Crossover from tunneling to Ohmic (incoherent) transport in a correlated nanostructure

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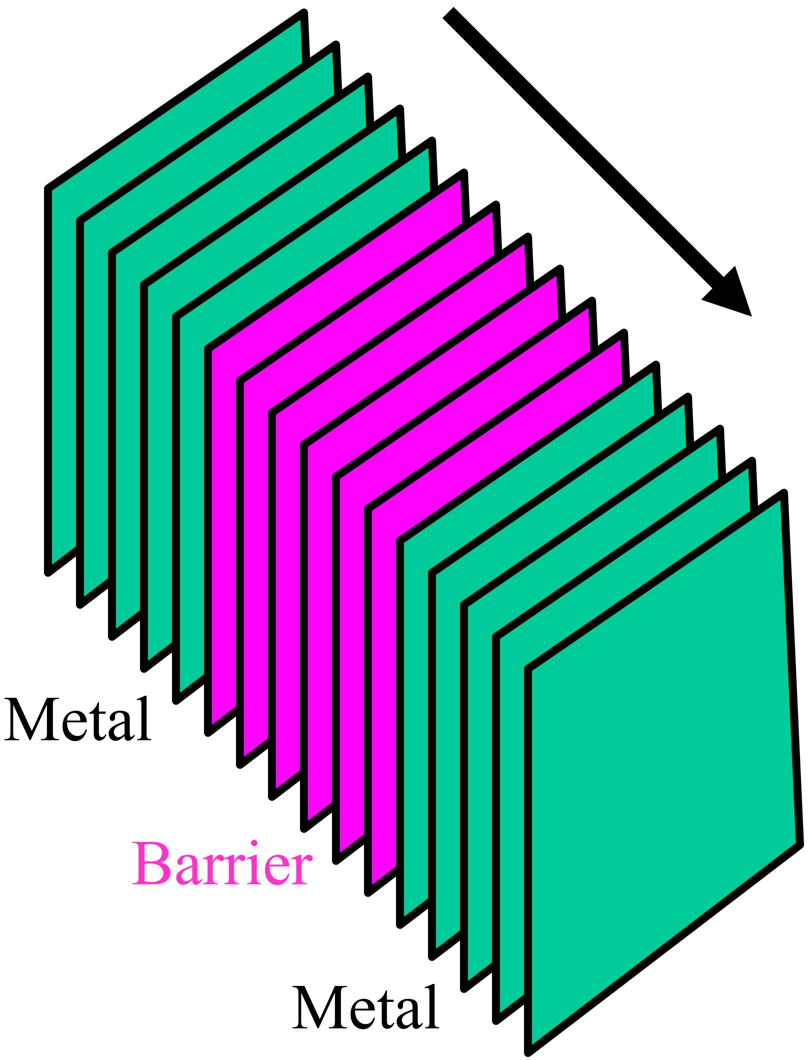
Tunnel junctions in electronics



- Sandwich of metal-barrier-metal with current moving perpendicular to the planes
- Nonlinear current-voltage characteristics
- Josephson junctions, diodes, spintronic devices, etc.
- Band insulators: AlO_x MgO
- Correlated materials: FeSi, $SrTiO_3$
- Near MIT: V_2O_3, Ta_xN

