Proximity Effect in Hybrid Superconducting/Organic molecule nano particle system

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Many thanks to

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10/23/2015
Molecular Electronics


Eleke Scheer break junctions

Our work on chiral induced spintronics
Electron transmission through molecules and molecular interfaces
Review by Abraham Nitzan

“Electron transmission through molecules and molecular interfaces has been a subject of intensive research due to recent interest in electron transfer phenomena underlying the operation of the scanning tunneling microscope (STM) on one hand, and in the transmission properties of molecular bridges between conducting leads on the other. In these processes the traditional molecular view of electron transfer between donor and acceptor species give rise to a novel view of the molecule as a current carrying conductor, and observables such as electron transfer rates and yields are replaced by the conductivities, or more generally by current-voltage relationships, in molecular junctions. Such investigations of electrical junctions, in which single molecules or small molecular assemblies operate as conductors constitutes a major part of what has become the active field of molecular electronics.
Can molecules support proximity effect?

Two transport channels in parallel of electrons and holes???
Or one channel near Fermi surface???
Huge difference between molecule and SC gap

Non trivial band alignment
How would proximity effect change with coupling???
Coupling NPs to superconductors through organic molecules


superconductors plays the role of the “known” system

1) Transport through molecules can be studied using the superconductors.
2) We can change the superconducting surface using the hybrid layers.
Introduction to superconductivity

Characteristics of superconductors.
Superconductor material has ZERO electrical resistance.  

[1957 BCS theory]: Bardeen, Cooper, Schrieffer - Superconductivity as a microscopic effect caused by a "condensation" of pairs of electrons. Cooper pairs

[1986 Johannes Georg Bednorz and Karl Alexander Müller - High $T_c$]

Non BCS

YBa$_2$Cu$_3$O$_7$ (3) lattice
This talk is related to the 4th superconductors Nobel price

*The Nobel Prize in Physics 2003*
Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett

Abrikosov - The sensing technique

Ginzburg – Motivation

Leggett Explanation?
Type II superconductivity – Mixed state

- $B = 0$
- Meissner State
- Abrikosov Vortex solid

Type I

Type II

\[ H_{c1} \quad H_{c2} \]

\[ H \]

\[ H \]

\[ B \]

\[ B \]

Neutron scattering

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Current transport through Abrikosov Vortex lattice

Lorentz Force
\[ F = J \times B \]
Causes vortex motion
Electric field
\[ E = v \times B \]
Can not carry any bulk current
Pinning

; Schematic illustrations of 3 different vortex pinning scenarios.
(a) Negligible pinning; vortices form a lattice.
(b) Strong pinning, large anisotropy.
(c) Strong pinning, small anisotropy. FROM Jenny Hoffman (Harvard).
Peak effect \((\text{NbSe}_2)\)

Small Angle Neutron Scattering (SANS) gives structure of the vortex lattice

Below peak – Long range order exists

Correlation volume \(V_c\) is large

Above peak – No long range order

\(V_c\) is small

X. S. Ling et al, PRL

Peak effect

Low \(T_c\) materials

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Proximity Effect in superconductors
Andreev reflection
Our System

Disilane molecules

Nb film
Sapphire Substrate

MPS
DiSilane
Hex DiSilane

Top view
Peak effect as a coupling sensor

We are pleased to inform you that your article, "Using the peak effect to pick the good organic couplers," published in Appl. Phys. Lett. 98, 223306 (2011) has been selected for the June 2011 issue of APL: Organic Electronics and Photonics
STM Results

\[ \Delta = 0.81 \text{ meV} \]

MPS

AFM of Au dot

Proximity effect!!!
We do have proximity effect!!!

We have proximity effect through a molecule when the coupling is strong
(small policemen is helping)!!!

