Conductance spectra of NbN-Bi_2Se_3-Au junctions: Tunneling gaps & ZBCPs

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Some basics & what is done here

- Topological Insulators (TOI) are band-gap insulators with conduction by surface states due to a strong spin-orbit interaction
- The hallmark of Topological Superconductivity is the presence of Majorana fermions (MF), which are a special sub-group of surface Andreev bound states (SABS) at zero energy
  In the experiments, they will appear as ZBCPs

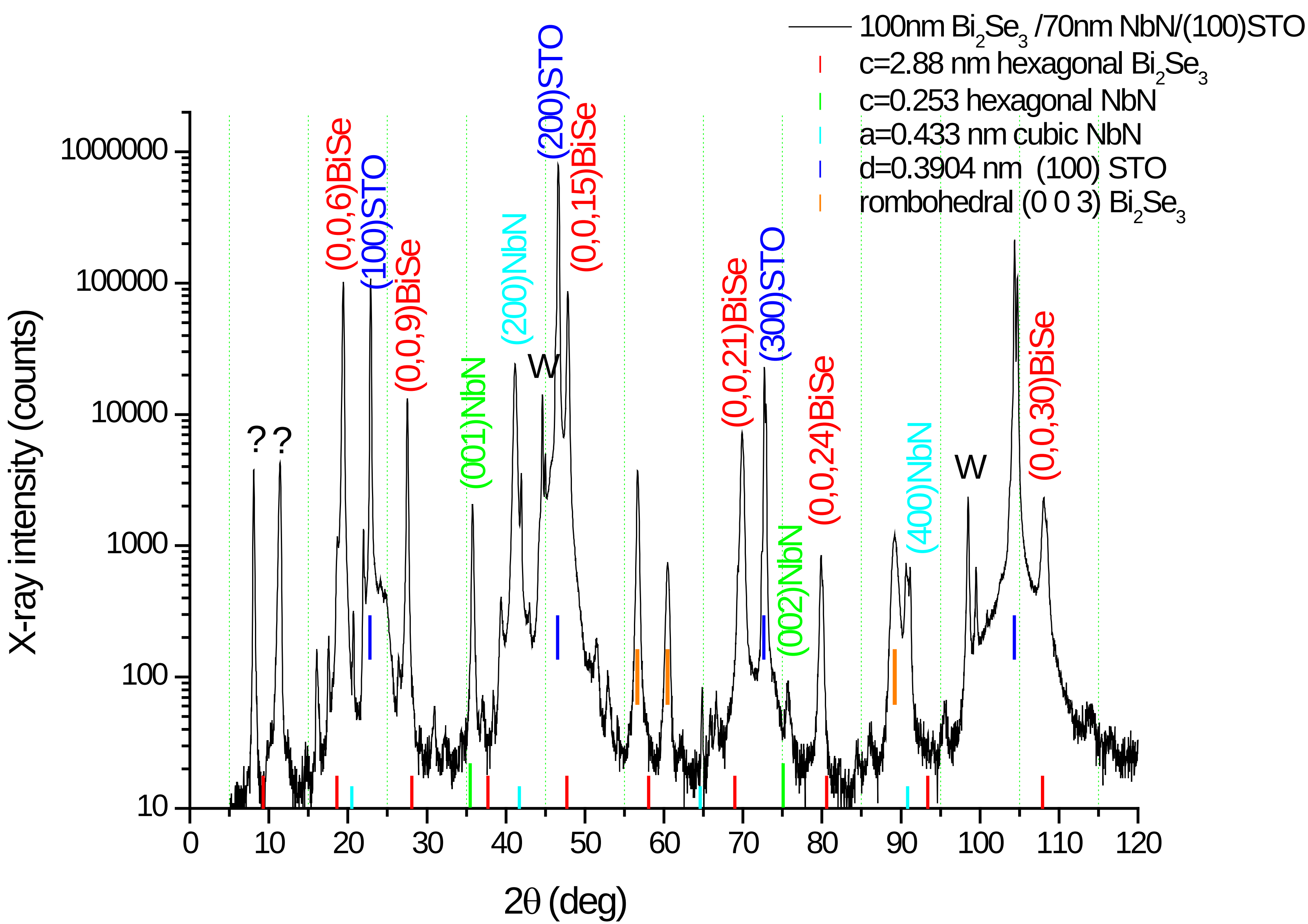
- We use proximity induced superconductivity in a TOI in NbN-Bi_2Se_3-Au junctions, similar to Yang & Li Lu, PE in Sn/Bi_2Se_3, PRB **85**, 104508 (2012)
  & G. Koren et al., PE in Bi/Bi_2Se_3, PRB **84**, 224521 (2011)

- We characterize the films structure & growth orientation, & measure transport (R vs T), and conductance spectra vs H & T

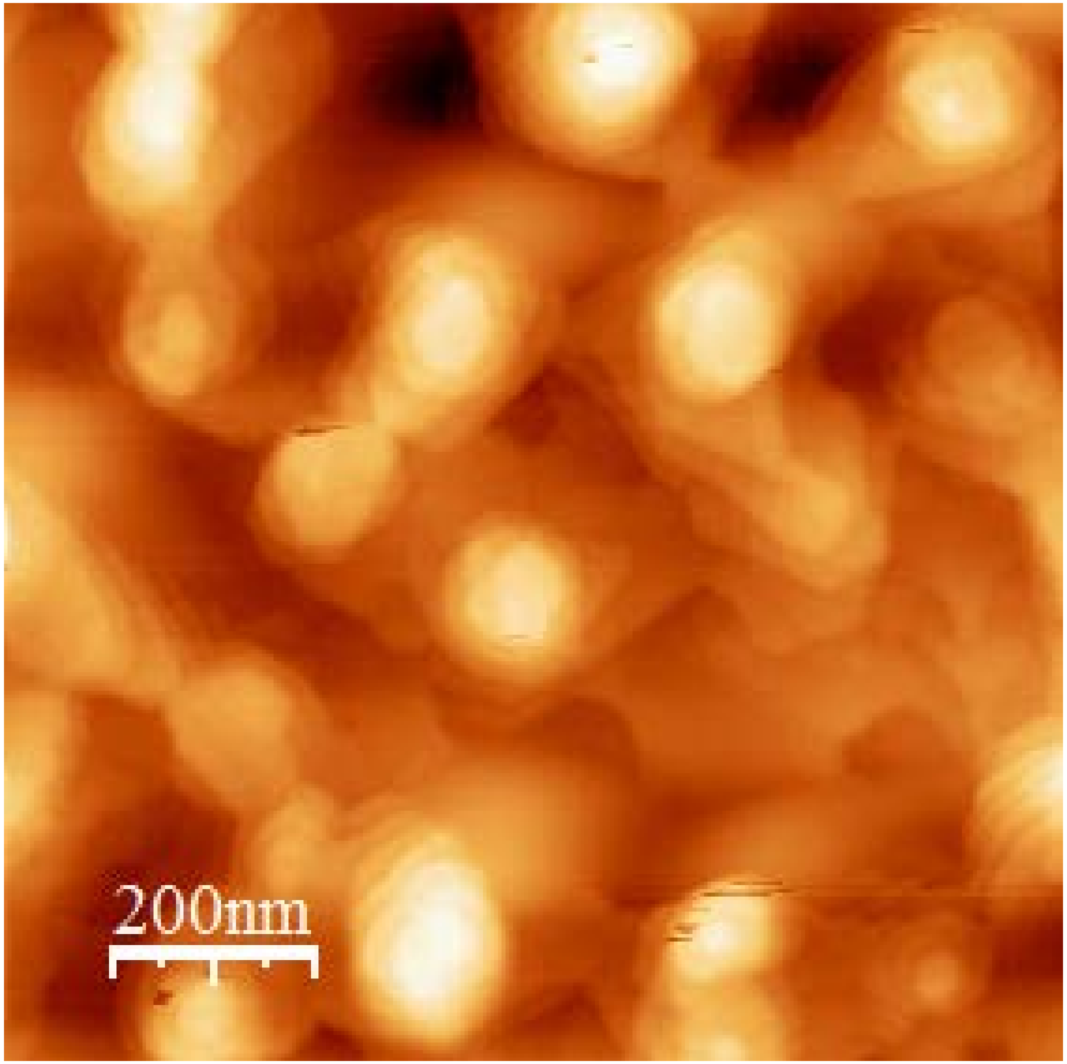
- The observed ZBCPs are ~0.15mV & ~0.9mV wide (FWHM). The narrower one is kT limited (~2K) & the broader one might be a result of thermally smeared split ZBCP (Yamakage & Tanaka, PRB **85**, 180509(R) (2012) or other non zero bound states

X-ray diffraction of Bi_2Se_3 /NbN bilayer on (100)STO

Shows hexagonal Bi2Se3 & mostly cubic but some hexagonal NbN



An AFM image of a
100nm thick Bi_2Se_3 on 70nm thick NbN bilayer on (100) $SrTiO_3$



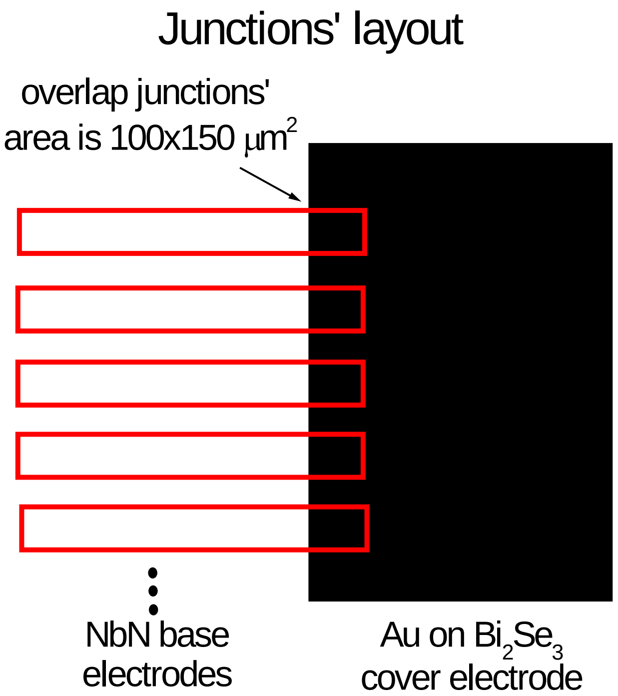
1x1 μm^2

Crystallized well,
in laterally disordered
hexagonal form

Junctions layout

- 10 base electrodes were patterned first in a NbN film on half the wafer
- Then a cover bilayer of Au/Bi_2Se_3 was deposited on the other half of the wafer with the aid of a shadow mask
- No further patterning was done, only Ag paste was added on the NbN contact pads

