Transport properties of compressed $La_{1.952}Sr_{0.048}CuO_4$ thin films

I. Zajcewa[1*], R. Minikaev[1], M. Chrobak[2,3], E. Dobročka[4], and M. Z. Cieplak[1]

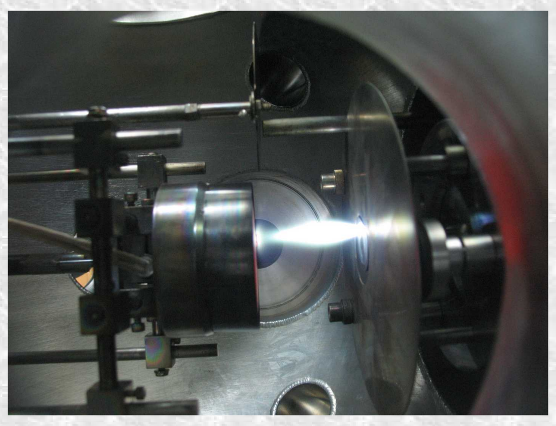
[1] Institute of Physics, Polish Academy of Sciences, 02 668 Warsaw, Poland
[2] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Solid State Physics Department, al. A. Mickiewicza 30, 30-059, Krakow, Poland.
[3] AGH University of Science and Technology, Academic Center for Materials and Nanotechnology, al. A. Mickiewicza 30, 30-059 Krakow, Poland.
[4] Institute of Electrical Engineering SAV, Dúbravská cesta 9, 84104 Bratislava, Slovakia

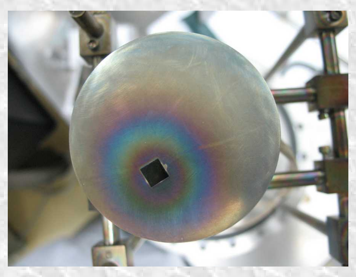
*zaytseva@ifpan.edu.pl

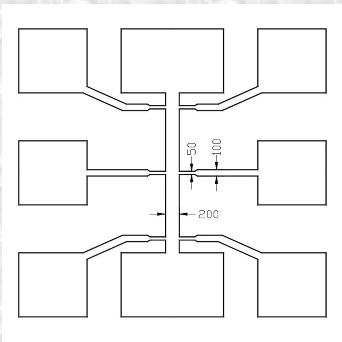
Motivation

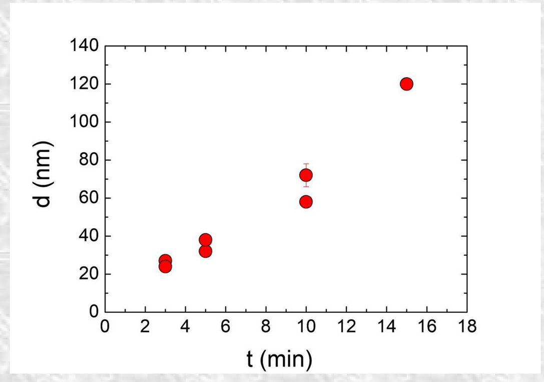
The properties of disordered or inhomogeneous superconducting systems are still not fully understood. Experiments show that a superconductor to insulator transition may be induced in thin superconducting films by decreasing the film thickness, which enhances the disorder, or by increasing the external magnetic field. In this work, we tune the inhomogeneity of the superconducting films by utilizing the strain introduced by the lattice mismatch between the substrate and film.

