SUPERCONDUCTING TUNNEL JUNCTIONS AND NANOREFRIGERATION USING InAs NANOWIRES

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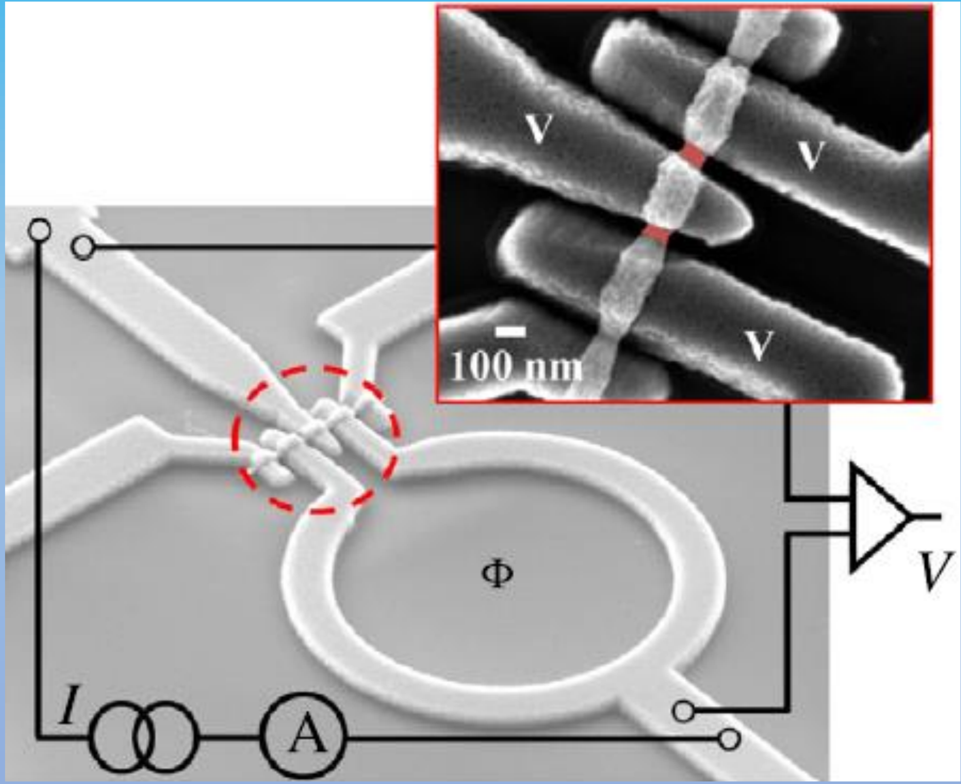
Why?

- The big picture: Controlling and measuring heat flows in mesoscopic structures
- Normal metal-Insulator-Superconductor (NIS) junctions can do this
- Here, N $\rightarrow$ one-dimensional semiconductor nanowires (NW)
- NWs are widely studied
  - Fascinating transport properties
  - May contain Majorana fermions
- So far only direct N or S contacts
- This study demonstrates the first NW-I-S junctions



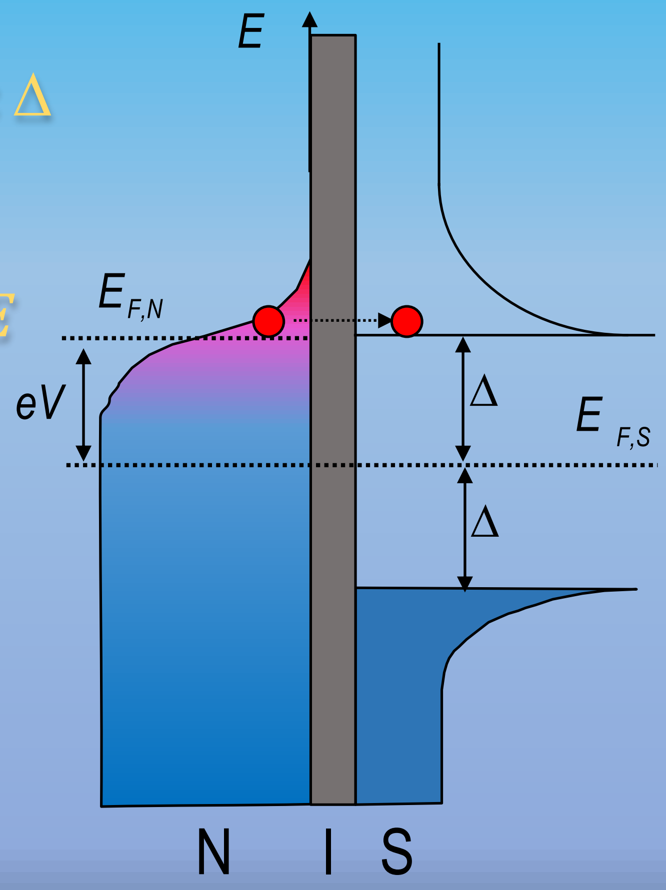
Adapted from P. Spathis et al., Hybrid InAs nanowire-vanadium proximity SQUID, *Nanotechnology*, **22** (2011), 105201

Normal metal-Insulator-Superconductor (NIS) junctions

- At $T = 0$, electrons are able to tunnel trough the thin insulating layer if $eV \geq \Delta$
- Current is given by

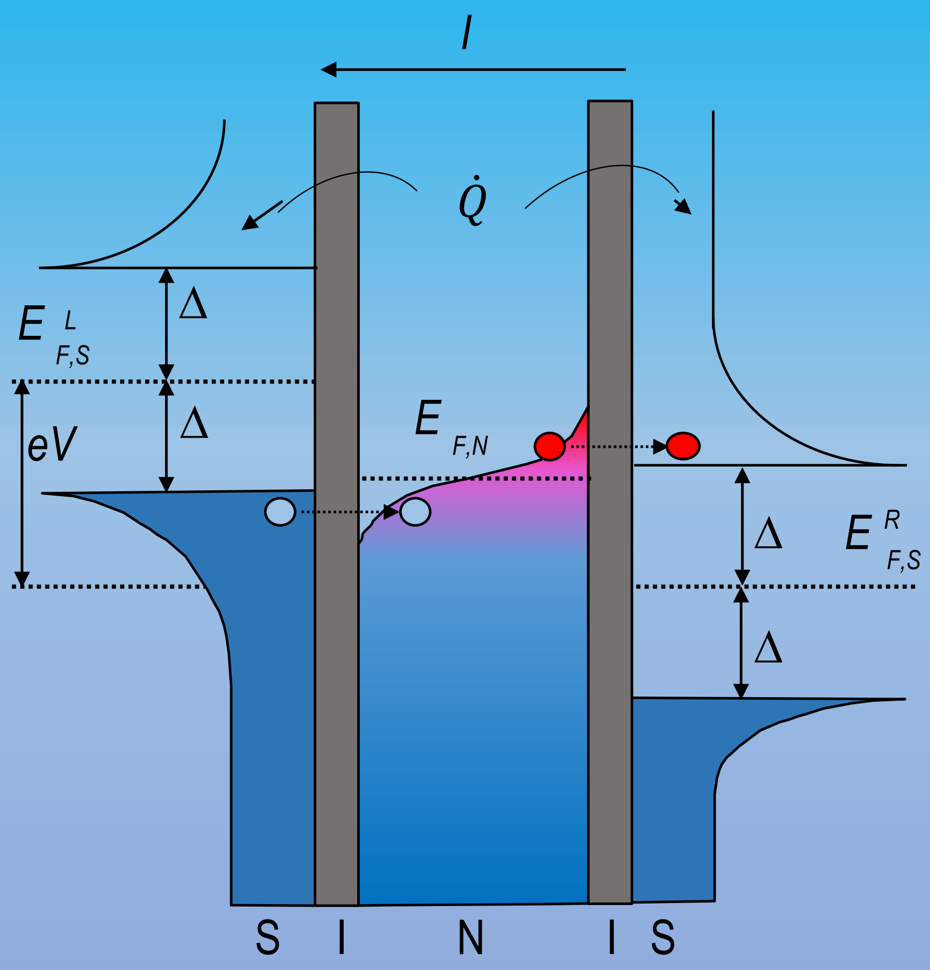
$$I(V, T_{e,N}) = \frac{1}{2eR_N} \int n_S(E) \left[f_N(E - eV, T_{e,N}) - f_N(E + eV, T_{e,N}) \right] dE$$

