Proximity induced triplet superconductivity in doped topological Bi_2Se_3 films in contact with the s-wave superconductor NbN

Or alternatively - A search of Majorana fermions ….

- Large junctions Au - Bi_2Se_3 - nox/NbN
  with overlap area of 100x30=3000 μm^2
  Native oxide (nox) barrier: ~1-2 nm Nb_2O_5/Nb_2NO_4/$NbN_{0.5}O_{0.5}$

- Ramp junctions Smaller, with ~5x0.5 μm^2 junction area, and a nox barrier

- Bilayers of 10 nm Bi_2Se_3/70 nm NbN
  even smaller area of a few nm diameter
  prepared in-situ, without a native oxide (nox) layer.
  Barrier is between the crashed STM tip and the Bi_2Se_3 layer.

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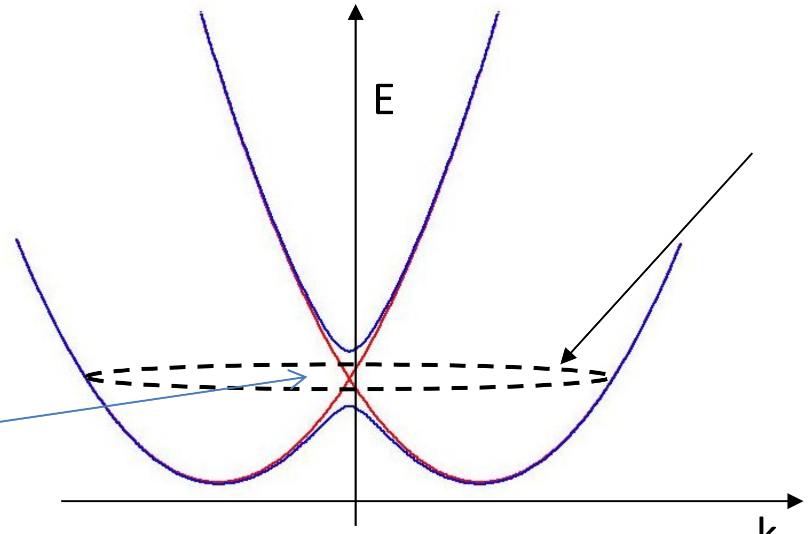
Topological superconductivity in spin-orbit coupled systems

$$H = k^2/2m + \alpha\vec{k} \times \vec{\sigma}.\hat{z} + V_Z\sigma_Z$$



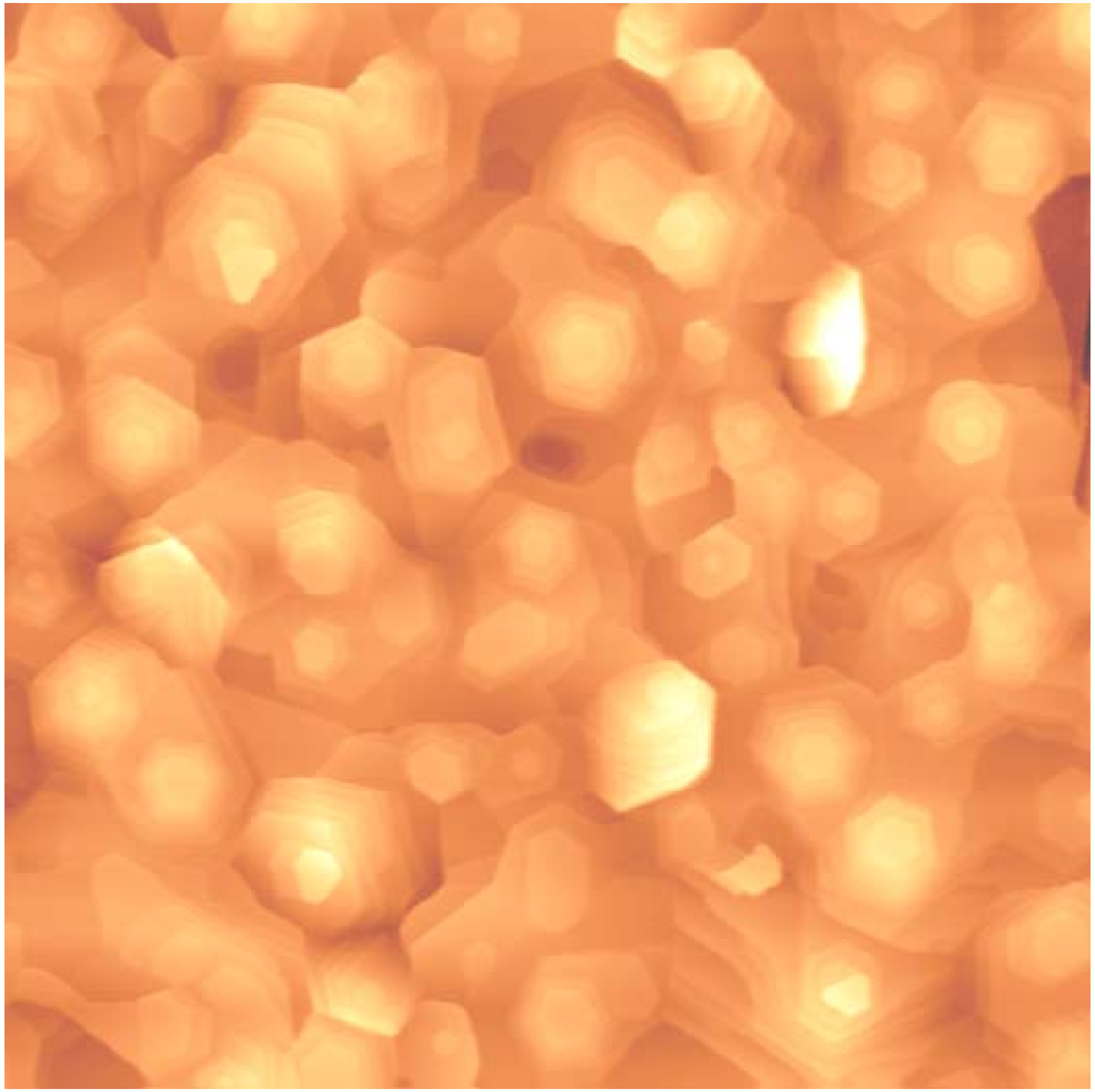
Band structure of spin-orbit coupled fermions with Zeeman field

