# Resonant Tunneling and Magnetoresistance

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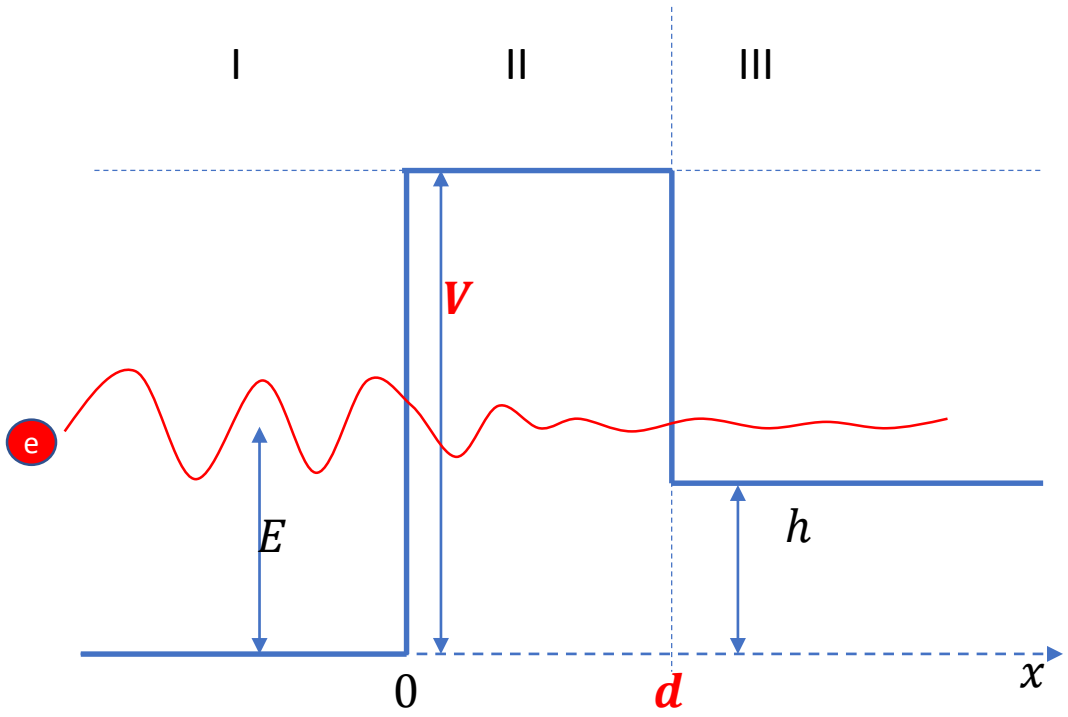
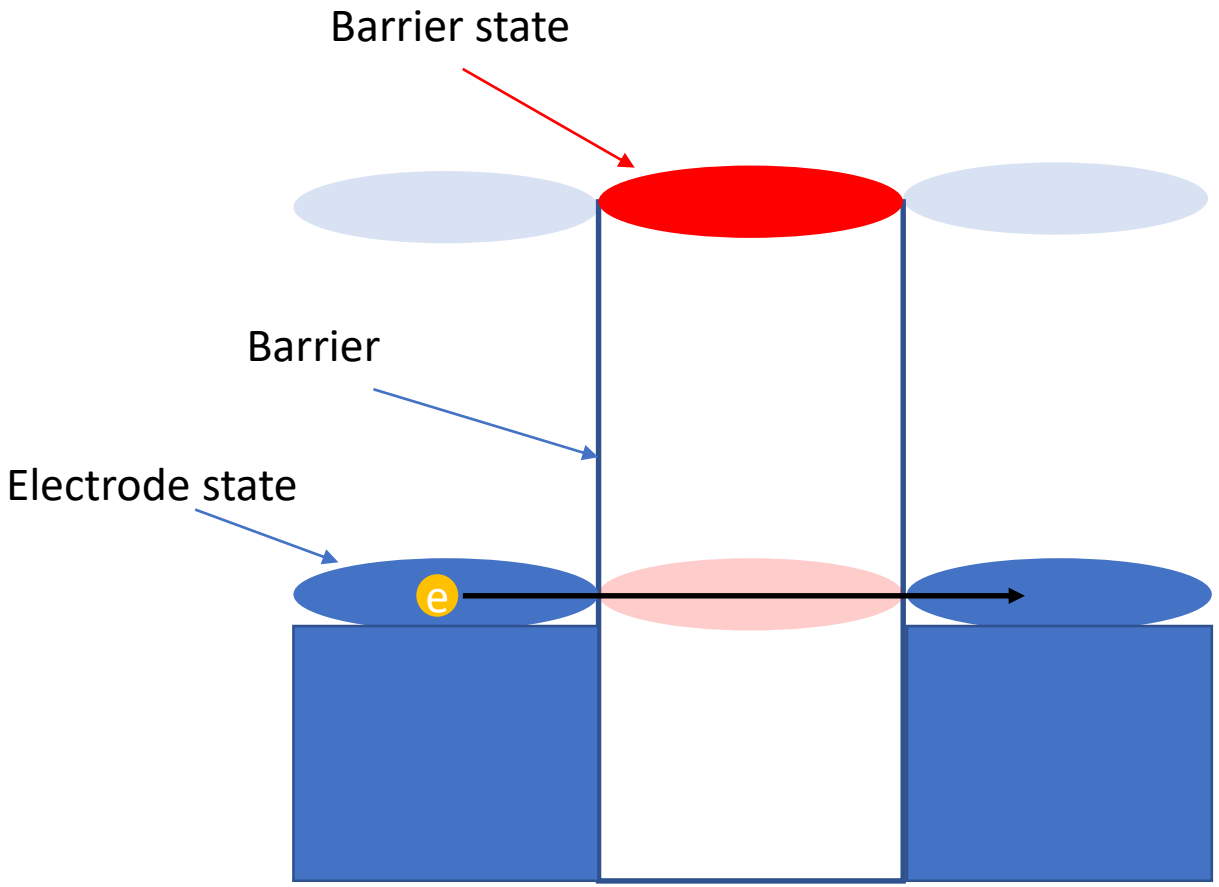
References: NATURE PHYSICS, **6**, 615, (2010). PRL 82, 4288 (1999);

# Types of tunneling

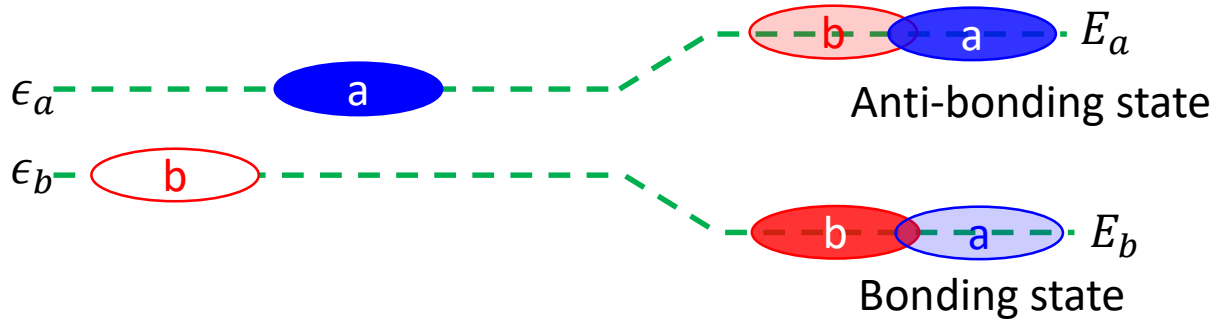



Direct tunneling




Resonant tunneling/hybridization

# Quantum mechanical view of hybridization between two levels




**Without bonding** **With bonding**

$$H = \frac{\hbar^2}{2m}\nabla^2 + V_a + V_b. \qquad V_a = -\frac{Z_a e^2}{|\vec{r} - \vec{r}_a|} \qquad V_b = -\frac{Z_b e^2}{|\vec{r} - \vec{r}_b|}$$

