Vortex-glass transition in superconducting Nb/Cu superlattices

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Abstract

Nb/Cu superconducting superlattices have been fabricated by dc magnetron sputtering. This system shows a vortex glass transition with critical exponents similar to high temperatures superconductors exponents. The transition dymensionality is governed by the superconducting coupling regime. The vortex glass transition shows a pure two dimensional behavior in decoupled superlattices and a quasi-two dimensional behavior in the superlattice coupling regime.
Since the discovery of High-Tc Superconductors (HTCS) vortex matter Physics has called
the attention of researchers in many fields, for example the vortex state provides a perfect
realm to study properties of liquid, crystalline and glassy phases. A plethora of different
phases is observed in HTCS,\(^1\) induced by the interplay of vortex-vortex interaction, thermal
fluctuations, different kinds of disorder, anisotropy, dimensional effects, etc.\(^2\) But the most
remarkable characteristic of the phase diagram is the existence of two different states: a
magnetically irreversible zero-resistance state, and a reversible state with dissipative trans-
port properties. In the absence of disorder, the former corresponds to a vortex-solid phase
with topological order, and the latter to a vortex-liquid phase, both of them separated by
a first-order melting transition. In the presence of strong quenched disorder, however, the
topological order of the vortex-lattice is lost, and the zero-resistance state corresponds to a
vortex-glass (VG), and the transition into the dissipative liquid state becomes a continuous
second-order phase transition.\(^3,4\)

After the rich phenomenology of vortex-phases came out with HTSC, Low-Tc Super-
conductors (LTCS) have been seldom revisited to check the possible application of HTCS
paradigms. The existence of a melting transition in Nb single crystals has been reported,\(^5\)−\(^7\)
but in the case of Nb thin films the existence of a glass transition remains controversial.\(^8,9\)

In this paper, we report on the observation of VG transitions in sputtered Nb/Cu low-
temperature superconducting superlattices. This system has been chosen mainly because
the presence of quenched disorder is similar to the one existing in sputtered Nb thin films
and because the artificially layered structure allows tailoring the anisotropy of the system
in a controllable fashion. In particular, the coupling of Nb layers through the Cu spacer can
be easily tuned.\(^10\) This has allowed us studying the dimensionality of the VG transition in
several different coupling regimes.

The VG transition has been investigated by measuring the electrical transport properties
in the mixed state of superlattices, in particular isothermal I-V characteristics in applied
magnetic fields. These characteristics have been collapsed, according to the scaling rules
proposed in the VG theory, in terms of critical exponents.\(^4\) Besides, the consistency of the
scaling analysis has been checked with some independent criterion, as recently proposed.\(^11\)
Moreover, we have found a dimensional crossover for a quasi-2D into a pure 2D VG transi-
tion, governed by the coupling of Nb layers in the superlattice.

Nb/Cu superlattices were grown on Si (100) substrates using \(dc\) magnetron sputtering at
room temperature in Ar atmosphere. Several series of superlattices Cu$_d$[Nb$_d$/Cu$_d$]$_N$ were grown with N being the number of bilayers. Structural characterization was made by X-Ray diffraction (XRD). The structural properties of Nb/Cu superlattices have been investigated early by other authors.\textsuperscript{12} In our multilayers XRD shows that Cu layers are oriented (111), while Nb ones are (110). We have refined the spectra using SUPREX program.\textsuperscript{13} From refinements the modulation length $\Lambda$, as well as several sources of disorder at the interfaces, like roughness or interdiffusion have been obtained. The samples studied here did not present interdiffusion, and have moderate roughness at the interfaces, ranging from 0.2 to 0.6 nm, being larger when the Nb layers are thicker. The samples were lithographed by wet etching into a measuring bridge 1 mm long and 100 $\mu$m wide for magnetotransport experiments with standard four-probe configuration.

