Electronic spin resonance and generation of magnetization and currents in a quantum wire

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Outline

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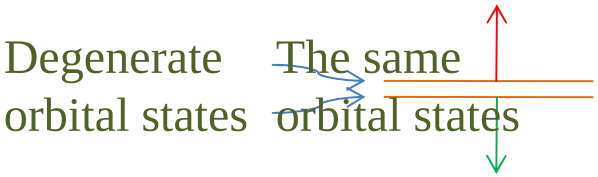
2. Spectra and eigenstates in 2 and 1 dimensions and spin resonance
3. Resonance heating and generation of permanent magnetization
4. Resonant generation of permanent currents by ac magnetic field
5. Relaxation processes and estimates of spin resonance effects
6. Influence of external permanent fields
7. Conclusions

1. Electronic spin resonance and spin-orbit interaction.

Standard ESR



Zeeman splitting

$$\Delta E_Z = g\mu_B B$$

•*The ac field realizing transition between Zeeman sublevels must have non-zero average over the orbital state*

• *Its frequency must be* $\omega_s = \frac{E_Z}{\hbar} = \frac{g\mu_B B_0}{\hbar}$ *independently on orbital state*

Very sharp resonance!

What is spoiled by SOI?

Effective magnetic field depends on electron momentum

$H_Z = -g\mu_B \mathbf{B}\mathbf{s}$ -- Zeeman Hamiltonian for a single electron

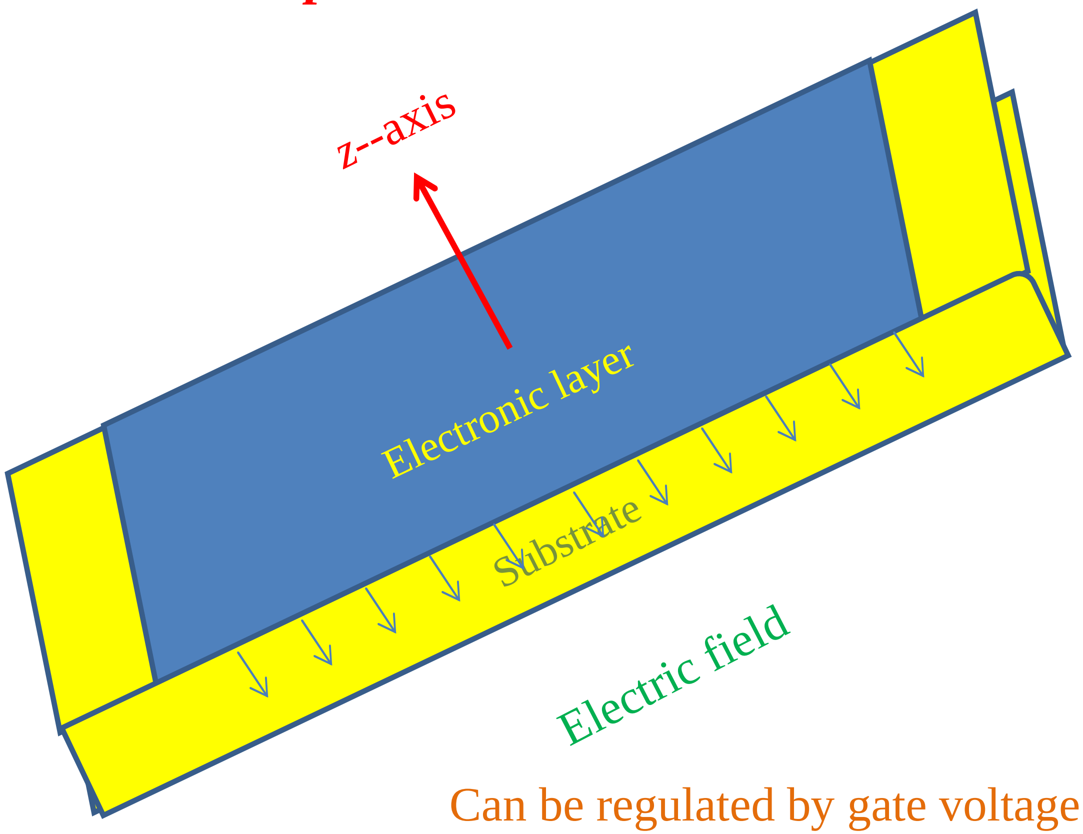
Dresselhaus interaction in a bulk superconductor with cubic rotational symmetry and violated inversion symmetry:

$$H_D = \beta \mathbf{s}\mathbf{B}_D(\mathbf{p}) \qquad B_{Dx} = p_x\left(p_y^2 - p_z^2\right)\ldots$$

Each momentum has its own spin-flip energy.
Resonance is smeared out.

