Mixed-order phase transitions driven by two types of interactions in a single disordered superconducting network

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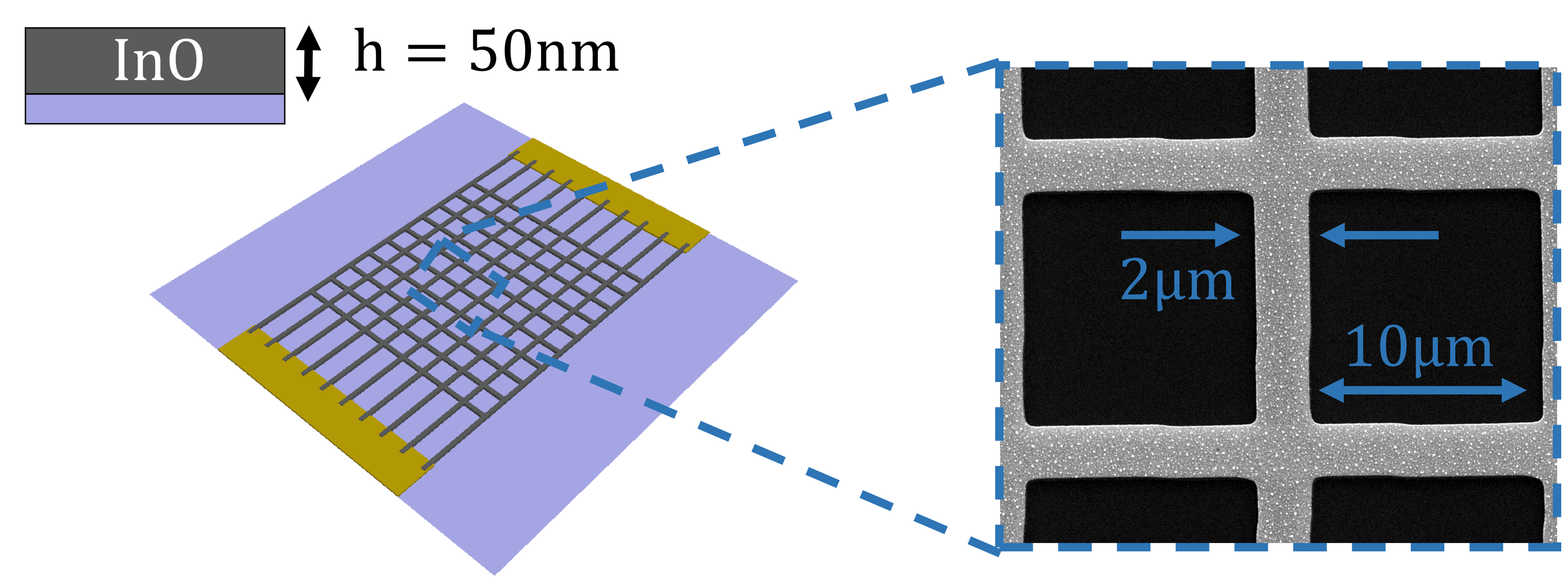
Frydman's superheroes

ABSTRACT

Mixed-order phase transitions, which combine abrupt phase switching with critical behavior, are uncommon in condensed-matter systems. Here, we demonstrate a mixed-order normal metal to superconductor transition in a single two-dimensional disordered superconducting network, driven by the interplay of two types of interactions: local electrical connectivity and long-range thermally mediated coupling generated by self-heating. Transport measurements reveal an abrupt, hysteretic transition that coexists with critical scaling exponents near the transition. Time-dependent measurements during the non-stationary abrupt transition further uncover a long-lived metastable resistance plateau, whose lifetime increases sharply as the bias current approaches the critical value. Scanning SQUID current imaging directly distinguishes the underlying current-flow morphologies: at low bias current, the transition is continuous and evolves through a complex percolative network of current paths, whereas at high bias current, the transition is abrupt and the current distribution changes discontinuously between normal and superconducting states. By fabricating otherwise identical networks on substrates with strongly different thermal conductivities, we show that the onset and strength of the abrupt transition are tunable, confirming the key role of thermal diffusion and heat retention. These results establish electro-thermal coupling as a practical route to engineer mixed-order criticality in single-layer superconducting networks.