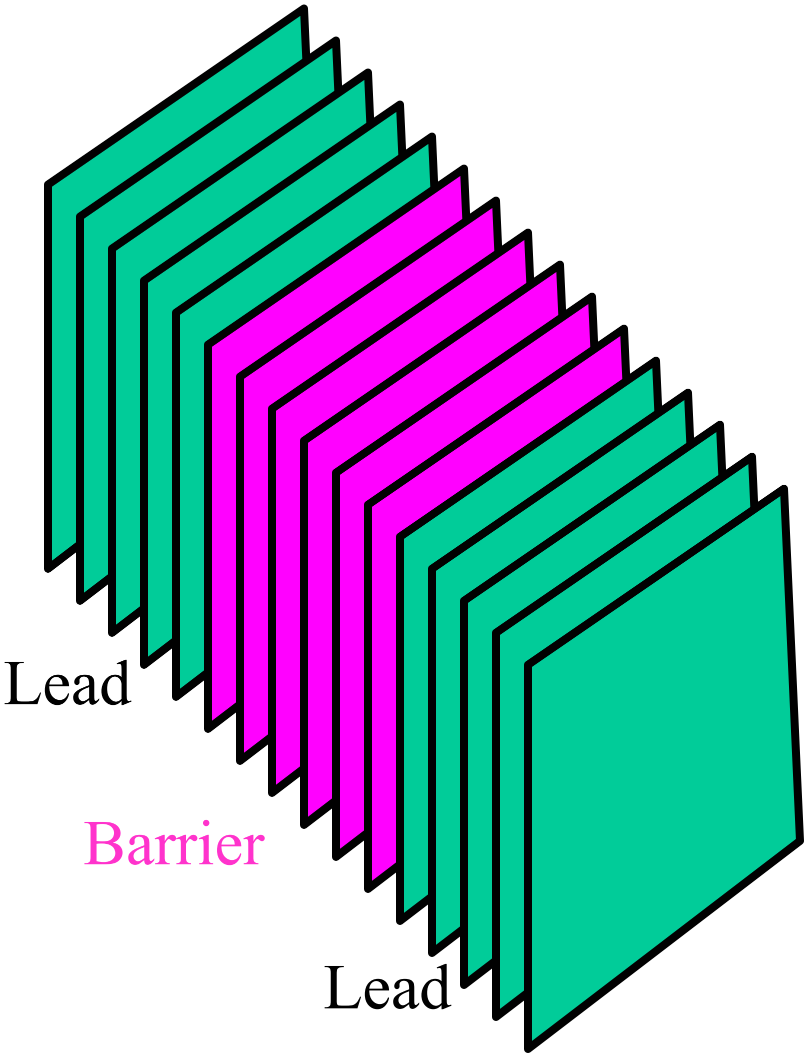
Theoretical Approaches

- Ohm's law: $R_n=\rho A/L$, holds for bulk materials
- Landauer approach: calculate resistance by determining the reflection and transmission coefficients for quasiparticles moving through the inhomogeneous device ($G_n=2e^2T/h[1-T]$)
- Works well for ballistic metals, diffusive metals, and infinitesimally thin tunnel barriers ("delta functions").
- Real tunnel barriers have finite thickness---quasiparticle picture breaks down inside the insulating barrier.
- As the barrier thickness approaches the bulk limit, the transport become incoherent (thermally activated) in an insulator.

Need a theory that can incorporate all forms of transport (ballistic, diffusive, and incoherent, and correlated) on an equal footing

- A self-consistent recursive Green's function approach called dynamical mean field theory can handle all of these wrinkles.

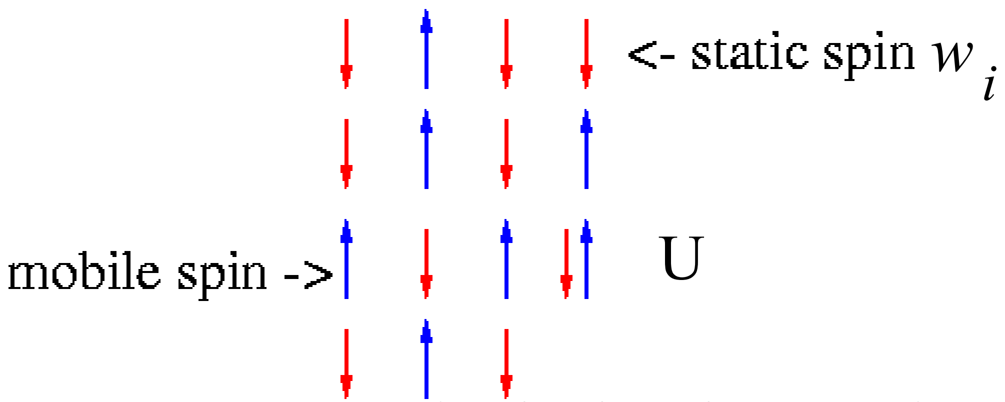
Our model



- The metallic leads can be ballistic normal metals, mean-field theory ferromagnets, or BCS superconductors.
- Scattering in the barrier is included via charge scattering with "defects" (Falicov-Kimball model)
- Scattering can also be included in the leads if desired.