Proximity effect with an s-wave superconductor induces in a topological insulator chiral-p wave superconductivity

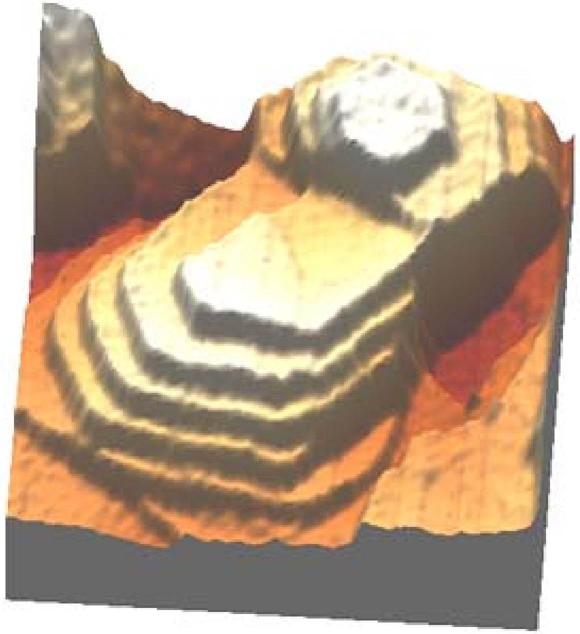
Zhang, Tewari, Lutchyn, Das Sarma, "$p_x + ip_y$ *superlfuid from s-wave interactions of fermionic cold atoms*" PRL (2008)

Sato, Takahashi, Fujimoto, *"Non-Abelian topological order in s-wave superfluids of ultracold fermionic atoms"* PRL (2009)