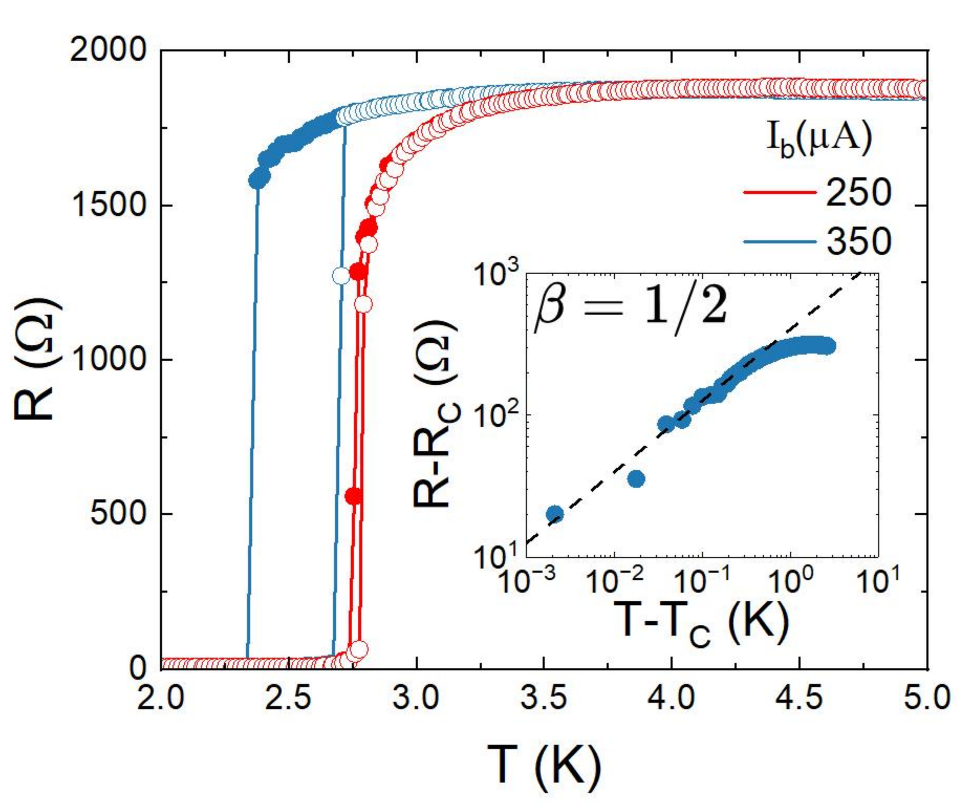
METHODS

- $50\mathrm{nm}$ of amorphous indium oxide (InO) deposited on a $\mathrm{Si/SiO_2}$ or glass substrate.
- InO Evaporated at $\mathrm{O_2}$ background pressure of $8\times10^{-6}\,\mathrm{Torr}$ to induce superconducting properties.
- Patterned into stripes of size $2\,\mu\mathrm{m}\times10\,\mu\mathrm{m}$ arranged in an $\mathrm{L}\times\mathrm{L}$ grid.
- $4\,\mathrm{nm}\ \mathrm{Cr}+35\,\mathrm{nm}\ \mathrm{Au}$ contacts for transport measurements are also deposited on the sides of the network.



RESULTS

Bias-driven heat yields a *mixed-order* transition



- Low currents = weak heat dissipation = single interaction systems
  - Smooth, continuous transition between normal (N) and superconducting (S) states.
  - No hysteresis.
- High currents = strong heat dissipation = two interactions systems
  - Sharp, abrupt transitions with hysteresis.
  - This indicates a first-order phase transition.
- Near the critical temperature, T_c, resistance follows:

