# Coulomb blockade effect in highly underdoped LSCO thin films

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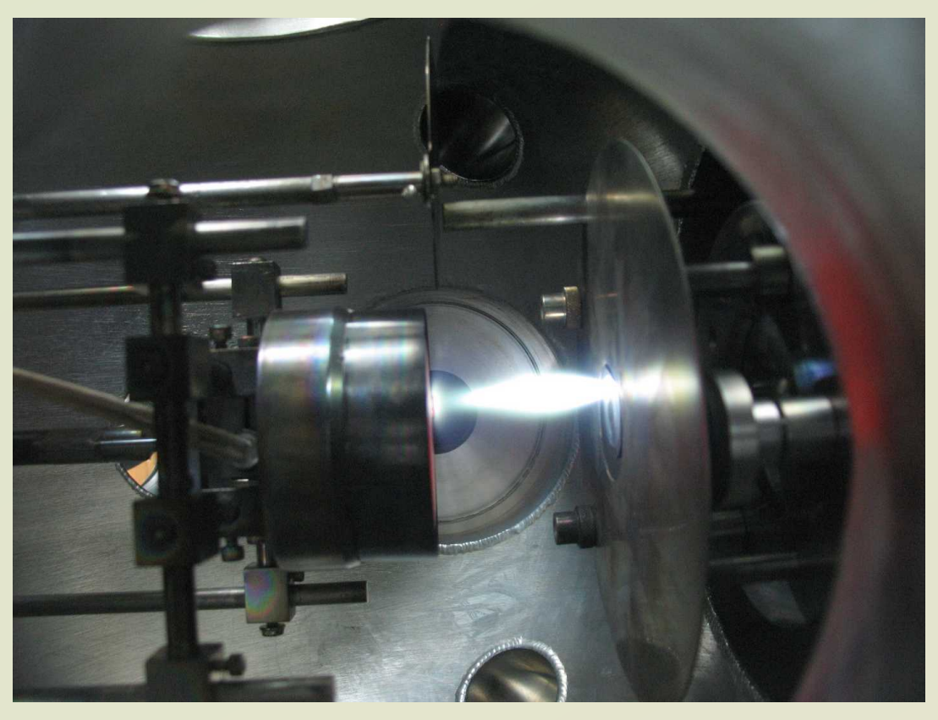
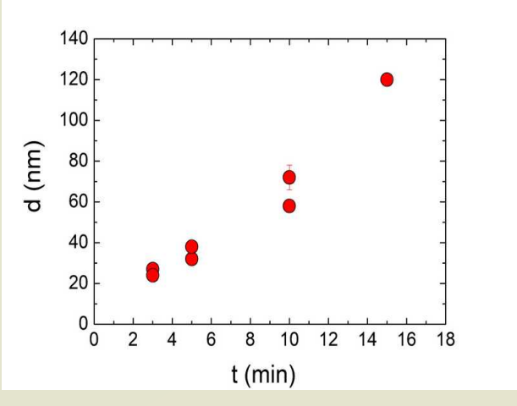
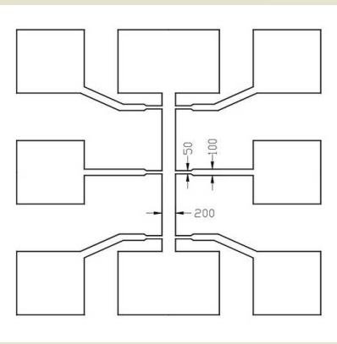
## Motivation

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.





