SPINTRONICS IN HYBRID FERROMAGNETIC METAL/SEMICONDUCTOR STRUCTURES

Tomasz DIETL, lecture III

Hybrid structures

- soft ferromagnets (eg. NiFe) => local field amplifiers
- hard ferromagnets (eg. SmCo) => local field generators

- overlayers or inclusions of ferromagnetic metals

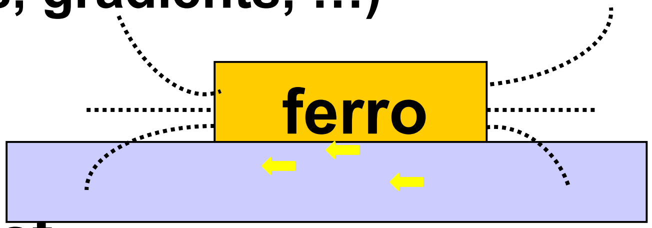
=> source of stray fields (field textures, gradients, …)

=> source of spin-polarized carriers

  --- spin injection

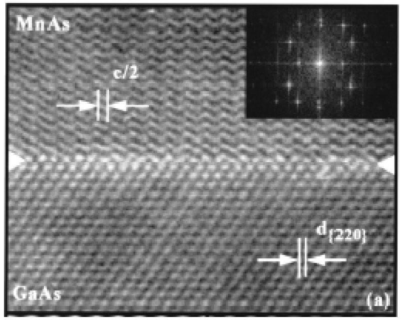
  --- ferromagnetic proximity effect

  --- TMR



best grown in the same reactor:

eg. MnAs on GaAs

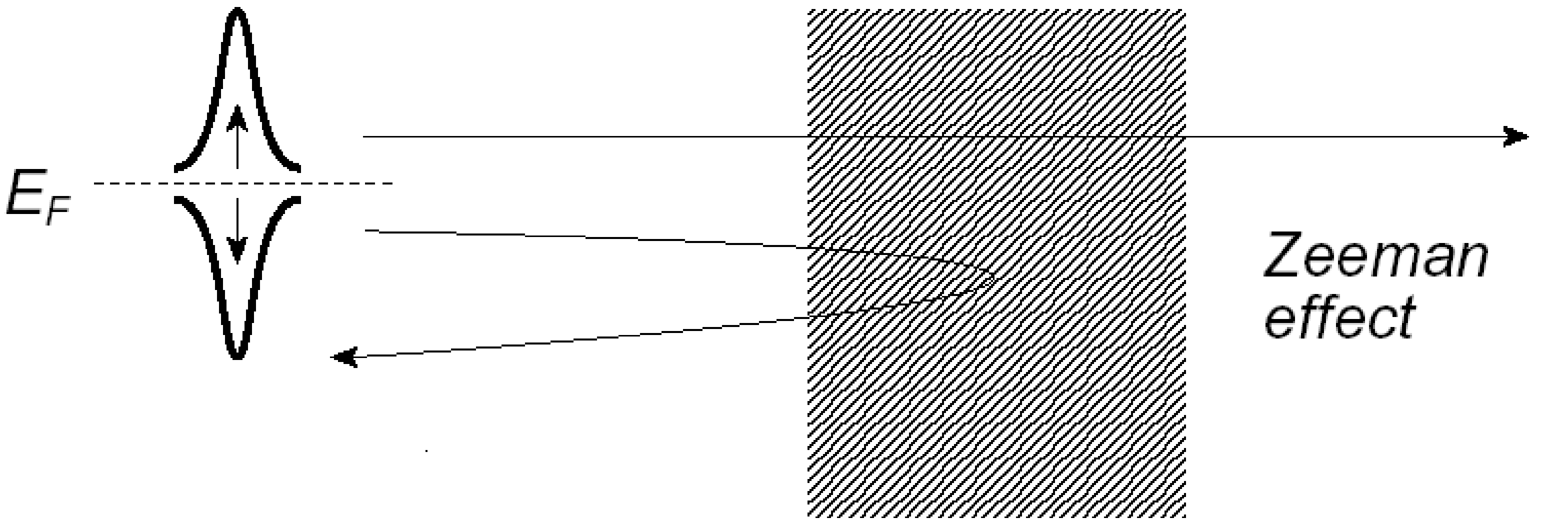


Tanaka et al.

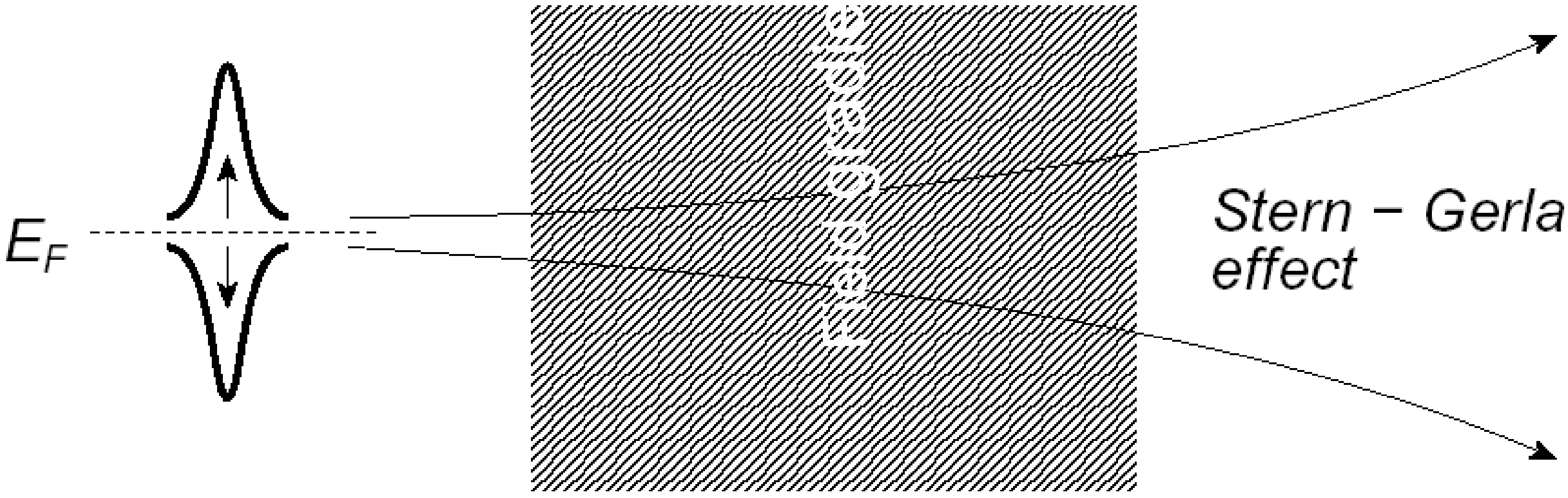
Stray fields: Stern-Gerlach effect

How spin was discovered ….