Magnetotransport experiments were made in a liquid He cryostat provided with a superconducting solenoid. The superconducting coherence length $\xi_S$ as a function of temperature was calculated from measured upper critical fields $H_{c2}(T)$, obtained from magnetoresistance measurements at constant fixed temperatures $R(H)_T$. The in-plane coherence length $\xi_{S\parallel}$ (parallel to Nb/Cu interfaces) and the perpendicular one $\xi_{S\perp}$ have been calculated by using

$$\xi_{S\parallel}(T) = \left[ \phi_0 / 2\pi H_{c2\parallel}(T) \right]^{1/2}$$

and

$$\xi_{S\perp}(T) = \left[ \phi_0 H_{c2\perp}(T) / 2\pi \left( H_{c2\parallel}(T) \right)^2 \right]^{1/2}$$

respectively.\textsuperscript{10} As an example, the observed behavior for sample Nb$_{13nm}$/Cu$_{27nm}$ is shown in Fig. 1. The perpendicular critical field displays typical linear dependence on temperature $H_{c2\perp}(T) \propto (1-T/T_c)$ (see Fig. 1 inset). However, the parallel critical field shows up a crossover from linear dependence $H_{c2\parallel}(T) \propto (1-T/T_c)$ at high enough temperatures to square-root $H_{c2\parallel}(T) \propto (1-T/T_c)^{1/2}$ at lower temperatures. A dimensional crossover takes place when the perpendicular coherence length $\xi_{S\perp}(T)$ reaches a value of the order of $d_{Cu}$ (thickness of Cu in the superlattice). Below the crossover temperature, $T_{2D} \approx 0.5T_c$, the Nb layers are decoupled, showing up two-dimensional (2D) behavior.\textsuperscript{10} In other cases, as for instance Nb$_{3.4nm}$/Cu$_{2.4nm}$, $\xi_{S\perp}(T) > d_{Cu}$ at all temperatures, and thus superlattices are always in the coupled regime. We have measured I-V characteristics with magnetic field $H$ applied perpendicular to Nb/Cu layers. For each fixed value of applied field $H$, we measured a set (\~{}20) of isothermal I-V curves at decreasing temperatures, as those shown in Fig. 2 and Fig. 3. For all measured samples and applied magnetic fields the results are similar. The isotherm at the highest temperature displays linear behavior at all current levels, with Ohmic resistance $R = V/I \approx R_n$, at this temperature $H = H_{c2\perp}$. For characteristics at slightly lower temperatures, the
Ohmic response is observed only up to a threshold current level \( I_{nl} \), above which the curves are non-linear. The Ohmic resistance in the low-current limit \( \lim_{I \to 0} V/I \neq 0 \) is smaller as the temperature decreases, as well as the onset of non-linear response \( I_{nl} \) shifts to lower current levels as temperature is reduced. Below a given temperature, isotherms become highly non-linear within the whole experimental window, and isotherms show up negative curvature in the low-current limit yielding zero resistance \( \lim_{I \to 0} V/I = 0 \).

The phenomenology described above suggests the existence of a continuous transition from a truly superconducting phase with zero-resistance (VG) to a vortex-liquid dissipative phase closer to \( H_{c2} \). As proposed by Fisher-Fisher-Huse,\(^4\) and shown experimentally for many HCTS systems, this glass-transition is a second order transition and the physical quantities must scale with the VG correlation length \( \xi_{VG} \) and the characteristic relaxation time \( \tau \). These two magnitudes diverge as temperature approaches the glass transition temperature \( T_g \), following \( \xi_{VG} \propto (T - T_g)^{-\nu} \) and \( \tau \propto (T - T_g)^{-\nu z} \), with \( z \) and \( \nu \) the dynamic and static critical exponents. Scaling laws have been proposed to collapse onto a single master curve all I-V (or \( E - J \)) isotherms within the critical region, by means of the relation\(^4\)

\[
E \xi_{VG} \tau \approx J \xi_{VG}^{D-1} \zeta_{\pm} \left( J \phi_0 \xi_{VG}^{D-1} / k_B T \right) \quad [\text{Eq. 1}]
\]