AFM images of the 400nm thick Bi_2Se_3 film on (111) $SrTiO_3$



$2x2\ \mu m^2$



$0.3x0.3\ \mu m^2$

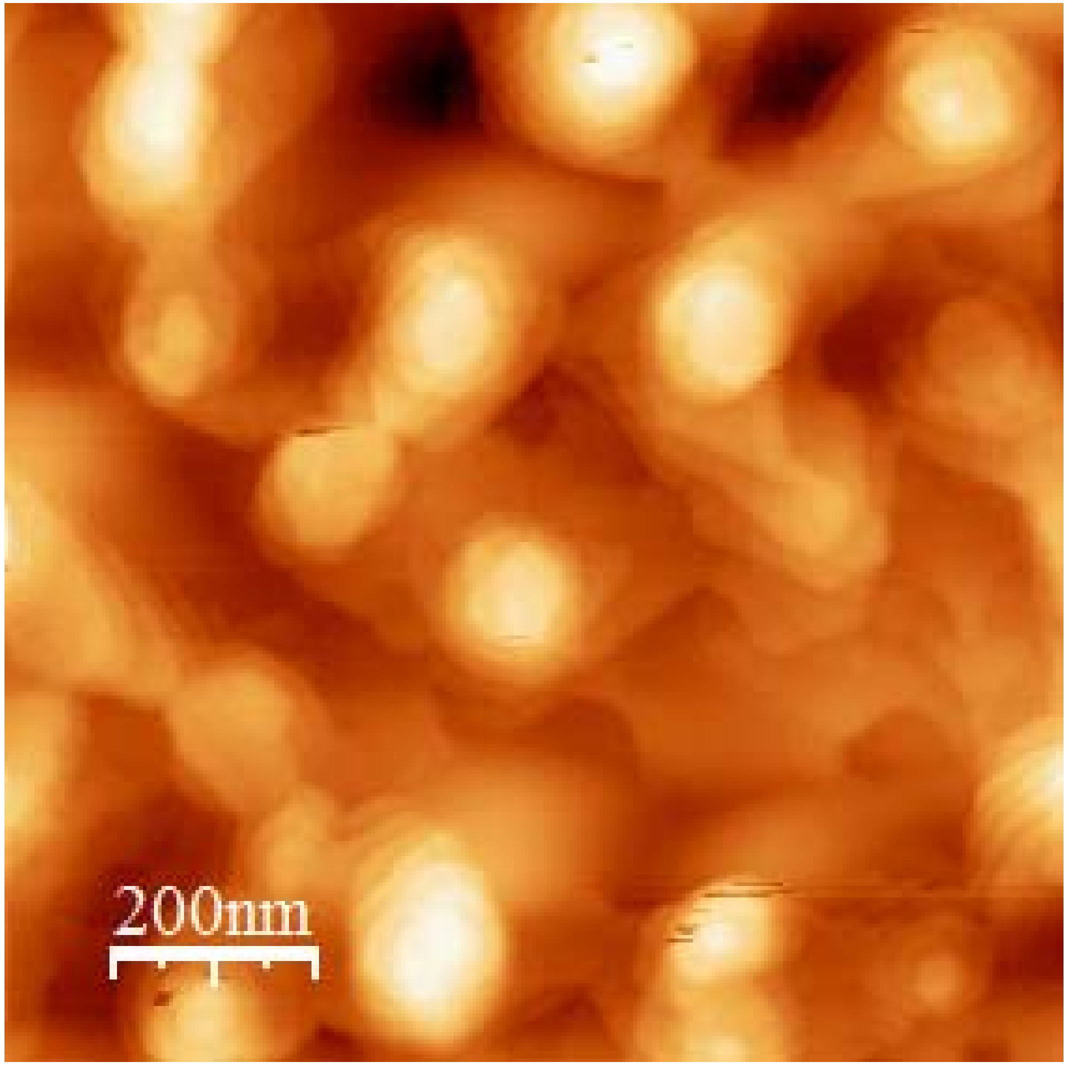
Hexagonal & epitaxial

c-axis: d=2.84 nm

(0,0,3n) peaks in x-ray

An AFM image of a

100nm thick Bi_2Se_3 on 70nm thick NbN bilayer on (100) $SrTiO_3$

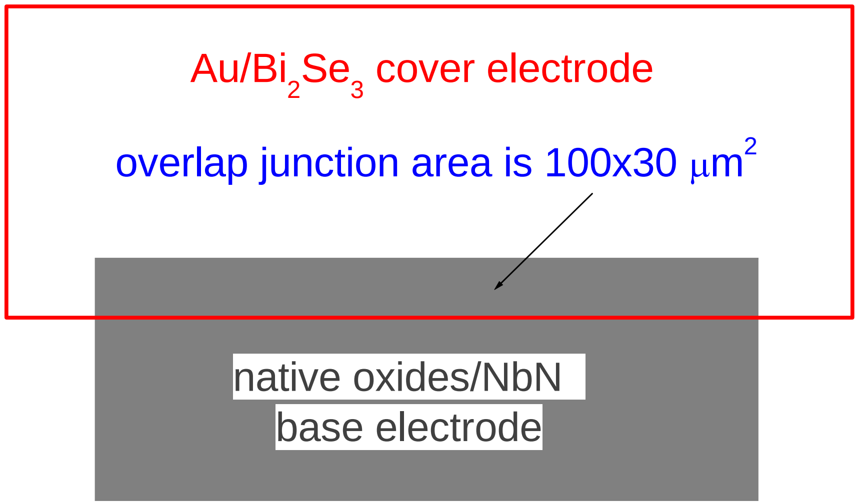


1x1 μm^2

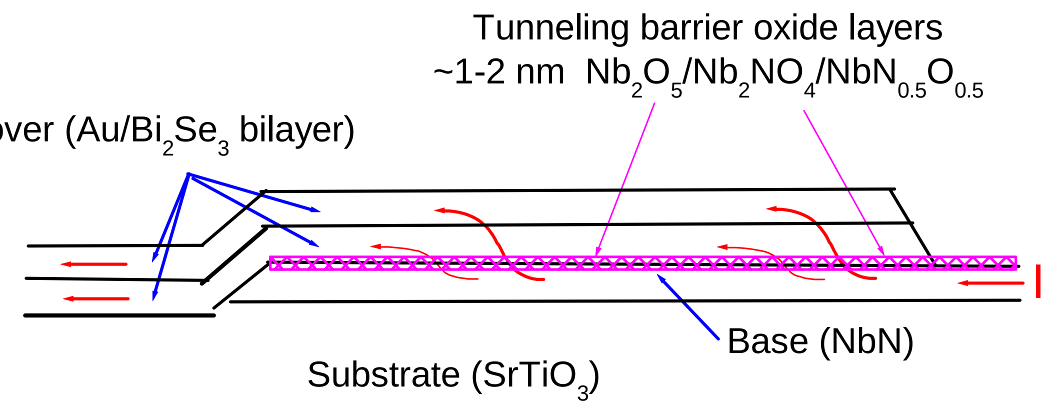
Crystallized well,
in laterally disordered
hexagonal form
Mosaic structure

