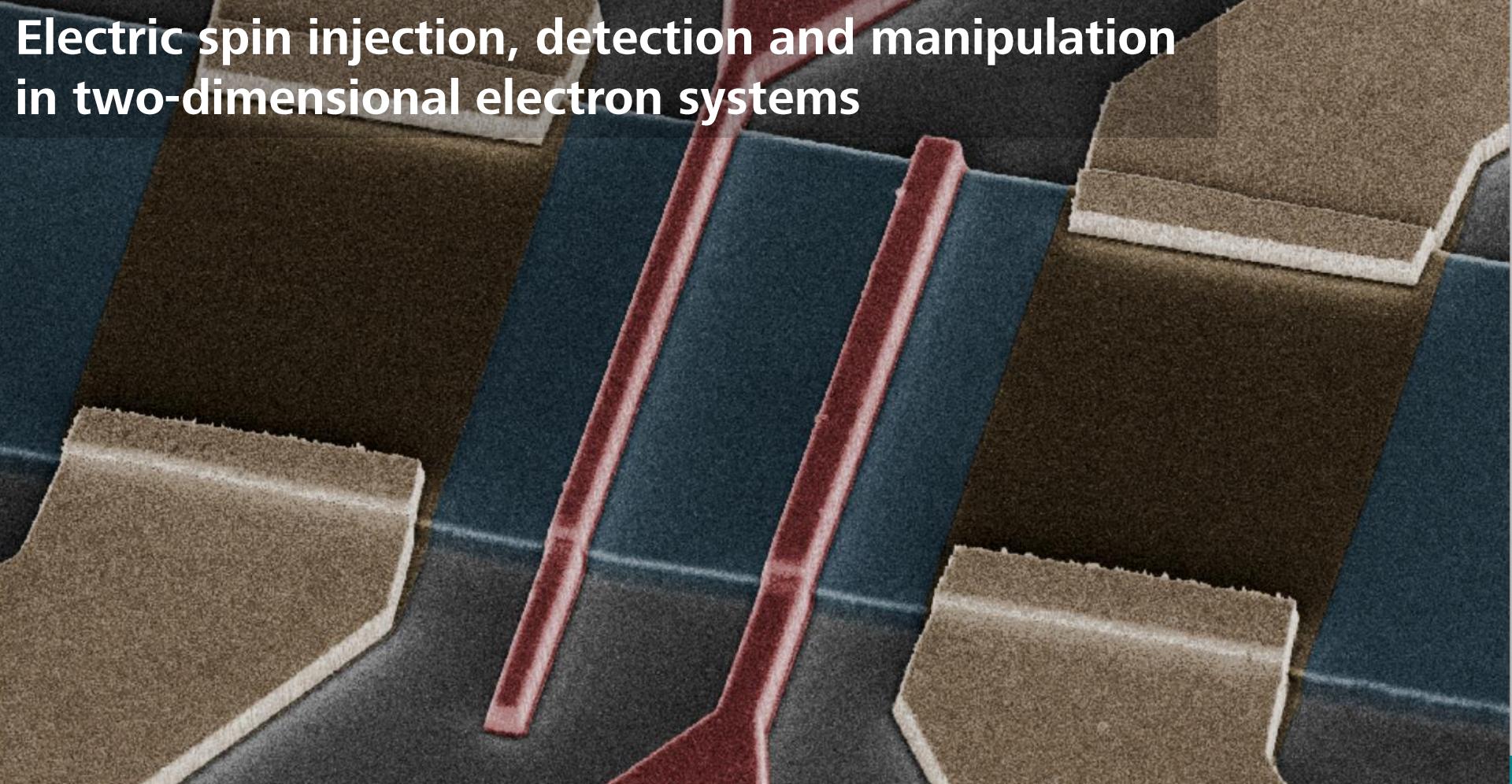


Electric spin injection, detection and manipulation in two-dimensional electron systems



