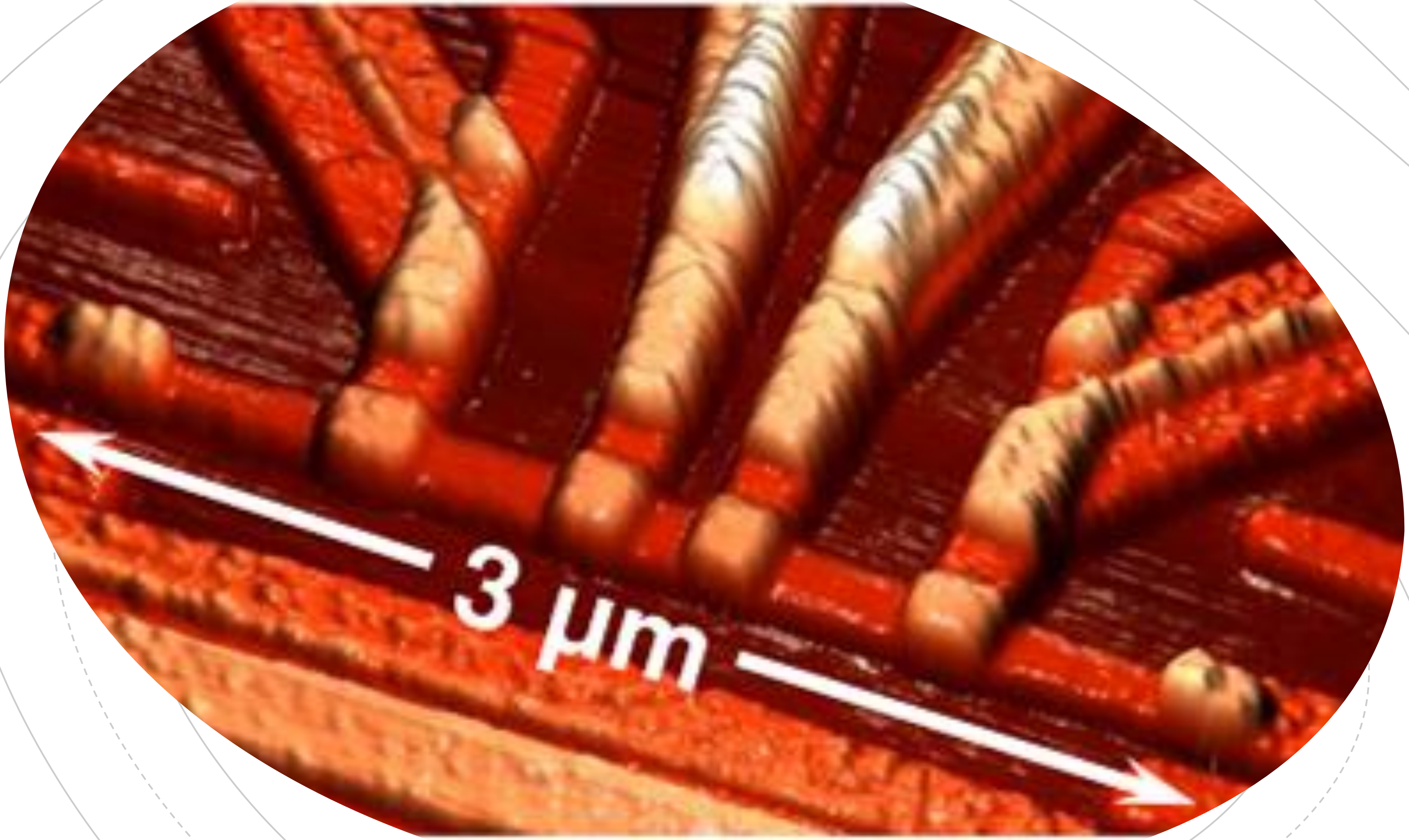
Temperature and thermometry



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