Reflections on the first year of PLD of HTS thin films & recent advances in PLD of Topological superconducting NbN-Bi_2Se_3-Au junctions

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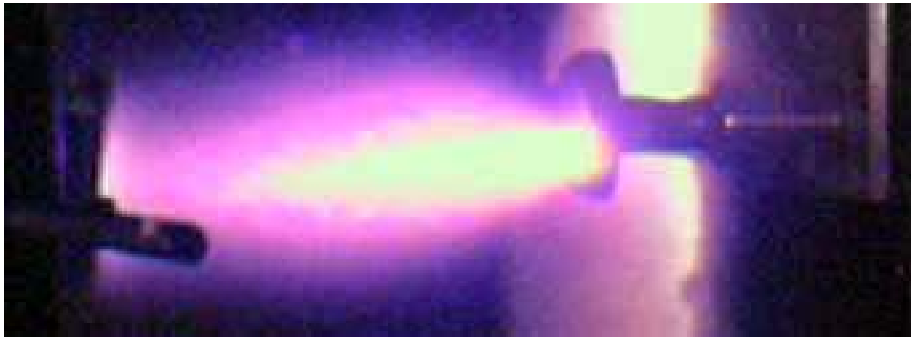
Reminiscences from the first year of PLD of HTS thin films 1987-1988

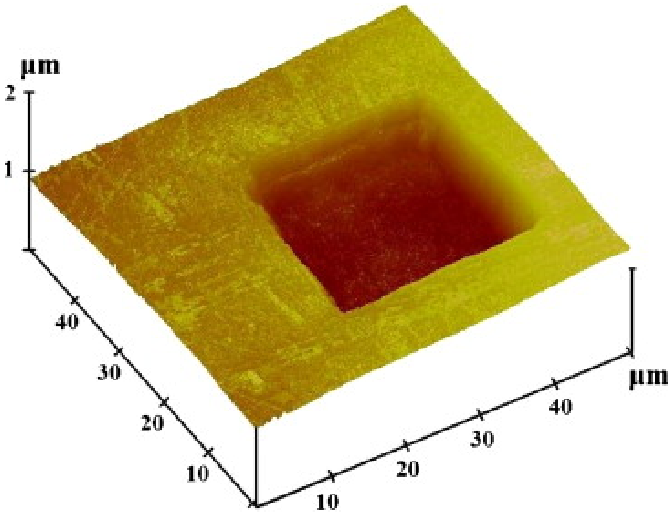
Preparation of the high temperature superconducting (HTS) thin films by pulsed laser deposition (PLD)

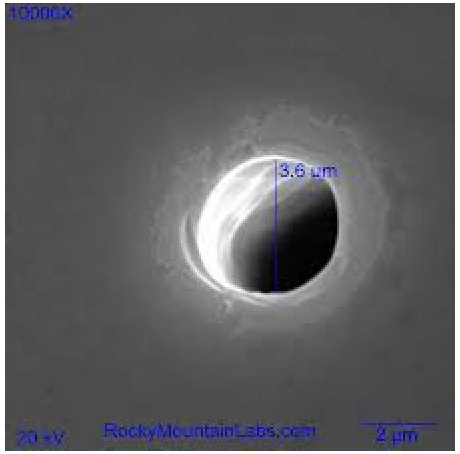
- 1-2-3 YBCO target
- pinkish plume



- Prior to 1987, I was working in UV laser ablation for etching of polymers & solids

The plume looks similar to the above, but the end result is a via-hole in the target





Moving from etching to deposition (1987-8)

- Since the UV laser ablation process was familiar to me, I moved quickly to deposition of HTS thin films by PLD
- It was easy to prepare ceramics film by PLD at low temperature and a post annealing process
- First, we wished to have *in-situ* annealing – necessitates 700-800 ^{o}C heater blocks (the stoichiometry of the 1-2-3 YBCO was preserved, since it is a stable phase) [even 2-1-1 yields 1-2-3 in PLD…]
- The second challenge was not to lose, or to stabilize, the YBCO phase during the deposition process – Oxygen role - below ~5-10 mTorr O_2 pressure, the 1-2-3 YBCO loses its stoichiometry due to Cu_2O evaporation – very volatile
- Venky's paper: APL **52**, 754 (1988) – used 5 mTorr & post annealing
- Our paper: APL **53**, 2330 (1988) – used 100 mTorr & *in-situ* anneal.
- Epitaxiality - lattice mismatch – $SrTiO_3$, $LaGaO_3$, $NdGaO_3$, $LaAlO_3$….. Work done in IBM Research, Yorktown, NY, 1989 →

My sabbatical in the IBM Research lab, Yorktown Heights, NY, 1988-9

- I brought the PLD technique, that was developed at the Technion, to the IBM Research lab (I was working in the group of Arunava Gupta)
- Work on epitaxiality and smoothness of the films versus the laser-wavelength, was done there.
- One day we had a visitor from Bellcore, Venky Venkatesan. He told us he was very relieved to see our APL paper on PLD from 1988, since this removed doubts in his own work, as people complained to him that they could not reproduce his results… (I guess this was due to the 5 mTorr deposition in that paper)