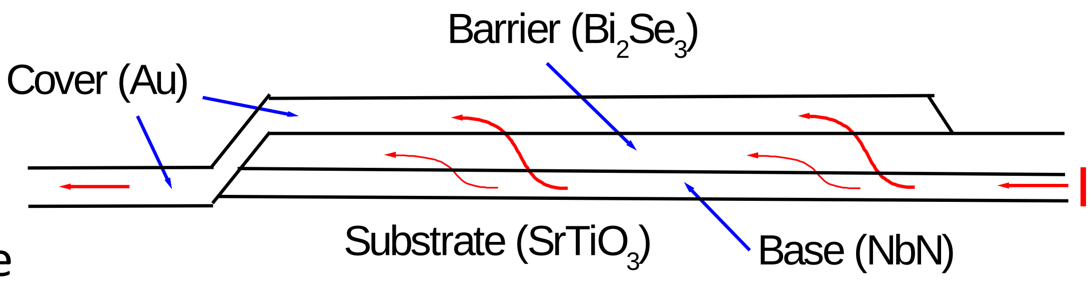
Junctions with *ex-situ* interface



Junction with *in-situ* interface

(Full patterning)

- Start with a Bi_2Se_3/NbN bilayer (base)
- Then add the Au cover electrode



AFM images

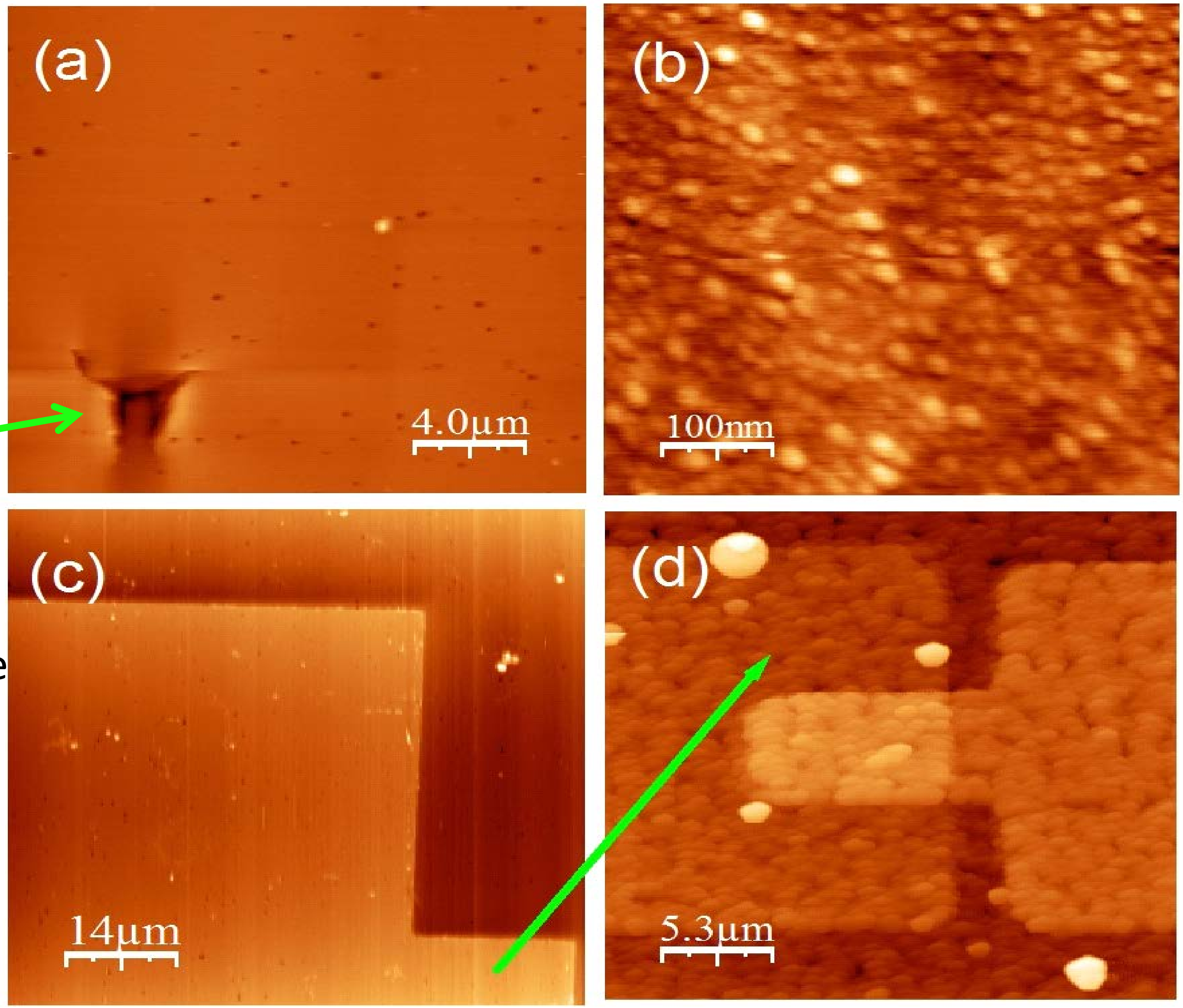
NbN films

As deposited
virgin films (a & b)

A large via-hole

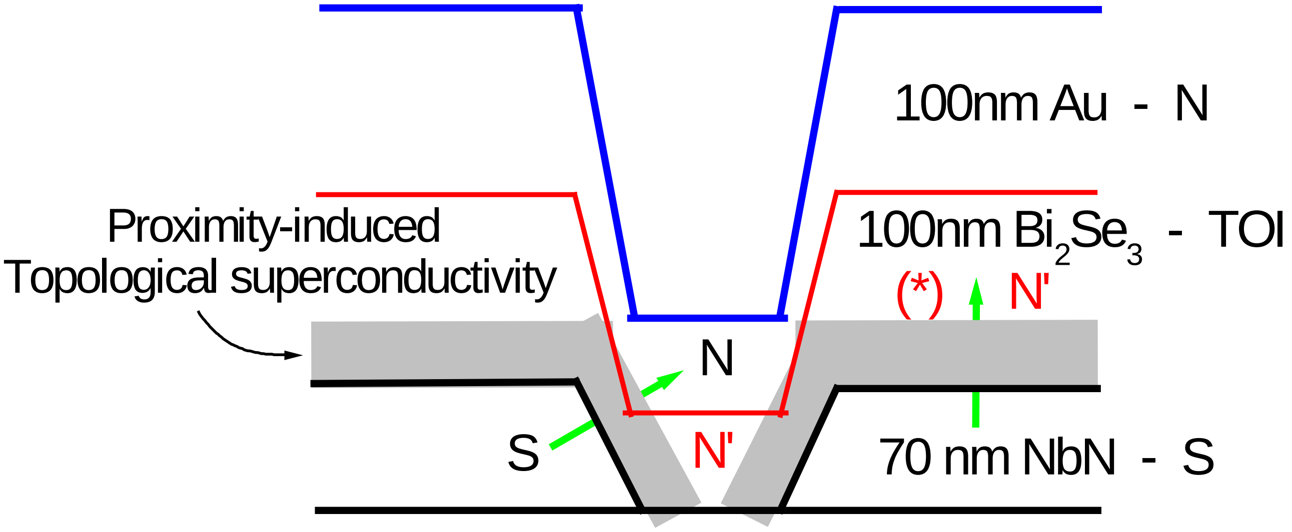
After patterning (c)
of the base electrode

