Evidence for finite-temperature glass transition in two dimensions

Qing-Hu Chen [a,b], Akihiro Tanaka [a], Xiao Hu [a]

[a] *Computational Materials Science Center, National Institute for Materials Science, Tsukuba 305-0047, Japan*

[b] *Department of Physics, Zhejiang University, Hangzhou 310027, P. R. China*

Abstract

Large-scale simulations have been performed in the current-driven two-dimensional XY gauge glass model with resistively-shunted junction dynamics, by means of a very effecient algorithm proposed before. It is found that the linear resistivity at low temperatures tends to zero, which indicates a finite temperature glass transition. Dynamical scaling analysis demonstrates that a nearly pefect collapse of current-voltage data can be achieved with the transition temperature $T_c = 0.22$ (in units of the Josephson coupling strength), dynamical critical exponent $z = 2.0$, and the static exponent $\nu = 1.2$, which agrees quite well with recent findings by an equilibrium Monte Carlo simulations and finete-size scaling analysis in RSJ simulations.

Key words: XY model; glass; superconductivity; scaling

1. Introduction

The vortex glass phase [1] in high-T$_c$ cuprates has attracted considerable attention both experimentally and theoretically. It is of practical significance that the vortex glass phase is a truly superconducting phase with zero linear resistivity. On the theoretical side, the gauge XY glass model [2] is believed to be in the same universal class as the vortex glass. In three dimensions, there is a growing consensus that the gauge glass model exhibits the finite-temperature glass transition [2–4]. However, in two dimensions (2D), experimental quest of the vortex glass transition in high-T$_c$ cuprate films [5,6] and numerical simulations [7–11] in gauge glass model have provided continuous excitement and puzzles for theorists. Zero-temperature numerical domain wall renormalization group study predicted that there is no ordered phase at any finite temperature in 2D [7]. On the other hand, the finite temperature transition has also been reported from extensive resistively-shunted junction (RSJ) [9,10] and Monte Carlo simulations [11]. Therefore, the existence of finite-temperature glass transition in 2D remains a topic of controversy.

In this work, we perform large-scale RSJ dynamical simulations in the 2D XY gauge glass model. The Hamiltonian is given by

$$H = -J_0 \sum_{\langle ij \rangle} \cos(\phi_i - \phi_j - A_{i,j}). \tag{1}$$

where ϕ_i specifies the phase of the superconducting order parameter on grain i, J_0 denotes the strength of Josephson coupling between neighboring grains, and the quenched variable $A_{i,j}$ is distributed uniformly on the interval $[-\pi, \pi)$. The sum is over all nearest neighbor pairs on a 2D square lattice.

The dynamical equations for the ϕ's are readily derived by requiring the sum of currents into each grains to vanish. Realizing that the sum of supercurrents into grain i can be expressed in terms of the derivative of H with respect to ϕ_i, we obtain,

$$\frac{\sigma\hbar}{2e} \sum_{j \in \mathrm{nn\ of\ } i} \left(\frac{d\phi_i}{dt} - \frac{d\phi_j}{dt} \right) = -\frac{2e}{\hbar} \frac{\partial H}{\partial \phi_i} + J_{\mathrm{ext},i} - \sum_{j \in \mathrm{nn\ of\ } i} \eta_{ij}. \tag{2}$$

[1] E-mail: Qinghu.Chen@nims.go.jp

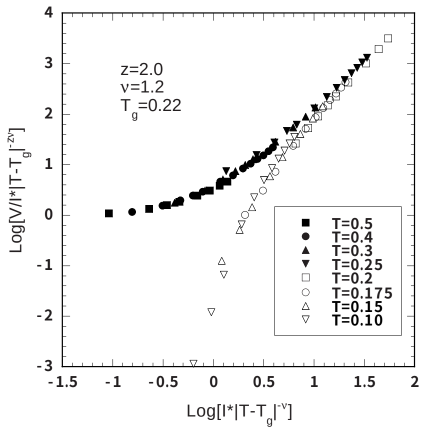

Fig. 1. Dynamical scaling plot of current-voltage data at various temperatures for $L_y = 512$.

Here $J_{\mathrm{ext},i}$ is the external current which vanishes except for the boundaries. The η_{ij} is the thermal noise current with zero mean and a correlator $\langle \eta_{ij}(t)\eta_{ij}(t')\rangle = 2\sigma k_B T\delta(t-t')$. In the following, the units are taken of $2e = J_0 = \hbar = \sigma = 1$.