- So far for nostalgia,

 and now we shall move to research of these days

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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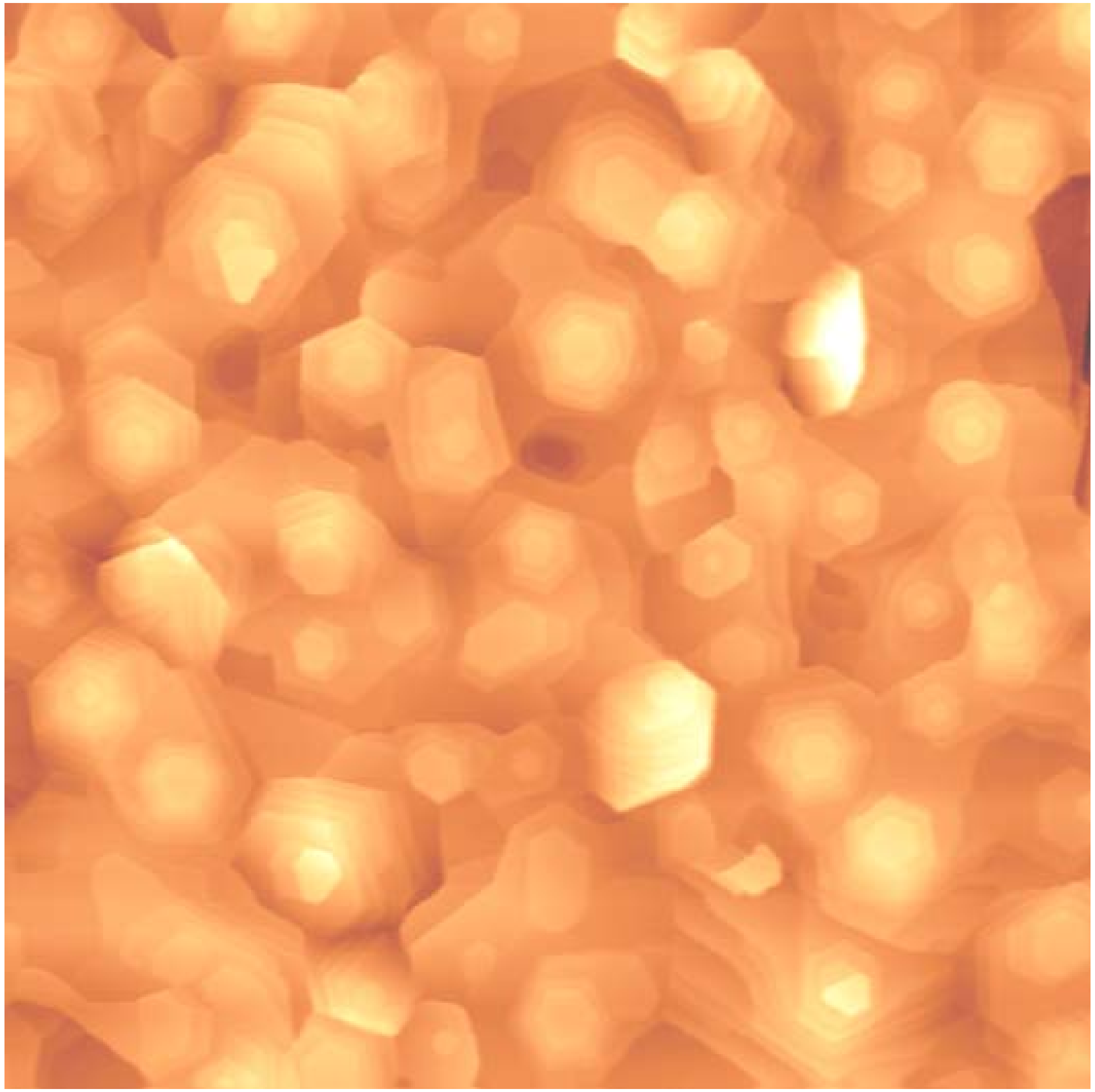
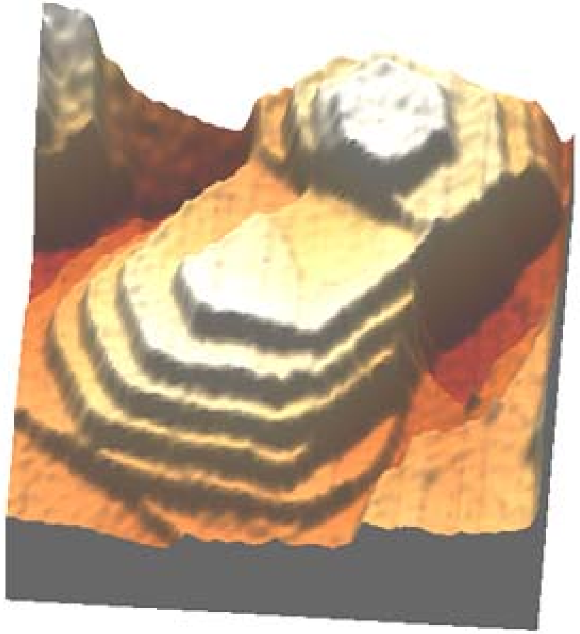
In collaboration with Tal Kirzhner, Yoav Kalcheim & Oded Millo

