

Spinelphysik / Spintronik

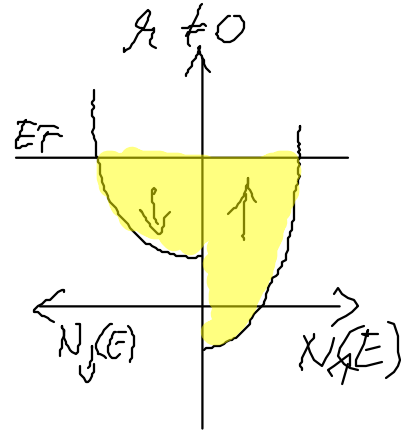
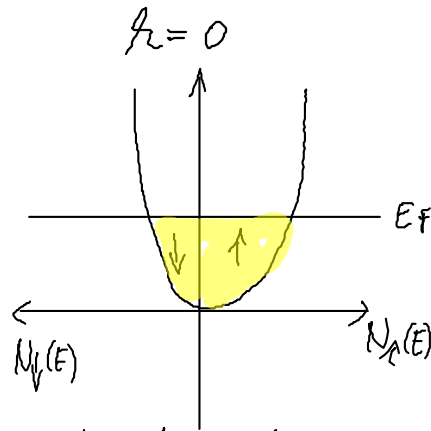
- Bandstruktur von Übergangsmetallen: Fe, Co, Ni

$$H = \frac{p^2}{2m} + V(\vec{r}) + \mu \vec{H} \cdot \vec{S}$$

μ : magnetisches Moment

\vec{H} : Austauschfeld

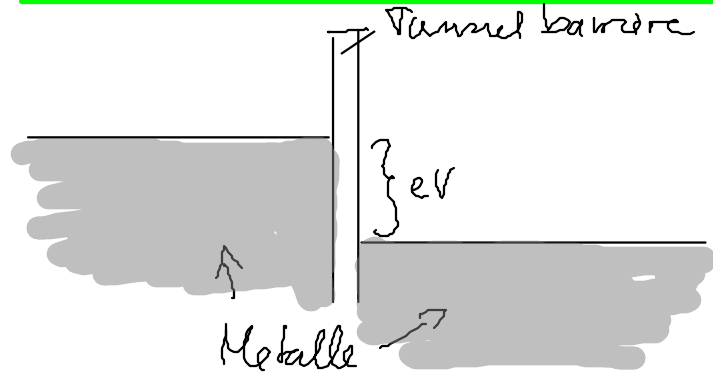
$$\vec{S} = \frac{1}{2} \vec{\sigma} \quad \text{Spin des Elektrons}$$



- für $h \neq 0$: Majoritäts- und Minoritätsladungsträger

$$N_M(E) = N(E + \mu h \frac{1}{2}) \quad N_m(E) = N(E - \mu h \frac{1}{2})$$

Tunnelhamilton-Formalismus



$$H = H_L + H_R + H_T$$

$$H_L = \sum_{k \in L, \sigma} \epsilon_{k\sigma} c_{k\sigma}^\dagger c_{k\sigma}$$

$$H_R = \sum_{q \in R, \sigma} (\epsilon_{q\sigma} - eV) c_{q\sigma}^\dagger c_{q\sigma}$$

$$H_T = \sum_{\substack{k \in L \\ q \in R \\ \sigma}} (T_{kq} c_{q\sigma}^\dagger c_{k\sigma} + T_{kq}^* c_{k\sigma}^\dagger c_{q\sigma})$$

T_{kq} erzeugt Teilchen rechts T_{kq}^* vernichtet Teilchen links

- beim Tunneln kein Spinflip

- Zustände sind charakterisiert durch Besetzung $|\{n_{q\sigma}\}, \{n_{k\sigma}\}\rangle$

- Tunnelrate $|i\rangle \rightarrow |f\rangle$ mit

$$|i\rangle = |\dots \underset{q\sigma}{1} \dots \underset{k\sigma}{0} \dots \rangle$$

$$|f\rangle = |\dots \underset{q\sigma}{0} \dots \underset{k\sigma}{1} \dots \rangle$$

- Fermis Goldene Regel

$$\Gamma_{i \rightarrow f} = \frac{2\pi}{\hbar} |\langle f | H_T | i \rangle|^2 \delta(E_f - E_i)$$

$$= \frac{2\pi}{\hbar} |T_{kq}|^2 \delta(\epsilon_{k\sigma} - (\epsilon_{q\sigma} - eV))$$

gesamte Übergangsrate (makroskopisch)

$$\Gamma_{L \rightarrow R} = \sum_{\substack{k \in L \\ q \in R \\ \sigma}} \frac{2\pi}{\hbar} |T_{kq}|^2 f(\epsilon_k) \cdot (1 - f(\epsilon_q)) \delta(\epsilon_k - \epsilon_q + eV)$$

• Typische Näherung $|T_{qk}|^2 = |T|^2 = \text{const}$

$$\Sigma = \int_{\text{kel}} d\varepsilon N_L(\varepsilon) \approx N_L(\varepsilon) \cdot \int d\varepsilon$$

$$\Gamma_{L \rightarrow R} = 2 \cdot \frac{2\pi}{\hbar} |T|^2 D_L(E_F) D_R(E_F) \int d\varepsilon \int d\varepsilon' f(\varepsilon) (1-f(\varepsilon')) \delta(\varepsilon - \varepsilon' + eV)$$

$$= \frac{1}{e R_T} \int d\varepsilon \frac{1}{e^{\beta\varepsilon} + 1} \left(1 - \frac{1}{e^{\beta(\varepsilon + eV)} + 1} \right) \quad \boxed{\beta = \frac{1}{k_B T}}$$

