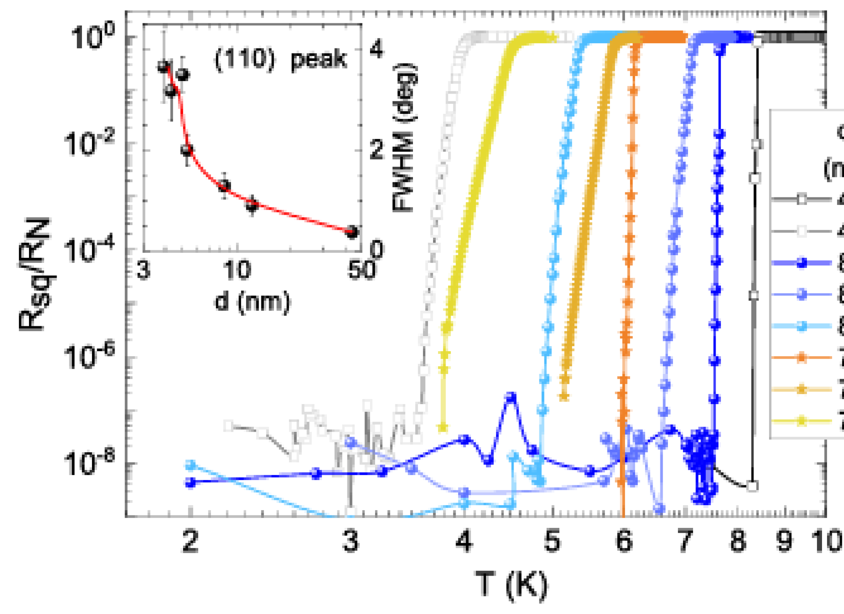

Fig.2 Normalized sheet resistance R_{sq}/R_N versus T on a log-log scale, measured at magnetic field B ranging from 0 to 1.6 Tesla for Nb films with d =7.4, 8.5, and 44 nm. Inset shows d dependence of FWHM for the characteristic (110) peak in the x-ray diffraction spectrum.

Transport Results continue...