where \( D \) is the dimensionality of the glass transition, \( \zeta_{\pm} \) is a universal scaling function above \( (\zeta_+ \text{ or below}) \ T_g \), \( \phi_0 \) the flux quantum, and \( k_B \) the Boltzmann constant. We have applied this scaling analysis to I-V characteristics measured within the experimental window \( 10^{-8} V < V < 10^{-4} V \) and \( I < 10^{-3} \) A. The voltage cut-off is \( 10^{-4} \) V, since above this limit all characteristics deviate towards Ohmic behavior. Therefore, the scaling analysis is not longer valid.\(^{11,14,15}\) This can be seen in the inset of Fig. 2 (b), where the slopes of isotherms [as plotted in Fig 2 (a)], \( d(\log V)/d(\log I) \), are displayed.

For Nb/Cu superlattices whose Nb layers are coupled, the scaling analysis yields very good collapses, as the one shown in Fig. 2 (b). Critical exponents were around \( z \approx 4 \) and \( \nu \approx 1.8 \), and the dimensionality was always \( D=2 \). These parameters are not magnetic field or sample dependent. The values of the critical exponents \( z \) and \( \nu \) are within the range 4-6 predicted by theory.\(^4\) Moreover, we want to underline that the obtained values are very similar to that observed for quasi-2D VG transitions in HTCS.\(^{16,17}\) For instance, the same values of the critical exponents were found in \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \) thin films.\(^{17}\) This fact stresses the universality of the VG transition, earlier suggested.\(^{17,18}\)

Recently, Strachan et al.\(^{11}\) have proved that the scaling method used is misleading, even in
the case of universal critical exponents with adequate values were found. They have argued that experimental limitations related to voltage sensitivity floor might allow achieving good collapses with arbitrary values of some of the scaling parameters, as for instance \( T_g \). Thus, Strachan et al.\(^{11}\) have proposed that a new criterion to unambiguously determine \( T_g \) should be met: isotherms above and below \( T_g \), but with equal \(|(T - T_g)/T_g|\), must have opposite concavities at the same applied current level. In our Nb/Cu superlattices this criterion was checked for every set of I-V curves that had been successfully scaled. In the inset of Fig 2 (b), the derivatives \( d(\log V)/d(\log I) \) of the I-V isotherms shown in Fig. 2 (b) are plotted. From the scaling procedure we obtained \( T_g=3.994 \) K for this set of isotherms. As can be seen in that Figure, the isotherms above and below this temperature (marked with an arrow in Fig. 2(d)) met the criterion. At the lowest current levels, upward and downward isotherms are observed at similar distance \(|(T - T_g)/T_g|\) below and above \( T_g \). Furthermore the VG transitions theory tells that the isotherm at \( T_g \) fulfills the relation \( E \propto J^{\alpha+1} \) in the low current limit, where \( \alpha = (z+2-D)/(D-1) \).\(^4\) Therefore, using the values obtained in our scaling, \( D=2 \) and \( z \approx 4 \), the expected slope of the critical isotherm would be \( \alpha + 1 \approx 5 \). Although the critical isotherm is not in the set of measured characteristics, we can give lower and upper limits to its slope from those of the isotherms just above and just below \( T_g \). In the low current limit (Fig. 2 (b) inset), the first isotherm below \( T_g \) has a slope larger than \(~5\), whilst the first one above \( T_g \) has a slope smaller than \(~4.5\). Thus the critical isotherm in between them should have a slope around \(~4.5-5\), as expected from the independently obtained scaling parameters.