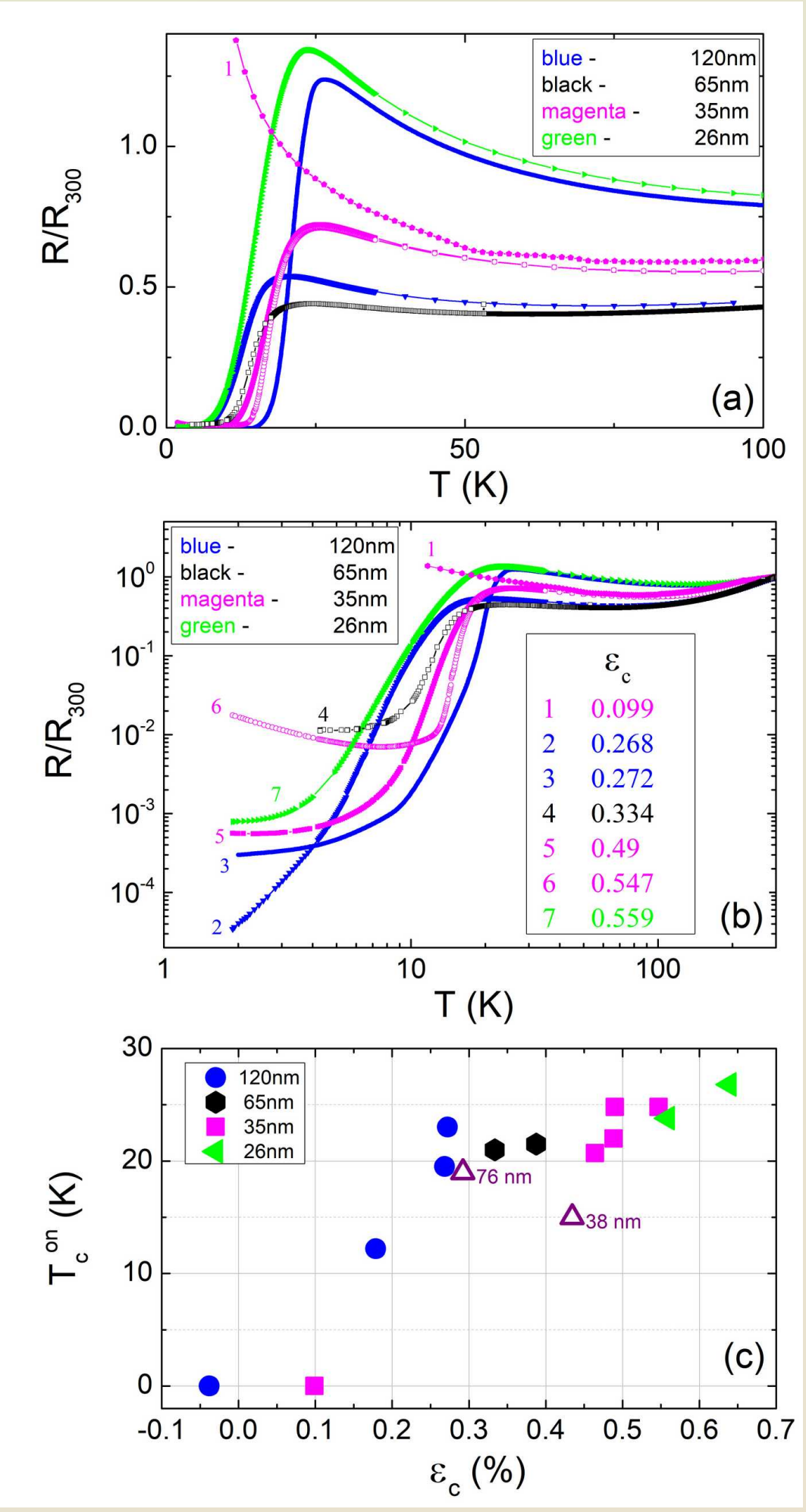


## Experimental details

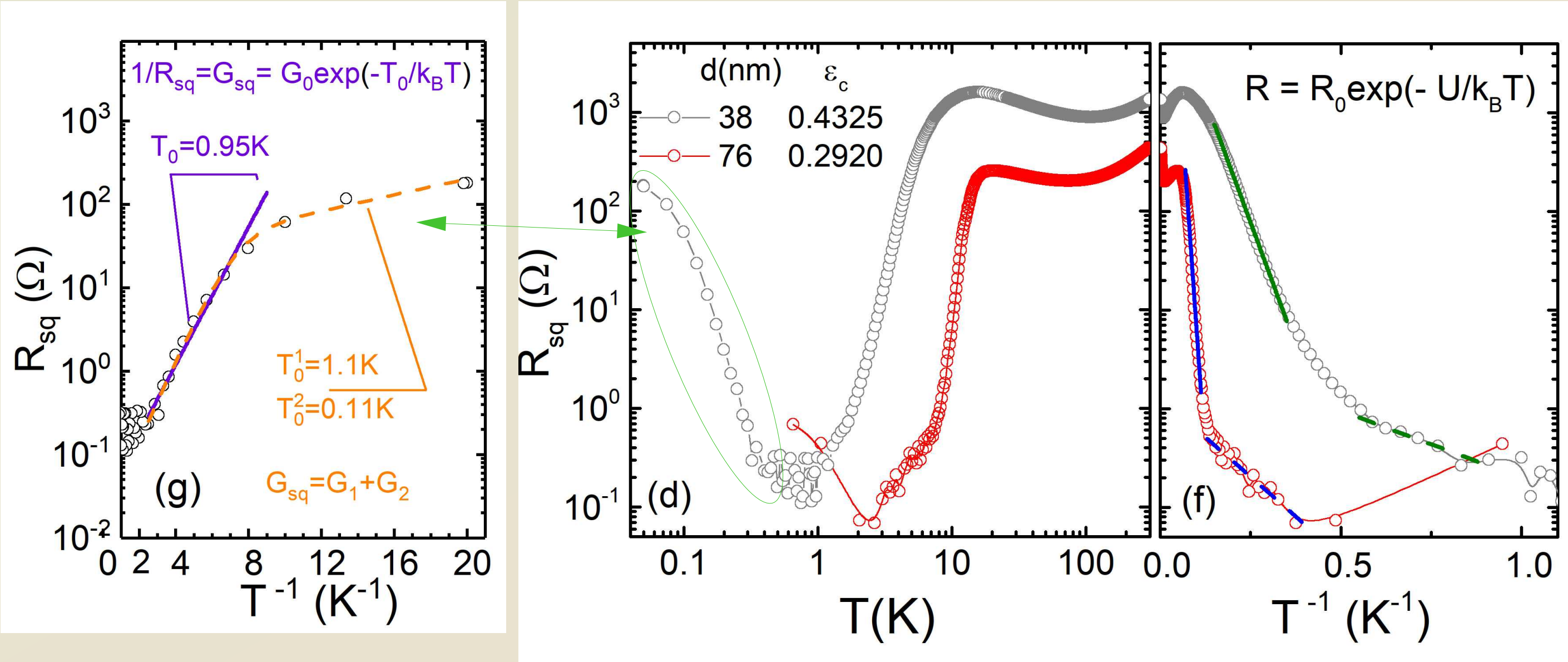
Epitaxial (LSCO) thin films were deposited from stoichiometric ceramic target by pulsed laser deposition (PLD) using Nd:YAG laser (λ = 266 nm), with repetition rate 1Hz and energy density 1.5 J/cm2 at the target surface. The target, with the Sr content $x = 0.048$, is not superconducting in the bulk. 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.

