Scanning Tunneling Microscopy (I) [Yazdani]

- Reasons for local probe:
  - Randomly doped system can be inhomogeneous
  - Systems close to transition may segregate into different phases
  - Can learn about correlation by measuring response to defects
  - Search for "fluctuating" order

- Length Scales:
  - Inter-atomic ~Å
  - e⁻ wavelength: good metal ~Å, bad metal ~10 Å, semiconductor ~100 Å
  - Correlation length: 100 - 1000 Å
  - Phase domain: 1000 Å ~ μm

- Tunneling junction by Giaever (1963) — Aluminum-oxide:
  - Al₂O₃ is "self-limiting" — the layer stops growing at ~30 Å

- Tunneling rate governed by Fermi's golden rule:
  - \( I(V, R) \propto \left| \sum_{\text{sample}} \epsilon \right| \right|^2 \frac{dE}{dE} \)
  - Assume tunneling is elastic
  - It is possible to use inelastic processes for measurement too.

- Vacuum Tunneling: Binning & Rohrer (IBM-1980)
  - Oxide insulating layer is highly varying in space
  - The idea was using tunneling for imaging data by to Russell Young (1972)
  - Key idea: is to use piezoelectric elements to move tips
  - \( V \sim 1\, \text{Å}, \text{stable voltage} \sim \text{mV} \)
  - Voltage noise not a problem.
• Tip & sample in vibration isolation. Feedback loop to adjust tunneling current constant.
  ▶ Vacuum between tip/sample ~ 5-6 Å
  ▶ First example: Si shows 7×7 pattern on (111) surface.

• Building STM.
  ▶ Ultra high vacuum (~10^{-6} torr), vibration isolation, cryogenics
  ▶ Main problem: noise associated with building vibration (~6 Hz),
    ac conditioning & pump noise, etc.

• Prefer single crystal, & cleave to nice surface, heat to remove defects, etc.

• Example: Cu (111)
  ▶ Surface states manifest as waves, & surface defects
    create dips in density.

• How clean vacuum needs to depend on sample (e.g., Au is tolerant).

• Can fix on particular pixel and measure full \( \frac{dI}{dV} \) curve, then
  scan through pixels.
  ▶ Caveat in data: matrix element \( |M|^2 \) need be almost invariant
    across space and voltage.

• Example: scattering through hard wall
  ▶ From fitting to one-particle wavefunction, can get
    dephasing scale as function of energy.

• Example: building particle-in-a-box (but leaky box!)
  & observe standing wave of surface states.
- STM on Ge\text{As} (110) surface
  - easy to cleave—exposed to O/H/V.
  - states at +1.6V dominated by Ga, states at +1.6V dominated by As \rightarrow able to distinguish atoms.
  - Dopants create a hydrogenic electronic density profile on top of original profile (it can get more complicated).
  - However, STM tip can modify (band) semiconductor band structure.

- Example: high-T\textsubscript{c} ferromagnet in Mn doped Ga\text{As}
  - Mn creates acceptor states \& also institutional defects.
  - STM indicates that dopant occupy random sites \& can have very different local environment.
  - It is possible to do spin polarized STM to observe magnetism directly.

- Example: STM on superconductor
  - data back to Giaever
  - detail analysis show bump \& wiggles
    \rightarrow indicate strong coupling between e\textsuperscript{+} \& phonon.
  - Conclusively shows that conventional SC. is phonon mediated.

- Example: STM on NbSe\textsubscript{2}
  - STM can reveal SDW. It also gives gap measurement.

- Other than mechanics, resolution of STM depends on temperature, since Fermi function enters into gap \& I
STM can be used to show vortices in SC.

- The vortex in NbSe₂ shows hexagonal structure, consistent with Bδ eqn.

STM can also show effect of a single magnetic impurity in SC.

- Theoretically, it bounds a quasiparticle (mixed e-/hole) to it.

- Data:

- Picture: spin-dependent potential \( \Rightarrow \) trap quasiparticles

- Vortex survives > coherent length while impurity effect generally decay quickly.

Spin-polarized STM:

- Take a usual tip, add a thin magnetic layer on top of it.

- Observed layered magnetization on Cr (an antiferro).

- The tip is more magnetically sensitive at specific energy.

- So far measurement focuses on simpler systems.

Inelastic STM:

- C₂H₂ on top of Cu (100). See jump at energy ideal with vibrational excitation of C₂H₂.