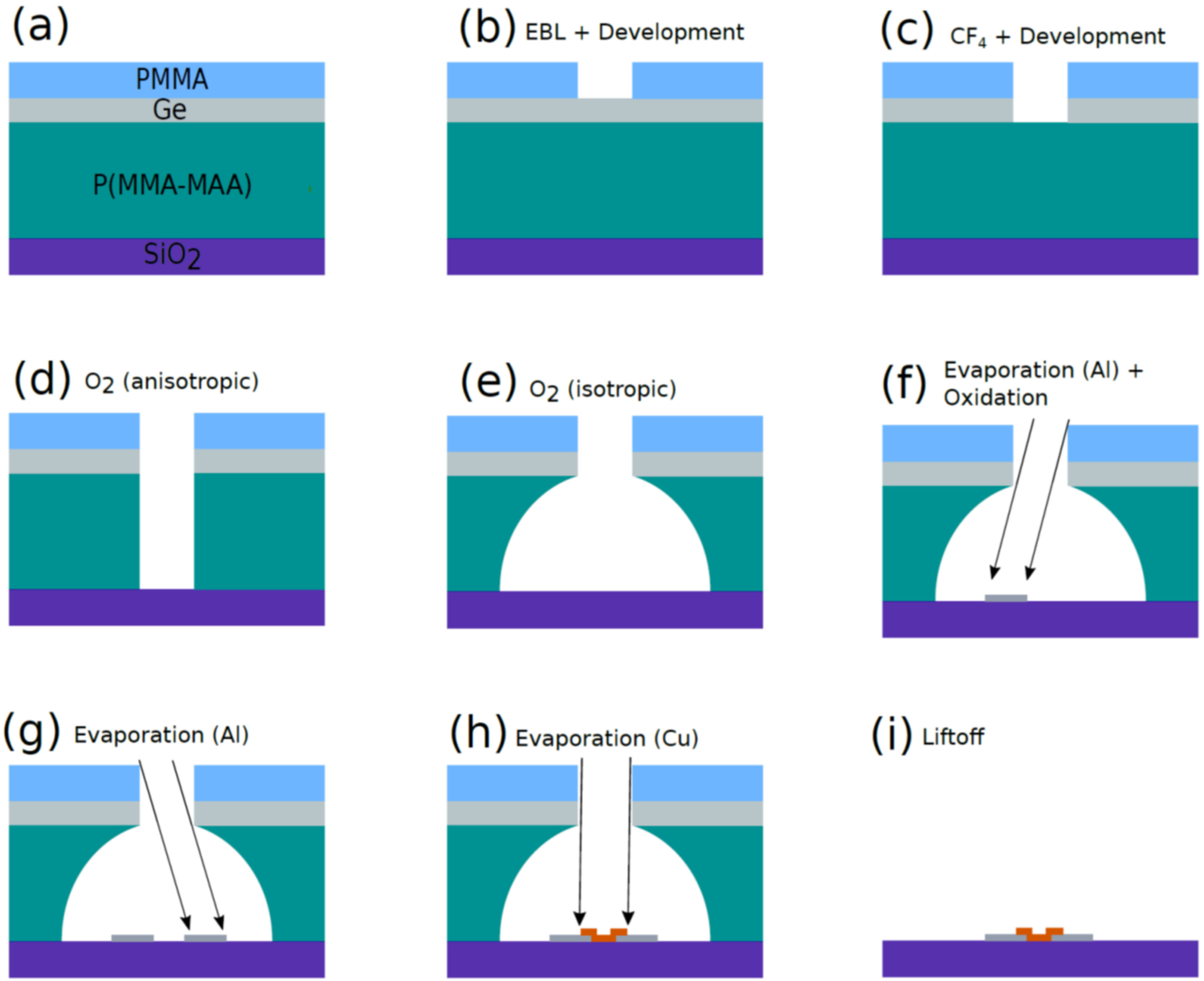
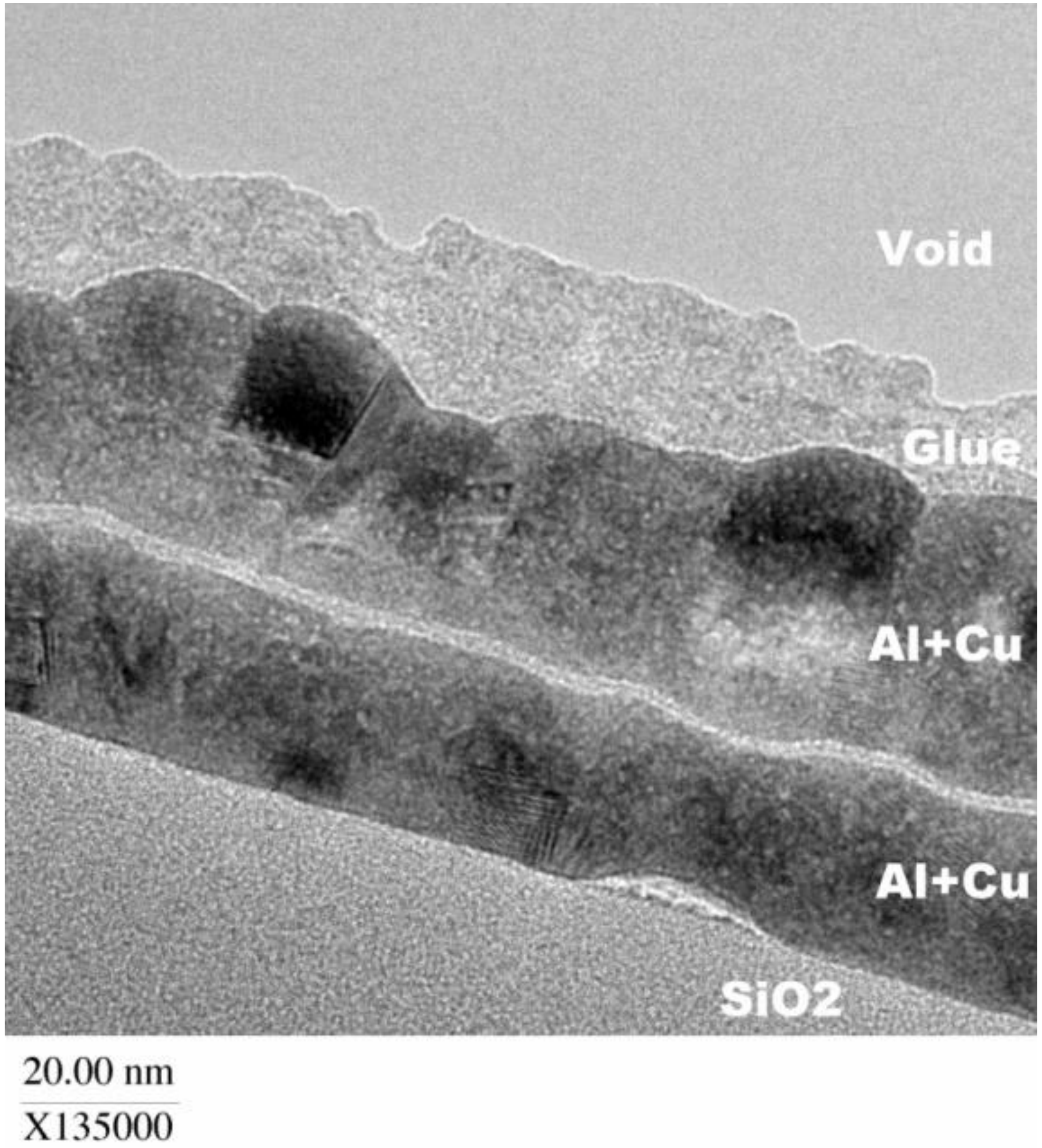
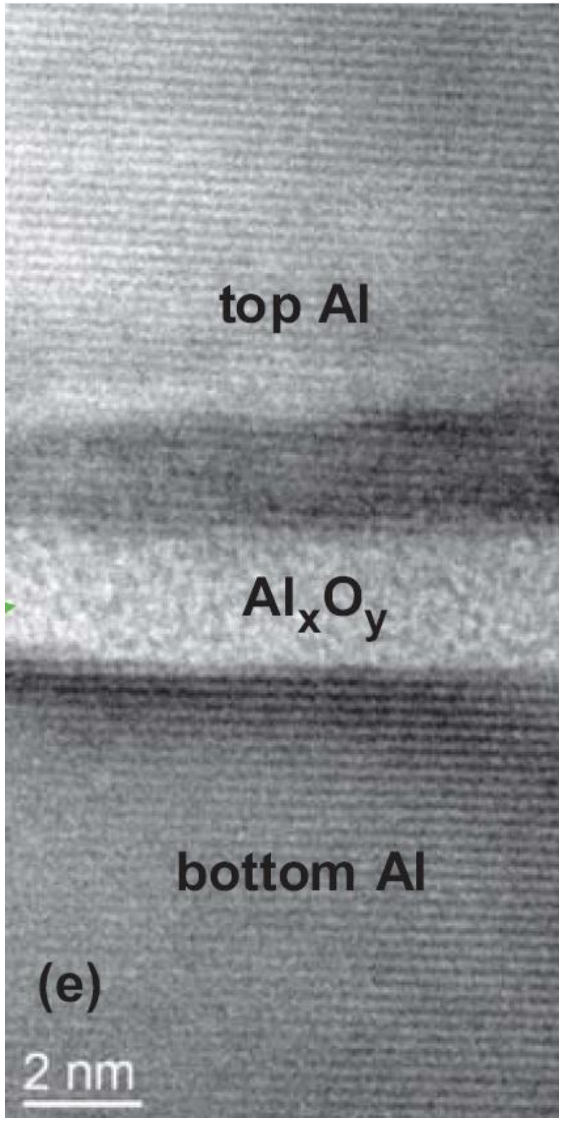
Sample fabrication