Experimental details







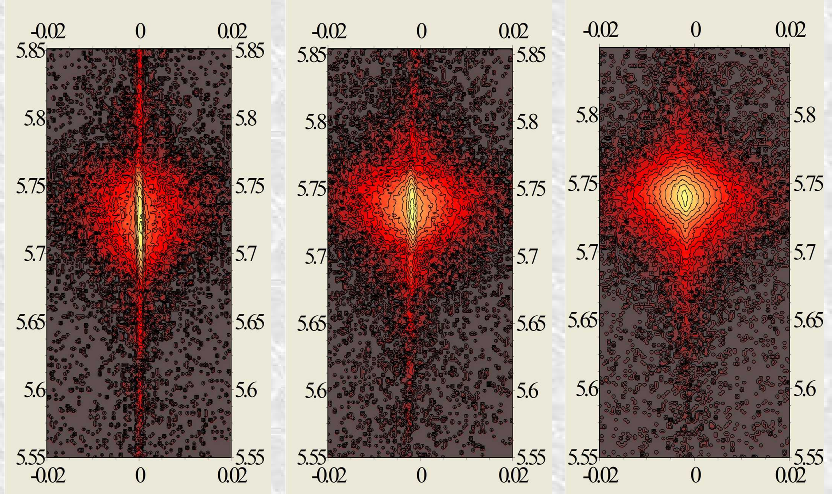


Thickness of the films vs time of deposition

Epitaxial (LSCO) thin films were deposited from stoichiometric ceramic target by pulsed laser deposition (PLD) using Nd:YAG laser (λ = 266 nm), with repetition rate 1Hz and energy density 1.5 J/cm2 at the target surface. The target, with the Sr content x = 0.048, is not superconducting in the bulk. The films were grown on $SrLaAlO_4$ (SLAO) substrates. During deposition the substrates were held at temperature 760^{0}C in the oxygen atmosphere of 300mTorr. After deposition, the O_2 pressure in the chamber was increased to 500Torr, and the films were slowly cooled down to room temperature with a rate of 3K per minute.

The films were studied using X-ray diffraction with high-resolution Philips XPert MRD diffractometer. The out-of-plane lattice parameters c were determined using XRD techniques for a series of thin films with thickness d ranging between 26 nm and 120 nm. The reciprocal space maps of the films were measured in a high-resolution mode on a Bruker D8 DISCOVER diffractometer with a rotating Cu anode operating at 12 kW (40 kV/300 mA). Superconducting transition temperature and magnetoresistance were measured on photolithographically patterned films using a standard four-probe method in a Quantum Design PPMS (Physical Properties Measurement System) at $T \geq 2$ K and in fields up to 9 T. In addition, some magnetotransport measurements were carried out at the Toulouse LNCMI high field facility, in a pulsed high magnetic field up to 50 T and in the temperature range 0.4 K < T < 25 K (H || c, I || ab). Also low-temperature resistivity (with current I = 100 nA) and current-voltage characteristics (IVC) measurements were performed in Closed Cycle Dilution Refrigerator TRITON (DR) from Oxford Instruments using low frequency lock-in technique. To minimize Joule heating, the IVC were measured using rectangular current pulses, with a current-on time of 50 ms and current-off time of 100 ms.

Structural and transport properties



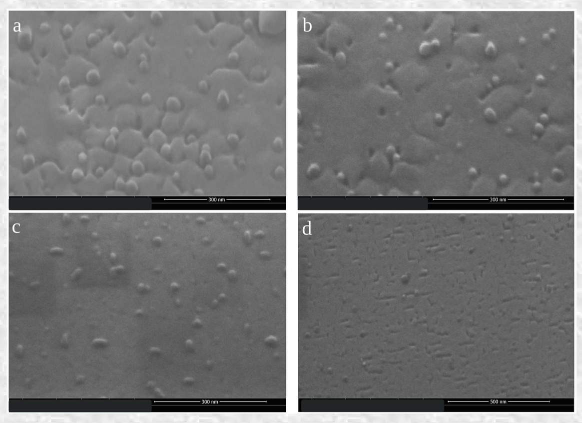
Reciprocal space maps (RMS) of layer maxima 006 for films with thickness (from left to right): 26 nm, 35 nm, and 65 nm. RSMs are presented with the coordinates h (horizon-tal) and l (vertical) having the units $1h = 1/d_{100}$ and $1l = 1/d_{001}$, respectively. d_{hkl} is the corresponding interplanar spacing of the substrate lattice.

