Multiband superconductivity in interface superconductors

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• Multiband superconductivity
• STO and LAO/STO
• Probes for multiband SC
• Multiband signature in $H_{c2}$
• Results for $H_{c2}$ in STO and LAO/STO

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Ordinary single band superconductivity

- One band crossing Fermi energy
- Pairing between opposite sides of the Fermi surface opens a gap $\Delta$ in the density of states
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Multiband superconductivity

- Two bands crossing the Fermi energy
- Two (different) gaps $\Delta$ open up

Suhl, PRL 1959
Multiband superconductivity

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Multiband superconductivity

- Intrinsically interesting extension of superconductivity
- Allows for the interplay between the two gaps, novel dynamics
- Increasing number of materials are found to be multiband superconductors
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Our interest: is the specific material SrTiO3 (STO) and the interface between LaAlO3 (LAO) and STO a multiband superconductor?
Examples of Multiband SCs

- MgB2 (2001)

- Fe based superconductors (2008)

- Various heavy fermion SCs
  - PrOs$_4$Sb$_{12}$ (2005), CePt$_3$Si
  - Uranium compounds...

Nagamatsu, J. et al., 2001
Seyfarth, PRL 2005
Mukuda, JPSJ 2009
Detecting Multiband SC

- Tunnelling spectroscopy: multiple coherence peaks
- superfluid density
- Heat transport
- upper critical field

Figure 1

Figure 2

Figure 3

Extended Data Fig. 3

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Strontium Titanate (STO)

• Wide bandgap insulator, bandgap \(~3\text{eV}\)

• Doping with Nb, La or oxygen vacancies make it conducting

• Ferroelectric instability - nearly developed

• Has been studied experimentally and theoretically for 50 years

Mannhart, Nature 2004

Müller, PRB (1979)
Superconductivity in STO

- First oxide superconductor to be discovered
- Doping-tunable SC dome
- Inspired the search which resulted in high Tc cuprate SC
- First material discovered to be a multiband superconductor

Koonce et al PR 163 380

Binnig, PRL 1980
Superconductivity in STO

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- Doping-tunable SC dome
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But: when interface pure STO and LAO find a metallic interface layer
LAO/STO interface

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Superconductivity at the LAO/STO interface

- Metallic layer turns superconducting at low T
- For 3 layers of LAO, STM superconducting areas can be patterned with STM on nm scale
- Holds the promise for SC circuits and devices
Central question: What is the relation between bulk and interface STO?

- $T_c$ is similar ($\approx 300 \text{mK}$), robust to quality variations of the sample/interface material.

- As a function of doping/gate voltage a narrow superconducting dome appears.

Koonce PR 1967

Caviglia Nature 2008
Is LAO/STO a multiband SC, like STO?

Probes which have tried to address this issue

- Tunnelling spectroscopy

- Superfluid density
Is LAO/STO a multiband SC, like STO?

Other potential probes

- Heat transport
- Heat capacity
- impractical for interface

The result is confirmed by specific heat data in presence of magnetic field (see the supplement). This brings us back to the shift observed at zero magnetic field between the bulk transition temperature and vanishing resistivity. In summary, we find that optimally-doped SrTiO$_3$:Nb is either due to the existence of a third scale of magnetic field set by a second superconducting gap. Points to the existence of an additional superconducting field scale, $H_{c2}$, lower than $H_{c1}$, thermal conductivity $\kappa$ becoming independent of magnetic field above a threshold magnetic field, which is 0.08 $H_{c1}$. For Nb and V$_3$Si, this is the case of Nb-doped SrTiO$_3$ superconductors, this is the case of Nb-doped SrTiO$_3$. Below a second magnetic field at which resistivity vanishes, but bulk electrons serve a vanishing resistivity at a temperature well above the bulk critical temperature. Recent near-field studies on the STO interfaces have detected enhanced electrical conductivity along twin boundaries [33, 34], providing an explanation. Invoking sample inhomogeneity does not provide an answer. In a wide doping range, the critical temperature does not show a strong dependence on doping. An additional constraint for theory.

As seen in Fig. 4b, the bulk upper critical field is significantly lower than the resistive upper critical field. This work is supported by Agence Nationale de la Recherche as a part of QUANTHERM and SUPERFIELD projects.