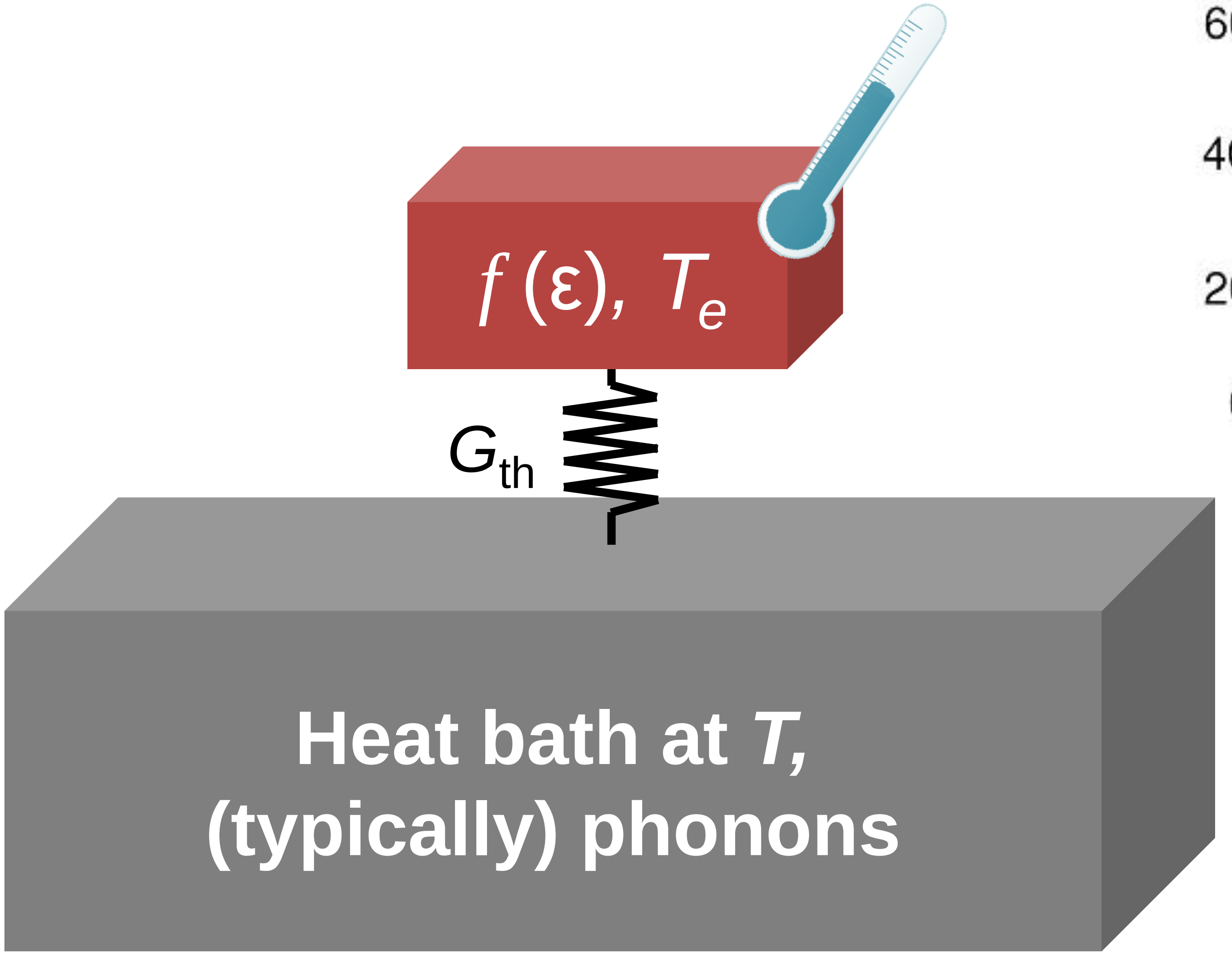
Tunnel barrier

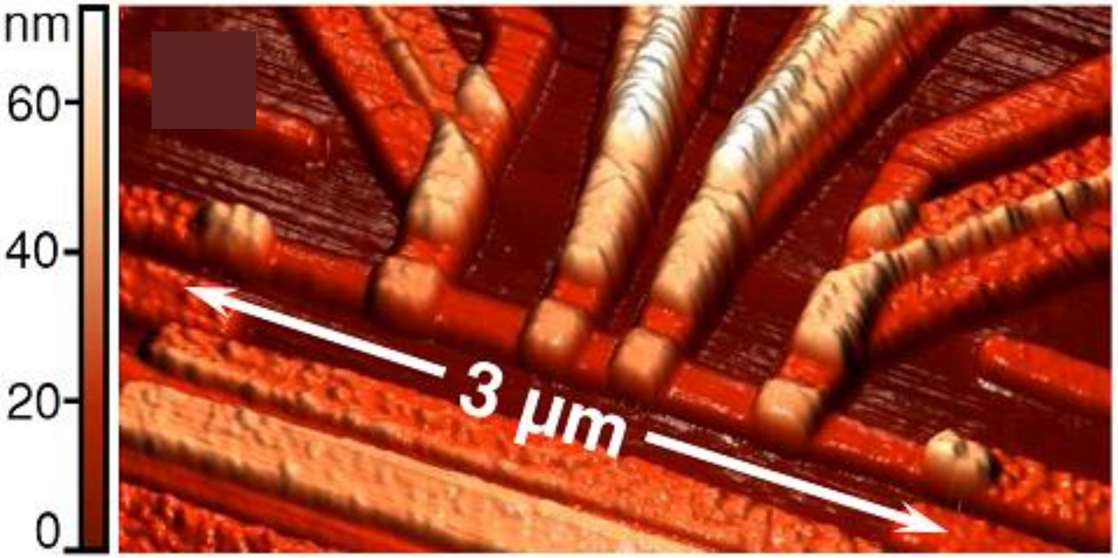


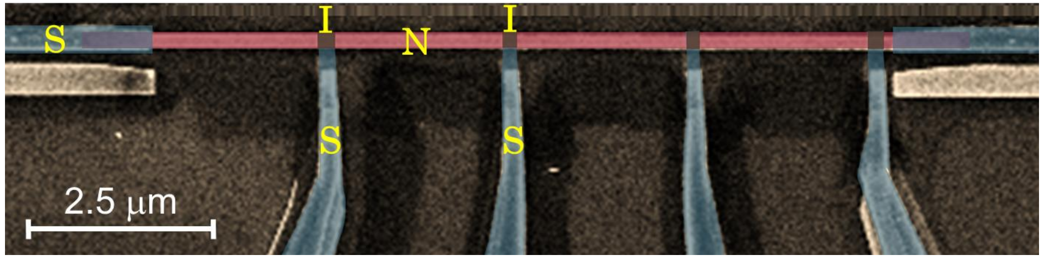


