Interactions Between Ferroelectricity and Superconductivity in $SrTiO_3$

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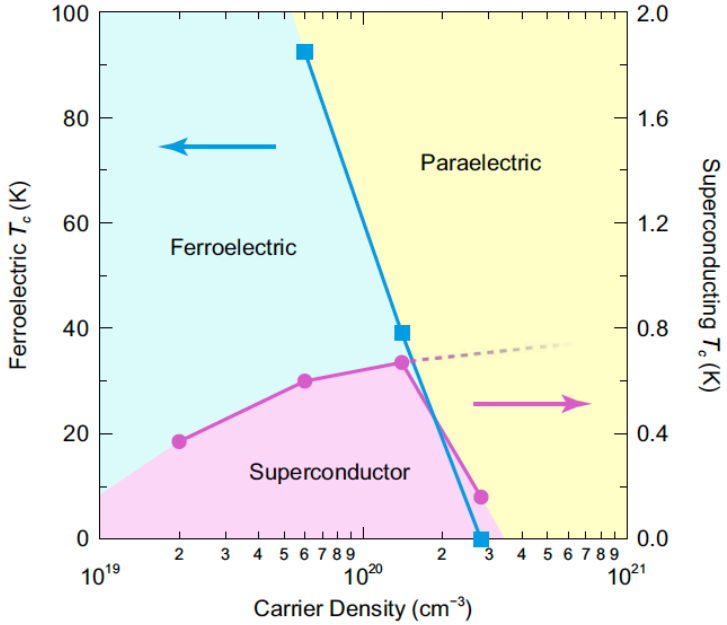
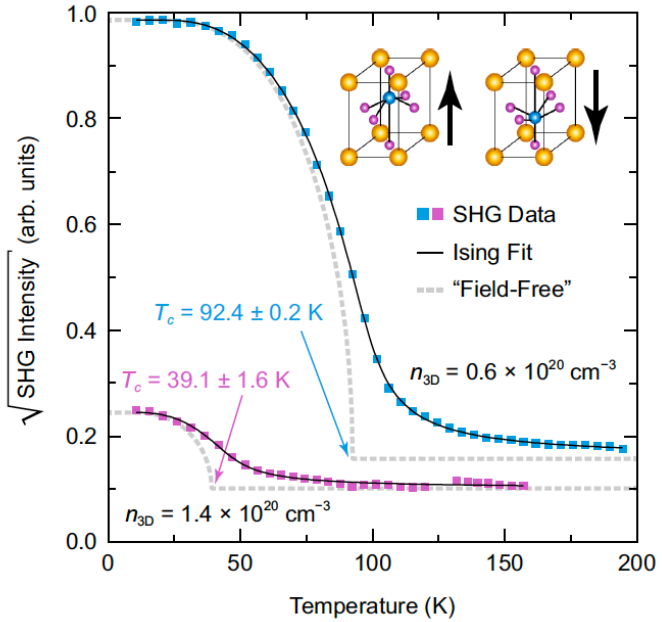
Phase Transitions in Doped, Strained $SrTiO_3$ Films