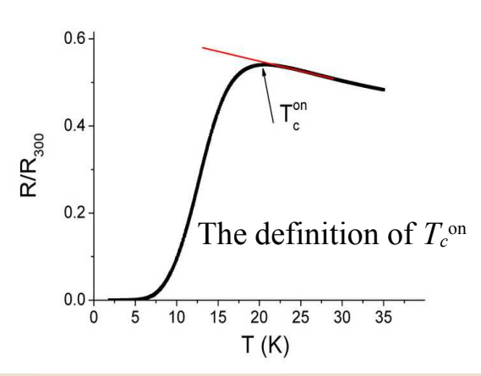
## Transport properties



$R = R/300$ 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 $\varepsilon_c$. (c) $T_c^{on}$ vs $\varepsilon_c$ for films with different $d$. The size of the errors is comparable to the size of symbols.

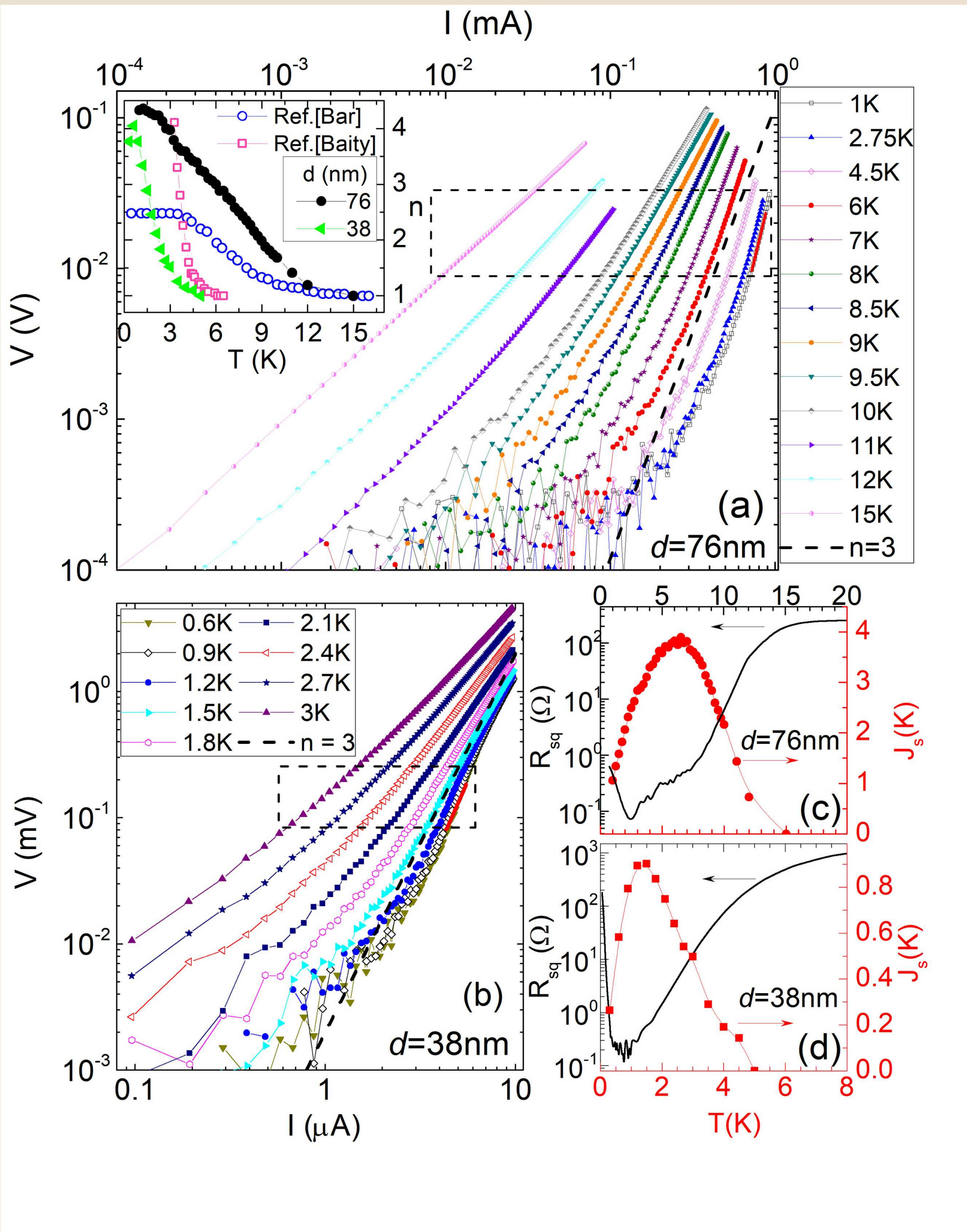


(d) $R_{sq}$ vs $T$ on a log-log scale for $d$ = 38 nm and 76 nm; (f), (g) $R_{sq}$ (log scale) vs $1/T$. Lines show fits: (f) in the superconductin region (where $U$ is activation energy for flux pinning); (g) in the insulating region (where $T_0$ is activation energy)

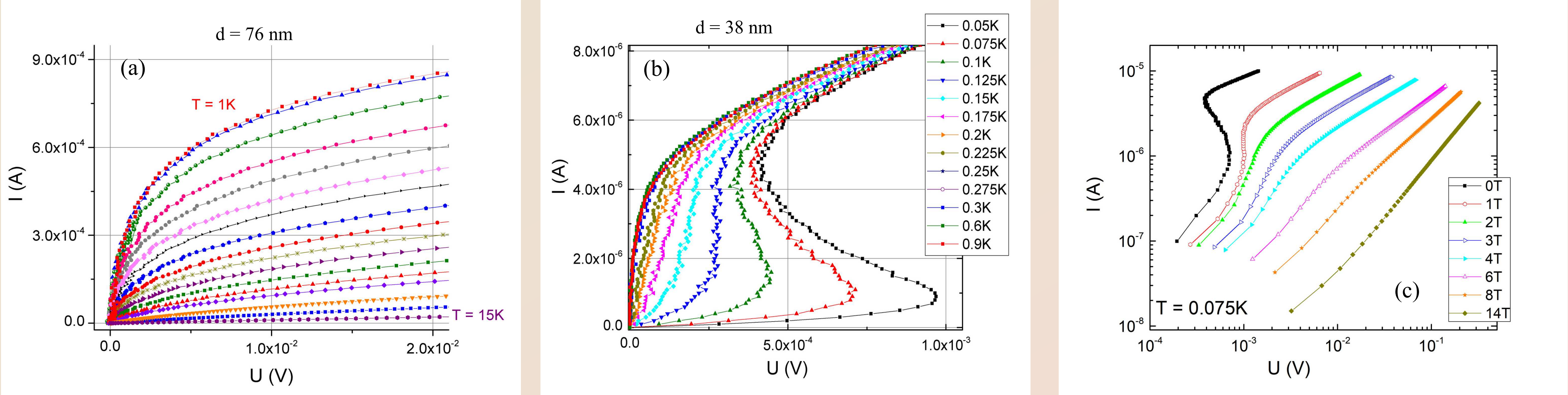


The IVC on a log-log scale at different $T$ in SC region for films with $d$ = 76 nm (a) and $d$ = 38 nm (b). Dashed rectangles indicate regions of power-law V-I dependence, and black dashed lines show $V \sim I^3$.
Inset (a): $n(T)$ for $d$ = 76 nm (black circles), and $d$ = 38 nm (green triangles); 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).