Tunnelwiderstand $\boxed{x = e^{\beta\varepsilon} \quad dx = \beta x d\varepsilon \quad \frac{1}{y} = e^{\beta eV}}$

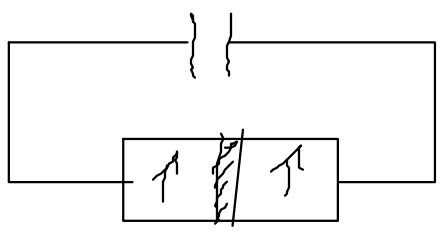
$$\int_0^\infty dx \frac{1}{\beta x} \frac{1}{x+1} \left(1 - \frac{x}{x+1} \right) = \frac{1}{\beta} \frac{1}{y-1} \int_0^\infty dx \left(\frac{1}{x+1} - \frac{1}{x+y} \right)$$

$$= \frac{1}{\beta} \frac{1}{y-1} \log\left(\frac{x+1}{x+y}\right) \Big|_0^\infty = \frac{1}{\beta} \frac{1}{y-1} \log(y) = -\frac{eV}{e^{-\beta eV} - 1}$$

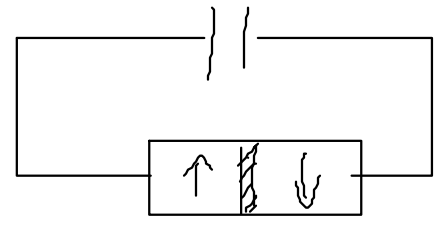
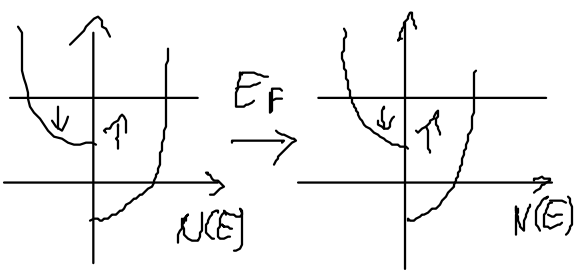
$$\Gamma_{L \rightarrow R} = \frac{1}{e R_T} \frac{-V}{e^{-\beta eV} - 1} \quad \text{analog} \quad \Gamma_{R \rightarrow L} = \frac{1}{e R_T} \frac{V}{e^{\beta eV} - 1}$$

• Tunnelstrom $I = e(\Gamma_{L \rightarrow R} - \Gamma_{R \rightarrow L}) = \frac{V}{R_T}$
 Leitwert $G = \frac{\partial I}{\partial V} \Big|_{V=0} = \frac{1}{R_T} = \frac{4\pi e^2}{\hbar^2} |T|^2 N_L(E_F) N_R(E_F)$

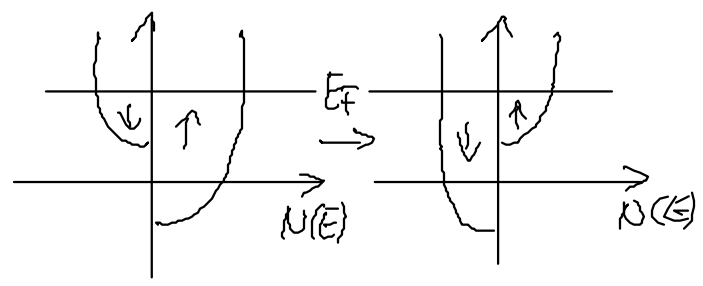
Tunneln zwischen ferromagnet. Elektroden (Jullien 1975)



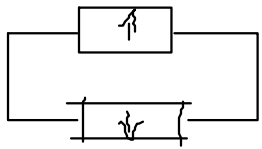
parallele Magnetisierung



antiparallele Magnetisierung



$$G^P = \frac{2\pi e^2}{\hbar} |T|^2 (N_{\uparrow L} N_{\uparrow R} + N_{\downarrow L} N_{\downarrow R})$$



$G^A = \frac{2\pi e^2}{\hbar} |T|^2 2 N_{\uparrow L} N_{\downarrow R}$
 Polarisierung $P = \frac{N_{\uparrow L} - N_{\downarrow L}}{N_{\uparrow L} + N_{\downarrow L}} \neq \frac{dEN_{\uparrow}(E) - dEN_{\downarrow}(E)}{dEN_{\uparrow}(E) + dEN_{\downarrow}(E)}$
 Anzahl der Zustände bei E_F

$P=0$: Normalmetalle

$P=1$: "Graf"metall

$$G^{P/AP} = \frac{Ze^2}{4\pi} |T|^2 \frac{(N_H + N_M)^2 \pm (N_H - N_M)^2}{2} = \bar{G} (1 \pm P^2)$$

• Tunnel magnetischer Widerstand

$$TMR = \frac{G^P - G^{AP}}{G^{AP}} = \frac{R^{AP} - R^P}{R^P} = \frac{2P^2}{1-P^2} \quad 0 \leq P \leq 1$$

• Versallgemeinerungen:

- beliebiger Polarisationswinkel $G^{P/AP} = \bar{G} (1 \pm P^2 \cos \theta)$
- endl. Barrierenhöhe
- unterschiedliche Transmissionsamplitude je nach Spin
- endl. Temperaturen Spinwellen

Spinakkumulation (siehe Skript)

GMR (siehe Skript)

Spin-Bahn-Kopplung (siehe Skript)