In contrast to all other known cases of multi-band superconductivity, one can here tune the Fermi surface (in sheer size as well as the number of its nodes. These are new pieces in this puzzle of exceptions to the nodeless superconductors. In particular, one of the two detected gaps has significantly lower than $H_{c2}$, thermal conductivity $\kappa$ rises of thermal conductivity by a small magnetic field, which is 0.08 $H_{c1}$. In this respect, our results are similar to those reported by Binnig et al. [3], who detected strong anisotropy of one of the two detected gaps. Two possibilities come to mind. Either two of the bands have similar to those reported by Binnig et al. [3], who detected strong anisotropy of one of the two detected gaps. Two possibilities come to mind. Either two of the bands have
Suggest looking at the upper critical field $H_{c2}$ as a probe for multiband superconductivity in LAO/STO
$H_{c2}$ as a probe for multiband SC in LAO/STO and STO

$H_{c2}$ is one of the few probes applicable both to the bulk and interface system

- Calculate expected $H_{c2}$ behaviour for both bulk and interface
- Show characteristic multiband behaviour
- Allows direct comparison of bulk and interface system
Disordered bulk STO: quasiclassical Usadel equations

- Solve linearised Usadel equations with a B-field $H \parallel \hat{z}$.

$$2\omega f_m - D_m \left( \nabla^2_x + \nabla^2_y + \nabla^2_z + \frac{4\pi i H x}{\phi_0} \nabla_y - \frac{4\pi^2 H^2 x^2}{\phi_0^2} \right) f_m = 2\Delta_m$$

$m$: band index ($\in \{1, 2\}$),
$D_m$: Diffusion coefficient in the band
$f_m$: quasiclassical anomalous Green’s function

- Linearised: valid for infinitesimal gaps $\Delta$, so at $T_c$.
- 2-band gap equation:

$$\Delta_m = 2\pi T \sum_{\omega > 0} \sum_{m'} \lambda_{mm'} f_{m'}(\vec{r}, \omega)$$

$\lambda$: coupling constants

- Solving this equation gives pairs $(H, T)$ and since $T = T_c$ (linearised equations) we get pairs $(H_{c2}, T_c)$. 
Results for $H_{c2}$

Solve for two sets of parameters:

$$\eta = \frac{D_2}{D_1}$$

Parameters: Fernandes, PRB 2013

$$\lambda_{11} = 0.14, \lambda_{22} = 0.13, \lambda_{12} = 0.02$$

Parameters: Bussmann-Holder, Ferroelectrics 2010

$$\lambda_{11} = 0.3, \lambda_{22} = 0.1, \lambda_{12} = 0.015$$
Interface system

Thin superconducting layer

- retain $\nabla_z$ term in the Usadel equation
- Incorporate the effects of Rashba spin-orbit coupling
Finite thickness

- need to retain $\nabla_z$ term in

$$2\omega f_m - D_m \left( \nabla^2_x + \nabla^2_z - \frac{4\pi^2 H^2 x^2}{\phi_0^2} \right) f_m = 2\Delta_m$$

- At the boundary to the vacuum, $\Delta = 0$

- An an interface between a SC and a metal $\frac{d\Delta}{dz} = 0$

- thickness: $d \sim 12$ nm

- $\nabla^2_z \to -\frac{\pi^2}{4d^2}$

- Incur an extra energy cost: effectively $H$ increases
Spin-orbit coupling (SOC) at the interface

- Due to inversion symmetry breaking get strong Rashba SOC

- Leads to a modification of the momentum operator, anomalous Green’s function $f$ becomes a matrix

$$\nabla_x f \rightarrow \nabla_x f + \frac{i\alpha m_e}{\hbar} [\sigma_y, f] \quad \alpha : \text{SOC coupling strength}$$

- singlet and triplet components of $f$ get coupled

- Concentrate on dominant singlet component

- singlet f gets energy penalty

![Graph showing the behavior of different components $f_s, f^a, f^c, f^0_s$ with respect to frequency $\omega$.]
LAO/STO results

\[ \lambda_{11} = 0.14, \lambda_{22} = 0.13, \lambda_{12} = 0.02 \]

Comparison: bulk STO results
Conditions under which $H_{c2}$ is a useful probe

$H_{c2}$ is useful when

- $\lambda_{11} \approx \lambda_{22}$

$\lambda_{12} \ll \lambda_{11}$

\[ \eta = \frac{D_2}{D_1} = 0.1 \]
Hc2 and superfluid density are complementary probes

• Superfluid density useful when: $\lambda_{11} \gg \lambda_{22}$

• Upper critical field Hc2 useful when: measure onset of SC $\lambda_{11} \approx \lambda_{22}$

following Kogan, PRB 2009
Summary

- Multiband superconductivity: Two or more gaps open
- Various techniques for detecting MBSC
- LAO/STO interface: metallic layer
- Upper critical field $H_{c2}$: Probe for multiband superconductivity - applicable to bulk and interface
- SF density and $H_{c2}$ are complimentary probes
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Thank you!