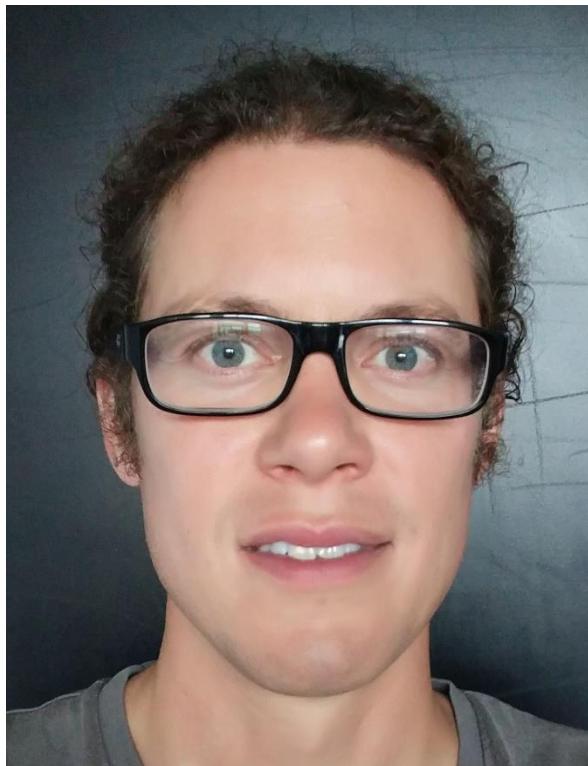
Dieter Weiss



Universität Regensburg

Collaborators

Martin Oltscher



Franz Eberle



Mariusz Ciorga



Experimentelle und Angewandte Physik, Universität Regensburg:

Thomas Kuczmik, Thomas Schmid, Junichi Shiogai¹⁾, Martin Utz, Andreas Bayer, Dieter Schuh, Dominique Bougeard, Christian Back

¹⁾ now Tohoku University

Spin-injection

(electrical)

Metals

TMR, GMR

Spin Charge coupling

Bulk semiconductors

CoFe/AlO_x/(Al,Ga)As/GaAs: Motsnyi *et al.* (2002)

Fe/Al₂O₃/Si: Van't Erve *et al.* (2007)

Fe/MgO/Si: Sasaki *et al.* (2009)

NiFe/Al₂O₃/Si: Dash *et al.* (2009)

Fe/GaAs: Lou *et al.* (2007)

CoFe/Si: Ando *et al.* (2011)

GaMnAs/GaAs: Ciorga *et al.* (2009)

...

Graphene

Tombros *et al.* (2007)

Ohishi *et al.* (2007)

Han *et al.* (2010)

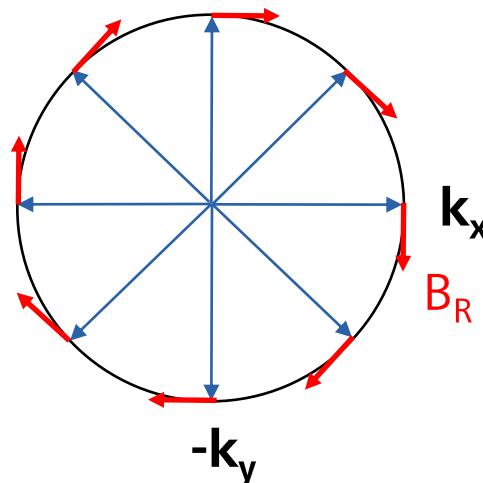
....

Two-dimensional electron gas

Topic of today's presentation

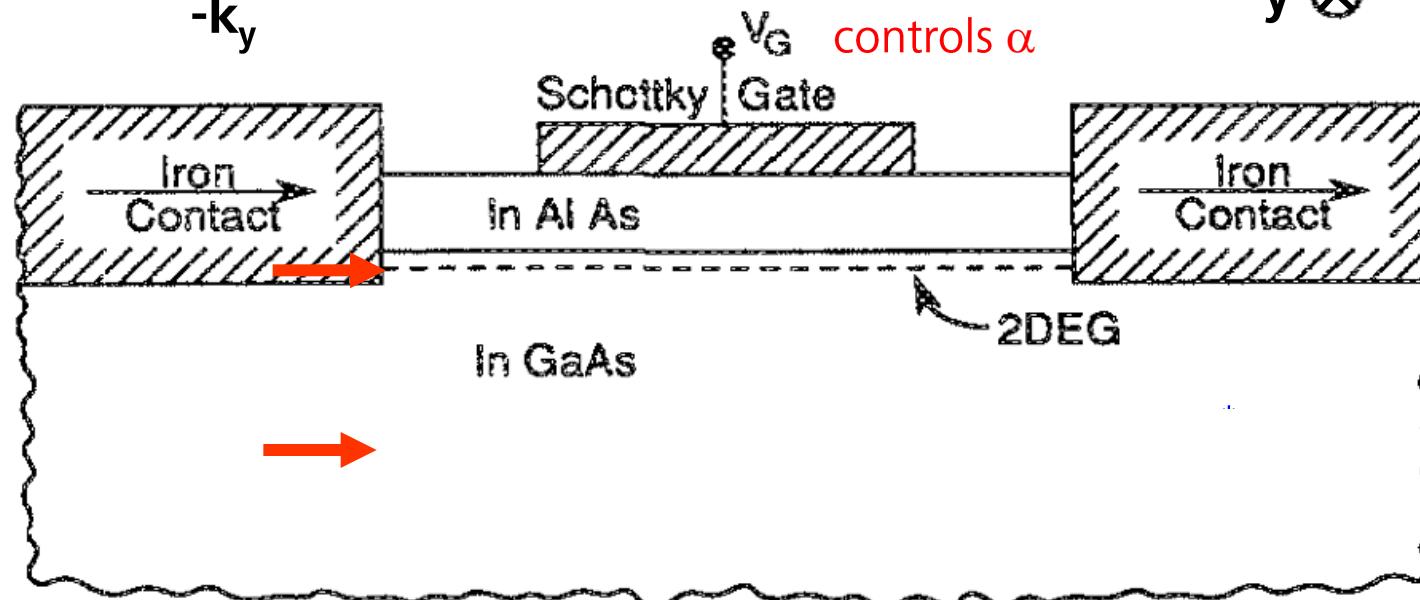
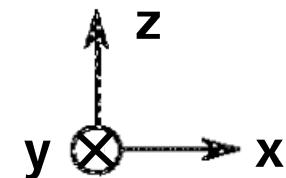
Datta-Das spin transistor: concept