- The films with the same thickness may exhibit different strain → strain may affect superconductivity
- Films with small compressive strain are insulating
- For d > 120 nm films are insulating
- For 0.25 < ε_c < 0.65 - $\Delta T_c^{on} \approx 7$ K

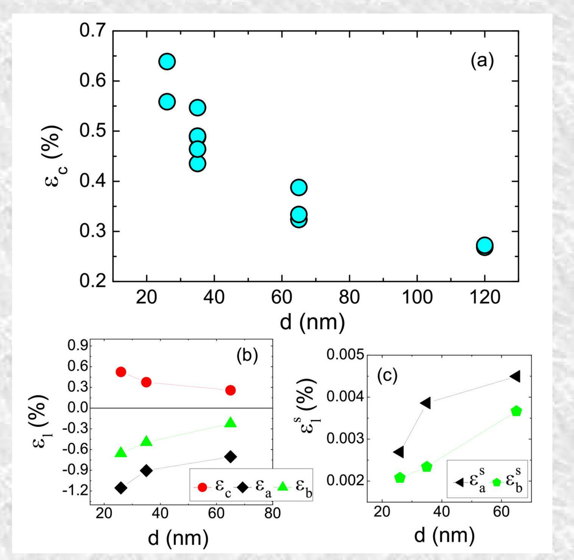
The a-axis (in-plane) lattice parameter of SLAO substrates is equal to 3.757 Å. This value is less than in-plane lattice parameters of the LSCO target with x = 0.048, which are equal to 3.806 Å and 3.784 Å for a and b lattice parameters, respectively.

$\varepsilon_l = (l_{film} / l_{bulk} - 1)*100\%$, where l is the corresponding lattice parameter value,

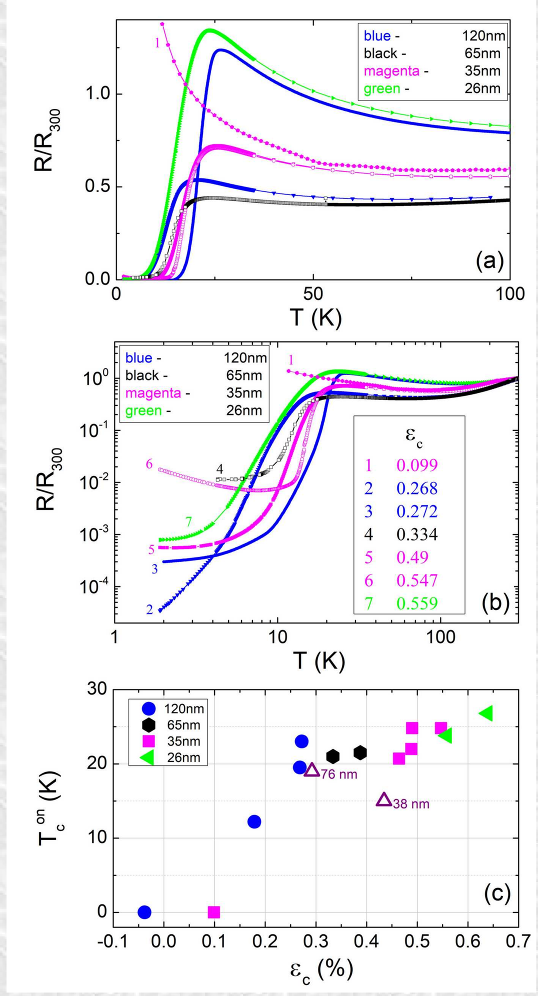
$\varepsilon^s_l = (l_{film} / l_{substrate} -1)*100\%$ - the relative change of film parameters with respect to the parameters of the substrate.