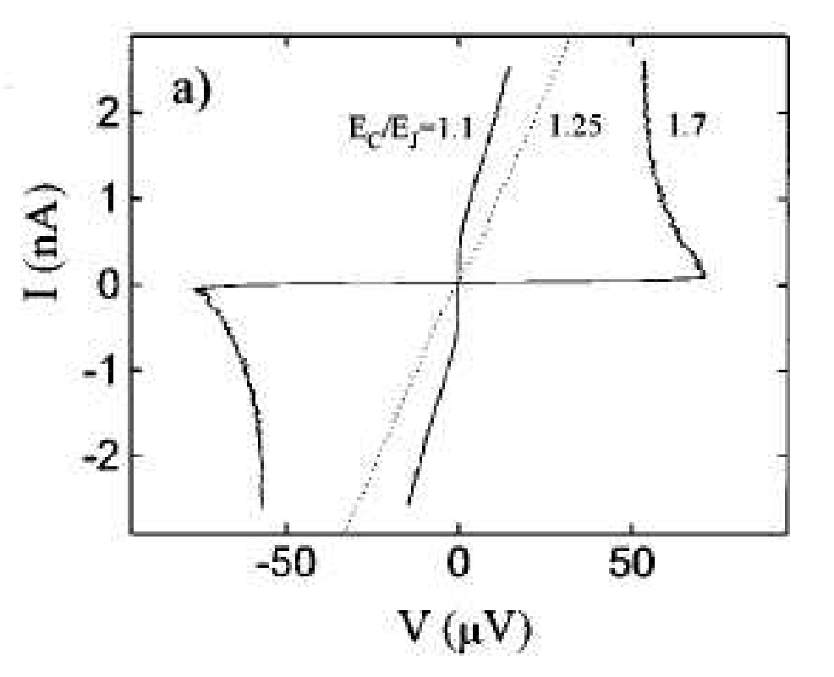
The voltage in the vicinity of the $T_{BKT}$ (Berezinskii-Kosterlitz-Thouless transition temperature):
$V \sim I^{n(T)}$;
$n(T) = 1+\pi J_s(T) / T$,
where $J_s(T)$-superfluid stiffness



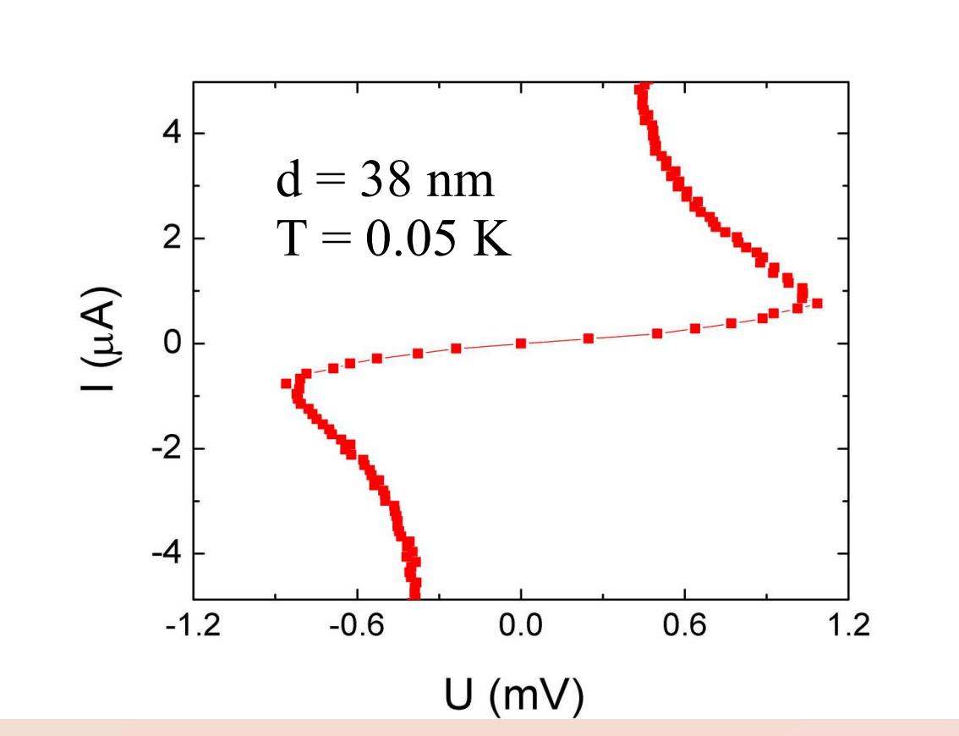
- The existence of residual resistance suggests that superconductivity in these strained films is inhomogeneous so that no global phase coherence is reached.
- While we see a quite good correlation between $\varepsilon_c$ and $T_c^{on}$, the behavior of resistance on the decrease of $T$ below $T_c^{on}$ 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)



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 magnetic fields.