(d) A small junction
with full patterning



A schematic cross section near a via hole

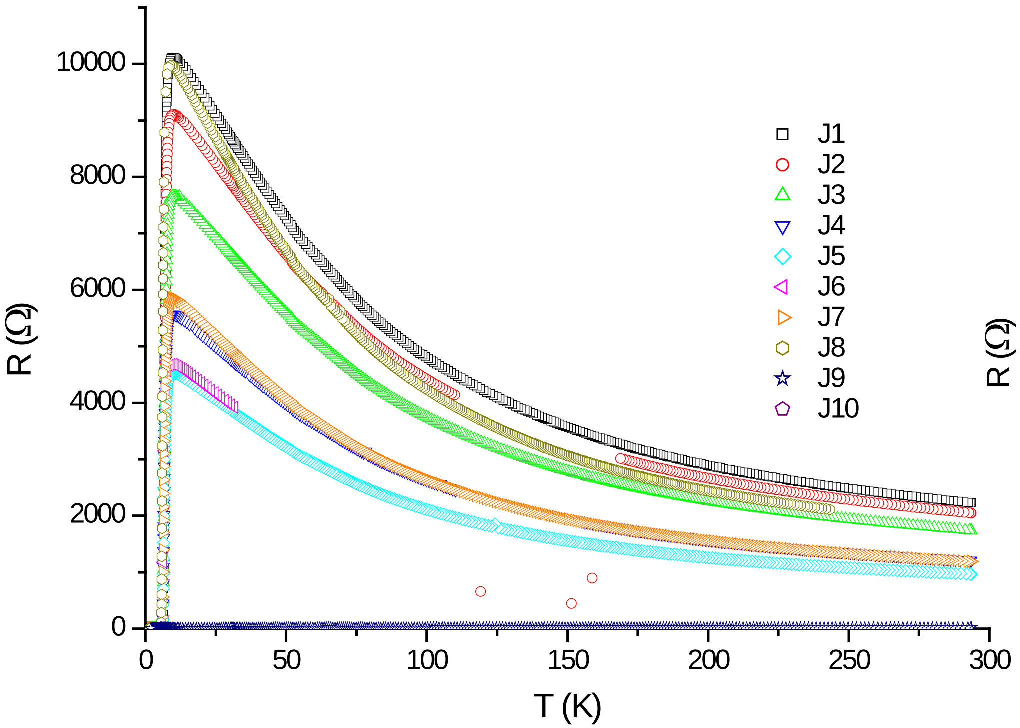
Via-hole in a trilayer junction

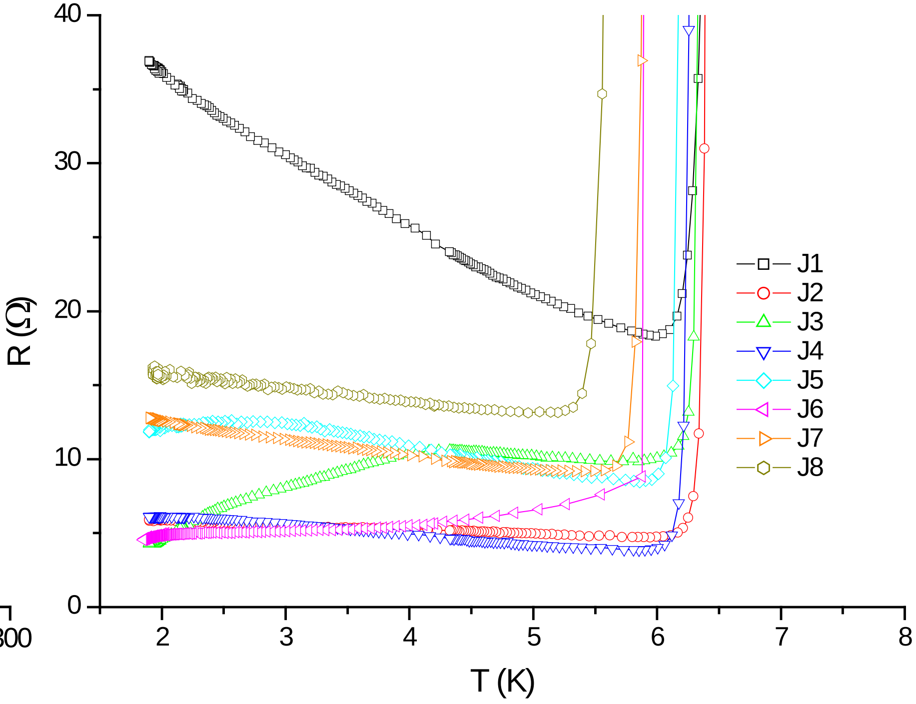


(100) $SrTiO_3$ substrate

(*) Since the Bi_2Se_3 film is heavily hole doped by Se vacancies, it can also be considered as N'

R vs T of a 100x150 μm^2 area *ex-situ* NbN-Bi_2Se_3-Au junctions





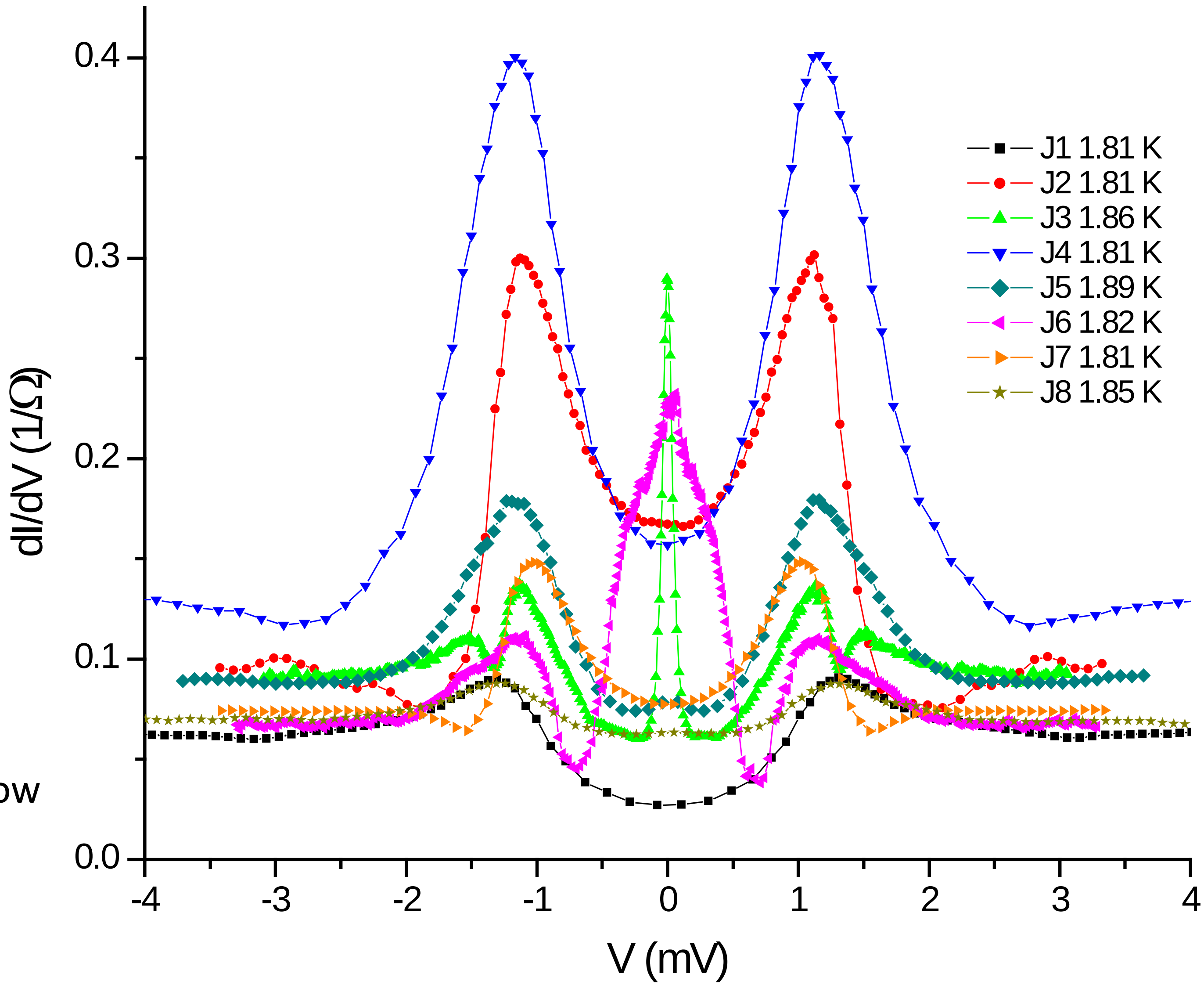
- Insulating vs T due to the low T_c NbN film (deposited in excess N_2)
- Superconductive transition only at T_c~8K (onset)
- Junctions' resistance at low T is of about 10Ω
- Junctions with a metallic behavior at low T have ZBCPs (#3, #5 & #6)

Conductance spectra of all working *ex-situ* junctions

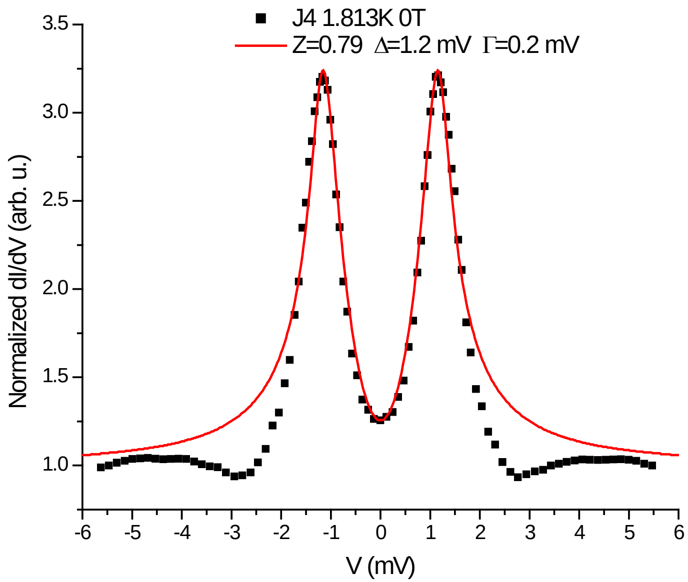
All junctions have coherence peaks of the NbN SC electrode at 1-1.2 mV, consistent with the BCS ratio: $2\Delta/kT_c$~3.5

Narrow (kT- limited) and broad ZBCPs

The broad one might be a thermally smeared split one, or with a narrow ZBCP superimposed

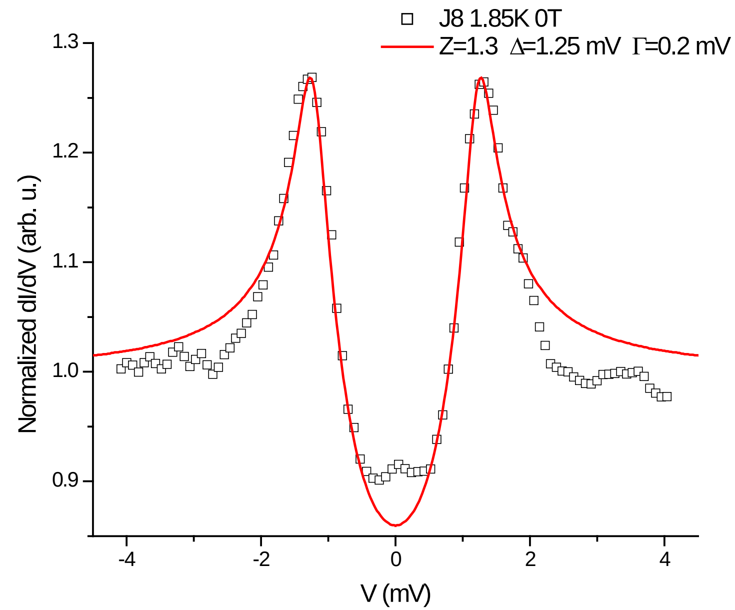


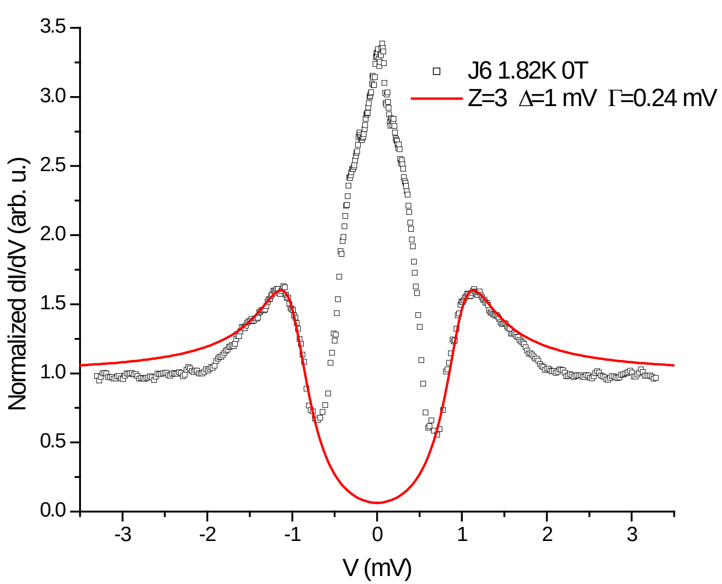
Conductance spectra with s-wave BTK fits of a few NbN-Au/Bi_2Se_3 junctions