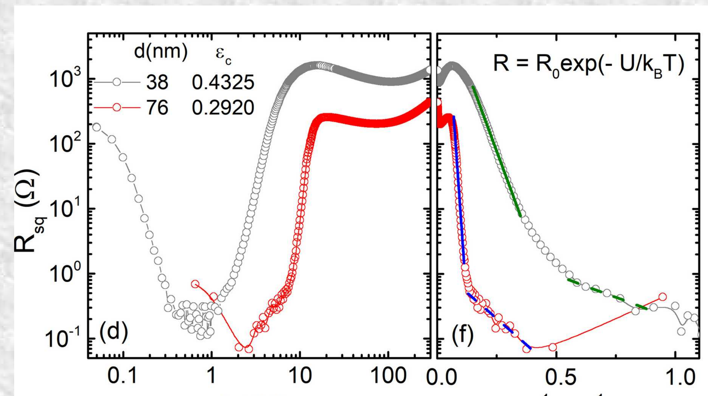


The images of LSCO films taken on scanning electron microscope: a) $d \approx 120$ nm; b) $d \approx 60$ nm; c) $d \approx 30$ nm; d) $d \approx 40$ nm.

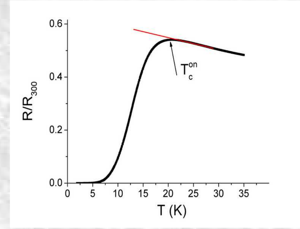


(a) Dependence of ε_c on the film thickness d for a series of films. (b) Strain parameters ε_a, ε_b, and ε_c vs d for three selected films. (c) The relative change of the in-plane film lattice parameters with respect to the substrate parameters vs d. The size of the errors is less than the size of the symbols.





$R = R/300$ vs T on a log-log scale (a) for films with different d: 26 nm (green points), 35 nm (magenta), 65 nm (black), and 120 nm (blue) and with different ε_c. (c) T_c^{on} vs ε_c for films with different d. The size of the errors is comparable to the size of symbols.

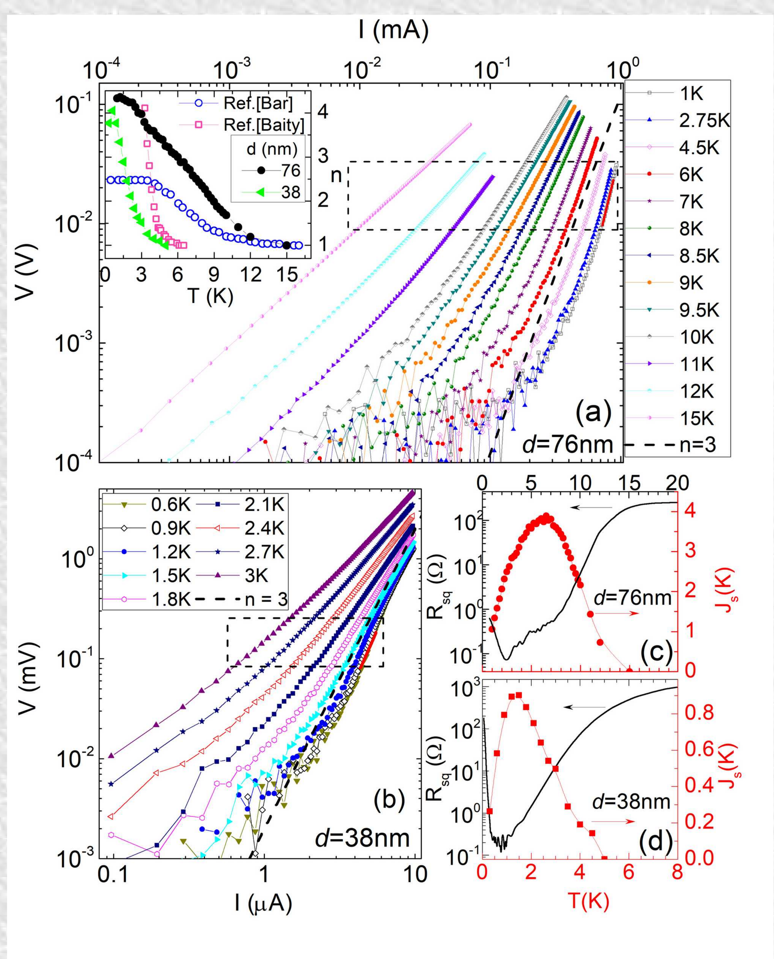


The definition of T_c^{on}

(d) R_{sq} vs T on a log-log scale for d = 38 nm and 76 nm; (f) R_{sq} (log scale) vs $1/T$. Lines show activation energy fits (where U is activation energy for flux pinning).