- R_N is the normal state resistance of the junction
- $f_N(E, T_{e,N}) = \left(e^{E/k_B T} + 1 \right)^{-1}$ and $n_S(E) = \left| \mathrm{Re} \left[\frac{E + i\gamma\Delta}{(E + i\gamma\Delta)^2 - \Delta^2} \right] \right|$
- Dynes parameter γ: the ”quality” of the junction
- $I(T_{e,N}) \rightarrow$ thermometry

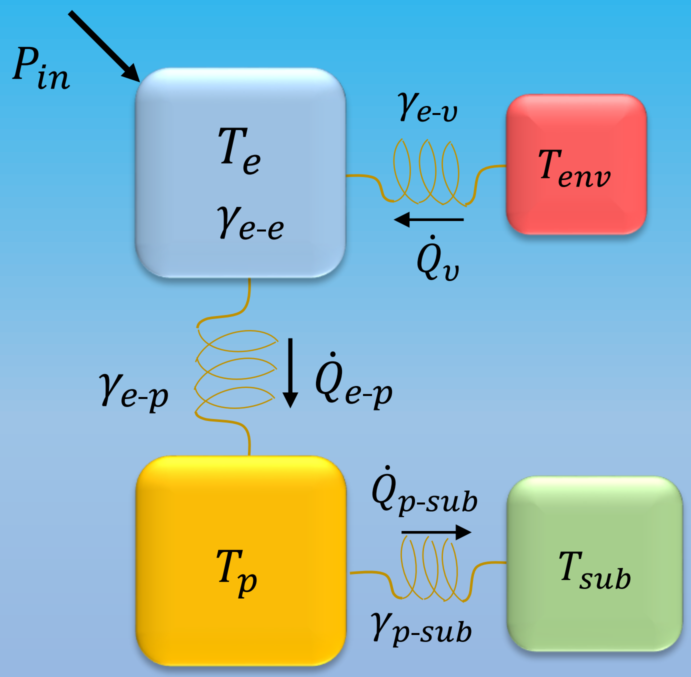


SINIS refrigeration

- Cold electrons tunnel into and hot electrons out of the normal metal⟶ cooling
- $\dot{Q}_{\mathrm{NIS}}(V, T_{e,N}, T_{e,S}) = \frac{1}{e^2 R_N} \int n_S(E)(E - eV)[f_N(E -$



Thermal model

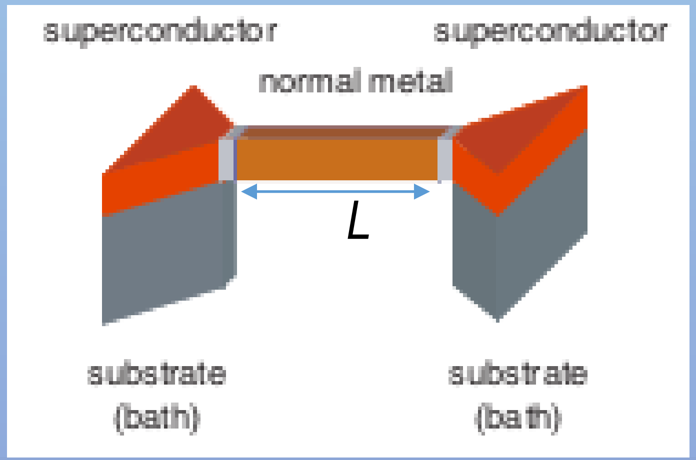


- N: The electron and the phonon system are coupled and exchange heat with rate $n = 4 - 6$

$$\dot{Q}_{e-p} = \Sigma U\left(T_e^n - T_p^n\right)$$

Material parameter Volume

- Ideally, at steady state $\dot{Q}_{\mathrm{NIS}}$ + $\dot{Q}_{e-p}$ = 0 → temperature can be solved



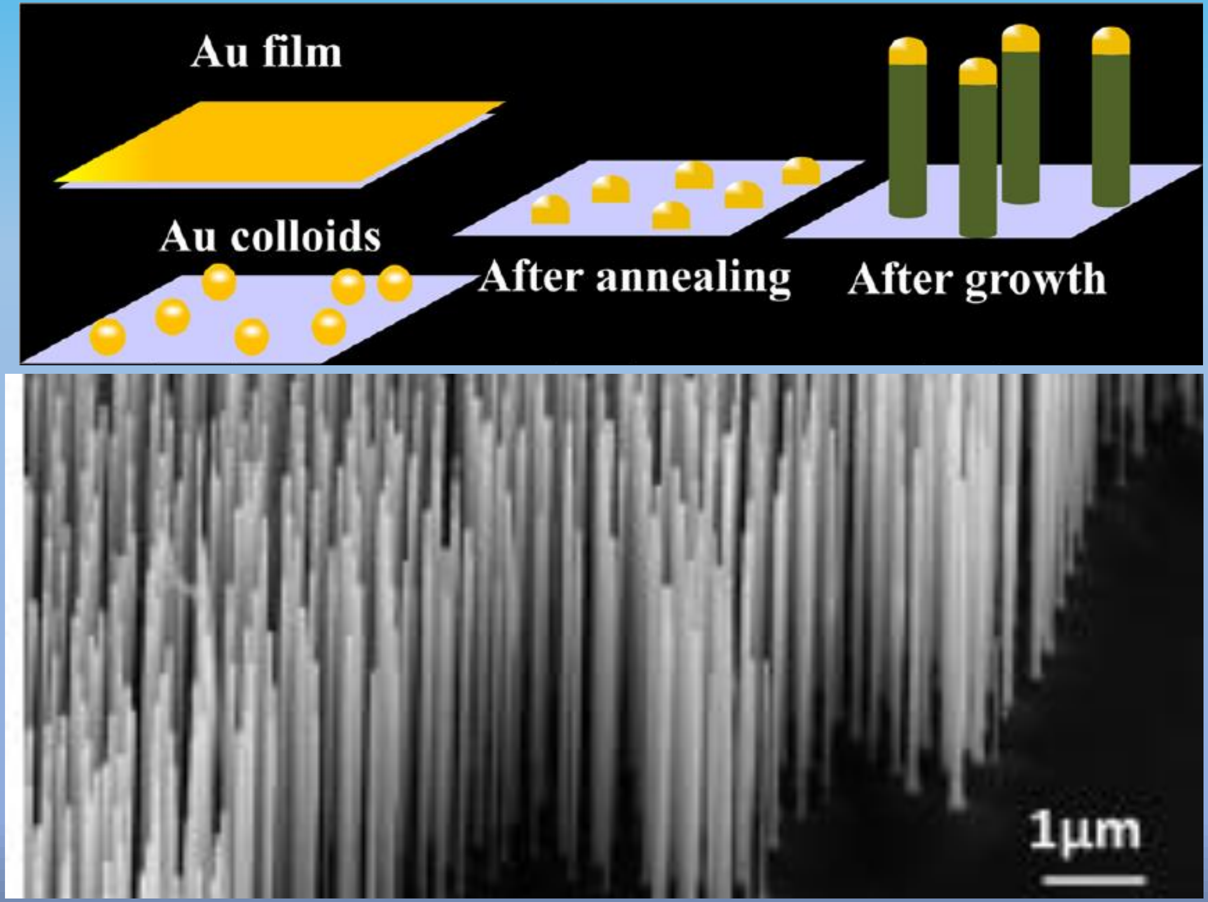
Adapted from F.W.J. Hekking et al. Electron-phonon coupling and longitudinal mechanical-mode cooling in a metallic nanowire, *Phys. Rev. B*, 77, 033401 (2008)