2. Current-voltage characteristics (IVCs) and VG transition

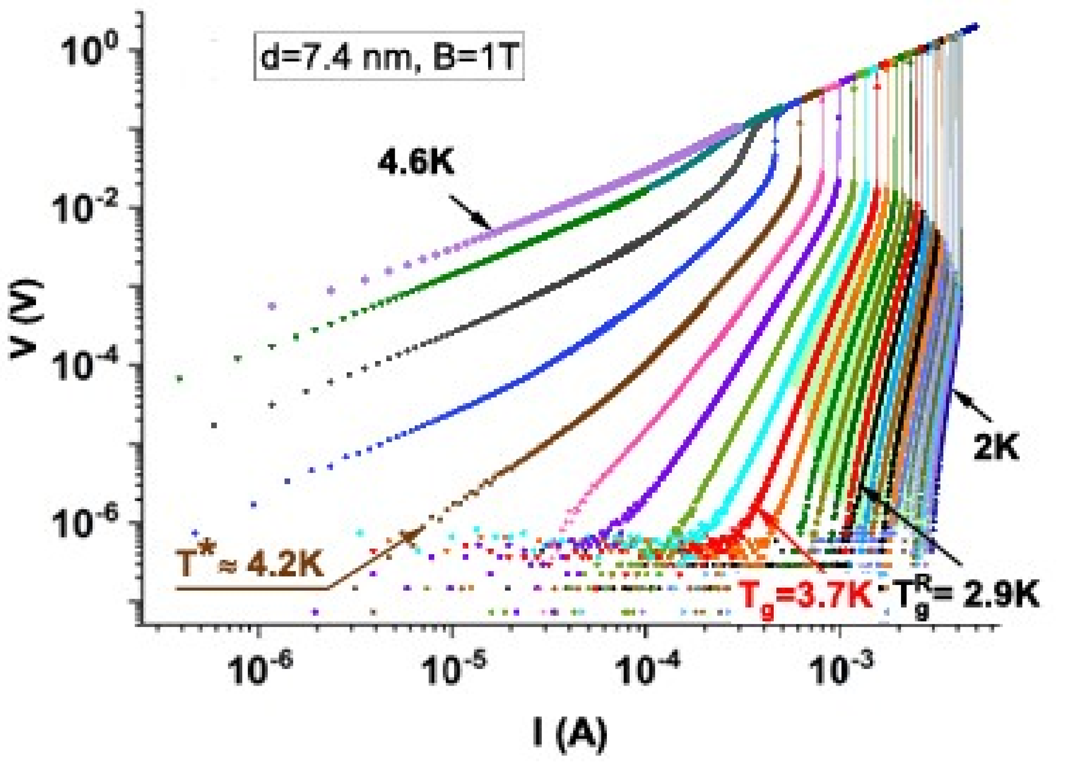

FIG.3 IVCs at variousT and B=1 Tesla for Nb film with thickness d=7.4 nm, measured at T from 2K to 4.6K . The black and red arrows show the vortex glass (VG) phase transition temperatures T_g=2.9 K and T_g=3.7 K determined by resistance and IVCs analysis (See Fig. 4) according to VG theory Ref. [2], respectively. T^* is the temperature above which VG phase is expected to vanish. The light green areas show the regions in which recent strong pinning theory (Ref. [3]) describe the IVC's, as described in view of Fig. 5. This can be an indication that the VG phase transition is affected by thermal creep of vortices.