2. **Electronic spectrum and eigenstates in 2 and 1 dimensions**

Rashba Spin-Orbit Hamiltonian



Violated reflection symmetry

$$H_R = \alpha \left(\hat{z} \times \mathbf{p} \right) \mathbf{s}$$

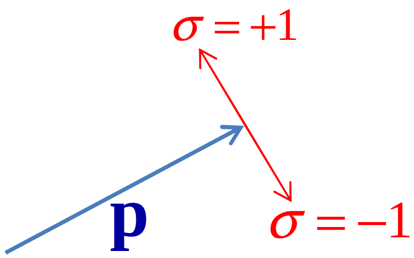
Equivalent form:

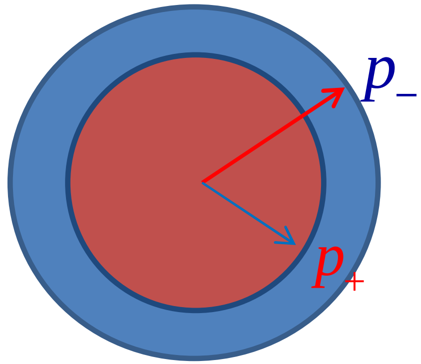
$$H_R = \alpha \left(\sigma_x p_y - \sigma_y p_x \right)$$

Can be regulated by gate voltage

Total Hamiltonian in 2d: $H = \frac{p^2}{2m} + \alpha\left(\hat{z} \times \mathbf{p}\right)\sigma$

Spectrum: $\varepsilon_{\mathbf{p},\sigma} = \frac{p^2}{2m} + \alpha p \sigma; \;\; \sigma = \pm 1 -$ **Chirality**





Fermi circles: $\frac{p_+^2}{2m} + \alpha p_+ = \frac{p_-^2}{2m} - \alpha p_-$

$$\frac{\pi\left(p_+^2 + p_-^2\right)}{\left(2\pi\hbar\right)^2} = n \; - \; \text{density}$$

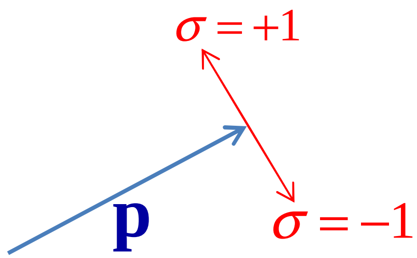
$$p_- - p_+ = 2m\alpha$$

$$p_- + p_+ = 2\sqrt{p_F^2 - m^2\alpha^2}$$

$$p_F^2 = 2\pi\hbar^2 n$$

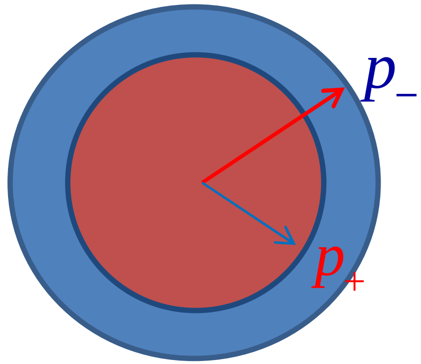
Fermi momentum at zero Rashba energy

Spin-flip:



Spin-flip energy: $\varepsilon_{\mathbf{p}+} - \varepsilon_{\mathbf{p}-} = 2\alpha p$

States able to perform spin-flip are located in the circular ring between two Fermi-circles



Chiral resonance at zero temperature

A. Shekhter, M. Khodas and A.M. Finkelstein, 2006

$$2m\alpha \ll p_F \longrightarrow \omega_c = \frac{2\alpha p_F}{\hbar} \gg \Delta\omega_c = \frac{4m\alpha^2}{\hbar}$$