- The existence of residual resistance suggests that superconductivity in these strained films is inhomogeneous so that no global phase coherence is reached.
- While we see a quite good correlation between ε_c and T_c^{on}, the behavior of resistance on the decrease of T below T_c^{on} is more comcplicated.
- The two-step superconductor transition resembles the behaviour reported for isolated superconducting islands on top of nonsuperconducting metallic film (S.Eley, Nat.Phys.Lett. 2012; Z.Han, Nat.Phys. 2014)

Carrent-voltage characteristics



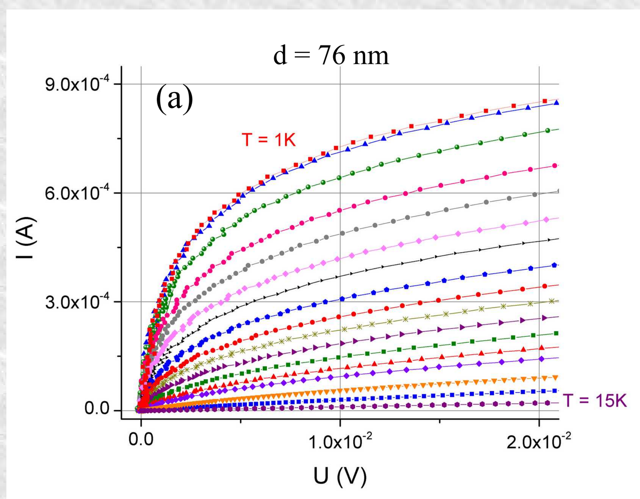
The voltage in the vicinity of the T_{BKT} (Berezinskii-Kosterlitz-Thouless transition temperature):

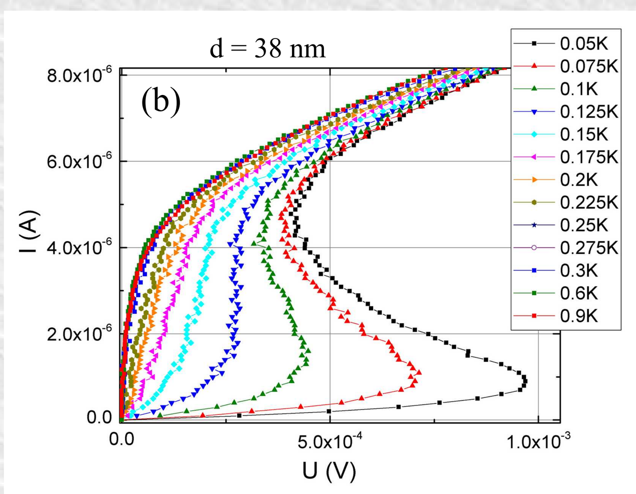
$V \sim I^{n(T)}$;