In our simulation, the network is chosen to be a strip of L_x with L_y nodes in each column. A uniform external current I_x along x-direction is injected into each node and the periodic boundary condition is employed in the transverse y-direction. The above equation can be solved efficiently by pseudo-spectral algorithm. The time stepping is done using a second-order Runge-Kutta scheme with $\Delta t = 0.05$. The detailed description of this method has been given in Ref. ([12]). To avoid boundary effect, we typically choose $Ly = 512, Lx = 512 + 2 \times 128$ and discard 128 columns at each end. We have checked that the finite-size effects on our IV data is convincingly excluded.

2. Simulation results and discussions

We have obtained the resistivity $R = V/I$ as a function of current I at various temperatures. In lower temperatures, resistivity tends to zero as the current decreases. It follows that there is a true superconducting phase with zero linear reisitivity in low temperature.

In analyzing the glass transition from a vortex liquid with ohmic resistance to a superconducting vortex glass state, Fisher, Fisher, and Huse (FFH) [1] proposed the following dynamic scaling ansatz,

$$V = I\xi^{d-2-z}\Psi_{\pm}(I\xi^{d-1}). \tag{3}$$

Here d is the dimension of the system, z is the dynamic exponent at the transition, and $\xi =\mid T - T_c \mid^{\nu}$ is the correlation length which diverges at the transition.

We examine the IV data at different temperatures by this dynamical scaling. As shown in Fig. 1, using $T_c = 0.22$, $z = 2.0$, and $\nu = 1.2$, an excellent collapse is achieved, which agrees quite well with recent findings by an equilibrium Monte Carlo simulations[11] and standard finite-size scaling in RSJ simulations with small sample size[10]. We therefore believe finite-temperature glass transition exist even in 2D.

In summary, we have performed extensive simulations on 2D XY gauge glass model by a very efficient algorithm. A strong evidence for the finite-temperature transition in 2D is provided. The nature of the low temperature superconducting phase [13] should be our future study.

Acknowledgements

The present simulations are performed on the Numerical Materials Simulator (SX-5) of National Institute of Materials Science, Japan. One of us (QHC) is financially supported by the JSPS invitation program and in part by the NSFC under Grant No. 10075039.

References

[1] D. S. Fisher, M. P. A. Fisher, D. A. Huse, Phys. Rev. B **43**, 130 (1991).

[2] D. A. Huse, H. S. Seung, Phys. Rev. B **42**, 1059 (1990).

[3] R. H. Koch, V. Foglietti, W. J. Gallagher, G. Koren, A. Gupta, M. P. A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989).

[4] T. Giamarch,P. Le Doussal, Phys. Rev. Lett. **72**, 1530 (1994); Y Nonomura, X Hu, Phys. Rev. Lett. **86**, 5140 (2001).

[5] C. Dekker, P. J. M. Woltgens, R. H. Koch, B. W. Hussey, A. Gupta, Phys. Rev. Lett. **69**, 2717 (1992).

[6] A. Sawa, H. Yamasaki, Y. Mawatari, H. Obara, M. Umeda, S. Kosaka, Phys. Rev. B **58**, 2868 (1998).

[7] M. P. A. Fisher, T. A. Tokuyasu, A. P. Young, Phys. Rev. Lett. **66**, 2931 (1991); J. M. Kosterlitz ,N. Akino, ibid. **81**, 4672 (1998).

[8] E. Granato, Phys. Rev. B **58**, 11 161 (1998).

[9] Y.-H. Li, Phys. Rev. Lett. **69**, 1819 (1992).

[10] B J Kim, Phys. Rev. B B **62**, 644(2000).

[11] M. Y. Choi, S. Y. Park, Phys. Rev. B **60**, 4070 (1999). B.J. Kim, M.Y. Choi, S. Ryu, D. Stroud, Phys. Rev. B **56**, 6007 (1997).

[12] Q. H. Chen, L. H. Tang, P. Q. Tong, Phys. Rev. Lett. **87**, 067001(2001); L. H. Tang and Q. H. Chen, Physica B **279**, 227(2000).

[13] H. Nishimori, Physica A **205**, 1(1994); Y. Ozeki, H. Nishimori, J. Phys. A26, 3399(1993).