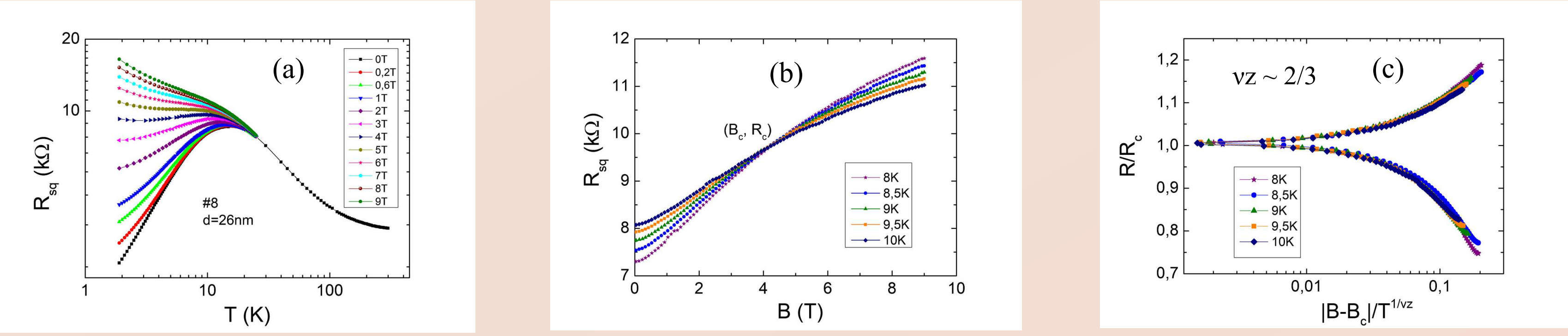


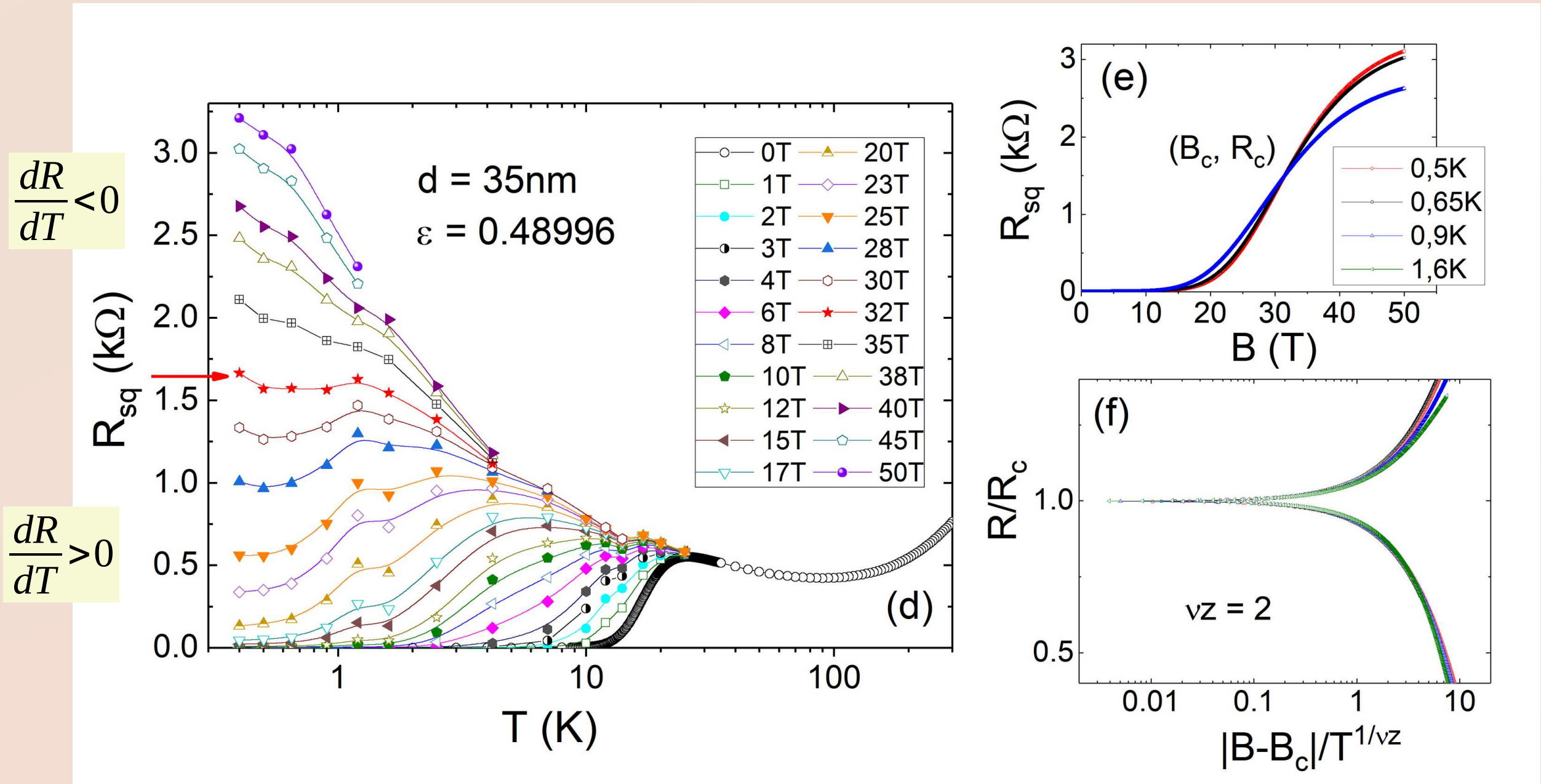
IVC measured at low temperatures as a function of the ratio $E_c/E_J$ in Josephson-junction arrays [Zant, PRB (1996)]