Examples of aluminium-oxide tunnel barriers

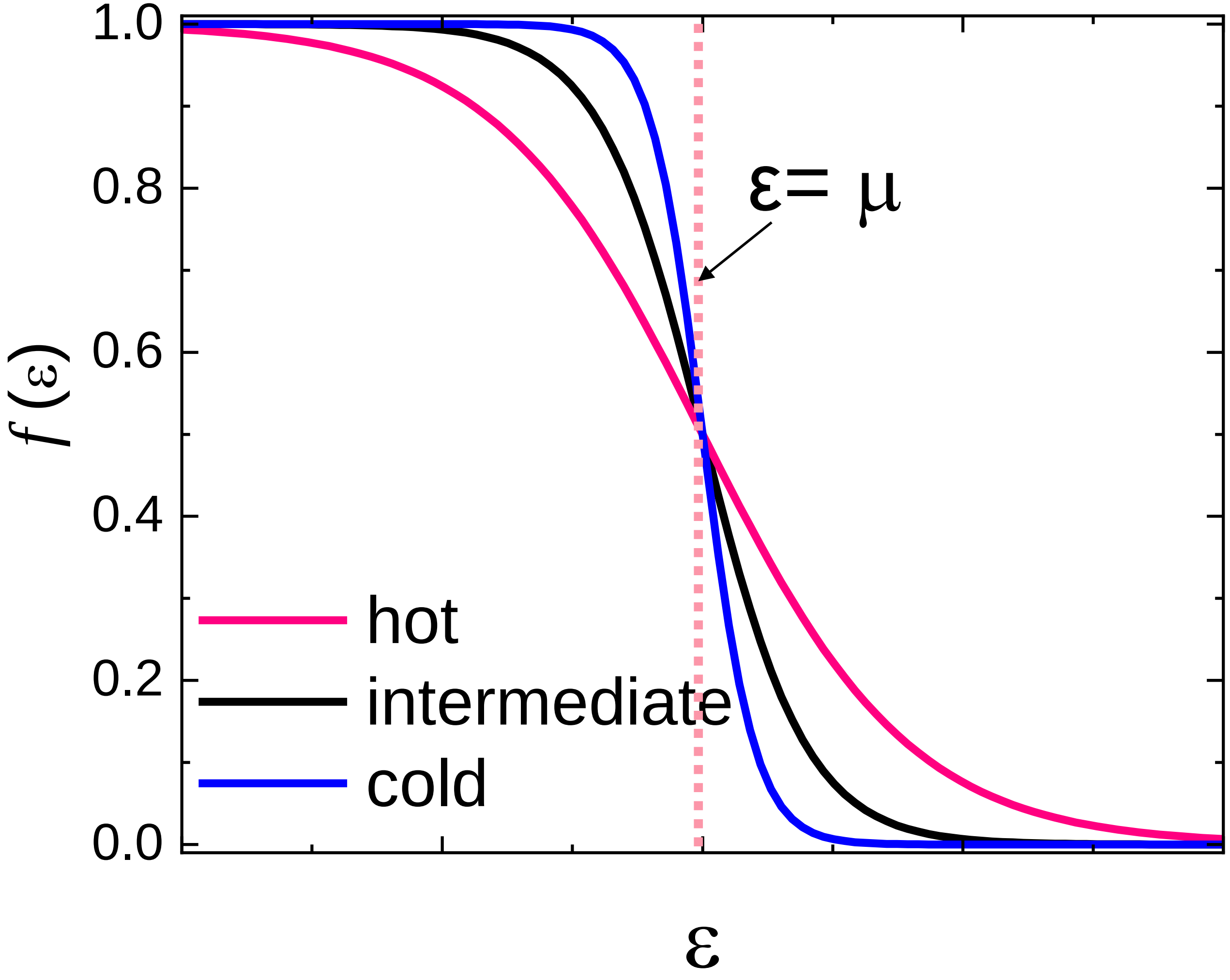
Generic thermal model for an electronic conductor