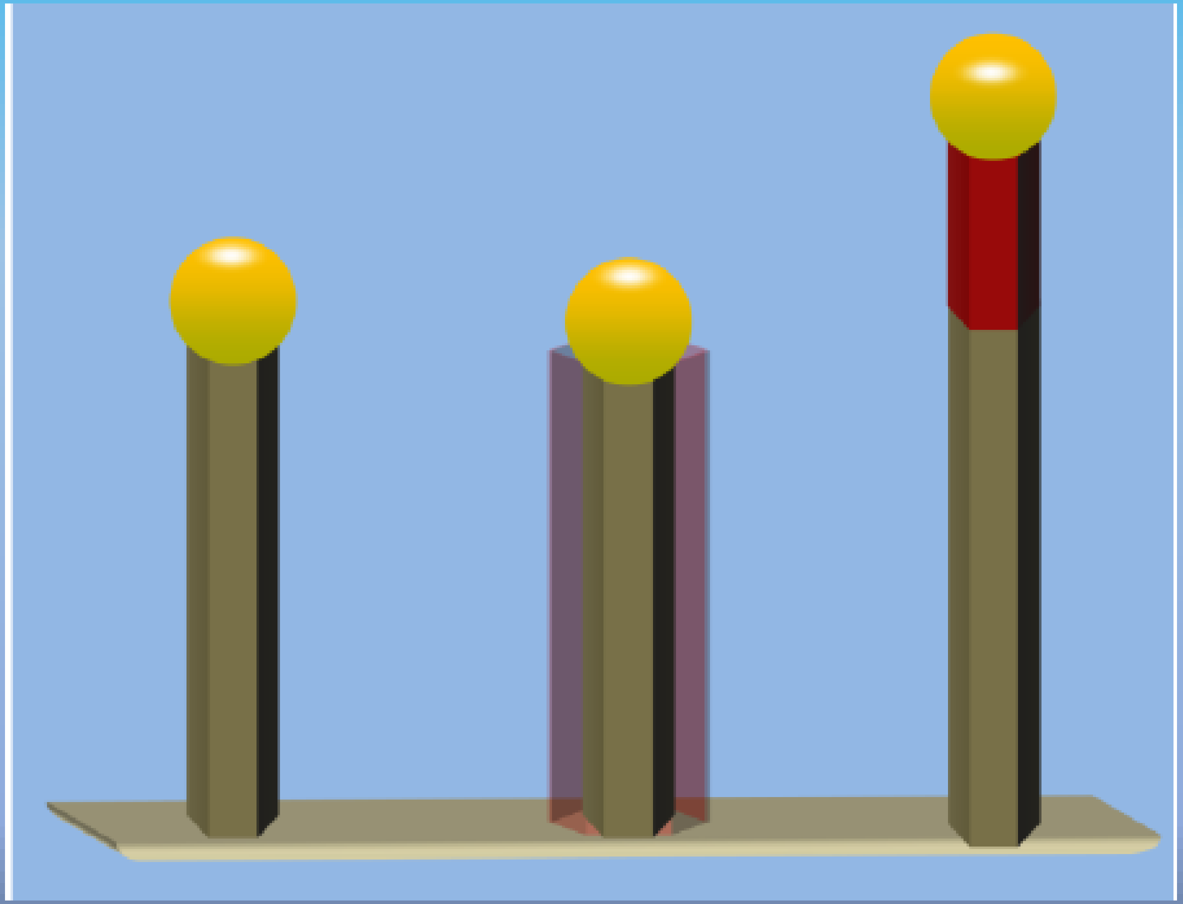
- A model for suspended metallic nanowires suggests

$$\dot{Q}_{e-p}^{1D} = \Sigma_{1D} L\left(T_e^3 - T_p^3\right)$$

Semiconductor Nanowires

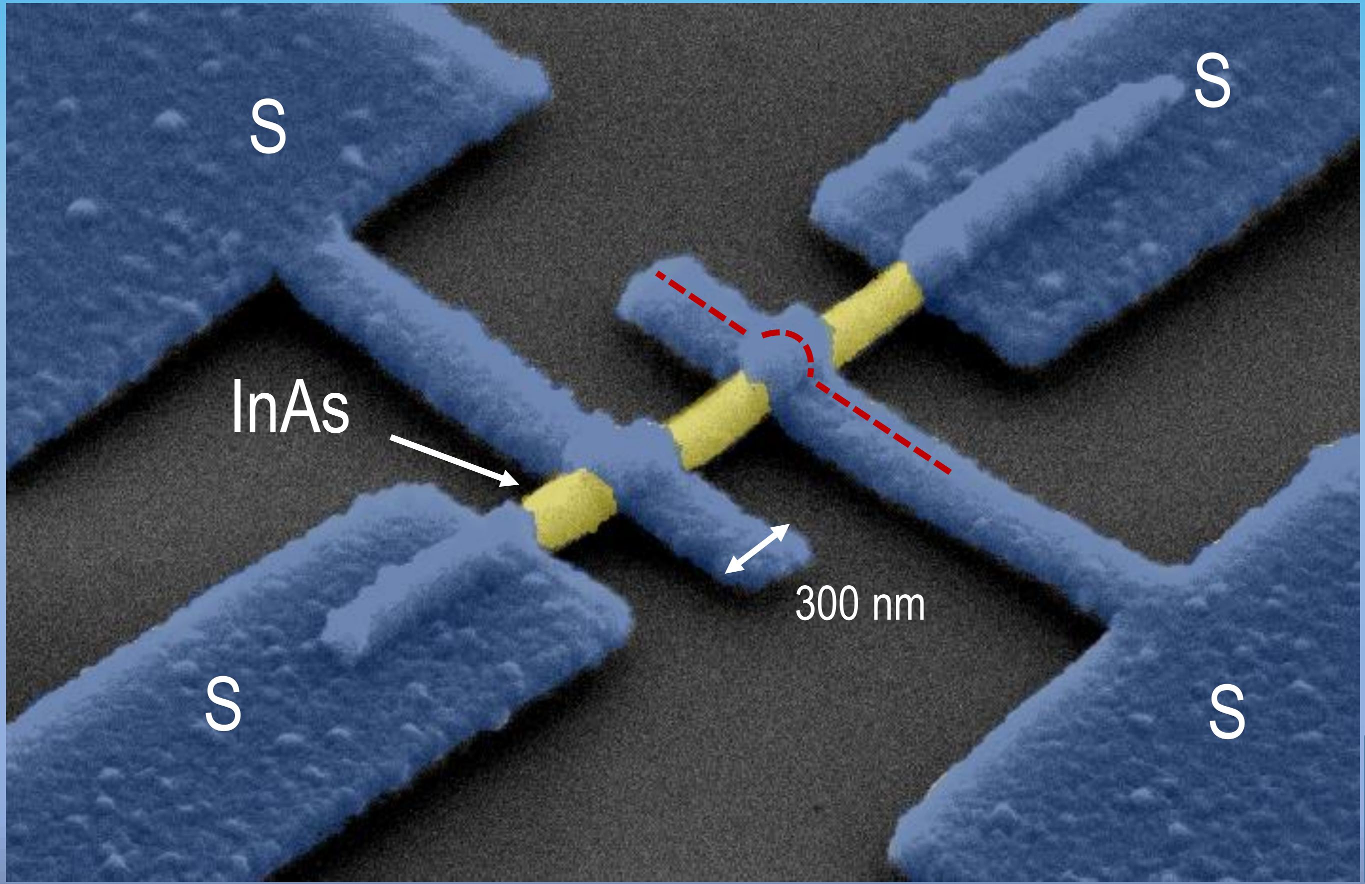
- Grown by Chemical Beam Epitaxy using Au nanoparticles as catalysts
- Possibility to fabricate heterostructures either in radial or axial directions