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



$2x2\ \mu m^2$



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

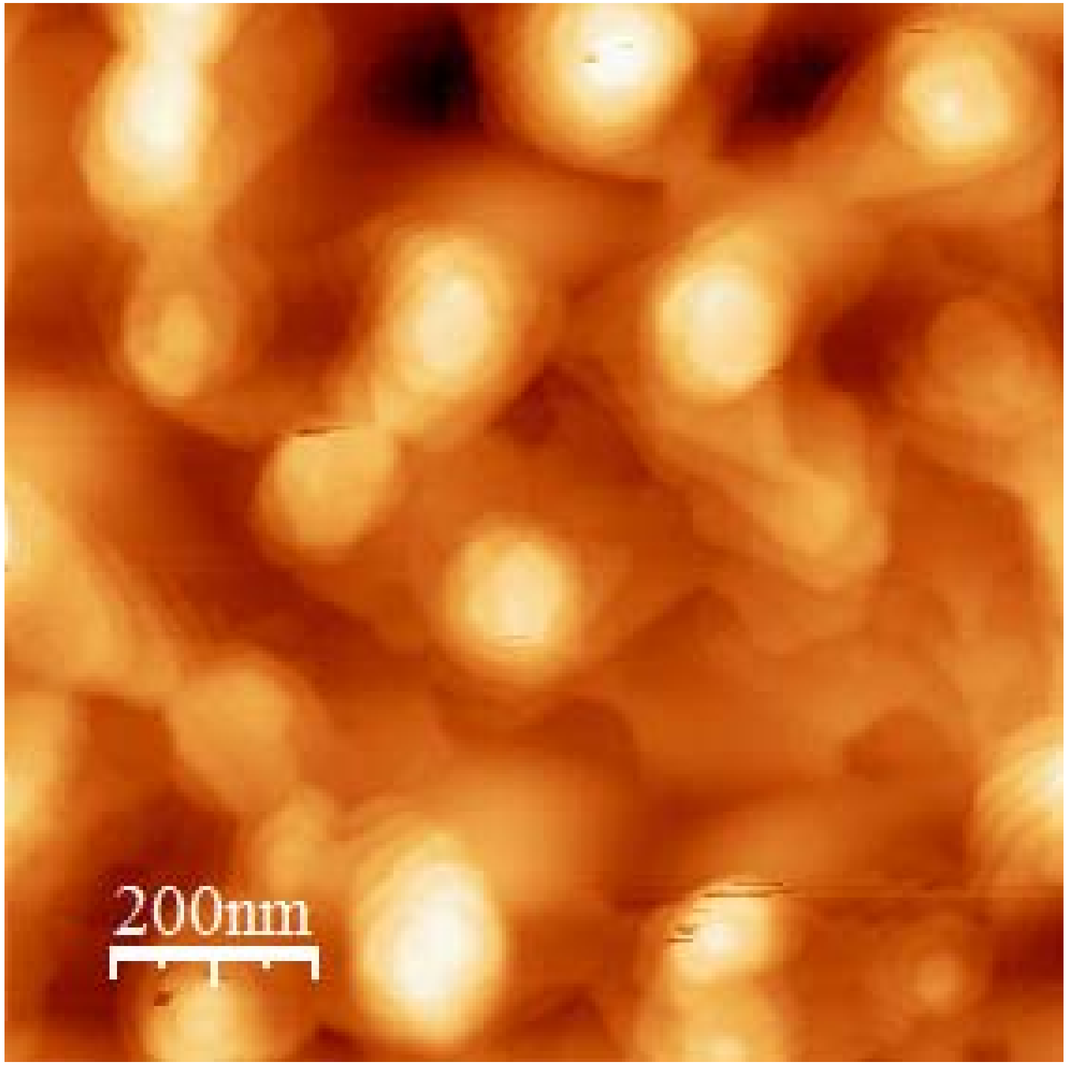
Hexagonal & epitaxial

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) $SrTiO_3$

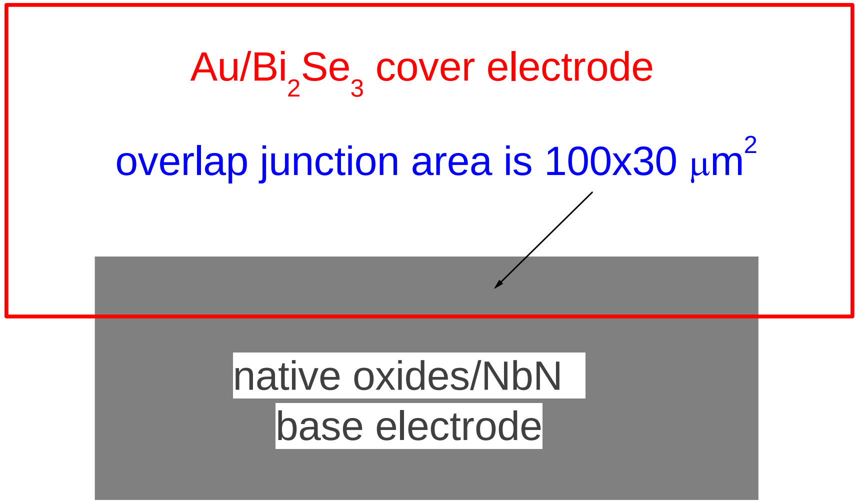


1x1 μm^2

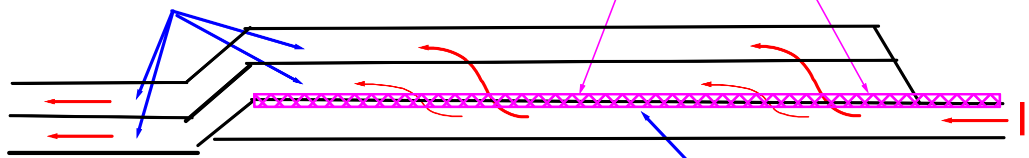
Crystallized well,
in laterally disordered
hexagonal form
Mosaic structure

