Proximity effect in multisheets of graphene, and transport through suspended multisheets

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Part 1: Why is the superconducting proximity effect interesting?

Josephson junction

More exotic junction

- Paired electrons can propagate in a non superconducting wire IF the wire is quantum coherent: no inelastic collisions, no fluctuating spins, etc...
- Propagation also depends on band structure

Test of quantum coherence and band structure
Use the proximity effect to probe a non superconducting sample.

- Metal wire
- Metallofullerene molecules
- Carbon nanotubes
- DNA molecules

Molecules with spins
Quantum wire
Intrinsically superconducting!
Conducting molecule?

Graphene???? Effect of the band structure on proximity effect?

Beenakker, 2006: modified Andreev reflection

Effect of the band structure on proximity effect?
Proximity effect in a multisheet of graphene connected to superconducting electrodes

Optical microscope

Electron microscope

Atomic force microscope

Thickness <2.3 nm
Properties of superconducting tungsten electrodes

- Length = several microns, typical width = 200 nm
- Auger analysis: 75% tungsten, 10% carbon, 10% gallium, 5% oxygen
- $R_{sq}$: between 1 and 50 Ohm
- $T_c = 4-5$ K (pure W has $T_c$ of less than 100 mK!)
- $H_C = 7$ T !!!

Already used in S-molecule-S junction
Previous work: fabrication of superconducting nanogap

Alik Kasumov

Focused ion beam microscope
Galium Ions (30 keV)

Metal
Si$_3$N$_4$
Si

W hexacarbonyl vapor

FIB image

TEM image
Previous work: S-molecule-S junction with Gd@C82


Dimer of Gd@C_{82}

A proximity effect where the molecule plays a role?
Graphene/ite band structure apparent at high T

\[ G \propto \rho(E_F + eV/2) + \rho(E_F - eV/2) \]

Differential conductance proportional to \( \text{dos} \)
No doping

Doping $d$ and $V/2 > d$

Doping $d$ and $V/2 < d$

Low doping of our sample
Linear conductance also seen in small graphite contacts

Conductance of HOPG
Van Kempen (2005)
Proximity effect in a graphene multisheet at lower T

Resistance halved at low T, but no zero resistance state! (because electrodes too far apart?)
Multiple Andreev reflection peaks. 2 gaps due to local doping by contacts?
Field dependence is more complicated

Can investigate proximity effect up to fields of a few Teslas!

Shailos et al, cond-mat 0612058
Field dependence is more complicated

Resistance alternates between local maximum and minimum:

Effect of orbit focusing by magnetic field?

Could we see focusing by magnetic field?

Shailos et al, cond-mat 0612058
Heersche et al, Nature 2006: gate-dependent supercurrent
S electrodes: Ti/Al, Tc=1 K, less than 400 nm apart

Andreev reflection

High field behavior?
Part 2: Suspended 30 sheet graphene/ite

Number of sheets determined by transmission electron microscope at the edge of the film. (M. Kociak, A. Kasumov)

Measure as deposited (bad contacts)
Also linear conductance at high voltage

Regularly spaced resistance peaks (20 mV)
Could these peaks be due to phonon modes?

Vitali et al. PRB 69, 121414 (2004)
Phonons and plasmons in graphite
(Scanning Tunneling Spectroscopy at 6 K)

Modes of 30 graphene layers differ from modes in graphite!
Could these peaks be due to Fabry-Pérot type interference?

\[ \delta E = e\delta V = \hbar v_F \delta k \approx 2 \text{meV} \]

Too small!
By the way, no side peaks in graphite
Vibrational mode of the whole sheet

\[ \hbar \omega \]

\[ f = 305 \text{ MHz} \]
\[ Q = 50 \]
Excitation of the fundamental vibrational mode

Fundamental vibrational mode of a doubly clamped beam

\[ f_0 = \left[ (E/\rho)^{1/2} \frac{t}{L^2} \right]^2 + \frac{0.57 T}{\rho L^2 wt} \]

300 MHz

Bulk graphite: Young modulus \( E = 1 \) TPa,
Density \( \rho = 2200 \text{ kg/m}^3 \)

McEuen et al., Science 2007

Our sample
Fundamental frequency OK
Conclusion and outlook

With superconducting W contacts:
Proximity effect without supercurrent.
Focusing of trajectories by magnetic field?
Solve problem of contamination to bring S electrodes closer together (Al mask?).

Suspended samples:
Fundamental vibrational mode excited with rf radiation.

High energy (vibrational) modes not yet understood.

Next: supercurrent and vibrations?
Interplay between Josephson effect and vibrations in suspended sample with S contacts?
Field dependence is more complicated

Can investigate proximity effect up to fields of a few Teslas!

Shailos et al, cond-mat 0612058
Proximity effect in a metallo fullerene dimer

Transition with $T_C = 0.7$ K, $H_C = 1$ T

But W contacts have $T_C = 5$ K, $H_C = 7$ T!

A proximity effect where the molecule plays a role?
Thickness <2.3 nm
Non linear transport in the Normal state

Symmetrical contacts: \[ G \propto \left( N(E_F + eV/2) + N(E_F - eV/2) \right). \]
Non linear transport: 
From normal to superconducting state

Low bias Anomalies at $T < 2K$
Signatures of proximity induced superconductivity
Also linear conductance at high voltage

![Graph showing linear conductance at high voltage](image)
$T = 100\text{mK}$
Peaks in differential resistance

$T = 100 \text{mK}$
$dV/dl$ (kΩ)

4 T
5 T
Magnetic field dependence not understood

\[ \frac{d^2 I}{dV^2} \text{ (A/V}^2\text{)} \]

\[ V \text{ (volt)} \]
Pics B non sensibles - champ B.
- cycles thermiques.

Pic B : 313 MHz