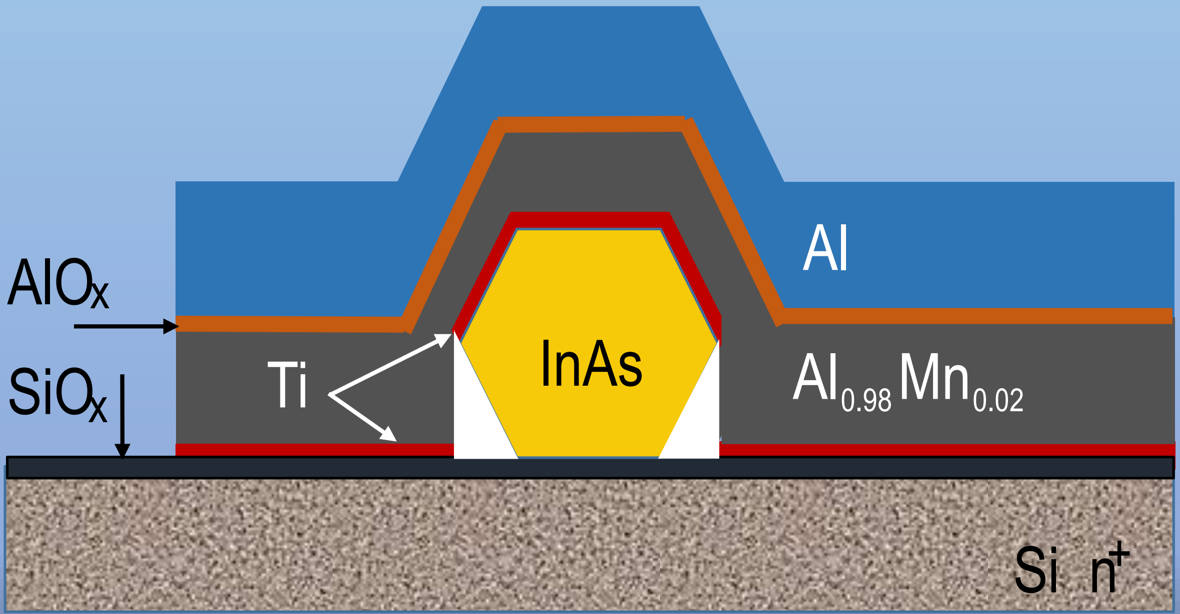




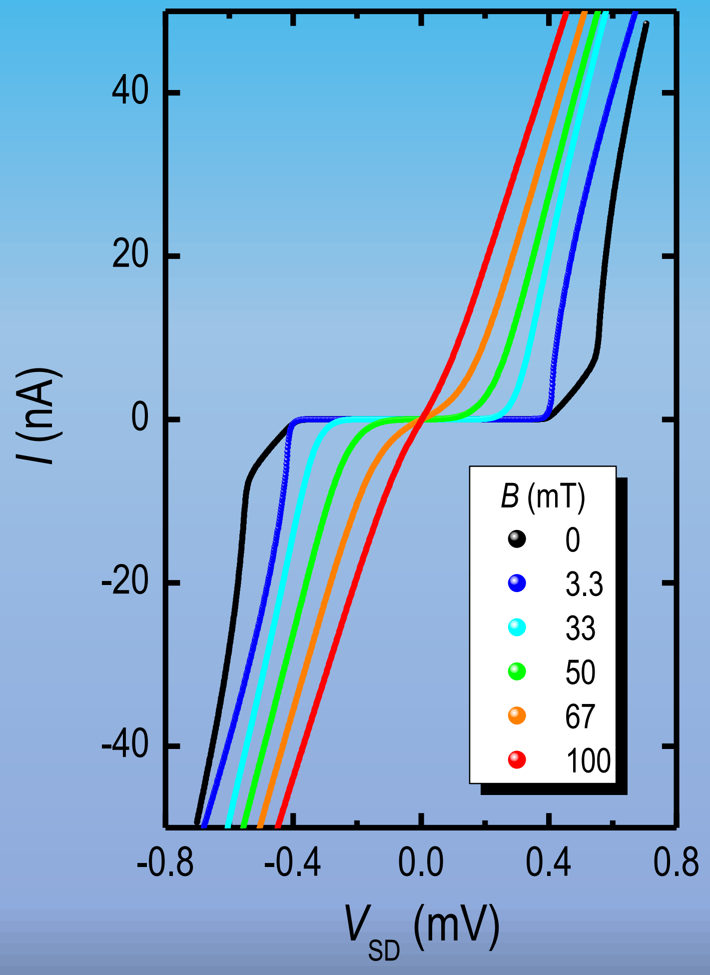
Figures adapted from Umesh Gomes, Catalyst-assisted and catalyst-free growth of III-V semiconductor nanowires. PhD thesis, Scuola Normale Superiore, 2017