Schematic drawings of a large junction layout

Top view of a shadow masked junction

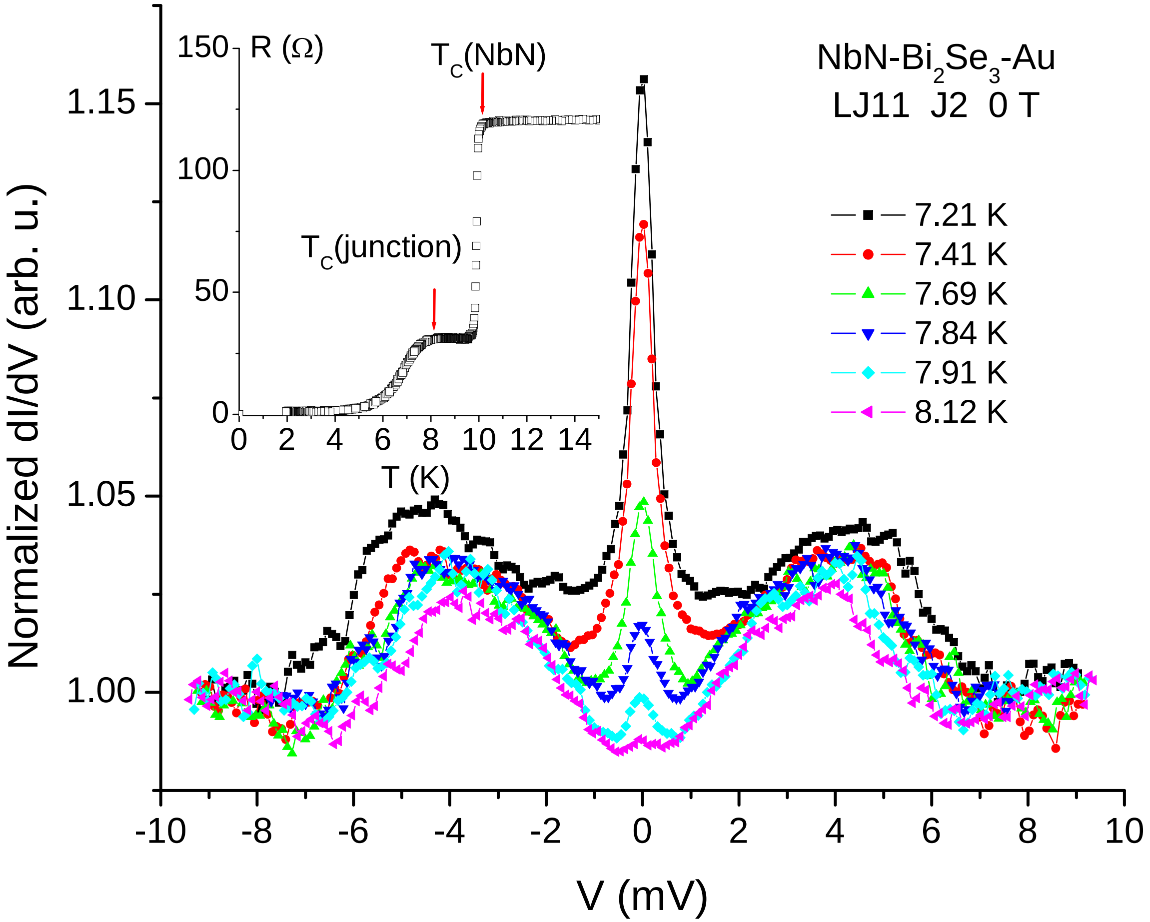


Junction cross-section



"nox" is the native oxide

R at various T and conductance spectra of a large junction near T_c 70nm NbN-1 to 2nm oxides-20nm Bi_2Se_3-100nm Au



- R vs T shows a proximity effect in Bi_2Se_3 below T_c~8K of the junction
- ZBCP vanishes above T_c junction,
- Coherence peaks survive up to T_c of the NbN electrode
- http://lanl.arxiv.org/abs/1303.0652

Previous results: Koren & Kirzhner, PRB **86**, 144508 (2012)
NbN – Bi_2Se_3 - Au

Comparison of fits with different pair potentials

- Singlet s-wave
- Triplet p-wave with Eu(2) pair potential:

$$\Delta_{\uparrow\uparrow} = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$$

or Eu(1) pair potential:

$$\Delta_{\uparrow\uparrow} = \Delta_0 \sin\theta(\cos\phi + \sin\phi)$$

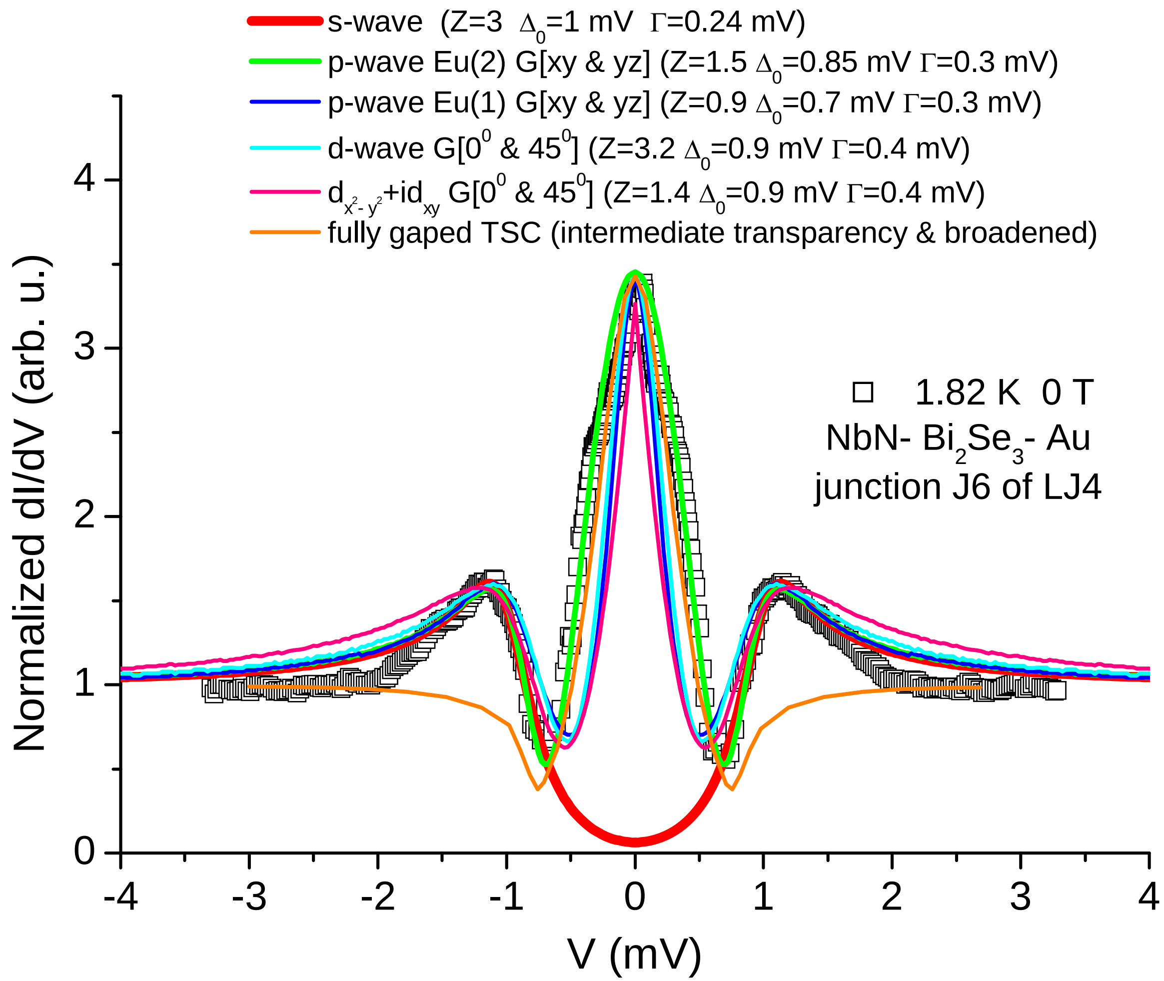
- Singlet d-wave $d_{x^2-y^2}$

$$\Delta_{\uparrow\downarrow} = \Delta_0(\cos 2\phi - \cos 2\alpha)$$

Where α is either 0^0 or 45^0

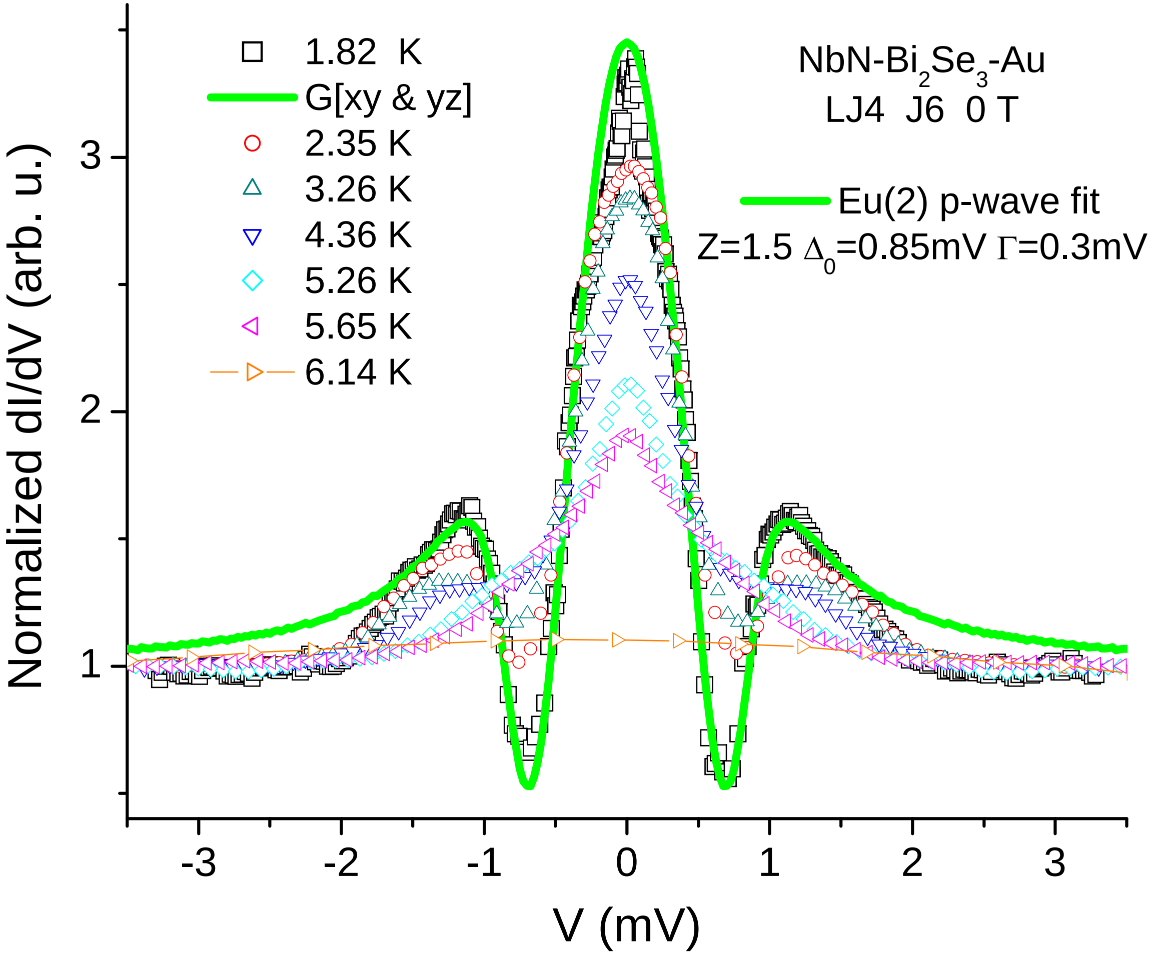
- Or $d_{x^2-y^2} + id_{xy}$ at 0^0 or 45^0

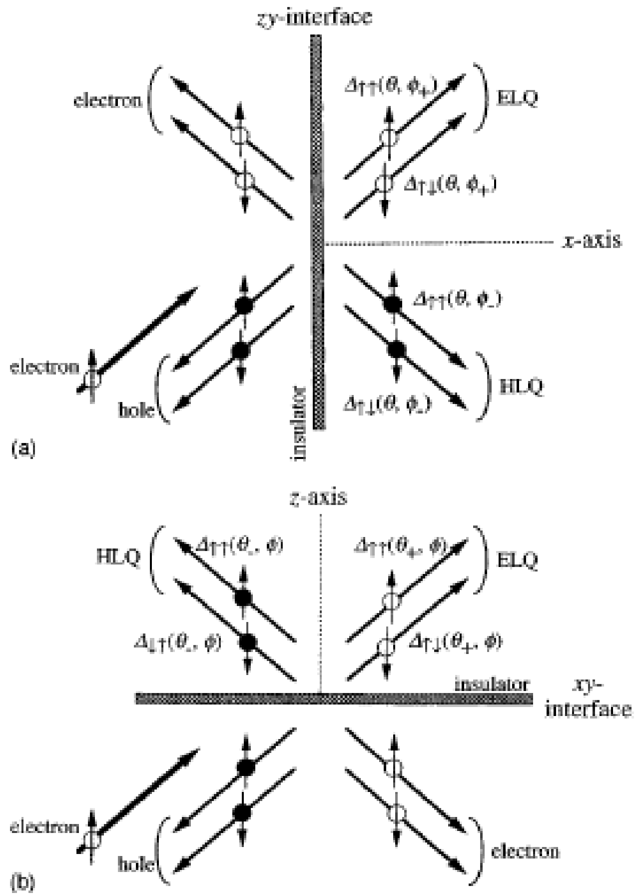
- Topological SC (TSC)



We ignored the hexagonal symmetry in the fits, but took weighted sums of G(xy) & G(xz) or G(0^0) & G(45^0), that should averaged over it (hexagonal yielded similar results)

