Proximity, magnetoresistance & gating effects in bilayers (BL) of doped topological Bi_2Se_3 & superconducting NbN

Gad Koren
Physics Dept., Technion

June 2015

- Part I compares bilayers to bare NbN films

Supercond. Sci. Technol. **28** 025003 (2015) & http://arxiv.org/pdf/1409.2975v1.pdf (2014)

- Part II Magnetoresistance & gating effects on these bilayers & films

http://arxiv.org/pdf/1506.08584v1.pdf (2015)

Outline

- Some background
- Ultra-thin bilayers of Bi_2Se_3-NbN for studying topological superconductivity

Part I

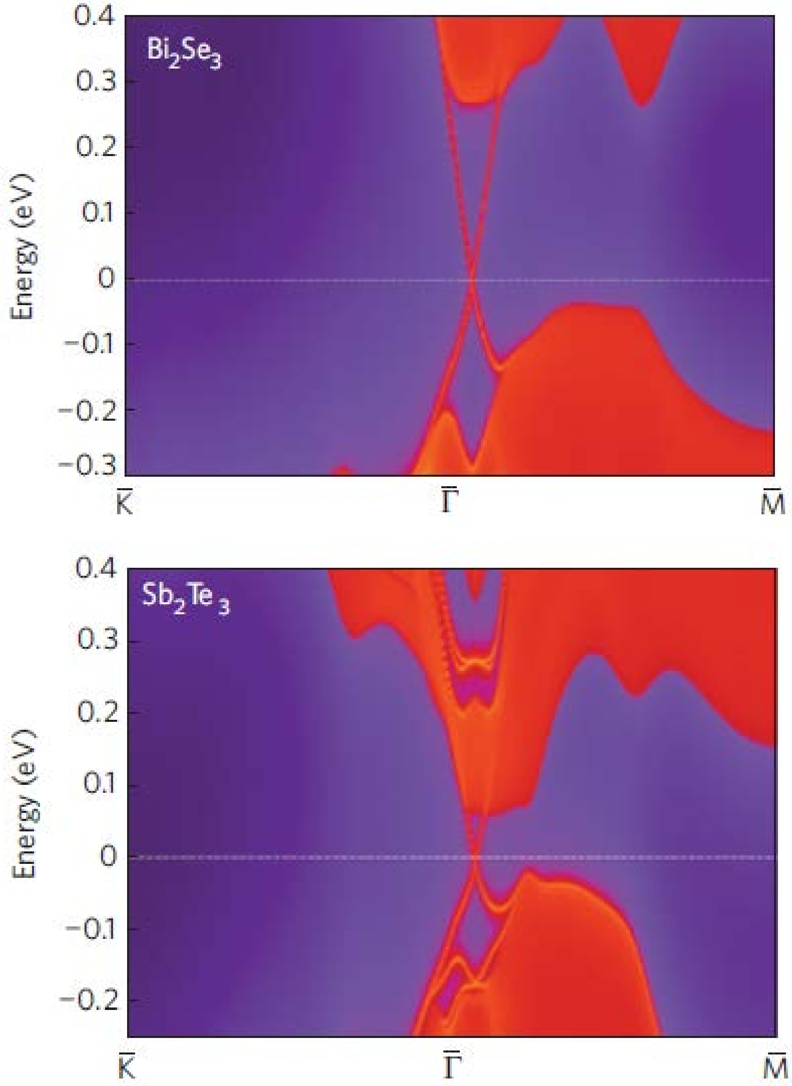
- Proximity effects in these bilayers

Part II

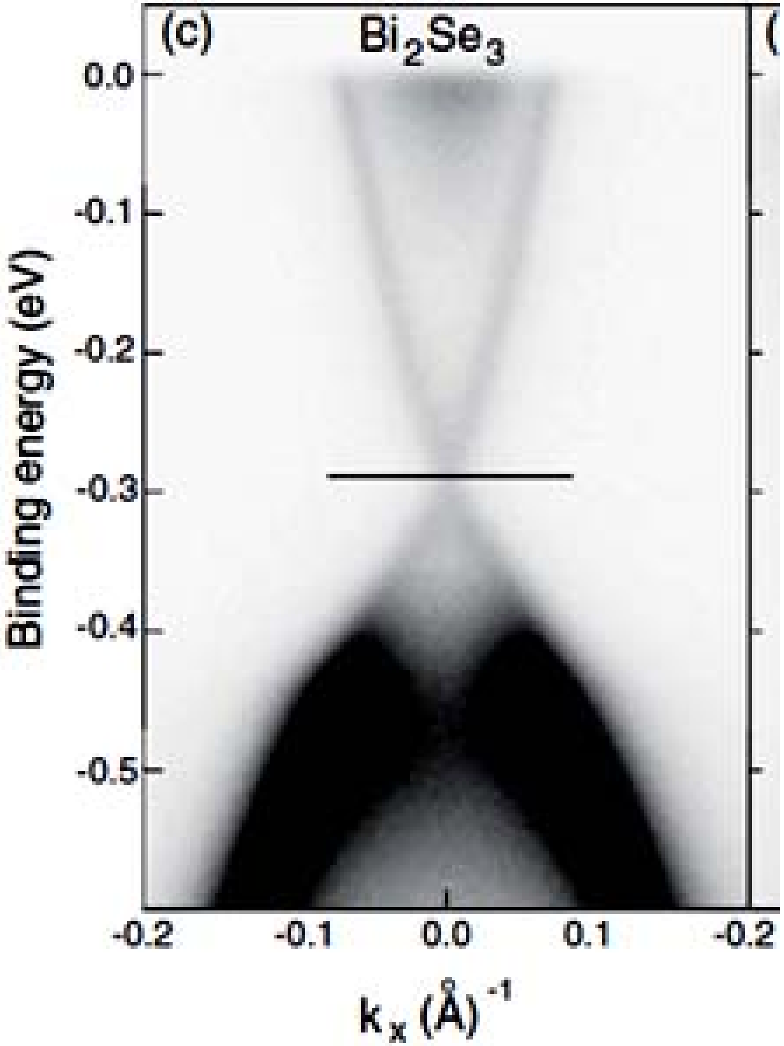
- Magnetoresistance & gating effects in Bi_2Se_3 films
- Magnetoresistance & gating effects in the bilayers
- Interpretation of the results in terms of vortex physics & pinning
- Alternative interpretations

Topological insulators are bulk insulators with surface conductance & a single Dirac cone of the surface states

Zhang… & S. C. Zhang, calc. bands
NATURE PHYSICS, **5,** 438 (2009)



T. Kirzhner &… *A. Kanigel*, meas.
ARPES, PRB 86, 064517 (2012)



Motivation for studying topological superconductors (TSC)

- It is predicted that Majorana fermions (MFs) exist in the vortex cores of topological superconductors (TSC)
- These MFs will appear as zero energy modes (or ZBCP) in conductance spectra of TSC/N junctions (N is a normal metal)
- They should be robust against disorder & decoherence
- & thus might be useful in quantum computing (*)

(*) Fermionic Quantum Computation
Sergey B. Bravyi and Alexei Yu. Kitaev, Annals of Physics **298**, 210–226 (2002)

Why studying transport in ultra-thin bilayers of Bi_2Se_3-NbN?

- If the NbN film is too thick (>10nm) & $T<T_c$, it will short all the effects of the Bi_2Se_3 cap-layer → no TSC at the interface could be investigated.
- Thus a thin NbN islands layer (~3 to 5nm) is needed, that behaves as a network of weak-links when bridged by the Bi_2Se_3 cap-layer
- → current will have to flow via the interface with the Bi_2Se_3 layer, allowing for the TSC to be studied
- Percolation paths of weak-links will constitutes 1D TSC, and their geometry relative to the voltage contacts will determine the TSC transport properties in the bilayers

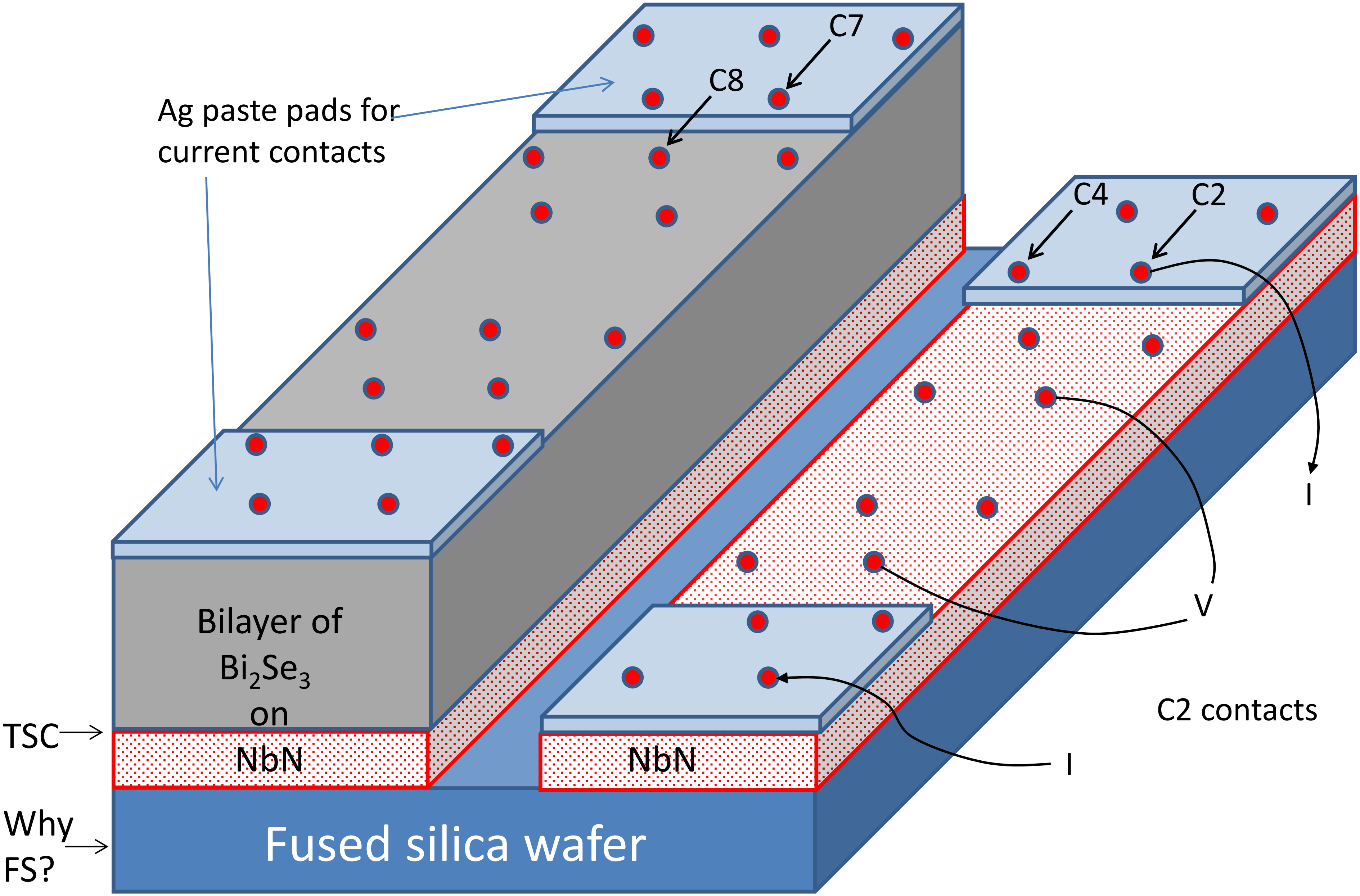
- In the following slides, this will be explained in details

- Some relevant parameters for 3-5nm thick NbN films:

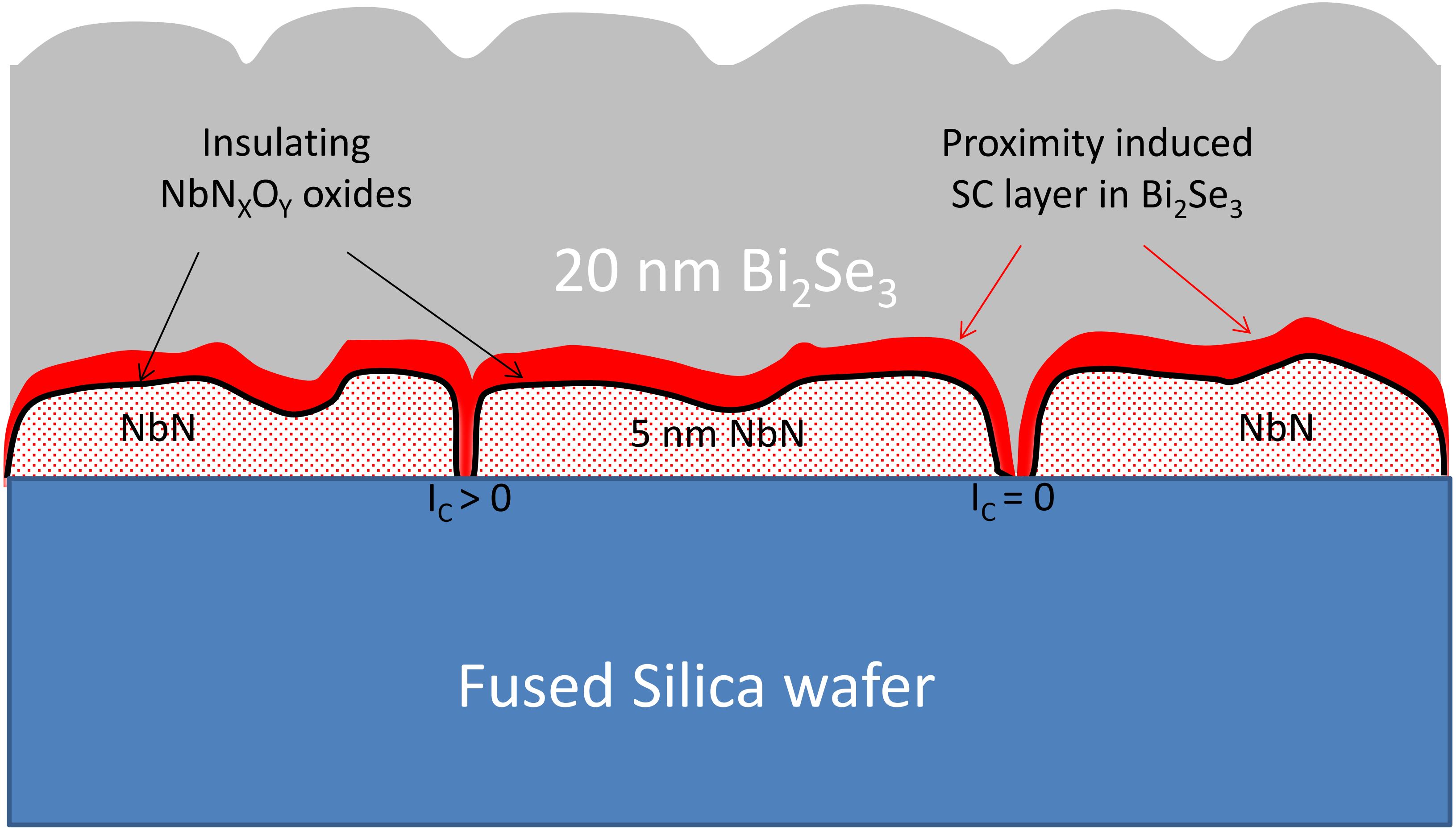
  Tc ~ 5-8 K, ξ ~ 5 nm, λ ~ 500 nm, Δ ~ 1.5 meV

