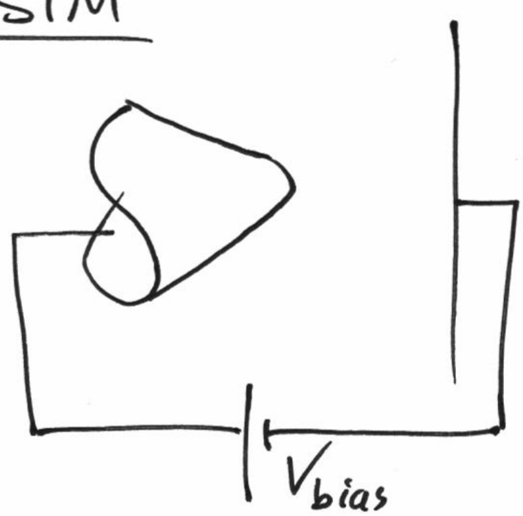
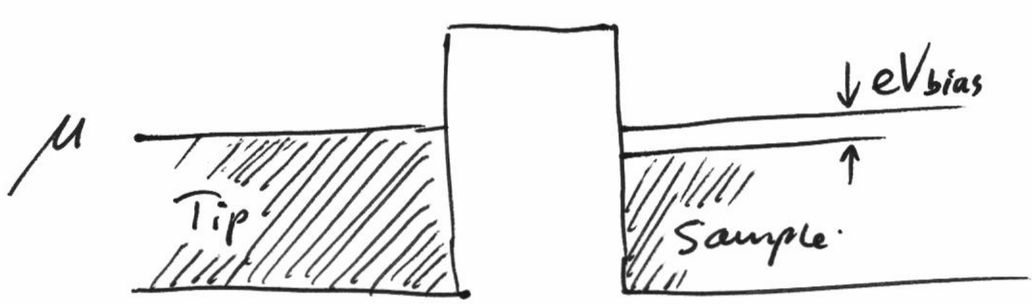
TRANSPORT PHENOMENA INVOLVING TUNNELING

- Scanning tunneling microscopy (STM)
- Superconducting Quantum Interference Devices (SQUIDs)
  [used for detecting extremely small $\vec{B}$-fields]
- Tunnel diodes
- a.c. Josephson effect (tunneling of Copper pairs)
- Tunnel Magneto Resistance devices (TMR)
  [used in disk drives]
- Leaky gates in modern transistors.

EXAMPLE 1: STM



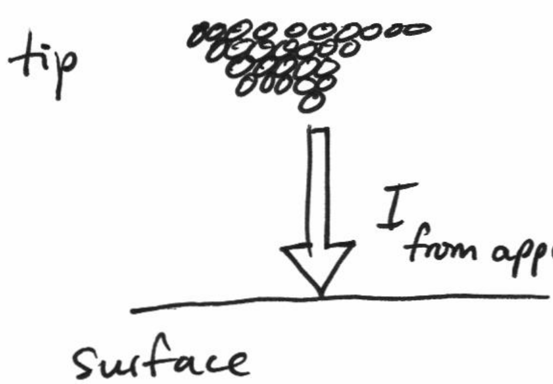


Tunneling is an elastic process. e^- leaves an occupied state of energy E and enters an unoccupied state of equal energy.

$$I_{tunnel} \propto \int_0^\infty D_{tip}(E) D_{sample}(E) \left[f_{tip}(E) \left(1 - f_{sample}(E) \right) \right] P_{tunnel}(E) \, dE$$

[Note: This eq^n does not address the attempt freq, how frequently e⁻s try to tunnel]

HIGH SPATIAL RESOLUTION OF STM



$I_{from\ appex} \gg$ all other tunnel currents.

$$\frac{I_{from\ appex}}{I_{other}} \cong \frac{P_{tunnel}(x_0)}{P_{tunnel}(x_0 + 3\text{Å})}$$

$$= \frac{\exp[-2k x_0]}{\exp[-2k(x_0 + 3\text{Å})]}$$

$$= \exp[-2k \cdot 3\text{Å}]$$

where $k = \frac{1}{\hbar}\sqrt{2m(V_0 - E)}$

$= \frac{1}{\hbar}\sqrt{2m(3\,\text{eV})}$ ← typical number for work fn of a metal.