S. Datta and B. Das, APL **56**, 665 (1990)



Rashba spin-orbit interaction:

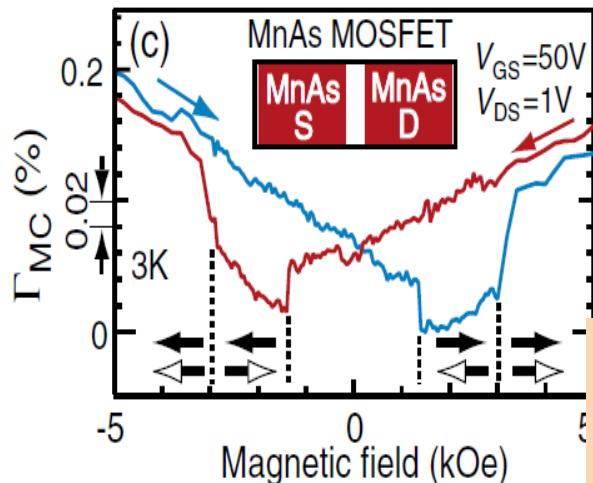
$$H_R = \alpha (\sigma_x k_y - \sigma_y k_x)$$



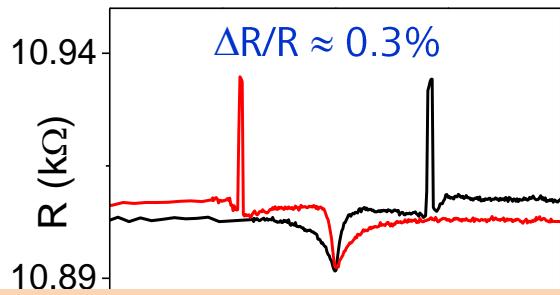
Rashba SO-coupling produces for electrons moving in x-direction a k-dependent **magnetic field** in -y-direction – spin precesses in xz-plane