- Andreev

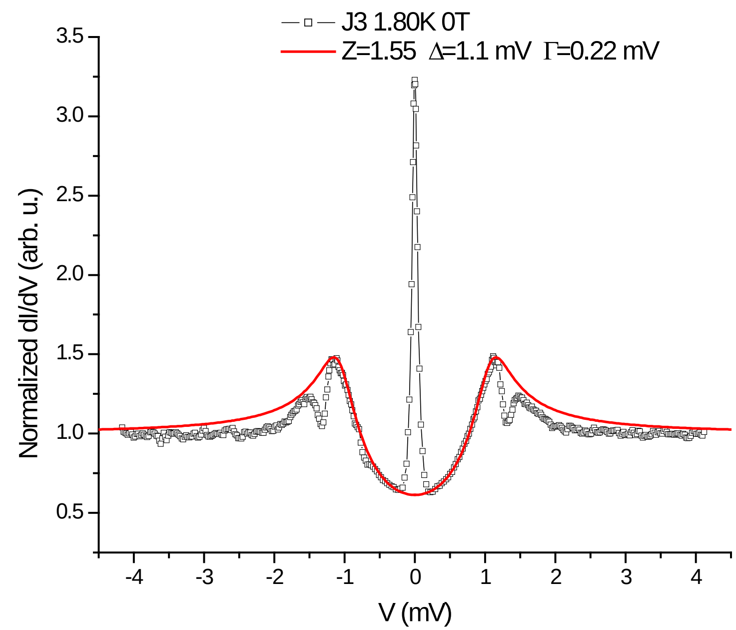
- tunneling





- Broad ZBCP
  0.9mV FWHM

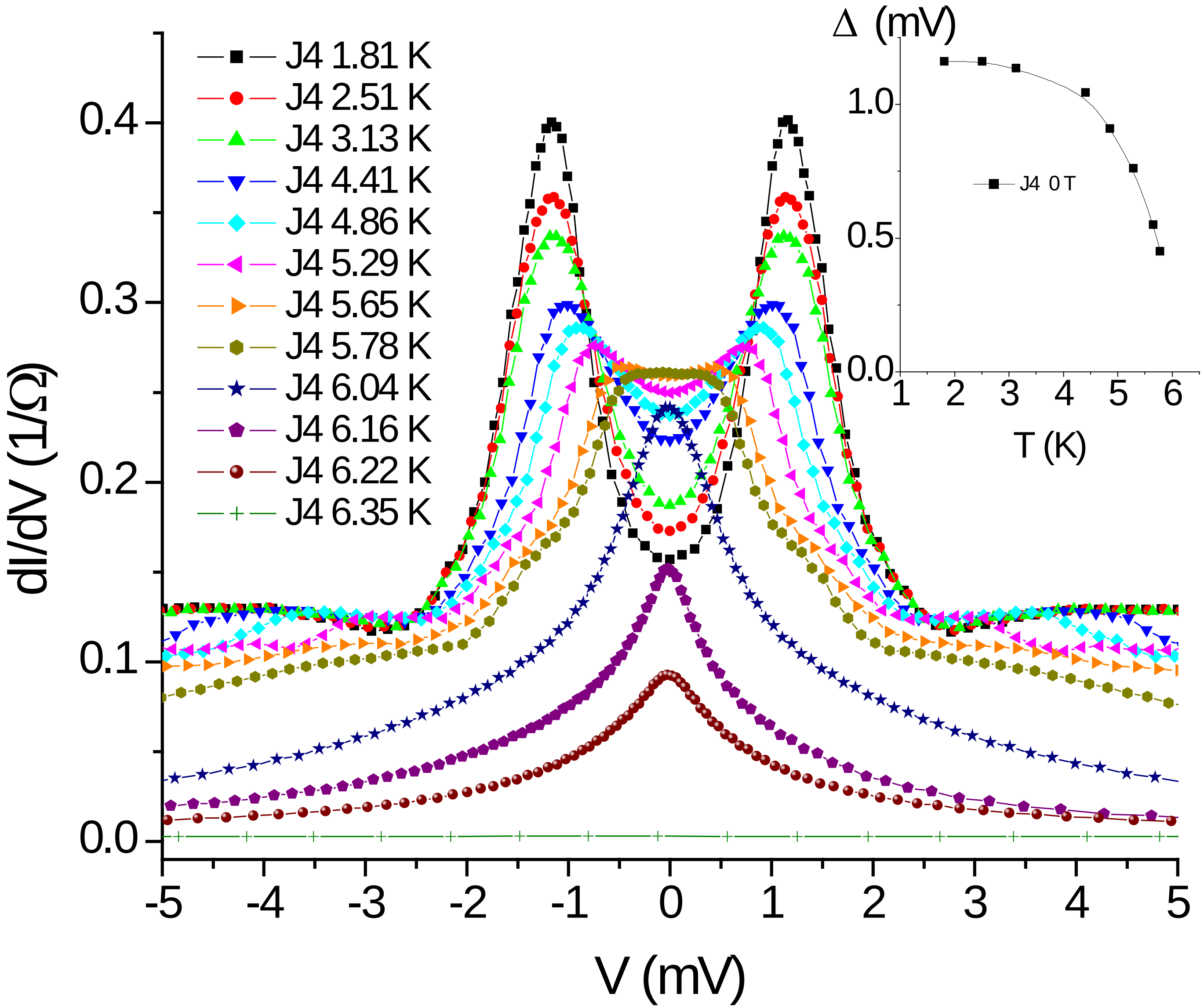
- Narrow ZBCP
  0.15mV FWHM



Conductance spectra at various temperatures

Coherence peaks (CP) & SC gap are suppressed vs T (as usual)

BCS-like gap Δ

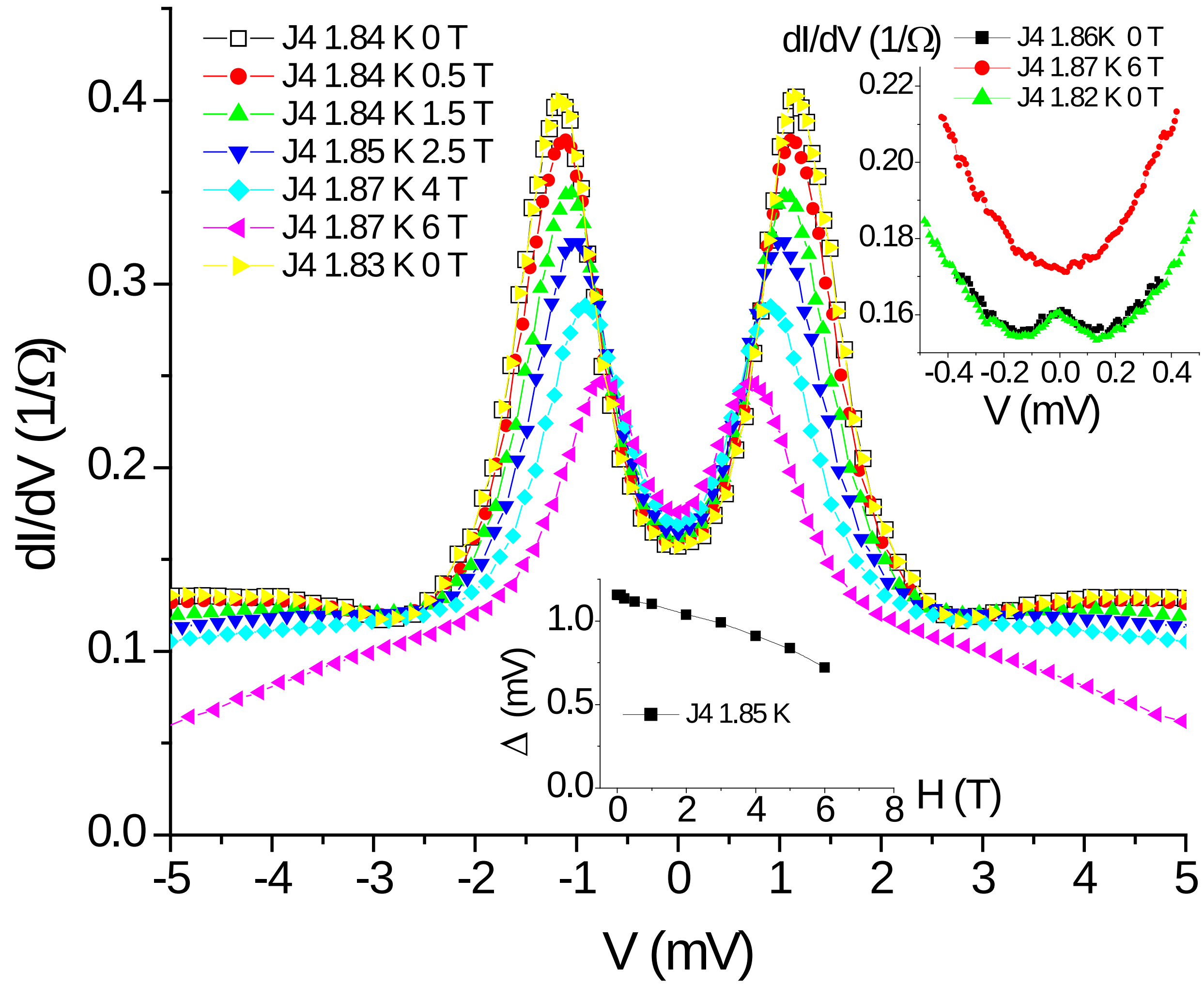


Conductance spectra under various magnetic fields

Coherence peaks & SC gap are suppressed vs H (also as usual)

