Proximity and Josephson vortices studied by scanning tunneling spectroscopy

Brun Christophe

Paris Institute of Nanosciences

CNRS

&

Sorbonne University

Paris, FRANCE

Rencontres de Moriond 2019
Paris Institute of Nanosciences - CNRS - SU

Lise Serrier-Garcia (PhD student)
Vladimir Cerchez (post-doc)
Vassily Stoliarov (post-doc)
François Debontridder (Engineer)
Brun Christophe (CNRS)
Tristan Cren (CNRS)

Technical Engineering School - ESPCI
Dimitri Roditchev (Prof)

Collaborations (Theory)

Juan-Carlos Cuevas – Madrid University, Spain
Sebastian Bergeret – San Sebastian, Spain

Milorad Milosevic – Antwerpen University, Belgium

Mikhail Y. Kupriianov – Moscow MIPT, Russia
Alexander A. Golubov – Moscow MIPT, Russia
OUTLINE

✓ Introduction: Proximity effect in superconductors

✓ S-N with 2D correlated N, lateral proximity effect
  PRL 110, 157003 2013

✓ S-N-S lateral network, Josephson vortices studied by STM/STS

✓ S-N vertical, proximity vortices studied by STM/STS
  Nature Commun. 9, 2277 (2018)
Superconducting proximity effect

Old experiments
Holm and Meissner (1932)
Bedard and Meissner (1956)
Meissner (1958), (1960)

First theories
De Gennes (1964)
McMillan (1968)
Clarke (1969)
Deutscher and De Gennes (1969)
Early understanding of proximity effect

First theories
De Gennes (1964)
McMillan (1968)
Clarke (1969)
Deutscher and De Gennes (1969)

### Interface

- **Density of Cooper pairs**: $|F(x)|^2$
- **Order parameter**: $\Delta(\vec{r}) = V(\vec{r})F(\vec{r})$

Diffusive metal

\[ L_T = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \]

\[ F(\vec{r}) = \langle \hat{\psi}_{\uparrow}(\vec{r})\hat{\psi}_{\downarrow}(\vec{r}) \rangle \]
Modern description of proximity effect

Andreev reflection at S/N interface + long-range phase coherence in N

Modern description of proximity effect

Andreev reflection S/N interface + long-range phase coherence in N

Larkin et al. (1968, 75, 77), Schmid & Schön (1975), Blonder et al. (1982), Zaitsev (1984)
Modern description of proximity effect

Andreev reflection S/N interface + long-range phase coherence in N

The decay length of pair correlations is energy dependent

Energy-dependent and spatially-dependent quantity:
The Local Density of States (LDOS)
Energy-dependent and spatially-dependent quantity: The Local Density of States (LDOS)

- mini-gap $\Delta_g$ linked to $\hbar D_N / L^2$

- McMillan (1968)
- Golubov & Kupriyanov (1988)
- Belzig et al. (1996)
Energy-dependent and spatially-dependent quantity:
The Local Density of States (LDOS)

N of finite length $L$

N of infinite length

mini-gap $\Delta_g$ linked to $\frac{\hbar D_N}{L^2}$

No mini-gap

McMillan (1968)
Golubov & Kupriyanov (1988)
Belzig et al. (1996)
Various length scales in proximity effect

\[ L_E = \sqrt{\frac{\hbar D_N}{E}} \]

\[ L_T = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \]

mean free path \( \ell_N \)

coherence length

thermal length

phase-breaking length \( L_\phi \)
Proximity effect for an S-N-S junction

Superconducting correlations propagate for $E < E_{Th}$

mini-gap $\Delta_g$ linked to $E_{Th}$

Golubov & Kupriyanov (1988)
Zhou et al. (1998)
Tunneling as a probe of proximity effect

Fixed tunneling probe

I(V)

Counter electrode

Thin tunnel barrier

N metal

Superconductor

Interface

Lithography techniques

Advantage: Direct information about spatial evolution of the DOS

Scanning tunneling probe

STM tip

N metal

Superconductor

Interface
Proximity effect in superconductors

First study of the spatial dependence: **nano-lithography**

S. Guéron *et al.* PRL 77, 14 3025 (1996)

Ex situ STS: Vinet *et al.* PRB 63, 165420 (2001); Mouussy *et al.* EPL 55, 861(2001)
OUTLINE