Dresselhaus interferes: $H_D = \beta\left(\sigma_x p_x - \sigma_y p_y\right)$

$$H_R + H_D = \sigma_x\left(\alpha p_y + \beta p_x\right) - \sigma_y\left(\alpha p_x + \beta p_y\right)$$

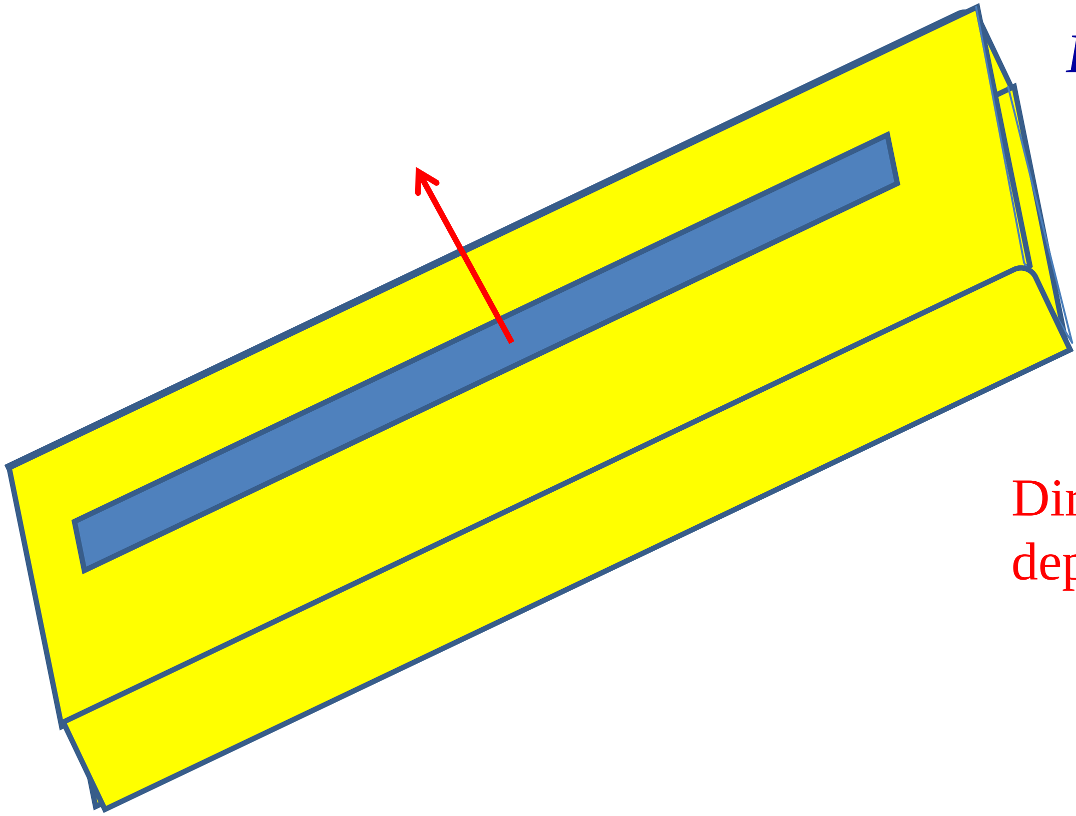
$$\frac{\Delta\omega_c}{\omega_c} = \sqrt{1+\delta} - \sqrt{1-\delta}$$

$$\varepsilon_{\mathbf{p},\sigma} = \frac{p^2}{2m} + \sigma\sqrt{\alpha^2+\beta^2}\, p\sqrt{1+\delta\sin 2\varphi}; \quad \delta = \frac{2\alpha\beta}{\alpha^2+\beta^2}$$

Strong anisotropic broadening of resonance!

SOI in Quantum Wires

Quantization of transverse motion. One-component momentum.