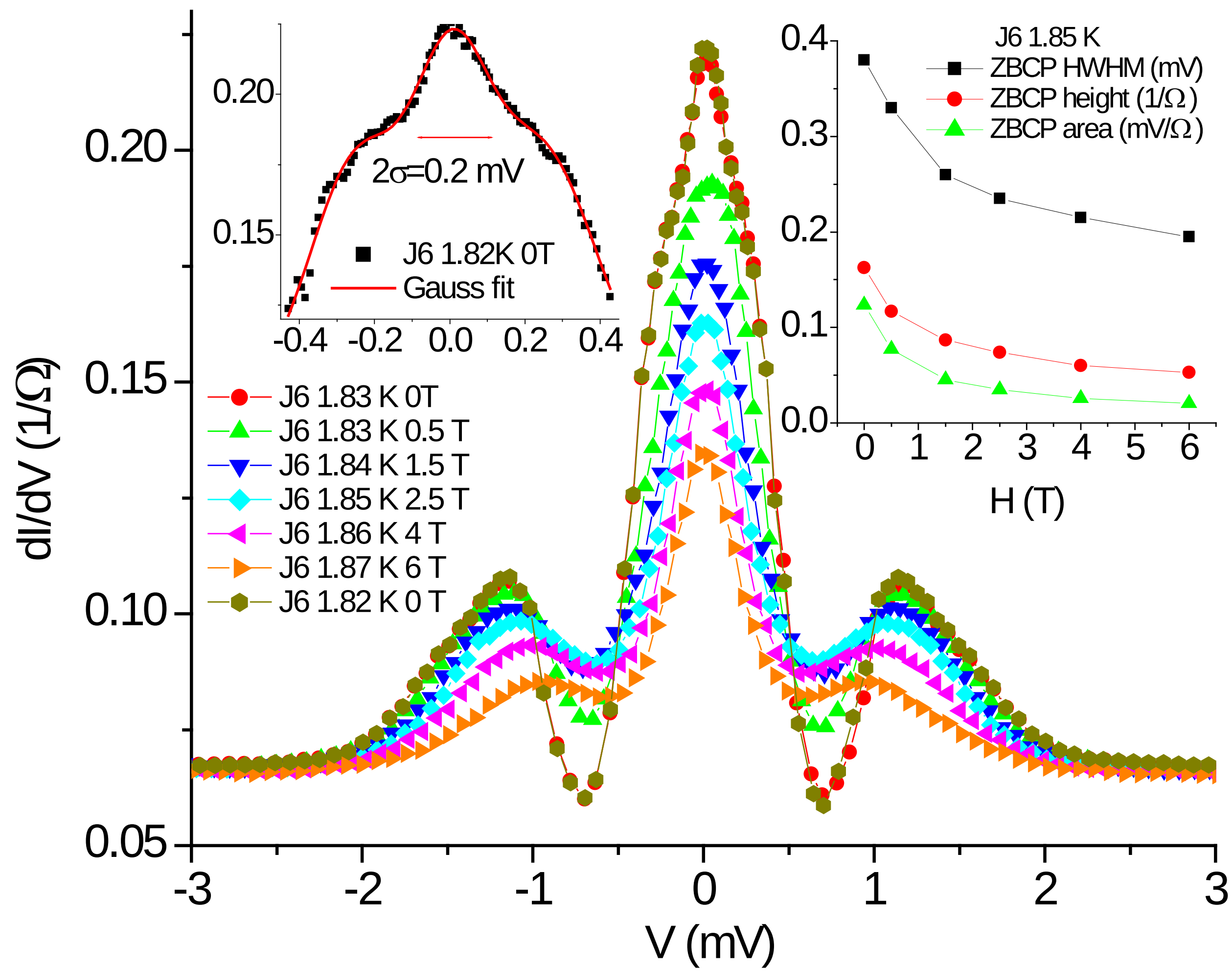
A small ZBCP at Low T, suppressed under 6 T, and recovers when field is removed

Need higher fields to test BCS behavior of the gap Δ



Conductance spectra at various T, CP & broad ZBCP

Coherence peaks,
SC Gap and ZBCP
height, width & area
are suppressed
vs H



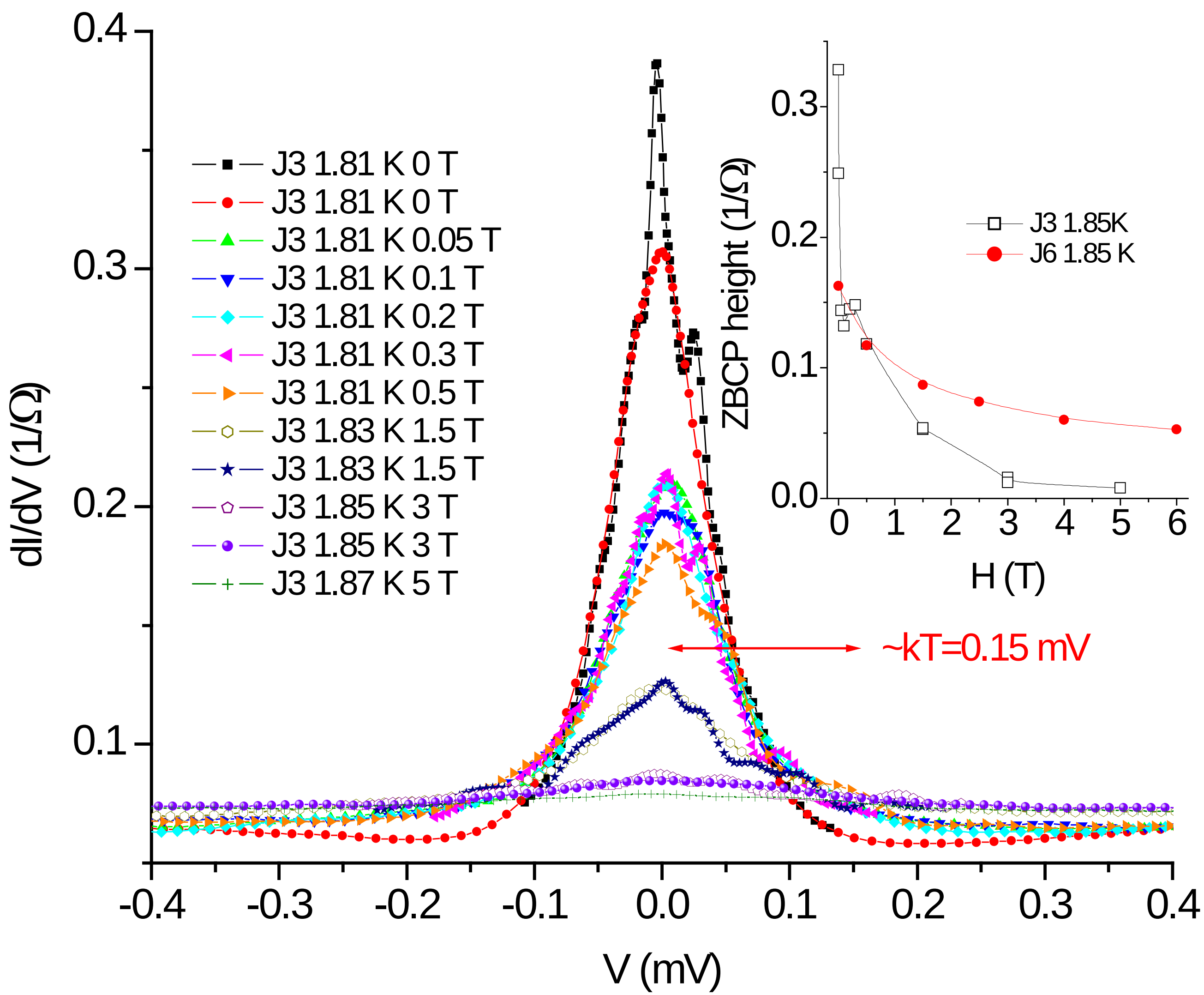
Broad ZBCP can be
due to a split ZBCP,
with superimposed
narrow ZBCP
Yamakage & Tanaka,
PRB **85**, 180509(R) (2012)

Conductance spectra at various T, narrow ZBCP

Narrow ZBCP with kT limited width (thermal smearing at 1.8 K)

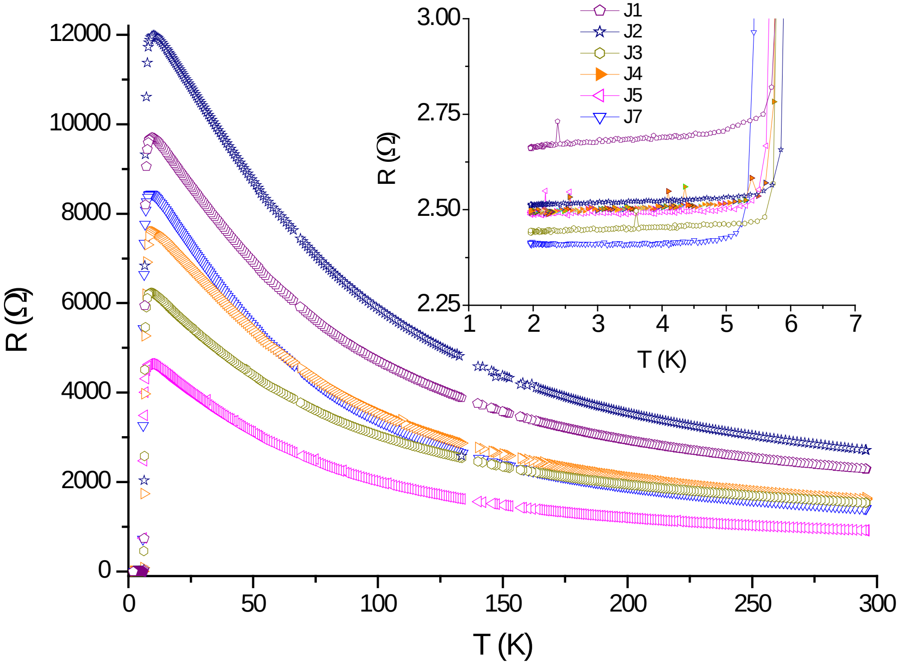
Its' ZBCP height is suppressed differently than the height of the broad ZBCP