✓ Introduction: Proximity effect in superconductors

✓ S-N with 2D correlated N, lateral proximity effect
  PRL 110, 157003 2013

✓ S-N-S lateral network, Josephson vortices studied by STM/STS

✓ S-N vertical proximity vortices studied by STM/STS
  Nature Commun. 9, 2277 (2018)
STM/STS

UHV: $p < 5 \times 10^{-11}$ mbar

*In situ* growth @ $p < 3 \times 10^{-10}$ mbar

Base $T^\circ$: 0.285 mK

$T_{electrons} \sim 380$ mK

Magnetic Field: 0 – 10 T

Home-made apparatus

STM head

e-beam evaporators
Silicon substrate

Si(111)-7x7

Mono-atomic steps separating atomically flat terraces

E_{\text{gap}} \sim 1 \text{ eV}

Insulating at low temperature

STM topography
**in situ** Pb grown on Si(111)-7x7 in UHV

Mono-atomic steps separating atomically flat terraces

Pb nanocrystals (8-16 ML)

STM topography

Pb wetting layer 1-2ML thick

100nm
Amorphous versus Crystalline atomic monolayers

Amorphous wetting layer

Si(111) substrate

Single crystal Pb island

S

7×7 interface
Disordered interface

Pb-√3×√3 interface
Crystalline interface
Striped incommensurate (SiC)

44 nm

Single crystal Pb island

S

Si(111) substrate

Crystalline monolayer

30 nm

Tunneling spectroscopy of superconductors

\[ \frac{dI}{dV}(r) = \int_{-\infty}^{\infty} N_s(E, r) \left[ -\frac{\partial f(E+eV)}{\partial(eV)} \right] dE \]

\[ N_s(E) = N_N(E) \frac{E}{\sqrt{E^2 - \Delta^2}} \]

\[ \Delta = 1.20 \text{ meV} \]
\[ T_{\text{eff}} = 0.38 \text{K} \]

BCS DOS

14 ML Pb/Si(111)
Proximity effect: Pb island – 2D disordered metal

\[ \ell_N \sim \text{few nm} \]

\[ \frac{\text{d}I}{\text{d}V(V=0)} \text{ map} \]

\[ 5\text{nm} \]

\[ l \text{ in situ transport} \quad R \square \sim 2-4 \text{ k}\Omega \]

Proximity effect: Pb island – 2D disordered metal

LDOS spatial dependence

Very high interface transparency
Reference spectrum on the 2D disordered metal

Zero-bias anomaly

- Altshuler-Aronov like ??
- Dynamical Coulomb blockade ??

Modeling the tunneling DOS of the 2D metal

Rollbühler and Grabert

Tunneling into a disordered 2D conductor

Dynamical Coulomb Blockade in an ultrasmall junction with an Ohmic environment

Modeling dynamical Coulomb blockade

\[ Z(\omega) = \left[ i \omega C_{WL} + 1/R_{WL} \right]^{-1} \]

\[ I(V) = e \left[ \Gamma_{WL\rightarrow\text{tip}}(V) - \Gamma_{\text{tip}\rightarrow WL}(V) \right] \]

\[ \Gamma_{WL\rightarrow\text{tip}}(V) = \frac{1}{e^2 R_T} \int_{-\infty}^{\infty} dE \int_{-\infty}^{\infty} d\epsilon n_{WL}(E) \times f(E)[1 - f(E - \epsilon + eV)]P(\epsilon) \]
\( C_{\text{WL}} = 80 \text{ aF} \) \( R_{\text{WL}} = 3.22 \text{ k}\Omega \)

\( R_{\text{WL}} \) consistent with \textit{in-situ} transport \( R_{\square} \sim 2-4 \text{ k}\Omega \)

\( E_c = \frac{e^2}{2C_{\text{WL}}} = 1 \text{ meV} \)
Combining 1D Usadel equations and dynamical Coulomb blockade

\[ \xi = \left( \frac{\hbar D}{\Delta_{\text{Pb}}} \right)^{1/2} \approx 15\text{nm} \]

\[ D = 4.1 \text{ cm}^2\text{s}^{-1} \]