$$E_a = \epsilon_a + \frac{4V_{aab}V_{bba}}{2(\epsilon_a - \epsilon_b)}$$

$$E_b = \epsilon_b - \frac{4V_{aab}V_{bba}}{2(\epsilon_a - \epsilon_b)}$$

$$\psi_a = \phi_a + \frac{V_{bba}}{2(\epsilon_a - \epsilon_b)}\phi_b$$

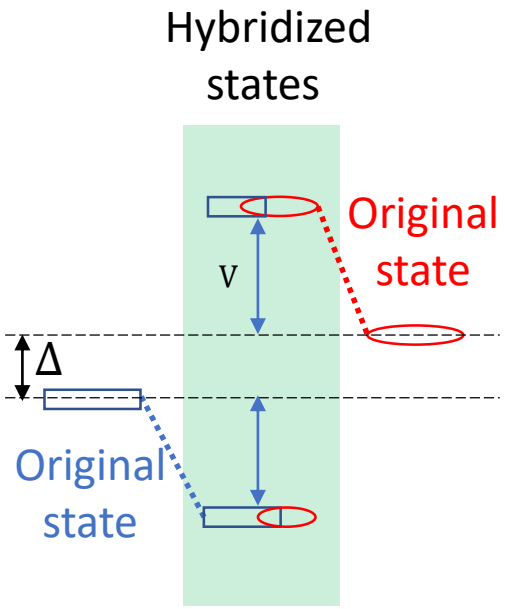
$$\psi_b = \phi_b - \frac{V_{aab}}{2(\epsilon_a - \epsilon_b)}\phi_a$$

$$V_{aab} \equiv < \phi_a | V_a \, | \phi_b >$$

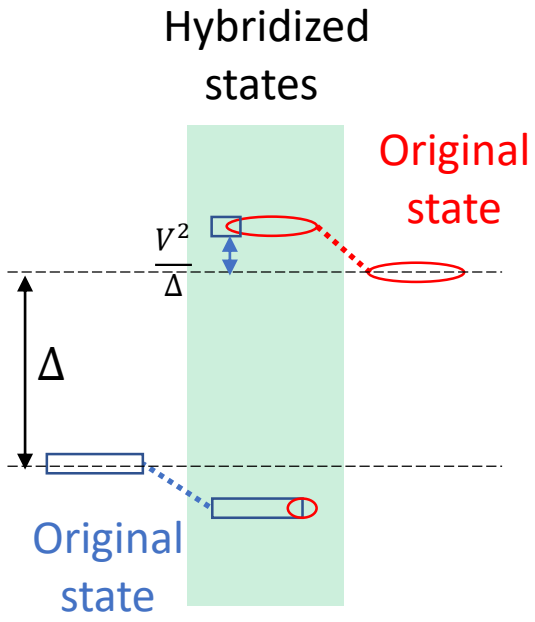
$$|V_{bba}| \approx |V_{aab}|$$

# Hybridization

- Hybridization between two levels




Strongly hybridized
***Large*** change of energy and reduction of spectra weight




Weakly hybridized
***Small*** change of energy and reduction of spectra weight

*Hybridization described using Hamiltonian*

$$H = \begin{bmatrix} \Delta & V \\ V & 0 \end{bmatrix}$$

The eigen energies are

$$E_{1,2} = \frac{\Delta \pm \sqrt{\Delta^2 + 4V^2}}{2}$$

$$\psi_{1,2} = \phi_1 \mp \frac{\Delta - \sqrt{\Delta^2 + 4V^2}}{2V}\phi_2$$

**$\Delta \gg$ V, weakly hybridized**

$$E = \frac{\Delta \pm (\Delta + \frac{2V^2}{\Delta})}{2}$$

approximately:

$$E_1 = \Delta + \frac{V^2}{\Delta}, \psi_1 = \phi_1 + \frac{V}{\Delta}\phi_2$$

$$\mathrm{E}_2 = -\frac{V^2}{\Delta}, \psi_2 = \phi_2 - \frac{V}{\Delta}\phi_1$$

**$\Delta \ll$ V, strongly hybridized**

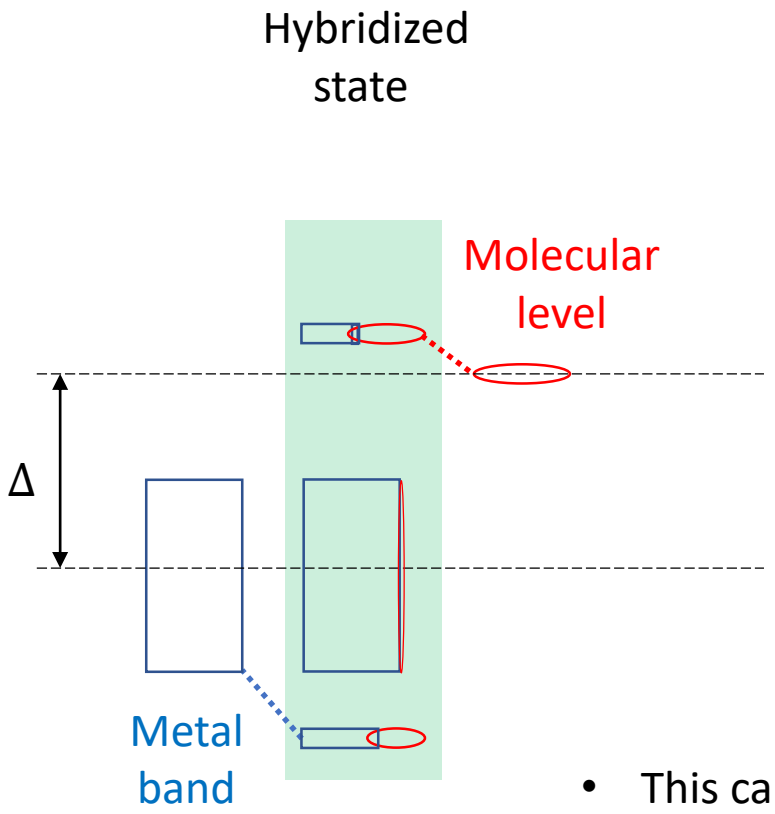
$$E_{1,2} = \frac{\Delta \pm (2\mathrm{V} + \frac{\Delta^2}{4V})}{2}; \psi_{1,2} = \frac{1}{\sqrt{2}}(\phi_1 \pm \phi_2)$$