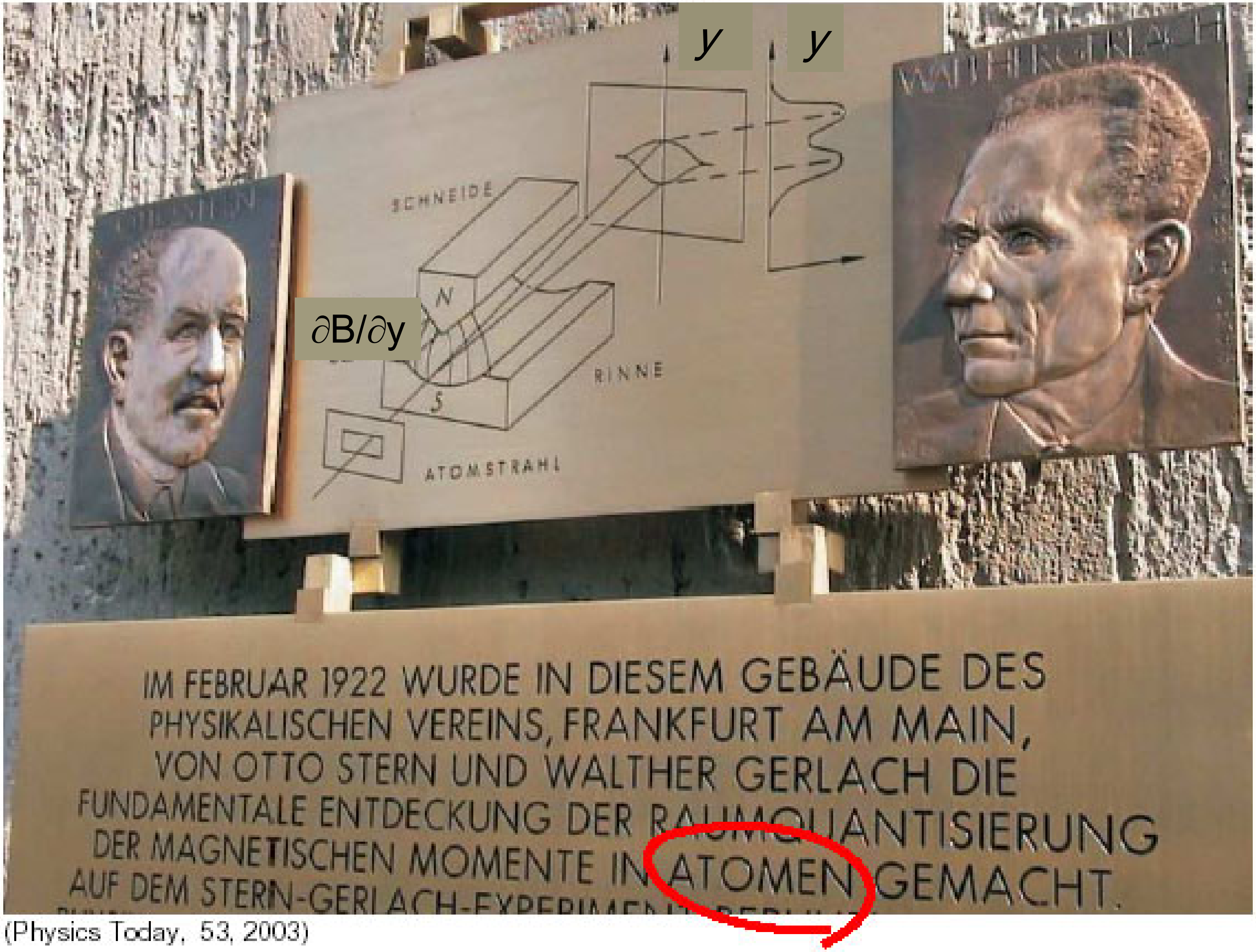
Two types of spin filters



Zeeman effect



Stern – Gerlach effect

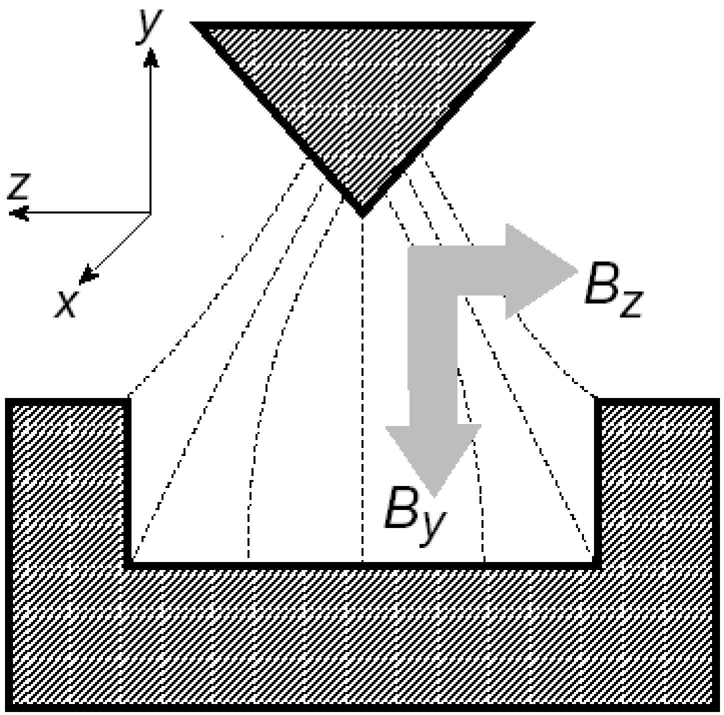


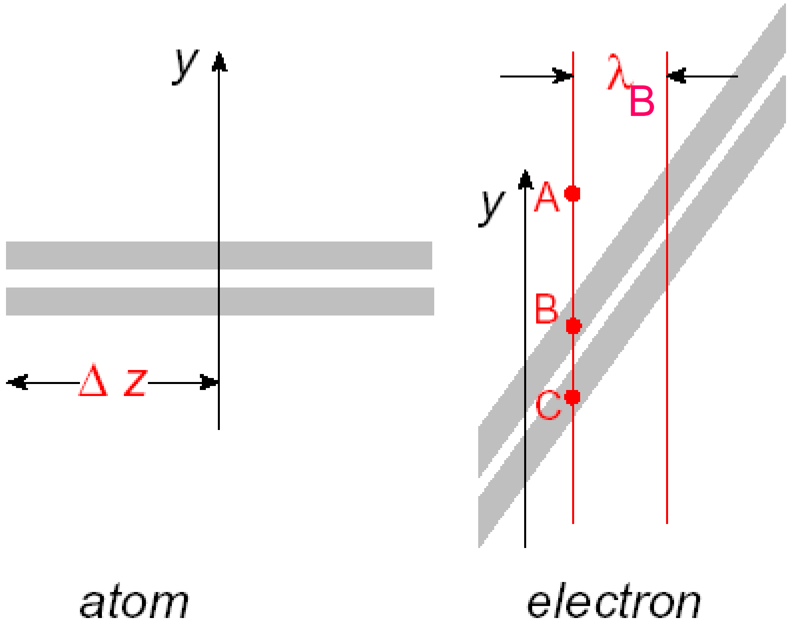
IM FEBRUAR 1922 WURDE IN DIESEM GEBÄUDE DES
PHYSIKALISCHEN VEREINS, FRANKFURT AM MAIN,
VON OTTO STERN UND WALTHER GERLACH DIE
FUNDAMENTALE ENTDECKUNG DER RAUMQUANTISIERUNG
DER MAGNETISCHEN MOMENTE IN ATOMEN GEMACHT.
AUF DEM STERN-GERLACH-EXPERIMENT

(Physics Today, 53, 2003)

Why S-G effect has not yet been observed for electrons? - *Lorentz force*

electron beams: $\Delta y, \Delta z << \lambda_B$





$$\mathrm{div}B = 0 \rightarrow \partial B_y/\partial y = -\,\partial B_z/\partial z$$

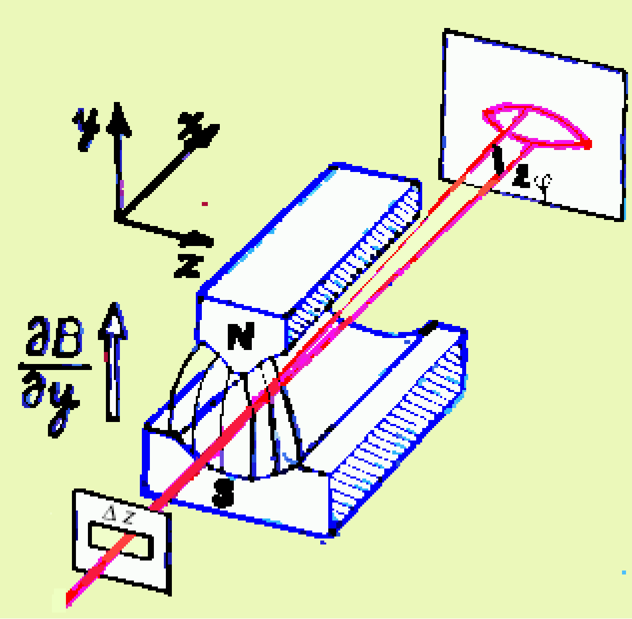
$$F_{\mathrm{zeeman}}/F_{\mathrm{Lorentz}} \approx g^*(m^*/m_e)\lambda_B/\Delta z << 1$$ *for electron beams*

Mott-Pauli argument

Feasibility of S-G experiment with electron beams

confinement!

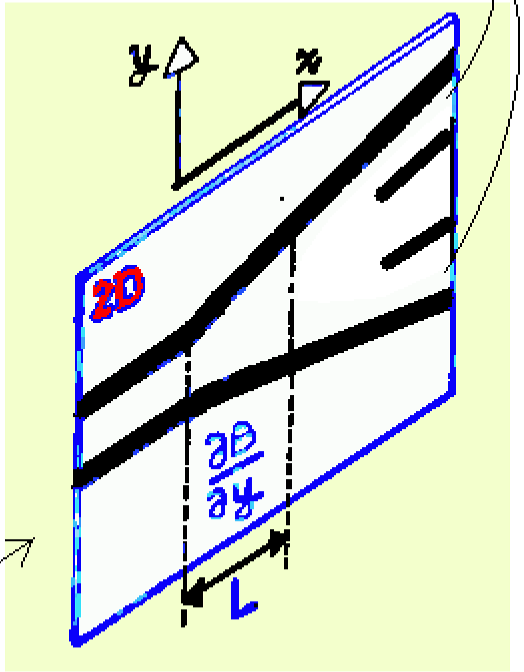
$\lambda_B / \Delta z >> 1$



Stern–Gerlach effect can't be observed for electrons. Lorentz force washes out the splitting because of the finite width of electron beam Δz. (Mott–Pauli argument).

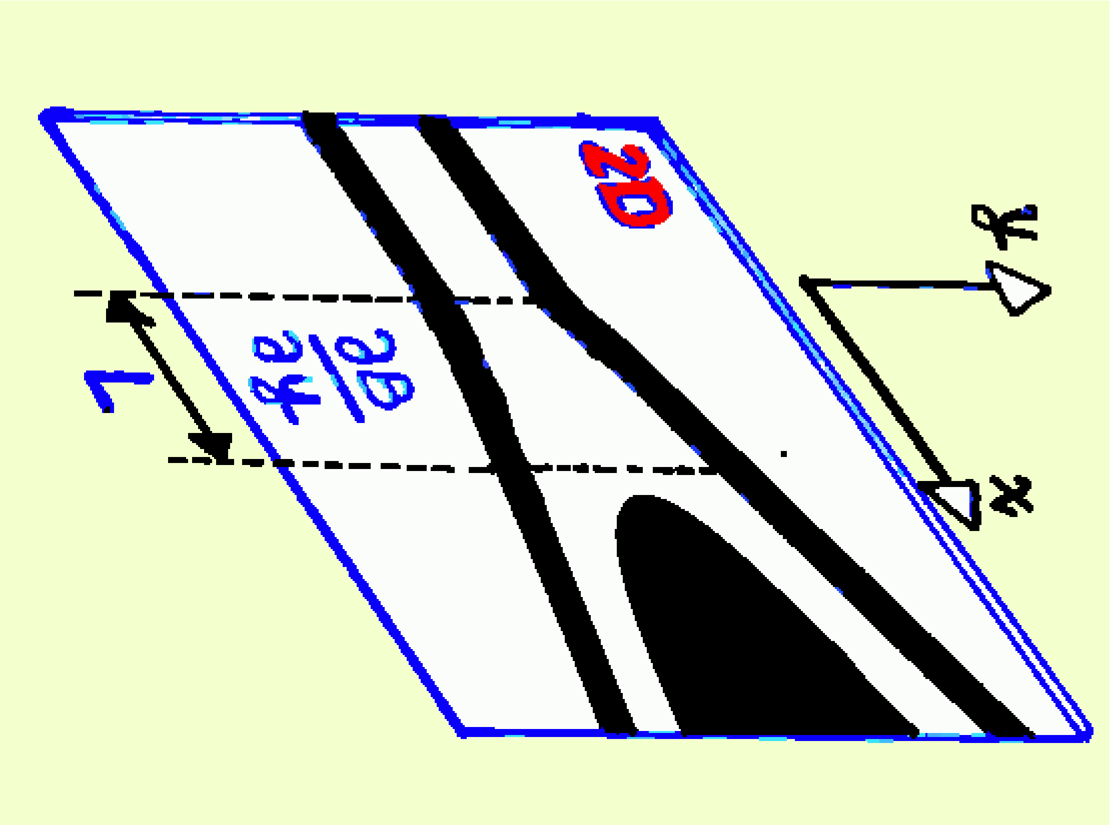
Does this argument hold for 2D electrons?

Should we expect the increase of current when field gradient is on?



J. Wróbel et al., Physica E'01

Idea of S-G apparatus



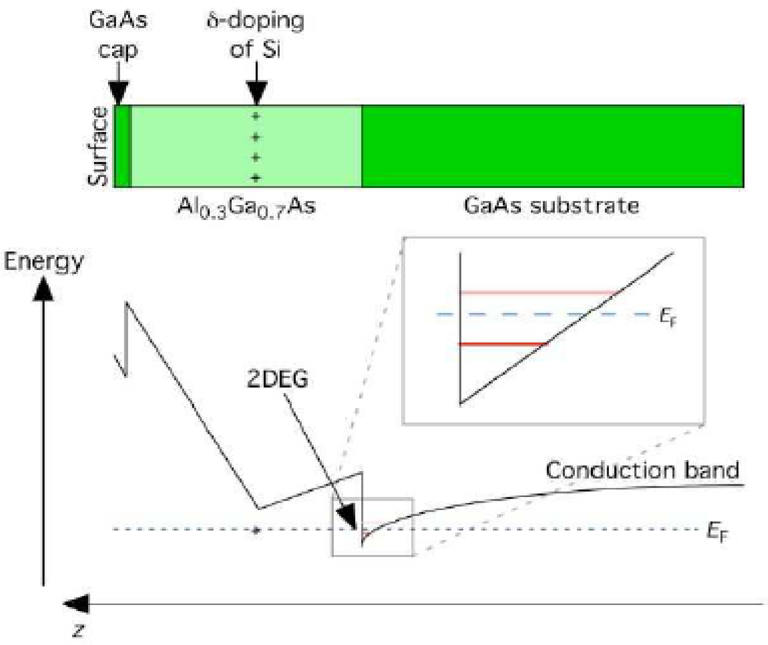
1D channel of 2DEG in a field gradient generated by micromagnets