Local two-terminal MR in semiconductor devices

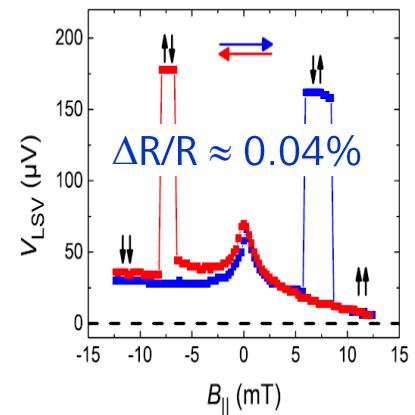
Nakana et al. 2010



Ciorga et al. 2011

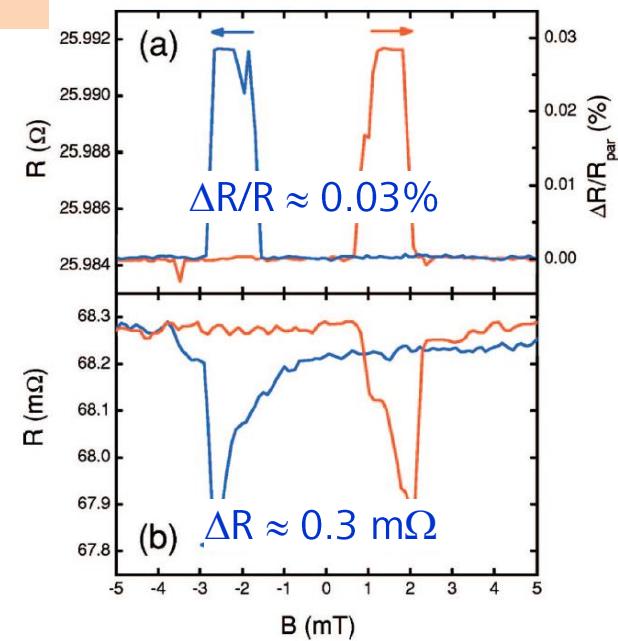
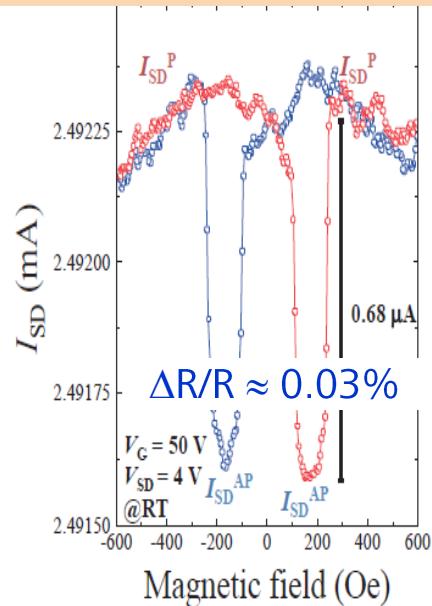
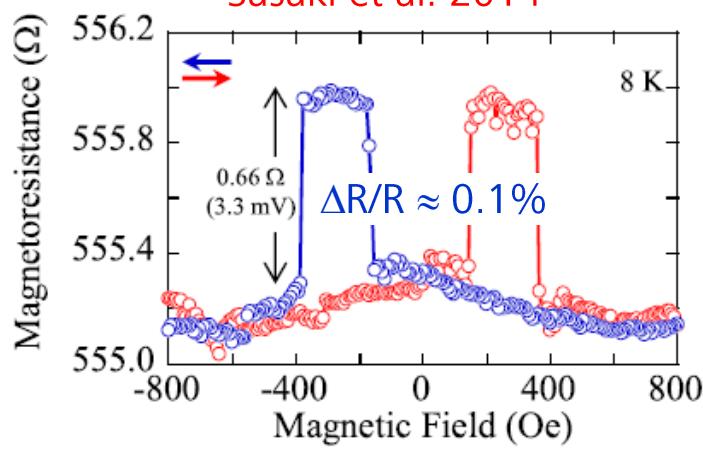