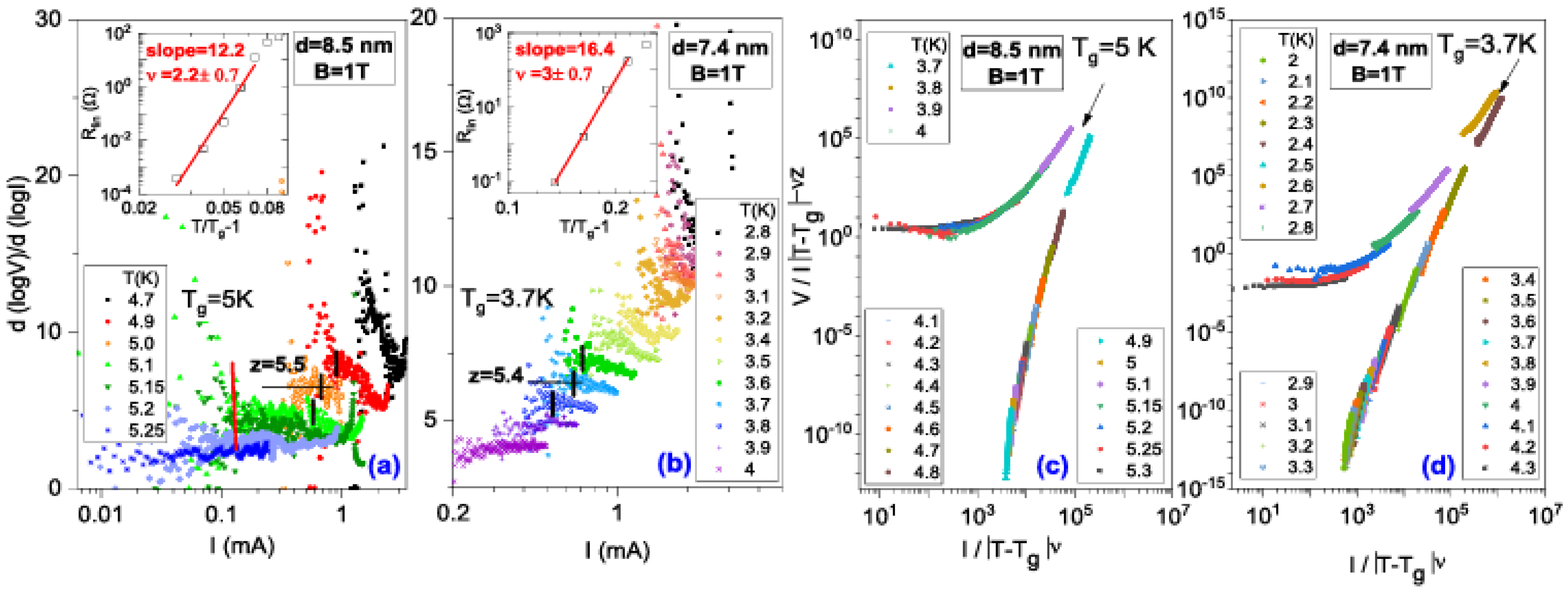

FIG.4 Differential resistance d(logV)/d(logI) versus I for film with d = 8.5 nm (a) and 7.4 nm (b) at the magnetic field of 1 Tesla. The black, horizontal lines indicate data sets at the VG tranistion temperature T_g, the black, vertical lines mark the onsets of creep revealed by strong pinning theory-based analysis, and the red, vertical line in (a) shows the the minimum current above which finite-size effect (due to film inhomogeneity) is negligible. The insets in (a) and (b) show the linear resistance R_{lin} versus $T/T_g - 1$. [(c) and (d)] Quasi-2D VG scaling, according to VG theory, of the I-V curves in the indicated temperature range in the vicinity of T_g demonstrating the two dynamic branches at B = 1 Tesla for d =8.5 nm (c) and 7.4 nm (d). VG theory predicts a rapid vanishing of the linear reistance at T_g in the low current limit . Standard VG transition according to theory is described by the critical behavior exponents (the static exponent ν in the range [1-2] and the dynamic exponent z in the range [4-7]). Our analysis shows results beyond these theoretical limits most likely due to sample inhomogeneity. Thickest film in our study, 44 nm-film, showed results in agreement with theory predictions, indicating true VG transition occuring in the film.

3. I-V characteristics and vortex pinning theory

The main idea of strong pinnig theory, **Ref. [3] & [4]**, is that at finite temperature (i.e., $T>0$), the I-V characteristics of type-II superconductor with strong but small density of pins (point-like defects) are modified due to the presence of thermal fluctuation (i.e., due to vortex thermal creep) leading to the following $V(I)$ dependence of the I-V characteristics with increasing current on the approach to the Flux-flow I-V regime (preceding the abrupt jump to normal state in our films):

$$V = R_{\mathrm{FF}}(I - I_c) + V_c\left[\frac{k_B T}{U_c}\ln\left(\frac{v_{\mathrm{th}}}{v_c}\frac{V_c}{V}\right)\right]^{1/\alpha}.$$

with creep exponent α =3/2 as predicted by theory. R_{FF} is the Flux-Flow motion resistance , I_c is the critical vortex-depinning current and $V_c = R_{FF} I_c$. U_c (the actvation barriere energy) and the vortex velocity ratio v_{th}/v_c are two main characteristic parameters describing creep behavior, extracted from fits of the I-V data to the above equation.