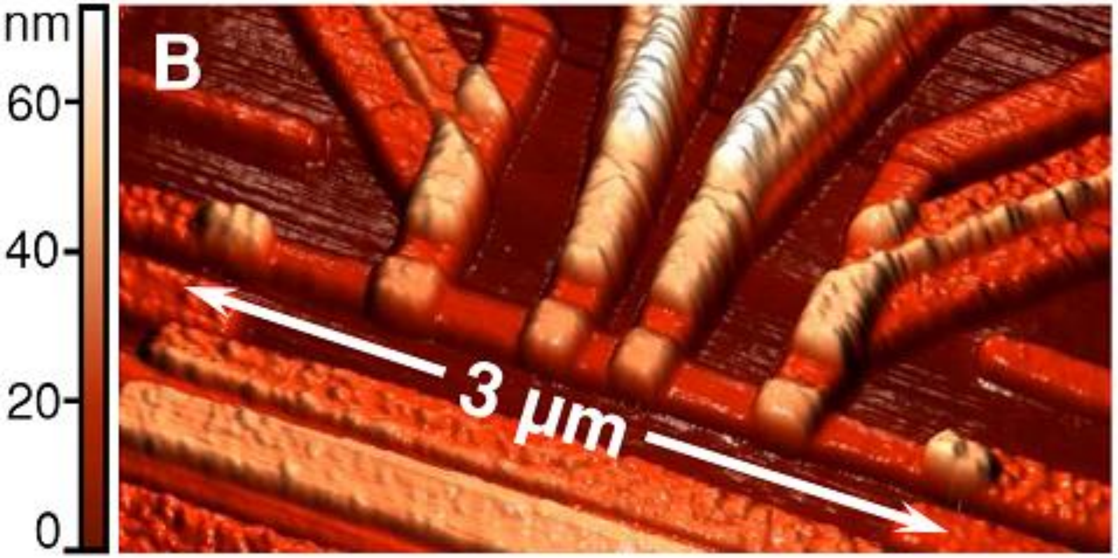






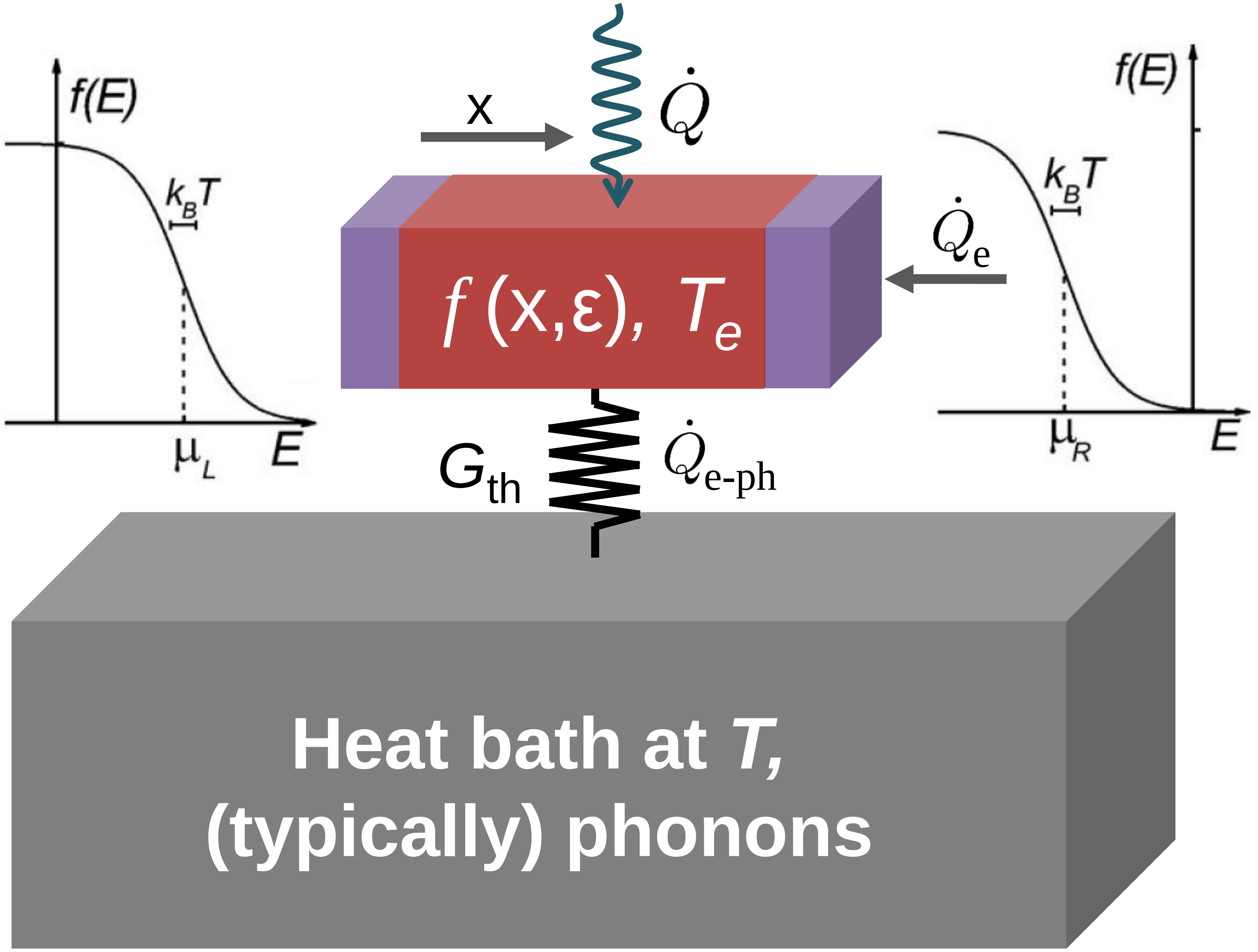
Temperature in an electronic device

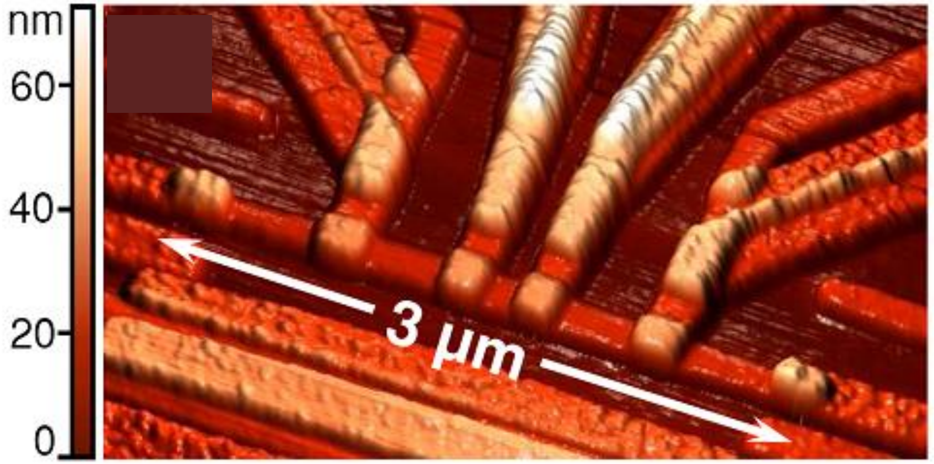




$$f(\epsilon) = \frac{1}{1 + e^{\beta(\epsilon - \mu)}}$$

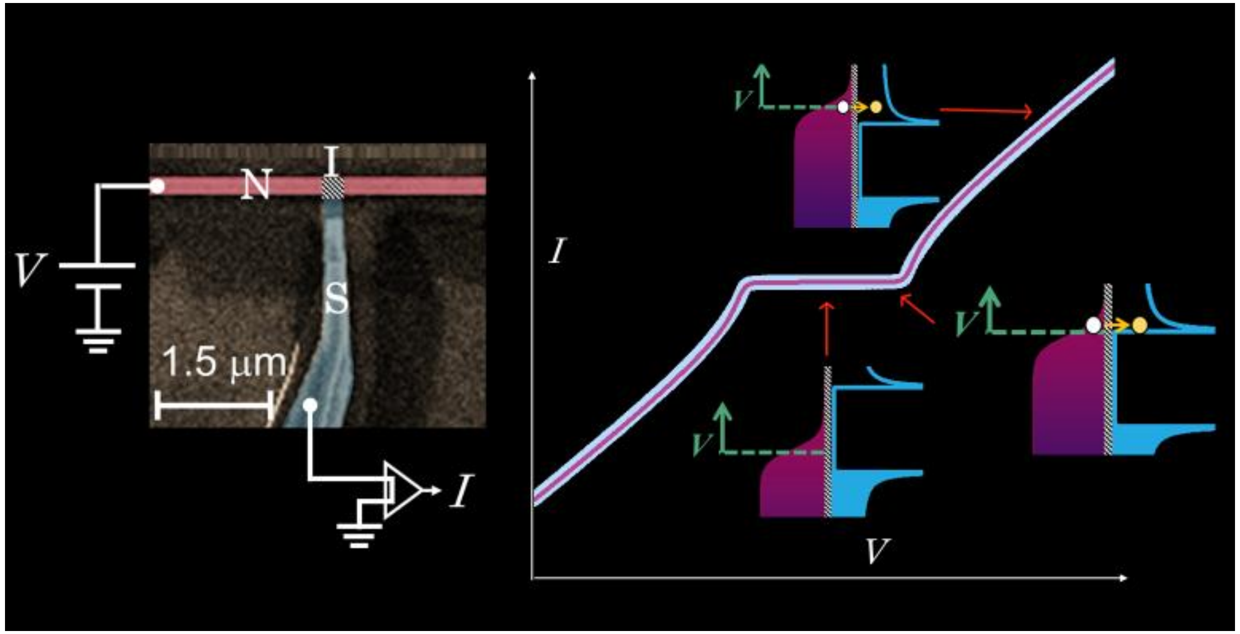
Generic thermal model for an electronic conductor

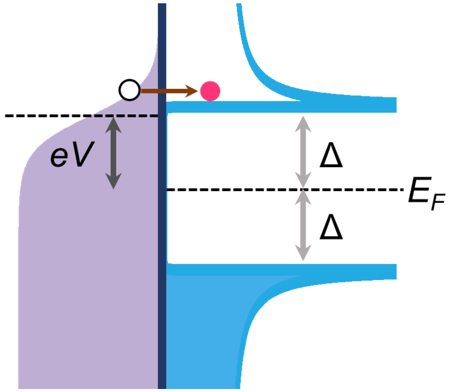




Separation of time scales:
$\tau_{e\text{-}e} < 10^{-9}$ s, $\tau_{e\text{-}ph} > 10^{-6}$ s