- What will happened in the weak coupling regime?
- What will happened if we changed to high Tc materials?
- What will happened if we take magnetic nano particles?
- Can we have proximity effect with chiral molecules, Where no standard Andreeev reflection can occur?
Surprise-Weak coupling limit improving superconductors

150nm Nb film

Normalized critical temperature

H=0 Oe
I=2 mA

disilane and 5nm
MPS and 5nm
disilane and 10nm

50nm Nb film

0.85 0.90 0.95 1.00 1.05 1.10
0
2
4
6

MPS and 5nm
disilane and 10nm

H=0 T
I=2mA

Normalized Temperature

Q N E L a b

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Control linkers experiments

- Non linking OTS molecules
- Density of gold NPs changes
Above and below $T_c$

2711 on Dot 15K averaged IV SM2:15K27IV

2711 on Dot IV SM2:4K27DTIV
Matching Fields

STM measurements showing the main spectroscopic features observed at 4.2K (below $T_C$)

Clear proximity

$dI/dV$ (arb. units)

Sample Bias (mV)

$\Delta = 0.81$ meV

$\Delta = 0.80$ meV

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STM Results Summary

a) H=0 Oe, I=2 mA,
Tc[Bare]=7.8K

- DiSilane and 10nM
- MPS and 5nM
- Clean Sample

b) H=0 T, I=2 mA,
Tc[Bare]=7.1K

- Bare Nb
- OTS and 10nm
- MPS and 10 nm
- diSilane and 10 nm

Normalized Critical Temperature

Sample Bias (mV)
dI/dV (arb. units)

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Cobalt Nano Particles

(a) Low purity
(b) High purity

Tc=9.14K  Tc=9.2K
R[Ohm]
T[K]

REF
DS+Co NP

Tc=7.545 K  Tc=7.565 K
R[Ohm]
T[K]

REF
DS+Co NP
STM Cobalt

![Graph showing STM Cobalt data with Sample Bias (mV) on the x-axis and dI/dV (normalized) on the y-axis.](image-url)
Density of Vo NPs

![Graph showing normalized resistance and temperature vs. specific heat capacity differences.](graph.jpg)
High Tc material
Optimally doped LSCO

La$_{2-x}$Sr$_x$CuO$_4$
Superconductors surface coupling measurements summary

Critical current

Actual behavior

Weak coupling

Expected curve

Critical Temperatures

ΔT

Actual behavior

Weak coupling

Expected curve

Critical current

Critical Temperatures

ΔT

Actual behavior

Weak coupling

Expected curve
Strange Proximity Effects

Long range collective proximity effect
Approaching zero-temperature metallic states in mesoscopic superconductor–normal–superconductor arrays

Serena Eley, Sarang Gopalakrishnan, Paul M. Goldbart and Nadya Mason

NATURE PHYSICS VOL 8 j 59 JANUARY 2012

Measurement of junction conductance and proximity effect at superconductor/semiconductor junctions
Michael Vissers, Victor K. Chua, Stephanie A. Law, Smitha Vishveshwara, and James N. Eckstein
Ginsburg Nobel Lecture

Nobel Lecture: On superconductivity and superfluidity ~what I have and have not managed to do! as well as on the “physical minimum” at the beginning of the XXI century*

REVIEWS OF MODERN PHYSICS, VOLUME 76, JULY 2004

“However, having familiarized myself with the paper of Little (1964), I put forward straight away Ginzburg, (1964) a quasi-two-dimensional model, wherein a plane conductor is in contact with a dielectric, say, a dielectric film. We termed the development of this version—the alternation of thin conducting layers with dielectric layers—a sandwich…”

Did we combine Ginsburg dream with molecular electronics recent knowledge?
Mechanism?

• **Enhancement of superconductivity by Anderson localization induced by pair pinning**  

• **Suppressing the surface phonon effect that tend to reduce the $T_c$ of the bare thin Nb films.**
  

• **Coulomb interaction between electrons in neighboring planes increase cooper paring.**
  
  (“Some Thoughts About Two Dimensionality and Cuprate Superconductivity”, Anthony J. Leggett)

We like to speculate that we have found the first step of the route to fulfill Ginsburg dream
Suggested Model

The critical temperature increases only if the following conditions occur:

i) **Moderate matrix element mixing** - The matrix element mixing the electron states in the NPs and the Nb film, must be of moderate values - small enough to keep electrons basically localized, but large enough to provide significant tunneling probability.

ii) **Large density of states** - The density of states in the non-superconducting subsystem (in Au) should be large.

iii) **Small electron-electron pairing** - The electron-electron pairing potential in the superconducting subsystem (in Nb) should be small.

iv) **Linkers vibrational modes** - There must be vibrational modes in the organic linker that can mediate the coupling between the electronic states in the Nb film and the gold NPs.