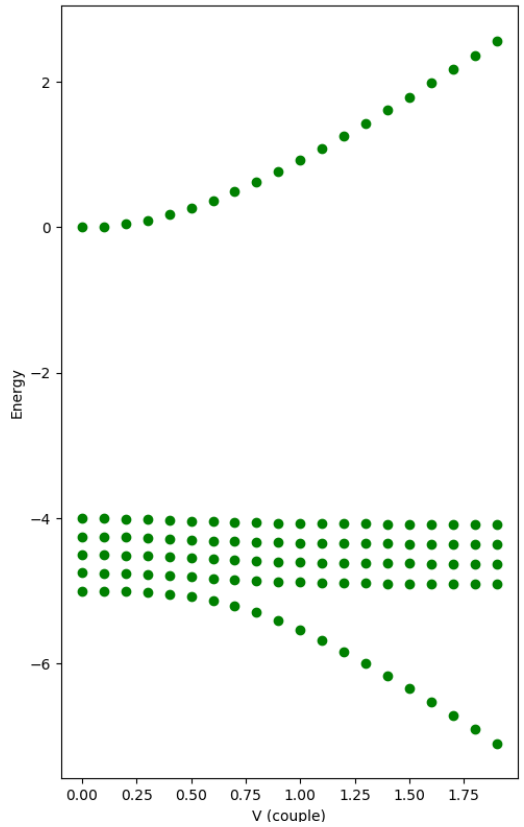
Approximately:

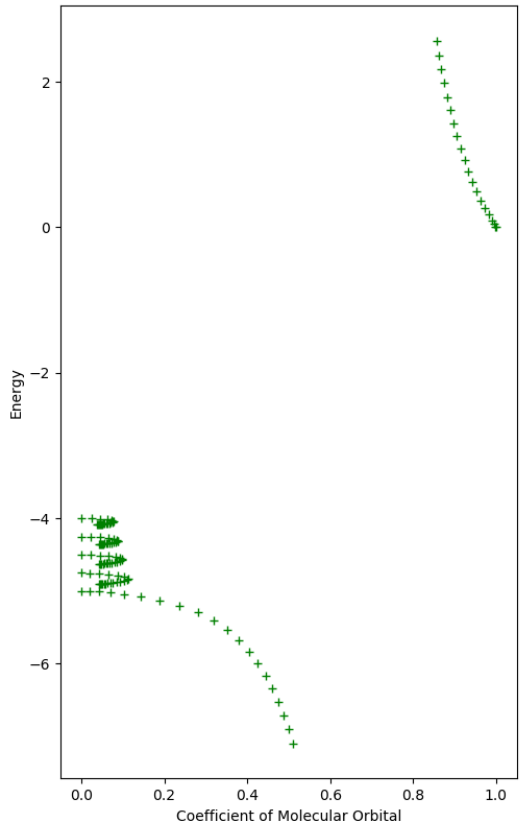
$$\psi_1 = \frac{1}{\sqrt{2}}(\phi_1 + \phi_2)$$

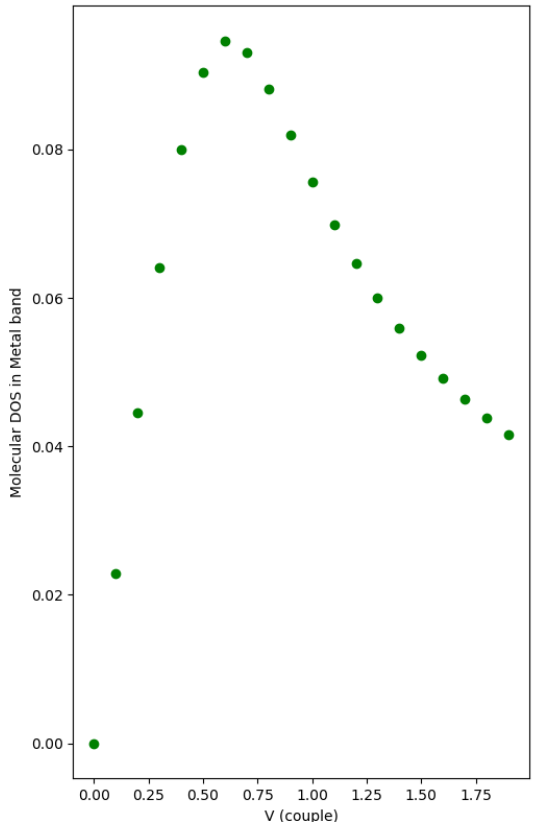
$$\mathrm{E}_2 = \Delta - \mathrm{V}, \psi_2 = \frac{1}{\sqrt{2}}(\phi_1 - \phi_2)$$