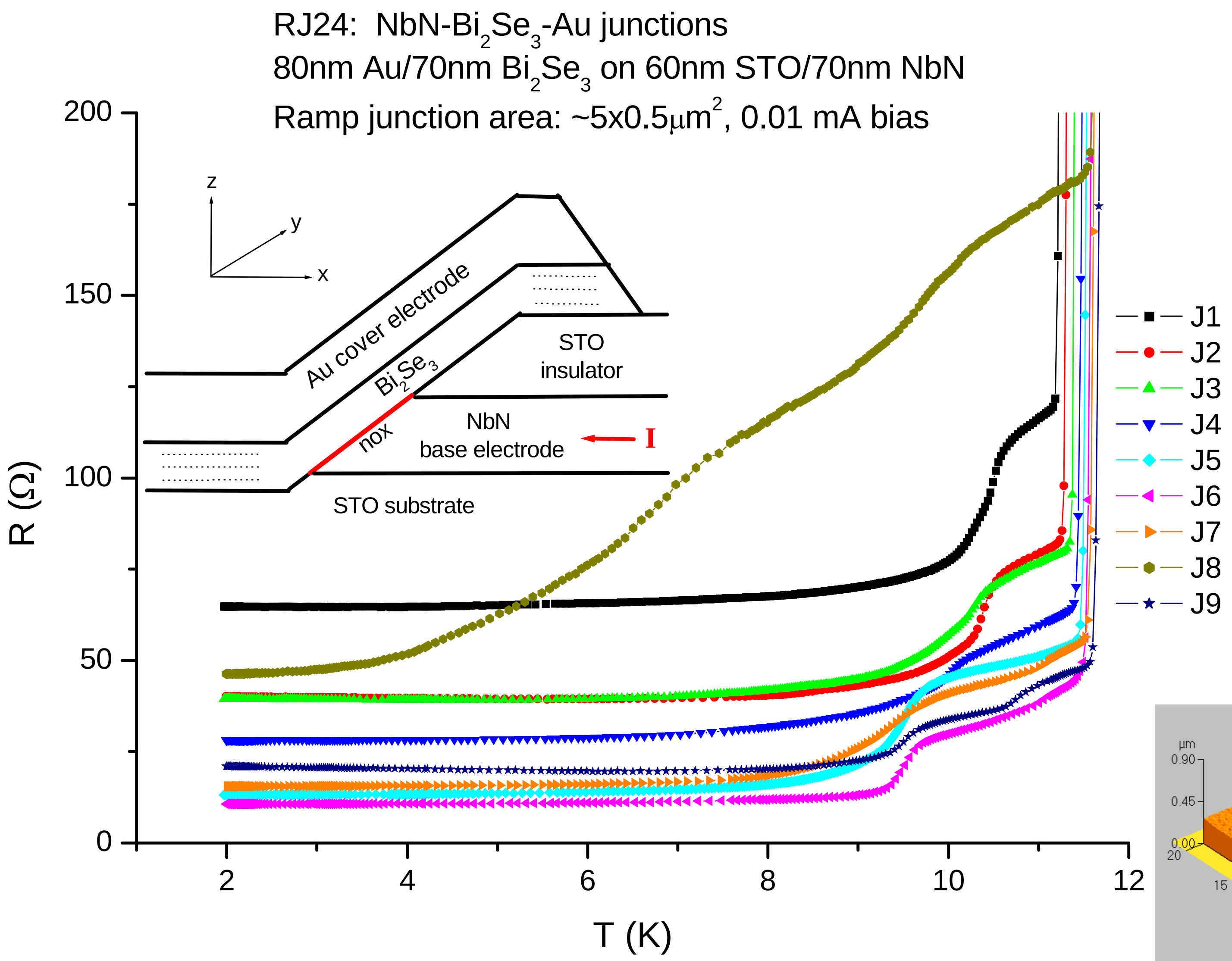
PRB **86**, 144508 (2012): same NbN-Bi_2Se_3-Au junction at various T

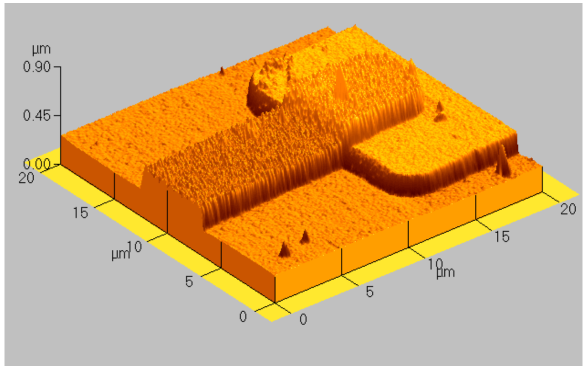




- ZBCP is suppressed with increasing T
- P-wave fit with Eu(2) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$
  using the same Z, Δ & Γ parameters for the two interfaces