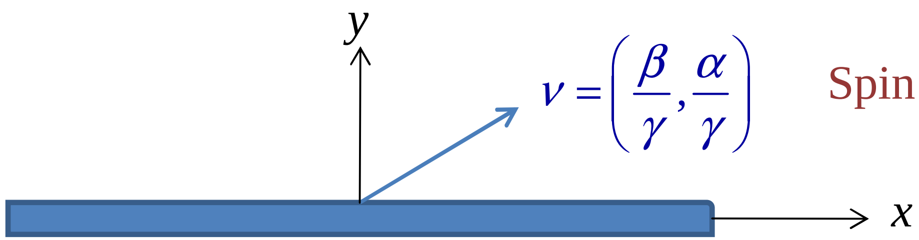
$$H_R = \alpha\left(\sigma_x p_y - \sigma_y p_x\right) \longrightarrow -\alpha p_x \sigma_y$$

$$H_D = \beta\left(\sigma_x p_x - \sigma_y p_y\right) \longrightarrow \beta p_x \sigma_x$$

$$H_R + H_D = p\left(\alpha\sigma_y + \beta\sigma_x\right)$$

Direction of effective field does not depend on the value of momentum

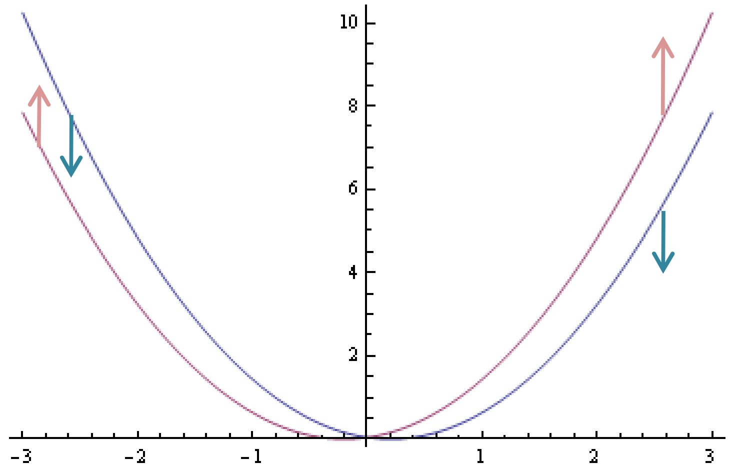
$$H = \frac{p^2}{2m} + p\left(\alpha\sigma_y + \beta\sigma_x\right) = \frac{p^2}{2m} + \gamma p \boldsymbol{\sigma}\mathbf{v} \qquad \gamma = \sqrt{\alpha^2 + \beta^2}$$



$$v = \left(\frac{\beta}{\gamma}, \frac{\alpha}{\gamma}\right)$$

Spin direction axis

Spectrum: $$\varepsilon_{p,\sigma} = \frac{p^2}{2m} + \gamma p \sigma$$

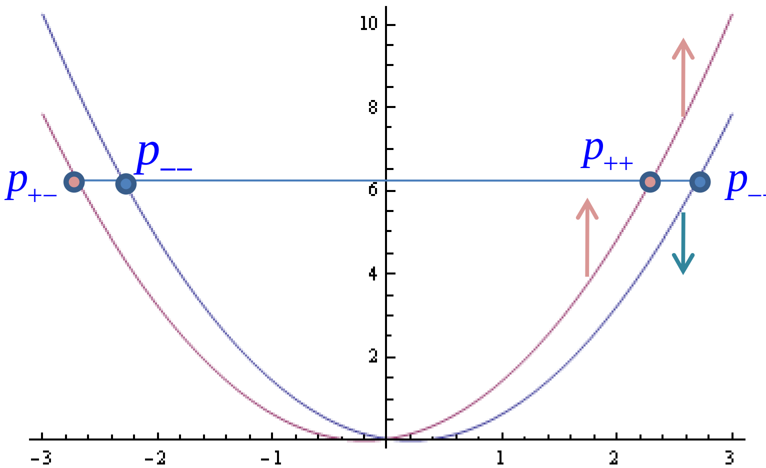


Fermi-points $p_{\sigma\tau}$

$\sigma = \pm 1$ -- spin variable

$\tau = \pm 1$ -- right or left movers

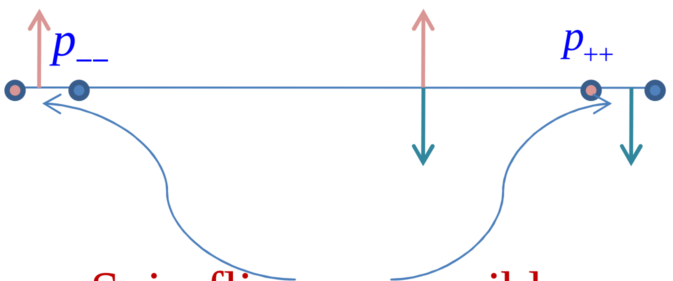
$p_{\sigma\tau} = p_F \tau - m\gamma\sigma$