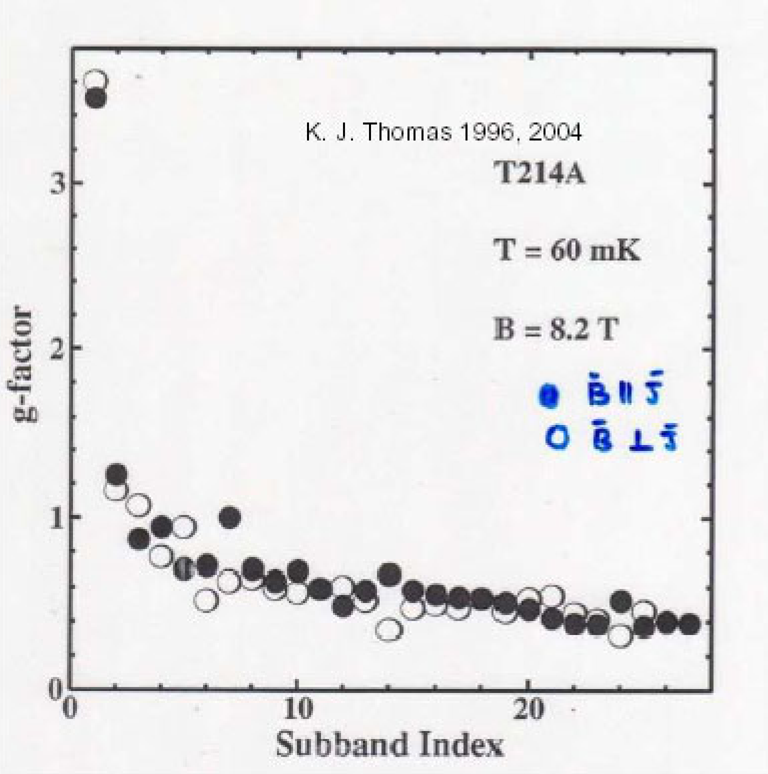
Choice of material

GaAs/(Al,Ga)As HEMTs

- **long mean free path ~ 5 μm** ☺
- **processing known** ☺

$g^*m^*/m_e << 1$ ☹

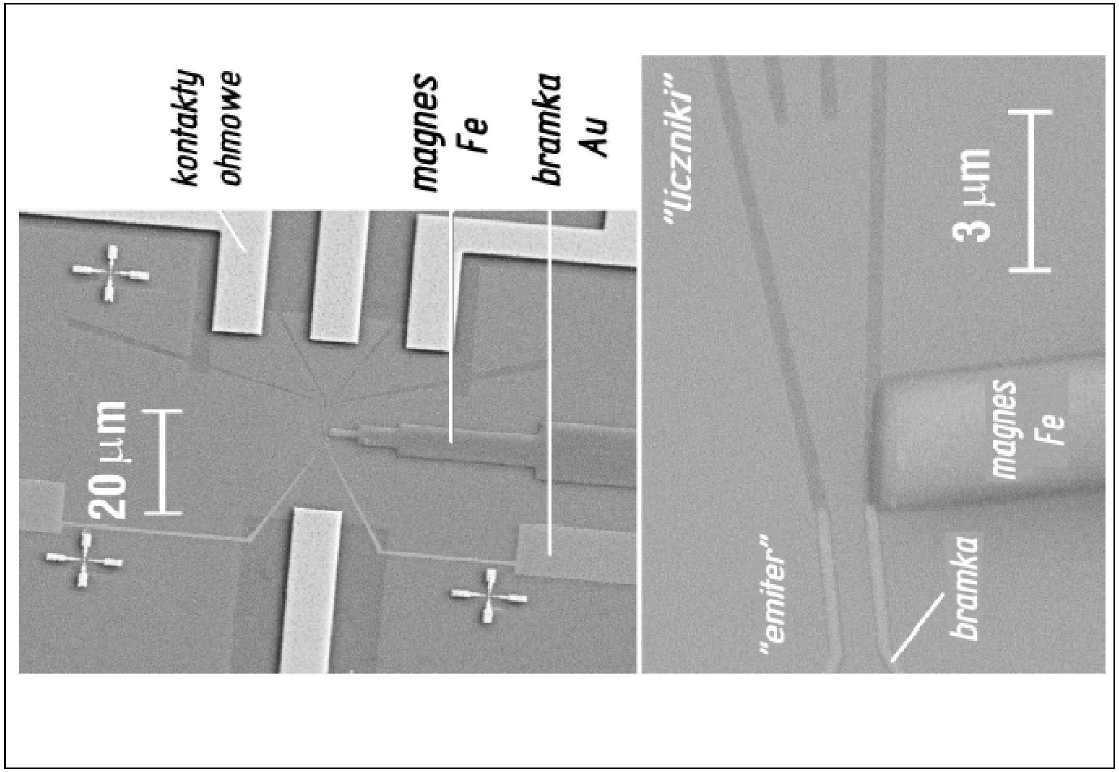




- **2DEG concentration can be** changed by V_g and illumination ☺

Fabrication method

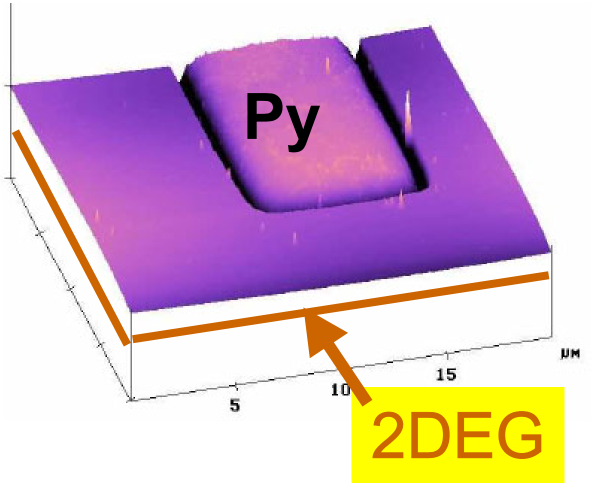
- Electron beam lithography (5 levels)
- Wet chemical etching (2 steps)
- Magnetosputtering (AuGe, AuPd, Py, Co)



One example
of probed
structures

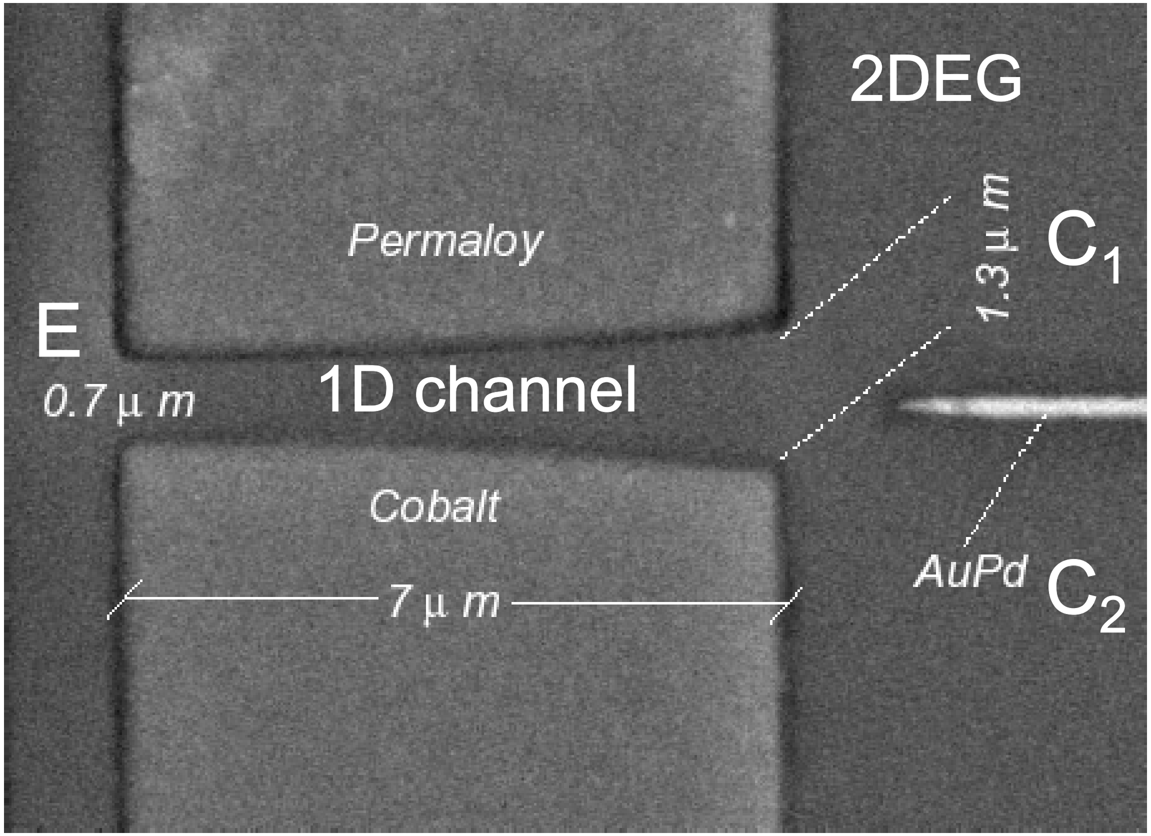
The S-G device

GaAs/AlGaAs



center of magnetic
film at 2DEG

GaAs/GaAlAs



Expl.: Does field gradient increase I_{EC1} and I_{EC2}?

Wróbel et al., PRL'04

Outline of the procedure

1. Theoretical modelling
2. Characterisation and modelling of
   - -- micromagnets
   - -- 1D channel
   - -- entire S-G device

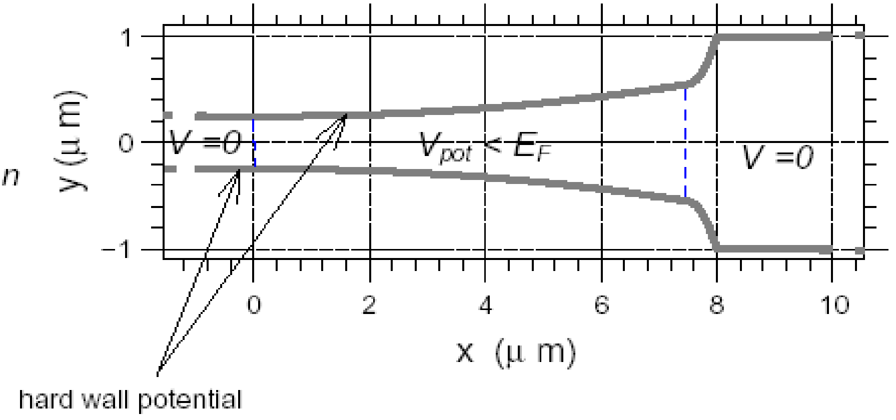
Theoretical modelling

Quantum transport

Model 1

Solution of the time independent Schrodinger equation by recursive Green function technique.

Model potential without "counters".



Łusakowski et al., PRB'03

Time independent

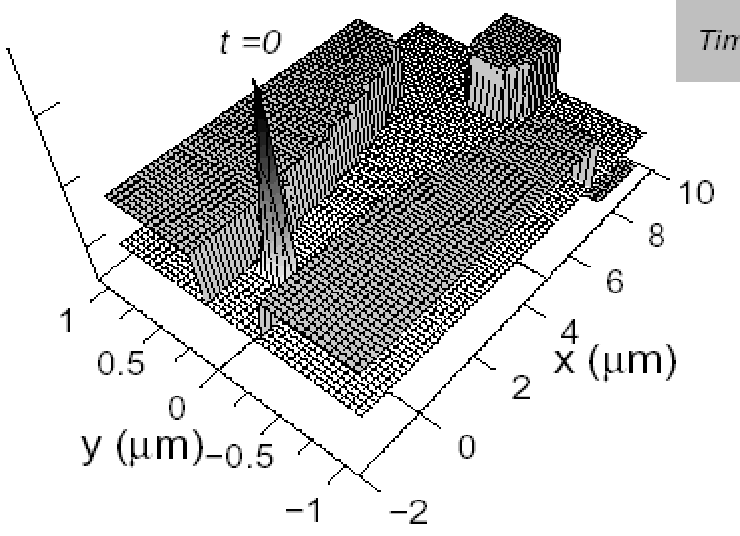
Time dependent

$g^* = 2$

Model 2

Time dependent Schrodinger equation (time evolution of wave packet).