OUTLINE

- Introduction: Proximity effect in superconductors

- S-N lateral proximity effect studied by STM/STS
  PRL 110, 157003 2013

- S-N-S lateral network, Josephson vortices studied by STM/STS

- S-N vertical proximity vortices studied by STM/STS
  Nature Commun. 9, 2277 (2018)
Network of short diffusive SNS junctions

STM topography
Elaborating short lateral diffusive SNS proximity junctions

STM topography

Proximity SNS junctions: growing islands closer to each other!

$$E_{Th} = \hbar D_N / L^2$$
Elaborating short lateral diffusive SNS proximity junctions

$\frac{dl}{dV} (V=0)$ map

Proximity link between two Pb islands
SNS proximity junction

dl/dV spectrum in the middle of N

\[ \frac{dI}{dV} \] spectrum in the middle of N

\[ \xi \approx 12\text{nm} \]
\[ E_{Th} = 0.063 \text{ meV} \]
\[ \Delta_{\text{mini-gap}} \approx 0.21 \text{ meV} \]
\[ D \approx 2.5 \text{ cm}^2\text{s}^{-1} \]

No adjustable parameter here (D,L fixed) good fit from 1D Usadel + DCB
We do have proximity effect, but…

…do we really have Josephson junctions ??
Real proof: the Josephson effect

Network of short diffusive SNS junctions

STM topography
Network of short diffusive SNS junctions

*topography*

*dl/dV (V=0) map*

Creating phase gradients in Pb islands

\[ \frac{dI}{dV} (V=0) \text{ map} \]

Direct observation of Josephson vortex cores

Mini-gap everywhere

Mini-gap destroyed

0 mT

60 mT

200 nm

S

N

A

B

C

A

B

C
Direct observation of Josephson proximity vortices

B = 120 mT

B = 180 mT

Modelling (I) Ginzburg-Landau

Order parameter

Phase

Supercurrents

$B = 60 \text{ mT}$

$$\mathbf{j} = \rho_s \mathbf{v}_S = D (\nabla \varphi - 2e \mathbf{A} / \hbar)$$

Nat. Phys. 11, 332 (2015)
Modelling (II) Ginzburg-Landau + SC Interference

\[ \varphi^*(\vec{r}, \vec{r}_i) = \varphi(\vec{r}_i) + \frac{2\pi}{\phi_0} \int_{\vec{r}_i}^{\vec{r}} A \cdot d\vec{l} \]

\[ \phi(\vec{r}) \propto \sum_i \int_{C_i} e^{-\frac{||\vec{r}-\vec{r}_i||}{2\xi}} e^{i \varphi^*(\vec{r}, \vec{r}_i)} d\vec{l} \]

STS experiment

Model
Explanation: shear phase gradients from neighboring islands

\[ \varphi^* = \varphi(r_2) - \varphi(r_1) - \frac{2e}{\hbar} \int_{r_1}^{r_2} A \, dl \]

Josephson current

\[ j_{1OC} = j_C \sin(\varphi^*) \]

Mini-gap destroyed for \( \varphi^* = \pm \pi \)
Where is the flux quantum?

2D Usadel calculations for rectangular SNS junctions

Magnetic field or current induced Josephson vortices

OUTLINE

✓ Introduction: Proximity effect in superconductors

✓ S-N lateral proximity effect studied by STM/STS
  PRL 110,157003 2013

✓ S-N-S lateral network, Josephson vortices studied by STM/STS

✓ S-N vertical proximity vortices studied by STM/STS
  Nature Commun. 9, 2277 (2018)
Behavior of proximity vortices in vertical S-N

3D proximity effect
mini-gap $\Delta_g$ linked to

$$\frac{\hbar D_N}{L^2}$$
Behavior of proximity vortices in vertical S-N

Diagram:
- STM tip
- Vortex core
- N (Cu)
- S (Nb)
- 50 nm Cu diffusive
- 100 nm Nb diffusive
- $\vec{\nabla}\phi$
- H
S-N bilayer R(T) characteristics