Schematic drawings of a large junction layout

Top view of a shadow masked junction

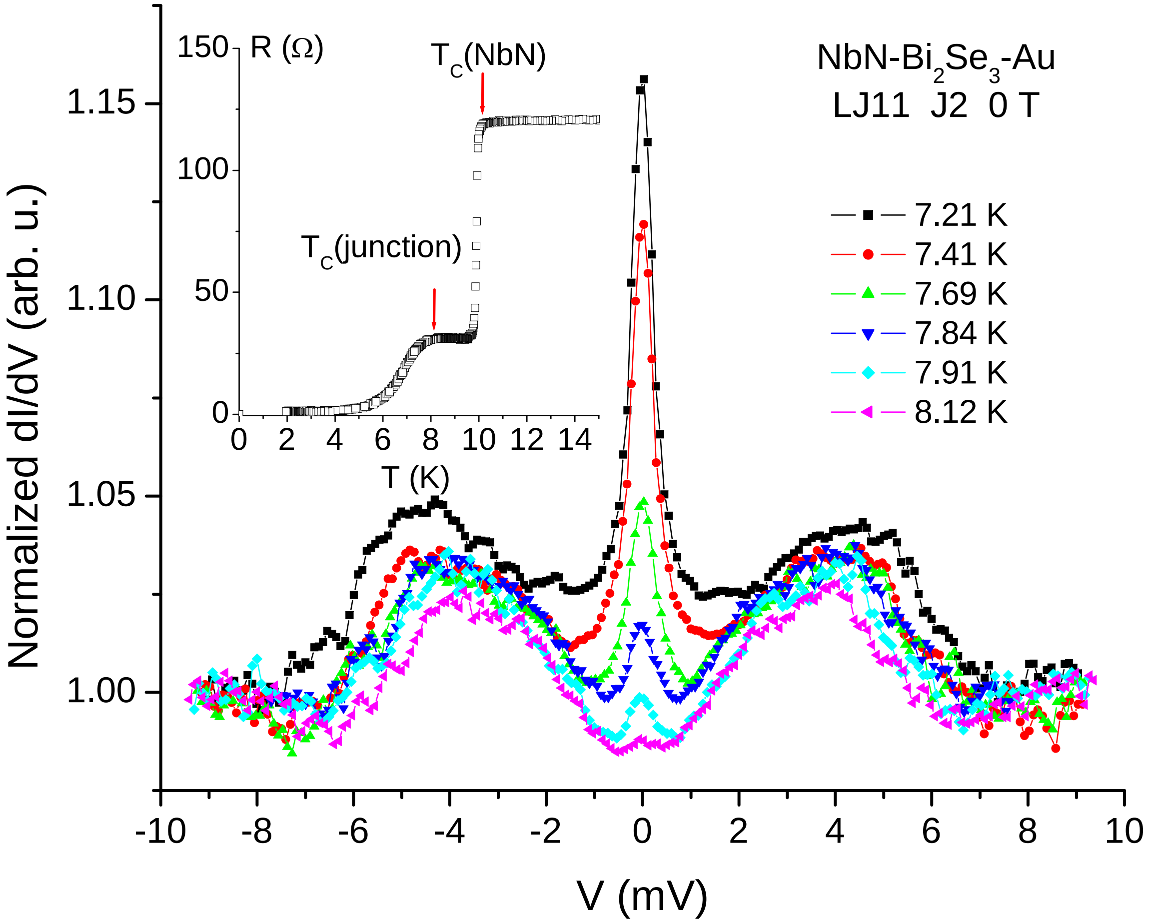


Junction cross-section



“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 $d_{x^2-y^2}$

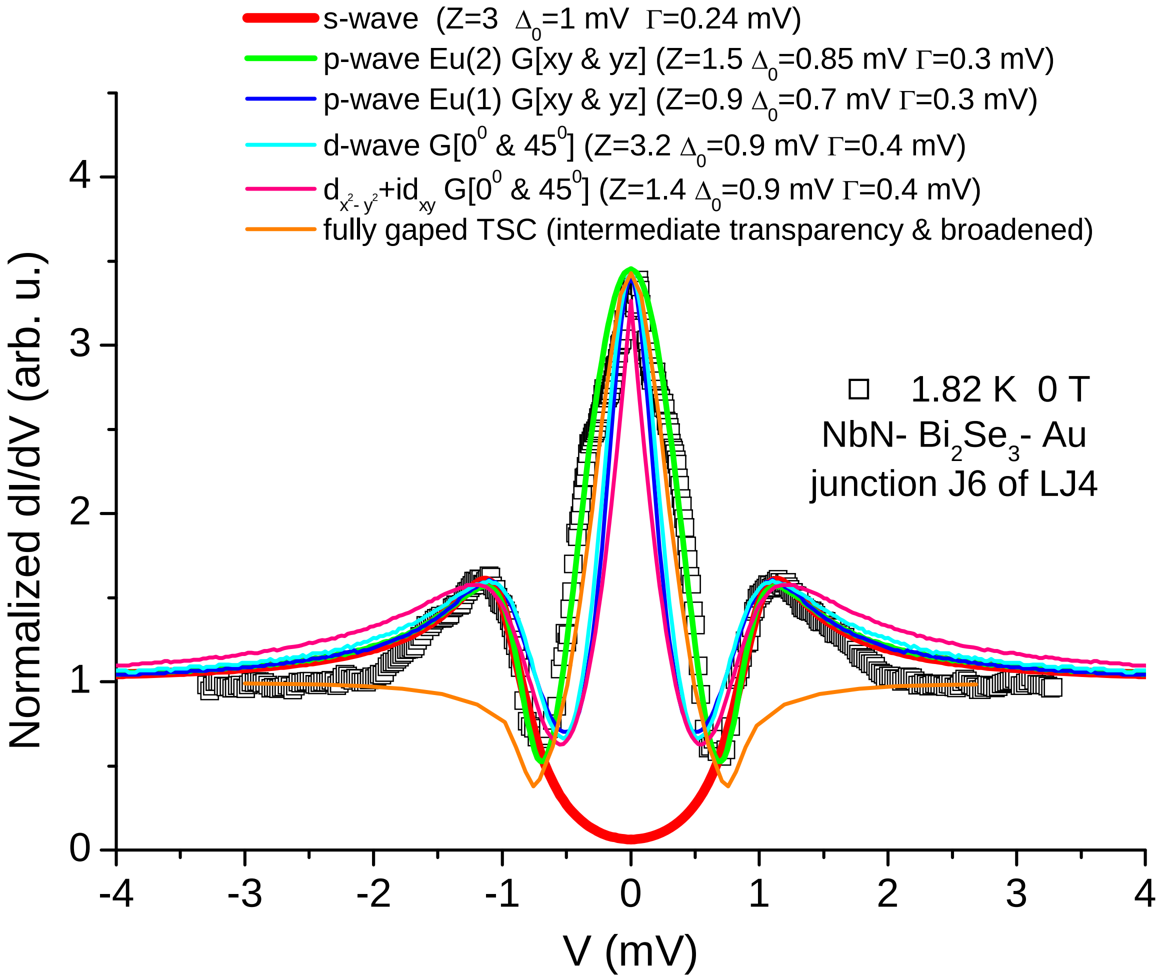
$$\Delta_{\uparrow\downarrow} = \Delta_0(\cos 2\phi - \cos 2\alpha)$$