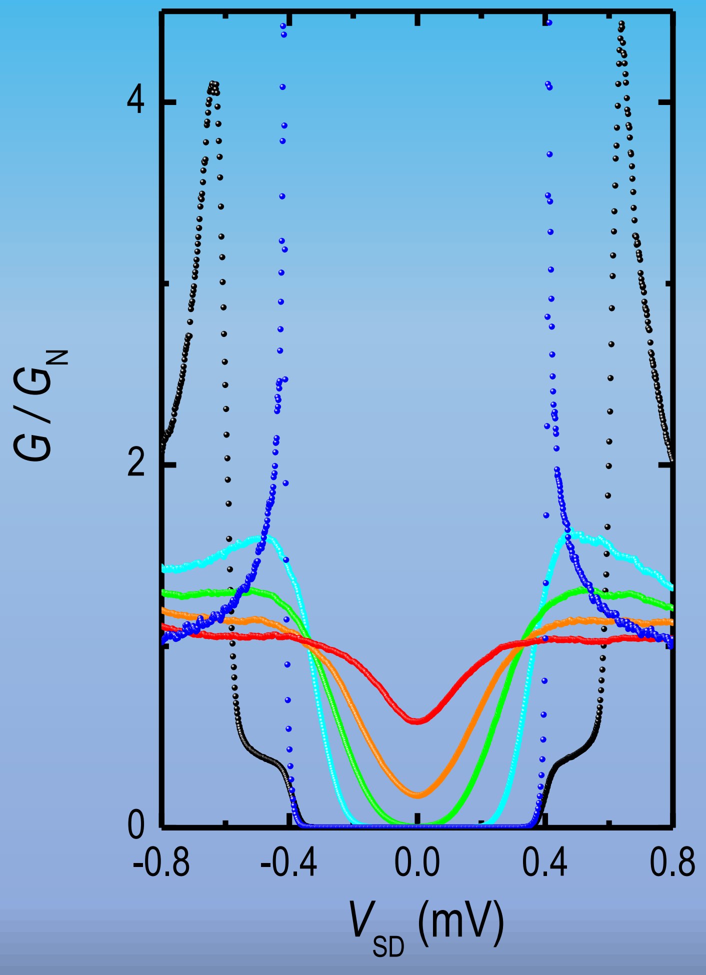
Realization of junctions



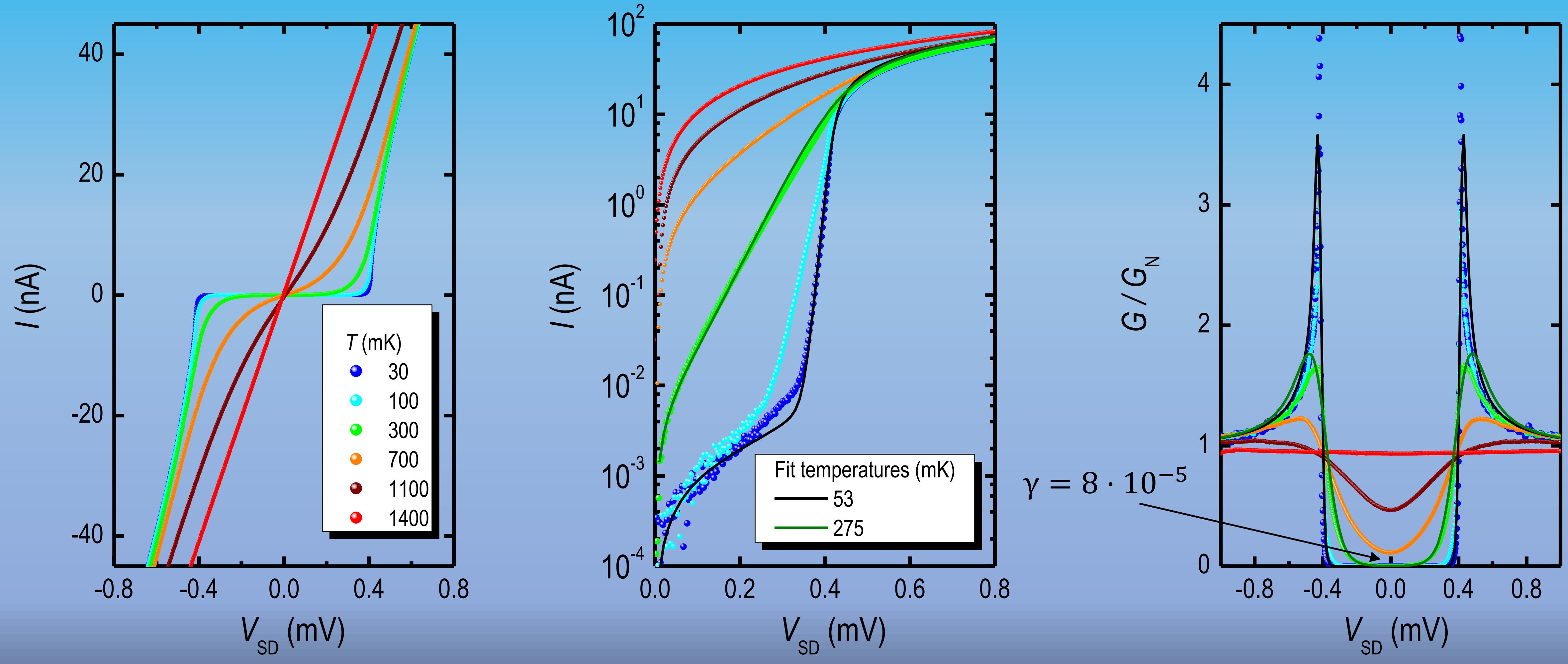


Results – a SINIS junction in external magnetic field