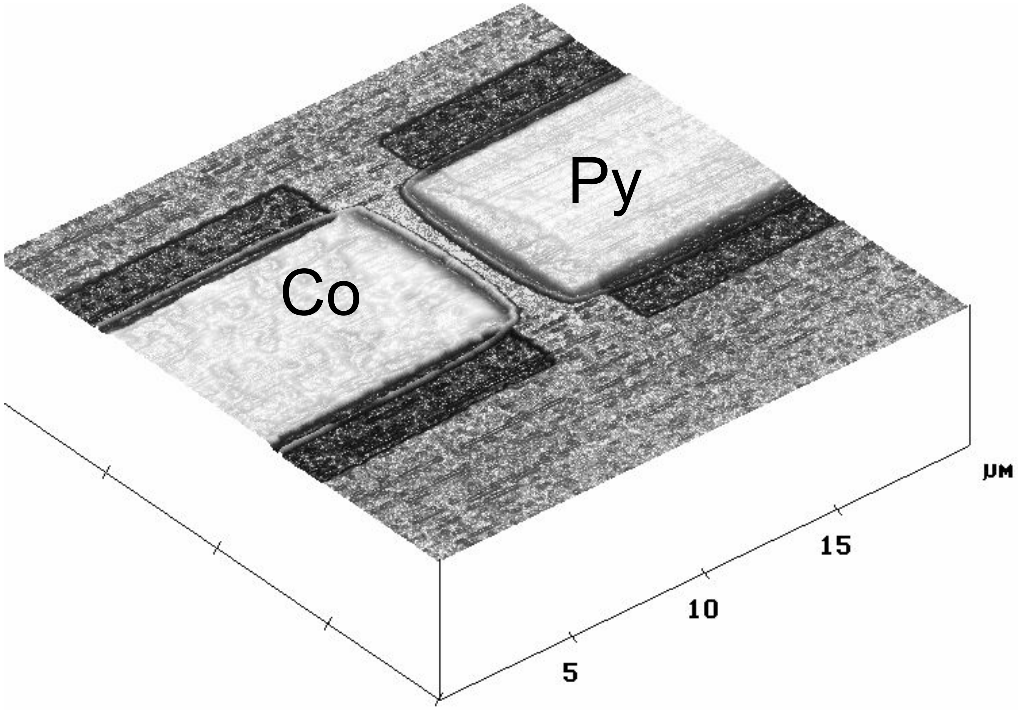
Model potential with separating groove and "counters" areas.



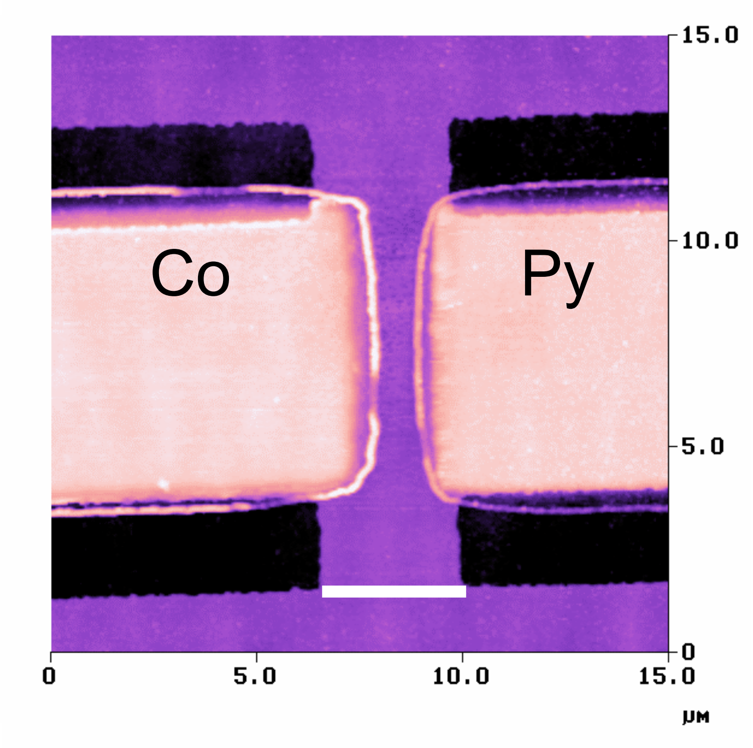
Wròbel et al..

Hall magnetometry

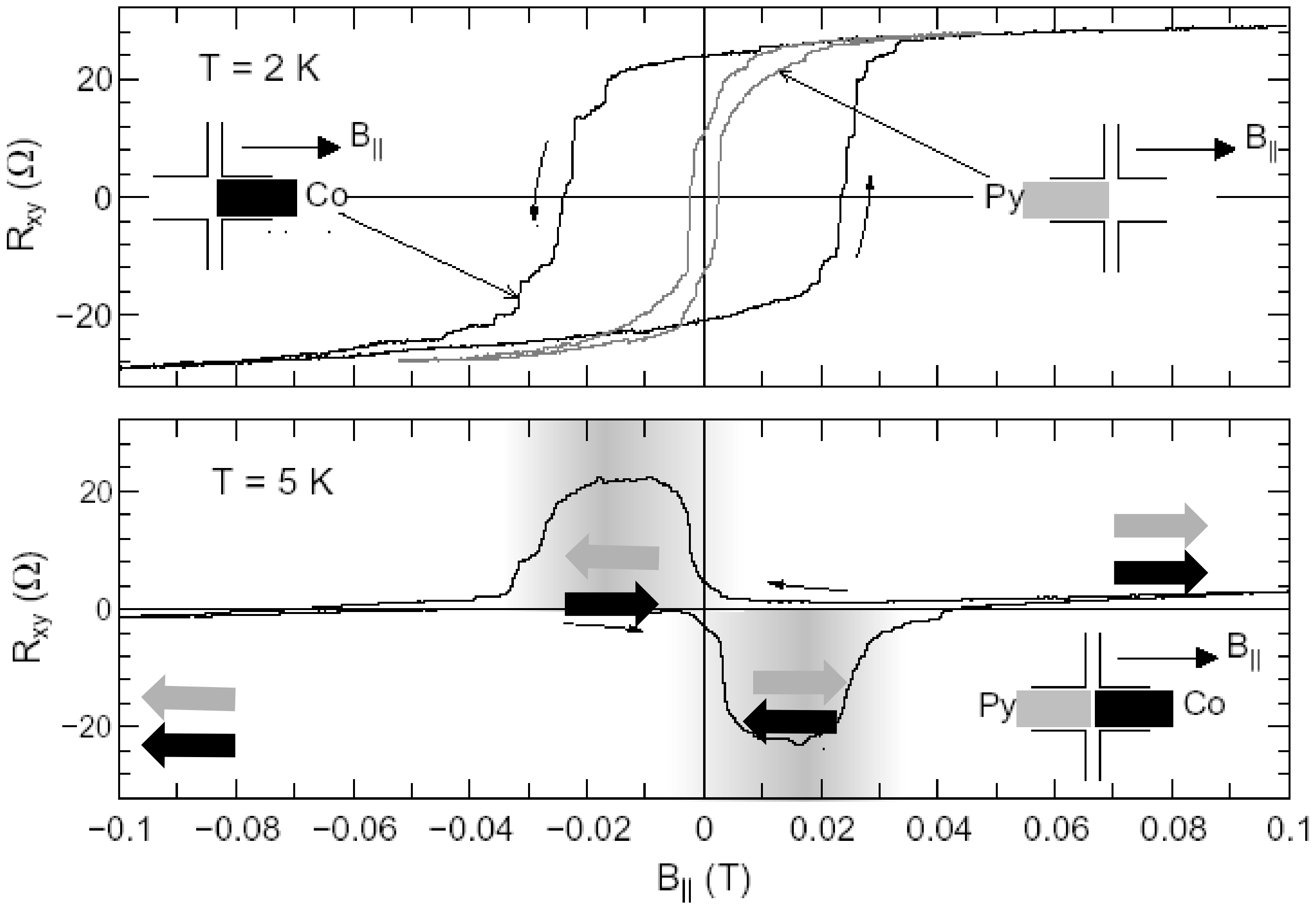
AFM image
(3D view)



AFM image
(top view)



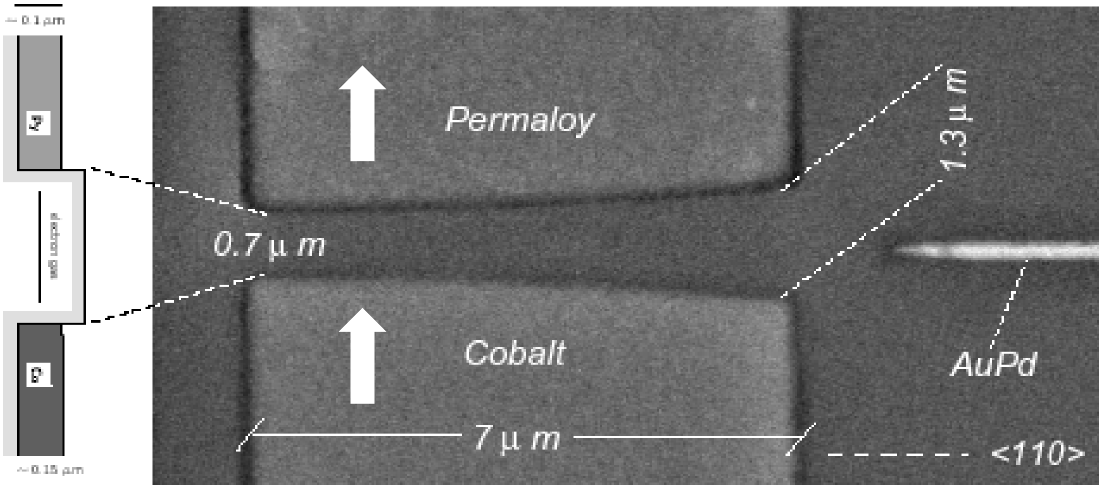
Results of Hall magnetometry



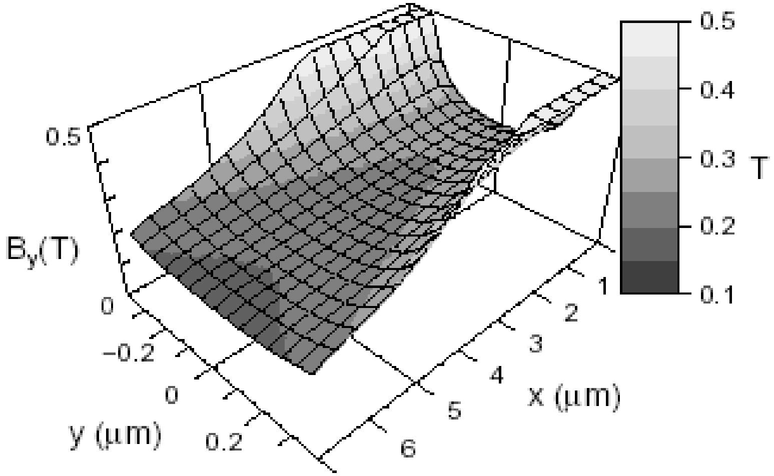
Uniform field: Zeeman mode

GaAs/GaAlAs
grown along [001]

$n = 2.3 \times 10^{11}\ cm^{-2}$
$\mu = 1.76 \times 10^{6}\ cm^{2}/Vs$
(dark)