R:$SrTiO_3$
LSAT

Paraelectric ➜ Ferroelectric ➜ Superconducting





K. Ahadi et al., Sci. Adv. 5, eaaw0120 (2019).
R. Russel et al., Phys. Rev. Mater. 3, 091401(R) (2019).

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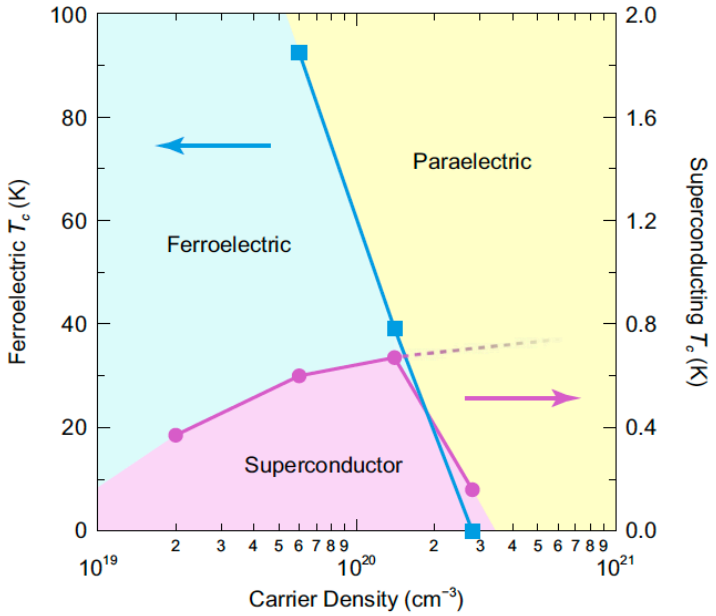

- Superconducting transition temperature is enhanced by a factor of two compared to unstrained films (T_c > 600 mK)*
- Superconducting dome is unaffected
- Ferroelectric transition temperature decreases with doping concentration
- Ferroelectric and and superconducting transitions "collapse" at a similar carrier density

K. Ahadi et al., Sci. Adv. 5, eaaw0120 (2019).
R. Russel et al., Phys. Rev. Mater. 3, 091401(R) (2019).

*See also: Tomioka et al., Nat. Comm. 10:738 (2019); Van der Marel, APS 2019; Stucky et al., Sci. Rep. 6, 37582 (2016); Herrera et al., Phys. Rev. Mater. 3, 124801 (2019); Rischau et al., Nat. Phys. 13, 643 (2017).