$$R(T)-R(T_c)\propto(T-T_c)^{\beta}$$

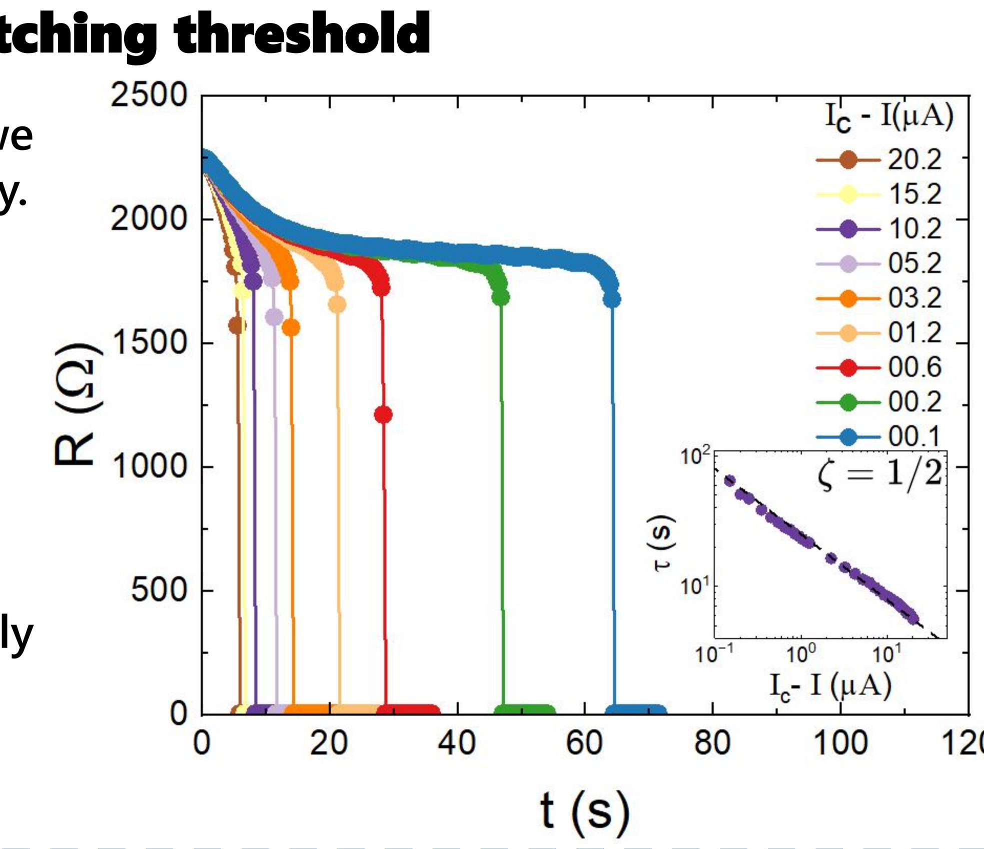
- Critical exponent $\beta=1/2$ (inset).

Critical slowing down and long-lived metastable plateaus near the switching threshold

- The collapse time τ increases as we bring the system closer to criticality.
- τ follows a scaling relation:

$$\tau\propto(I_c-I)^{-\zeta}$$

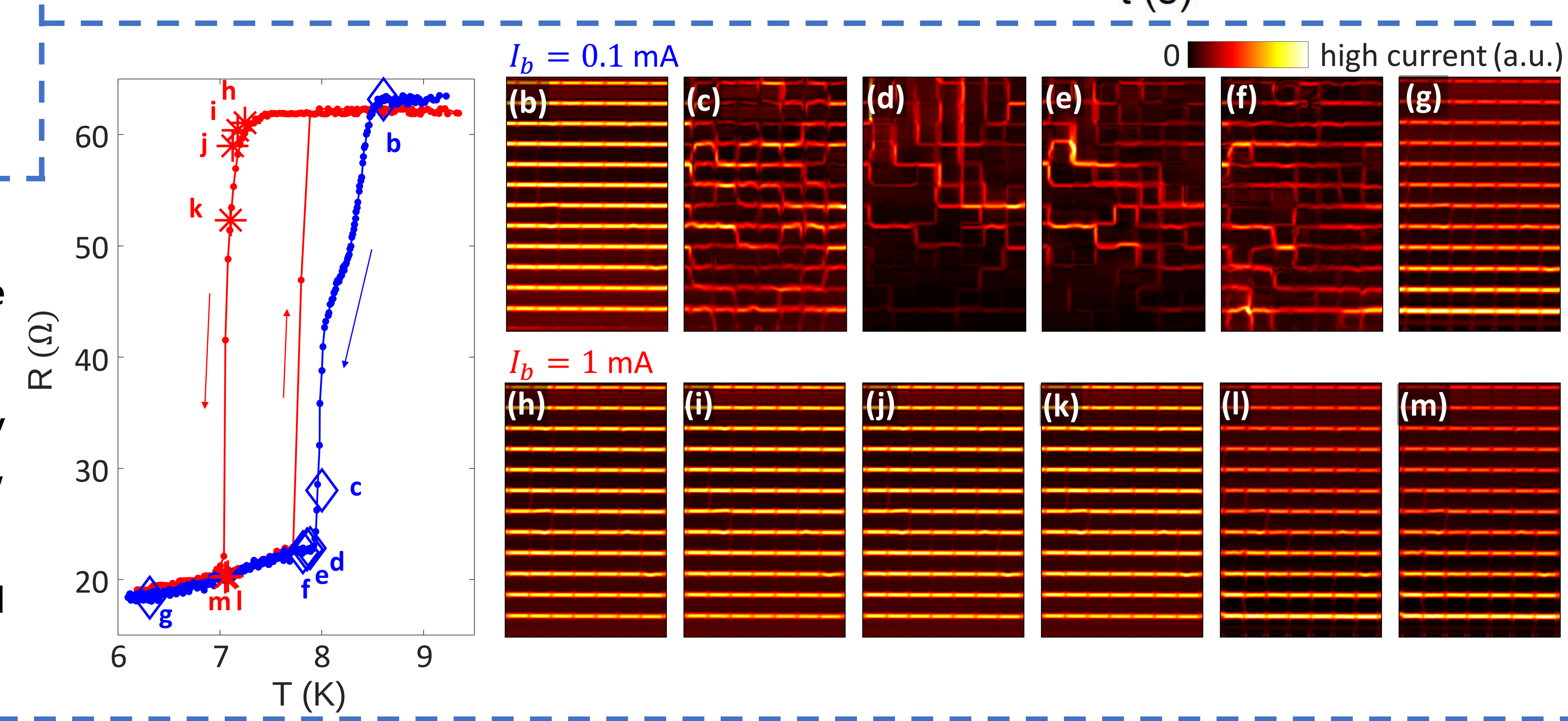
- Critical exponent $\zeta=1/2$ (insets).
- A long-lived *plateau* is clearly observed.