The behavior of superlattices whose Nb layers were decoupled was investigated too. The inset of Fig. 3 (a) shows I-V characteristics of sample Nb\(_{13nm}\)/Cu\(_{27nm}\) in applied magnetic field \( \mu_0 H=0.4 \) T, such that all isotherms, within the critical region, were at temperatures well below \( T= T_{2D} \approx 0.5T_c \) (see Fig. 1). Attempts to use the scaling rule (Eq. 1) did not yield collapses as the ones obtained in the coupled regime. In fact, from the derivatives of I-V curves [Fig. 3 (b)], one can observe some features that rule out the scaling of these isotherms according to a \textit{quasi}-2D or 3D VG transition. On one hand, it is not possible determining a finite \( T_g \) using the criterion outlined above, since two isotherms of opposite concavities at the same current level can not be found. Besides, as can be seen in Fig. 3 (b), a maximum slope a maximum slope of \(~9\) is displayed by the lowest temperature isotherm among those showing up a decreasing slope in the low current limit (marked with an arrow).
The isotherm at $T_g$ should be above this one, and therefore it should have a slope larger
that $\sim 9$. As we said before, in a quasi-2D or 3D VG transition the slope of the critical
isotherm is $\alpha + 1 = (z + 2 - D)/(D - 1) + 1$, which would imply that the critical exponent
$z > 8$ for $D = 2$, or $z > 17$ if $D = 3$. These are very high values of the critical exponents, not
supported by theory. As argued earlier, this strongly suggests that a quasi-2D or 3D
VG transition has to be dismissed. However, a good scaling of the isotherms is achieved by
assuming a different pure 2D VG transition, as first proposed by Dekker et al., and later
found in HTSC systems. In a pure 2D VG transition, the glass transition temperature
$T_g = 0$. Therefore a pure 2D VG phase does not exist at any finite temperature, although
in-plane correlations (2D) develop, diverging as $\xi_{VG} \propto 1/T^\nu'$ when temperature approaches
$T_g = 0$. In this transition, the scaling of the isotherms is achieved by plotting $\rho \exp[(T_0/T)^p]$ vs. $J/T^{1+\nu'}$, where $\rho = E/J$ is the resistivity, $T_0$ is a characteristic temperature, and $p$ and $\nu' = 2$ are characteristic exponents of the pure 2D VG transition. The exponent $p$ is related
to the mechanism of vortex motion: $p \geq 1$ for thermal activation over the relevant energy
barriers, whereas $p \approx 0.7$ is expected in the case of quantum tunneling across them. As can
be seen in Fig. 3 (a), a good collapse has been obtained with parameters $T_0 = 300 \pm 20$ K,
$p = 1.05 \pm 0.02$, and $\nu' = 2$.

Finally, in our experimental situation, a layered superconductor with magnetic field applied
perpendicular to layers, one may distinguish between the in-plane VG correlation length
$\xi_{VG\parallel}$, and the perpendicular one $\xi_{VG\perp}$ (along the vortex line). The quasi-2D character of the
glass transition was explained in high $T_c$ superconductors assuming that anisotropy induces
limited vortex length, that precludes $\xi_{VG\perp}$ to diverge. Thus, when approaching $T_g$, only
$\xi_{VG\parallel}$ diverges up to the macroscopic size of the sample, whereas $\xi_{VG\perp}$ would remain finite
with nearly a constant value. This applies to Nb/Cu superlattices in the coupled regime.
Following Yamasaki et al. and Zefrioui et al. we can estimate an upper limit of $\xi_{VG\perp}$ from
I-V characteristics. Isotherms above $T_g$ show up Ohmic behavior at low current level, but
they becomes non-linear above $I_{nl}$. At this current level, the work done by the Lorentz force
to create vortex excitations equals the thermal energy, $J_{nl} \phi_0 \xi_{VG\parallel} \xi_{VG\perp} = k_B T$. We used
the isotherm at the highest temperature within the critical region, in particular the one at
$T = 4.038$ K shown in Fig. 3 (a), for which $J_{nl} \approx 125$ Acm$^{-2}$. The in-plane correlation length
$\xi_{VG\parallel}$ should be larger than the mean inter-vortex distance $a_0 = (\phi_0/\mu_0 H)^{1/2} \approx 130$ nm for
$\mu_0 H = 0.11$ T. In particular we assumed $\xi_{VG\parallel} > 2a_0$, and thus we obtained $\xi_{VG\perp} < 90$ nm.
That is, the correlation length along vortex line is always shorter than sample thickness. However, it may be longer than other relevant characteristic lengths, as the superlattice modulation length $\Lambda=40$ nm and the superconducting coherence length $\xi_{S\perp}(T)\approx 35$ nm. We have estimated the vortex length $l$ in the regime where this superlattice is decoupled, in which we observed a pure 2D VG transition, with the work done by Lorentz force $J_{nl}\phi_0\xi_{VG||}l = k_BT$.\textsuperscript{19} Taking the isotherm at $T=2.150$ K [Fig. 3 (a)], $J_{nl} \approx 80$ Acm$^{-2}$, and $\xi_{VG||}>2a_0 = 150$ nm for $\mu_0H = 0.4$ T, we get $l < 30$ nm. Therefore, the vortex length $l$ is shorter than superlattice modulation length $\Lambda=40$ nm, and cannot be much longer than the coherence length at this $T$, $\xi_{S\perp} \approx 20$ nm. A picture emerges from those estimations, in which coherence length $\xi_{S\perp}$ and sample thickness $d$ are the relevant length scales to which correlation length along vortex line $\xi_{VG\perp}$ has to be compared. The quasi-2D character of the glass transition in the coupled regime develops since $\xi_{VG\perp}$ longer that $\xi_{S\perp}$ is shorter than sample thickness $d$. At lower temperatures, Nb layers are decoupled by Cu ones. Therefore the vortex length $l$ is limited below modulation length $\Lambda$. Because of this, the vortex length $l$ and coherence length $\xi_{S\perp}$ are similar This yields a pure 2D VG transition. This is similar to what is observed in highly anisotropic HTCS, for which pure 2D VG transitions have been observed when vortex length is limited to superconducting coherence length.\textsuperscript{17,20,21}