Nature of the Ferroelectric Transition

Paraelectric ➜ Ferroelectric

R:$SrTiO_3$
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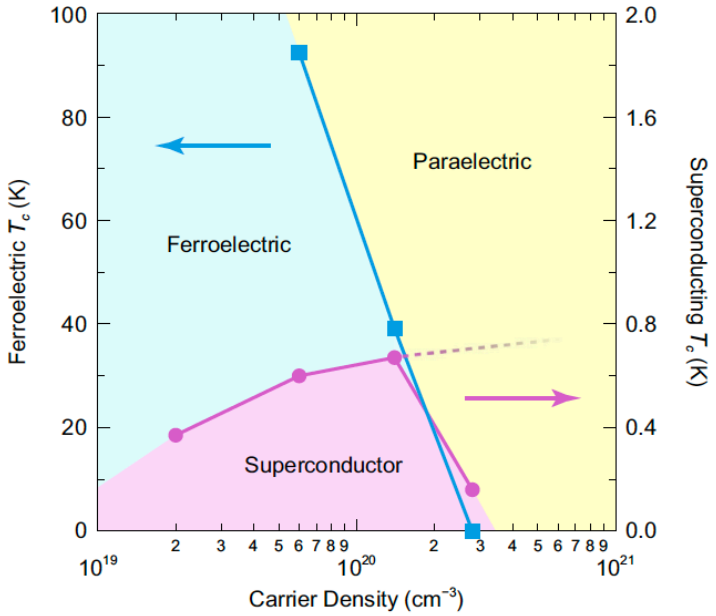
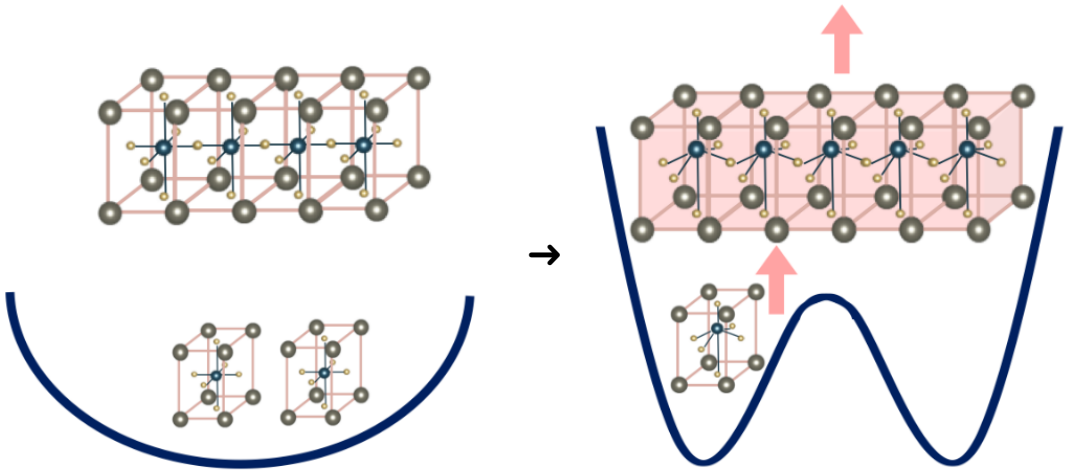
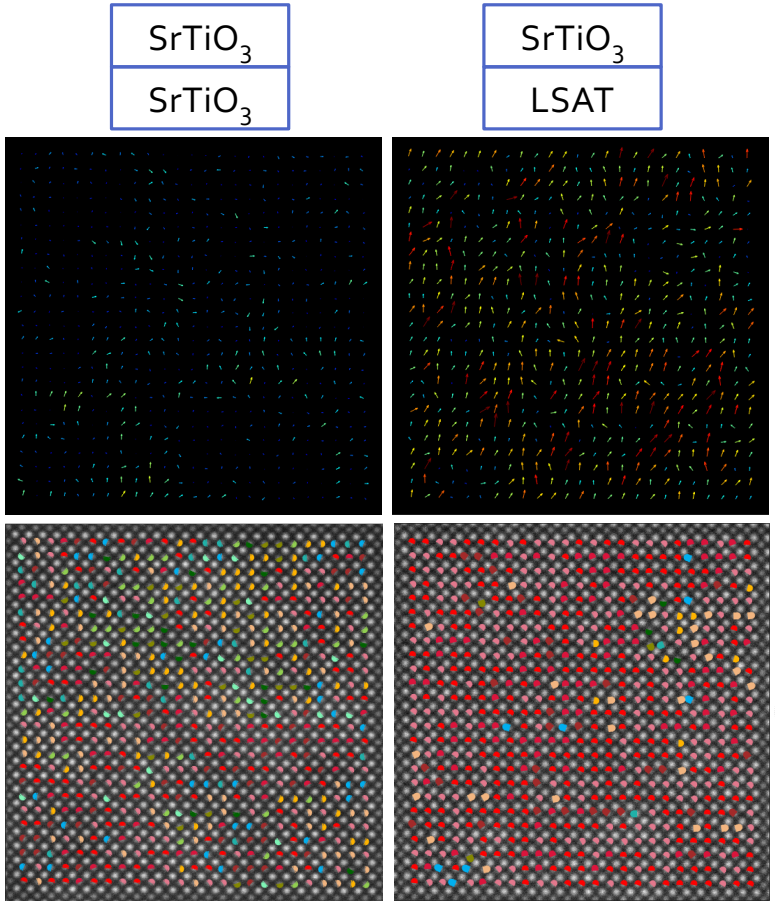
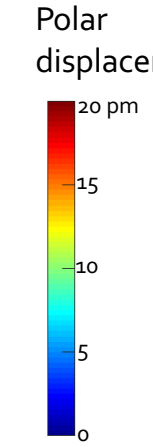




Prototype displacive/softmode phase transition?