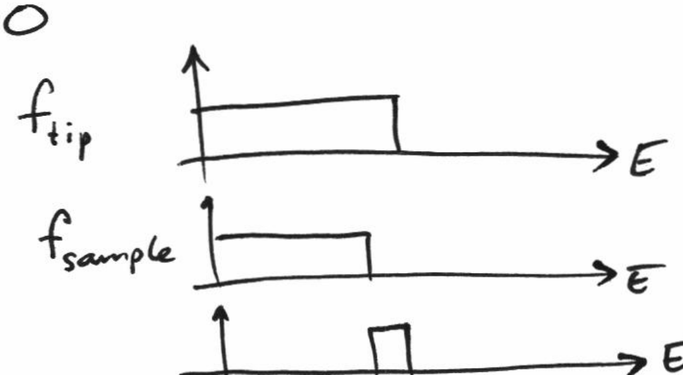
$= 10^{10}\ \text{m}^{-1}$

$$\frac{I_{\text{from apex}}}{I_{\text{other}}} \cong 400$$

SPECTRAL RESOLUTION OF STM

Consider the term $f_{tip}(E)\left(1 - f_{sample}(E)\right)$

when $T = 0$



The integral for I_{tunnel} reduces to

$$I_{tunnel} \propto \int_{\mu}^{\mu + eV_{bias}} D_{tip}(E) D_{sample}(E) P_{tunnel}(E)\, dE$$

If we assume $D_{tip}(E) \approx \text{const}$

$P_{tunnel}(E) \approx \text{const}$

and $D_{sample}(E)$ varies strongly with E

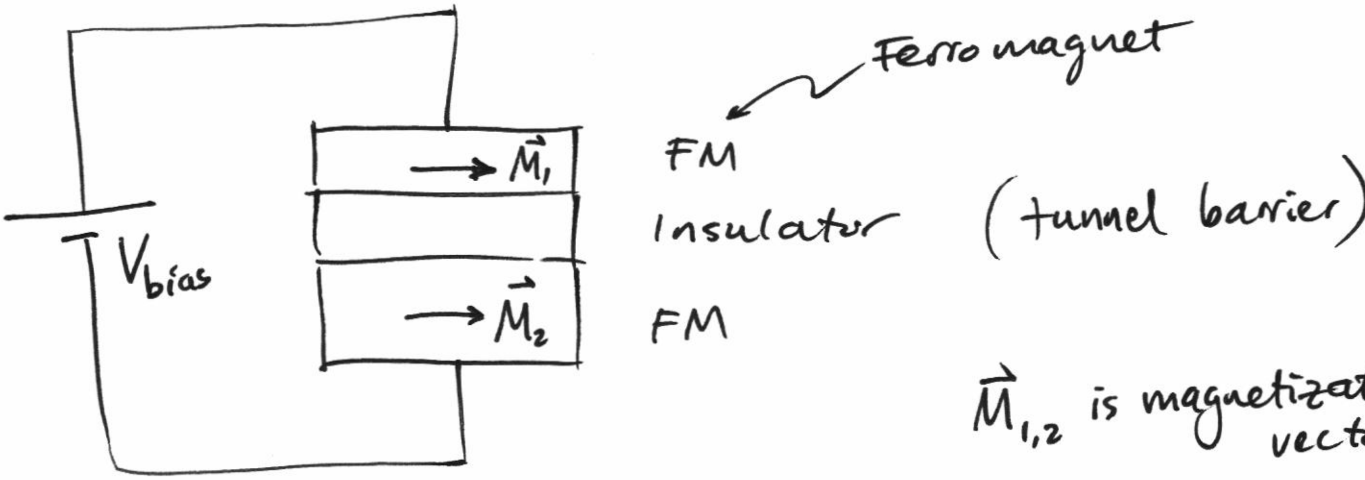
then

$$I_{tunnel} \propto \int_{\mu}^{\mu + eV_{bias}} D_{sample}(E)\, dE$$

$$\boxed{\frac{dI_{tunnel}}{dV_{bias}} \propto D_{sample}(E)}$$

Popular technique for measuring density of states.