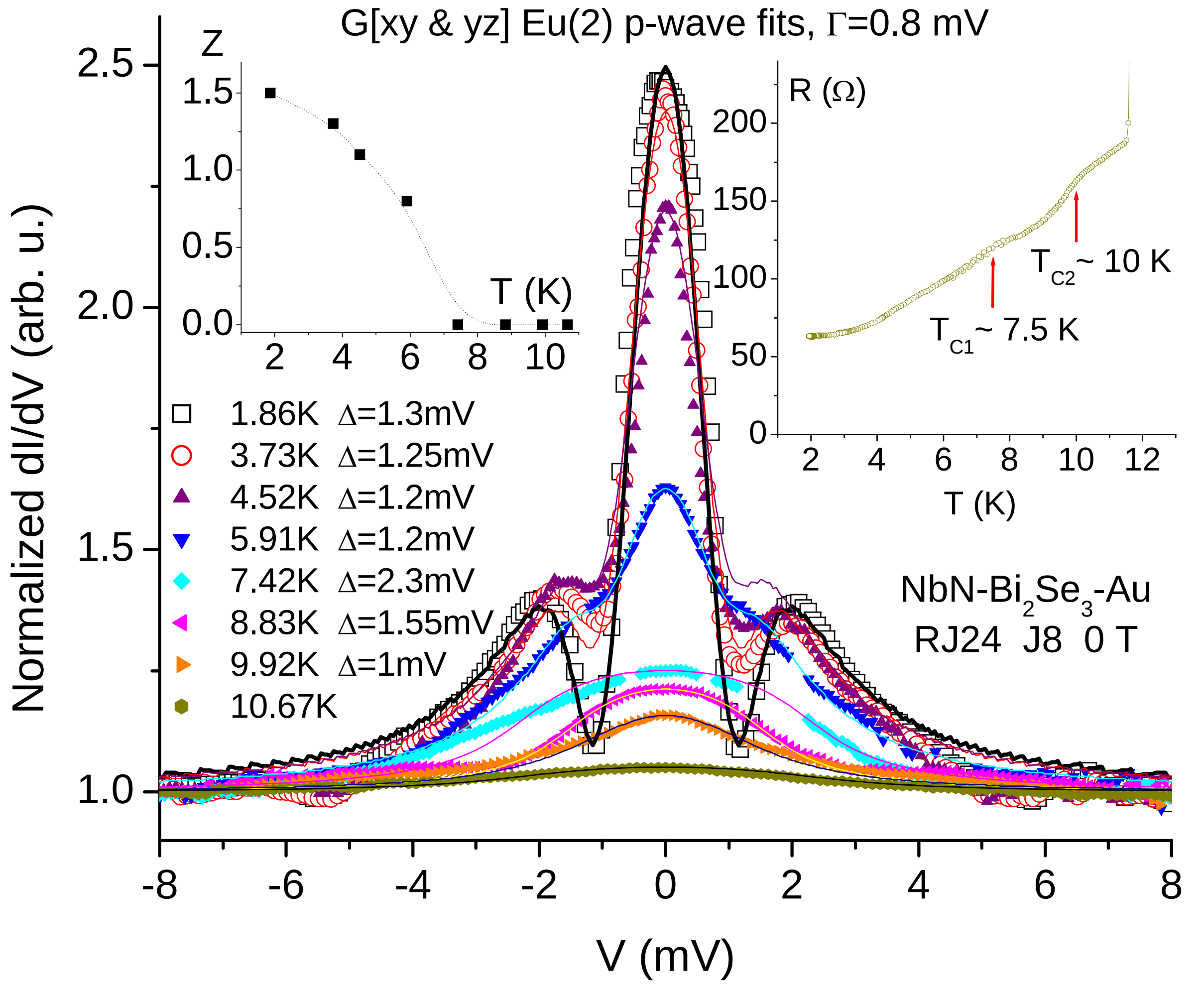
Ramp junction geometry & R vs T of all RJ on the wafer





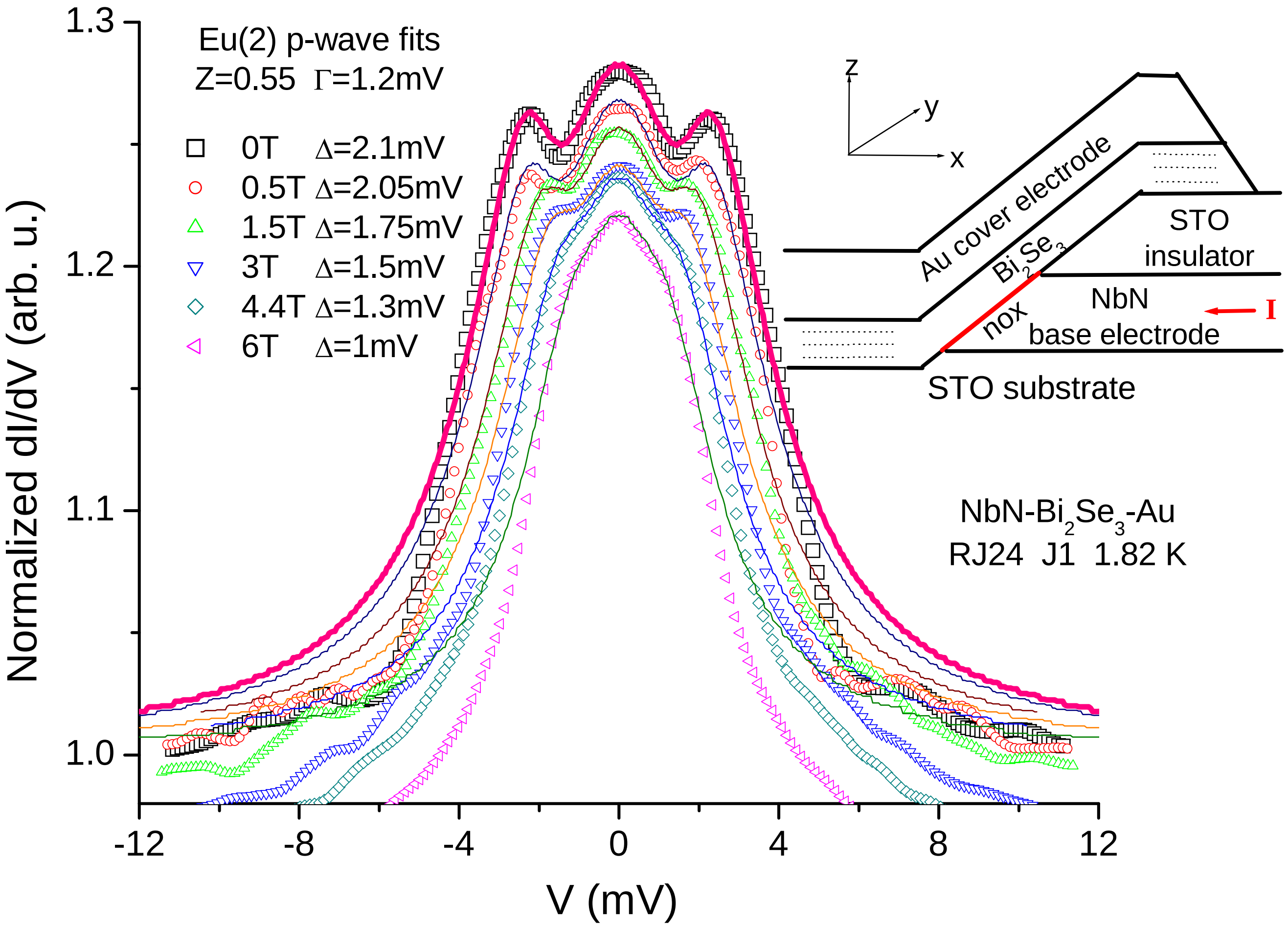
- Proximity transition at 10-11 K
- Second transition, see next