# Hybridization between a level and a band of 5 states



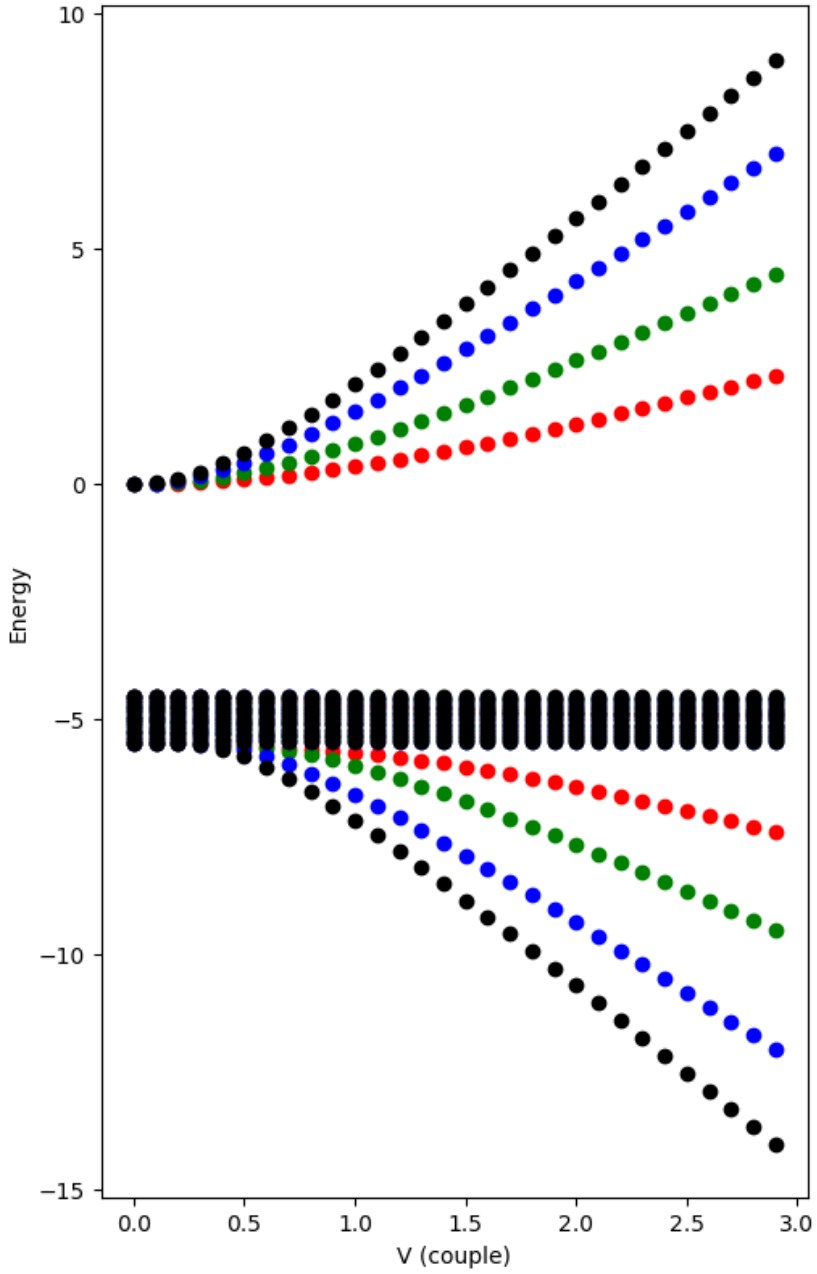



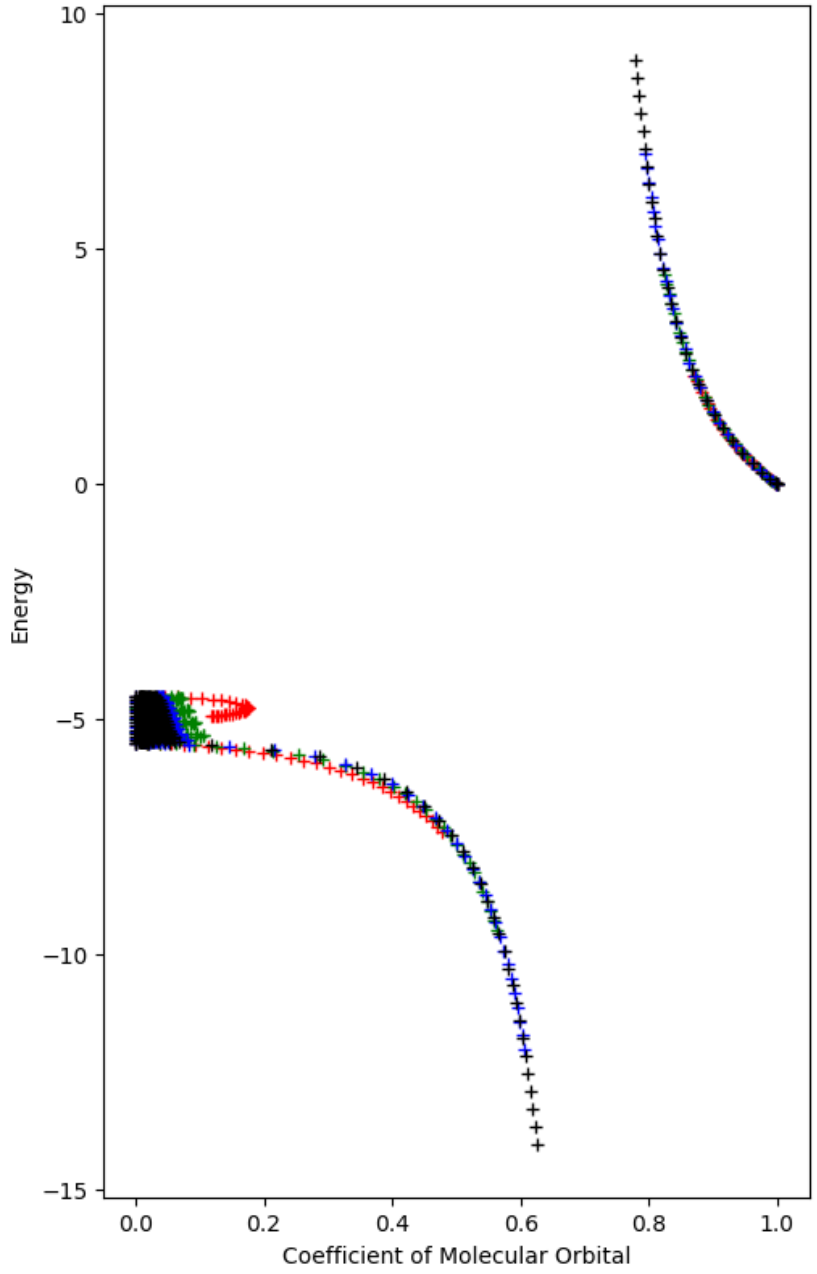



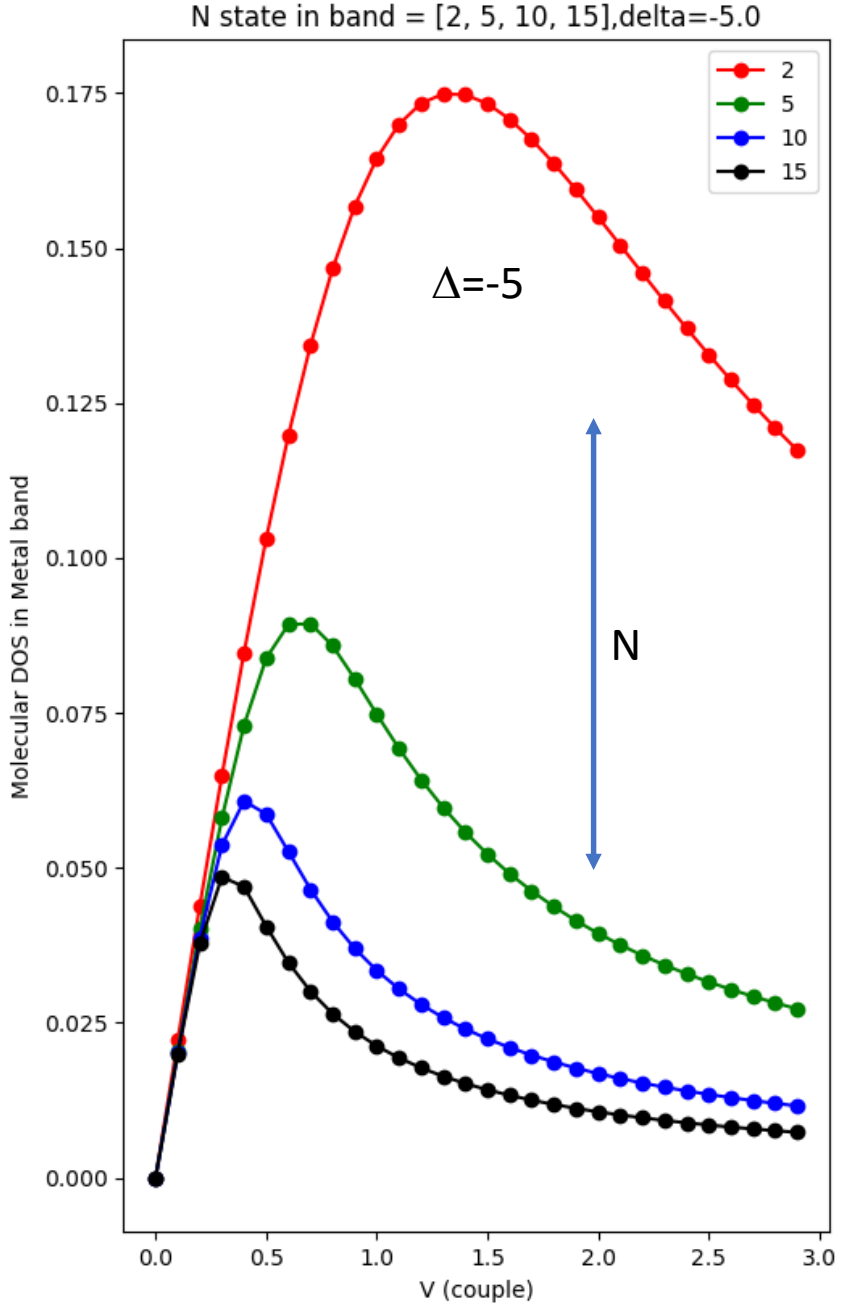




- This can be simulated using a 5-state band interacting with a single level, as shown above.
- The state in the band that is farthest from the single level (when V>> level separation)
  - strongest hybridization.
  - pushed away from the band (E decrease significantly).
- The majority of the band (this is the most important part for the transport).
  - hybridize with the level only slightly
  - energy does not change much.