Spin-flip process

Spin-flip energy:

$$\varepsilon_{sf}(p) = 2\gamma|p|$$



Spin-flips are possible

Resonance frequency:

$$\omega_{sr} = \frac{2\gamma p_F}{\hbar}$$

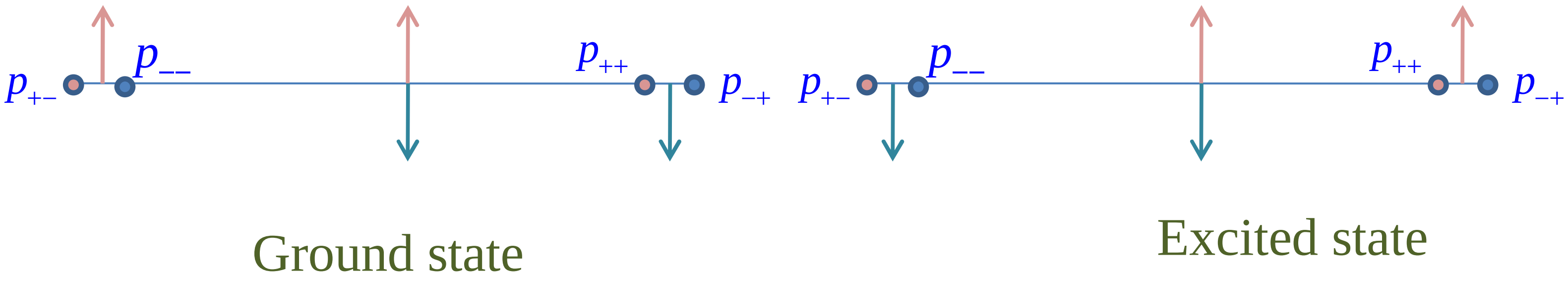
Resonance width:

$$\frac{\Delta\omega_{rs}}{\omega_{rs}} = \frac{2m\gamma}{p_F}$$

The temperature smearing of Fermi boundaries must be less than $p_{-+} - p_{++} = 2m\gamma \longrightarrow T < 2p_F\gamma$

3. Resonant heating and generation of permanent magnetization

Linearly polarized ac magnetic field (along z-axis)



Zero total magnetization

Absorbed energy per particle in single occupied interval: $E_{abs}^{(ex)} = 2\gamma p_F \min\left(w\tau_{sr}, 1\right)$

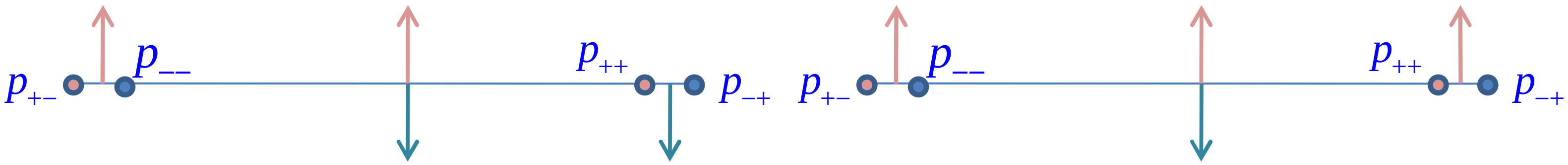
w is the spin-flip rate due to ac field; τ_{sr} is spin-relaxation time

Absorbed energy per any particle: $E_{abs} = E_{abs}^{(ex)} \dfrac{2\gamma}{v_F} = 4m\gamma^2 \min\left(w\tau_{sr}, 1\right)$

Resonant heating: $\Delta T = \dfrac{E_{abs}}{C} = \dfrac{E_{abs}\varepsilon_F}{T} \geq 2\gamma p_F \min\left(w\tau_{sr}, 1\right)$ $\quad w\tau_{sr} \leq 1\,?$