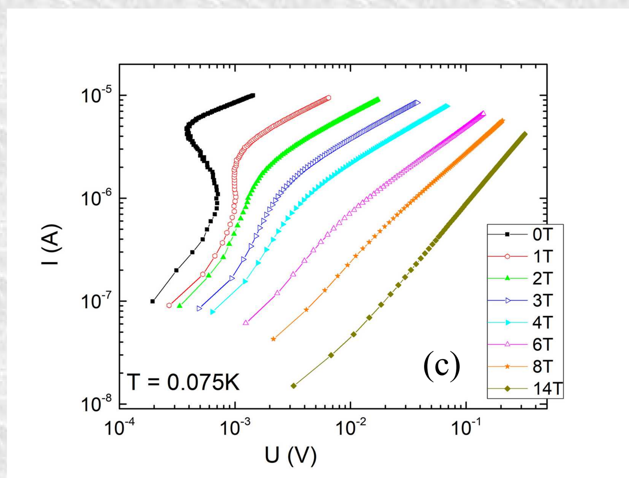
$n(T) = 1 + \pi J_s(T) / T$,

where $J_s(T)$-superfluid stiffness

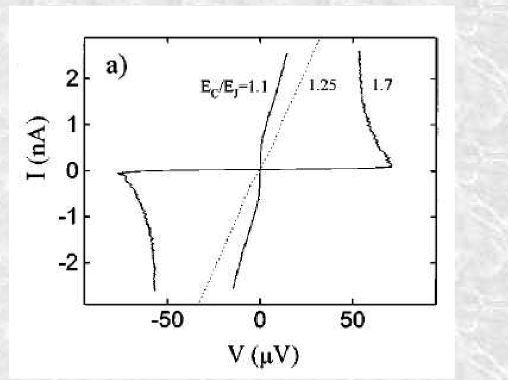
The IVC on a log-log scale at different T in SC region for films with d = 76 nm (a) and d = 38 nm (b). Dashed rectangles indicate regions of power-law V-I dependence, and black dashed lines show $V \sim I^3$.
Inset (a): $n(T)$ for d = 76 nm (black circles), and d = 38 nm (green triangles); open points show data from literature: for homogeneous LSCO film [Baity, PRB(2016)], and for YBCO nanobridge [Bar, PhysC(2014)].
$J_s(T)$ for d = 76 nm (c) and d = 38 nm (d).



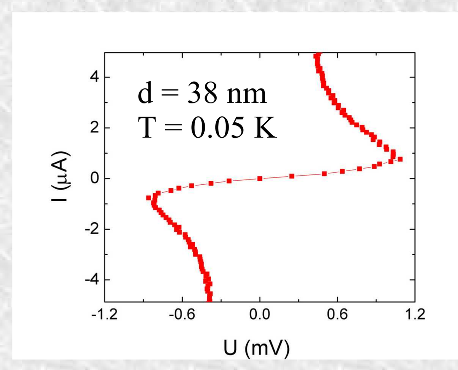




IVC for films with d = 76 nm (a) and d = 38 nm (b) for various T, and magnetic field B = 0;
(c) IVC for film with d = 38 nm for T = 0.075 K and various B.

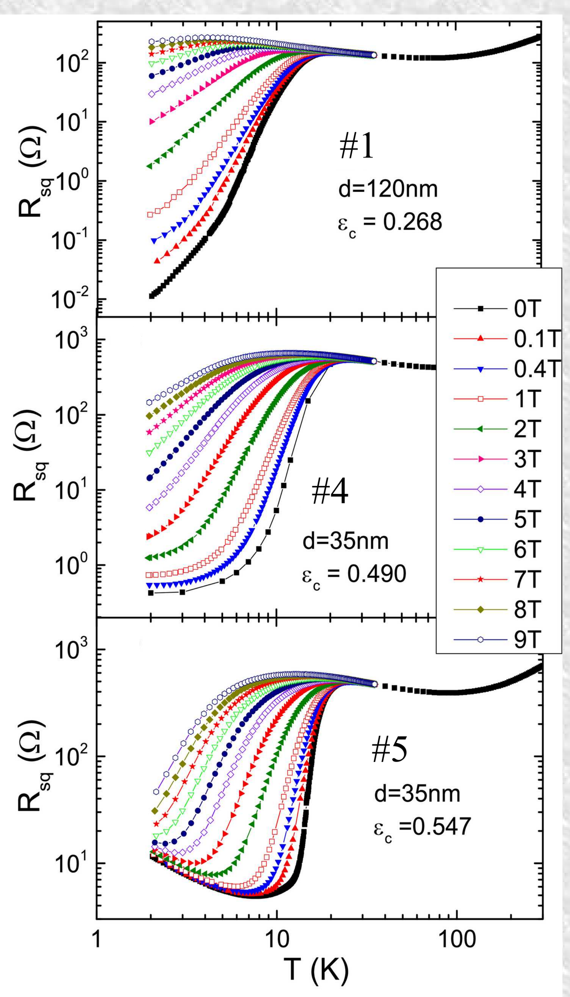


IVC measured at low temperatures as a function of the ratio E_C / E_J in Josephson-junction arrays [Zant, PRB (1996)]