Spinless Falicov-Kimball Model

$$H = -\frac{t}{2\sqrt{d}}\sum_{<i,j>} c_i^{\dagger} c_j + E\sum_i w_i + U\sum_i c_i^{\dagger} c_i w_i$$

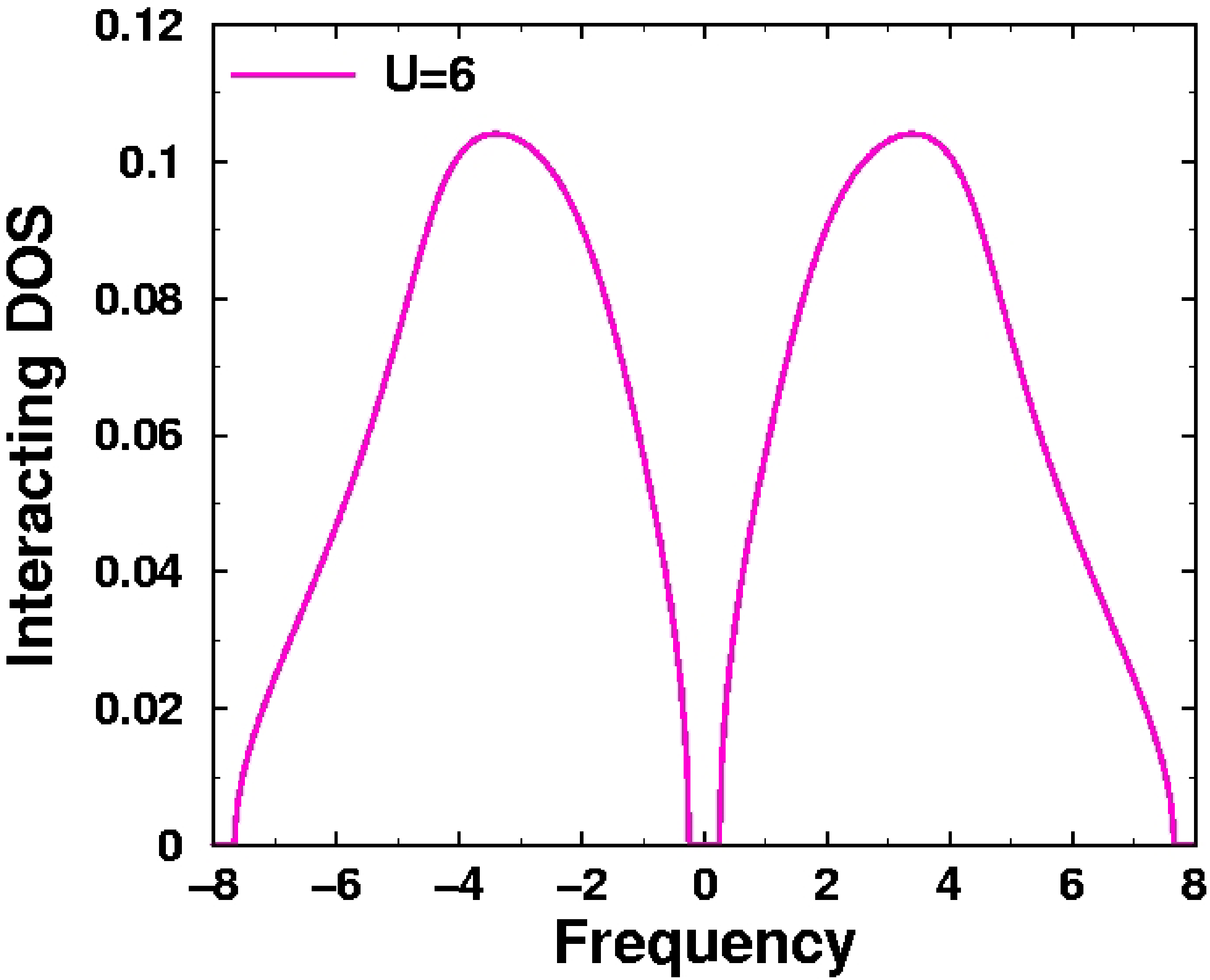


•**exactly solvable model** in the local approximation using dynamical mean field theory.

•possesses homogeneous, commensurate/incommensurate CDW phases, phase segregation, and **metal-insulator transitions**.