Model in detail

Two-band BCS Hamiltonian in the form

\[ H = \sum_{\alpha, \sigma} \varepsilon_{n, \alpha} c_{n, \alpha, \sigma}^+ c_{n, \alpha, \sigma} + \sum \Lambda_{\alpha \beta \gamma \delta}^{nmsu} c_{n, \alpha, \sigma}^+ c_{m, \beta, \sigma}^+ c_{s, \gamma, \sigma} c_{u, \delta, \sigma}. \]

\[ \Lambda_{\alpha \beta \gamma \delta}^{nmsu} = \int \varphi_{n, \alpha}^* (r') \varphi_{m, \beta}^* (r) \Lambda (r-r') \varphi_{s, \gamma} (r') \varphi_{u, \delta} (r) dr dr'. \]

The matrix element of electron-electron effective interaction potential

\[ T_c = 1.13 \omega_e \exp \left( \frac{g_{11} - \sqrt{g_{11}^2 + 4g_{12}^2}}{2g_{12}^2} \right), \quad g_{12}^2 = N_{11}N_{22} |\Lambda_{1212}|^2, \quad g_{11} = N_{11} \Lambda_{1111}. \]

For a large mixing term \( g_{12} \geq g_{11} \)

\[ T_c = 1.13 \omega_e \exp \left( -\frac{1}{g_{12}} \right) \]

\( T_c \) can be higher than the bulk values
We do have proximity through a molecule

Why? We don’t know!!!

• Two opposite channels of a hole and an electron passing through the molecules (both HOMO and LUMO).

• Chiral molecules and triplets superconductivity?
Applications ???

Maybe for low dissipation logic devices
Reduce the high level of energy dissipation associated with the present semiconductor-based integrated-circuit

Combine: Superconductivity and Spintronics
Spin electronics - Spintronics

- Consuming lower power than the conventional charge based semiconductor technologies
- Circuitry can be scaled down.
- Processing speeds can be faster.

But:
- Materials Problem
- Large currents to generate spins
Spintronics Devices

The 2007 Nobel Prize in Physics was awarded to: [Albert Fert](https://www.nobelprize.org/prizes/physics/2007/fert-bio) and [Peter Grünberg](https://www.nobelprize.org/prizes/physics/2007/gruntberg-bio) for the discovery of GMR.
The CISS effect - Chiral induced Spin Selectivity.
Spin dependent transport through double stranded DNA
Chiral Induced Spin Selectivity - CISS

Zuoit Xie, Tal Markus, Sidney Cohen, Zeev Vager, Rafael Gutierrez, Ron Naaman
The Charity Molecular based Universal Memory

Fast  Dense  Non-Volatile  Power efficient

nm size transport  Unit size 10nm  stable  No back scattering

The industry needs are met without compromising in **cost, compatibility to standard Si process** & complexity of **design**
Potential difficulty- pin-holes in the organic monolayer. The problem was solved by evaporating thin layer (3-5 nm) of AlOx on top of the organic monolayer.

*Nature Communications* 4, 2256 DOI: 10.1038 (2013).

**Optically induced** local magnetic memory

Highly localized magnetization device • (measured with MFM)

- CdSe QD (610nm)
- α-Helix L-Polyalanine 36C

- 532nm Circular Polarized Beam
- 5nm Au
- 1.5nm Co

Nano Letters 2014
CISS May Address the Material Problems in Spintronics

- Consuming lower power than the conventional charge based semiconductor technologies
- Circuitry can be scaled down.
- Processing speeds can be faster.

However, in devices made of standard magnetic materials, large charge currents are required to generate sufficiently high spin currents, causing considerable Joule heating!!!
Superconducting Spintronics

Superconducting Spintronics
NATURE PHYSICS 11 307 (2015)
Jacob Linder and Jason W. A. Robinson

Not Simple and required careful layers growth!!!
Chiral proximity effect

Tunneling spectra measured on Nb film on which chiral polyalanine a-helix molecules were adsorbed (T_c = 7 K). Three main types of spectroscopic features were observed. Smeared superconducting gaps (red curve in (a)), smeared gaps with a small ZBCP embedded inside.
Simple superconductivity spintronics main idea

STM tip

Ferromagnet

contact

Tunnel barrier

Chiral layer

contact

S

STM tip

STM tip
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