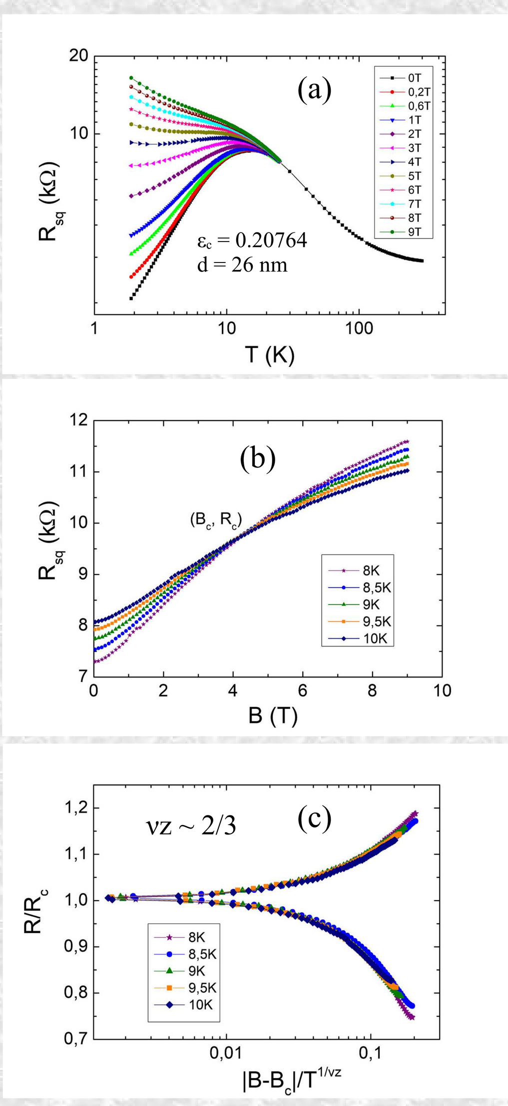


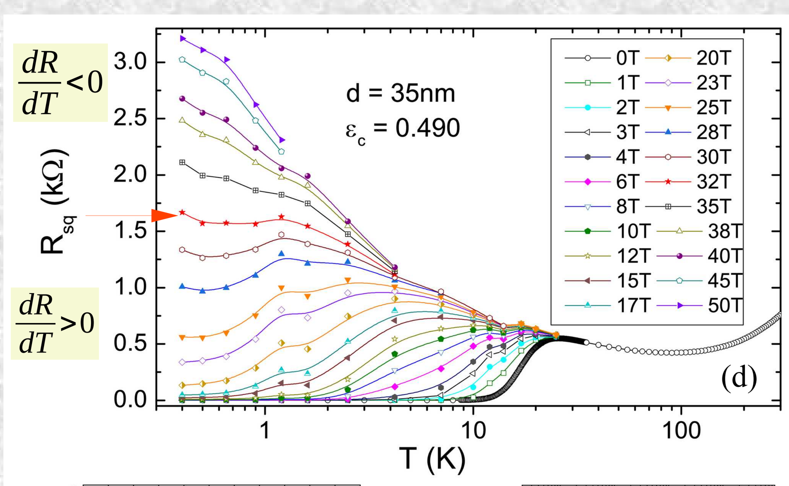
IVC for film with d = 38 nm T = 0.05 K B = 0;