RH can be found by measurement of the wire resistance

Circularly polarized ac magnetic field (in the plane perpendicular to effective magnetic field)



Ground state Excited state

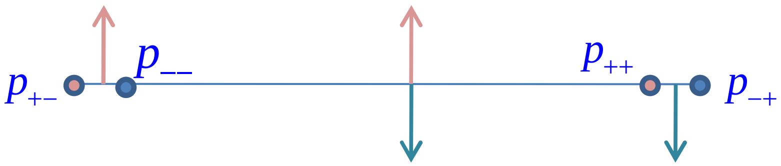
Circularly polarized ac field changes spin projection by +1!

It generates permanent magnetization: $M = g\mu_B$ per a single occupied momentum.

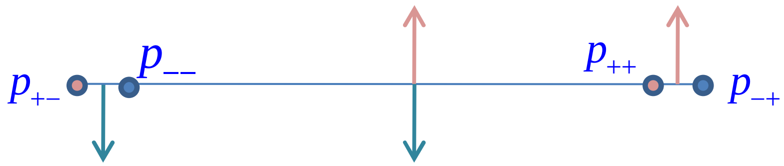
$$M = g\mu_B \frac{2\gamma}{v_F} \min\left(w\tau_{sr}, 1\right)$$ per any particle.

3. Resonant generation of permanent currents by ac magnetic field

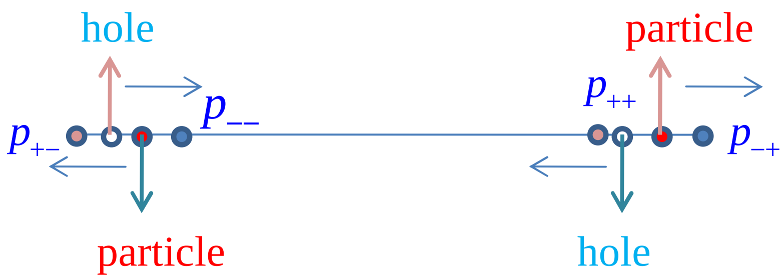
Linearly polarized ac magnetic field (along z-axis)



Ground state



Excited state



Excitations

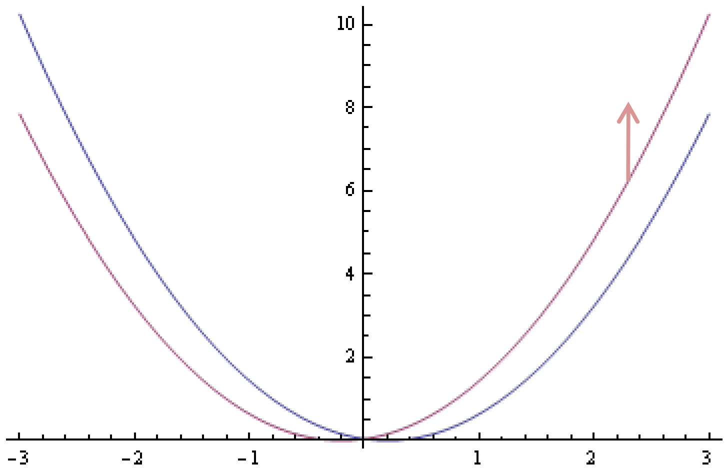
Velocity of hole is opposite to velocity of particle with the same momentum.

Spins up move right, spins down move left →

Permanent spin current.