$T_c = 8.1\text{K}$
S-N bilayer sample preparation

Cu, Nb: magnetron sputtering

\(d_{\text{Nb}} = 100 \text{ nm}\)

\(d_{\text{Cu}} = 50 \text{ nm}\)

\(d_{\text{SiO}_2} = 270 \text{ nm}\)

\(d_{\text{Si}} = 0.3 \text{ mm}\)

Stoliarov et al. APL 104, 172604 (2014)
Grain size $\sim \ell_N \sim 20\ \text{nm}$

$D_N = \ell_N v_F / 3 \approx 100\ \text{cm}^2\text{s}^{-1}$

$\xi_N = (\hbar D_N / \Delta)^{1/2} \approx 37\ \text{nm}$
S-N bilayer in finite perpendicular B

d$I$/d$V(V=0)$ maps  \hspace{1cm} T=300 mK

B = 5 mT \hspace{1cm} B = 55 mT

Comparison of Abrikosov and proximity vortex
dI/dV(V=0) spatial dependence through the vortex core

Frequency: 5 mT
S-N bilayer in finite perpendicular B

dI/dV(V=0) maps

T = 300 mK

B = 5 mT

Δ_g ~ 0.5 meV

$\frac{dI}{dV}(V)$ spectra across vortex cores

B = 5 mT

B = 55 mT
Usadel modeling of S-N bilayer in perpendicular B

- Circular geometry of the vortex unit cell (radial symmetry around vortex core centers) → \( \theta(r,z) \)  Wigner-Seitz approximation for low B
- Self-consistently solved in N and S
- External field assumed constant inside a unit cell (OK since \( \lambda_S \gg \xi_S \))
- Boundary conditions at N, S surfaces and at Z=0 interface
- Numerical method: Newton Finite Element Method

Igor A. Golovchanskiy, Daniil I. Kasatonov, Mikhail M. Khapaev, Mikhail Yu. Kupriyanov, Alexander A. Golubov

Nature Commun. 9, 2277 (2018)

Other 2D Usadel : Cuevas & Bergeret PRL (2007)
Usadel modeling of S-N bilayer in perpendicular $B = 5\ mT$
Usadel modeling of S-N bilayer in perpendicular B

\[ B = 55 \text{ mT} \]

\[ B = 120 \text{ mT} \]
Temperature dependance

B = 5 mT
Usadel modeling of S-N bilayer in perpendicular $B$

Size of the vortex core at $V=0$

$$L = \left( \frac{\hbar D}{\Delta_g} \right)^{1/2} \approx 110 \text{ nm at 5mT}$$
SUMMARY

Proximity effect to a 2D correlated metal
(Usadel 1D + dynamical Coulomb blockade)

Josephson proximity vortices
(Ginzburg-Landau, Usadel 2D)

Proximity vortices in S-N vertical bilayer
(Usadel 3D->2D)
**Usadel Equations**

\[
\ln t + \psi \left( \frac{1}{2} + \frac{t}{r_c^2} \right) - \psi \left( \frac{1}{2} \right) = 0. \quad (1)
\]

\[
\frac{d^2 \theta_S}{dz^2} + \frac{1}{r} \frac{d}{dr} \left( r \frac{d \theta_S}{dr} \right) - (\Omega + Q^2 \cos \theta_S) \sin \theta_S = -\Delta \cos \theta_S, \quad (2)
\]

\[
\frac{d^2 \theta_N}{dz^2} + \frac{1}{r} \frac{d}{dr} \left( r \frac{d \theta_N}{dr} \right) - \frac{\Omega + k^2 Q^2 \cos \theta_N}{k^2} \sin \theta_N = 0, \quad (3)
\]

\[
Q = \frac{1}{r} \left( 1 - \frac{r^2}{r_S^2} \right), \quad (4)
\]

\[
\Delta \ln t + 2t \sum_{\Omega > 0} \left( \frac{\Delta}{\Omega} - \sin \theta_S \right) = 0. \quad (5)
\]

\[
t = \frac{T}{T_c}
\]

\[
k = \frac{\xi_N}{\xi_S}
\]