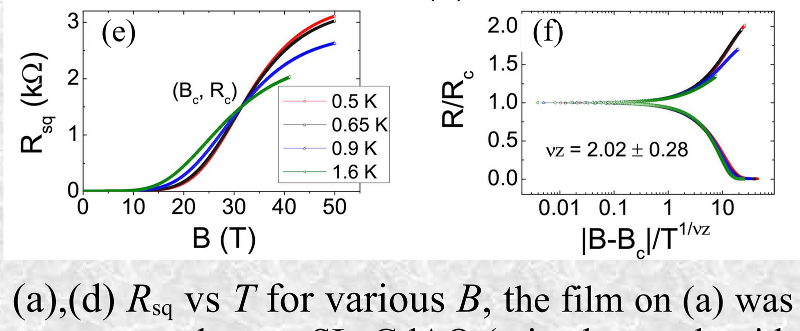
Magnetoresistance and scaling analysis



R_{sq} vs T on a log–log scale, for B in the range of 0 - 9 T





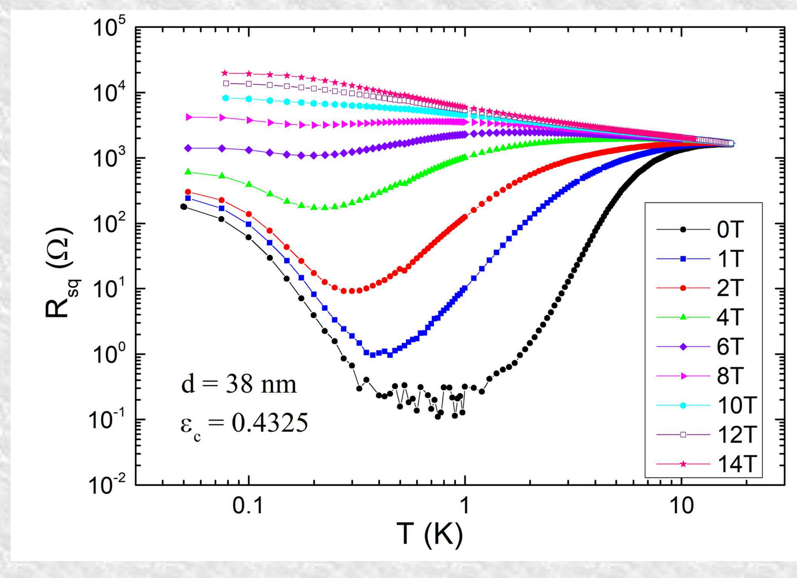


(a),(d) R_{sq} vs T for various B, the film on (a) was grown on substrate SLaGdAO (mixed crystal, with some Gd substituted for La);
The T-independent crossing point of isotherms:
(b) at B = 4 T and R_c = 9.7 kΩ;
(e) at B = 31.79 T and R_c = 15.44 kΩ;
(c),(f) Resistance as a function of scaling variable, $|B - B_c| / T^{1/\nu z}$.

- $R_{sq} = R^c_{sq} |B - B_c| / T^{1/\nu z}$

ν – correlation length exponent
z – dynamical critical exponent

- $\nu z > 1$ – corresponds to the T = 0 superconductor-insulator transition in a 2D disordered system
- $\nu z \sim 2/3$ → the universality class of the 2D SIT in the clean limit, as described by the (2+1)D XY model owing to the long-range Coulomb interaction between charges.



R_{sq} vs T for various B

Conclusions

The disordered $La_{1.952}Sr_{0.048}CuO_4$ films with superconductivity induced by compressive strain appears to be an interesting system to study the nature of the metallic phase at the superconductor-insulator boundary. The degree of strain influences the onset of superconductivity and the residual resistance. The evolution of resistance and current-voltage characteristics with temperature and magnetic field supports the scenario of inhomogeneous superconductivity, which resembles a disordered array of superconducting islands immersed in a nonsuperconducting matrix.
I. Zaytseva, et. al., J. Appl. Phys. 127, 073901 (2020).

Acknowledgments: We would like to thank M. Berkowski and M. Głowacki for substrate preparation. This work has been supported by Polish NSC Grant No.DEC-2018/02/X/ST3/00582.