Where α is either 0^0 or 45^0

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

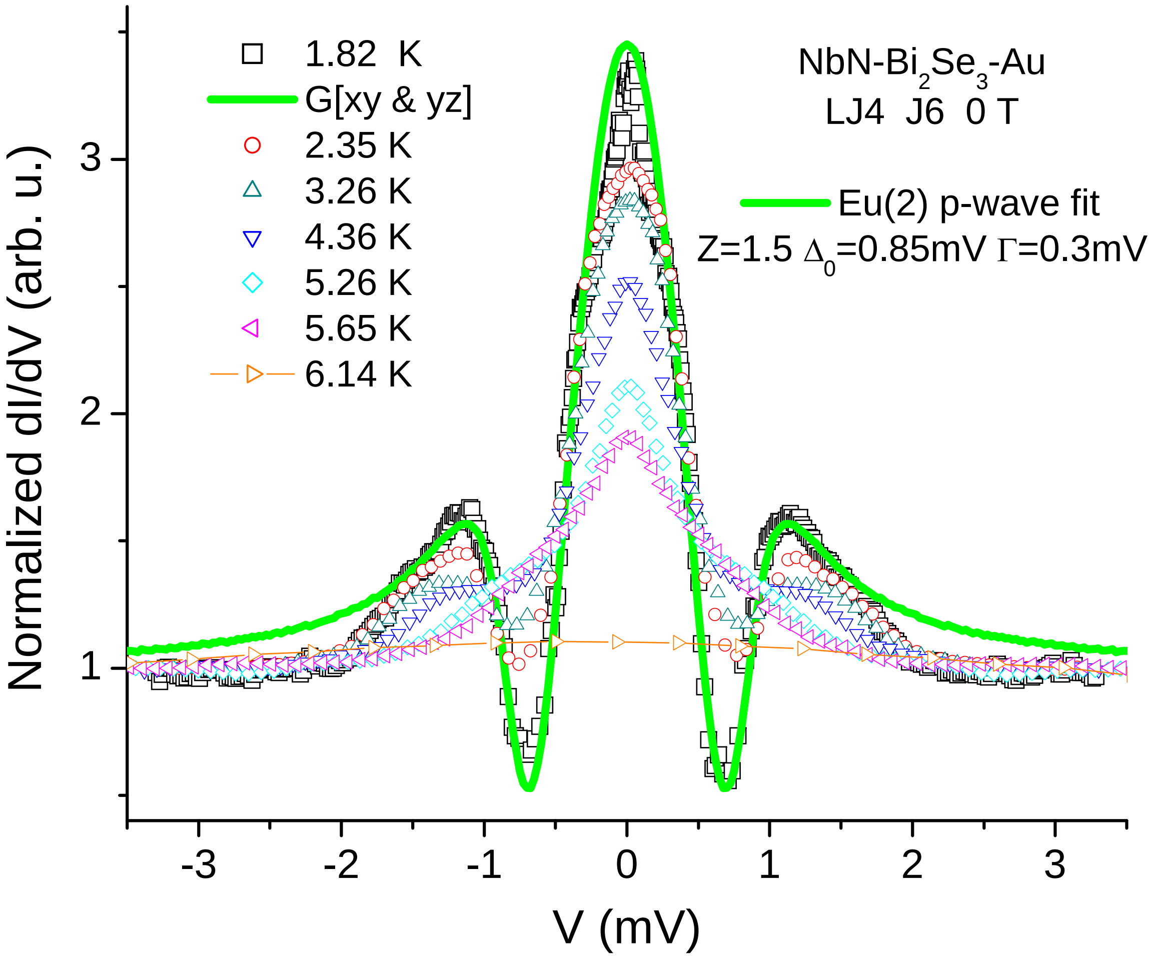
- Topological SC (TSC)