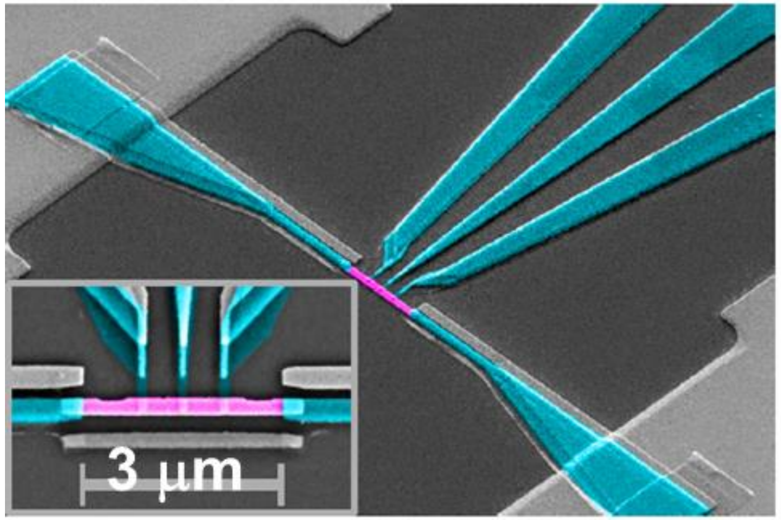
Normal-Metal – Insulator – Superconductor
NIS tunnel junction





$$I = \frac{1}{eR_T}\int d\epsilon\, n_S(\epsilon)[f_S(\epsilon) - f_N(\epsilon + eV)]$$

$$I(-V) = -I(V)$$

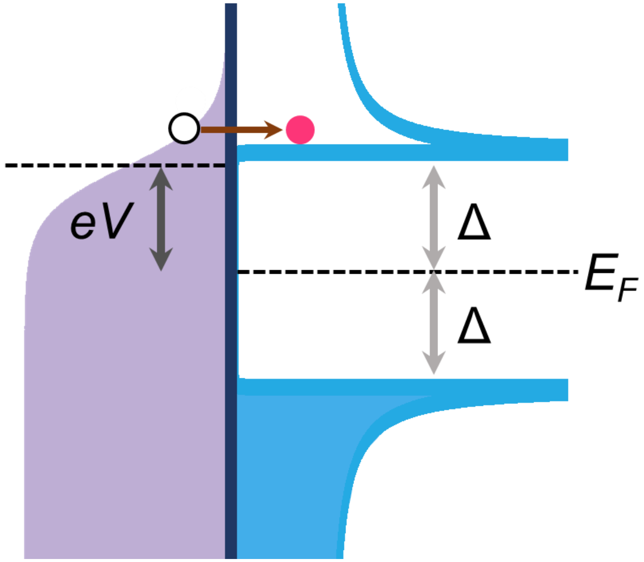


$$\boxed{I = \frac{1}{2eR_T}\int d\epsilon\, n_S(\epsilon)[f_N(\epsilon - eV) - f_N(\epsilon + eV)]}$$

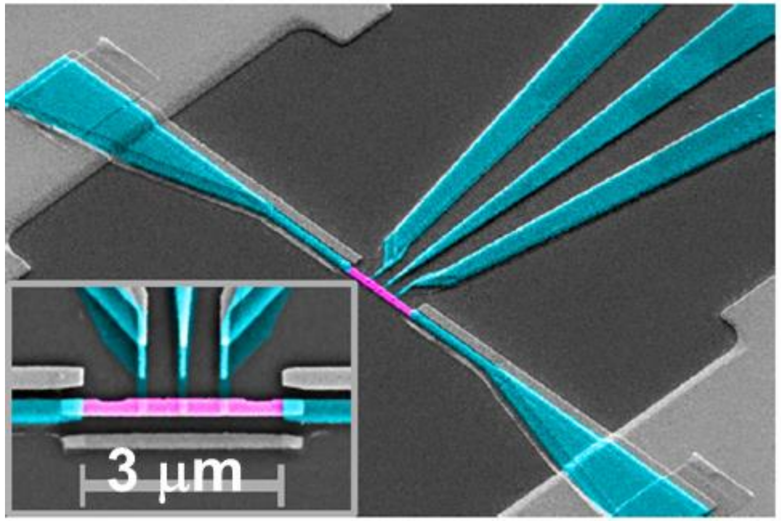
Probes electron temperature of N electrode (and not of S!)