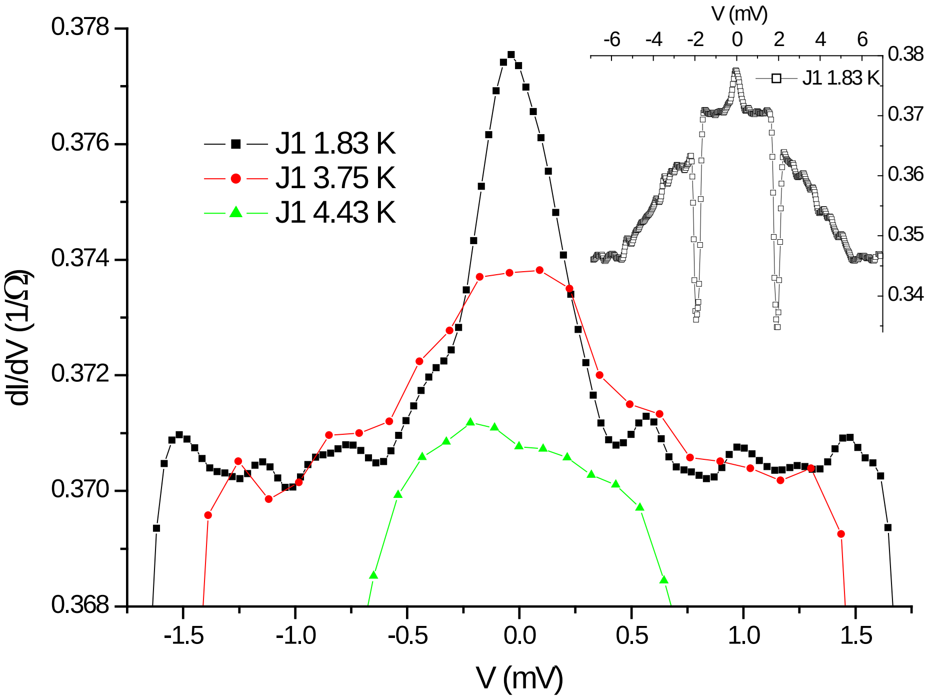
Can be due to Majorana fermions
Yang & Li Lu PRB 85, 104508 (2012)
Mourik et al., Science 336, 1003 (2012).
Das et al., arXiv:1205.7073
0.03-0.05 mV widths at 0.1K



Smaller 10x5 μm^2 area *ex-situ* NbN-Bi_2Se_3-Au junctions

R(junction) went down!
Se vacancies doping by milling.
⇒ Get a low R shunt resistance,
Strongly shunted junction.





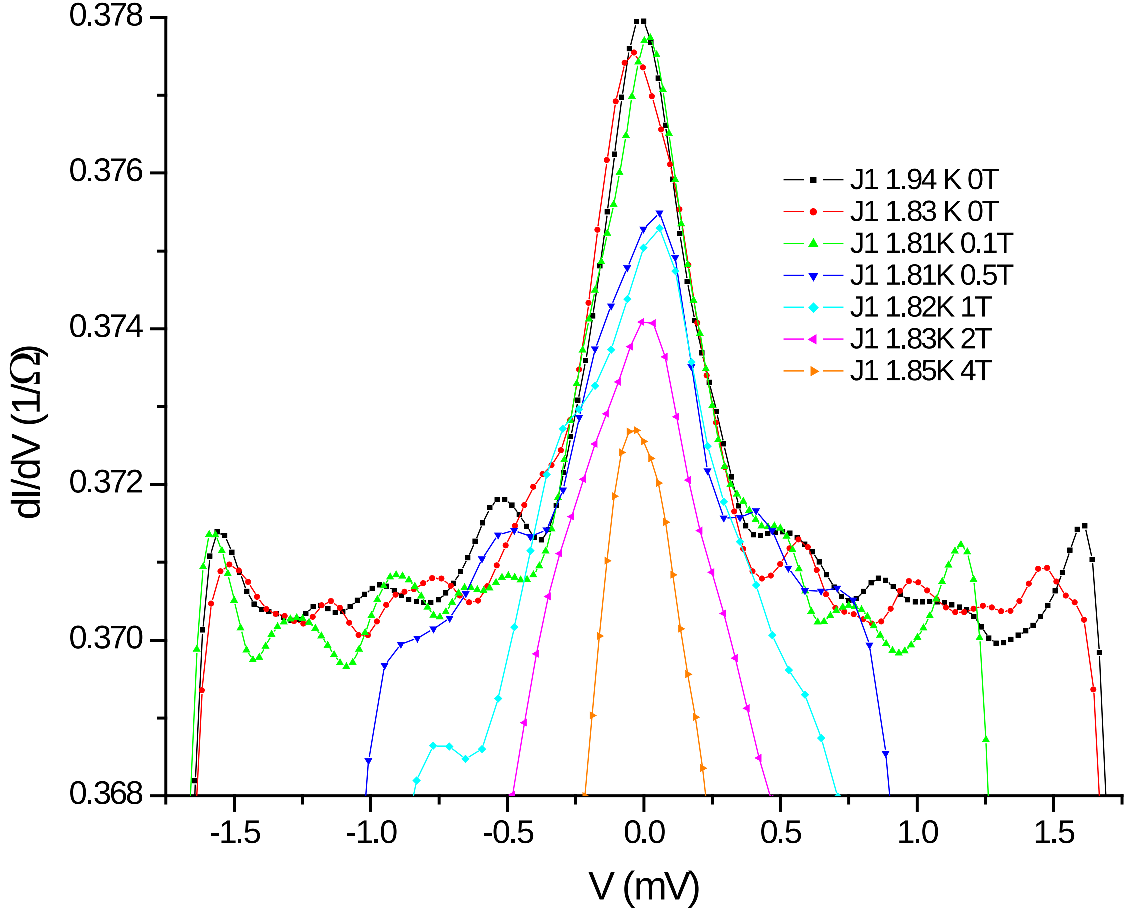
One weak ZBCP survived

No coherence peaks now
(must be a milling effect)

10x5 μm^2 area *ex-situ* NbN-Bi_2Se_3-Au junctions under different fields

The ZBCP is suppressed with increasing magnetic field

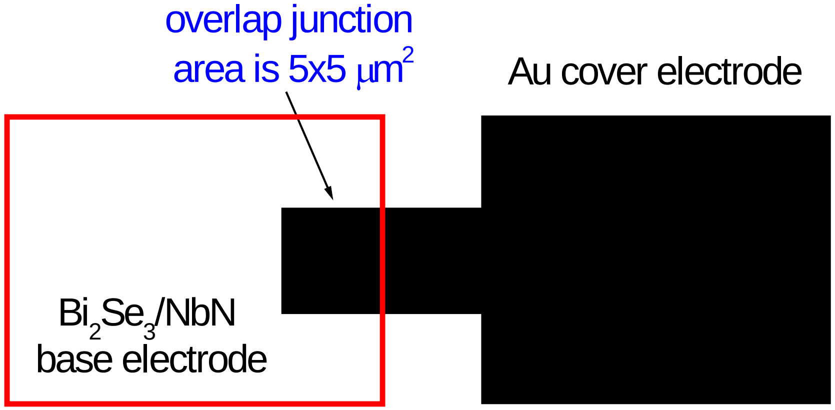
Also the critical current goes down with increasing field (the “dips”)



Layout of a fully lithographically-patterned, *in-situ* junction

- 10 base electrodes are patterned first in a Bi_2Se_3/NbN bilayer on half the wafer
- Then a cover gold film is deposited on the whole wafer, followed by further patterning of this cover electrode
- The resulting junction area is A~5x5 μm^2

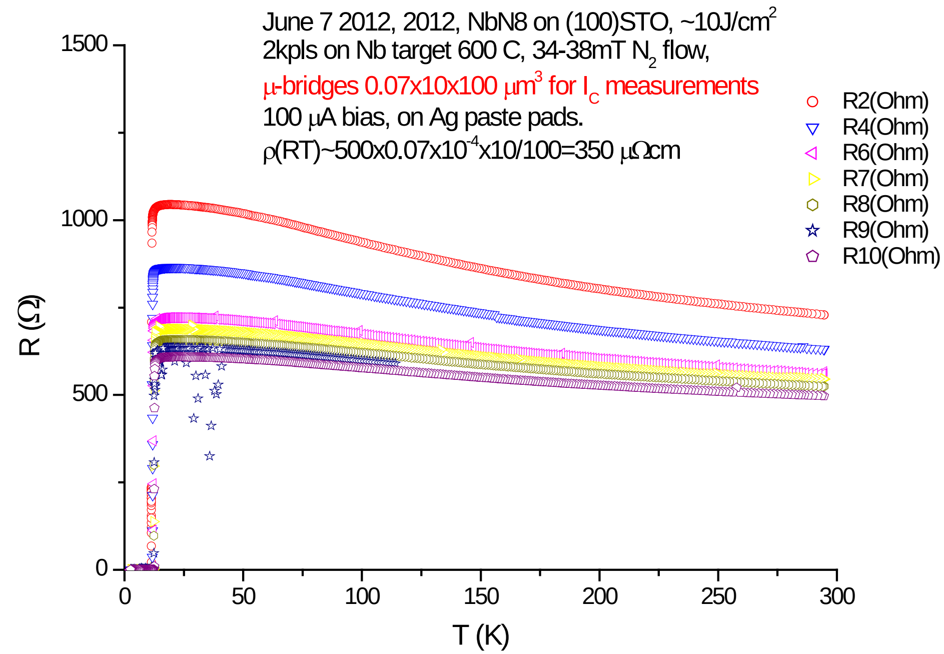
A fully lithographically-patterned junction layout