  A. Kamlapure et al. Appl. Phys. Lett. **96**, 072509 (2010)

A scheme of the film, bilayer & contacts geometry on the wafer

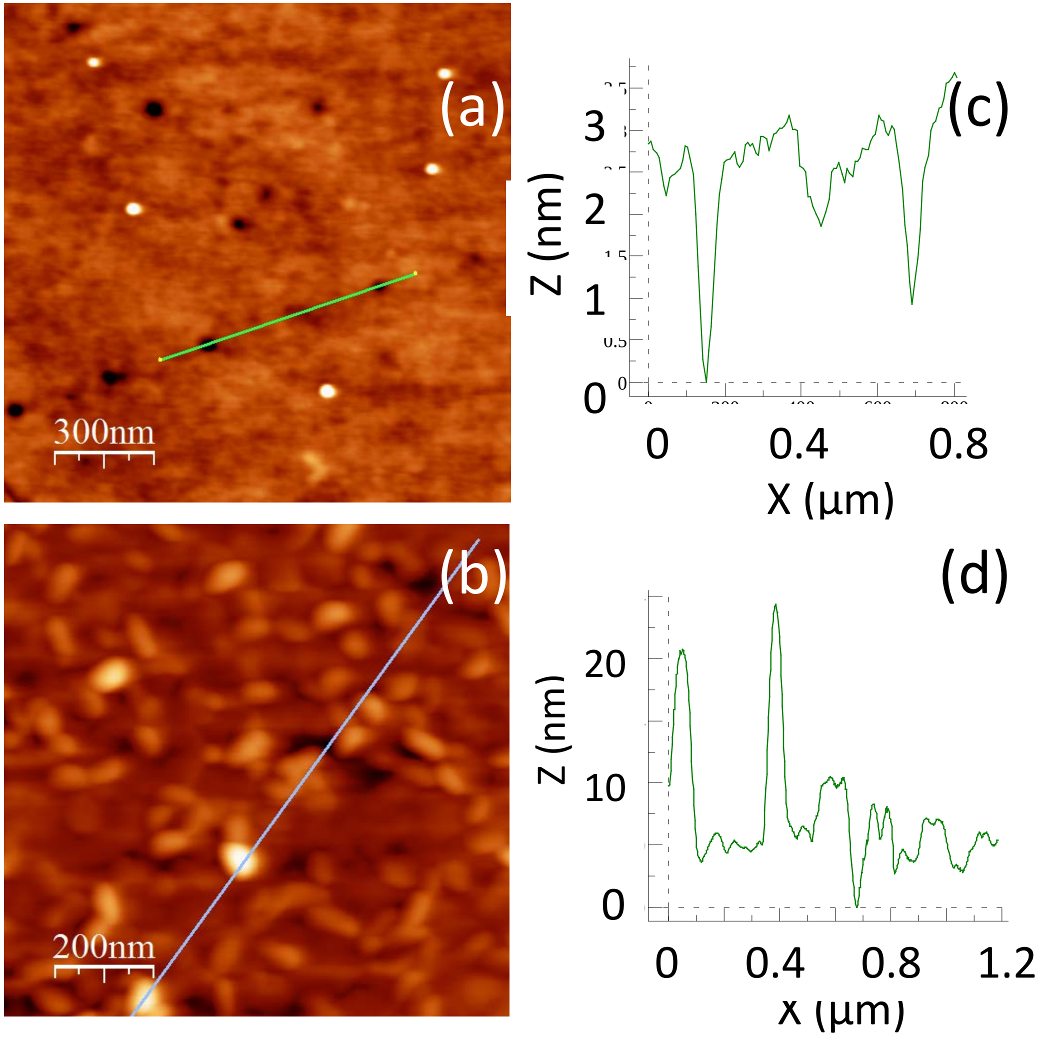


A model for the transport in the bilayer



- Weak-links between the NbN grains (I_C with serial resistance)
- Proximity induced superconductivity in Bi_2Se_3 cap layer (at interface)

Topography of: (a) a 5nm thick NbN film, and of a bilayer (b) of 20nm Bi_2Se_3 on 5nm NbN on FS & typical line profiles

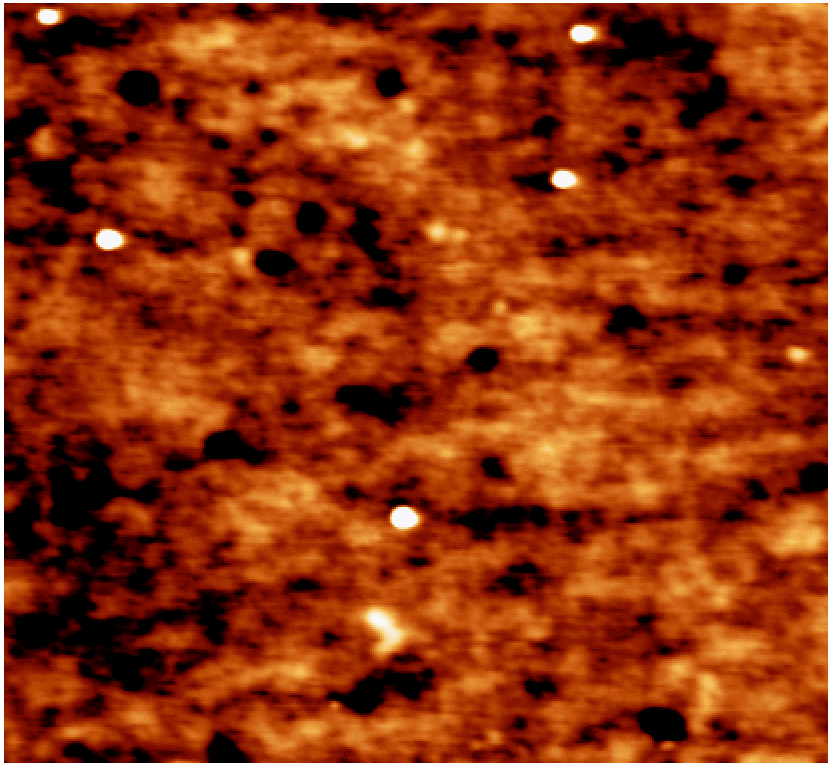


Holes:
~2-3 nm deep
r ~ 30 nm

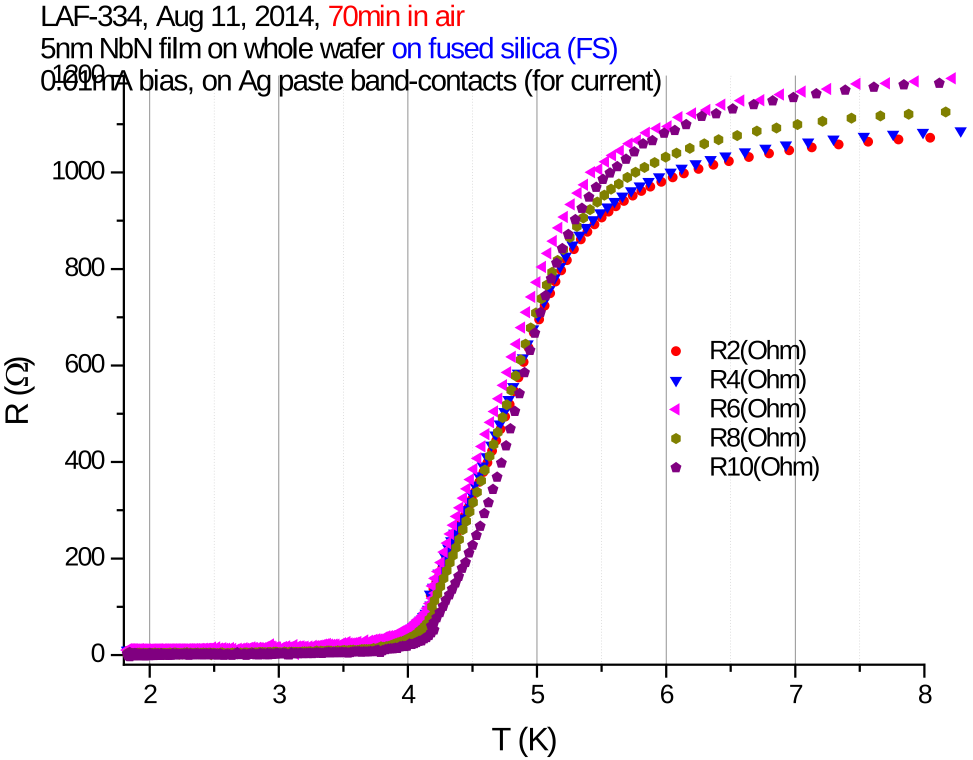
Outgrowth:
~5-7 nm high
& similar r

On $SrTiO_3$ the NbN films are so smooth, that there are no weak-links.

RT & contrast-topo of a 5nm thick NbN film on FS



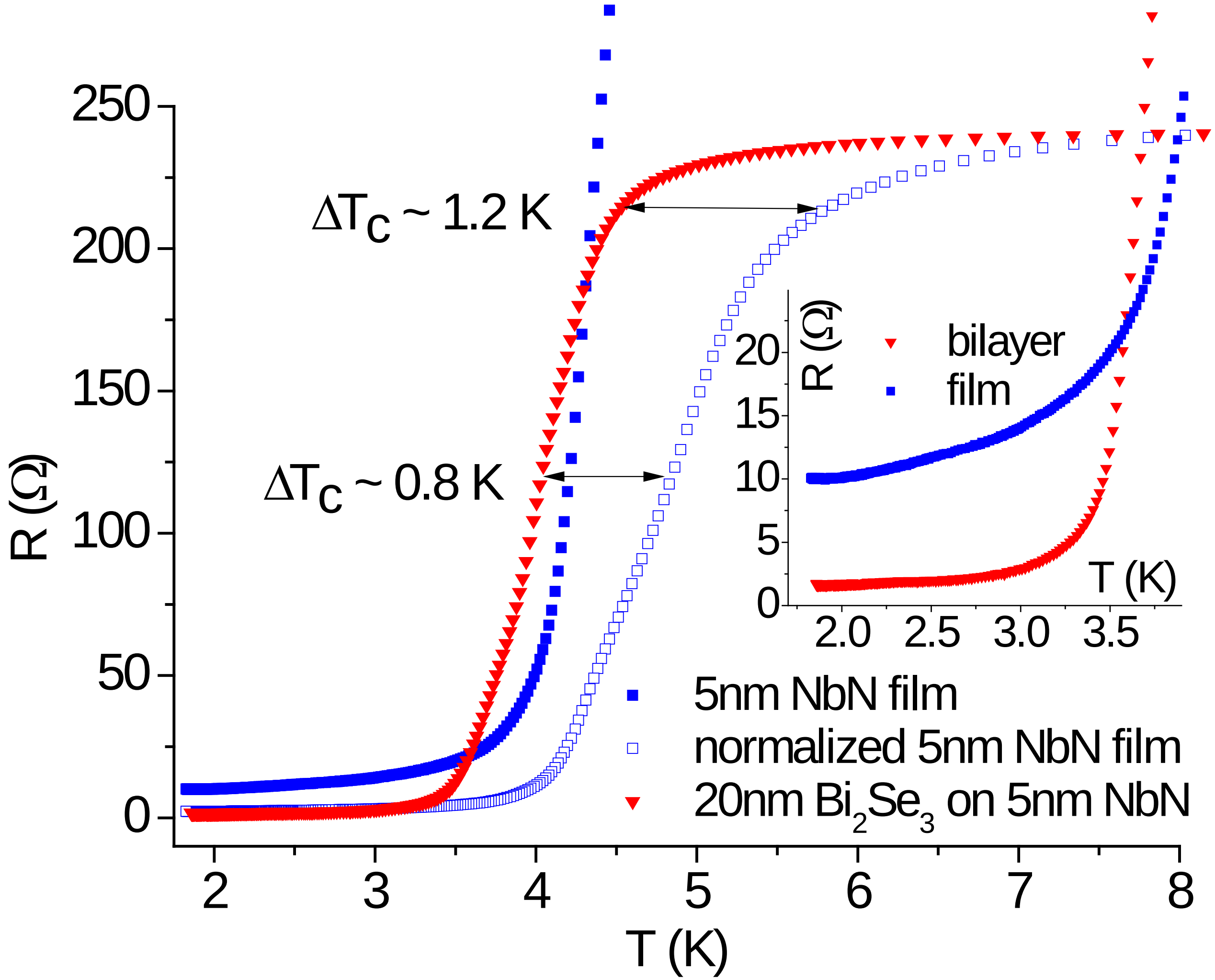
1.6 x 1.5 µm^2



LAF-334, Aug 11, 2014, 70min in air
5nm NbN film on whole wafer on fused silica (FS)
0.01mA bias, on Ag paste band-contacts (for current)

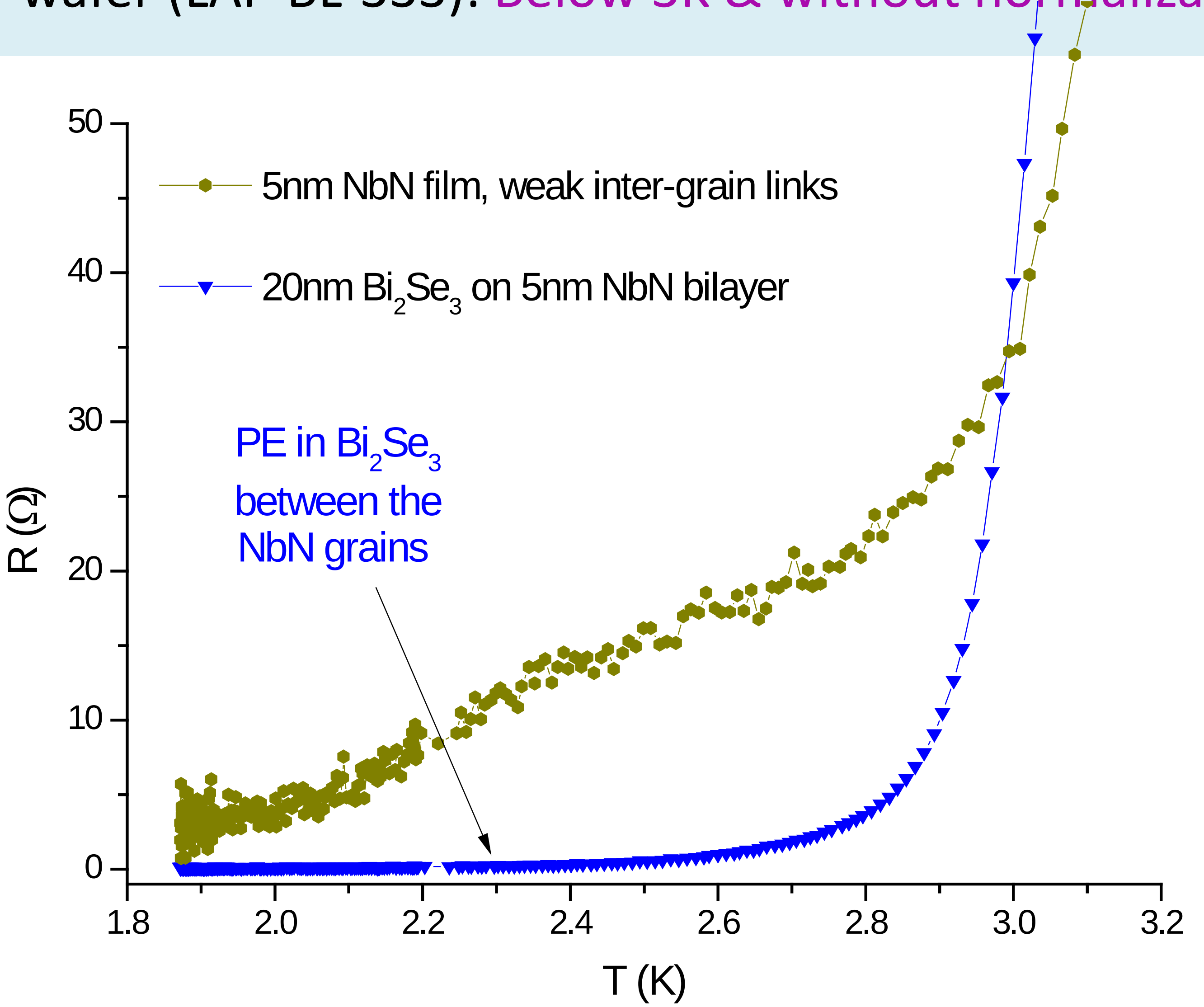
- NbN islands (bright areas) connected by weak-links (dark areas)
- rms – roughness: ~0.5nm (0.1nm on STO – not shown)

R vs T of a 5nm thick NbN film after 10min in air, compared to an *in-situ* deposited bilayer of 20nm Bi_2Se_3 on 5nm NbN (LAF-BL-334)