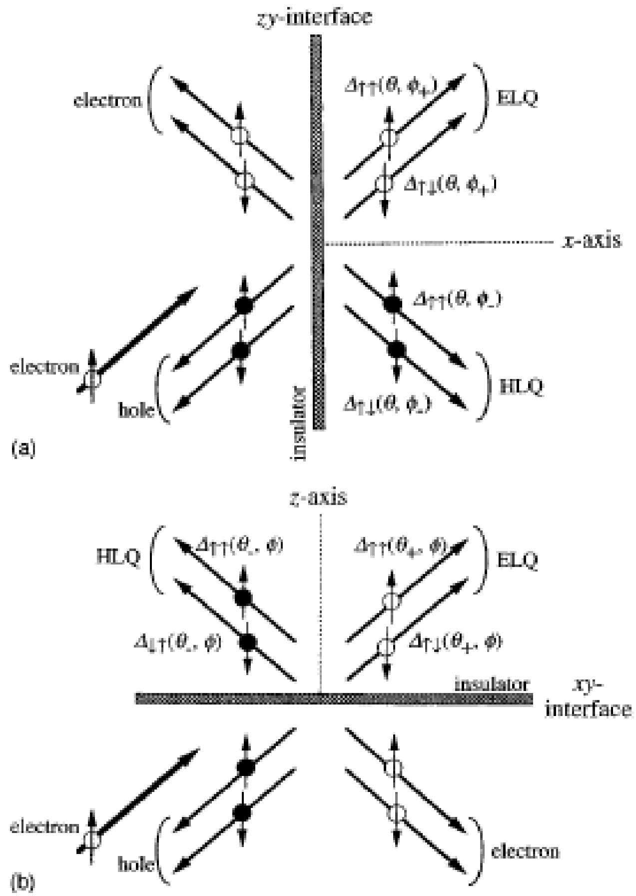
Yamakage… & Tanaka
PRB **85**, 180509(R) (2012)



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



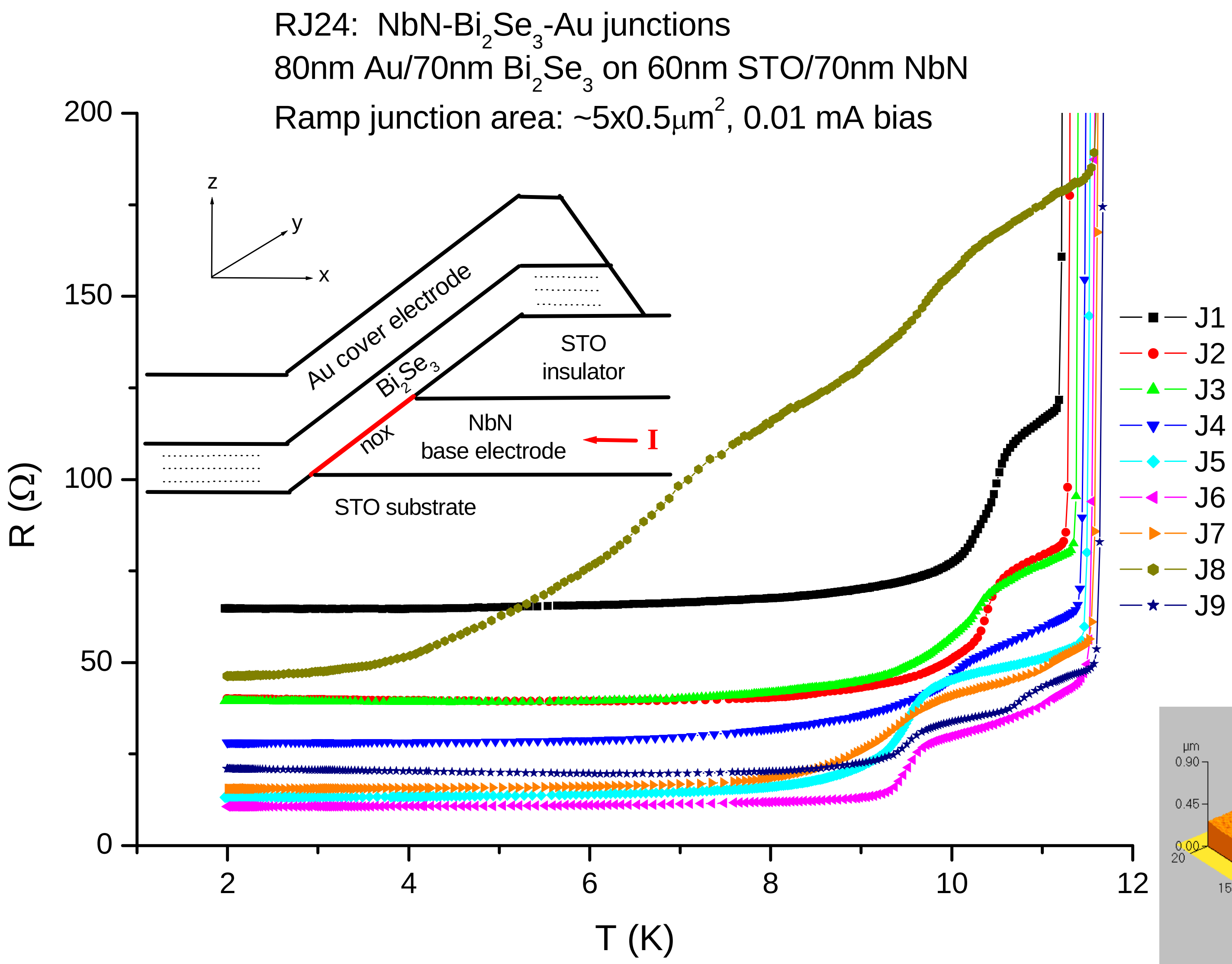


Yamashiro, PRB **56**, 7847 (1997)

- ZBCP is suppressed with increasing T
- P-wave fit with Eu(2) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$

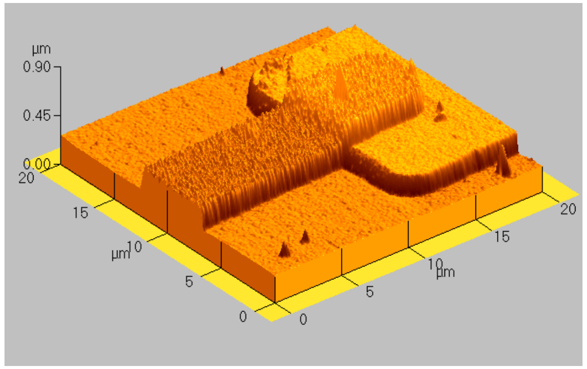
  using the same Z, Δ_0 & Γ parameters for the two interfaces