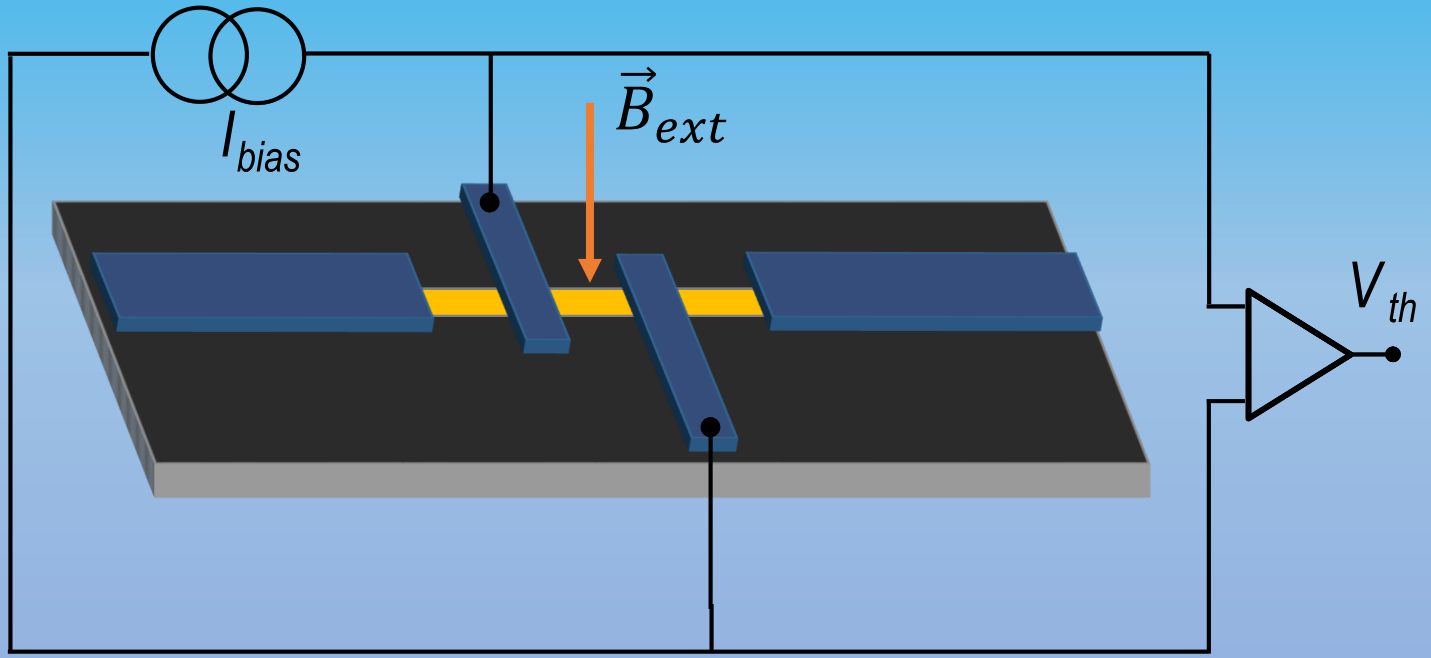




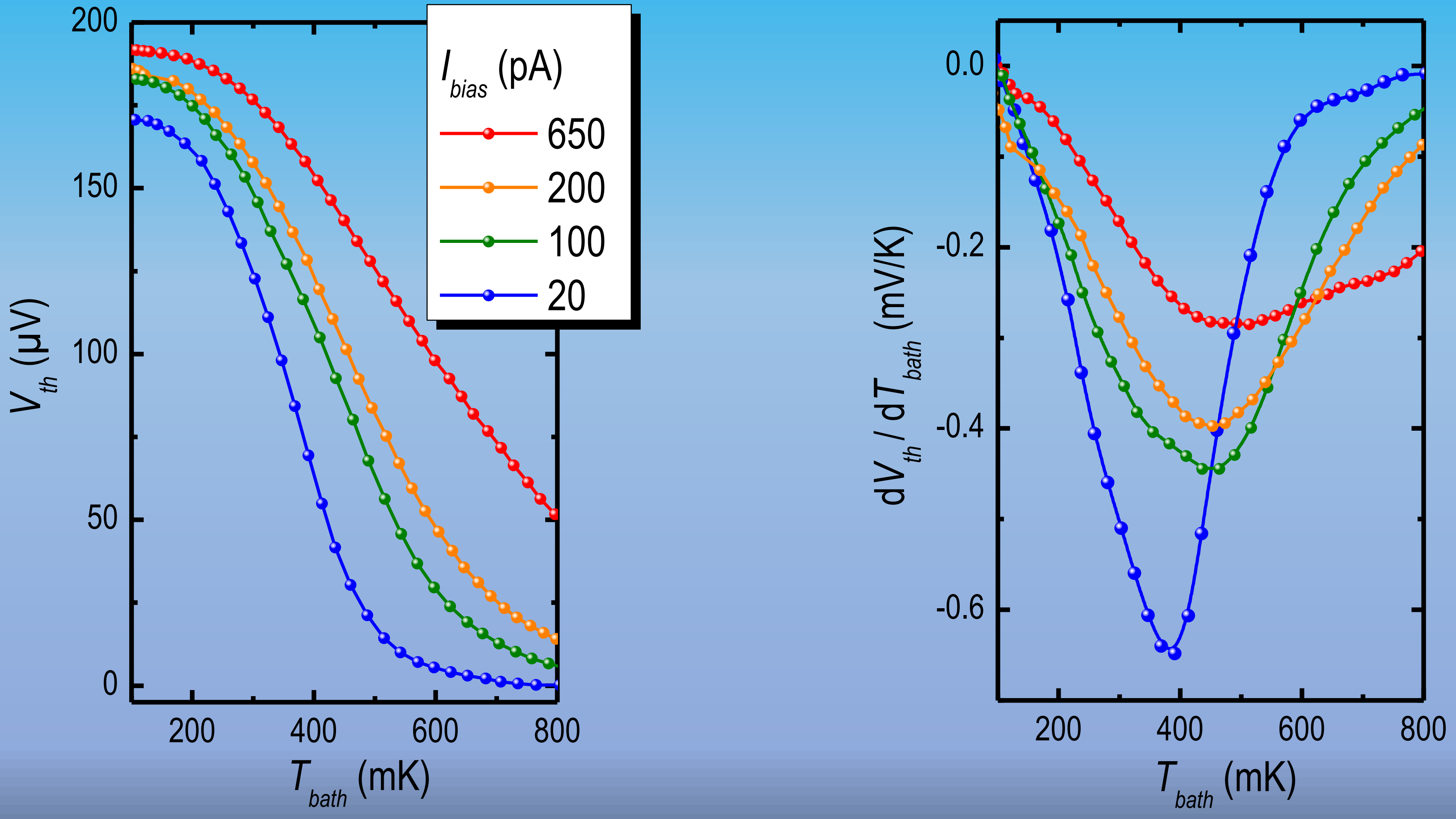
Results – a SINIS junction at different temperatures