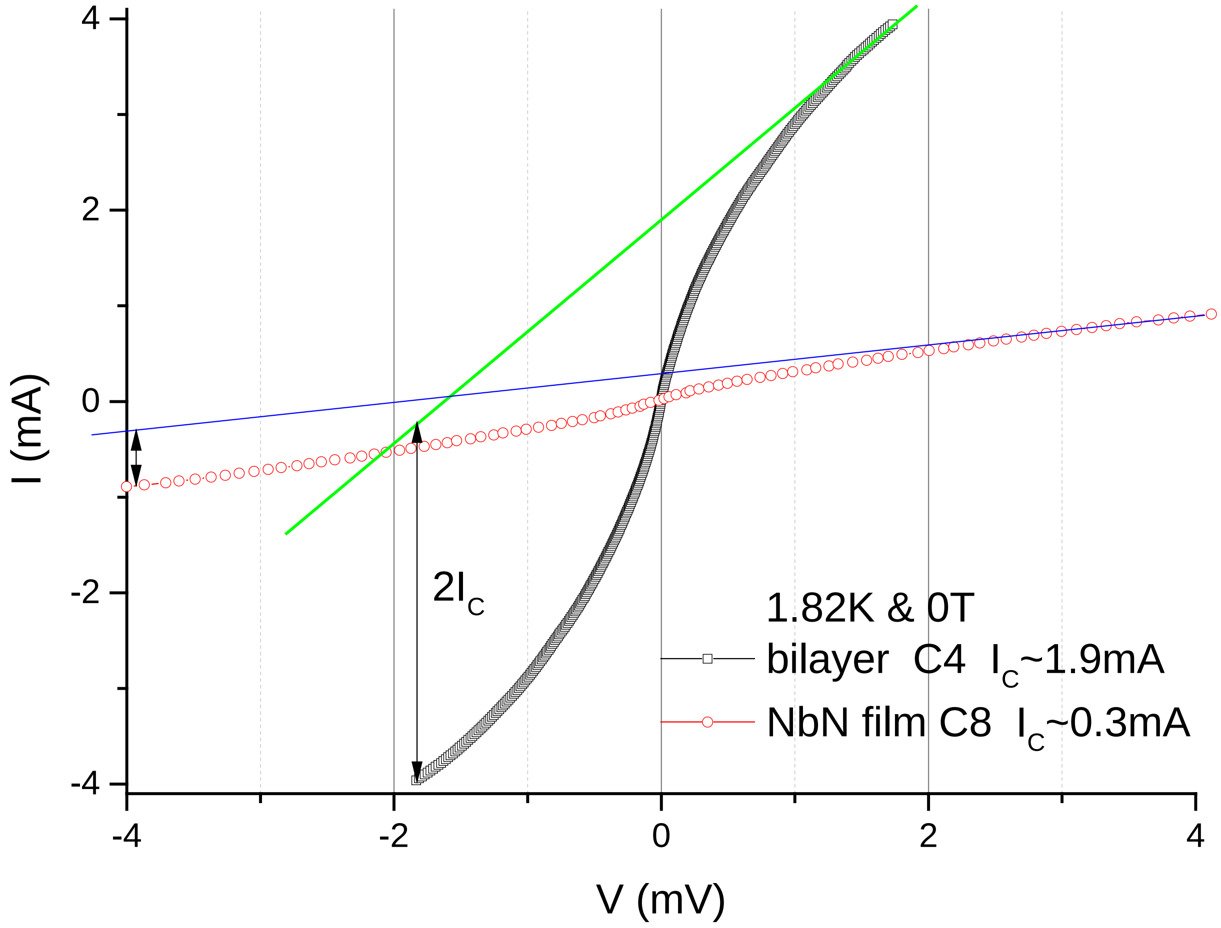
- Proximity effect (PE) in BL suppresses superconductivity in NbN grains (lower T_C)

Similar wafer (LAF-BL-333): Below 3K & without normalization of R



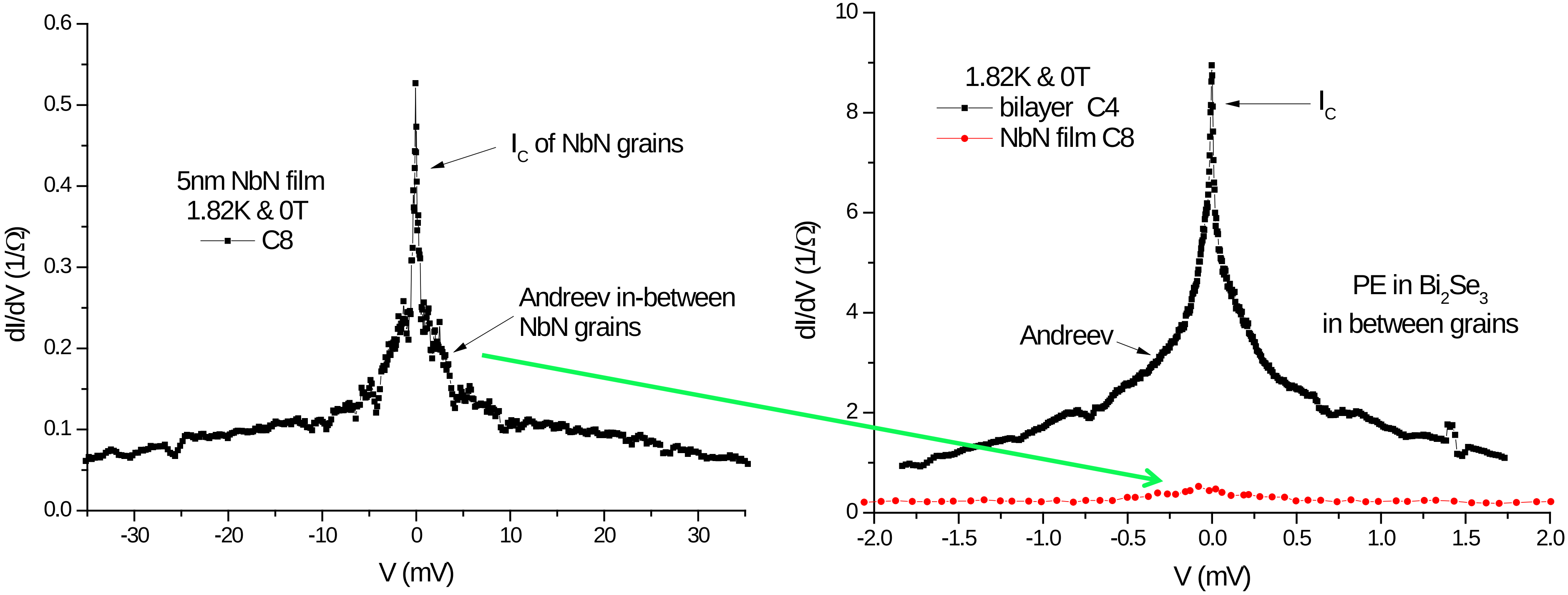
- Induced SC in Bi_2Se_3 at the interface with NbN with no serial resistance
- T_C(bilayer at R=0) ~ 2.3K, No T_C(film) down to 1.9K ➔ inverse PE in BL…

Same wafer (LAF-BL-333): IVC at 1.82K



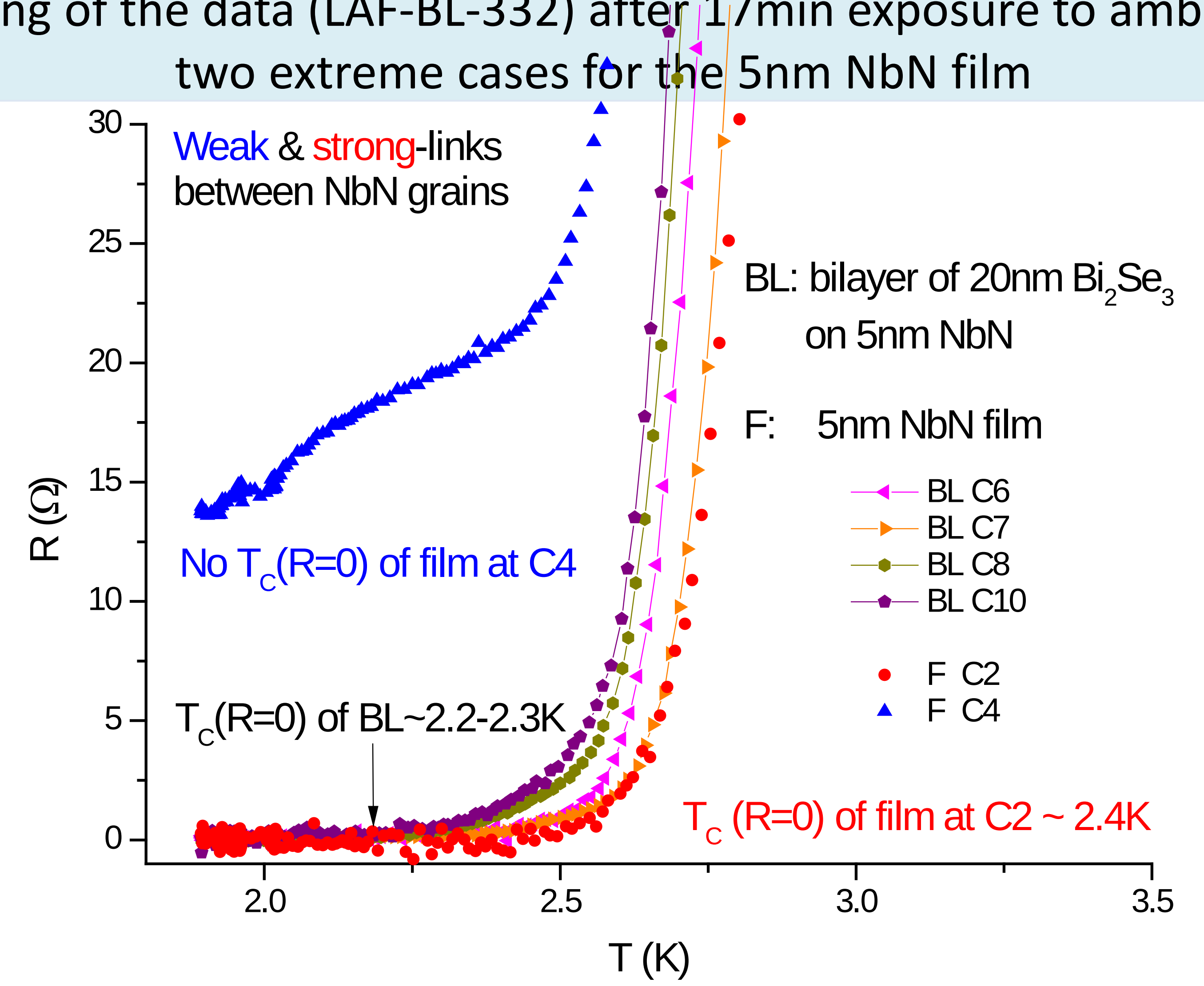
- Both have I_C at 1.82K, but I_C(bilayer) is about 6.3 times larger than I_C(film)
- I_C enhancement in BL at low T indicates (inverse) PE in the TI

Conductance spectra of in-situ prepared bilayer and film (LAF-BL-333)



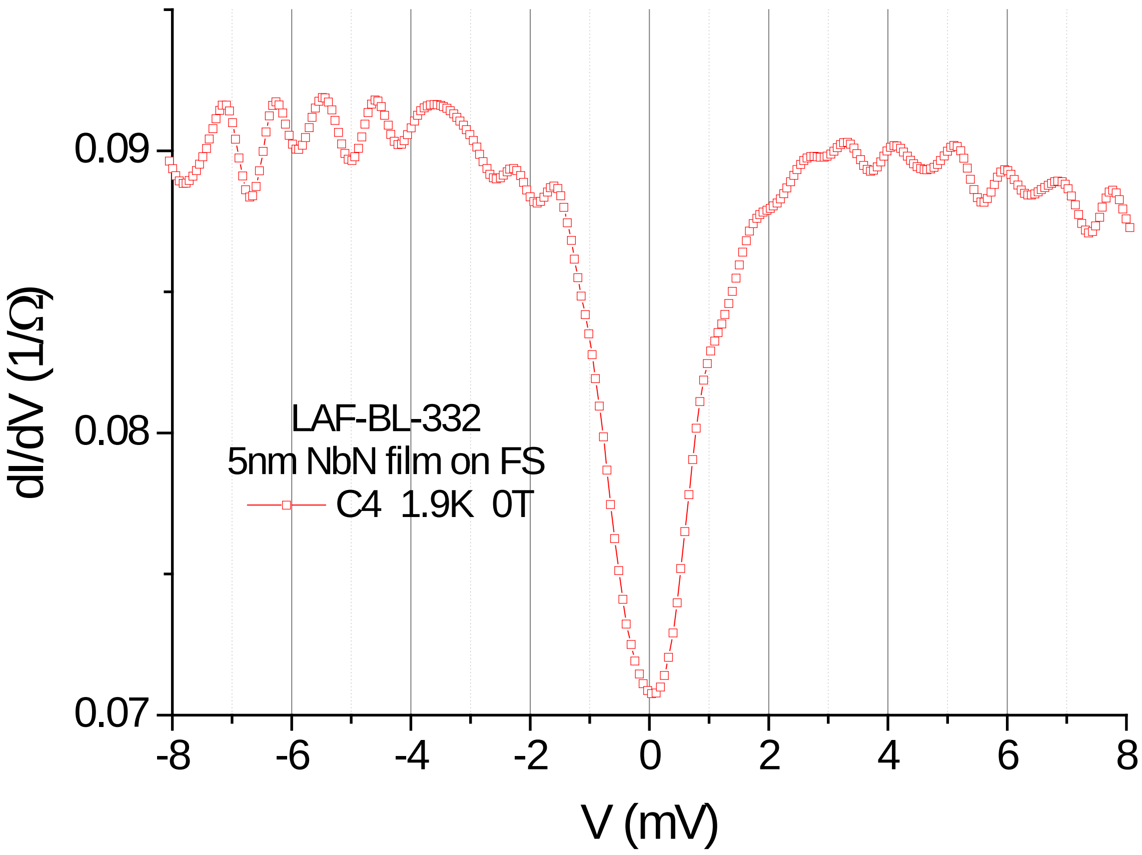
- I$_C$ and Andreev peaks
- Andreev enhancement in BL at low T indicates (inverse) PE in the TI
- ZBC (1/R) of BL is about 20 times higher than that of the NbN film
  [R(normal of NbN film) ~ 6 x R(normal bilayer)]

Scattering of the data (LAF-BL-332) after 17min exposure to ambient air: two extreme cases for the 5nm NbN film



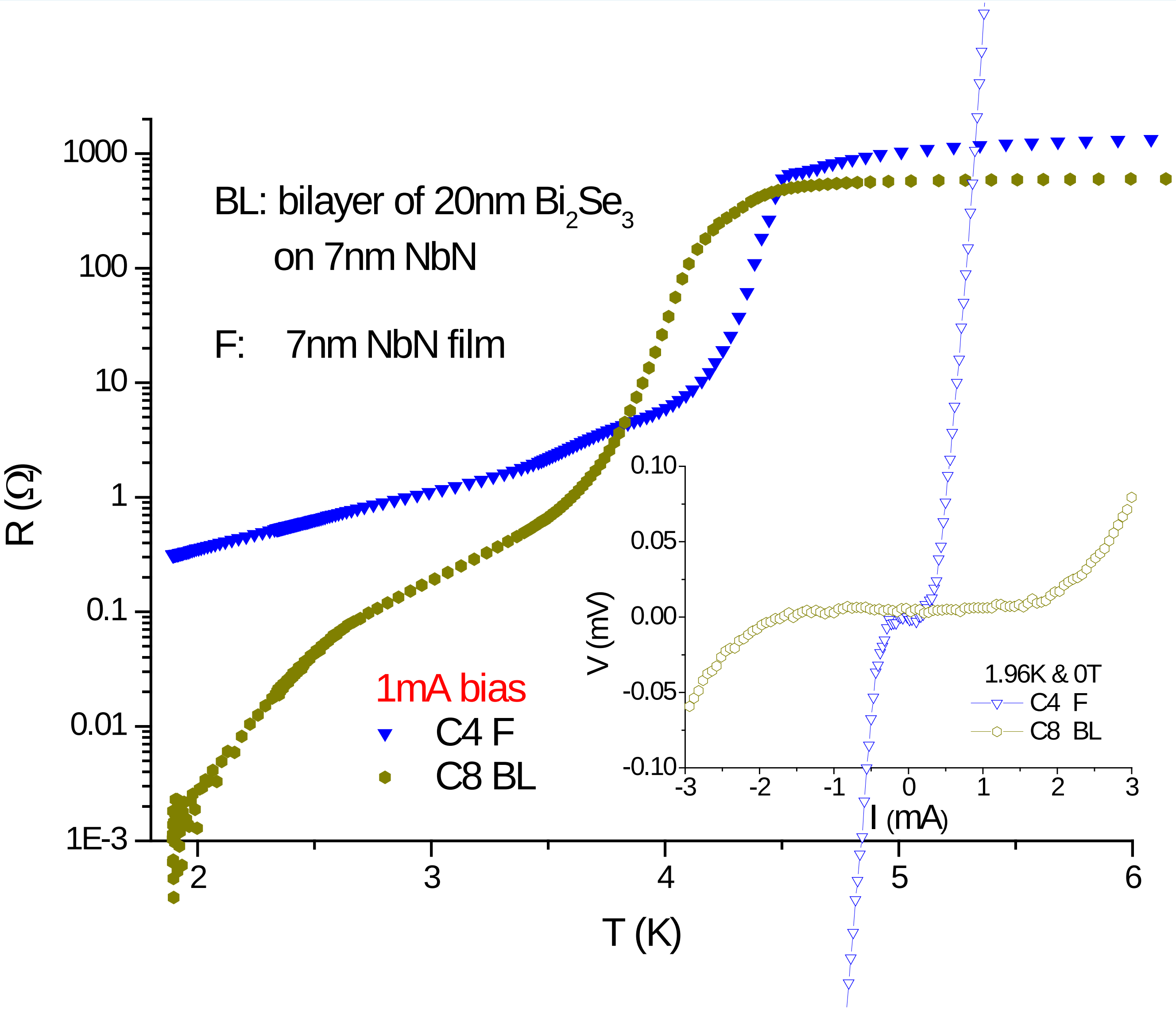
- Percolation of strong-links between the SC grains that connects the V-contacts of C2
- Percolation of weak-links between the SC grains that cuts the V-contacts of C4
- PE in Bi_2Se_3 in the BL, T_C of 2.2-2.3K, low scattering of the data (thick cap layer)

Tunneling conductance of the C4 contact of LAF-BL-332



- Gap-like feature at 2Δ ~ 2 mV ➔ Δ of the NbN grains ~ 1mV (assuming 1 SNS junction)
- The weak-link here could originate in stronger defects like nm scratches etc.