Feshchenko et.al., Phys. Rev. Appl. 4, 034001 (2015)
Giazotto et al., Rev. Mod. Phys. 78, 217 (2006)

Normal-Metal – Insulator – Superconductor
NIS tunnel junction

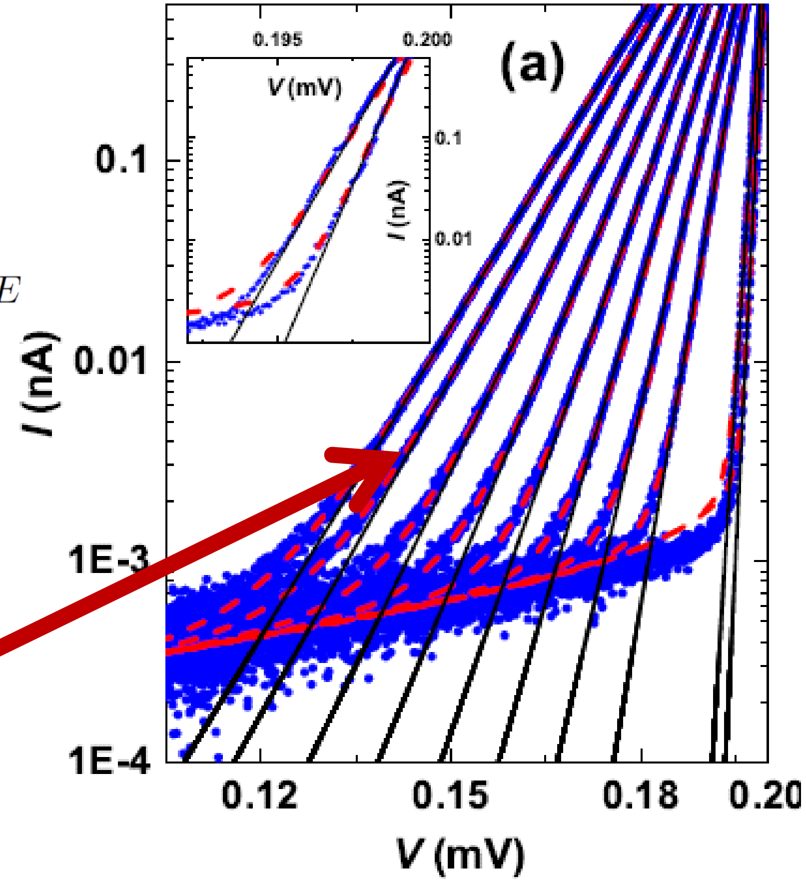


$$I = \frac{1}{2eR_T}\int n_S(E)[f_N(E-eV) - f_N(E+eV)]dE$$



$$I \approx I_0 e^{-(\Delta - eV)/k_B T}$$

$$\frac{\mathrm{d}\ln(I/I_0)}{\mathrm{d}V} \approx \frac{e}{k_B T}$$



Feshchenko et.al., Phys. Rev. Appl. 4, 034001 (2015)
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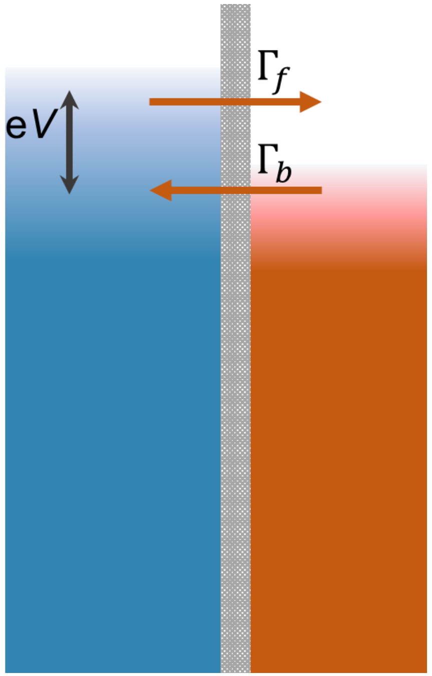
Heat current in tunneling

Phenomenological derivation



$$\dot{Q}_{L\to R} = |\mathcal{T}|^2 \int d\epsilon(\epsilon - eV)\ n_L(\epsilon - eV) n_R(\epsilon) f_L(\epsilon - eV)[1 - f_R(\epsilon)]$$

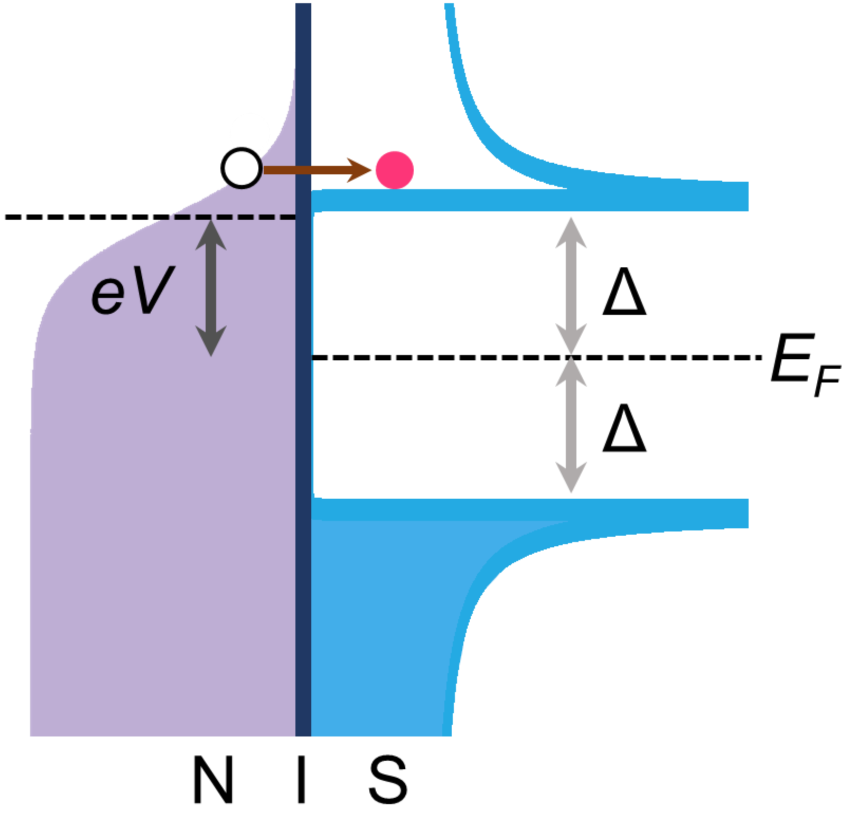
$$\dot{Q}_{R\to L} = |\mathcal{T}|^2 \int d\epsilon(\epsilon - eV)\ n_L(\epsilon - eV) n_R(\epsilon) f_R(\epsilon)[1 - f_L(\epsilon - eV)]$$