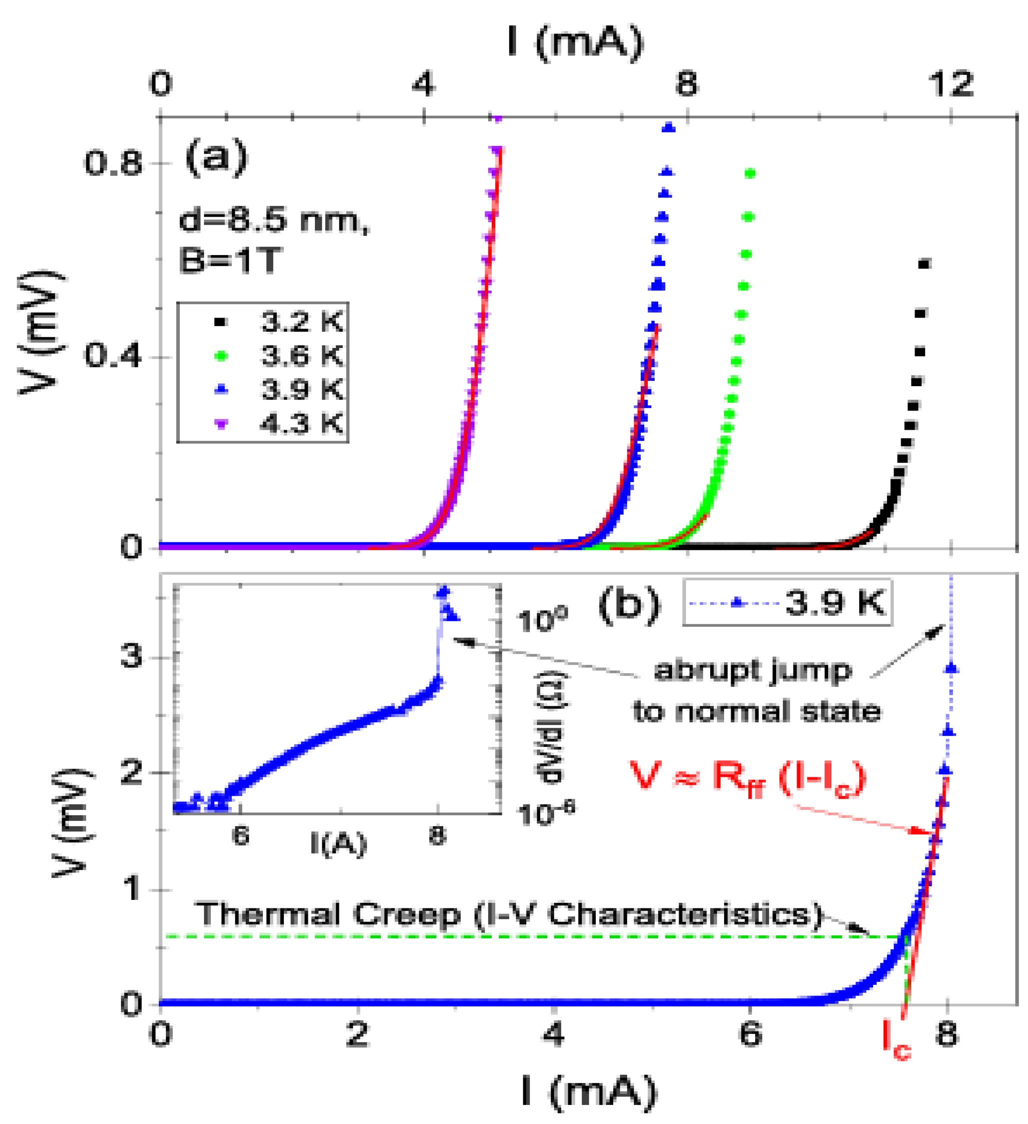

Fig.5 I-V characteristics measured for Nb film with thickness d=8.5 nm at a fixed magnetic field B = 1 Tesla and temperatures T from 3.2 K to 4.3 K. Red lines are fits to the data to the above equation based on the prediction of strong pinning theory (b) Thermal creep and excess (I-V) characteristics for 3.9 K under the same conditions in (a) demonstrating the linear response at large drives preceding the abrupt jump to normal state. Thermal creep is restricted to the confined zone (dashed green rectangle) and the red, straight line defines I_c and R_{FF}. Inset in (b) shows monotonic increase of dV/dI with increasing I.

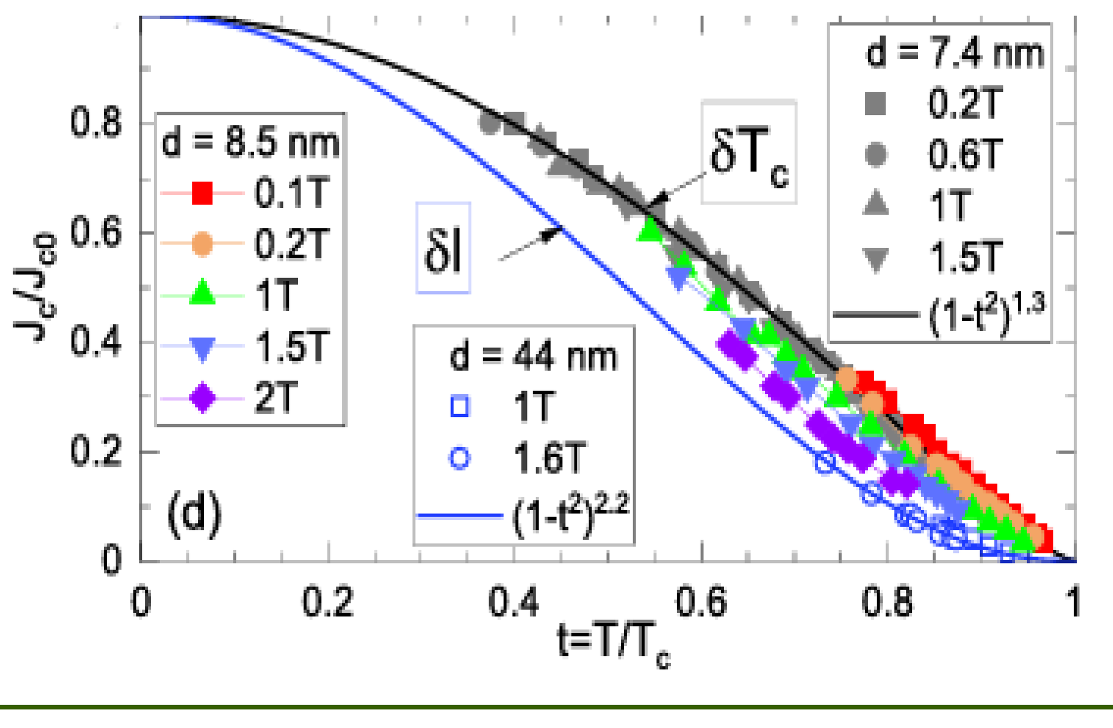

Fig.6 Critical (de-pinning) current density ratio J_c/J_{c0} versus reduced temperature $t = T/T_c$ for Nb films with different thickness d and magnetic fields. J_{c0} is the critical current density at zero temperature and T_c is the mean field tranition temperature. Continuous lines display the dependence on t with exponents equal to 2.2 (blue line) and 1.3 (black line), characteristic for δl (due to spatial variations in the mean free path l) and δT_c (due to spatial variations in the mean field tempearture T_c)pinning, respectively. The δT_c is characterized by faster growth of the J_c/J_{c0} below T/T_c= 1.