Bruski et al. 2013



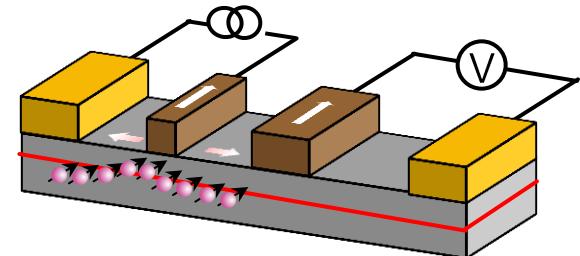
$\Delta R/R < 1\%$

H.C.Koo et al. 2007

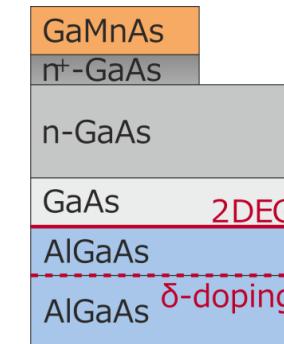


Sasaki et al. 2014

- Sample design, spin-injection/detection, principle of non-local geometry

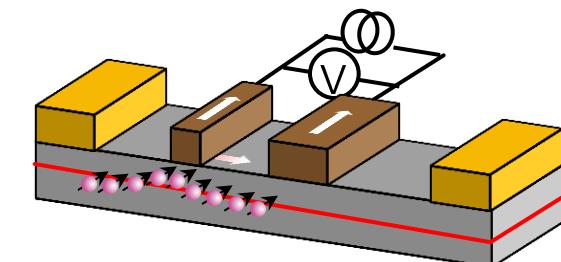


- Spin-injection/detection in 2DES

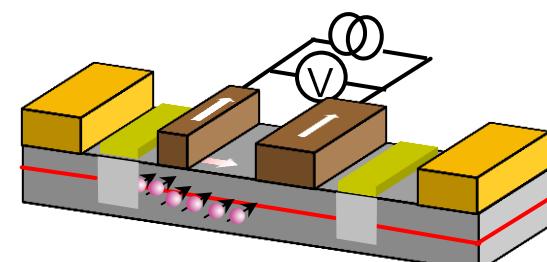


- Local (spin valve) measurements using 2DES: principle and experiments

$$\Delta R / R \sim 80\%$$

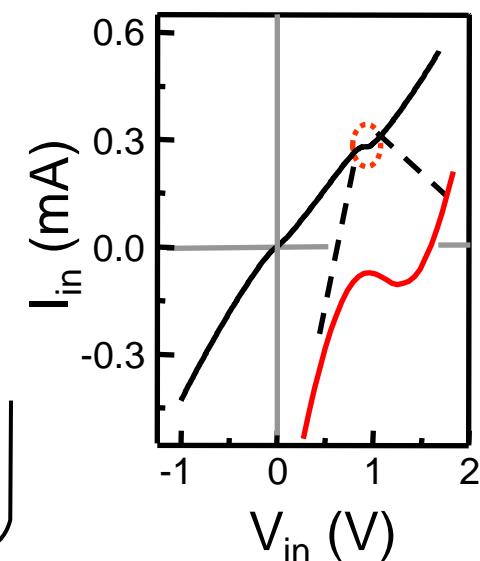
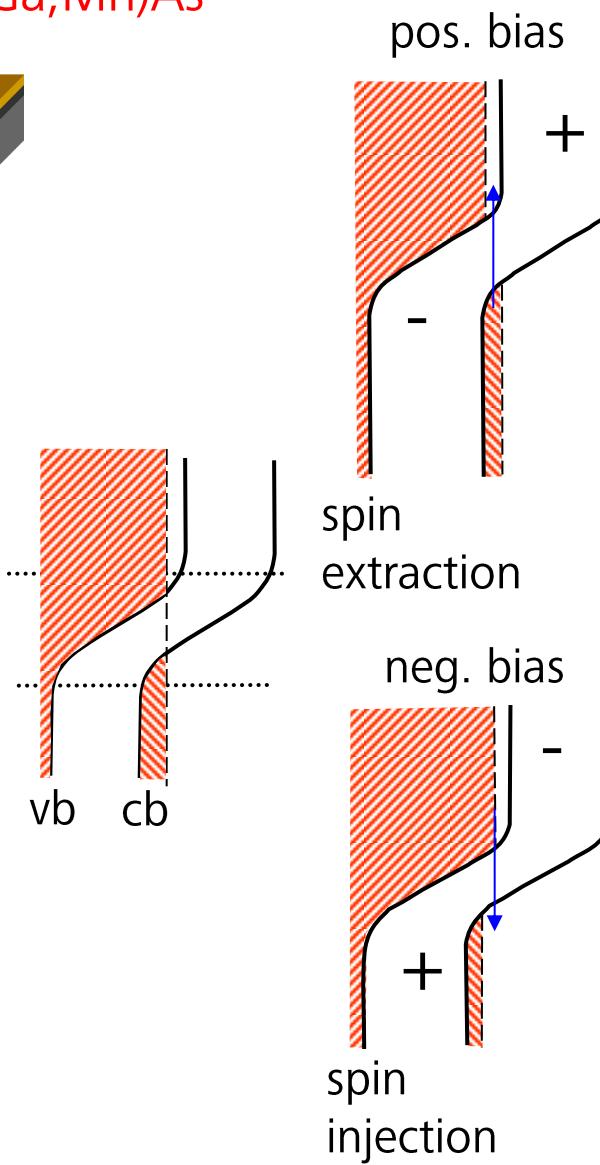
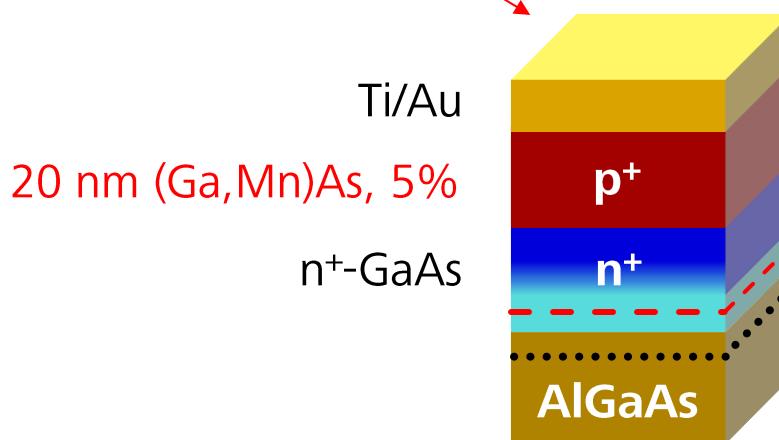
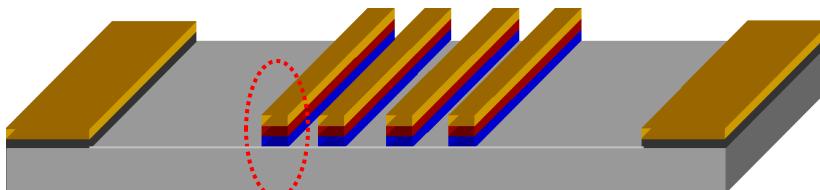


