Interactions Between Ferroelectricity and Superconductivity in SrTiO$_3$

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Phase Transitions in Doped, Strained SrTiO$_3$ Films

Paraelectric $\rightarrow$ Ferroelectric $\rightarrow$ Superconducting

Phase Transitions in Doped, Strained SrTiO$_3$ Films

Paraelectric $\rightarrow$ Ferroelectric $\rightarrow$ Superconducting

- 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 superconducting transitions "collapse" at a similar carrier density


Nature of the Ferroelectric Transition

Paraelectric $\rightarrow$ Ferroelectric

Prototype displacive/softmode phase transition?

$R$:$\text{SrTiO}_3$

$\text{LSAT}$
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

"...low-temperature SrTiO$_3$ is locally ferroelectric already at zero stress."

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 $^{2}$


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

- 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 a rapid drop in $T_c$ at low doping.

- 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

Experimental Signatures of Odd-Parity SC

“Nonreciprocal current” \( R = R_0 (1 + \gamma BI) \) \( V = RI + \gamma RBI^2 \) Only for \( I \perp B \)

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


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

Role of polar fluctuations?

Summary and Open Questions

- Signatures of odd-parity SC in doped, polar SrTiO₃ 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