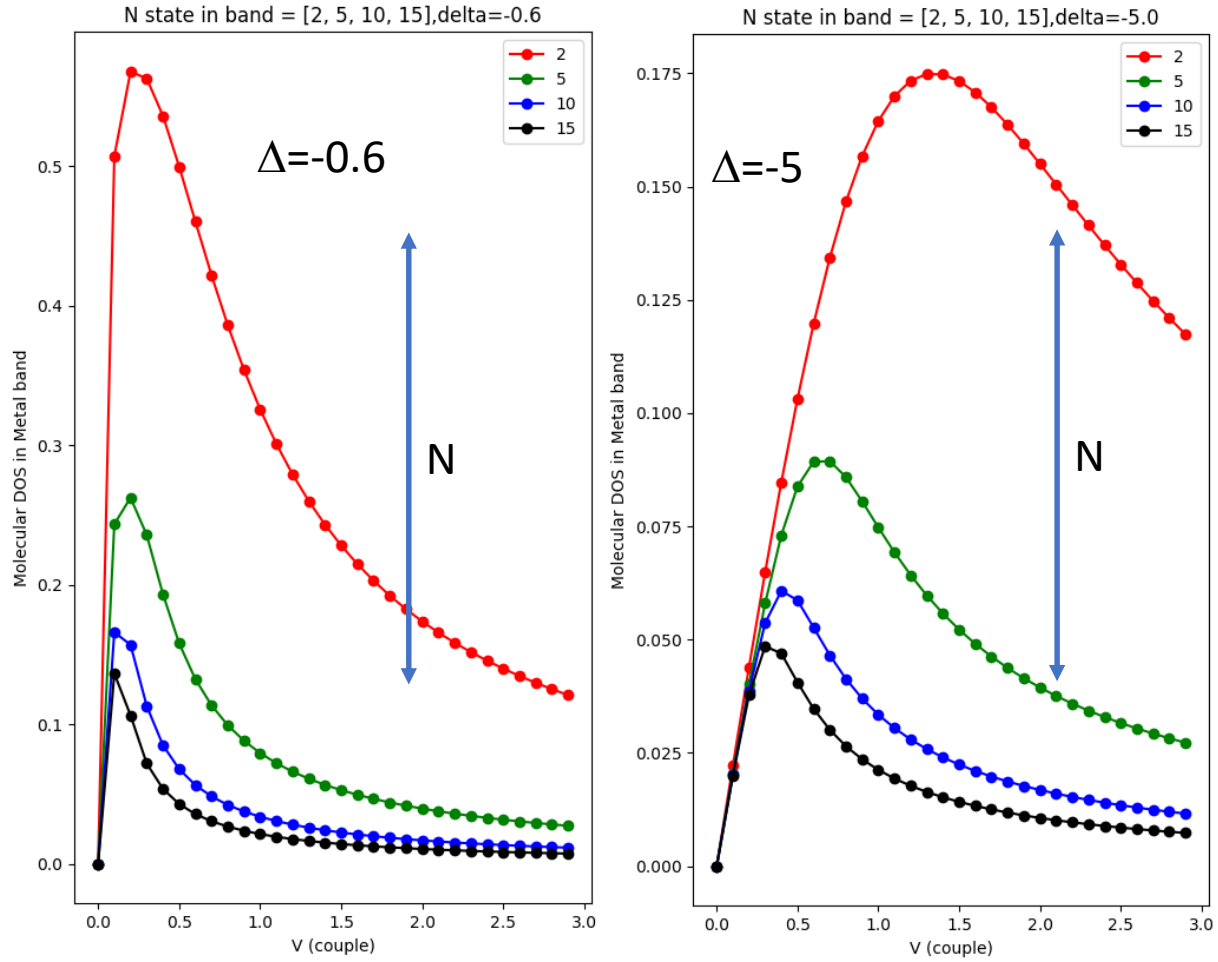
# Hybridization between a level and a band of N states



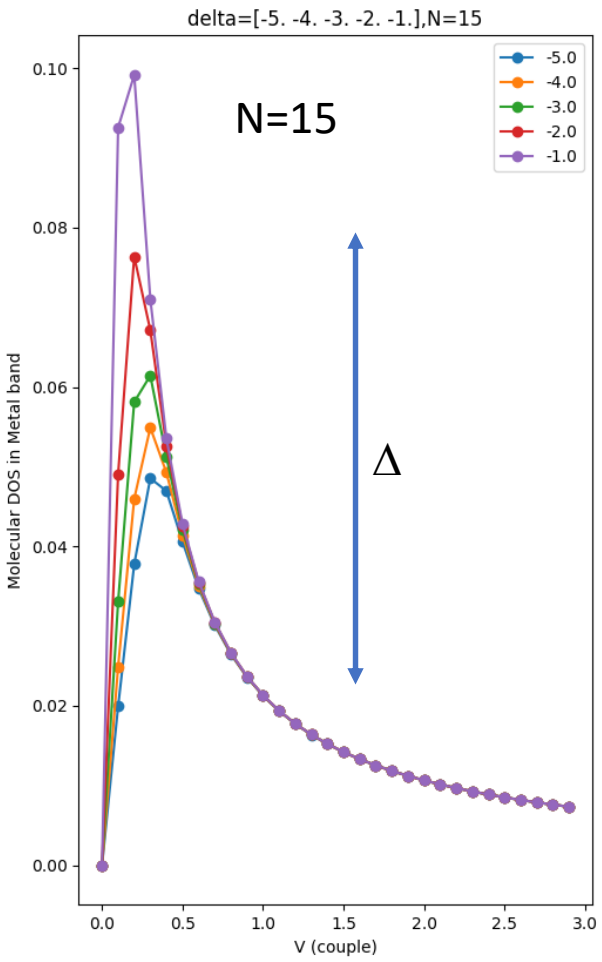



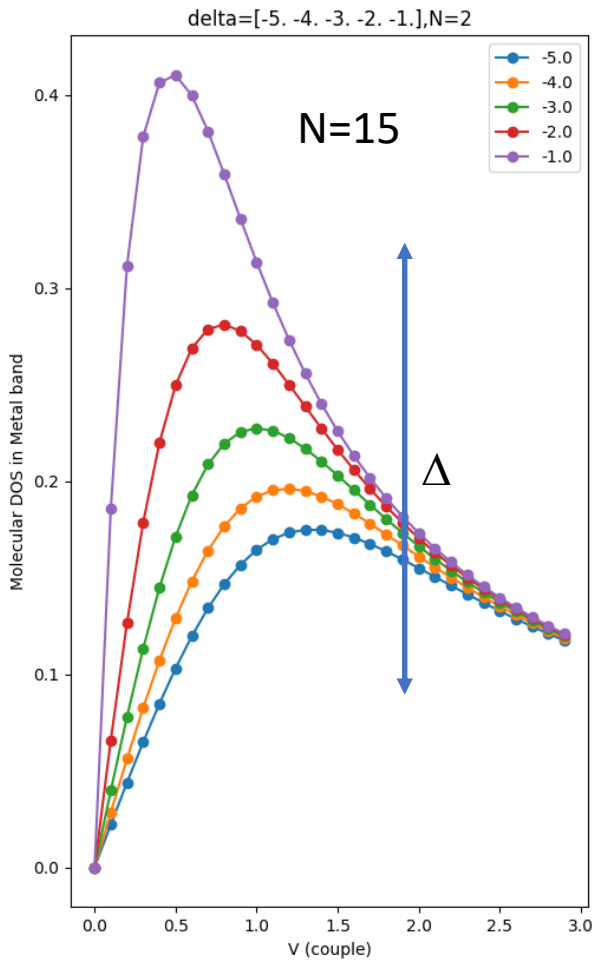
# Hybridization between a level and a band of N states (V, Δ)