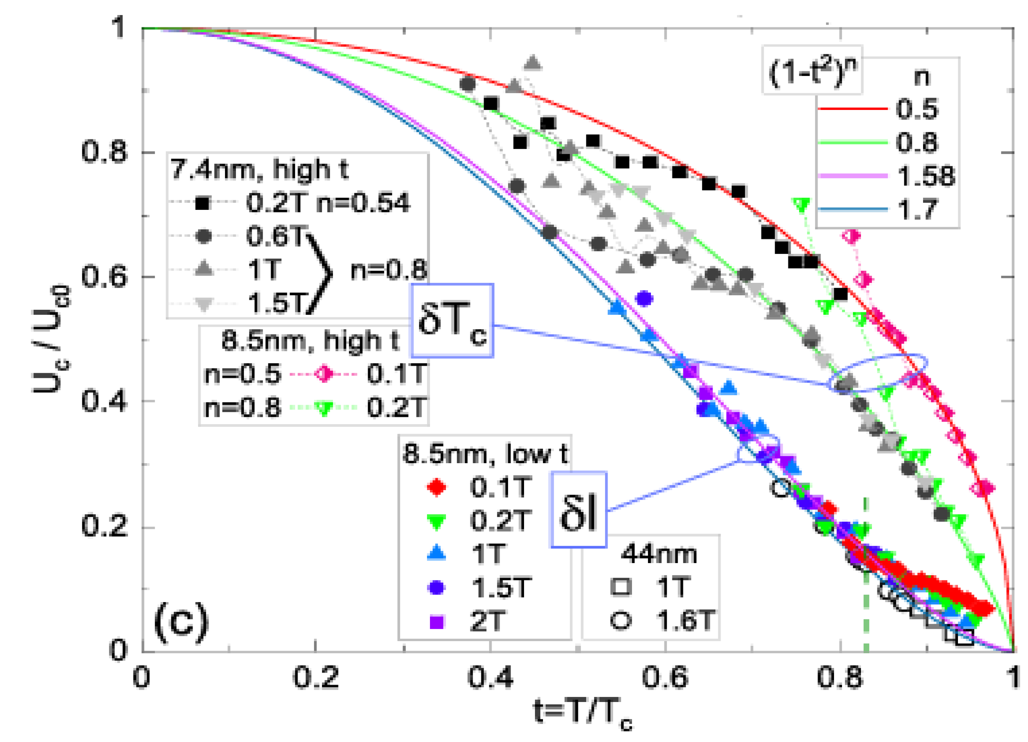

Fig.7 U_c/U_{c0} versus t for d = 44 nm film (open points), 8.5 nm-film (low-t region: solid color points; high-t region: half-filled points), and 7.4 nm-film (gray-black solid points) for various magnetic fields. U_{c0} is the zero temperature-activation barrier energy. Continuous lines show function $(1-t^2)^n$,with n = 0.5 (red), 0.8 (green), 1.58 (purple), and 1.7 (blue). Curves which follow the behavior governed by either the δl or δT_c pinning mechanisms are indicated.

Conclusions

- *Standard scaling laws, are applied to identify the VG transition temperature. While quasi-2D VG transition is confirmed in case of the thickest film (44 nm), the presence of creep in thinner films (8.5 nm and 7.4 nm) complicates this identification, resulting in large uncertainty in the putative VG transition temperature and scaling exponents.*
- *The creep regime is subsequently analyzed using recent strong pinning theory . The T dependence of the activation energy for vortex pinning U_c, extracted from this analysis, reveals two quite distinct regimes of pinning, which we propose to identify with δl and δT_c type of pinning. The first of these regimes, δl, with slow increase of the U_c/U_{c0} below T/T_c = 1, is observed in thickest film. As the film thickness decreases, the second regime (δT_c) appears, characterized by faster growth of the U_c/U_{c0} below T/T_c = 1.We link these two different regimes with the grain boundaries existing in the films, which in thicker films produces carrier scattering, while in thinner films it gradually evolves into amorphous inclusions, leading to local depression of the T_c . Experimentally obtained T dependence of the U_c does not strictly follow existing theoretical predictions, which calls for more theoretical studies of the subject.*

References

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