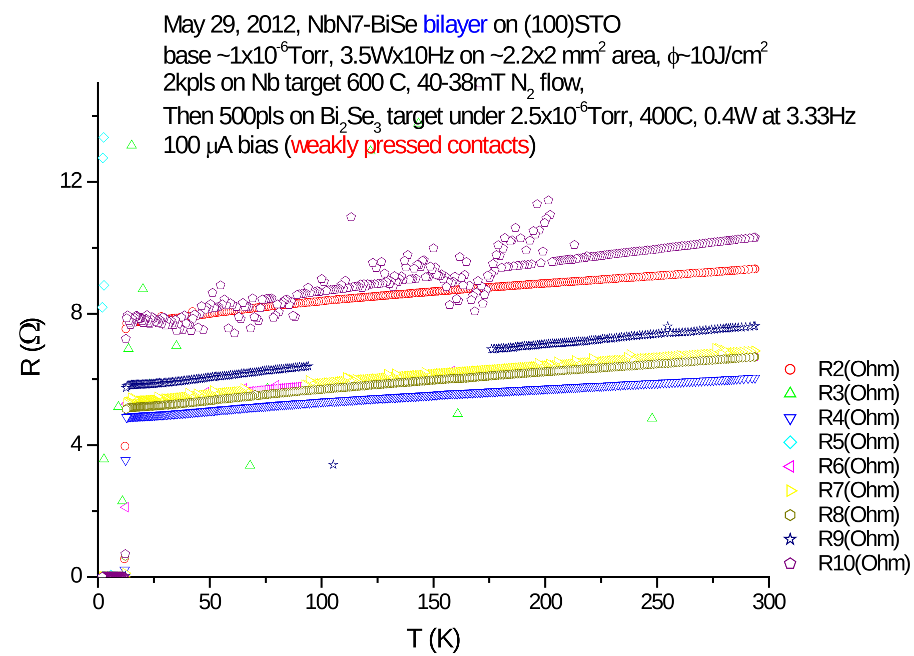
Top view

R vs T of bridges in a 70nm thick NbN & of 100nm Bi_2Se_3/70nm NbN bilayer

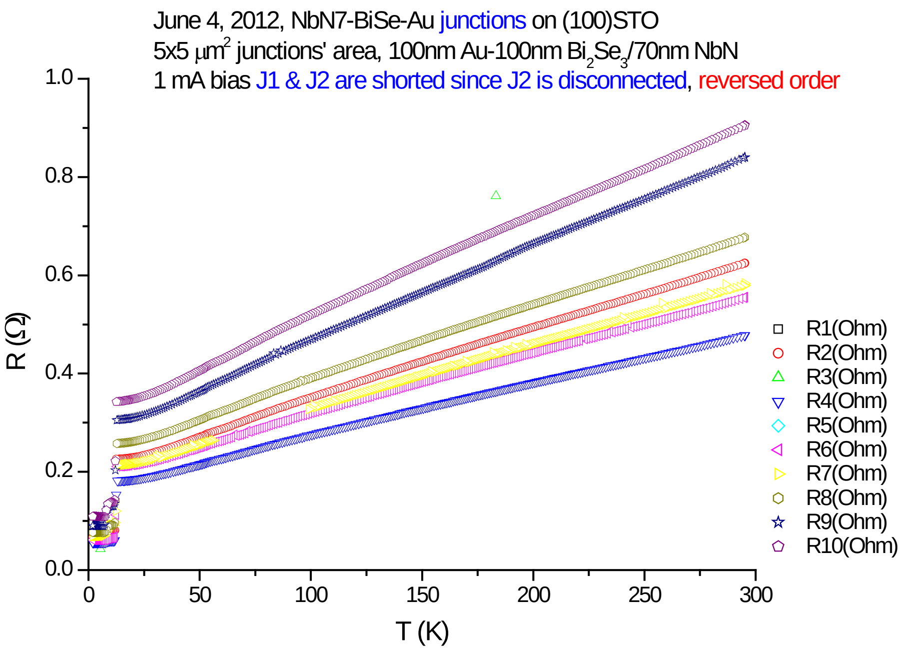
- ρ of bare NbN bridges at RT is similar to that of YBCO, but is not metallic vs T.
- T_c of the bare NbN film is ~12.5K (onset)
- J_c(2K) of NbN bridges with 0.07x10μm^2 cross-section area is ~1.4MA/cm^2, which is equivalent to 10mA/10μm width

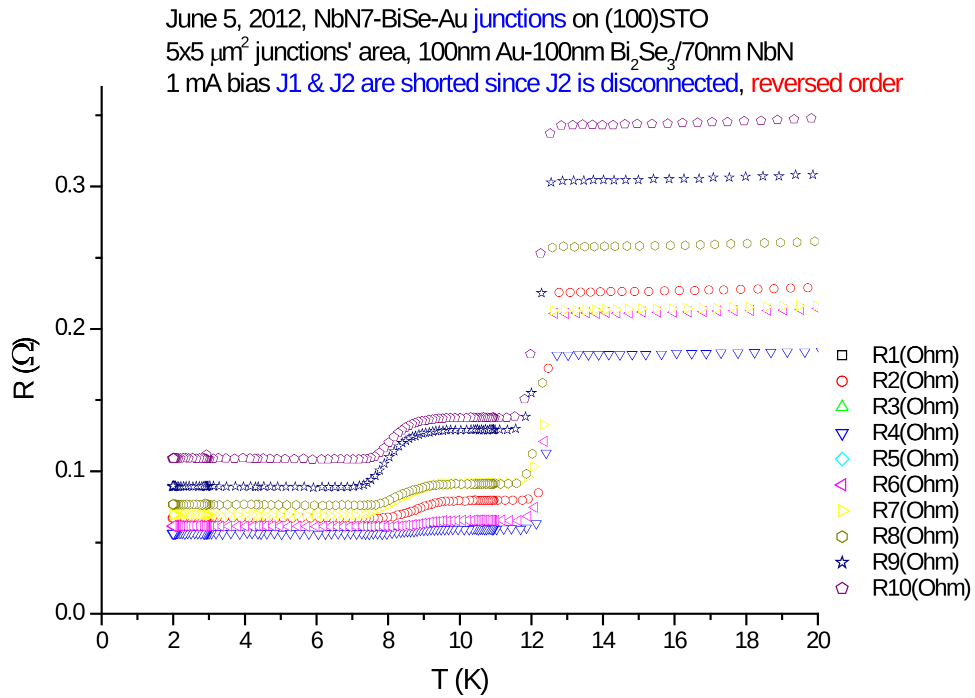


- An un-patterned bilayer. When patterned, its' resistance R would probably be similar to that of the patterned NbN bridges.



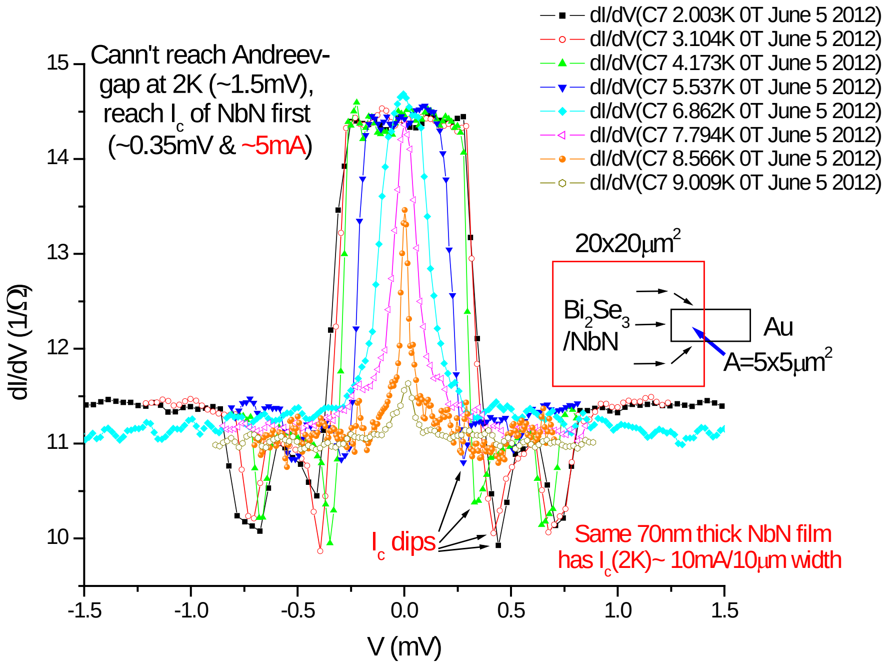
R versus T of 100nm Bi_2Se_3/70nm NbN-100nm Au *in-situ* junctions



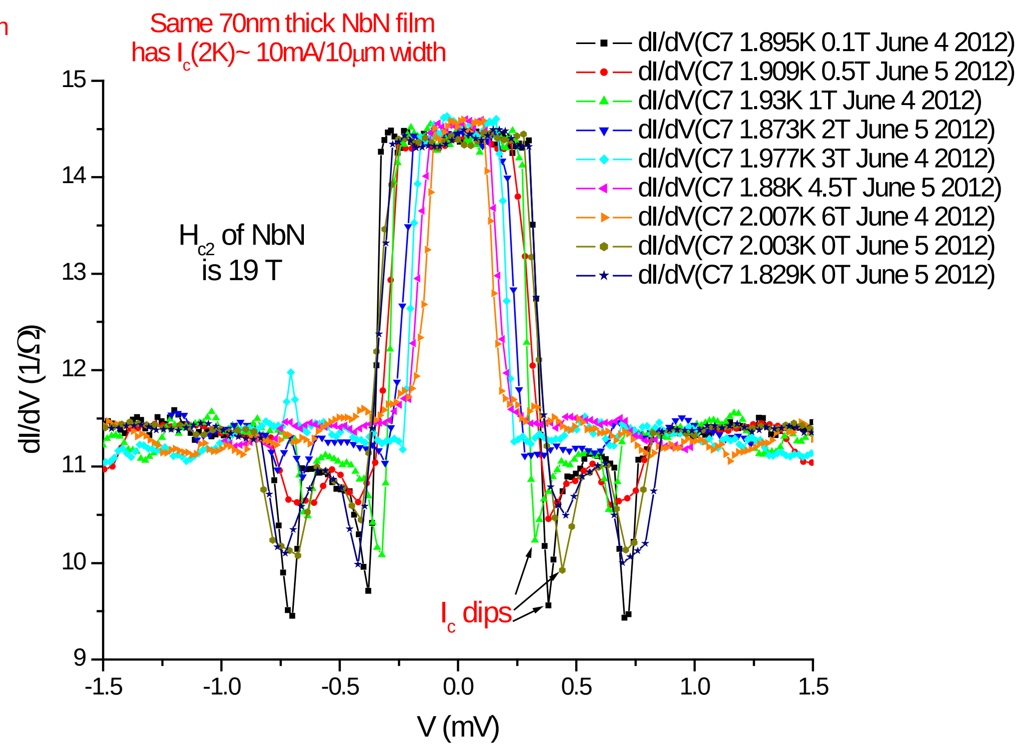


- Metallic vs T. Very low ρ even when compared to that of the unpattern bilayer (x10 lower). This seems to be due to additional Se vacancies in the Bi_2Se_3 layer (hole doping), possibly created by the direct Ar ion beam on the Bi_2Se_3 when milling the gold cover electrode. ⟶ Should use a shadow mask instead
- T_c of the NbN electrode is ~12.5K (onset) & ~8K of the junction
- Junctions' resistance at low T is very low, about 0.1Ω (cleanest interface due to *in-situ* deposition of the bilayer). In the previous *ex-situ* junctions with the x600 larger area, this resistance was x100 larger!!!