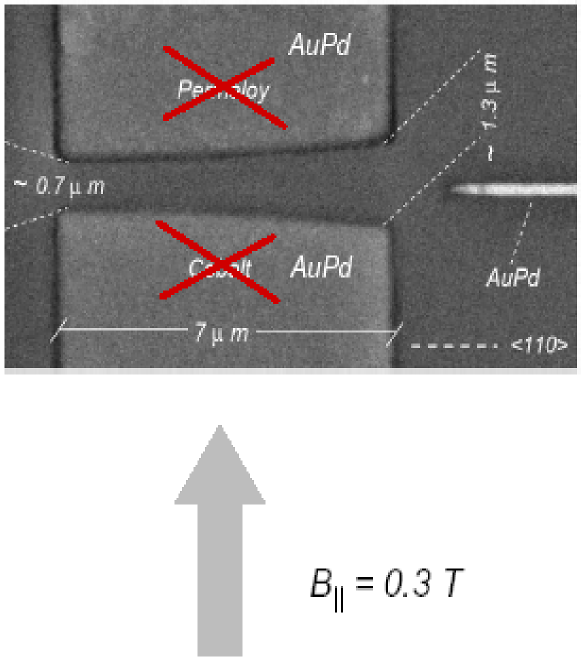
magnetic field B_y
for parallel magetizations
("gradient off")

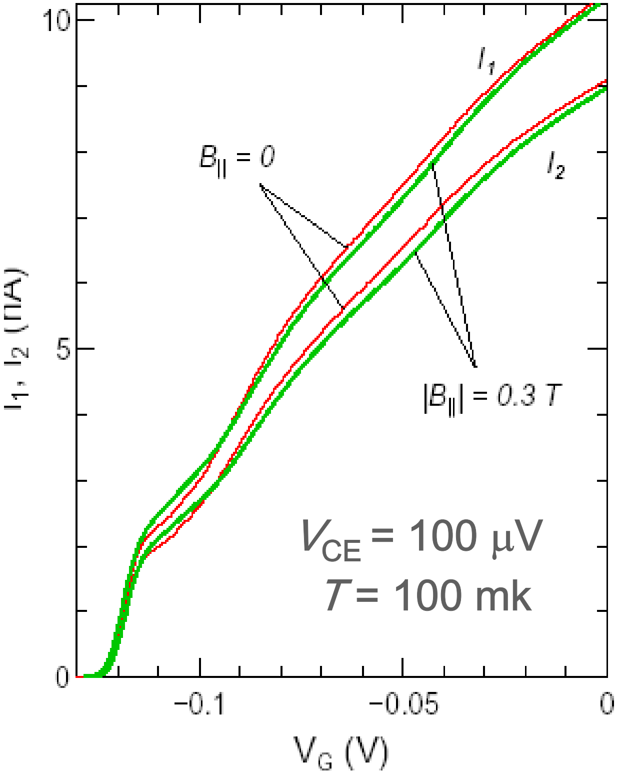


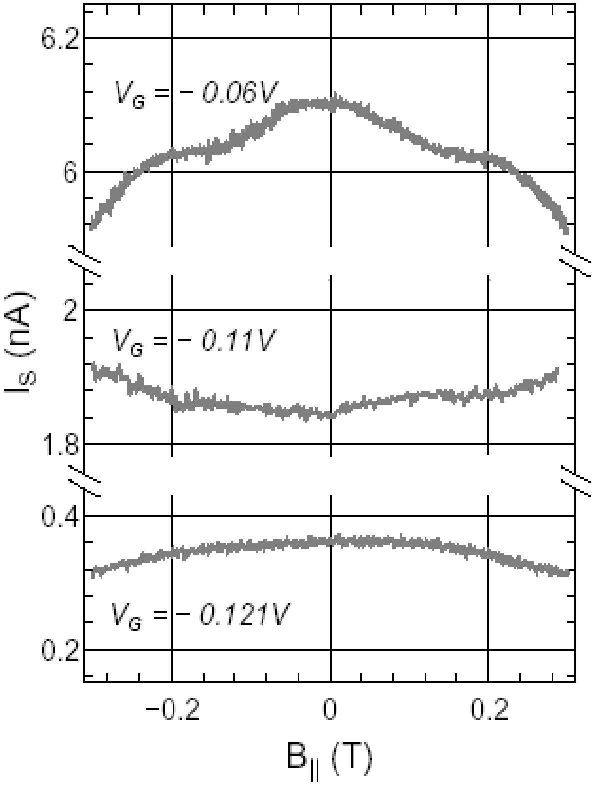
B_y up 0.3 T

Tackling between S-G and Zeeman modes

Effect of $B_{//}$ on I_{EC}





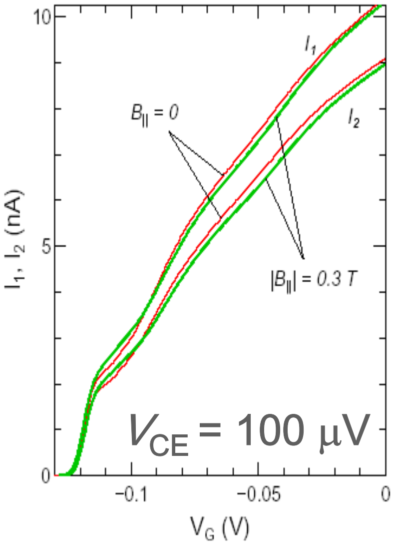


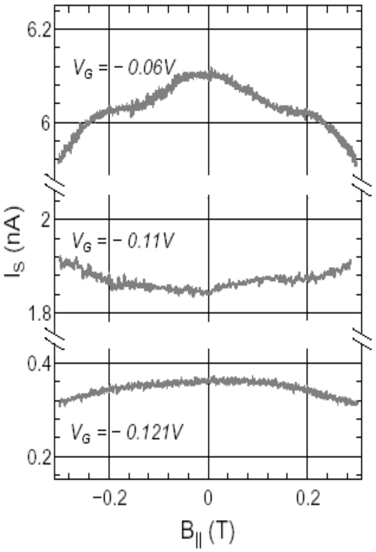
$$I_S = (I_1 + I_2)/2$$

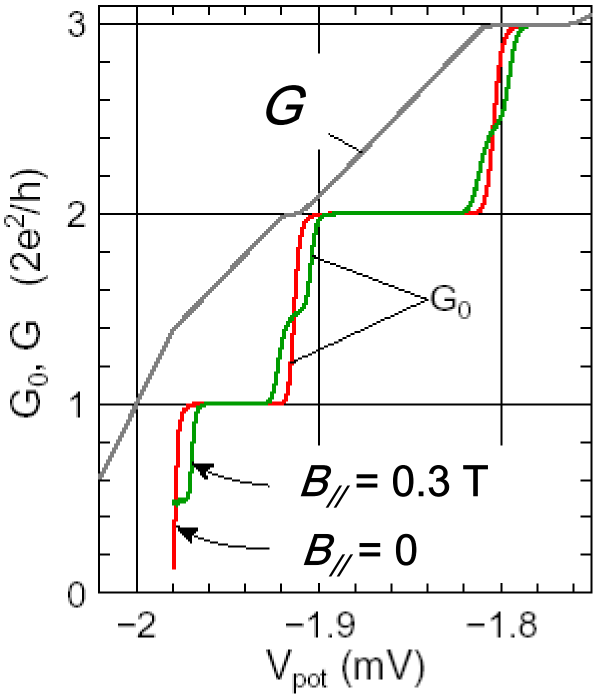
Zeeman barrier usually reduces I_{CE}

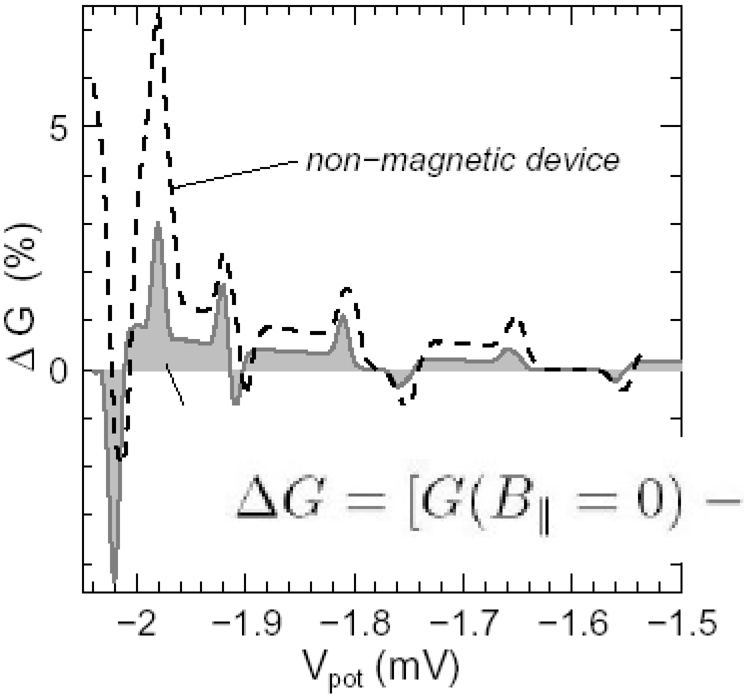
Comparison between experiment and theory