7nm NbN film and bilayer with 20nm Bi_2Se_3: R vs T & IVC



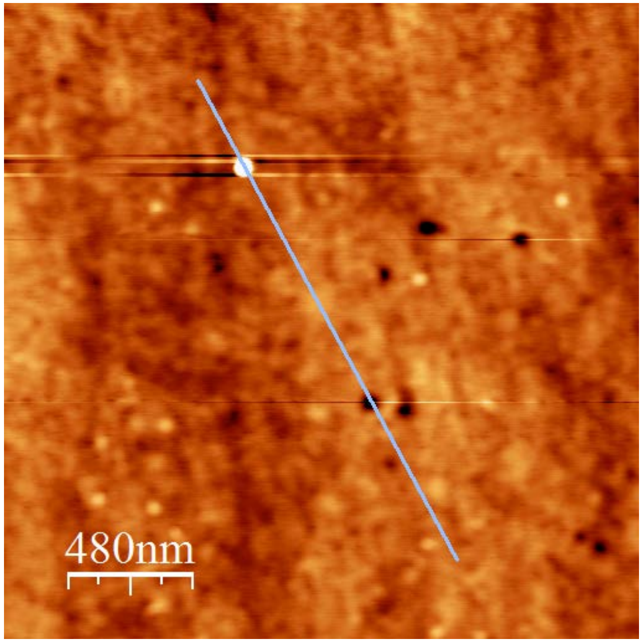
- Stronger links in thicker film which is less resistive at low T
- Need a higher bias to see PE in Bi_2Se_3 below 3.5K, see IVC at low T.

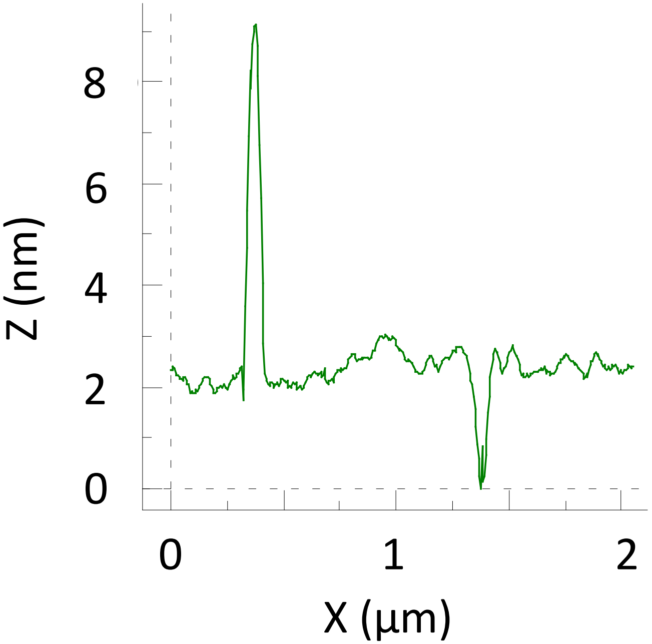
Conclusions I

- Transport properties of *in-situ* prepared bilayers of a TI (Bi_2Se_3) & a SC (NbN) were compared to the bare SC film
- Standard proximity effect (PE) was observed in all bilayers in the main part of the SC transition (high T), where the TI layer (N) suppressed T_C of the SC layer
- At low T, an inverse PE in the TI of the bilayers was observed, as indicated by enhancement of I_C & Andreev conductance in the bilayer compared to the SC film

- Next we shall present part II which deals with gating effects on the magnetoresistance of even thinner bilayers and films.

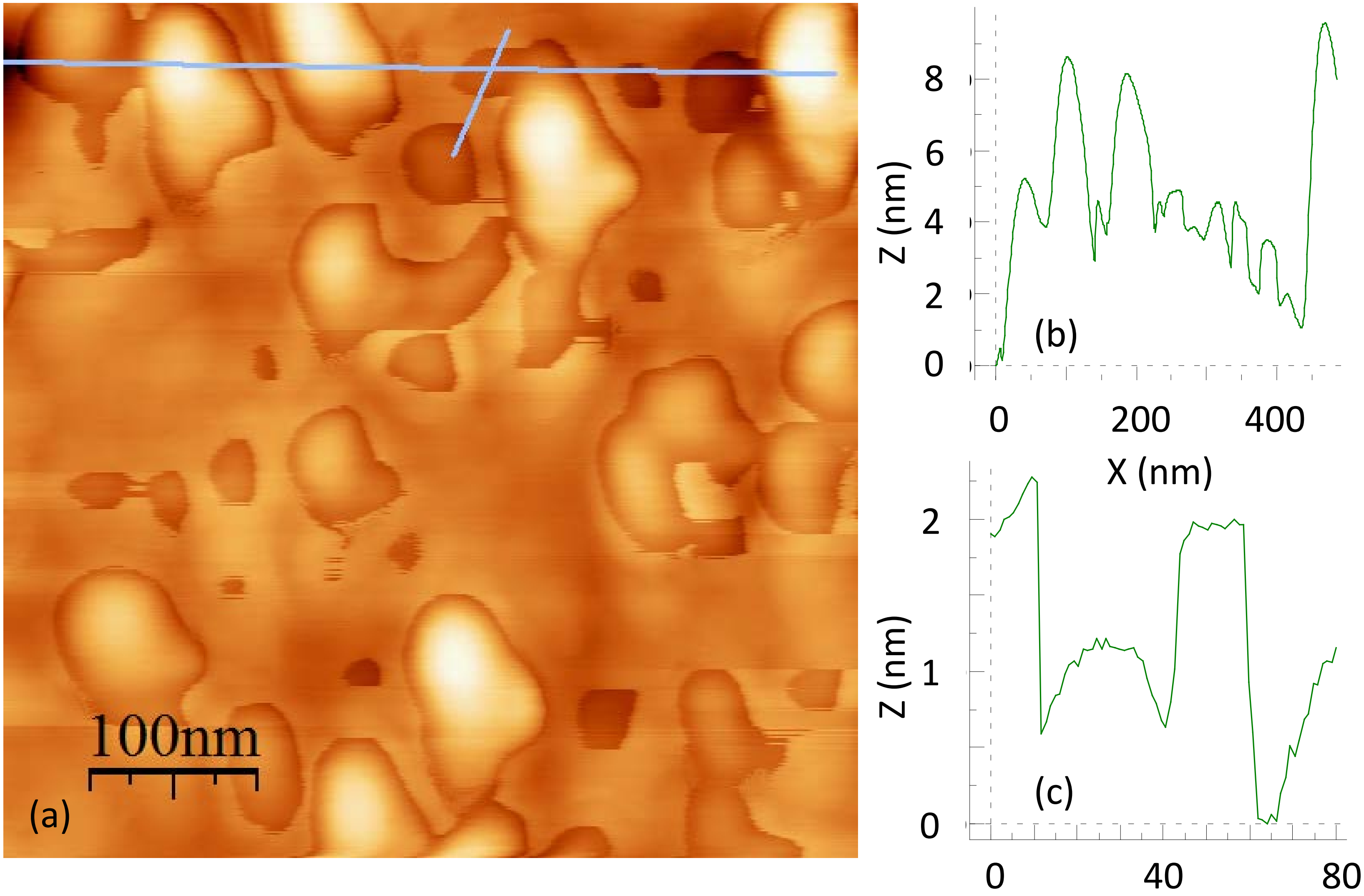
AFM image of a 3nm thick NbN layer on FS





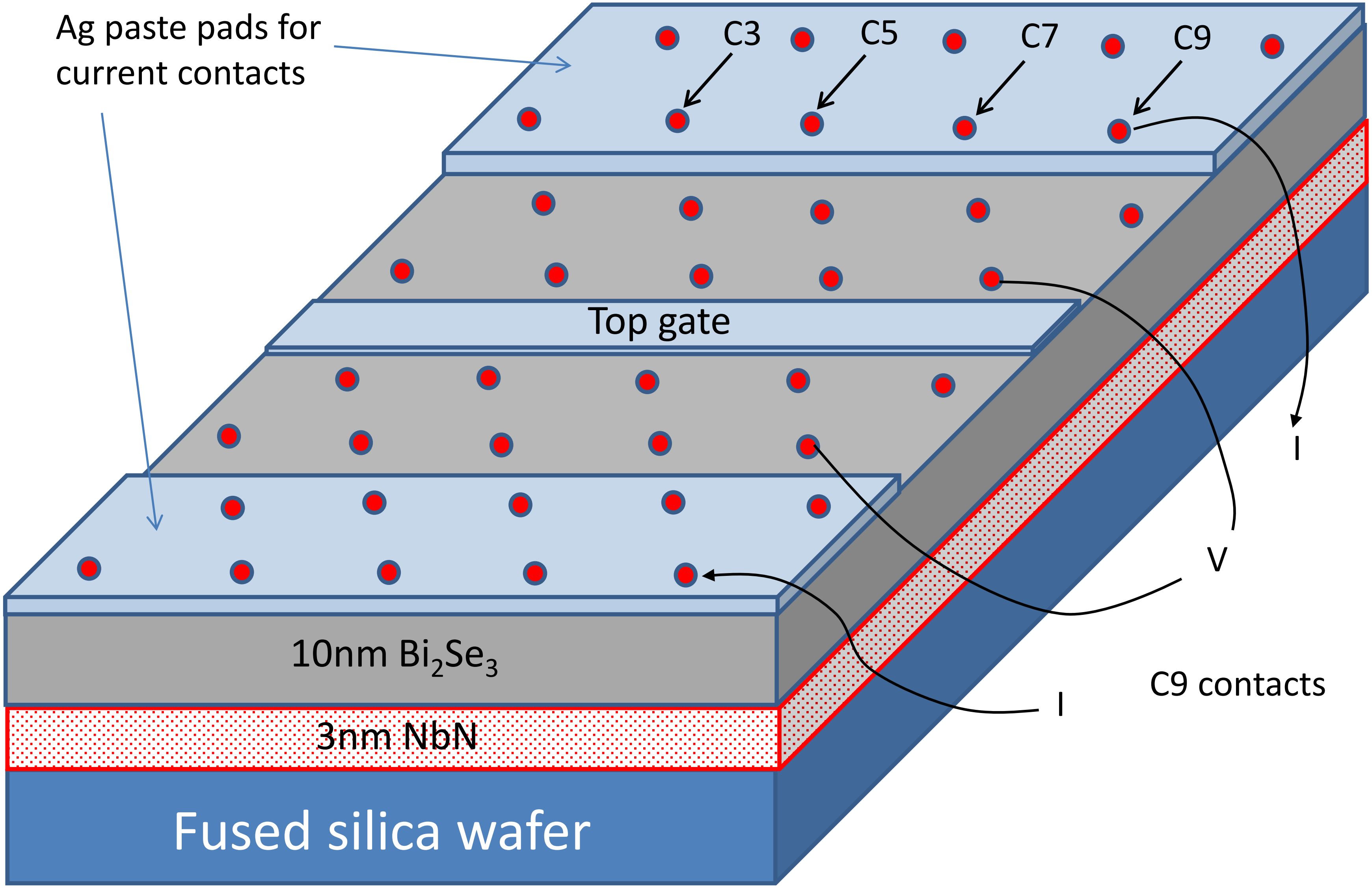
- Nano holes of ~70nm diameter
- ~0.35 nm rms roughness

AFM image of a 10nm Bi_2Se_3 on 3nm NbN bilayer on FS & the corresponding line profiles in (b) & (c)

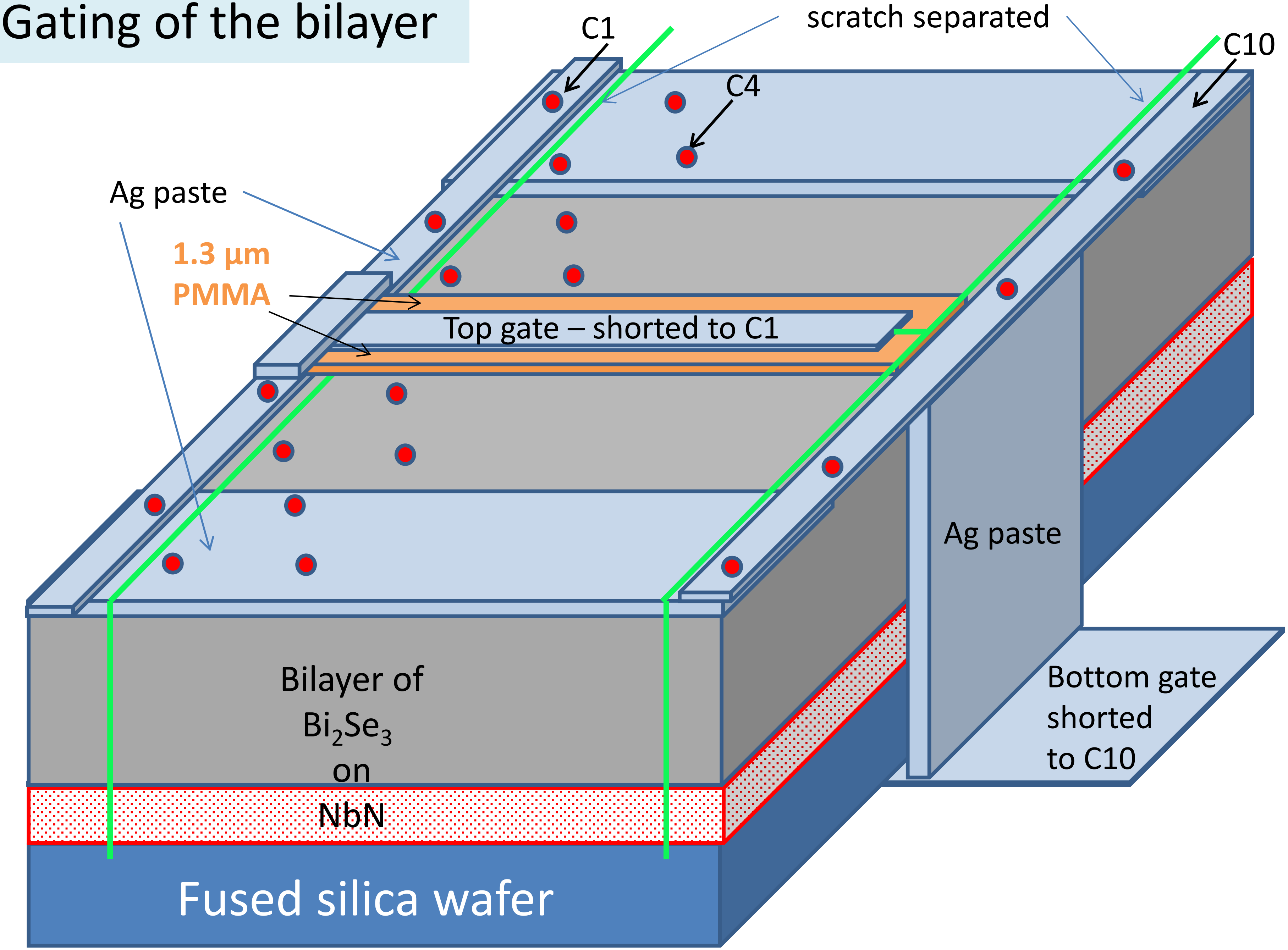


~1.1 nm rms roughness & Quintuple steps of 1 and 2 nm can be seen in (c)