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

## Magnetoresistance and scaling analysis



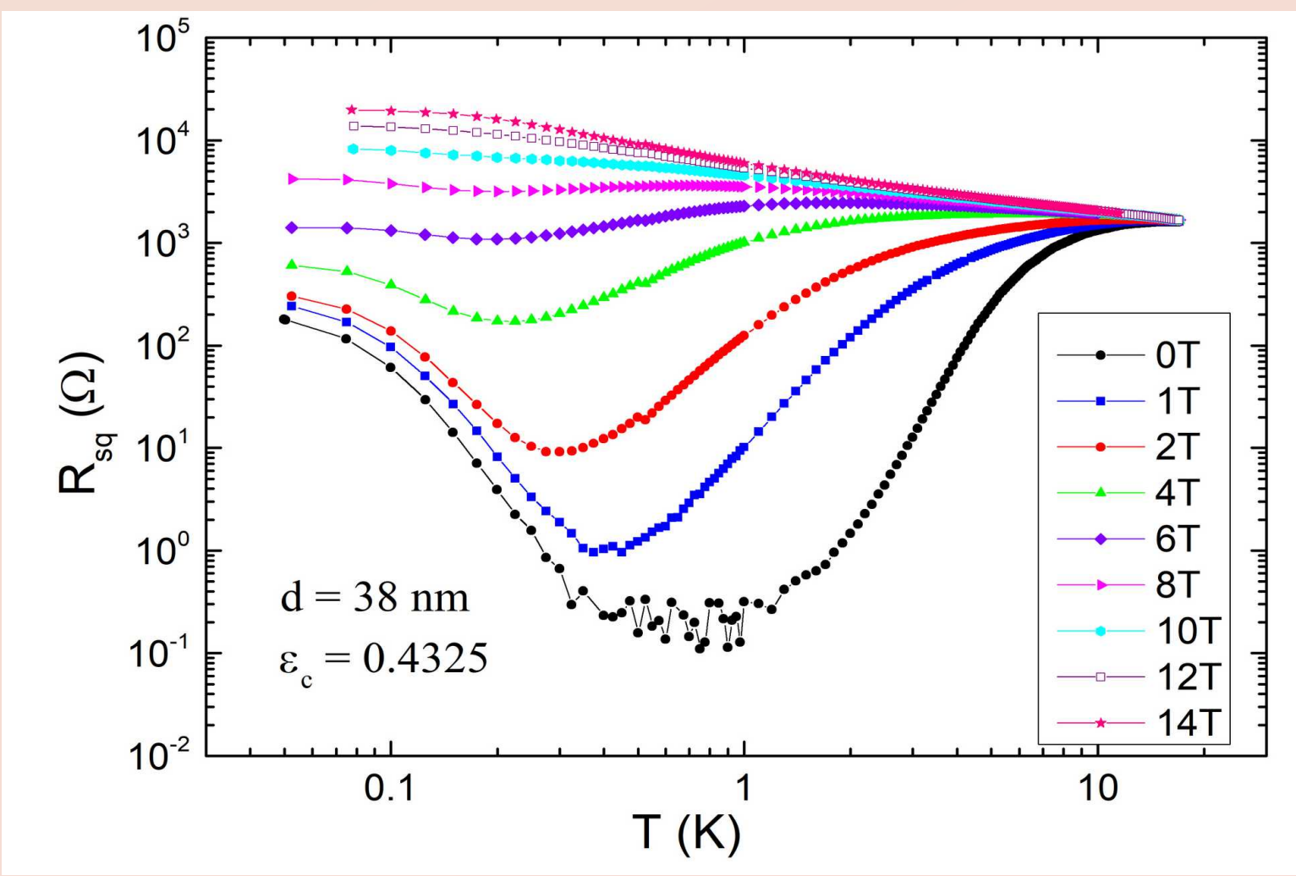


(a),(d) $R_{sq}$ vs $T$ for various $B$, the film on (a) was grown on substrate SLaGdAO (mixed crystal, with some Gd substituted for La);
The $T$-independent crossing point of isotherms:
(b) at $B$ = 4 T and $R_c$ = 9.7 kΩ;
(e) at $B$ = 31.79 T and $R_c$ = 15.44 kΩ;
(c),(f) Resistance as a function of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