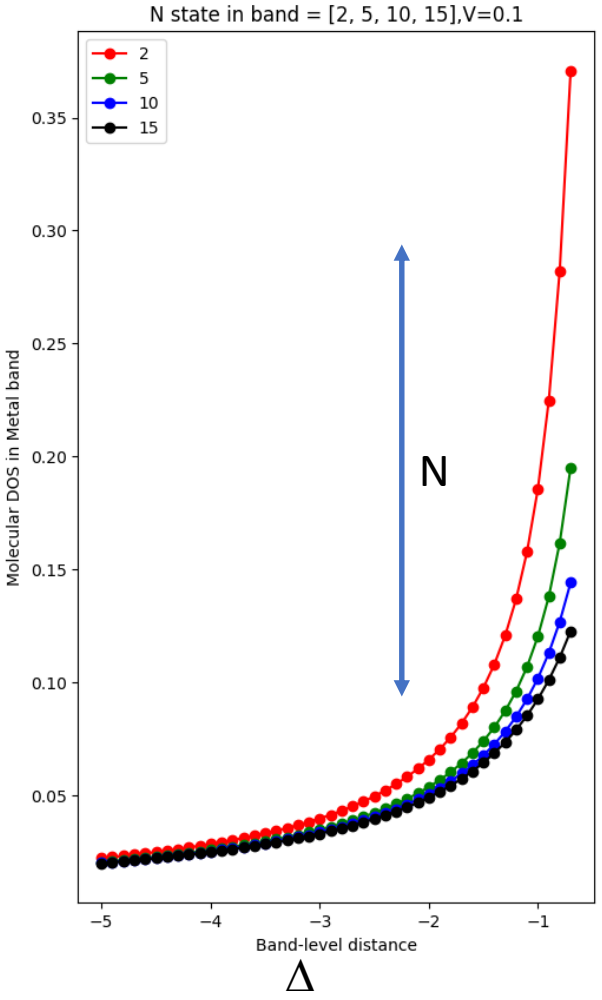


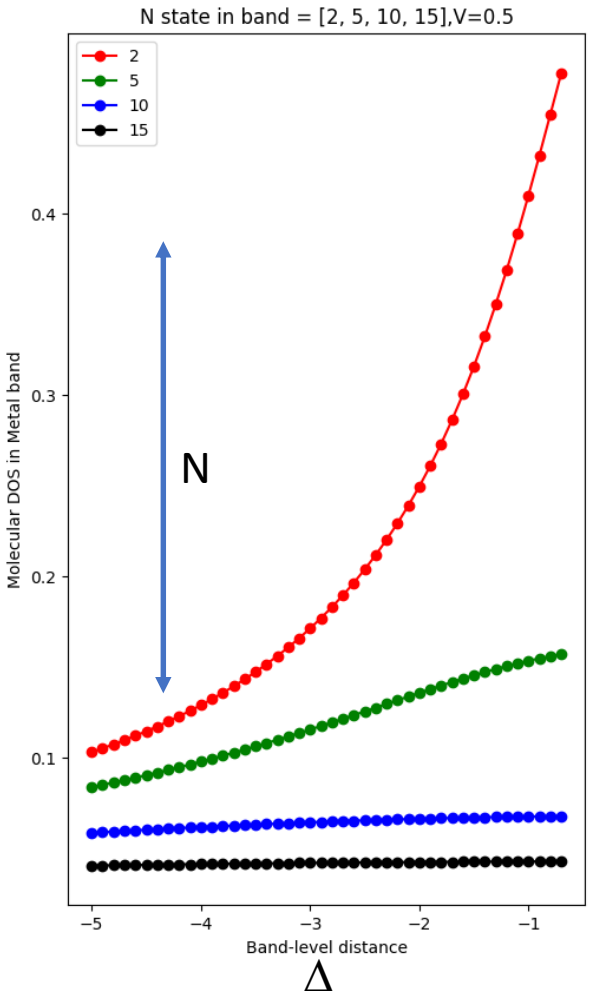


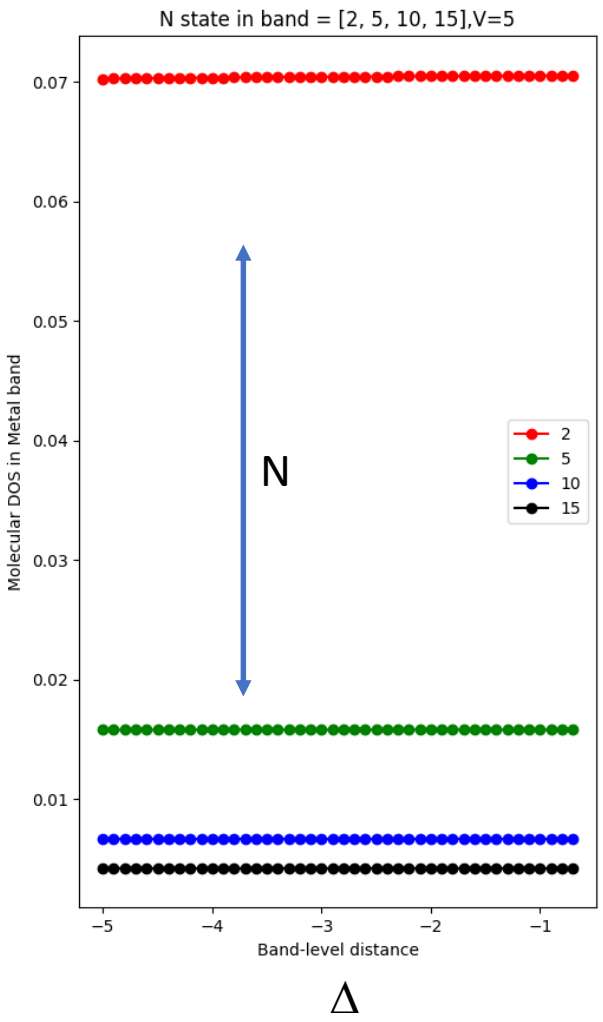


# Hybridization between a level and a band of N states




$DOS_{ml}$ (DOS of molecular at the metal side) v.s. $N_{band}$, Δ and V.