A schematic drawing of the bilayer & contacts geometry now



Gating of the bilayer

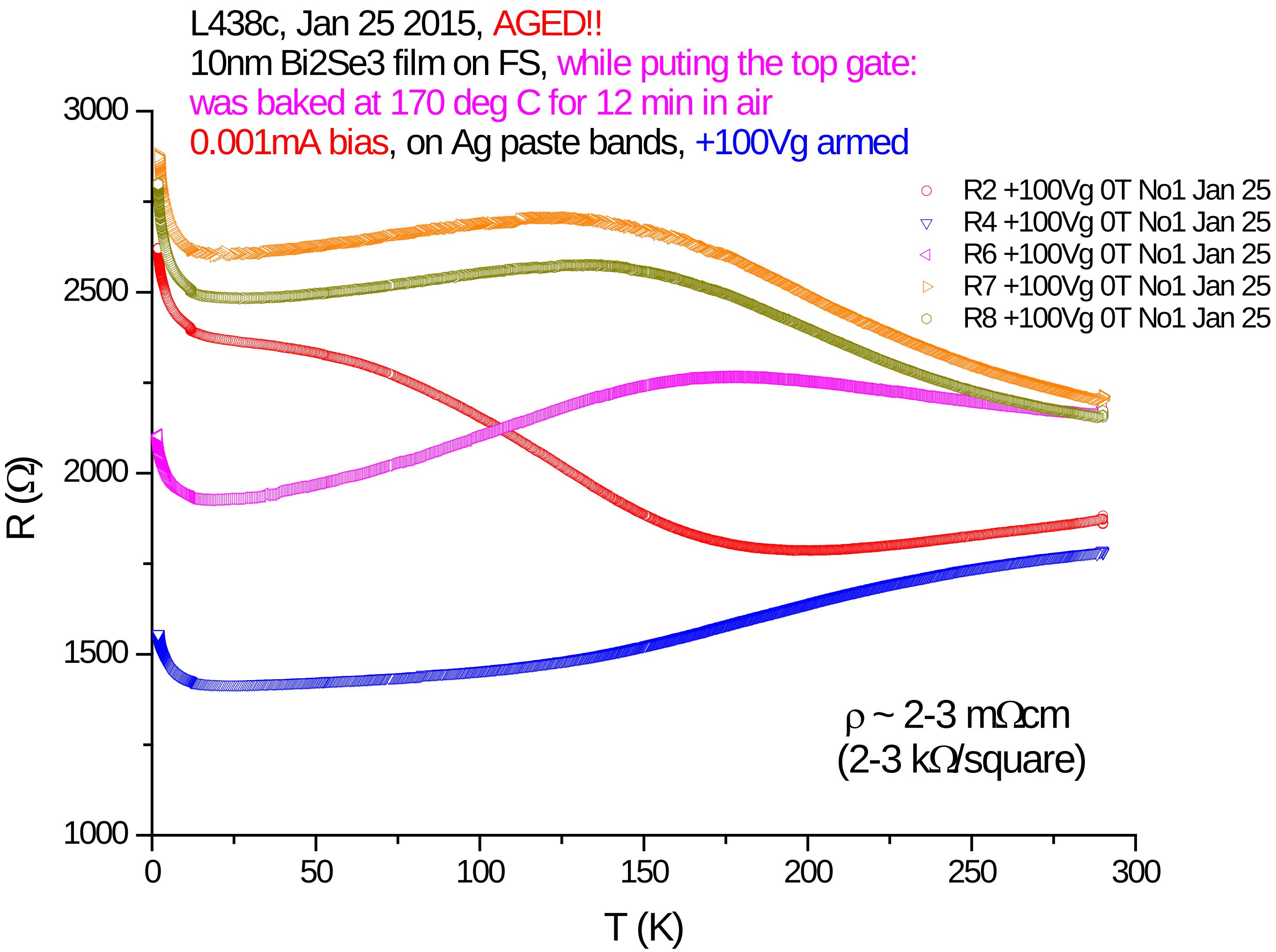


10 nm Bi_2Se_3 reference film on fused silica
(1) R vs T results

For similar resistivity,
The electron densities
according to
Butch *et al*. PRB
81, 241301R (2010)
are:

- 4-6 x 10^{17} elect./cc
From Hall measurements

- 3-4 x 10^{17} elect./cc
From SdH oscillations



L438c, Jan 25 2015, AGED!!
10nm Bi2Se3 film on FS, while puting the top gate:
was baked at 170 deg C for 12 min in air
0.001mA bias, on Ag paste bands, +100Vg armed

ρ ~ 2-3 mΩcm
(2-3 kΩ/square)

10 nm Bi_2Se_3 reference film on fused silica
(2) MR results

- Magnetoresistance $MR = [R(H)-R(0)] / [R(H)+R(0)]/2$ H is the magnetic field

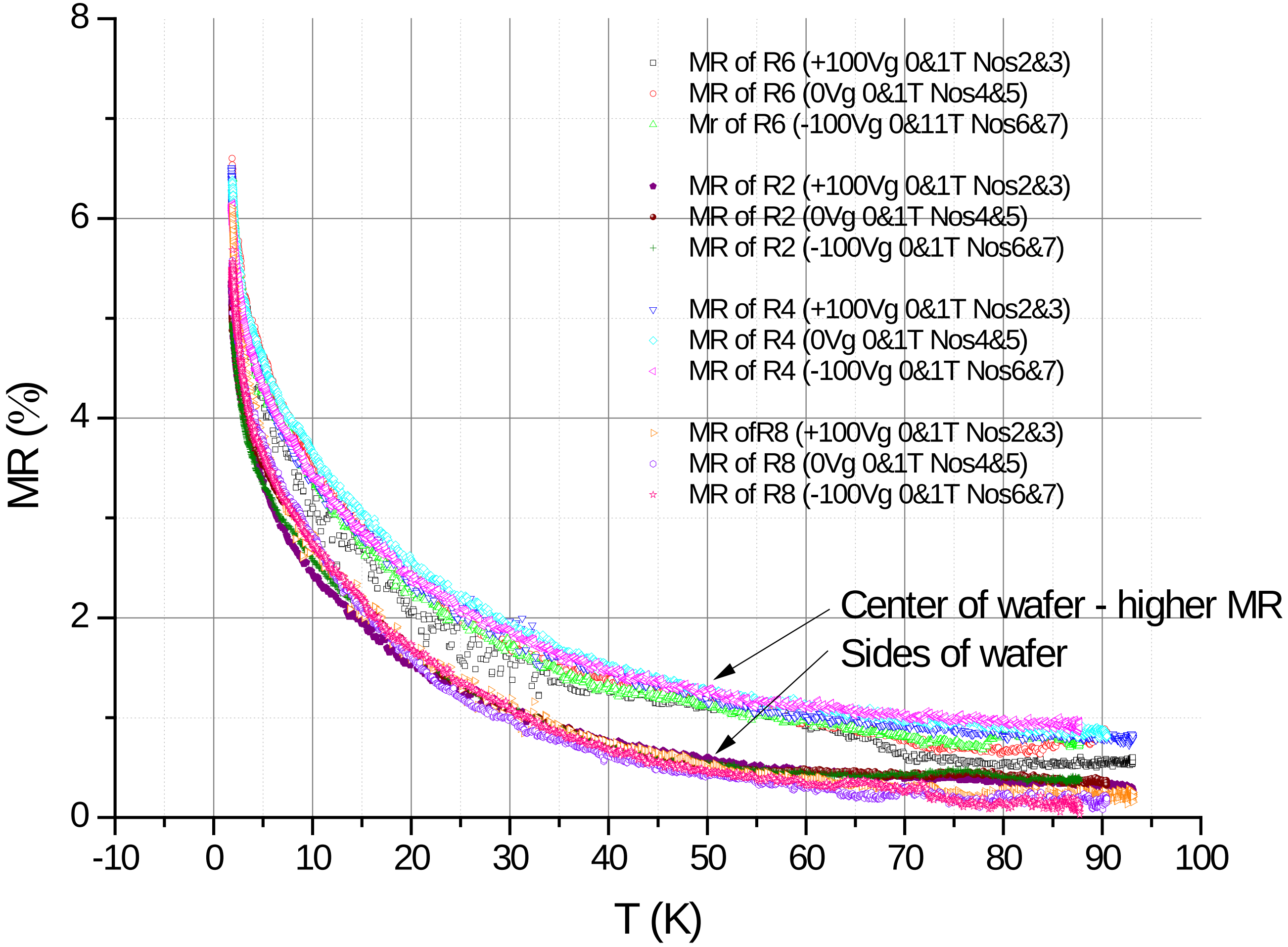
- H is 1T here

- Fit a double-exponential decay, but not $A/T^{0.5}$

- Almost insensitive to gate-voltage Vg, unlike Steinberg et al. PRB **84**, 233101 (2011)

- Eg-field of top gate for -100Vg & $\varepsilon \sim 2.6$ is: 2.6x100V/0.00013cm =2 MV/cm (vs x 40 higher of Steinberg)

L438c, Jan 25 2015, 10nm Bi2Se3 film on FS
0.001mA bias, on Ag paste bands



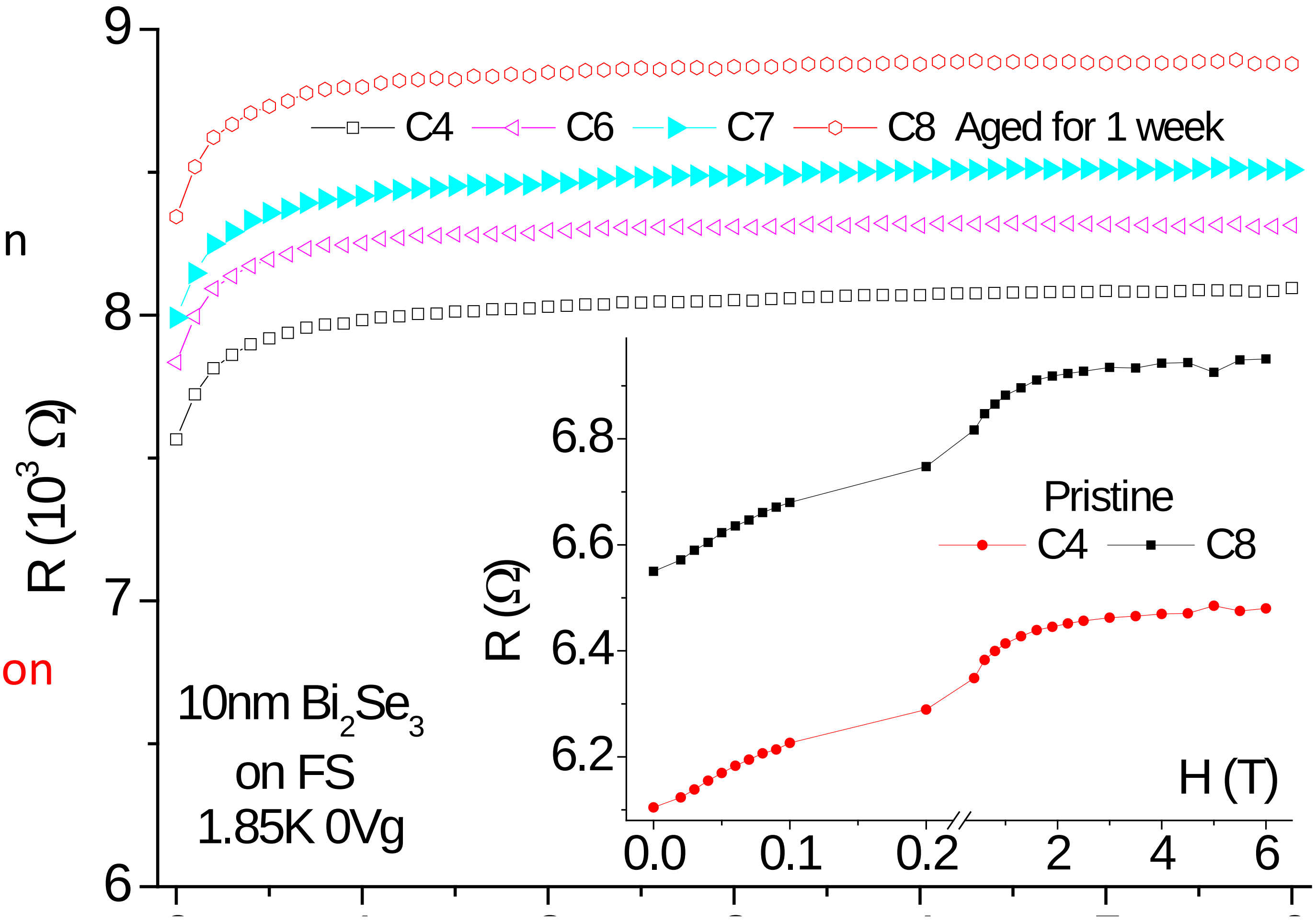
Center of wafer - higher MR

Sides of wafer

(3) R versus H of another 10nm Bi_2Se_3 film on FS

- Linear MR at low H results from edge currents with linear dispersion (Dirac-like)

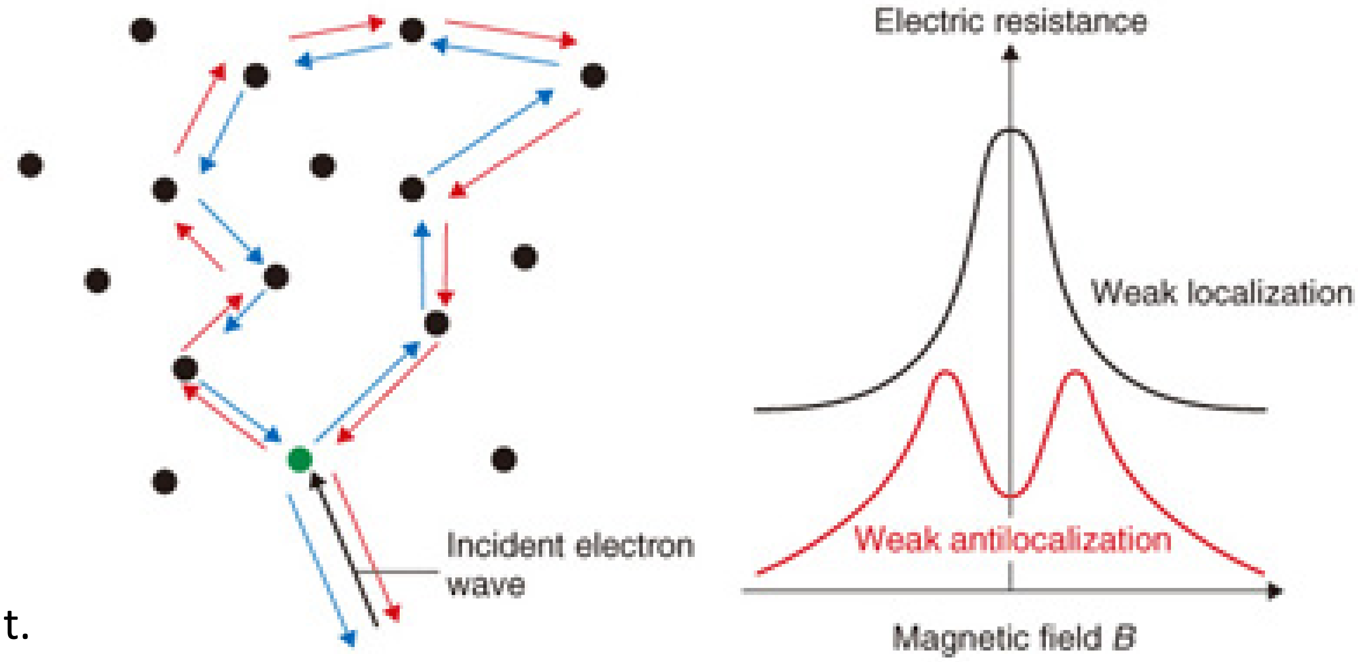
- See Weak Anti-Localization (WAL) analysis next



Weak localization (WL) and Anti-localization (WAL)

- Disordered 2D electron systems can have coherent closed-loop electron trajectories due to elastic scattering (a), which lead to WL when interfere constructively, and WAL when interfere destructively.
- Since MR $\propto$ dR/dH & added flux destroys pure WL and WAL, MR<0 for WL & MR>0 for WAL, see (b)
- Under strong spin-orbit int., the spins rotate & $\psi(e\uparrow)$ returns to itself only after 2 loops - yielding added phase of $\Delta\phi=4\pi$.
- For 1 loop $\Delta\phi=2\pi$, the spins ↑ & ↑ rotate in opposite directions & one can show that they interfere destructively, thus WAL occurs (*).