$$G = \int_{\mu_1}^{\mu_2} G_0(E)\,dE$$
$$\mu_2 - \mu_1 = eV_{CE}$$



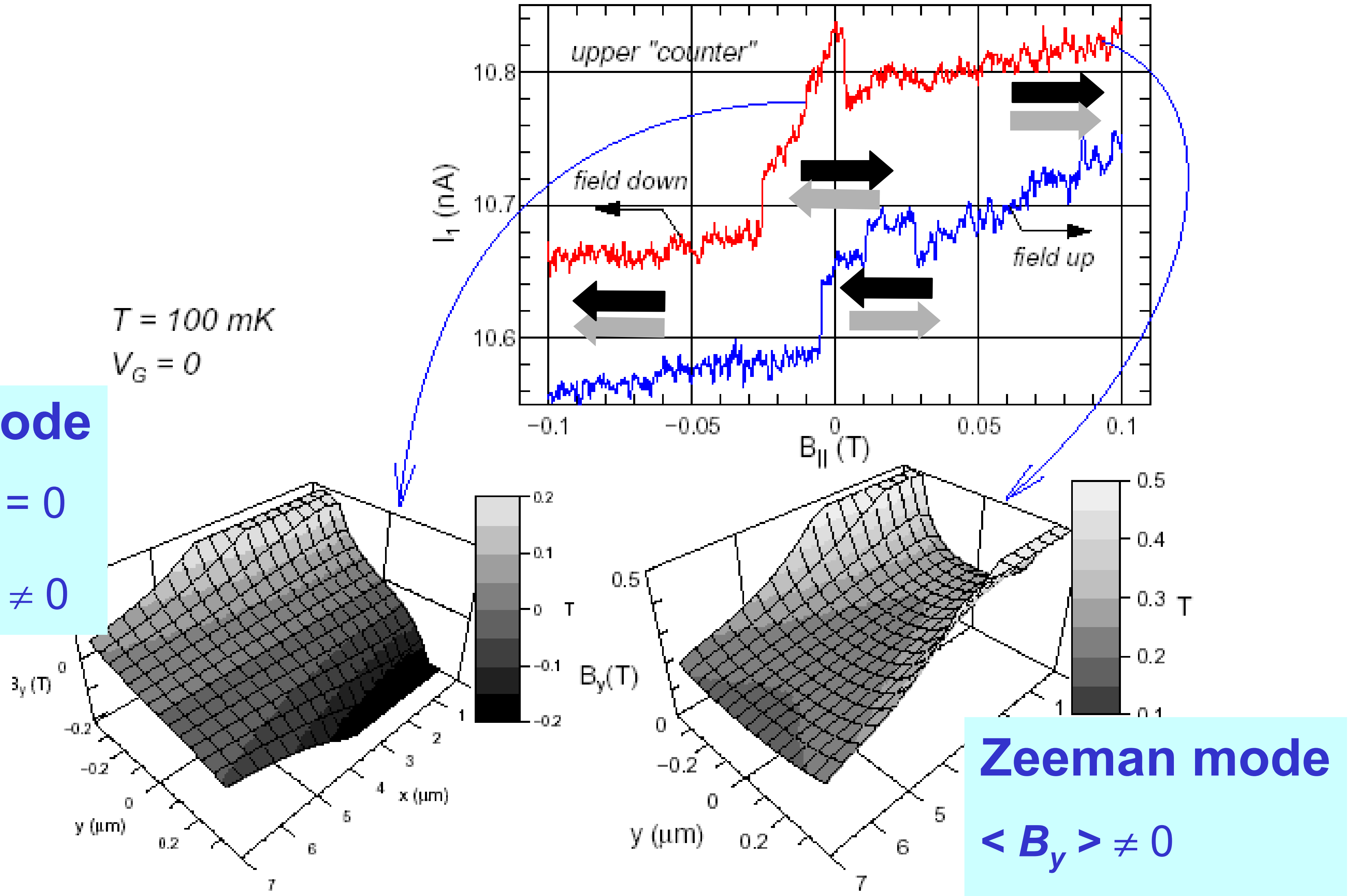






$$\Delta G = [G(B_\| = 0) - G(B_\| = 0.3\ \mathrm{T})]/\langle G \rangle$$

Effect of micromagnets’ magnetisation on I_{EC}



T = 100 *mK*
$V_G = 0$

S-G mode

$< B_y > = 0$

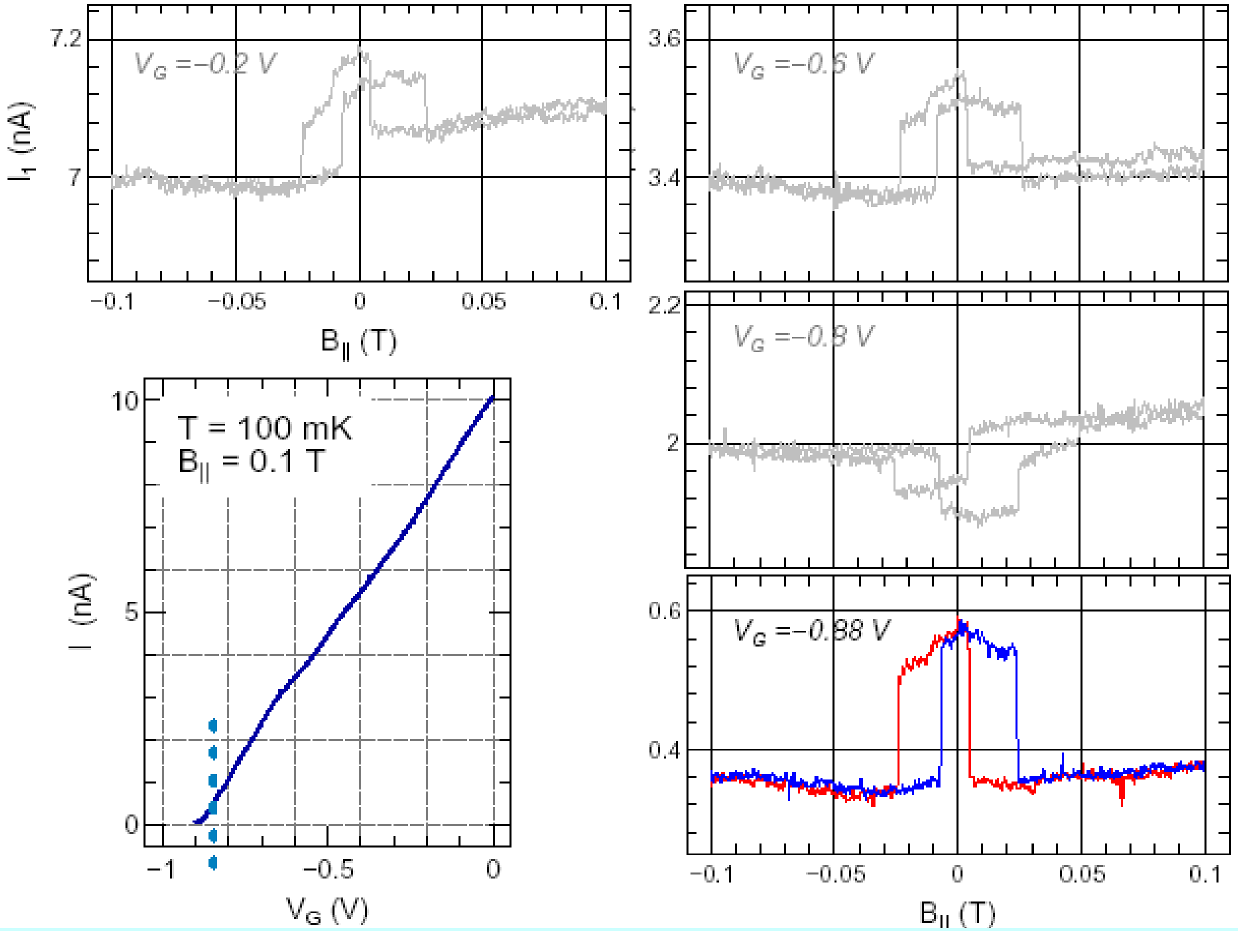
$\partial B_y / \partial y \neq 0$

Zeeman mode

$< B_y > \neq 0$

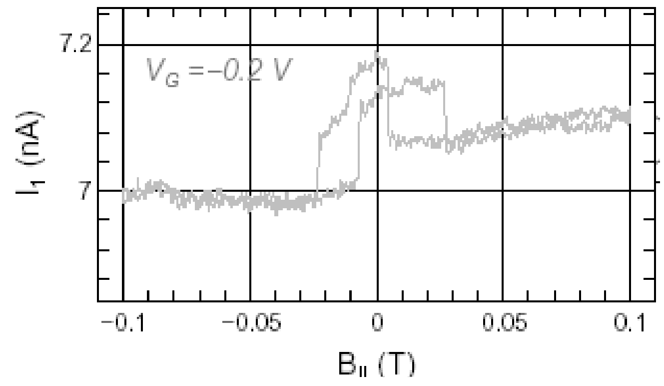
$\partial B_y / \partial y \approx 0$

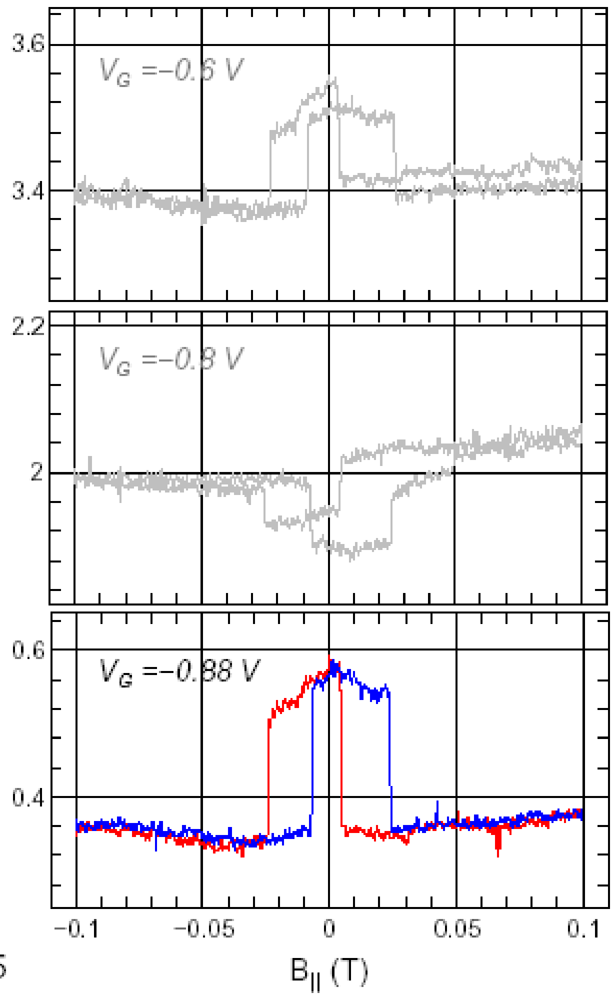
Effect of micromagnets’ magnetisation on I_{EC}

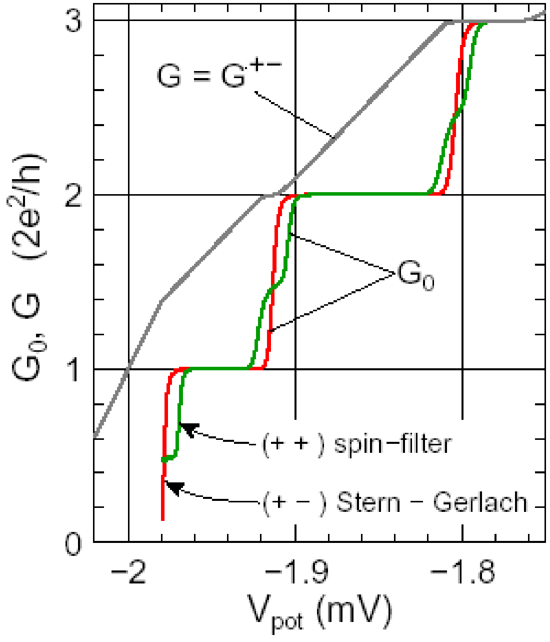


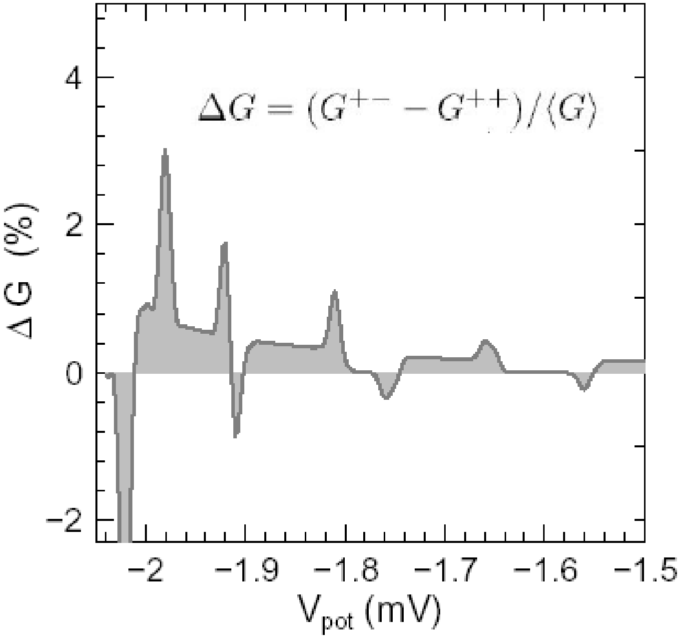
Questions:
- **Are I_{EC} changes due to S-G or Zeeman effect?**
- **Are spin currents spatially separated?**

