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Dimension effects in insulating NbTiN disordered films and asymptotic freedom of Cooper pairs

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Building on the measurements of NbTiN film which is on the insulating side of the disorder-driven superconductor-insulator transition [1–4], we show that the threshold voltage of measured step-like $I(V)$ curves is a linear function of the distance between the measuring electrodes. The measurements are taken on polycrystalline film with 10 nm thickness obtained by the atomic layer deposition [5] at temperature 350 °C.

At temperatures $T > 0.8\,\mathrm{K}$, $R_\square(T)$ collapse on top of each other and are well fit the activation behavior. At $T < 0.8\,\mathrm{K}$, $R_\square(T)$ for larger samples demonstrate hyperactivation growth characteristic to superinsulator, the curves for different sizes converging, smaller systems revealing the tendency of bending down. Decreasing the film size leads to suppression of the insulating properties down to quasi-metallic saturation of the resistance. Analysis of the $R_\square(T)$ dependence for the largest film in terms of the charge Berezinsky–Kosterlitz–Thouless (CBKT) transition shows deviation from the CBKT criticality at lowest temperatures, manifesting the finite electrostatic screening length λ (the perfect criticality would have been observed for $\lambda > 10^5$ [1]).

To explore possible consequences of the string model of a superinsulator, we measure I–V curves demonstrating the threshold behavior on the device comprising the parts of the same film but with different distances between measuring electrodes, see Fig. 1. Interestingly, the similar threshold $I(V)$ dependencies were observed in

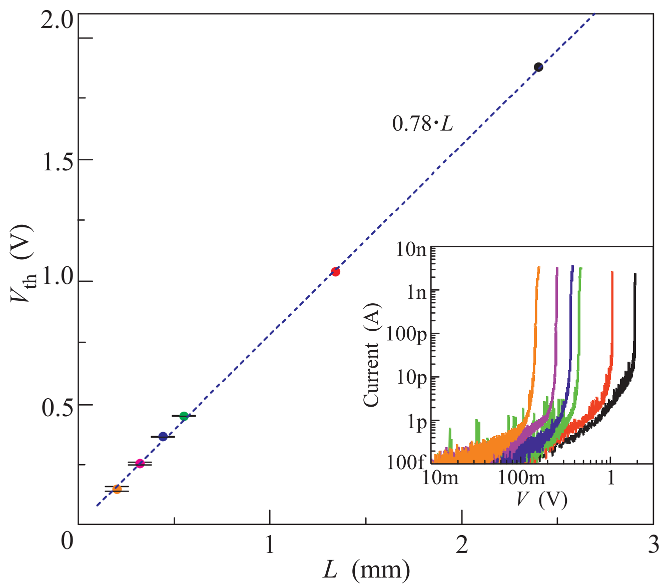

Рис. 1. (Color online) Dependence of the threshold voltage upon the distance between electrodes. The dashed line is the fit $V_{\rm th} = 0.78L$. Inset: Evolution of the I–V curves of the insulating NbTiN film as function of the distance between electrodes taken at 20 mK

strongly-interacting 2D electron system in silicon MOSFETs and were successfully described by the depinning of the 2D Wigner crystal [6, 7]. However, in our case of the Mott Cooper pair insulator in strongly disordered films, formation of the Cooper pair Wigner crystal that requires weak pinning, seems unlikely, and is

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not supported by the data that do not follow the formulas of [6, 7]. The current jumps become less sharp upon shortening the distance between electrodes, while threshold voltage dependence upon L exhibits linear behavior, implying that the threshold electric field $E_{\mathrm{th}} = V_{\mathrm{th}}/L$ is independent on the distance between electrodes. This was only observed in gases and liquids [8] or in nano-scale solids with $L < 1\,\mu$m [9], i.e., in samples which are over three orders of magnitude shorter than those examined in our work. At the same time, the observed linear dependence is in accordance with the prediction of [10], see Fig. 1.

We now can compare the experimental findings with the theoretical predictions of [10]. The asymptotic freedom scale, i.e., the minimum string size below which the linear confinement of charges in a superinsulator vanishes estimated as [10]

$$\lambda_{\mathrm{string}} \simeq \frac{\hbar v}{k_B T_{\mathrm{CBKT}}}, \qquad (1)$$

where $v = c/\sqrt{\varepsilon}$ is the light velocity in the material, c is the light velocity in vacuum, and ε is the bare dielectric constant of NbTiN near the SIT. Taking the experimental values of $T_{\mathrm{CBKT}} \simeq 400$ mK and $\varepsilon \simeq 800$, we find $\lambda_{\mathrm{string}} \simeq 0.2$ mm which agrees fairly well with the observed size of 0.2 mm at which the temperature dependence of $\ln R_{\Box}(T)$ vs. $1/T$ turns to saturation.

With using a non-relativistic version of the Polyakov's compact QED model [11, 12] we can show that the superinsulating state is the state in which Cooper pairs are localized and the electrostatic potential of the charges is screened by the Bose condensate of vortices. To estimate the threshold field, we use interpolation formula for the attractive interaction between charges of the opposite sign separated by the distance r:

$$U(r) \simeq \sigma(T)r + k_B T_{\mathrm{dc}} \ln(r/\ell), \qquad (2)$$

where ℓ is the ultraviolet (UV) cutoff of the theory identified with the film thickness, σ is the linear tension of the confining electric string, T_{dc} is the deconfinement temperature coinciding with T_{CBKT}. The threshold voltage marks the voltage that capable to overcome the confinement, i.e., break the electric string. This gives the estimate $\sigma \simeq 2eV_{\mathrm{th}}/L$. Using the experimental values from Fig. 1, one estimates $\sigma \simeq 10^5$ K/cm. At the same time, in order to deconfine, the charges have to overcome the maximum of the potential $k_B T_{\mathrm{CBKT}} \ln(r/\ell) - \sigma_{\mathrm{eff}} L$, where $\sigma_{\mathrm{eff}} \simeq 2eE - \sigma$, E being the applied electric field. This gives the estimate for $\sigma_{\mathrm{eff}} \approx T_{\mathrm{CBKT}}/r^*$, $r^* \approx 3\ell$. One expects $\sigma_{\mathrm{eff}} \simeq \sigma$. Taking $\ell \approx 10$ nm and $T_{\mathrm{CBKT}} \simeq 0.4$ K, one obtains $\sigma_{\mathrm{eff}} \simeq 1.3 \cdot 10^5$ K/cm. Considering the crudeness of the model, one can view this as an excellent agreement of the obtained experimental data with the theoretical expectations. Thus, the far reaching implication of our findings is that one can use the desktop measurements in order to determine experimentally the linear tension of the Polyakov's electric strings.

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