The net heat current out from L electrode:

$$\begin{aligned} \dot{Q}_L &= \dot{Q}_{L\to R} - \dot{Q}_{R\to L} \\ &= \frac{1}{e^2 R_T} \int d\epsilon(\epsilon - eV)\ n_L(\epsilon - eV) n_R(\epsilon)[f_L(\epsilon - eV) - f_R(\epsilon)] \end{aligned}$$

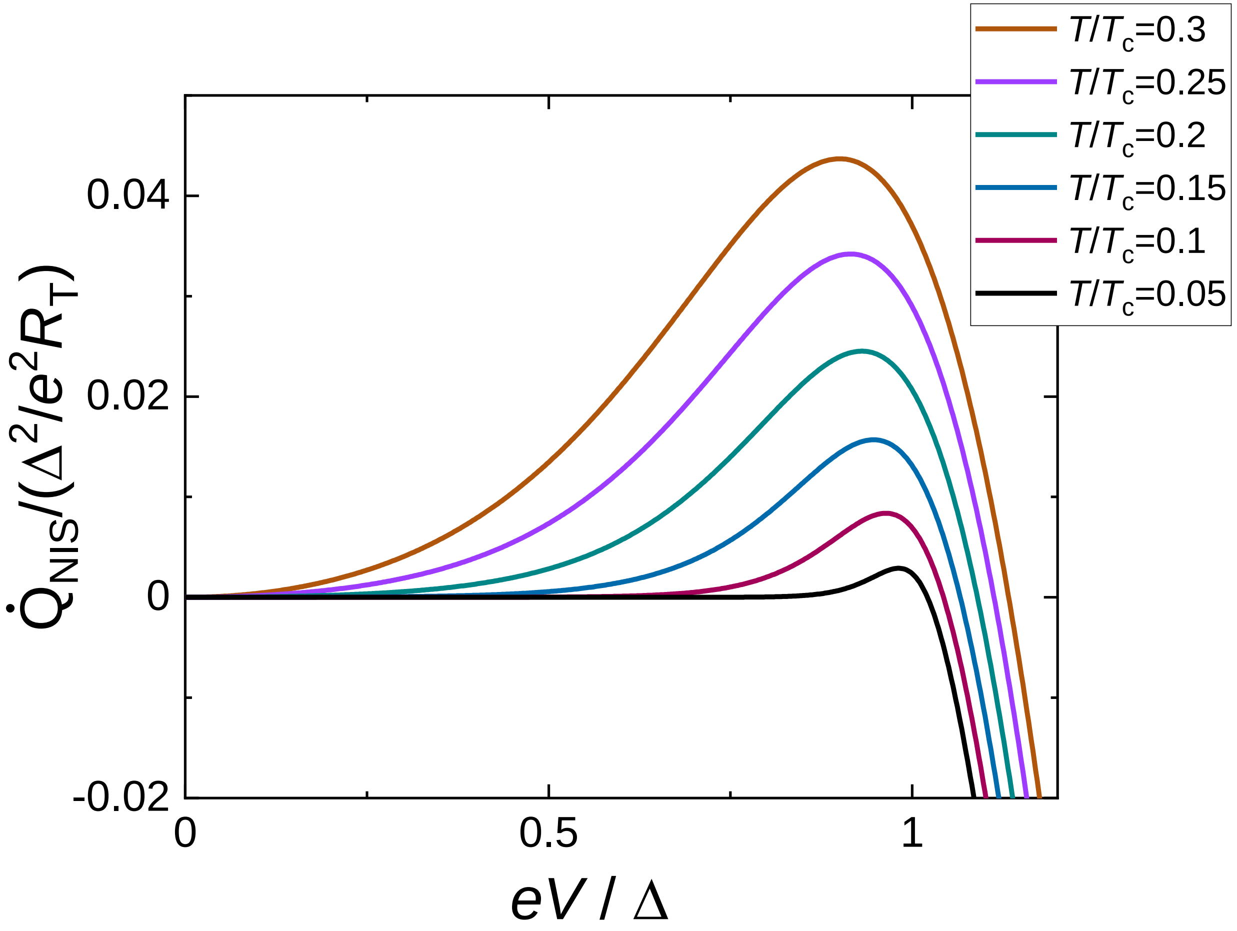
Example 1: for NIN junction (constant DOSes), $\dot{Q} = -\frac{V^2}{2R_T}$, meaning that Joule power is distributed equally between L and R.
Example 2: Wiedemann-Franz law

NIS junction



Cooling power of a NIS junction:

$$\dot{Q}_{NIS} = \frac{1}{e^2 R_T}\int_{-\infty}^{\infty} d\epsilon\ (\epsilon - eV) n_S(\epsilon)\{f_N(\epsilon - eV) - f_S(\epsilon)\}$$



Maximal cooling power is reached at V ≅ Δ/e for first approximation:

$$\dot{Q}_{NIS} \approx 0.63\frac{\Delta^2}{e^2 R_T}\left(\frac{k_B T_N}{\Delta}\right)^{\frac{3}{2}}$$

Low-temperature thermometry

- The thermometer should have a wide operating temperature range and should be insensitive to environmental changes, such as magnetic fields.
- The property x to be measured must be easily, quickly, and exactly accessible to an experiment.
- The temperature dependence of the measured property, $x(T)$ should be expressible by a reasonably simple law
- The sensitivity $(\Delta x/x)/\ (\Delta T/T)$ should be high
- The thermometer should reach equilibrium in a “short” time, both within itself and with its surroundings whose temperature it is supposed to measure. Therefore it should have a small heat capacity , good thermal conductivity and good thermal contact to its surroundings. In particular, the thermal contact problem is ever present for thermometry at $T \leq 1$ K.
- The relevant measurement should introduce a minimum of heat to avoid heating of the surroundings of the thermometer and of course, above all, heating of itself; this becomes more important the lower the temperature.

Frank Pobell, Matter and methods at low temperatures, Third Edition, Springer, 2007.