•*A self-consistent recursive Green's function approach solves the many-body problem*

Near the MIT (U=6)



If we take t=0.25ev then W=3ev, and the gap size is about 100mev.

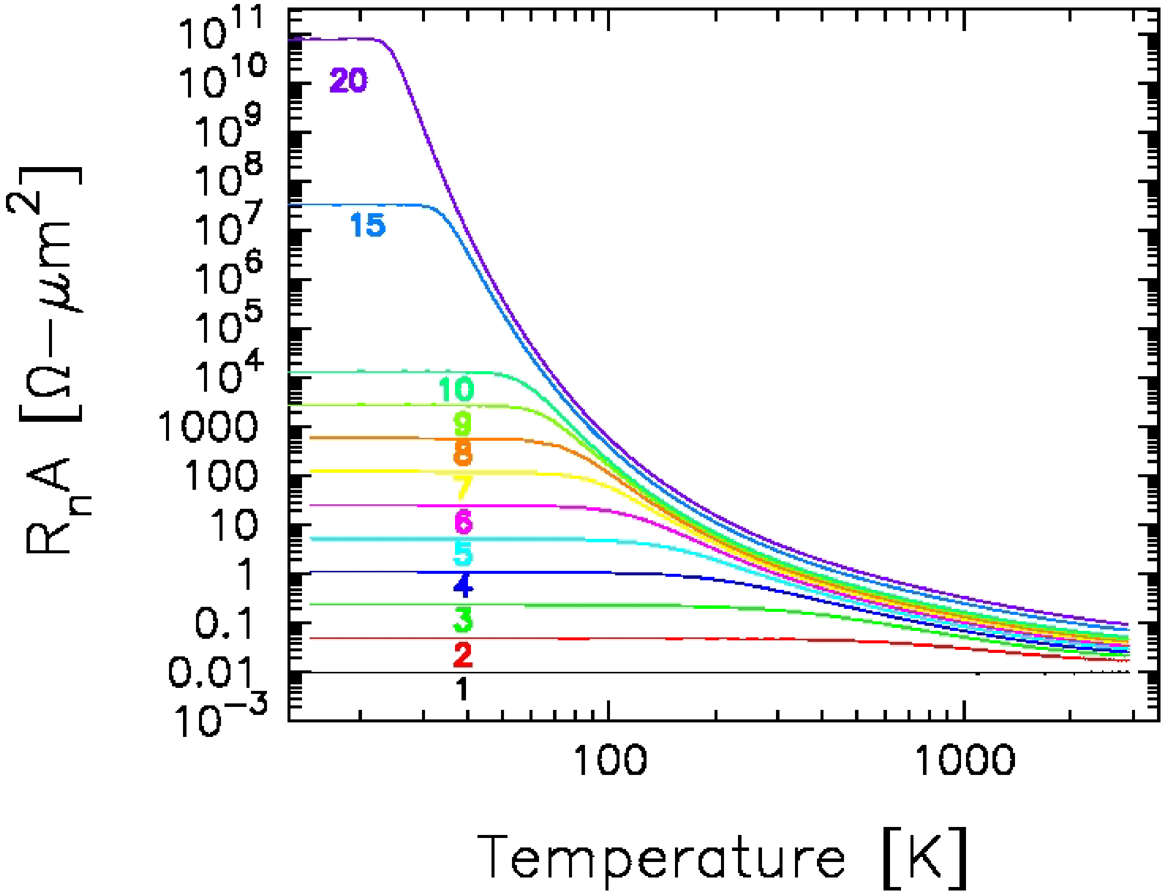
This is a correlated insulator with a small gap, close to the MIT.

Junction resistance

- The linear-response resistance can be calculated in equilibrium using a Kubo-Greenwood approach.
- We must work in real space because there is no translational symmetry.
- Rn is calculated by inverting the conductivity matrix and summing all matrix elements of the inverse.

Resistance for U=6 (correlated insulator)

- Resistance here clearly shows tunneling plateaus, and a strong temperature dependence in the incoherent regime.