Comparison between experiment and theory

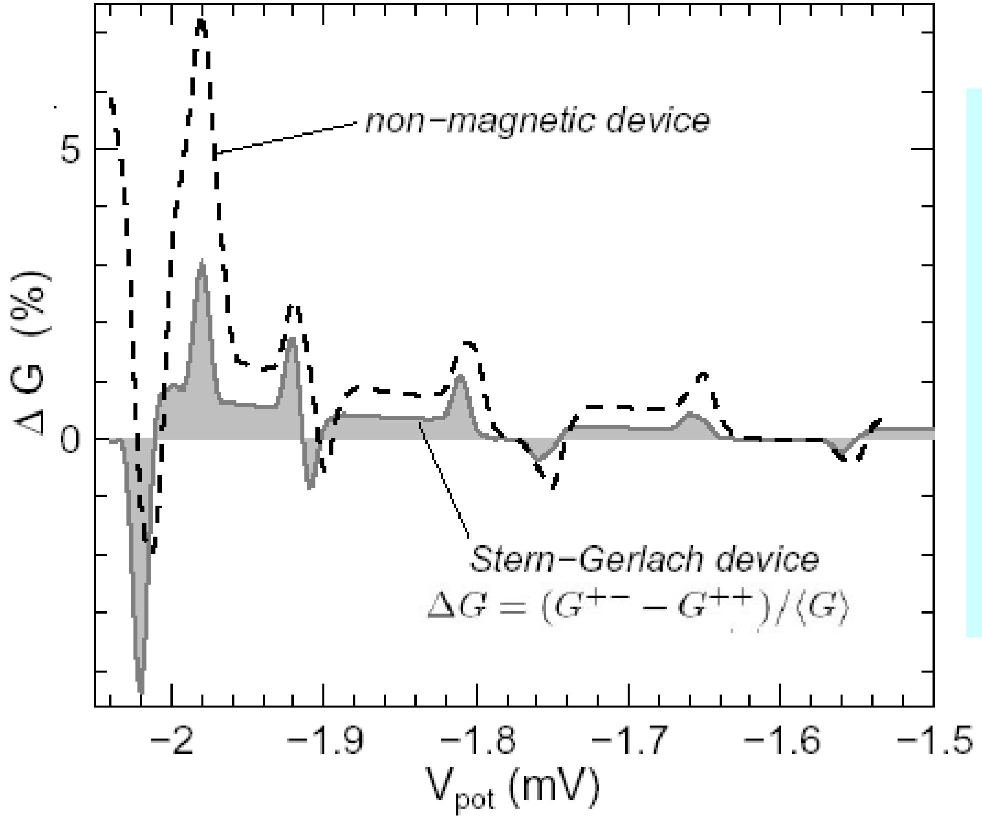








Conclusion from modelling of I_{EC}



$$\Delta G = [G(B_{\parallel} = 0) - G(B_{\parallel} = 0.3\ \mathrm{T})]/\langle G\rangle$$

- I_{EC} changes mostly due to Zeeman effect
- Are spin currents spatially separated?

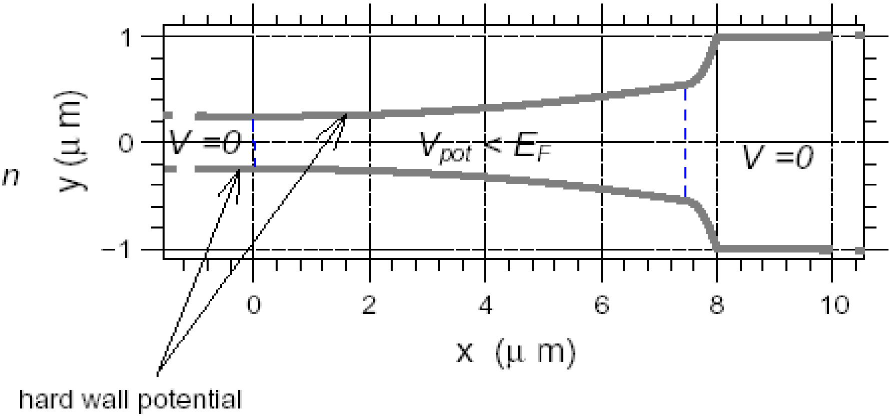
Theoretical modelling

Quantum transport

Model 1

Solution of the time independent Schrodinger equation by recursive Green function technique.

Model potential without "counters".

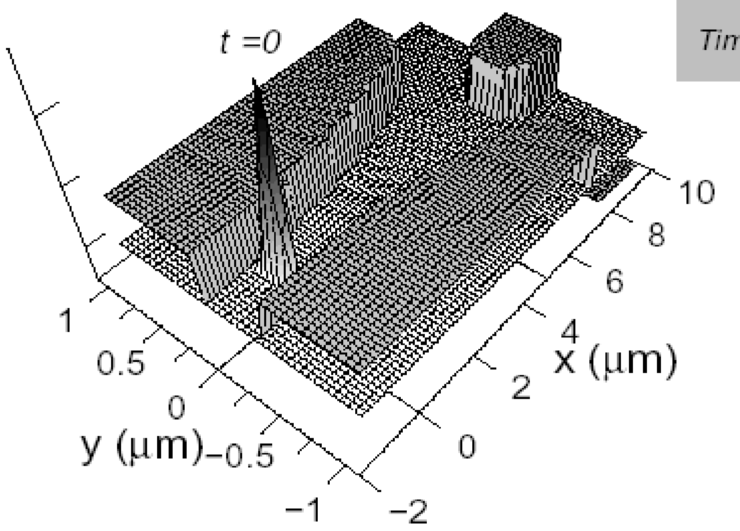


$g^* = 2$

Model 2

Time dependent Schrodinger equation (time evolution of wave packet).

Model potential with separating groove and "counters" areas.



Time independent

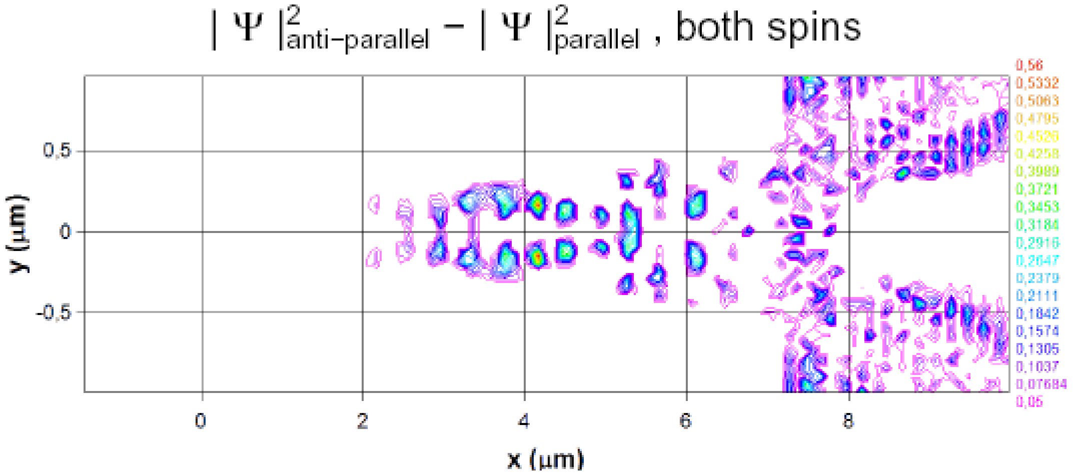
Time dependent

Theoretical studies of spin separation

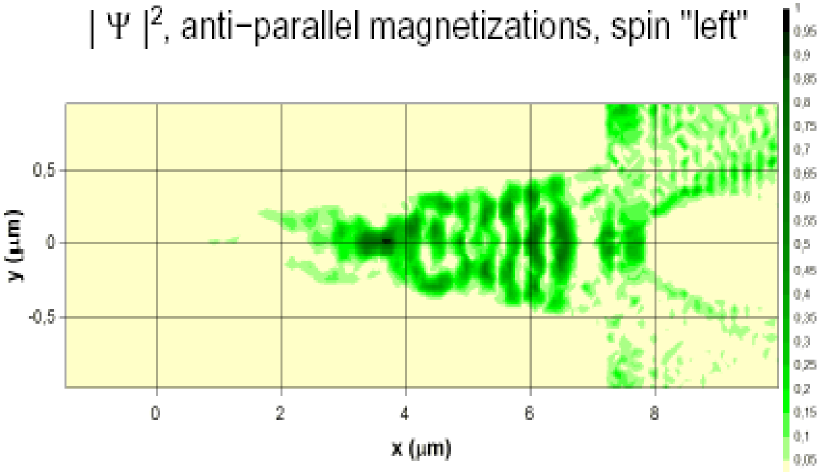
Model 2, time = 92.5 ps

Wave packet
kinetic energy
E_{kin} = 0.5 meV
Initial channel
width W = 0.5 μ m

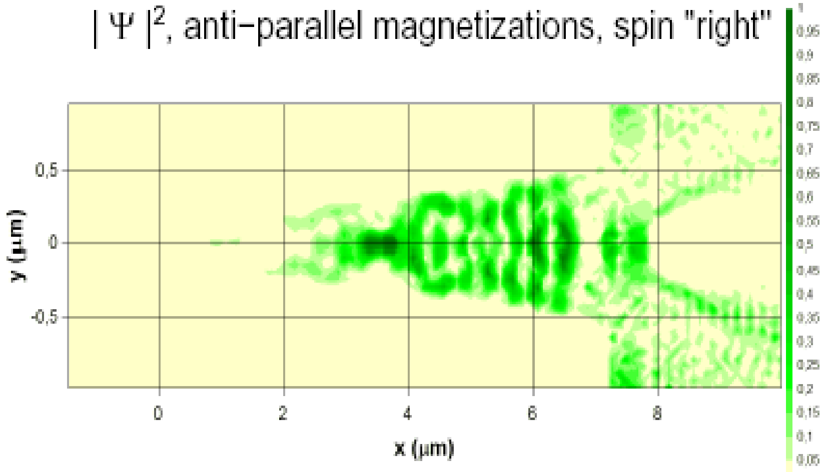
$\Delta I_{EC} / I_{EC}$ = 2.0%
as in model 1



$| \Psi |^2_{\text{anti-parallel}} - | \Psi |^2_{\text{parallel}}$, both spins



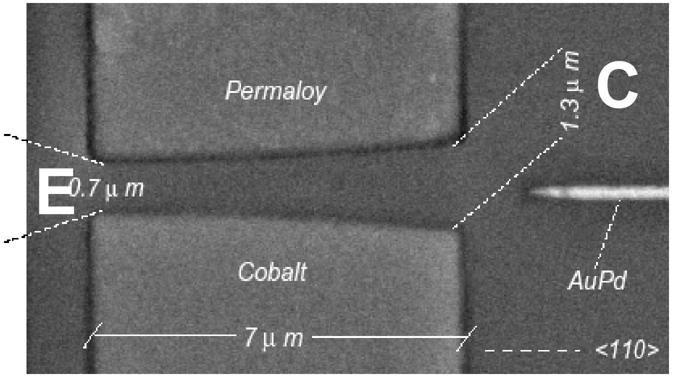
$| \Psi |^2$, anti-parallel magnetizations, spin "left"

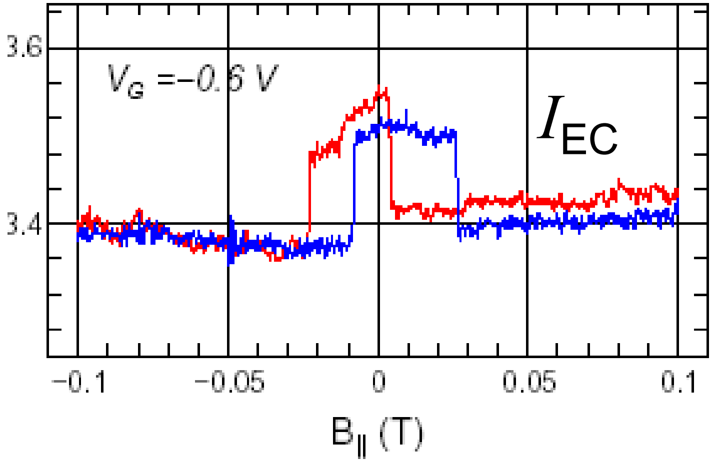


$| \Psi |^2$, anti-parallel magnetizations, spin "right"