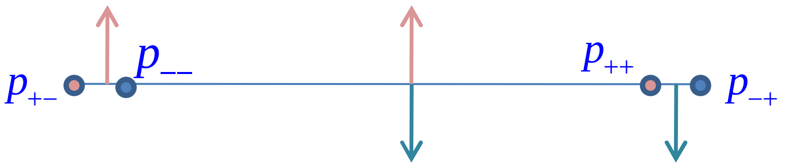
No electric current

Reduced by the back scattering



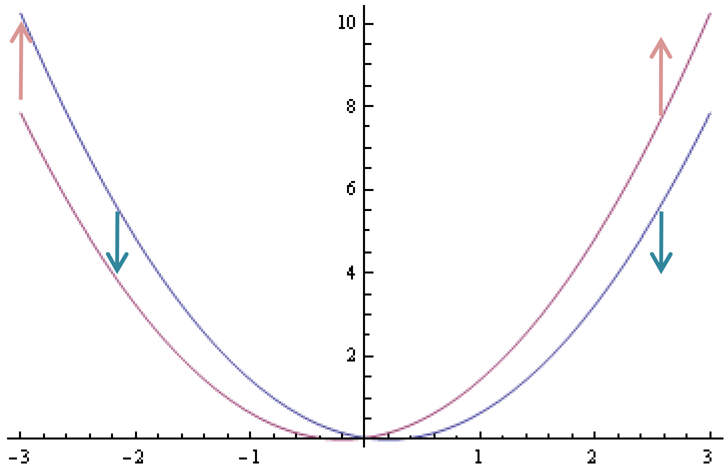
$$I_s = 2\gamma n_1 w \tau_b$$

Circularly polarized ac magnetic field (in the plane perpendicular to effective magnetic field)



Ground state

Excited state



These two currents compensate each other

Permanent completely polarized electric current

Suppressed by back scattering

$$I_e = 2en_{ex}\gamma\tau_b w = en_1\gamma^2\tau_b w / v_F$$

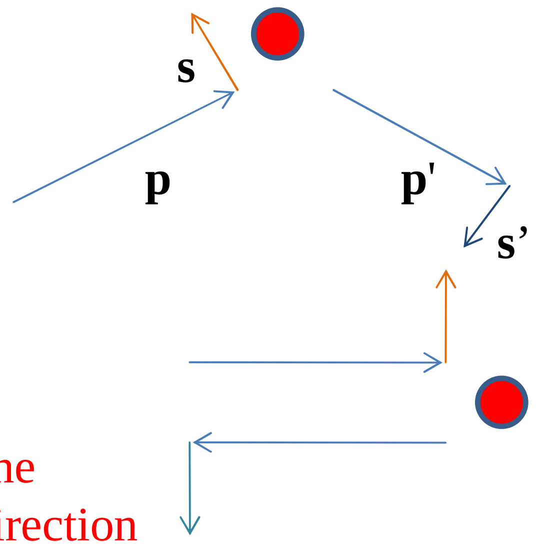
This mechanism of the permanent current generation is possible in 1d systems only in contrast to the known photo-galvanic effect (PGE) (E.I. Ivchenko and G.E. Pikus, 1978; V.I. Belinicher, 1978).

It is possible in non-degenerate electron gas, i.e. at higher temperatures, Then it is not resonant.

4. Relaxation processes

Spin relaxation

Dyakonov-Perel' mechanism



Elastic impurity scattering in 2 and 3 d:
Spin eigenstates before and after scattering
are not orthogonal.

D-P mechanism does not work in 1d since the
spin states are orthogonal due to invariant direction
of effective magnetic field.

Spin-flip time in phonon processes: $2-3ms$ if the wire is acoustically insulated

$10^{-8}s$ if the wire has ideal acoustic contact with the bulk substrate

Spin-flip time at magnetic impurities scattering: □ $3ms$ at concentration of magnetic impurities $10^{18}cm^{-3}$ and cross section area of the wire $10^{-12}cm^2$

All numerical calculations for InGaAs

Energy relaxation

Electron-electron and electron-hole interaction

Decay of a particle into two particles and one hole is forbidden

Decay of a particle into three particles and two holes is very slow due to small statistical weight of the final states $\sim (p - p_{\sigma\tau})^4$