In summary, we have shown strong evidence of the VG transition in the mixed state of low-temperature superconducting Nb/Cu superlattices. The HTCS analysis applies directly to this system, and the same universality has been observed, in spite of the very small thermal fluctuations of LTCS in comparison with HTCS. Besides, a dimensional crossover from a quasi-2D into a pure 2D VG transition has been observed, which is governed by the ratio of the VG correlation length $\xi_{VG}$ to the superconducting coherence length $\xi_{S}$.

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FIG. 1: Superconducting coherence lengths of sample Cu$_{27}$nm[Nb$_{13}$nm/Cu$_{27}$nm]$_{10}$ as a function on temperature, both parallel $\xi_{S\parallel}(T)$ and perpendicular $\xi_{S\perp}(T)$ to Nb/Cu layers. Inset: Measured parallel (black circles) and perpendicular (open circles) critical fields $H_{c2}$. Solid lines are linear fits $H_{c2\perp}(T) \propto (1-T/T_c)$, while the dashed one is the best fit to $H_{c2\parallel}(T) \propto (1-T/T_c)^{1/2}$.
FIG. 2: (a) I-V isotherms for sample Cu\textsubscript{27nm}[Nb\textsubscript{13nm}/Cu\textsubscript{27nm}]\textsubscript{10} in applied field $\mu_0 H=0.11$ T at temperatures (from left to right) 4.060 K$>T>3.865$ K, separated $\sim$5-15 mK. The dashed line separates isotherms above and below $T_g=3.994$ K. Vertical and horizontal dotted lines delimit the experimental window used for scaling. (b) Scaling of the above isotherms as explained in the text. Inset: Derivatives of the log(I)-log(V) isotherms at temperatures (from bottom to top) 4.060 K$>T>3.908$ K. Black dots are within the experimental window used for scaling. The arrow separates derivatives of isotherms just below and above $T_g$. 
FIG. 3: (a) Scaling of the isotherms shown in the inset with a pure 2D VG model. Inset: I-V isotherms for sample Cu_{27nm}[Nb_{13nm}/Cu_{27nm}]_{10} in applied field $\mu_0H=0.4$ T at temperatures (from left to right) 2.160 K $> T > 1.780$ K, separated ~5-15 mK. Horizontal dotted line delimit the experimental window used for scaling. (b) Derivatives of the log(I)-log(V) isotherms at temperatures (from bottom to top) 2.160 K $> T > 1.856$ K. Black dots are within the experimental window used for scaling. The arrow marks derivatives of the isotherm at the lowest temperature showing decreasing slope in the low current limit.