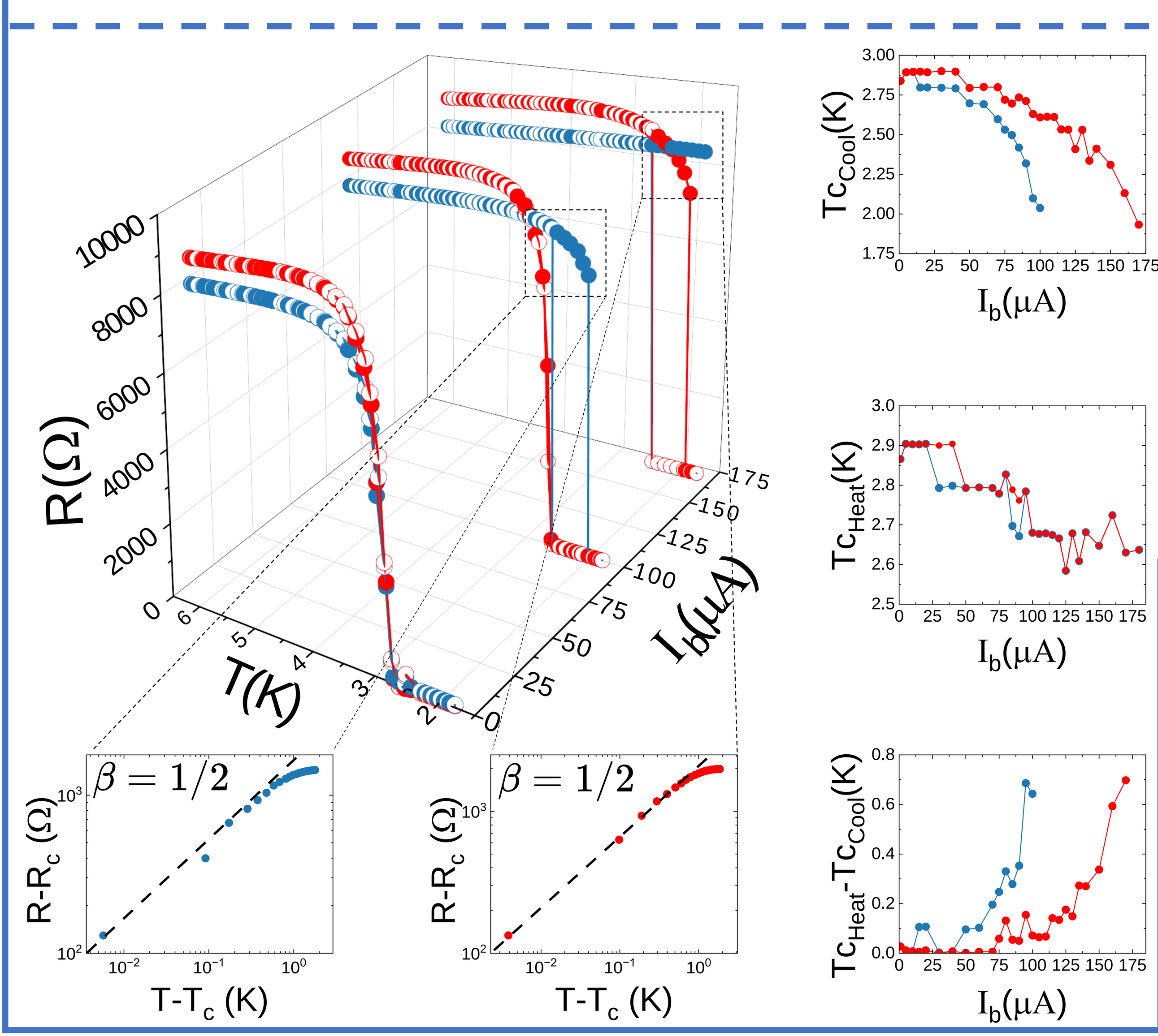


Imaging current-flow morphologies

To directly visualize how the network carries current through the transition, we performed scanning SQUID current imaging on a superconducting niobium network.

- At low bias current, the transition is accompanied by a complex, spatially heterogeneous current paths characteristic of a connectivity-dominated, percolation-like flow network.
- At high bias, the current distribution changes abruptly between normal and superconducting patterns consistent with a collective switching event.





The effect of substrate thermal conductivity on the properties of the abrupt switching

Since heat spreads through the network substrate, it is expected that the thermal conductivity (κ) of it will have some influence on the network. Blue is for a network on glass ($\kappa\approx0.1\frac{W}{mK}$ at $T=4K$) and red is for a network on silicon ($\kappa\approx1000\frac{W}{mK}$ at $T=4K$).

Both networks develop an abrupt, hysteretic, phase transition, while the one on glass requires less heat (i.e., current) to do so.

Same critical exponent $\beta=1/2$ is observed.

SUMMARY & CONCLUSIONS

- We have shown that a single superconducting network can undergo different types of phase transitions, depending on the existence of two interactions within it.
- The dependency interaction can be controlled via the substrate of the network. This provides additional proof for the effect of the dependency interaction

APPLICATIONS

- Single network systems are abundant in nature. The principle of two-interaction systems may be true for many of them and explain the origin of not yet fully understood phase transitions.
- Modeling modern networks of Infrastructure as two-interactions systems has the potential to allow the improvement of their robustness and help prevent catastrophic failures.