**1) $N_{band}$ ↗, $DOS_{ml}$ ↘.**

2) |Δ| ↗, $DOS_{ml}$ ↘

3) V:

Small V: V ↗, $DOS_{ml}$ ↗

Large V: V ↗, $DOS_{ml}$ ↘

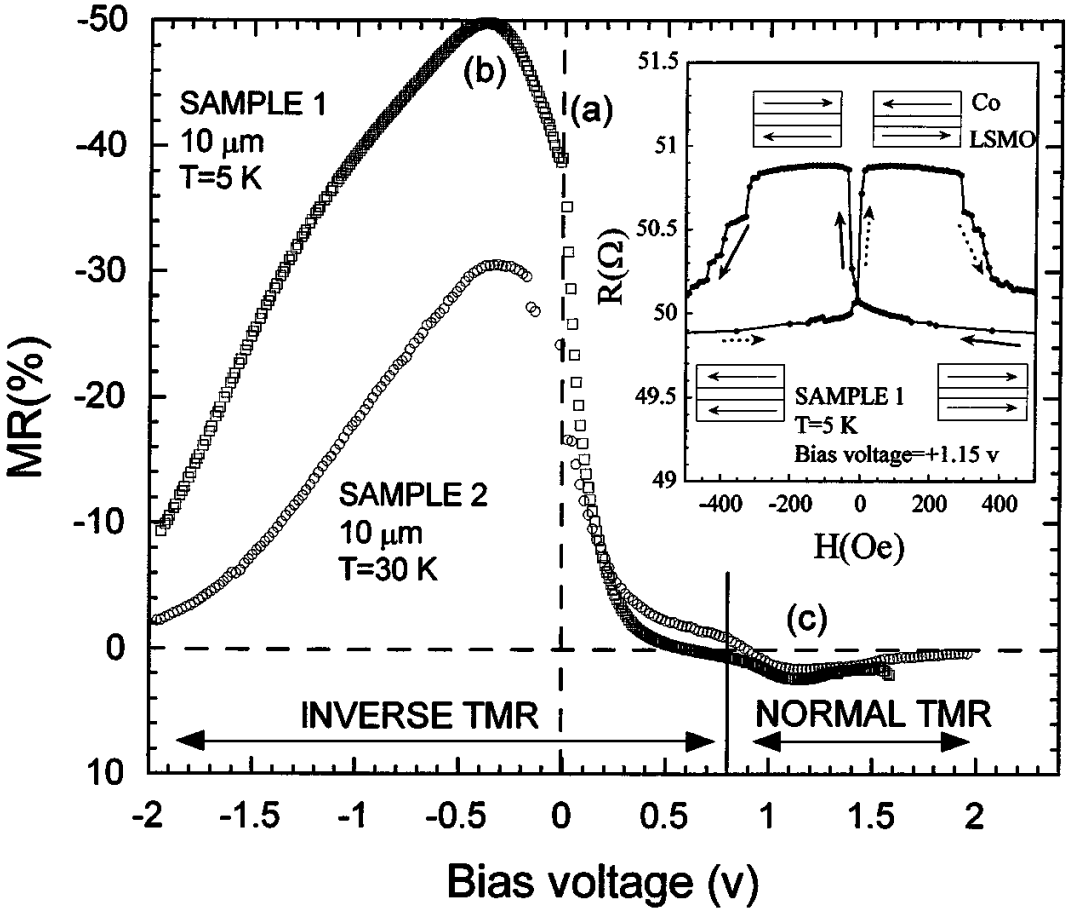
Therefore, for small V, the formula

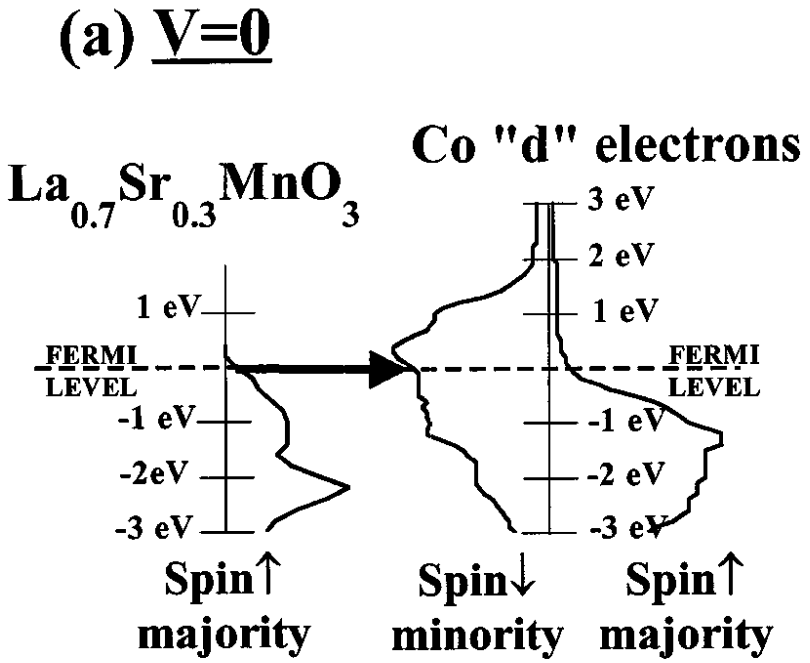
$$DOS_{ml} \propto \frac{V^2}{\Delta^2 + V^4 * \mathrm{DOS}_{metal}^2} \propto \frac{1}{\Gamma_{ml}}$$

should work.