A large spin separation takes place

Summary

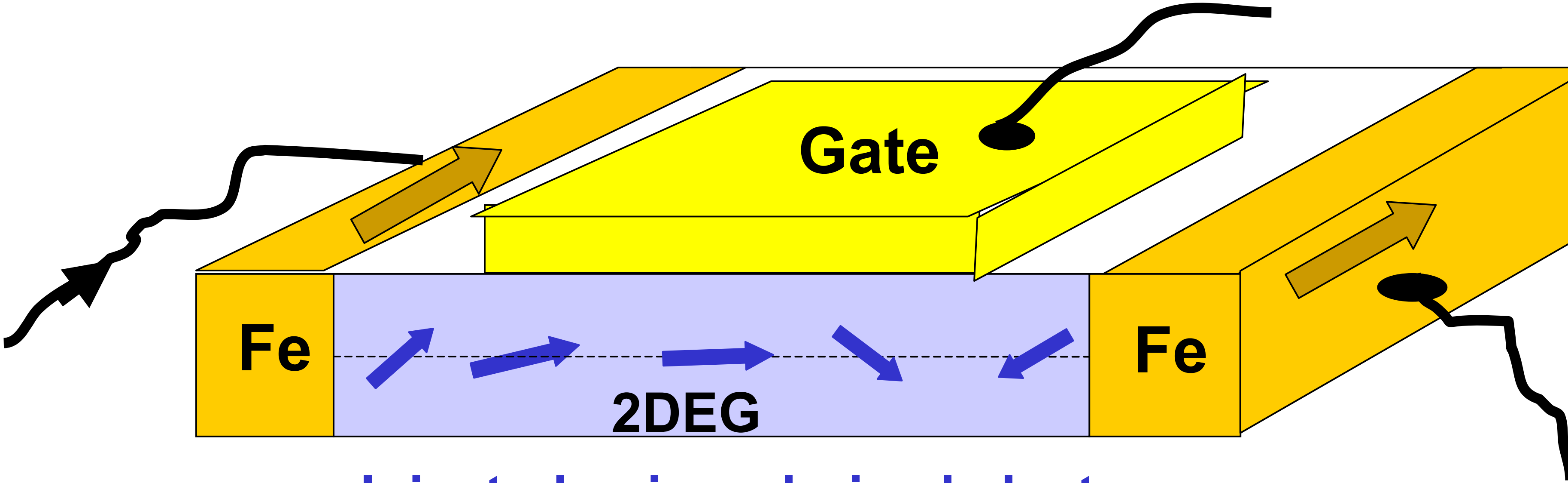




1. Changes of total current occur mostly due to Zeeman effect
2. Spin currents appear in the Stern-Gerlach mode
3. Spin current detector needed
   - -- S-G devices in series
   - -- LED
   - -- nuclear effects
   - -- shot noise spectroscopy
   - -- Andreev reflection

Datta-Das transistor and spin injection

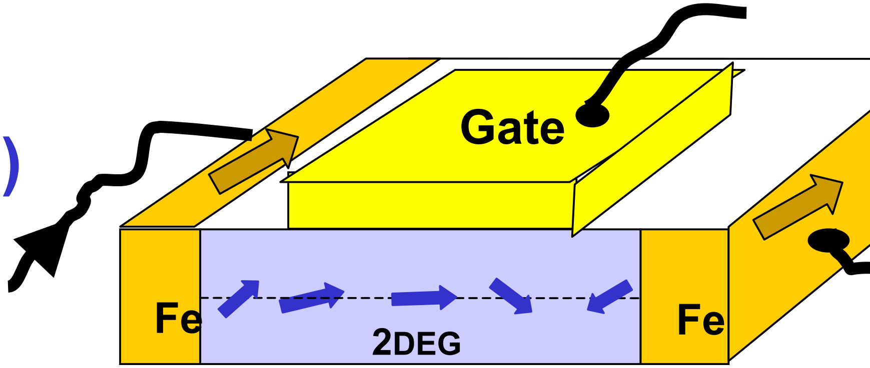
Datta-Das spin transistor



Injected spin-polarized electrons from ferro contacts precess in the Rashba field controlled by the gate voltage

$$H_R = \alpha_R(\mathcal{E})\hat{c}\,(\boldsymbol{s}\times\boldsymbol{k})$$

Datta-Das spin transistor - difficulties



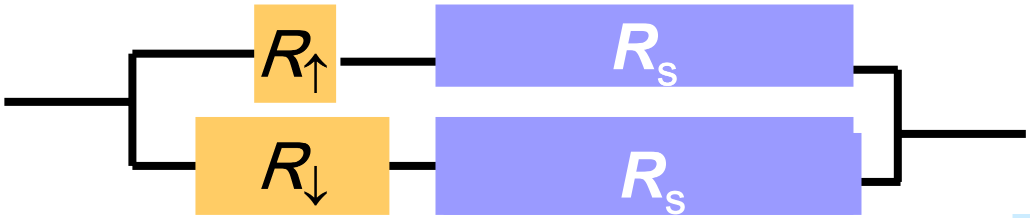
- **stray fields (magnetoresistance, Hall effect)**

- **interface chemistry (eg. silicides)**

- **"resistance mismatch"**

  spin injection from ferromagnetic metal to non-magnetic semiconductors

  two independent channels (spin up and spin down)

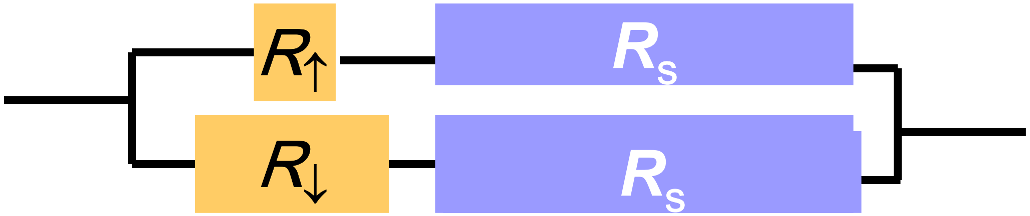


since $R_s >> R_{\downarrow\uparrow}$

$R_{tot} \approx 2R_s$

No spin injection !?

Ways to succeed



1. **Half metals:** $R_\downarrow \rightarrow \infty$

   Heusler alloys, manganites, CrO_2, Fe_3O_4, …

2. **Ferromagnetic semiconductors:** $R_{\downarrow\uparrow} \approx \boldsymbol{R_s}$

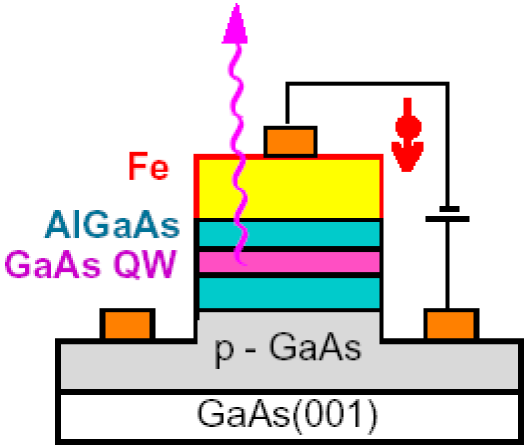
3. **Large contact resistance between FM and SC**

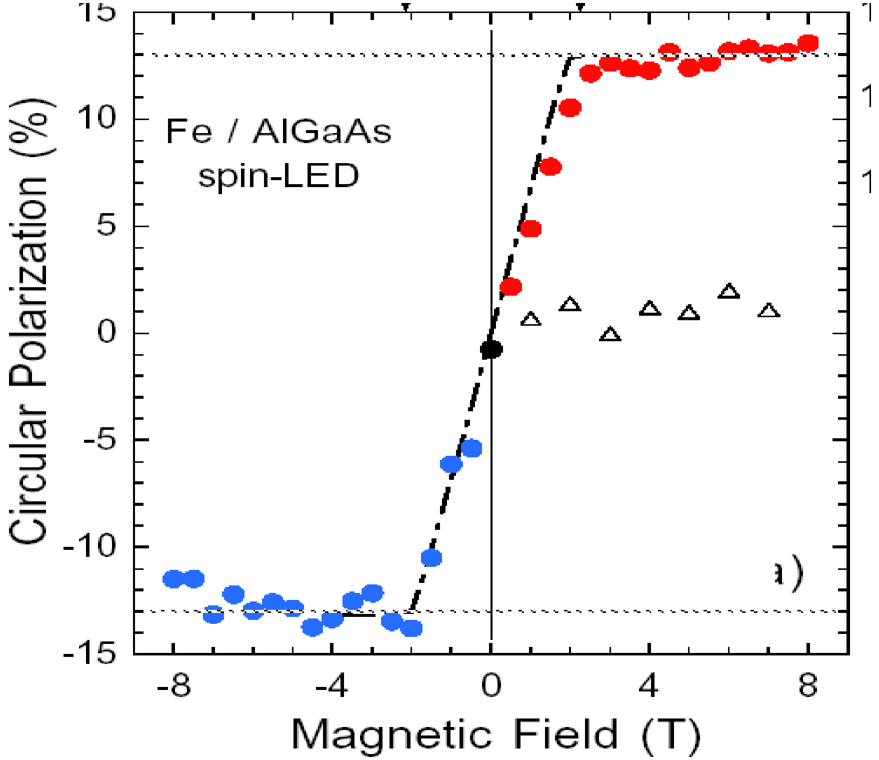
   -- tunnelling barrier AlO_x, …

   -- Schottky barrier

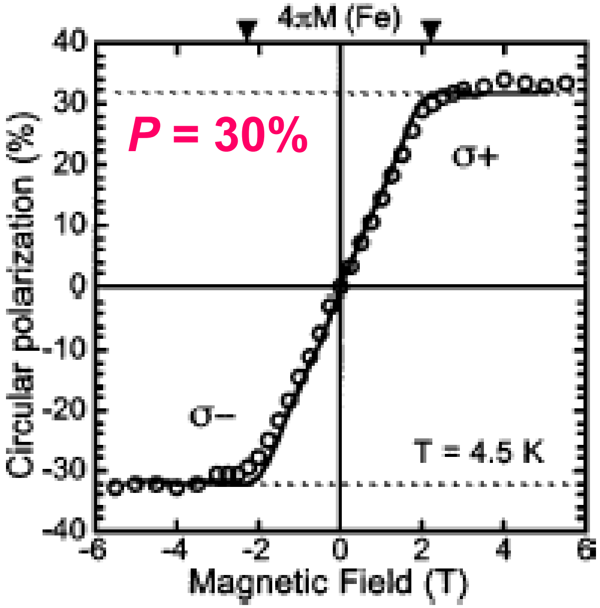
Rashba PRB'00

Observation of efficient spin injection





Hanbicki et al. (NRL) APL'02



Summary – hybrid structures

1. Magnetic field spatially inhomogenous on submicron scale can be generated by micromagnets

2. Efficient spin injection from ferromagnetic metals into semiconductors possible

   eg. Fe → GaAs

   no yet spin injection to Si demonstrated