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

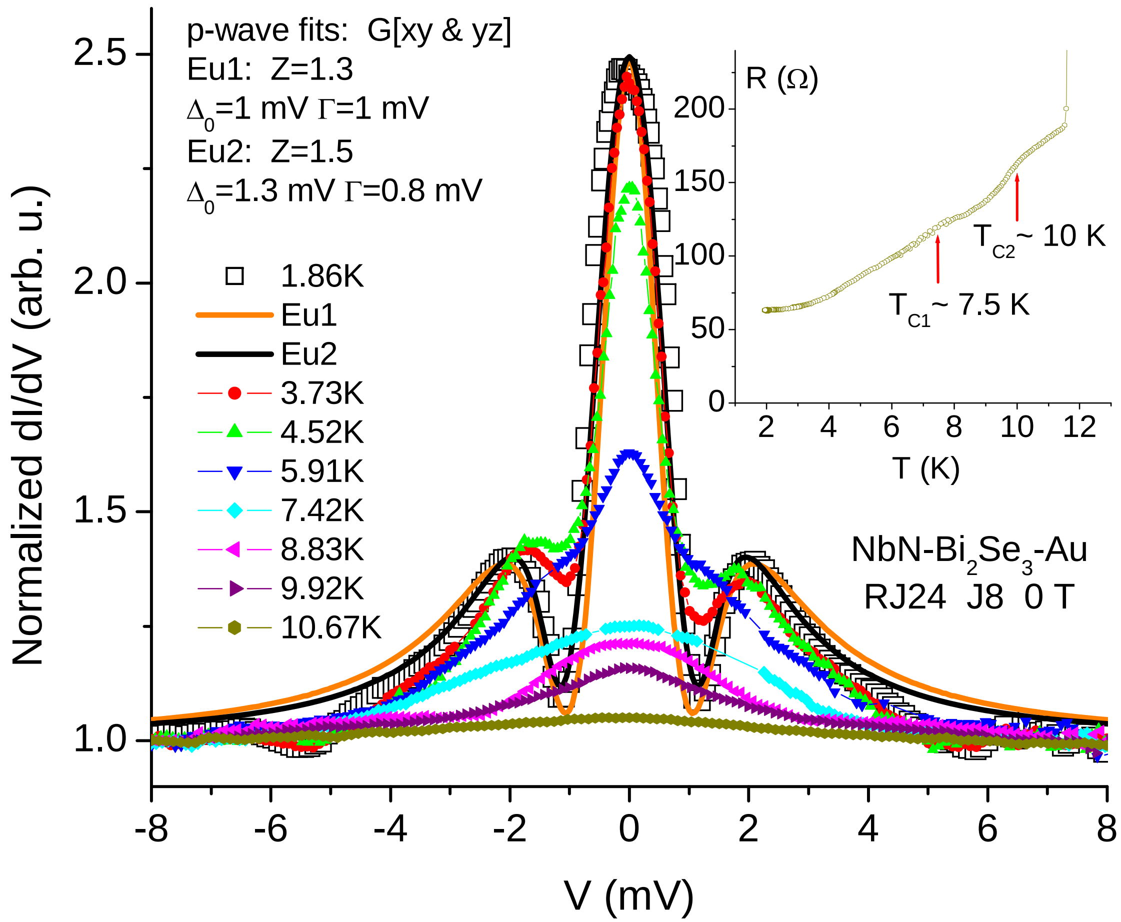


- Proximity transition at 10-11 K

- Second transition, see next



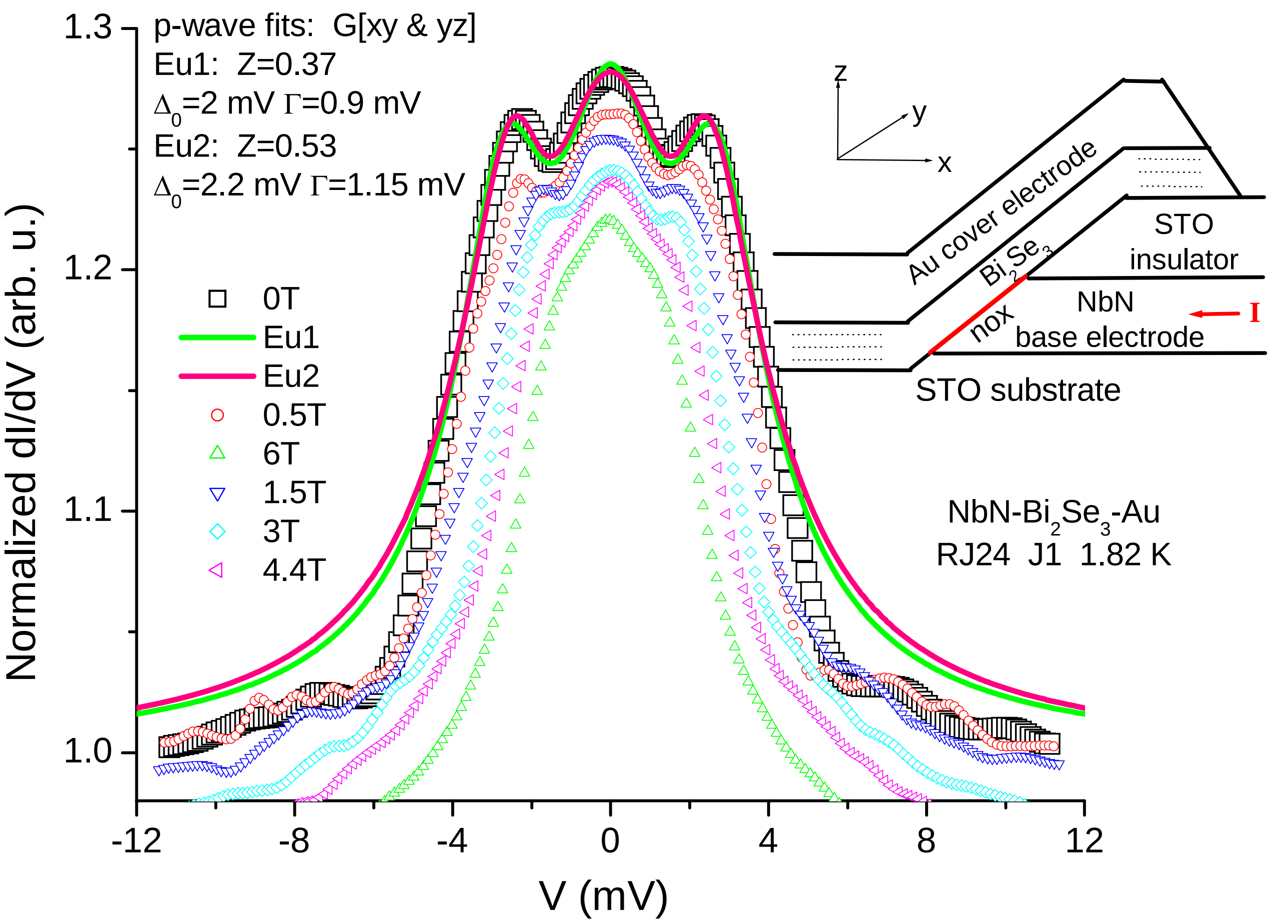
Ramp junction at various T: NbN-Bi_2Se_3-Au