Khodas, Pustylnik, Kamenev, Glazman, 2007

Numerically: $\tau_{en}^{(d)} \sim 0.25ms$

Electron-phonon interaction

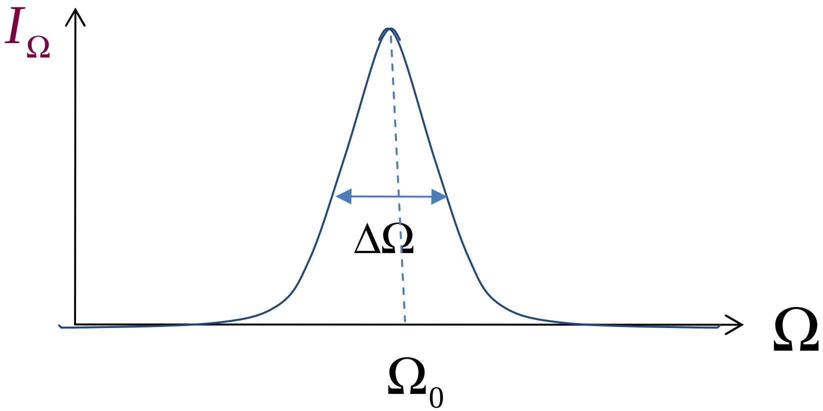
Acoustically insulated wire: $\tau_{en}^{(ph)} \sim 10^{-11} s$

Wire acoustically connected with the bulk: $\tau_{en}^{(ph)} \sim 10^{-13} s$

Energy relaxation is much faster than the spin relaxation

Resonance spin-flip rate: $w(p) = \frac{g^2 \mu_B^2}{\hbar^2} I_{\frac{2\gamma p}{\hbar}}$ (Fermi Golden Rule)

Spectral intensity of the ac magnetic field: $I_\Omega = \int_{-\infty}^{\infty} \overline{B^*(t) B(0)} e^{-i\Omega t} dt$



For simplicity: $\Omega_0 = \omega_{sr} = \frac{2\gamma p_F}{\hbar}$

$\Delta\Omega = \Delta\omega_{sr} = \frac{4m\gamma^2}{\hbar}$

For $In_{0.47}Ga_{0.53}As$ $\omega_{sr} = 0.7\times 10^{13} s^{-1}; \Delta\omega_{sr} = 2\times 10^{11} s^{-1}$ $w \approx 4\times 10^3 B^2 \left(G^2\right) s^{-1}$

A source of 1kW at a distance 1mm gives B^2=33G^2 , $w \approx 1.3\times 10^5 s^{-1}$

M. Sherwin, Nature **420**, 131 (2002); A. Deminger and A.S. Renner, Laser Focus World, Jan. 2008, p. 111; M.C. Hoffman et al., arXiv 0904.2516. MW power was achieved.

Spin-flip probability $P_{sf} = w\tau_{sf}$ is about 1 for acoustically insulated wire

$$n_{ex} = n\frac{2\gamma}{v_F}$$

$w\tau_B = 10^{-6}$ at power 1kW

$$I_e = en_{ex}v_F\left(w\tau_B\right) = 2en\gamma\left(w\tau_B\right) \approx 1pA \text{ for InGaAs}$$

How can the current be increased?

Narrow spectral width ΔΩ: $I_\Omega \sim \frac{\overline{B^2}}{\Delta\Omega}$

Increasing density and SOI by the gate voltage

5. Influence of permanent external fields

Permanent magnetic field

$$\varepsilon_{p\sigma} = \frac{p^2}{2m} + \sigma\sqrt{\left(\gamma p - g\mu_B H_\parallel\right)^2 + \left(g\mu_B H_\perp\right)^2}$$

$$\omega_{sr} = 2\sqrt{\left(\gamma p_F - g\mu_B H_\parallel\right)^2 + \left(g\mu_B H_\perp\right)^2} / \hbar$$

Gate voltage $n, \alpha, g \propto A + BV_g$

$$I_e = e n_{ex} v_F \left(w\tau_B\right) = 2en\gamma\left(w\tau_B\right)$$ --sensitive to the gate voltage.

6. **Conclusions**

- In a quantum wire a permanent direction of effective SO magnetic field together with Fermi-degeneration enables a narrow spin resonance even in the absence of external magnetic field.
- The resonance frequency is typically in terahertz region.
- The relative resonance width linearly depends on the Rashba-Dresselhaus constants.
- At any polarization ac field heats the wire resonantly
- Linearly polarized ac magnetic field with a resonant frequency generates a permanent spin current in the wire.
- Circularly polarized ac magnetic field with a resonant frequency generates a permanent magnetization and completely spin-polarized electric current in the wire.
- Experimental observation of the resonant heating, magnetization and permanent currents is feasible in an acoustically insulated wire.