Polar Nanodomains in the Paraelectric Phase



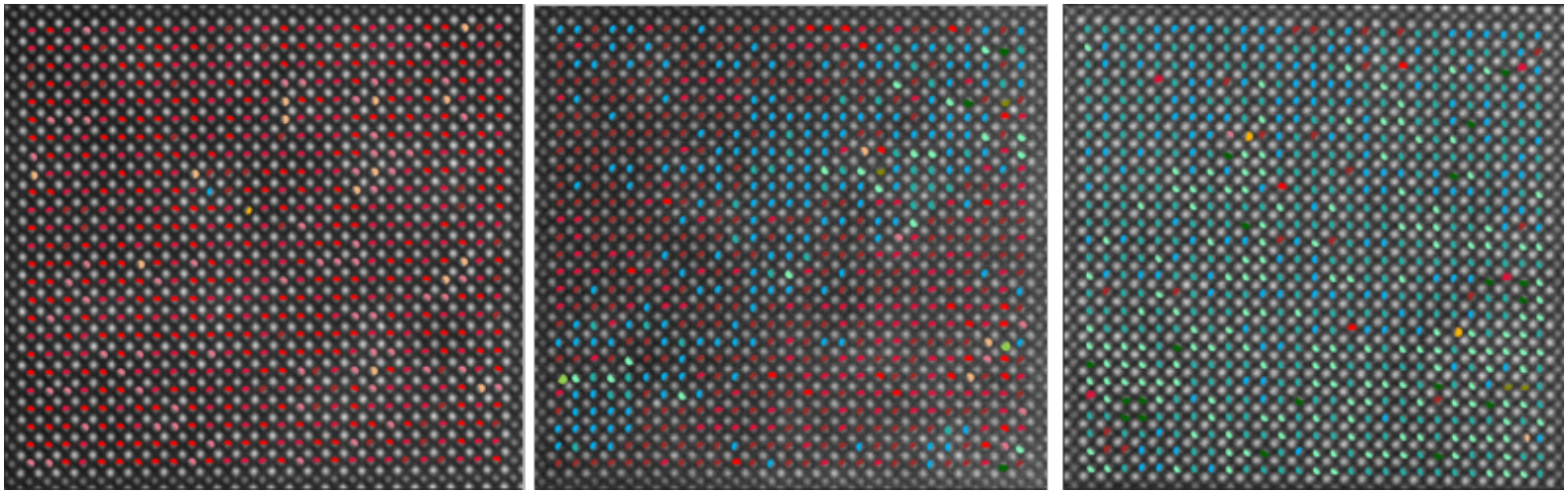


- Static Ti-column displacements and polar nanodomains in the paraelectric phase of strained $SrTiO_3$ films
- Local order, global disorder
- Coulomb interactions cause displacements already in the paraelectric phase
- **Order-disorder transition**
- Domains grow as temperature approaches the transition and reorient for a globally polarized phase

S. Salmani-Rezaie et al., submitted.

Polar Nanodomains in the Paraelectric Phase

Local ferroelectric order in the paraelectric phase



$SrTiO_3$

LSAT

S. Salmani-Rezaie et al., submitted.

Indication for a novel phase in the quantum paraelectric regime of $SrTiO_3$

K. Alex Müller[1], W. Berlinger[1,†], and E. Tosatti[2]

Z. Phys. B – Condensed Matter 84, 277–283 (1991)

"…low-temperature $SrTiO_3$ is locally ferroelectric already at zero stress."

$SrTiO_3$

reason: below this temperature, at least as far as structural modes (short correlation length) are concerned, the low-temperature $SrTiO_3$ is locally ferroelectric already at zero stress. Actually there is absolutely no anomaly, or jump – as noted in [22] – in the structural Raman-active modes at the onset of stress-induced ferroelectricity. However, the stress-free crystal is clearly not globally and macroscopically ferroelectric, which implies that, if present, the ferroelectric order parameter must fluctuate in space, averaging out to zero.

Polar Superconductor + Spin Orbit Coupling

- Breaking of inversion symmetry makes spin-orbit coupling relevant
- Singlet–triplet mixing expected, but details matter
- Topological superconductivity and unconventional pairing often occur together*
- Proposals of **polar fluctuations** mediating odd-parity/topological and unconventional SC

PHYSICAL REVIEW B **93**, 134512 (2016)