- Tuning the spin valve signal

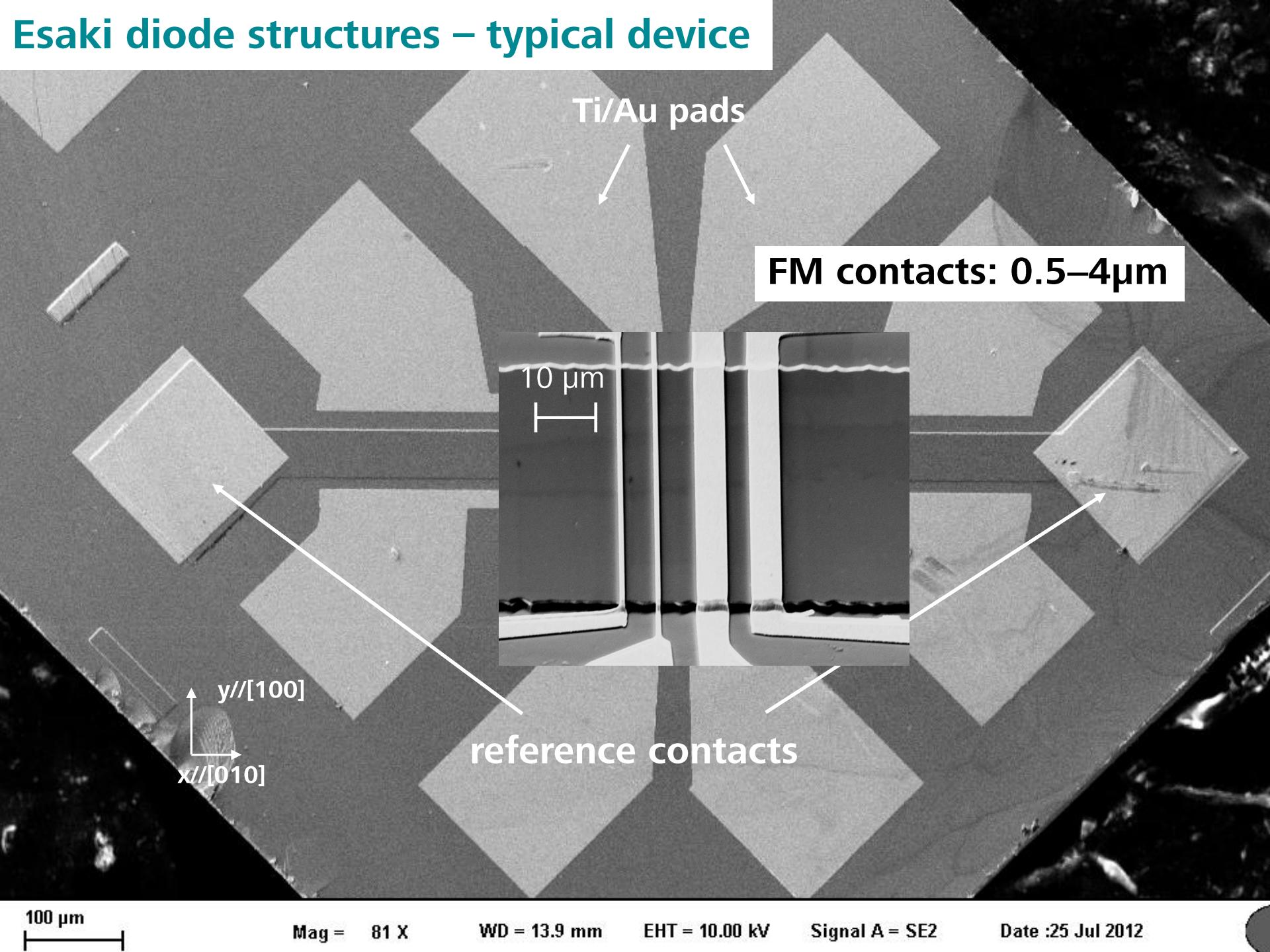


Sample design – Esaki diode structure

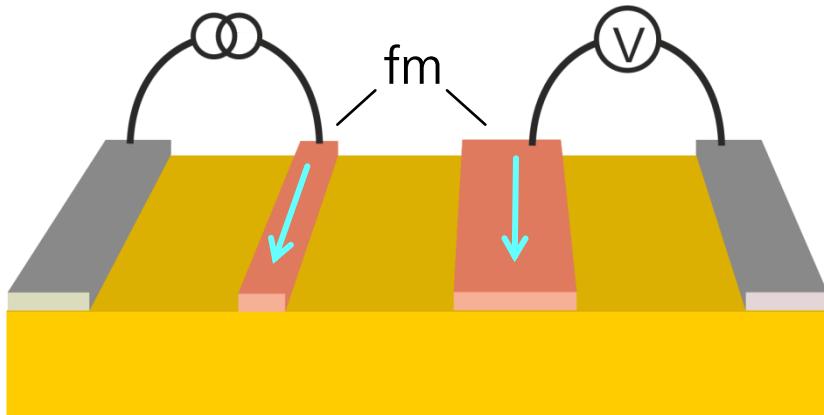
Ferromagnetic injector/detector: (Ga,Mn)As