Conductance spectra of J7 at different T & H



- Looks like s-wave Andreev, but gap can't be at 0.35mV.
- Reach I_c first via the 5+10 μm length of the bilayer-Au overlap boundary. See Ic dips.



- 6T is not sufficiently high to suppress the low bias conductance

Conductance spectra of J1, an *in-situ* junction at different T

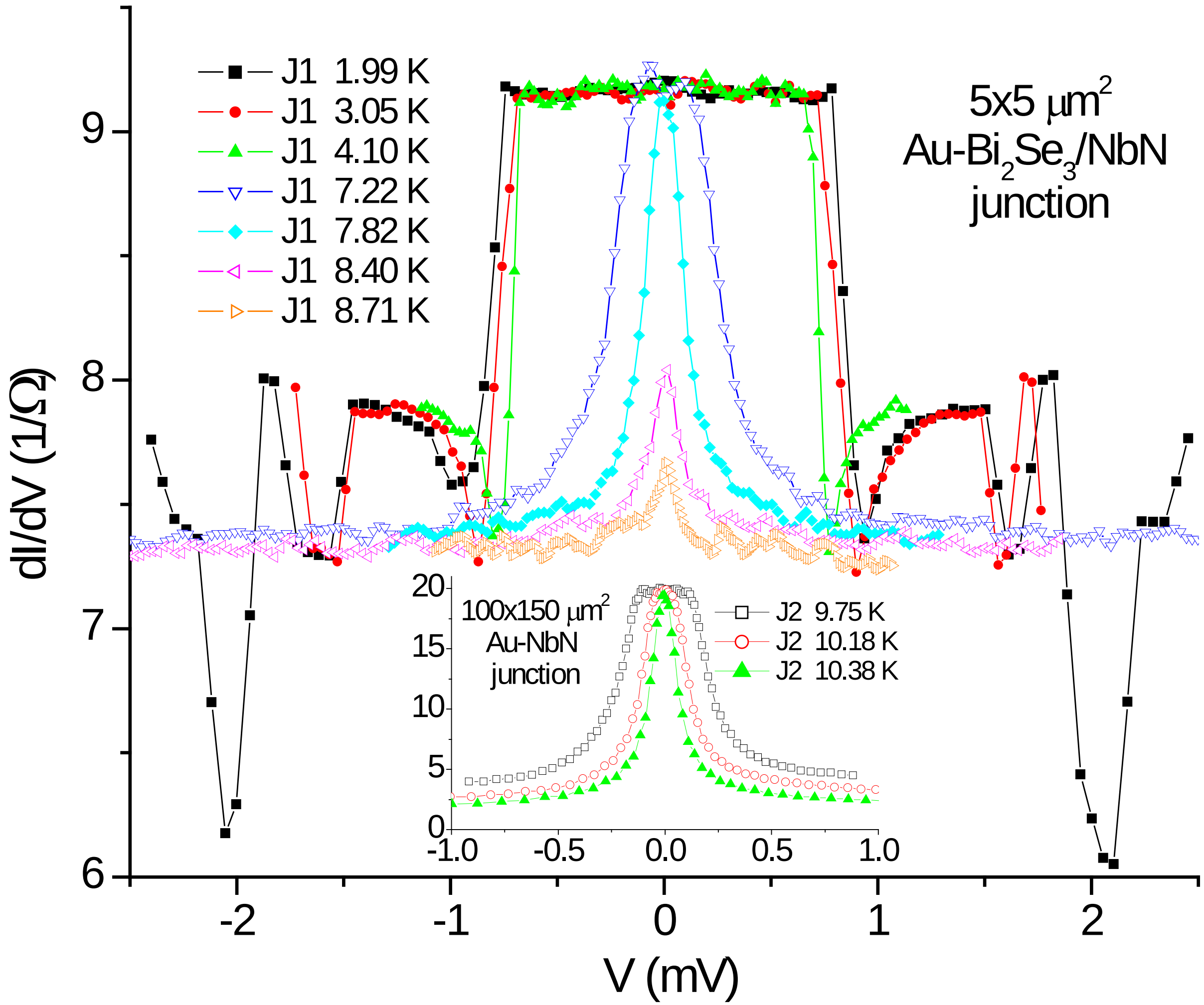
I_c dips at ~±1, 1.5 & 2mV

No CP, I_c is reached first

No ZBCP, just decreasing critical current with increasing T (and H)

Same seemingly "emergent" ZBCP in reference NbN-Au junction with no Bi_2Se_3 in between

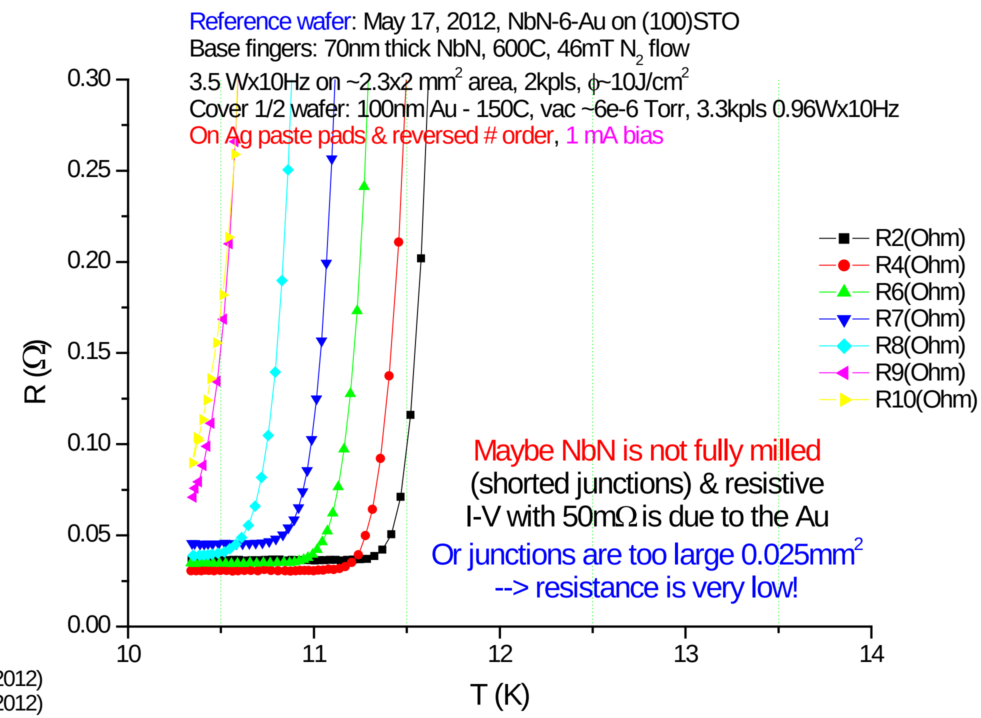
Need a strong tunneling Barrier to observe ZBCPs



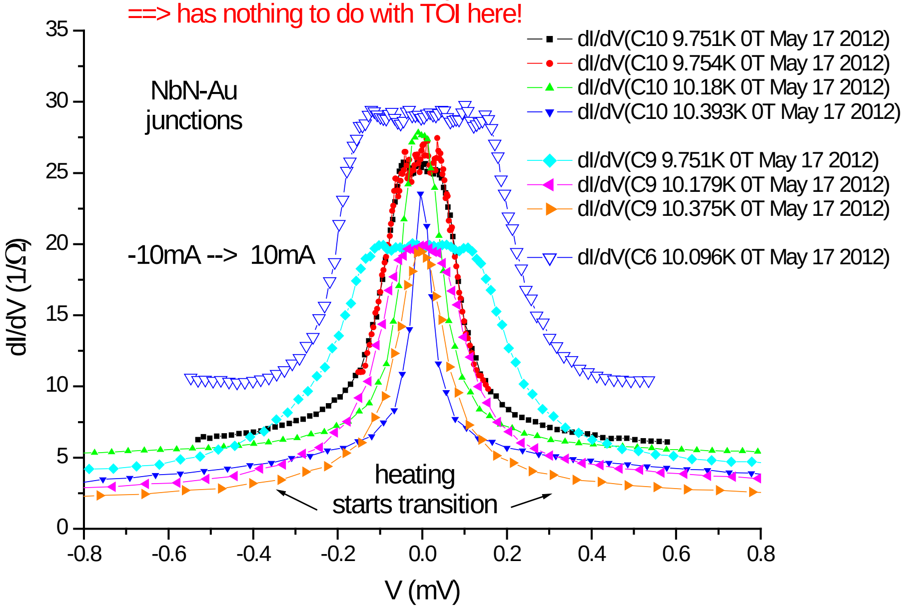
Reference NbN-Au junctions

T_c^{onset} ~ 12.5K

$R^{junction}$ ~ 50 mΩ



Similar to junctions with Bi_2Se_3 barrier
==> has nothing to do with TOI here!



- Same as in Au-Bi_2Se_3/NbN junctions !!
- The “ZBCP” seems to be an I_c effect due to heating.

Conclusions

- Proximity superconductivity is induced by NbN in Topological Bi_2Se_3 films
- Tunneling and Andreev bound states (ZBCP) were observed
- The broad ZBCP (~0.9mV) can't originate in simple Andreev since coherence peaks exist. It may be due thermally smeared, split ZBCP.
- The narrow ZBCP (~0.15mV) width is kT limited (~1.8K)
- Both types of ZBCP could originate in Majorana fermions of a Topological SC