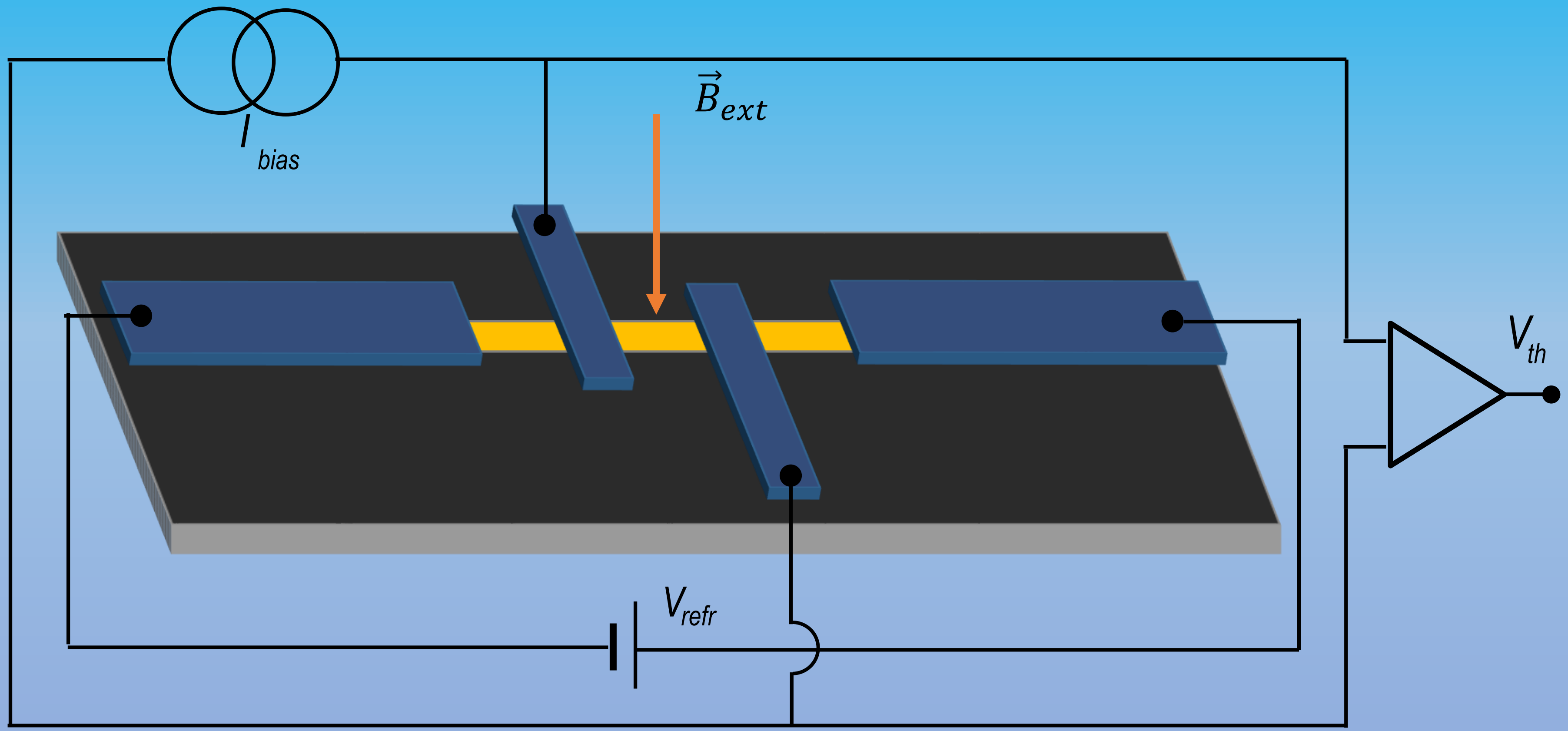
Results – a NIS thermometer



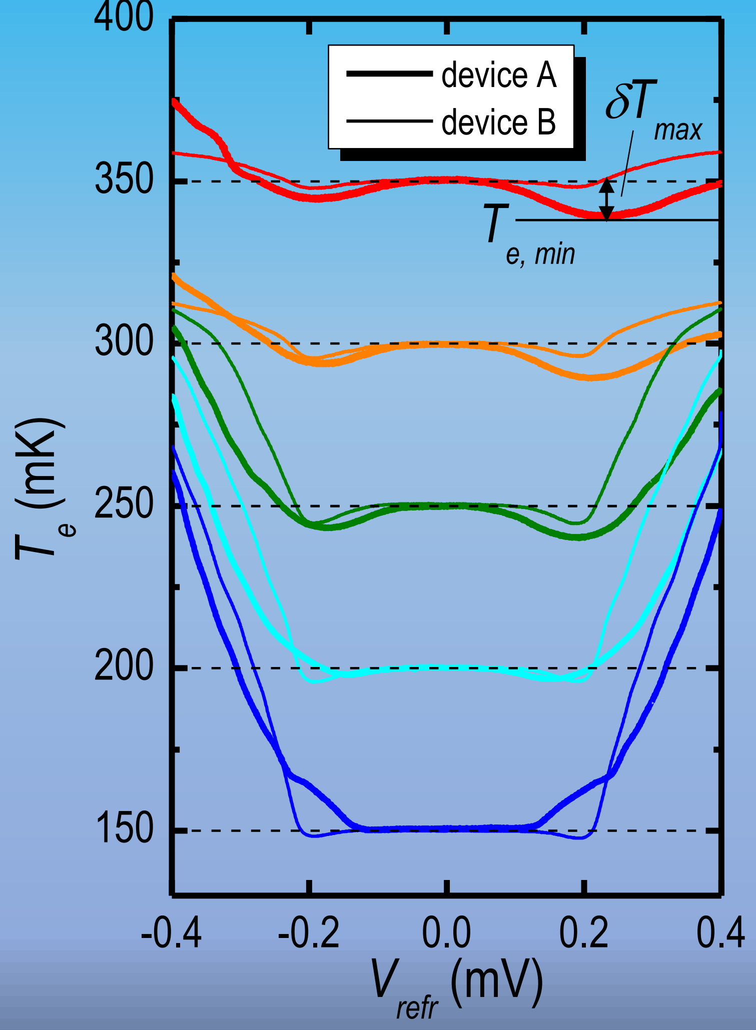
Results – a NIS thermometer

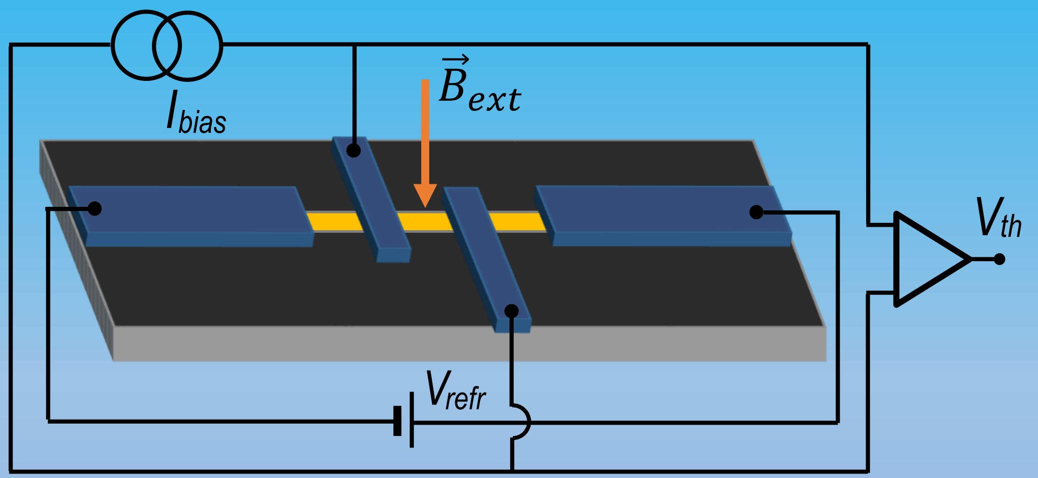


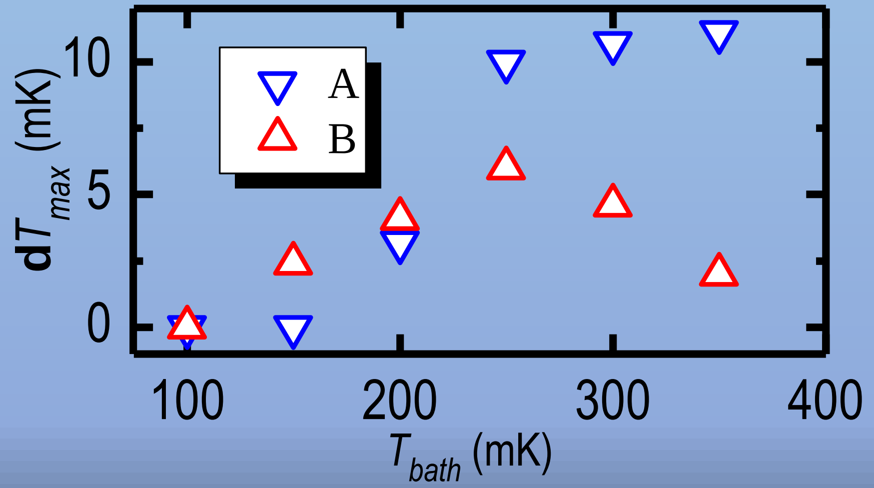
Results – a NIS refrigerator



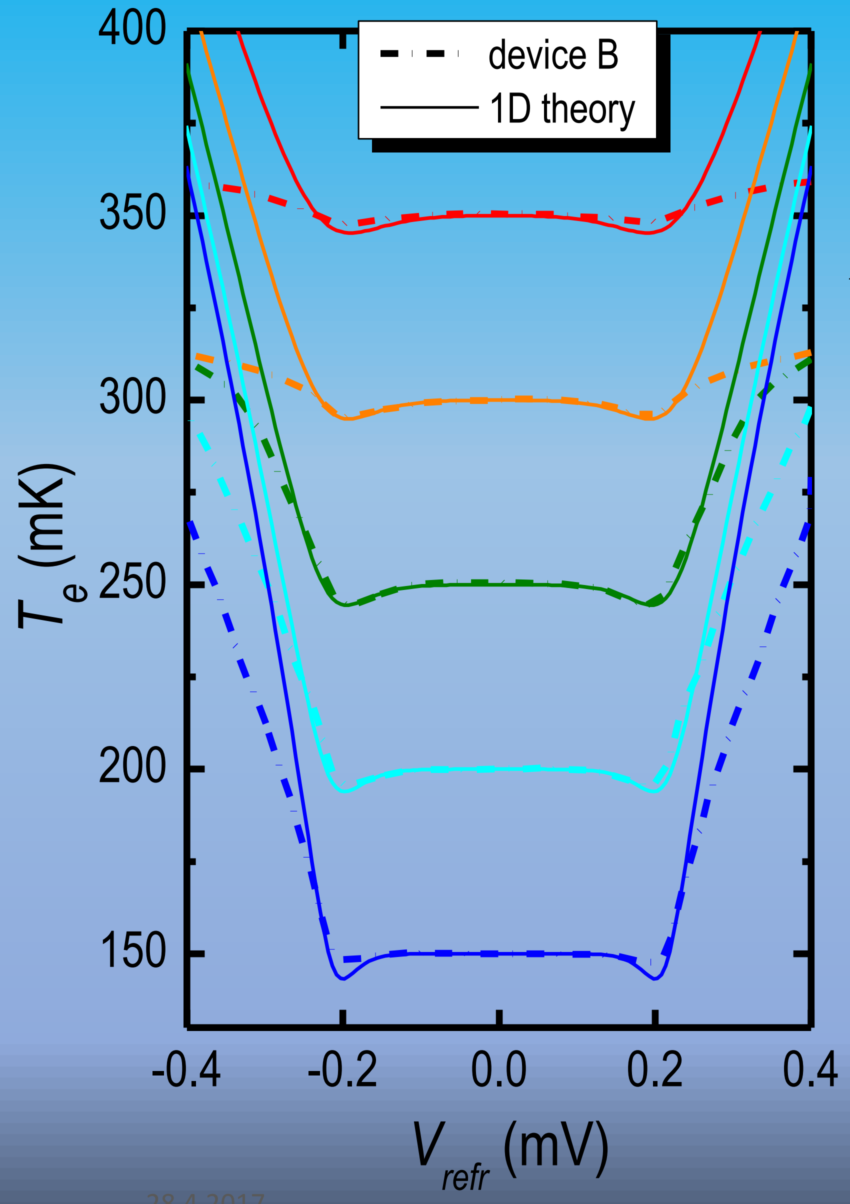
Results – a NIS refrigerator





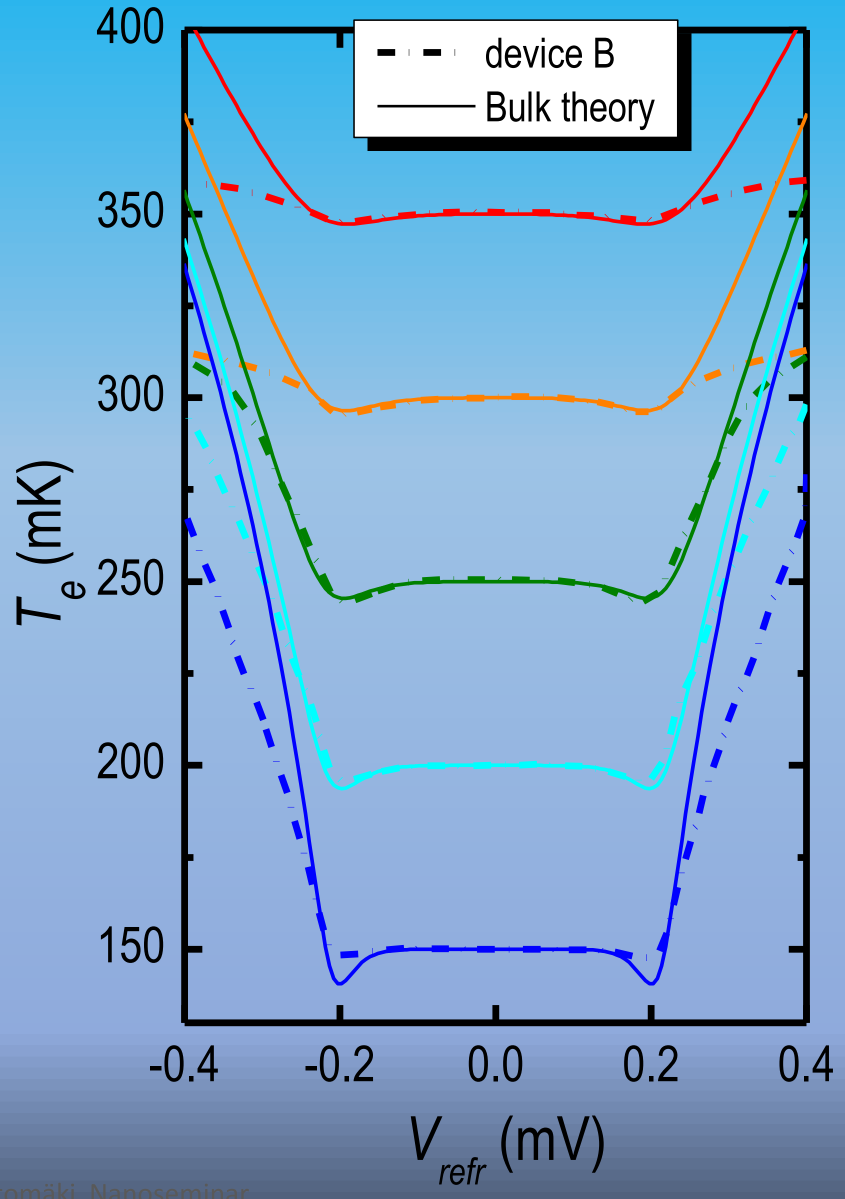


Results – a NIS refrigerator



$L = 2.5\ \mu\mathrm{m}$

$\Sigma_{1D} = 1.5 \cdot 10^{-4}\ \mathrm{Wm^{-1}K^{-3}}$



$\Sigma = 0.4 \cdot 10^{-9}\mathrm{Wm^{-3}K^{-4}}$

Conclusions

- With a small external magnetic field, the tunnel junctions showed almost ideal BCS characteristics with $\gamma = 8 \cdot 10^{-5}$
- The junctions can be utilized for thermometry and refrigeration of InAs NWs, the maximum temperature reduction of $\delta T \approx 10$ mK taking place at $T_{bath} \approx 250 - 350$ mK. Modest cooling probably due to actively cooled AlMn
- The results can be applied in NW transport and Majorana fermion research

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  - Dr. Daniele Ercolani*
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  - Dr. Elia Strambini*

§ Currently at Center for Quantum Devices, University of Copenhagen

- Outcome: JM et al., InAs nanowire superconducting tunnel junctions: Quasiparticle spectroscopy, thermometry and nanorefrigeration. *Nano Research,* DOI 10.1007/s12274-017-1558-7 (2017)

Thank you!