Thouless energy

- The **Thouless energy** measures the quantum energy associated with the time that an electron spends inside the barrier region of width L (Energy extracted from the resistance).

$$E_{Th} = \hbar / t_{Dwell}$$

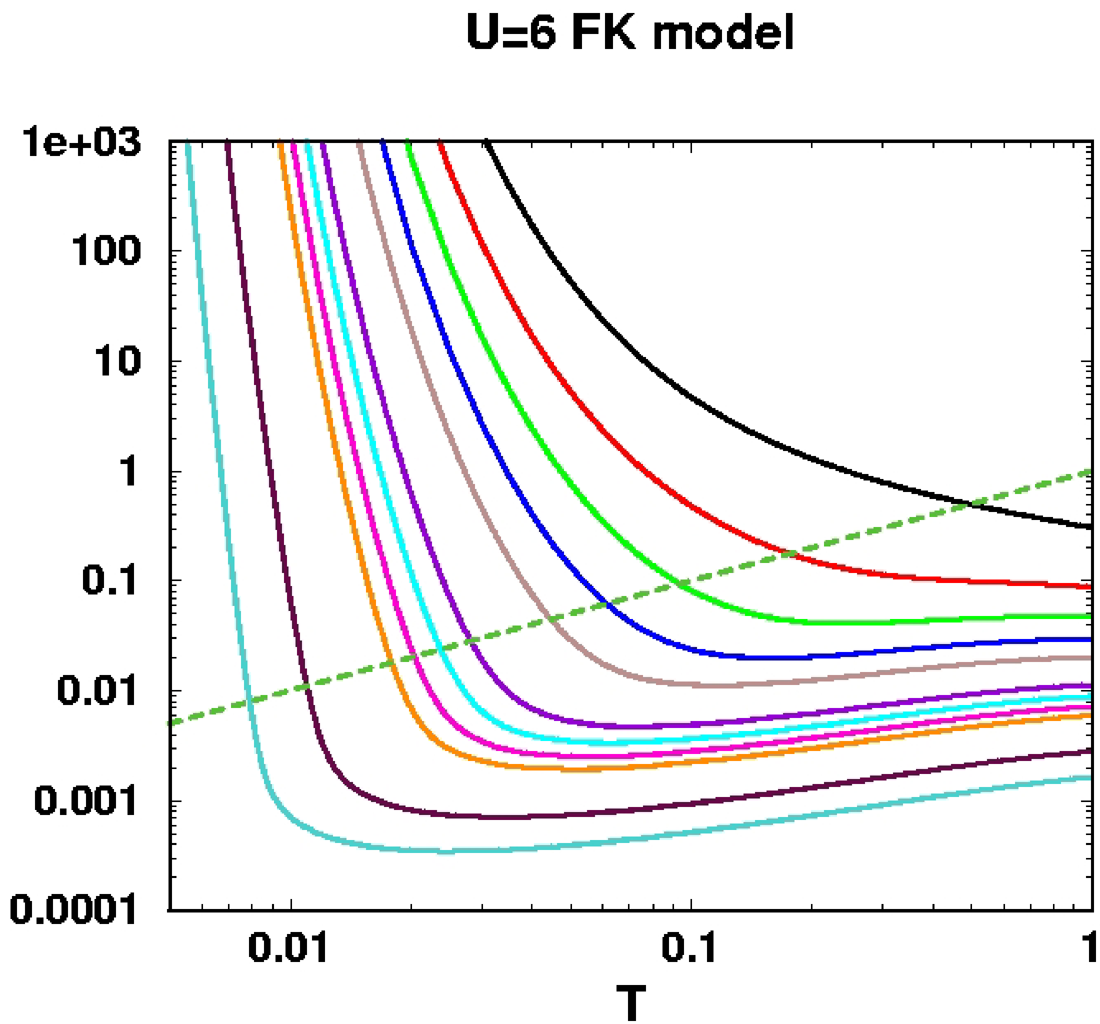
- A **unifying form** for the Thouless energy can be determined from the resistance of the barrier region and the electronic density of states:

$$E_{Th} = \frac{\hbar}{2e^2 \int d\omega N(\omega) \frac{-df(\omega)}{d\omega} R_N A L}$$

- This form produces both the **ballistic** $E_{Th} = \hbar v_F^N / \pi L$ and the **diffusive** $E_{Th} = \hbar D / L^2$ forms of the Thouless energy.