Incoming e↑
Forward scattered e↑
Back scattered e↑



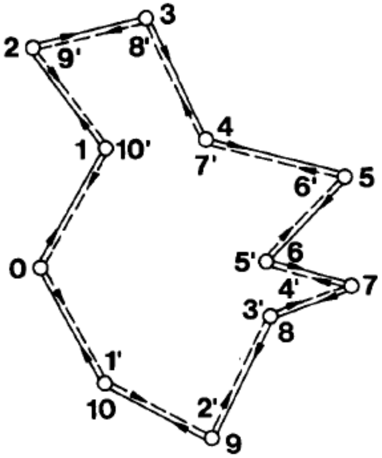
(a) Generation mechanism

(b) Magneto-resistance effect

(*) G. Bergmann, Sol. Stat. Comm. **11**, 815 (1982)

Weak anti-localization – WAL & quantum diffusion
The Hikami-Larkin-Nagaoka (HLN) model (*)

2D + disorder + spin-orbit => Interference effects



$$\Delta G_{\square}(B) \cong \alpha \frac{e^2}{\pi h}\left[\psi(\frac{1}{2}+\frac{B_\phi}{B}) - ln(\frac{B_\phi}{B})\right]$$

ψ is the Digamma function d/dz[ln Γ(z)] & for z=n, Γ=(n-1)!

$$B_\phi = \hbar / 4eL_\phi^2 \qquad \& \qquad \alpha \approx -1/2$$

$$\Delta G_{\square}(B) = G_{\square}(B) - G_{\square}(B=0) \quad \& \quad G_{\square}(B) = L/W\, R_{\square xx}$$

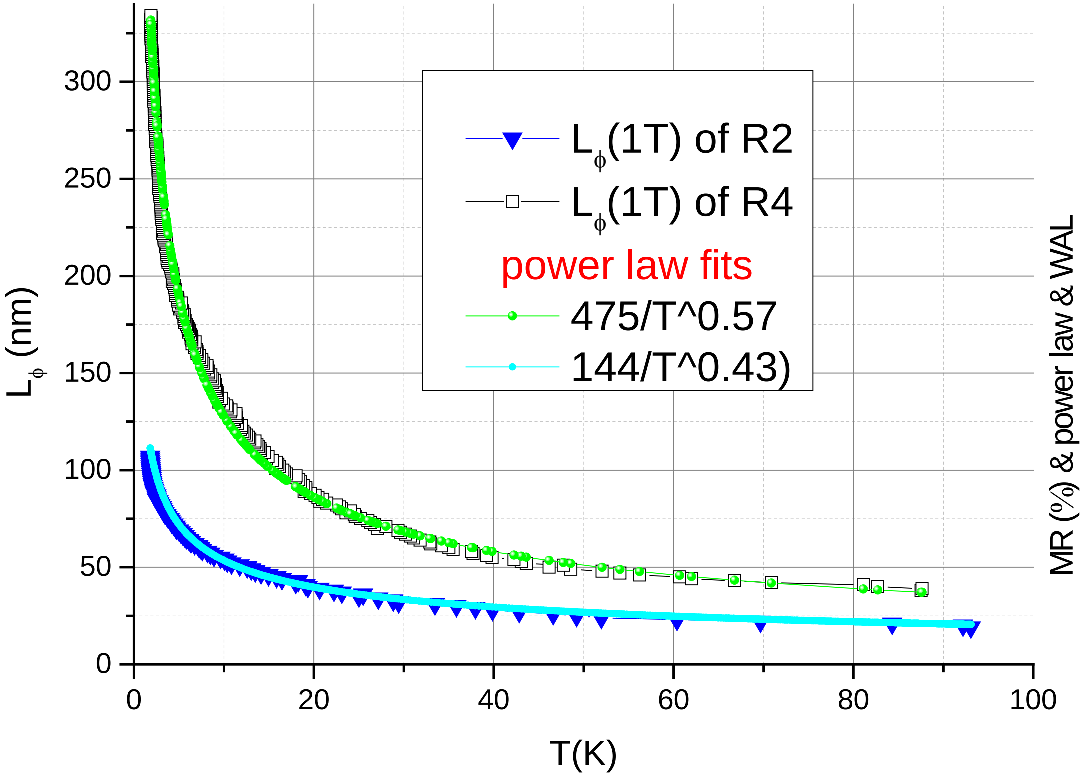
For B=1T & phase coherence length L_ϕ in nm:

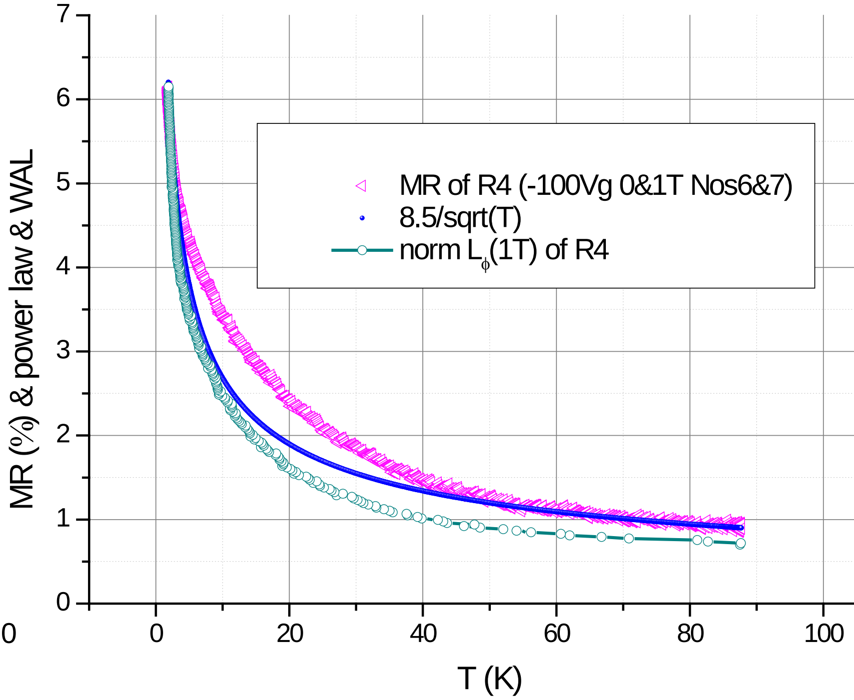
$$1.2\times10^5 \frac{R(B)-R(0)}{R(0)R(B)} \cong \psi\left(\frac{1}{2}+\frac{156}{L_\phi^2}\right) - \ln\left(\frac{156}{L_\phi^2}\right)$$

- R(B)-R(0) is the un-normalized magnetoresistance (MR)
- Since R is temperature dependent, this formula yields L_ϕ(T)

(*) Prog. Theor. Phys. **63**, 707 (1980)

10 nm Bi_2Se_3 reference film on fused silica
(4) MR, WAL & power law results vs T

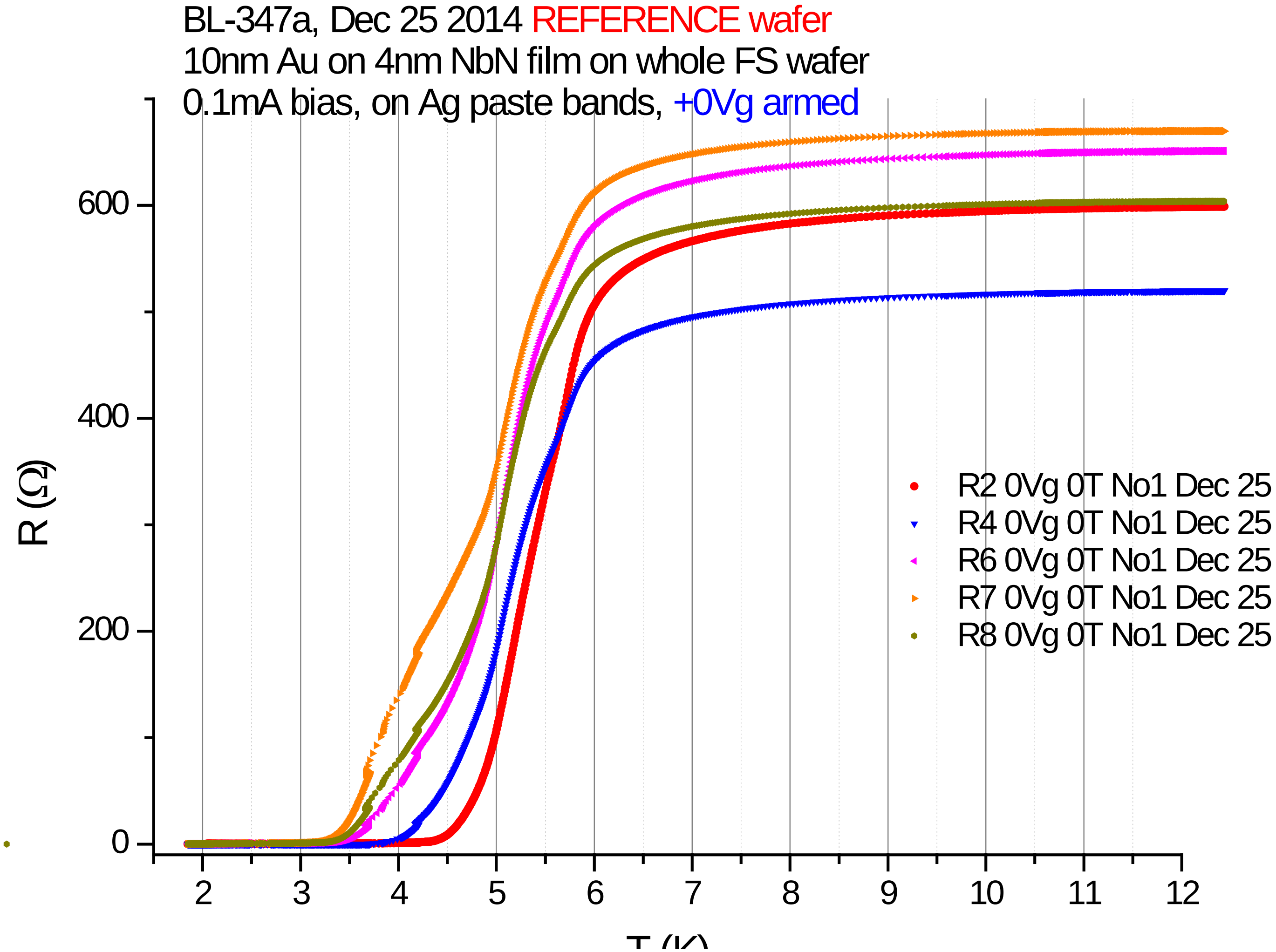




- On the same wafer, different L_ϕ & power-law exponents for different contacts
- On same contact, different behavior of MR, power-low (-1/2 for 2D) & L_ϕ (WAL)
- $L_\phi=\sqrt{D\tau_i}$ where for T>2K, τ_i is the electron-phonon scattering time (shortens vs T)

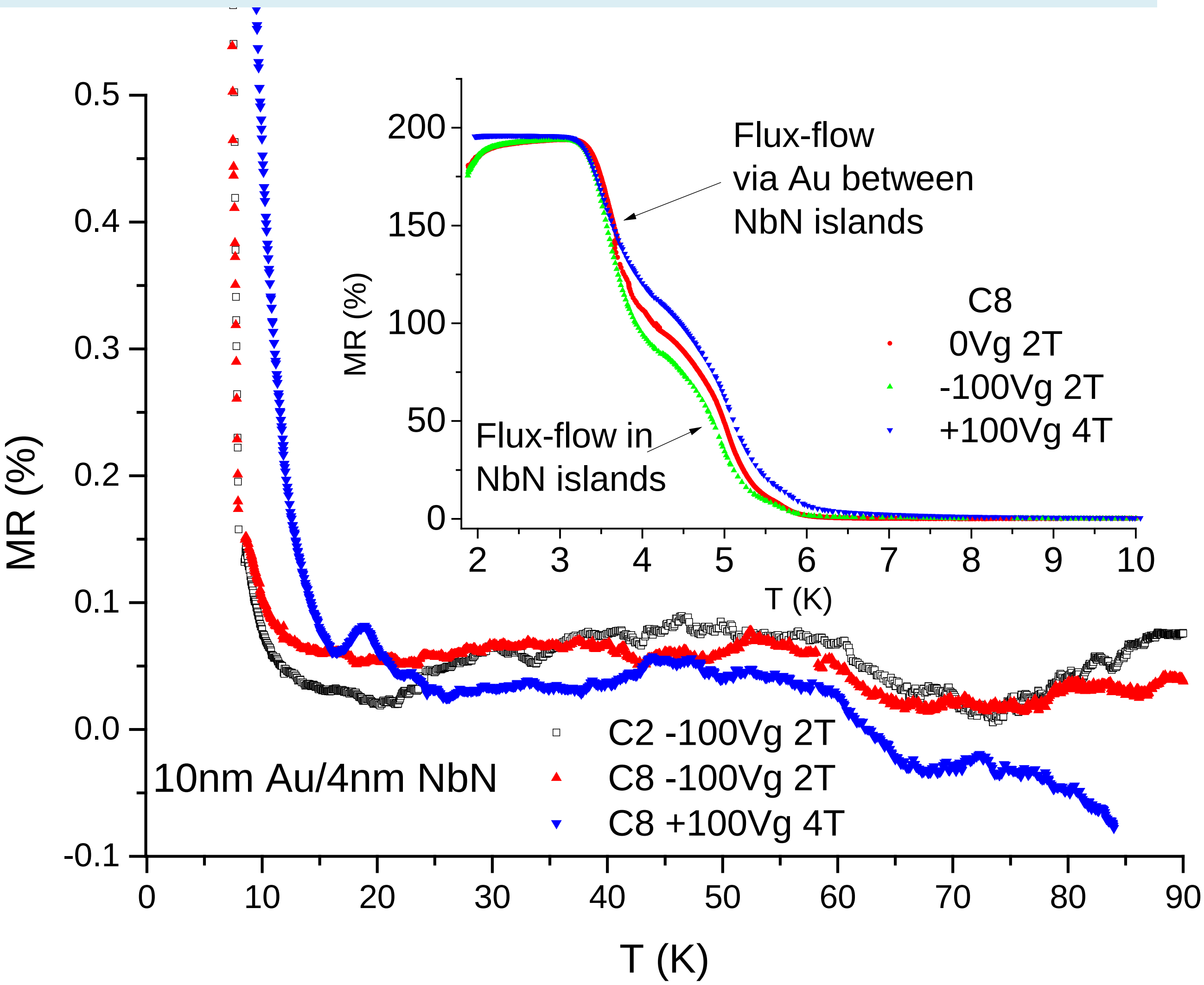
(1) A second reference bilayer of 10 nm gold (Au) on 4nm NbN on fused silica

R vs T results

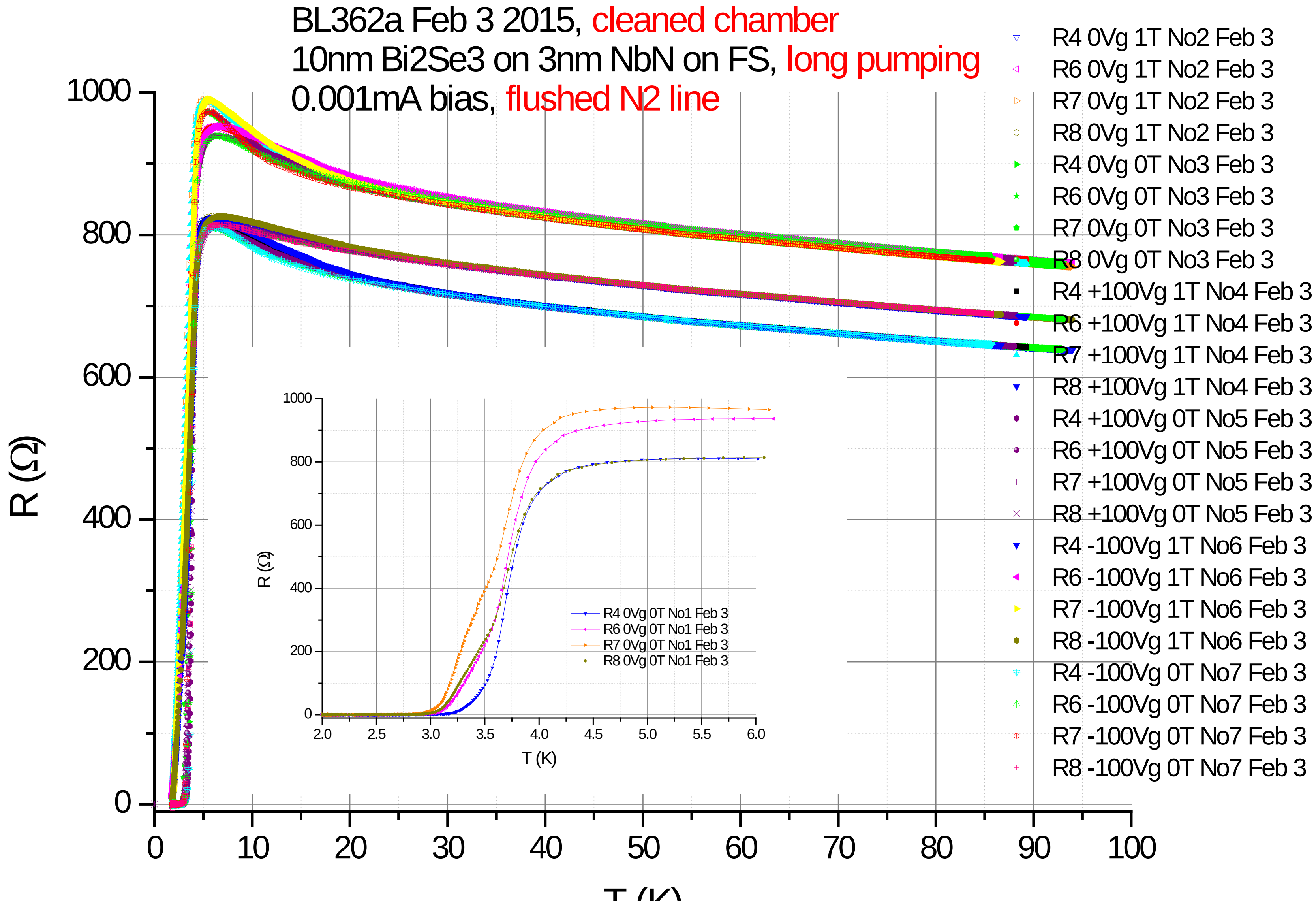


(2) MR results & Flux-flow (FF) in this bilayer below Tc (10 nm gold (Au) on 4nm NbN on fused silica)