# Magnetoresistance Co/SrTiO3/LSMO

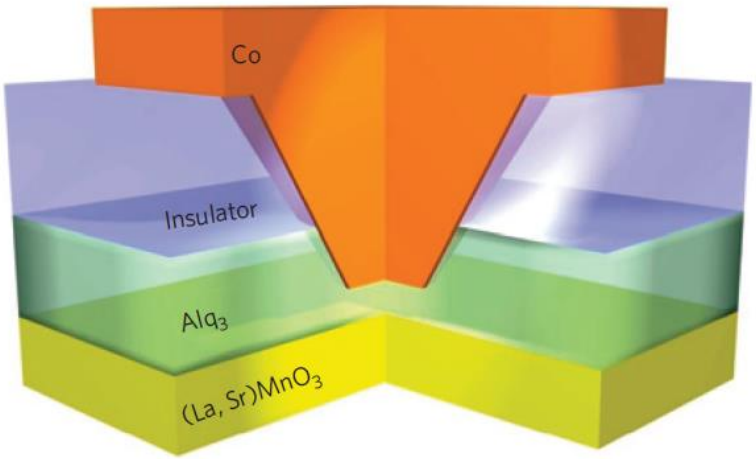
## Weak coupling, direct tunneling

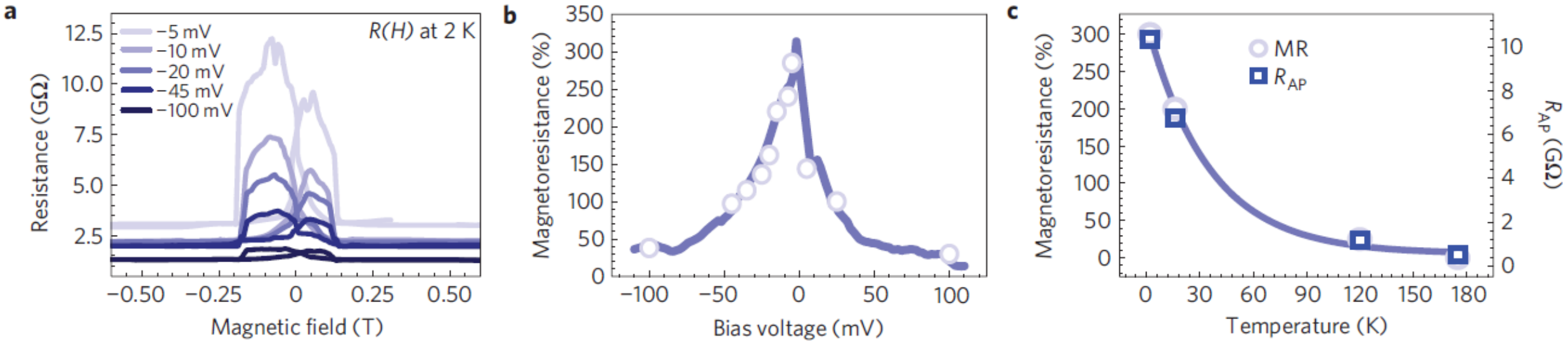


# Magnetoresistance Co/Alq3/LSMO

## Strong coupling, resonant tunneling

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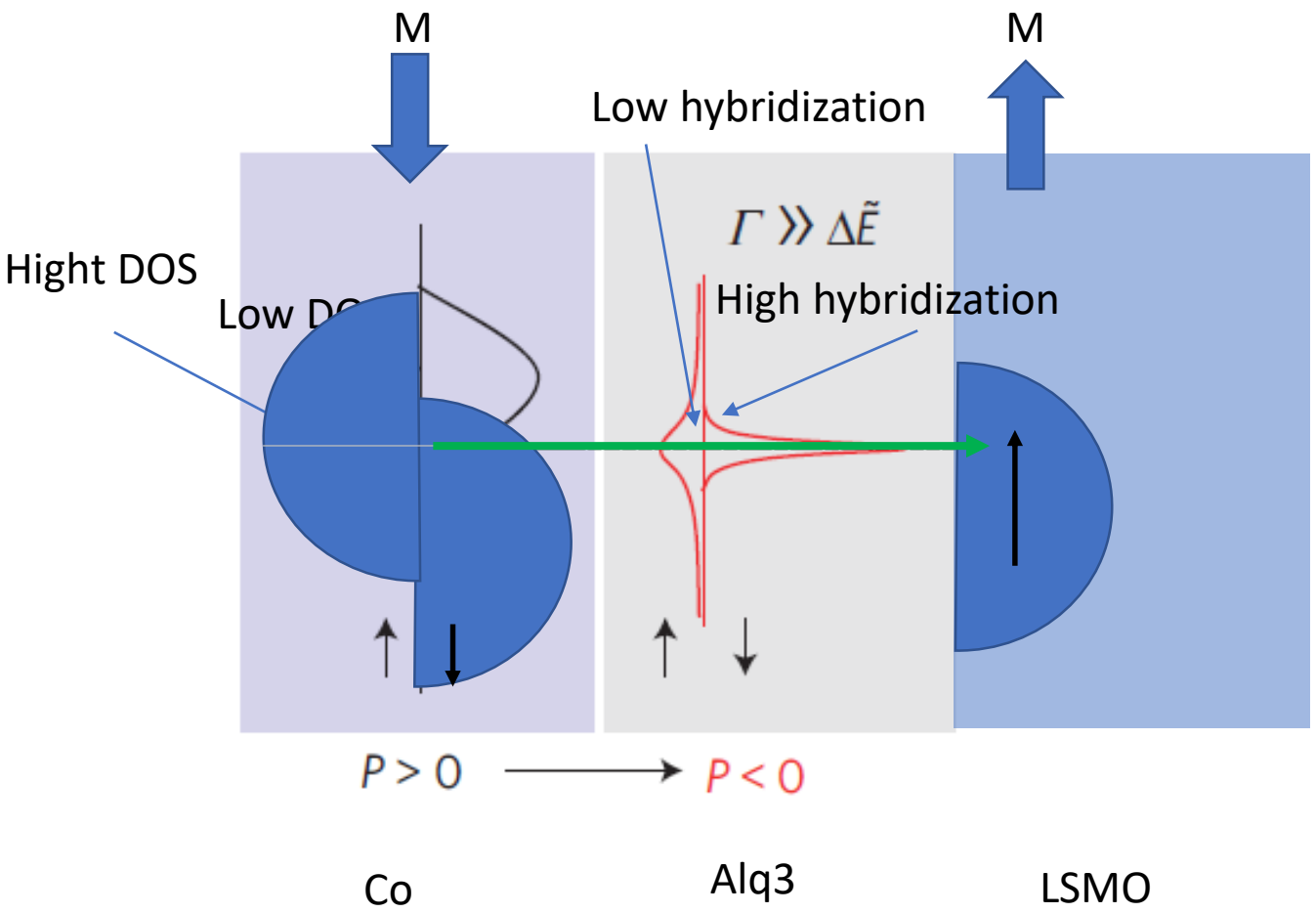
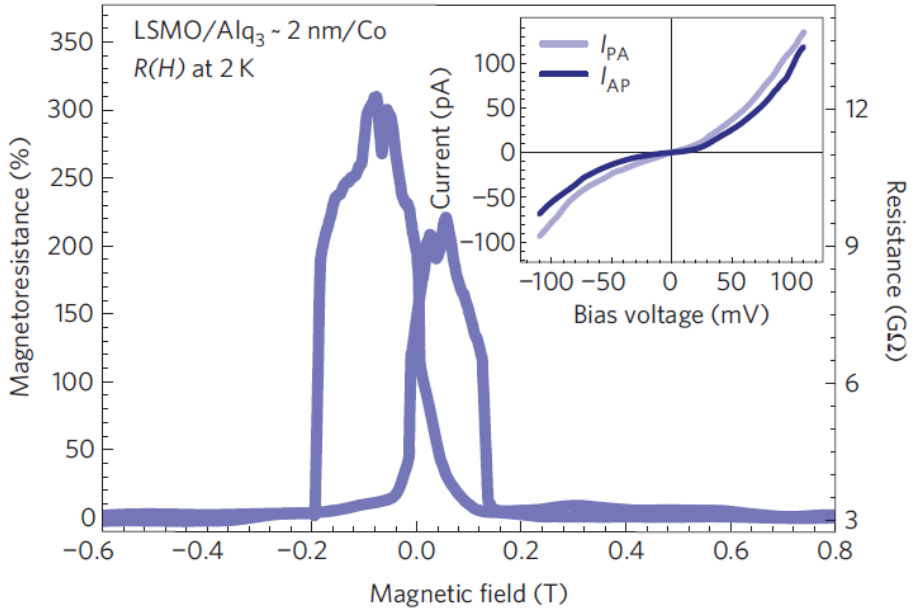

M
M
Low hybridization
$\Gamma \gg \Delta\tilde{E}$
Hight DOS
Low DO
High hybridization
P > 0
P < 0
Co
Alq3
LSMO


LSMO/Alq3 ~ 2 nm/Co
R(H) at 2 K
Magnetoresistance (%)
Current (pA)
Resistance (GΩ)
Magnetic field (T)
Bias voltage (mV)
$I_{PA}$
$I_{AP}$

# Conclusion

- Depending on the interfacial hybridization, the tunneling can be direct or resonant coupling
- For direct tunneling, MR sign is the sign of spin polarization at the Fermi level P1*P2.
- For resonant tunneling, MR sign is reversed from the direct tunneling.