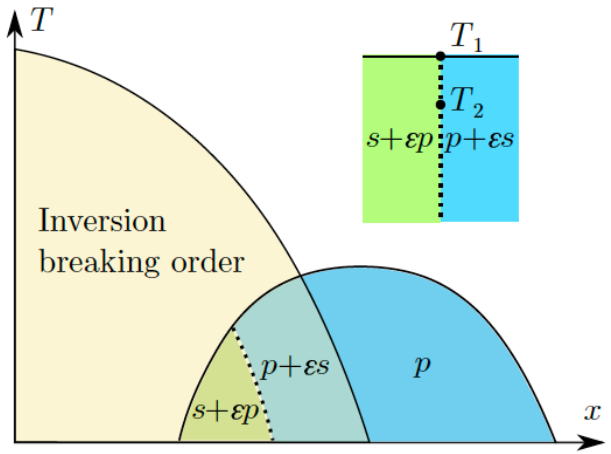
Topological superconducting phases from inversion symmetry breaking order in spin-orbit-coupled systems

Yuxuan Wang,[1] Gil Young Cho,[2] Taylor L. Hughes,[1] and Eduardo Fradkin[1]

PRL **115**, 207002 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

Odd-Parity Superconductivity in the Vicinity of Inversion Symmetry Breaking in Spin-Orbit-Coupled Systems

Vladyslav Kozii and Liang Fu



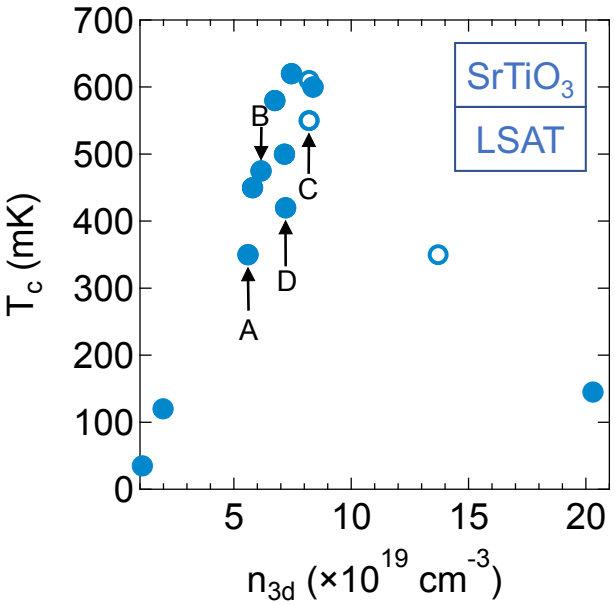
- **Experimental signatures?**

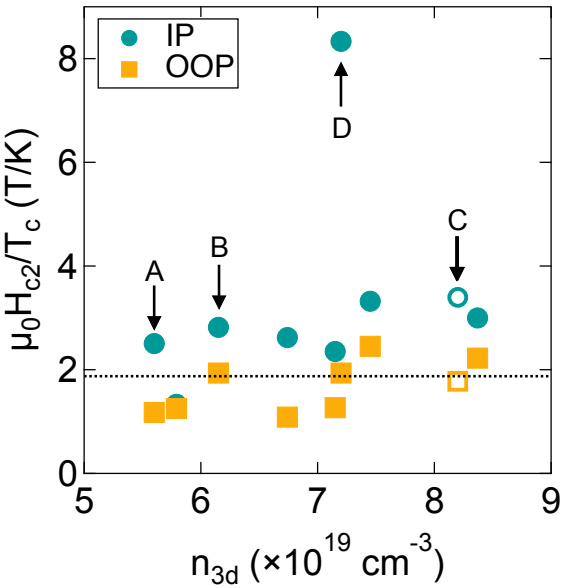
* For LAO/STO interfaces, see Scheurer et al., Nat. Commun. 6, 6005 (2015).