- ZBCP is suppressed with increasing T
- Above 7.5 K only the broad peak survives
- P-wave fits with Eu(2) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$

  & Eu(1) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + \sin\phi)$

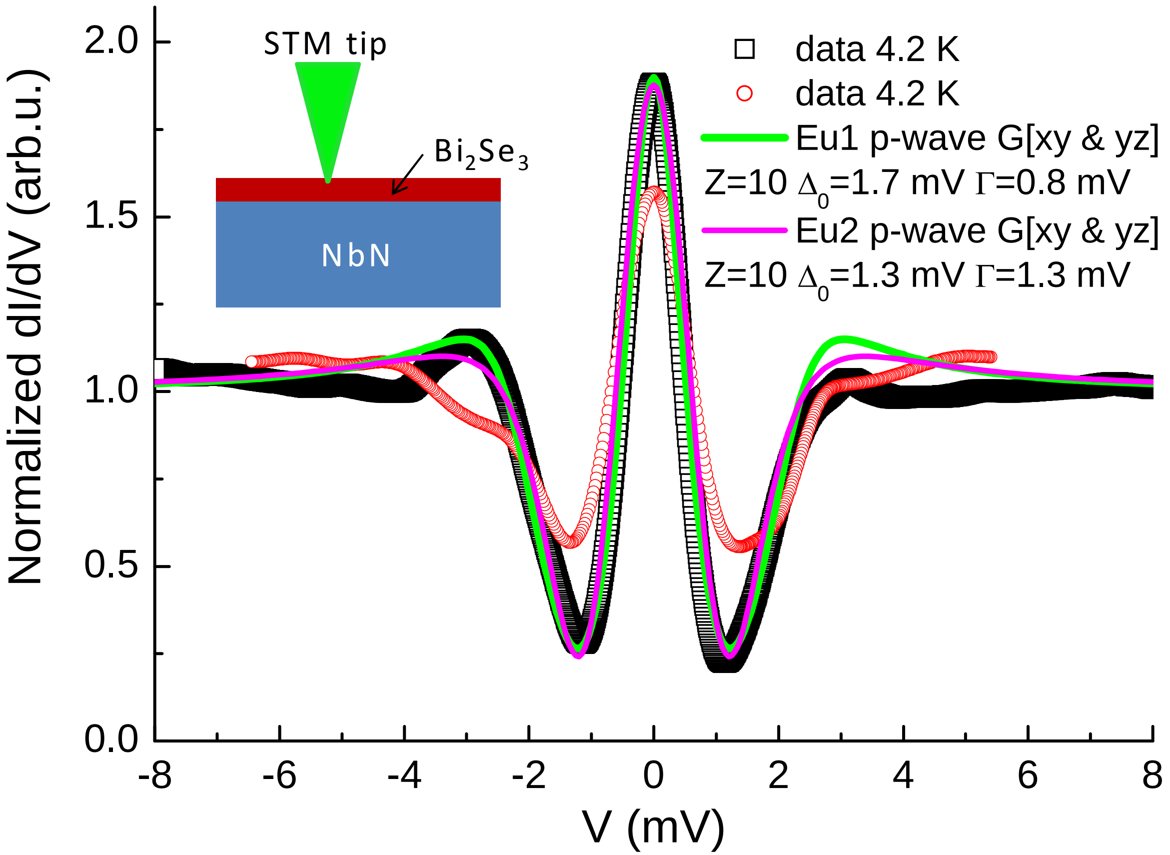
Ramp junction at various H: NbN-Bi_2Se_3-Au



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

  & Eu(1) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + \sin\phi)$

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 are shown in the figure. These are point contact spectra, measured on a few nm contact area.
- P-wave fits with Eu(2) pair potential: $\Delta = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$

  & 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 (spin-full) triplet SC