- H is 2 & 4T here
- MR(T<Tc) due to flux-flow (FF) of NbN grains and in between the grains in the Bi_2Se_3 cap-layer
- For 2T, negligible MR of ~± 0.1% above Tc ~ 7-8 K
- At 4T, the SC MR starts at ~12 K due to FF(4T) > FF(2T)



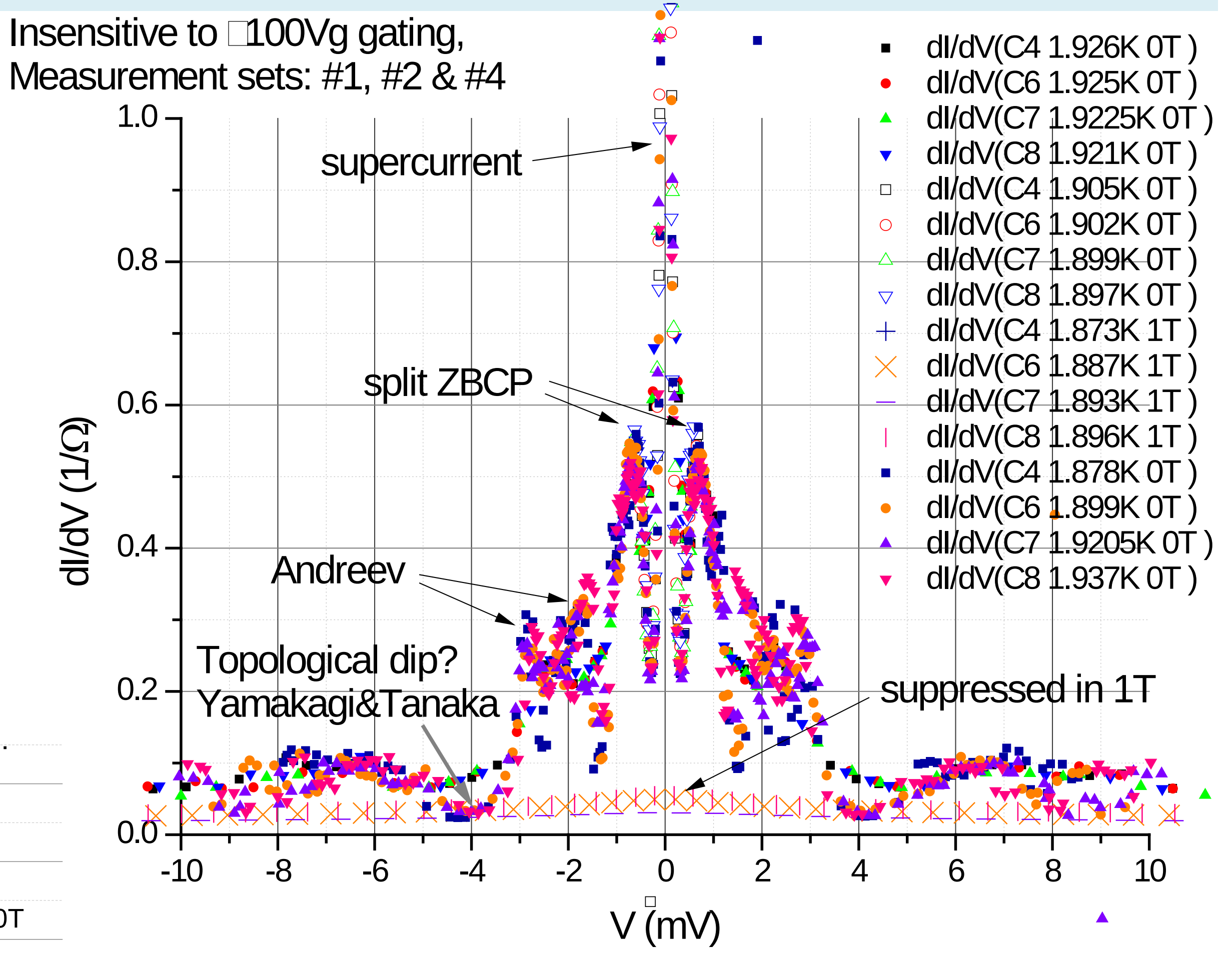
(1) R vs T of a bilayer of 10 nm Bi_2Se_3 on 3nm NbN on fused silica [low R_{max} case]

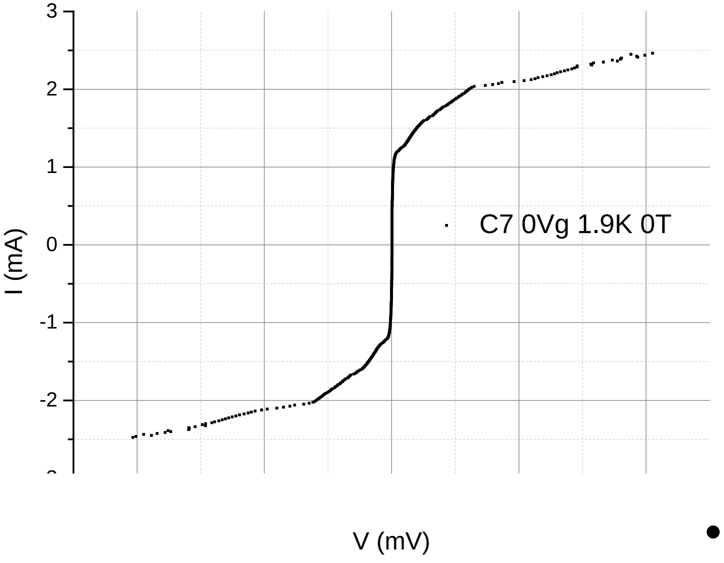


BL362a Feb 3 2015, cleaned chamber
10nm Bi2Se3 on 3nm NbN on FS, long pumping
0.001mA bias, flushed N2 line

(2) dI/dV & IVC of BL362a (10 nm Bi_2Se_3 on 3nm NbN on FS)

- Vg=0V
- I_C(1.9K)~1.2 mA
  (strong links)
- dI/dV is almost fully suppressed at 1T

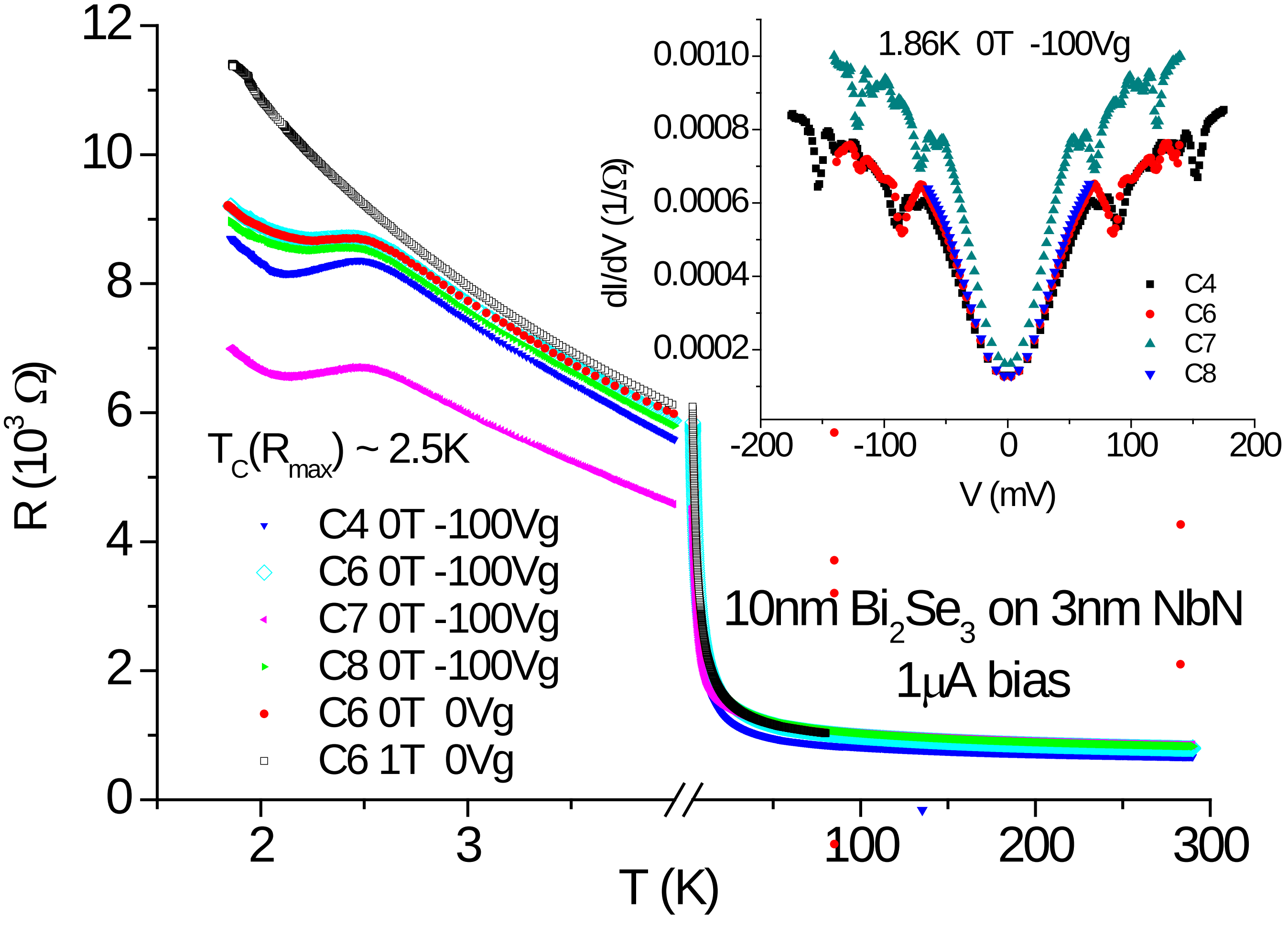




- Monotonous decreasing MR vs temperature (not shown)

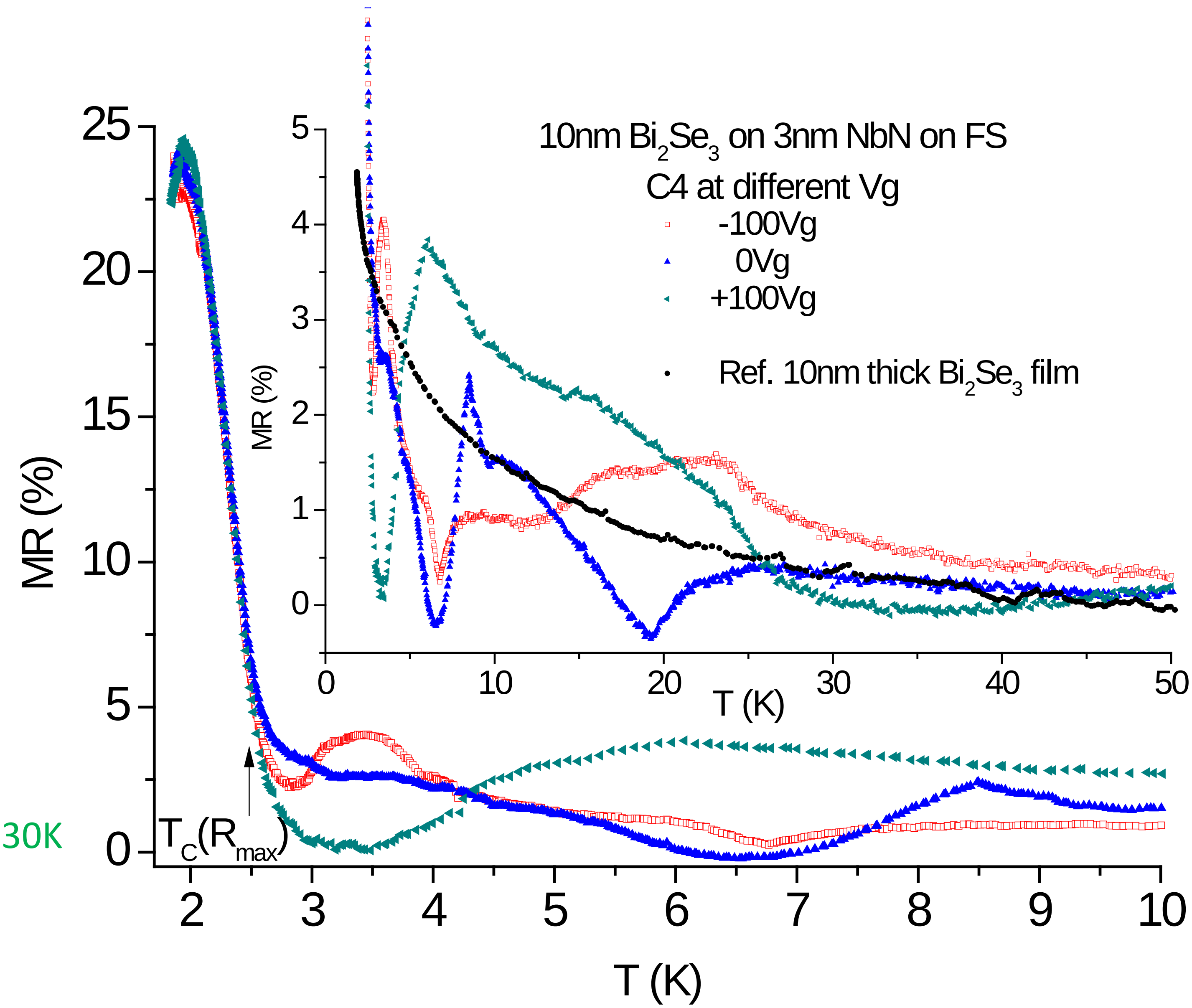
(1) R vs T of another bilayer of 10 nm Bi_2Se_3 on 3nm NbN on fused silica [highest resistance, some air in NbN deposition?]