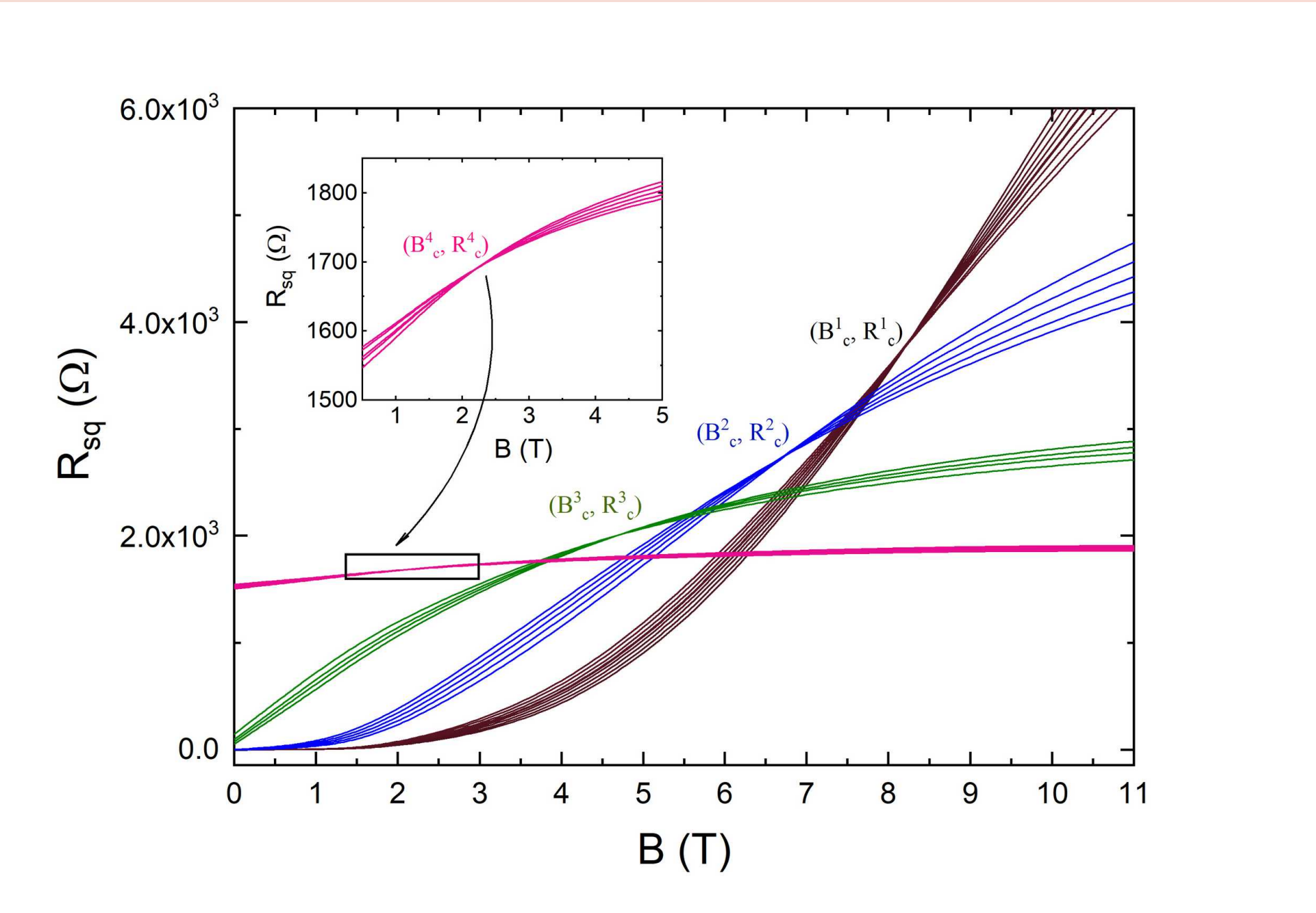
- $R_{sq} = R^c_{sq} |B - B_c| / T^{1/\nu z}$

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 $B$



The $T$-independent approximate crossing points of isotherms for film with $d$ = 38 nm:
(1) at $B$ = 8.4 T and $R_c$ = 3.78 kΩ;
(2) at $B$ = 6.6 T and $R_c$ = 2.7 kΩ;
(3) at $B$ = 4.6 T and $R_c$ = 2 kΩ;
(4) at $B$ = 2.2 T and $R_c$ = 1.69 kΩ;

### 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).
I. Zajcewa, et. al., Supercond. Sci. Technol. 35, 015009 (2022).

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