Ramp junction at various T: NbN-Bi_2Se_3-Au



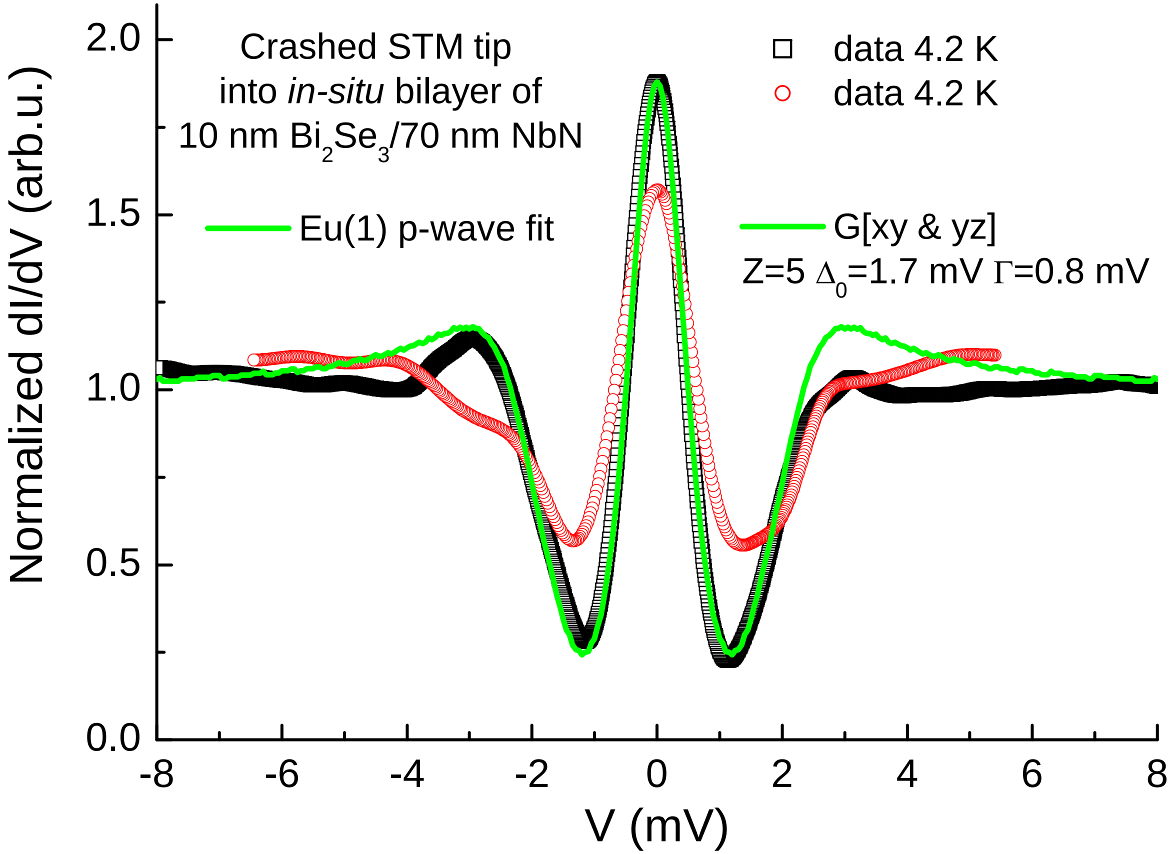
- ZBCP is suppressed with increasing T
- Above 8 K only the broad peak survives
- P-wave fit with Eu(2) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$

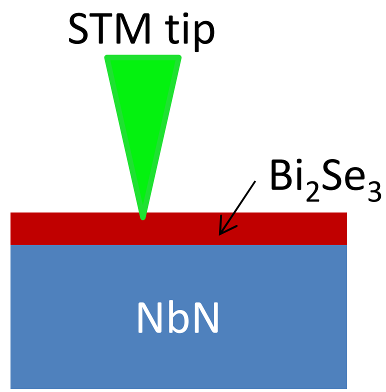
Ramp junction at various H: NbN-Bi_2Se_3-Au



- A more transparent junction, Andreev-like spectra with small CP & ZBCP
- P-wave fit with Eu(2) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$

Crashed STM tip on a bilayer (Point-Contact spectra) at 4.2 K





- No clear SC was measured on the bare (oxidized) NbN surface, or on the (deteriorated) bilayer surface before the tip crashing
- Tunneling spectra after crashing the tip into the surface of the bilayer is shown in the figure. These are point contact spectra, measured on a few nm contact area.
- The p-wave fit is with the triplet Eu(1) pair potential $\Delta = \Delta_0 \sin\theta(\cos\phi + \sin\phi)$

Conclusions

- ZBCPs and coherence peaks were observed in the in conductance spectra of many types of junctions
- Triplet p-wave pair potential fitted all the spectra best when using the modified BTK theory with a minimal number of parameters
- A TSC model failed to fit our data (no CPs)
- Therefore, we apparently do not observe MFs 

  but seem to observe an equal-spins (spinfull) triplet SC