- Semiconducting
- Very weak SC suppressed under 1T
- Tunneling between NbN grains



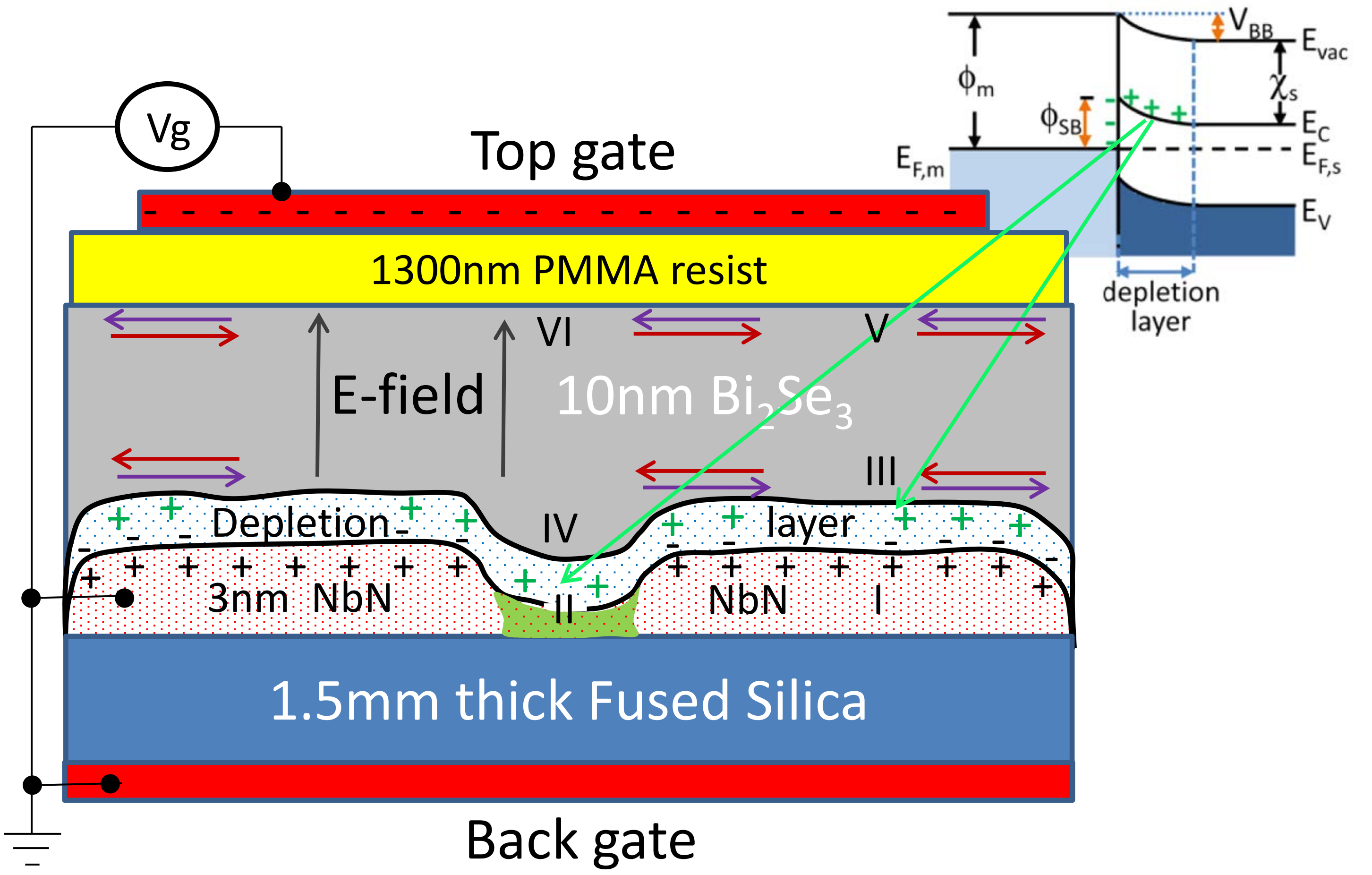
(2) MR of this bilayer of 10 nm Bi_2Se_3 on 3nm NbN on FS

- H is 0&1T for all measurements
- All contacts show the same behavior vs Vg
- Most MR Peaks are due to flux flow → Analysis next, on the model cross-section of SC islands & PE regions of the TI cap-layer
- Possible flux flow in a pseudogap at 15-30K
- Possible Majorana contribution at 1.9K



Model: electron density (n) under E-field in the bilayer

- +E-field [Vg of top gate < 0] Binds electrons of the Bi2Se3 to the NbN surface, leaving a positively charged depletion layer - DL [less n]
- -E-field binds holes, leaving electrons in the DL



MR peaks analysis:

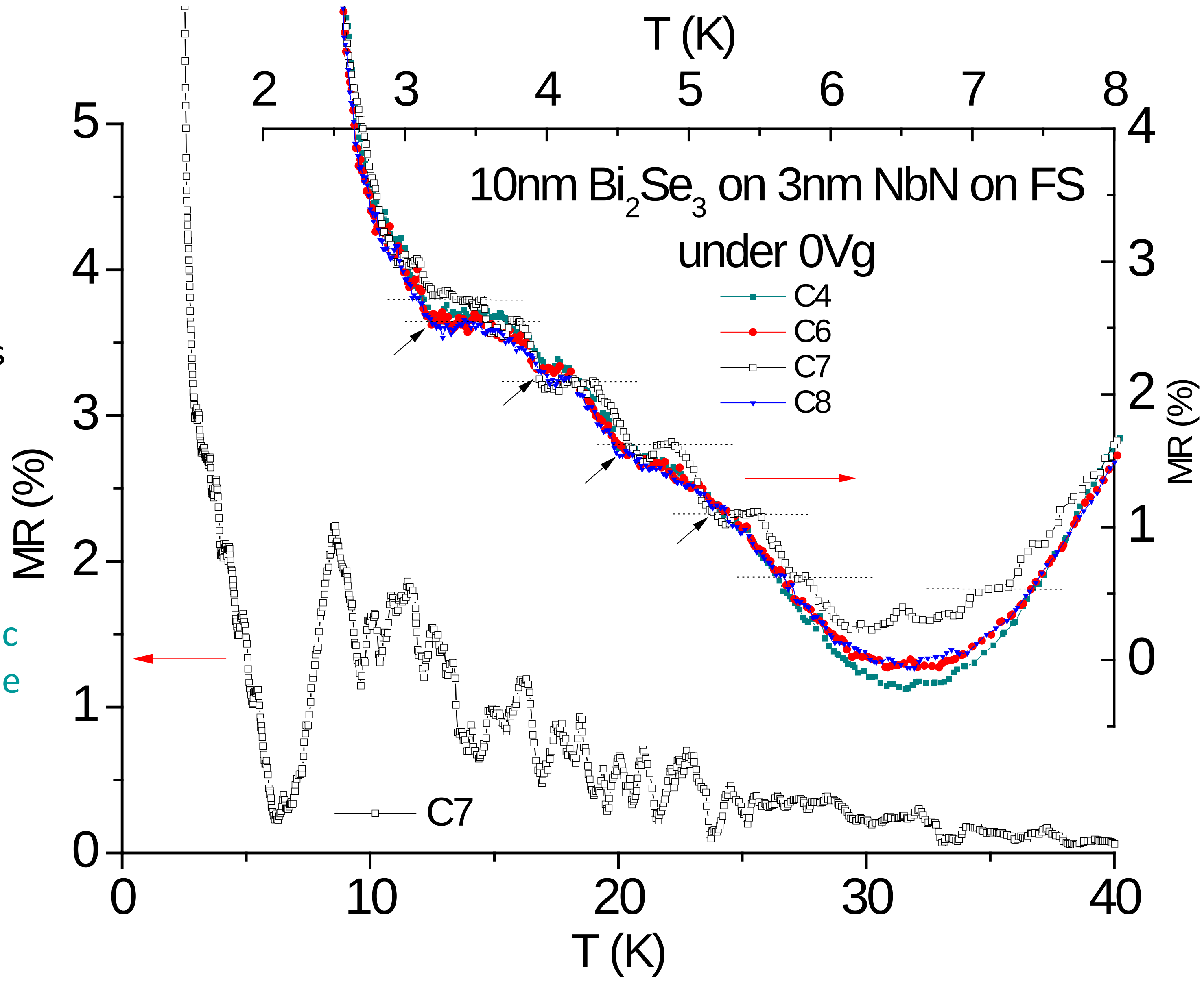
- For 0Vg: MR peaks at 7-15K, due to NbN islands – regions I, and PE in region III
  MR knee at 2.5-6K is due to PE in region II (& IV ?)
  Large MR peak below 2.5 K can be due to enhanced PR in region IV or to other effects
- For -100Vg: MR peak at 3-4K originates in the –e depleted region II
- For +100Vg: Broad MR peak at 6K originates in –e rich region II

(3) MR of C7 of this 10 nm Bi_2Se_3 on 3nm NbN on FS bilayer

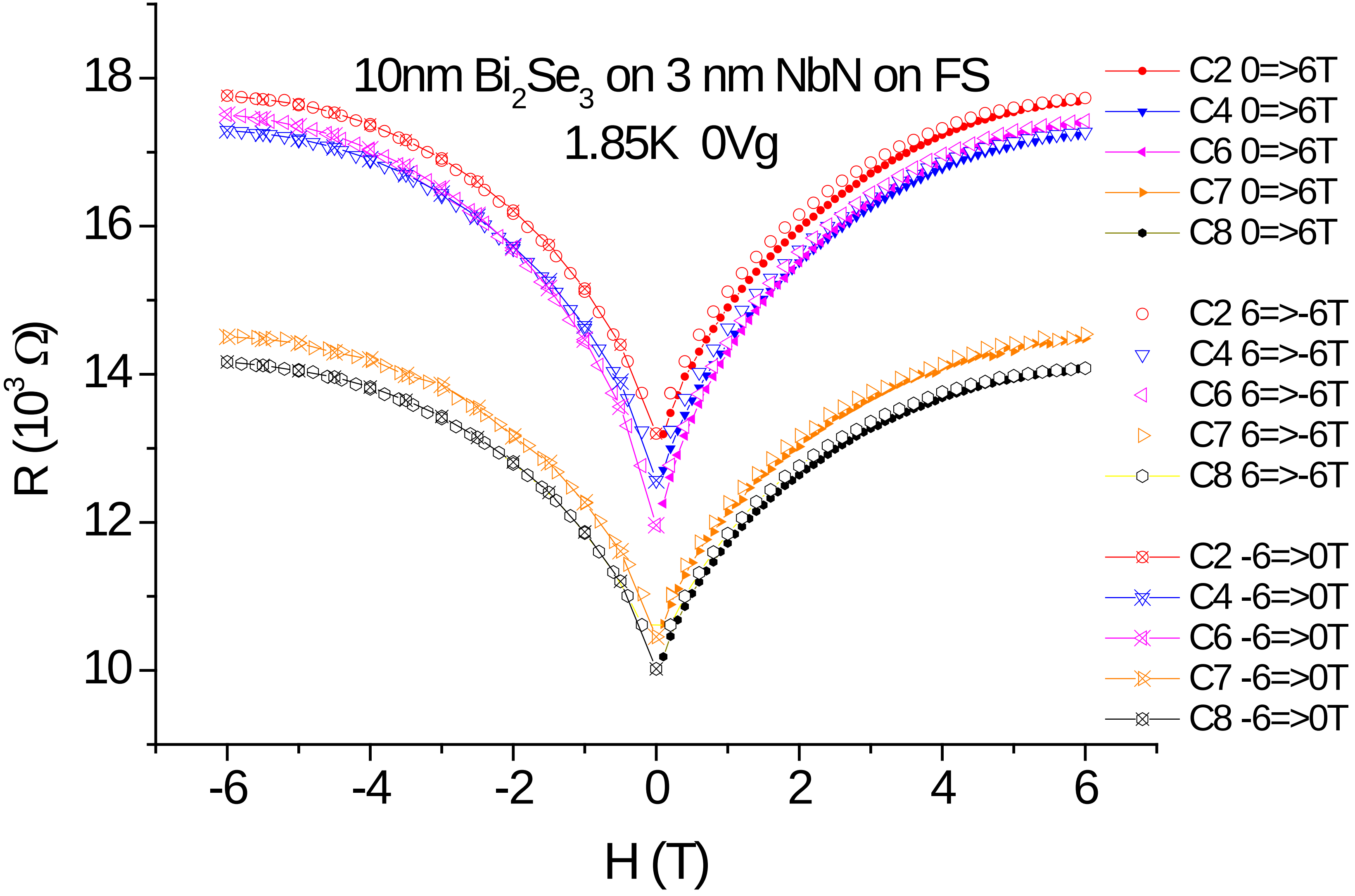
- Only C7 shows these oscillations under 0Vg

- No oscillations under ±100Vg

- Is the magnetic field causing these oscillations? See next….



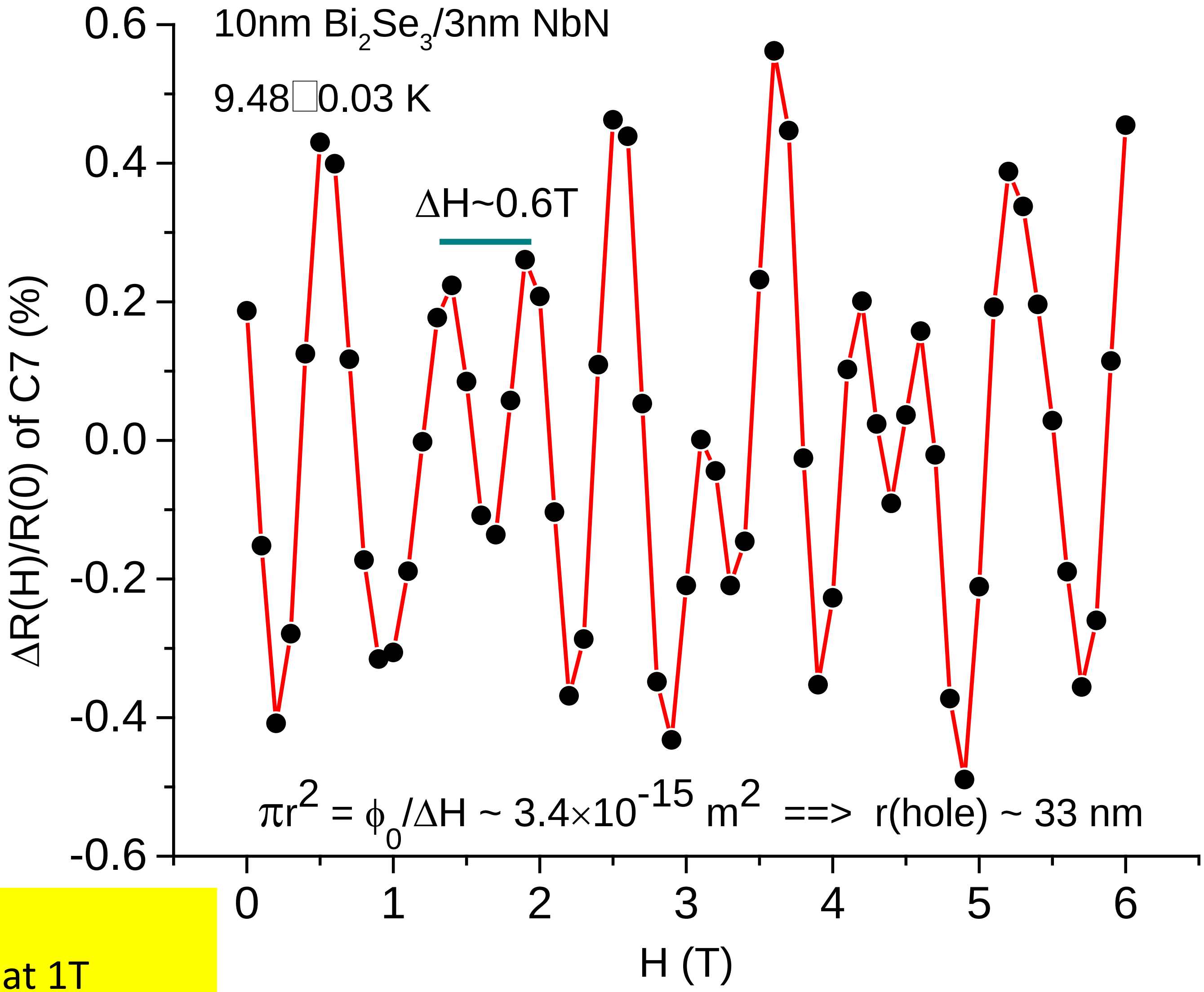
(4) R vs H of this 10 nm Bi_2Se_3 on 3nm NbN on FS bilayer



No oscillations here, but see next…

(5) ΔR/R(0) vs H at 9.5K of this bilayer (10 nm Bi_2Se_3 on 3nm NbN)

- ΔR(H) is R(H) minus a smooth background
- Oscillations vs H with a period of ΔH ~ 0.6T
  adding ϕ_0 for each period of ΔH~0.6T
- Corresponding to a hole radius of r ~ 33nm
- In agreement with the AFM image
- Tc(islands) ≥ 10K



Similar energy scales:
Magnetic ~μH ~ 0.06 meV at 1T
Thermal ~kT ~ 0.08 meV at 1K
ΔE(Landau at 1T) = $h\omega_c/2\pi$ = 0.12 meV

Conclusions II

- MR & WAL of 10nm Bi_2Se_3 films were observed in agreement with the literature
- MR of the 10nm Bi_2Se_3 on 3nm NbN bilayers was:

  1. Strongly dependent on the gate voltage Vg
  2. Varied with the peak resistance at low T
  3. Showed Vg dependent peaks and dips structure
  4. Oscillations vs H at 9.5K are

due to flux quantization in nano holes

& indicate Tc above 10K of the SC islands

  5. MR vs T response is due mostly to vortex physics & pinning
  6. Enhanced PE in the Bi_2Se_3 in between NbN islands at T=1.9 K
     can be due to: helical surface currents contribution,
     or to Majorana zero mode contribution