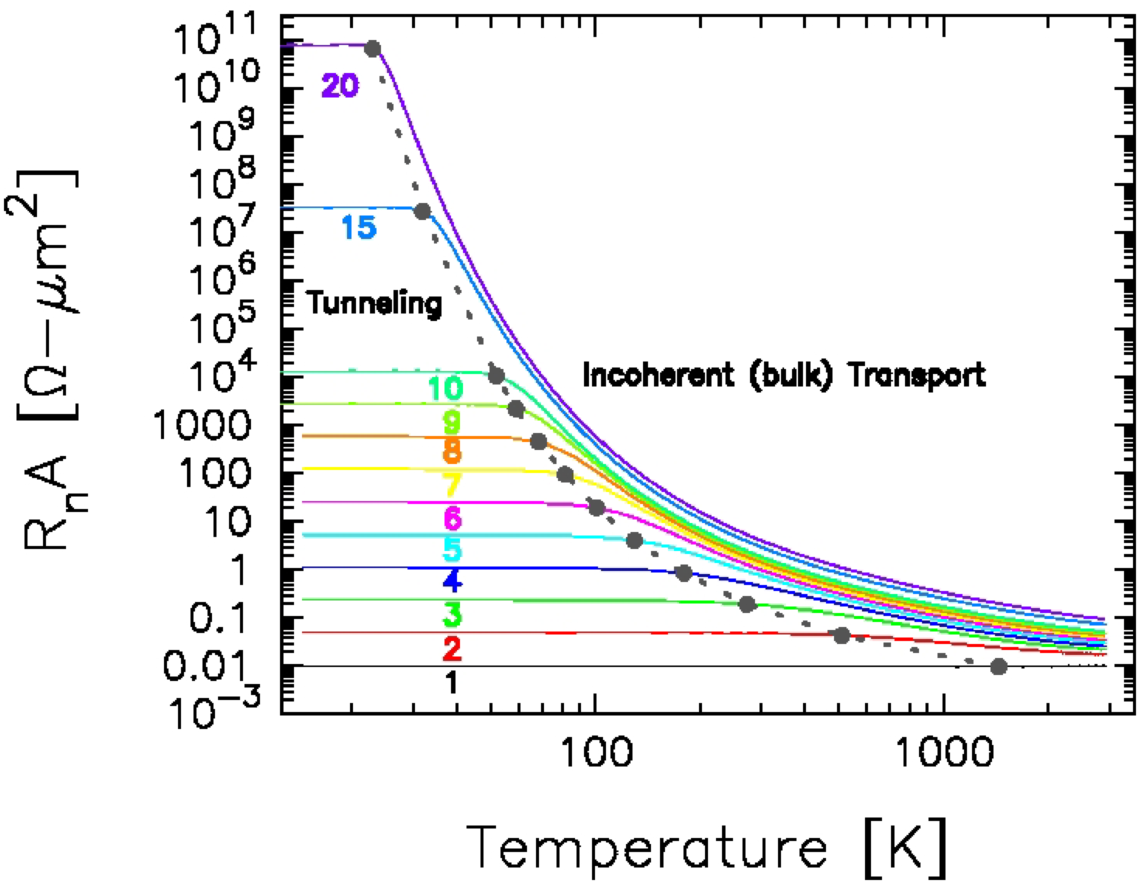
Temperature dependence

The Thouless energy depends strongly on temperature for the insulator. Here plots for different thickness barriers show similar temperature dependence. the dashed line is where the Thouless energy equals the temperature.



Temperature dependence (II)

The Thouless energy appears to be able to determine the transition From tunneling to incoherent transport as a function of temperature. Note that this temperature is not simply related to the energy gap/barrier.



Tunnel diagnostic/engineering

- The Thouless energy and the crossover point can be estimated with the low temperature resistance and the bulk DOS of the insulator, since Rn has weak temperature dependence in the tunneling regime.
- The junction can be optimized for tunneling properties if the operating temperature and barrier properties are known.
- It may be possible to use the Thouless energy to investigate the presence of pinholes as well.

Benefits of junctions near a MIT

- Thicker barriers are likely less susceptible to pinholes, and may not require as flat interfaces.
- Junction reproducibility on a chip may be easier with a thicker barrier.
- Likely to have a smaller junction capacitance (faster switching for the same value of the resistance).