EXAMPLE 2: TUNNEL MAGNETO RESISTANCE



$\vec{M}_{1,2}$ is magnetization vector.

The resistance of this stack can be changed by applying a magnetic field.

$\rightarrow M_1$, $\rightarrow M_2$ } Low resistance state

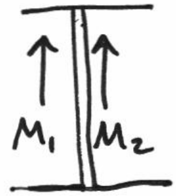
$\rightarrow M_1$, $\leftarrow M_2$ } High resistance state.

IMPORTANT NOTE: The e^- spin cannot flip during the tunneling process.

We consider the flow of spin $\uparrow$ e^- separate from the flow of spin $\downarrow$ e^-.

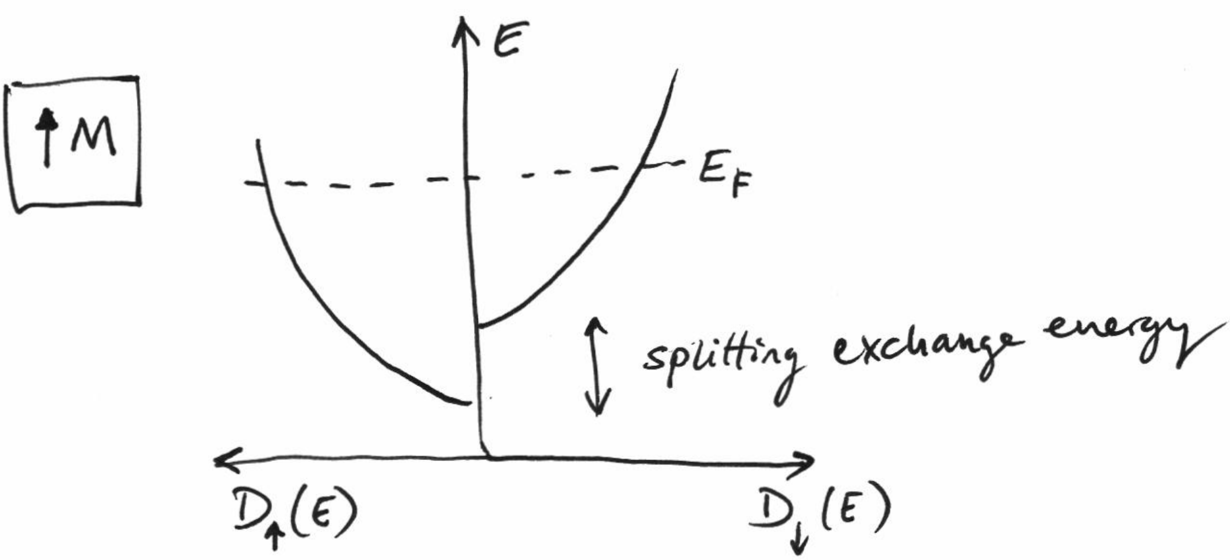
$$I_{TOT} = I_{\uparrow} + I_{\downarrow}$$

when



$$I_{\uparrow} = \text{const} \int_0^{\infty} D_{\uparrow 1} D_{\uparrow 2} \, P_{tunnel} \, f_1 (1 - f_2) \, dE$$

$$I_{\downarrow} = \text{const} \int_0^{\infty} D_{\downarrow 1} D_{\downarrow 2} \, P_{tunnel} \, f_1 (1 - f_2) \, dE$$



See HW #5

EXAMPLE 3: TUNNEL DIODES

Paper #1: MIM diodes by John Wager's group at OSU.

Advanced Materials ~~[illegible]~~ 23 74 (2011)

Paper #2: Vertical Graphene-Base Hot-electron Transistor by Zeng et al. Nano Letters 13 2370 (2013)

Other interesting papers:

"Tunnel field-effect transistors as energy-efficient electronic switches"

Nature 479 329 (2011)