\[
\xi_S = \sqrt{\hbar D_S / 2\pi k_B T_c}
\]

\[
\xi_N = \sqrt{\hbar D_N / 2\pi k_B T_c}
\]
**Boundary Conditions \( z = 0 \)**

\[
\gamma_B k \frac{d\theta_N}{dz} = \sin \theta_N \cos \theta_S - \sin \theta_S \cos \theta_N, \quad (6)
\]

\[
\frac{d\theta_S}{dz} = \gamma k \frac{d\theta_N}{dz}, \quad (7)
\]

where \( \gamma_B \) and \( \gamma \) are the suppression parameters

\[
\gamma_B = \frac{R_{SN} A_{SN}}{\rho_N \xi_N}, \quad \gamma = \frac{\rho_S \xi_S}{\rho_N \xi_N}. \quad (8)
\]

\[
\frac{d\theta_S}{dz} = 0, \quad z = -d_S, \quad (9)
\]

\[
\frac{d\theta_N}{dz} = 0, \quad z = d_N, \quad (10)
\]

\[
\frac{d\theta_N(r_S)}{dr} = \frac{d\theta_S(r_S)}{dr} = 0, \quad \theta_N(0) = \theta_S(0) = 0. \quad (11)
\]
Conclusion

✓ Remarkable superconducting properties of single atomic layers


- New short-scale peak height variations – non BCS e-e terms in 2D

\[ \ell_{\text{fluct}} \sim 2-10 \text{ nm} < < \xi_0 \sim 50\text{nm} \]

- Rashba spin-orbit coupling effect on superconductivity sing-triplet

Subgap filling \( \ell_{\text{fluct}} \sim 10 \text{ nm} < \xi_0 \sim 50\text{nm} \)

- Josephson barriers at step edges - Josephson-Abrikosov vortices

✓ Proximity to a 2D monolayer superconductor PRX 4, 011033 (2014)

✓ Proximity to a 2D diffusive metallic layer PRL 110, 157003 (2013)

\[
\frac{1}{q} \oint m \vec{v}_s \cdot d\vec{l} = \frac{1}{q} \oint \hbar \nabla \varphi(\vec{r}) \cdot d\vec{l} - \oint \vec{A}(\vec{r}) \cdot d\vec{l},
\]

\[
\Phi_s = 2\pi \frac{\hbar}{2e} - \frac{1}{2e} \oint m \vec{v}_s \cdot d\vec{l} = \Phi_0 - \frac{1}{2e} \oint m \vec{v}_s \cdot d\vec{l},
\]
Suggested SNS nano-device
Gauge-Independent Phase Difference
Self-Consistent JV positioning

Since the islands are independent, their gauge-independent phase portraits also are. There is an arbitrary global phase difference between each pair of islands. It decides where Josephson Vortices are located inside junctions.
Self-Consistent JV positioning

For each pair of islands the total current crossing each junction and corresponding kinetic energy are calculated as a function of global phase difference $\Delta \phi_0$. The exact position of JV is obtained when $j_{\text{TOT}}=0$ and $E_c=\text{Min}\{E_c(\Delta \phi_0)\}$.

\[
\vec{j}(\vec{r}) = \frac{2e}{2m} |\phi(\vec{r})|^2 (\hbar \vec{V} \theta + 2e \vec{A}),
\]

\[
E_c = \iint_{N \text{ region}} \frac{1}{2m} \left|(-i\hbar \vec{V} + 2e \vec{A})\phi(\vec{r})\right|^2 d\vec{r}.
\]
Induced proximity minigap

Very high interface transparency
Elaborating lateral SNS proximity junctions

Line mode $dI/dV$ spectroscopy

The mini-gap exists in the proximity region

$\Delta_{\text{mini-gap}} \sim 0.2 \text{ meV}$
Direct observation of Josephson vortex cores

(a) Pb island, Pb WL, Pb island
(b) Pb island, Pb WL, Pb island
(c) Pb island, Pb WL, Pb island
(d) Pb island, Pb WL, Pb island
(e) Pb island, Pb WL, Pb island
(f) Pb island, Pb WL, Pb island