Experimental Signatures of Odd-Parity SC

Surface depletion of ~ 150 nm thin films causes rapid drop in T_c at low doping

R:$SrTiO_3$ | LSAT





- Critical fields above the Pauli limit seen in most films
- Usually taken as a strong indicator of odd-parity SC
- For odd-parity states, there is no suppression of superconductivity if the field is along with the direction of Cooper-pair spin
- Other explanations possible, e.g. multiband SC

Sample D is has an interfacial layer
Samples B and D are **partially strain-relaxed**

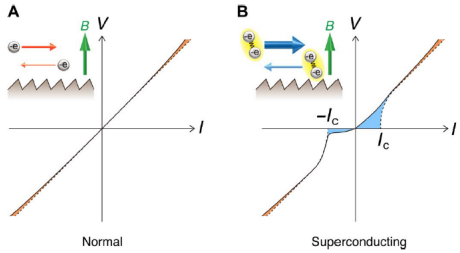
T. Schumann, L. Galletti et al., Phys. Rev. B 101, 100503(R) (2020)

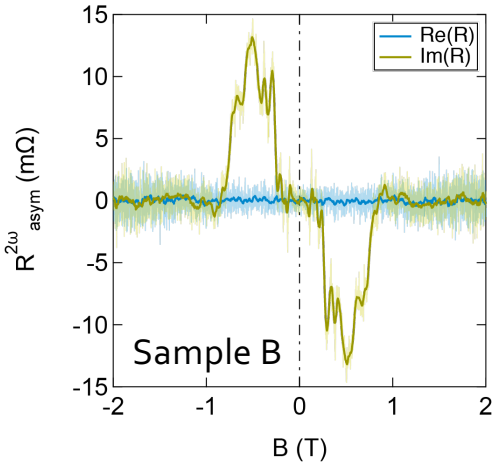
Experimental Signatures of Odd-Parity SC

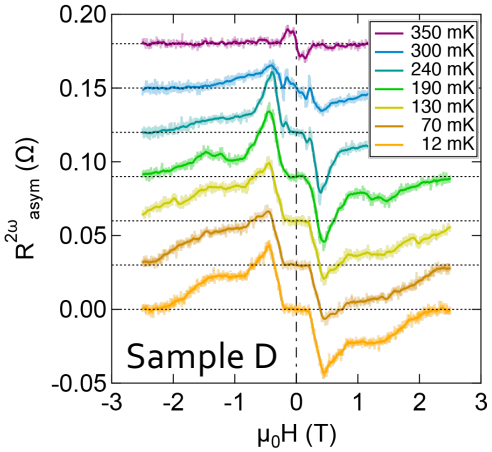
"Nonreciprocal current" $R = R_0(1 + \gamma BI)$ $V = RI + \gamma RBI^2$ Only for I ⊥ B

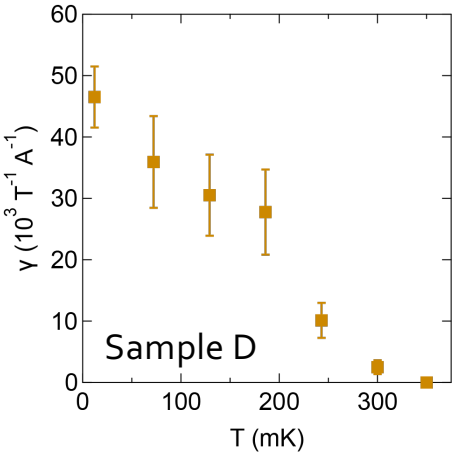
γ is the nonreciprocity and is predicted to be enhanced in case of triplet pairing in a theory of two-dimensional Rashba superconductors

R. Wakatsuki et al., Sci. Adv. **3**, e1602390 (2017).
R. Wakatsuki et al. Phys. Rev. Lett. 121, 026601 (2018).









Large nonreciprocal current in partially-strain relaxed films.
No signal in other films.

Role of polar fluctuations?

T. Schumann, L. Galletti et al., Phys. Rev. B 101, 100503(R) (2020)

Summary and Open Questions

- Signatures of odd-parity SC in doped, polar $SrTiO_3$ films
  - Need to be better understand role of spatial nonuniformity, polar fluctuations, 2D, …
- Suppression of polar nanodomains with doping in the paraelectric phase is key to suppressing the ferroelectric transition
- This increases the superconducting transition temperature, until disorder destroys both