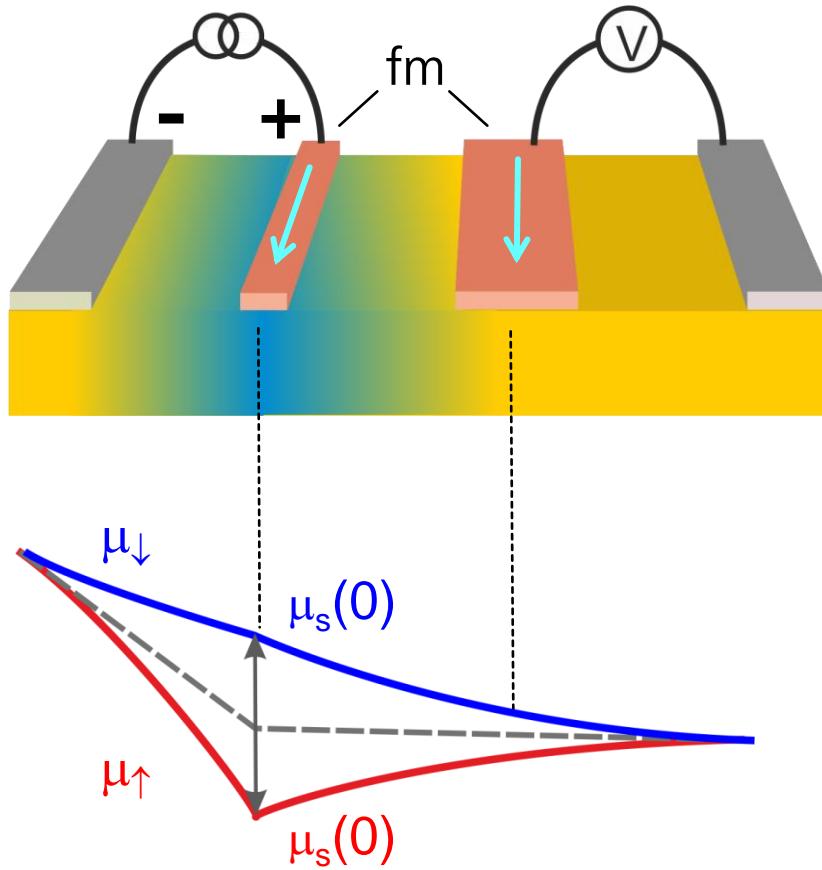


Esaki diode structures – typical device



Non-local injection/detection

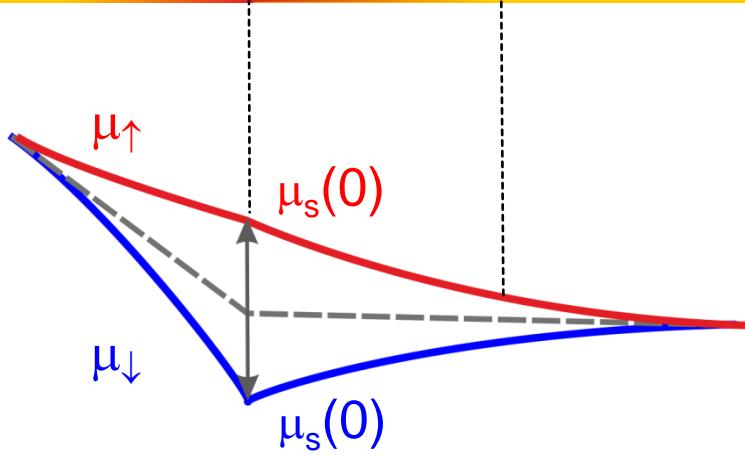
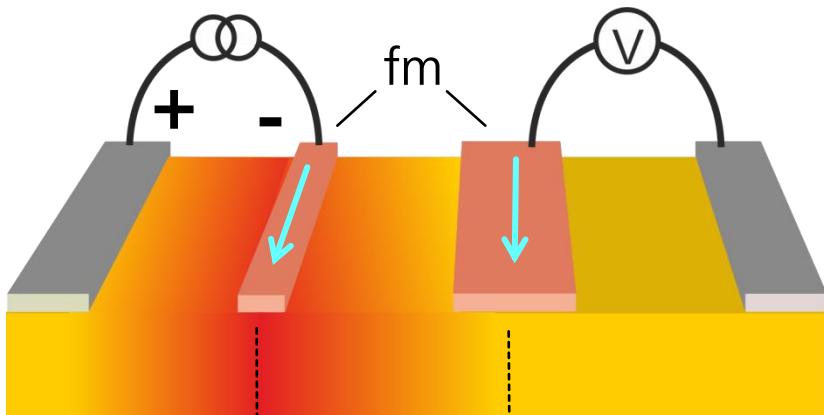




Spin accumulation:

$$\mu_s(0) = -\frac{1}{2} j P_{\text{inj}} \lambda_s \rho_N$$

J. Fabian and I. Zutic,
Acta Phys. Slovaca, **57**, 566 (2007)



Spin accumulation:

$$\mu_s(0) = -\frac{1}{2} j P_{inj} \lambda_s \rho_N$$

J. Fabian and I. Zutic,
Acta Phys. Slovaca, **57**, 566 (2007)

Spin injection efficiency P_{inj} :

$$P_{inj} = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}$$

$$\mu_s(x) = \mu_s(0) \exp(-x / \lambda_s)$$

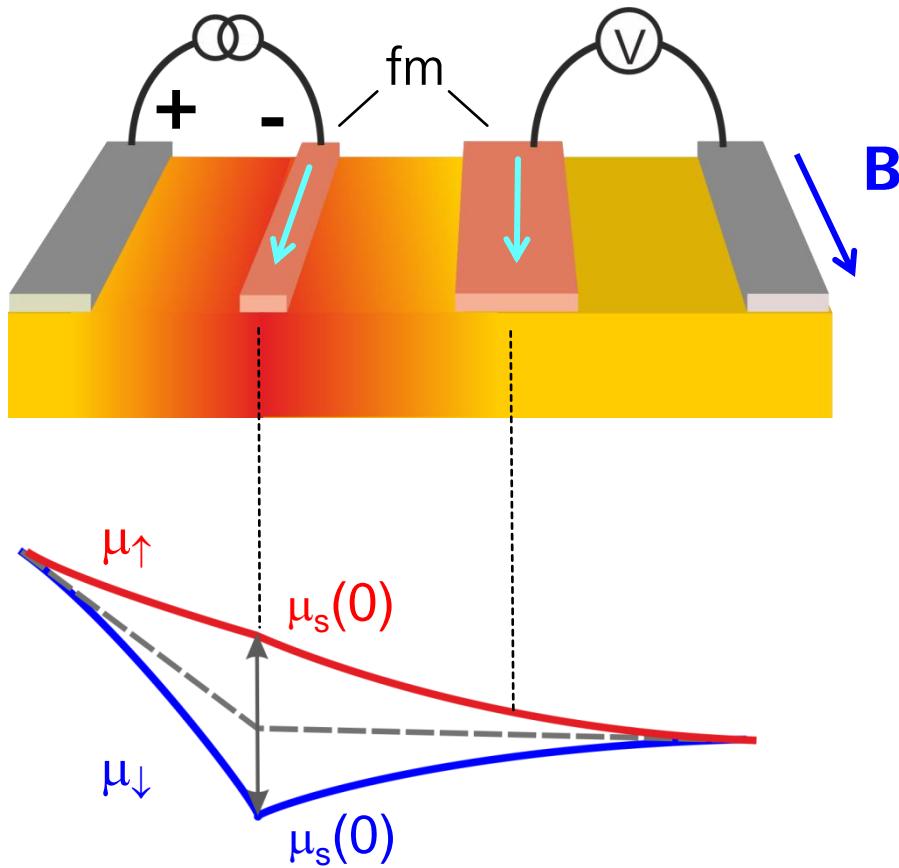
Spin-charge
coupling

$$V_{nl} = -P_{det} \mu_s(x)$$

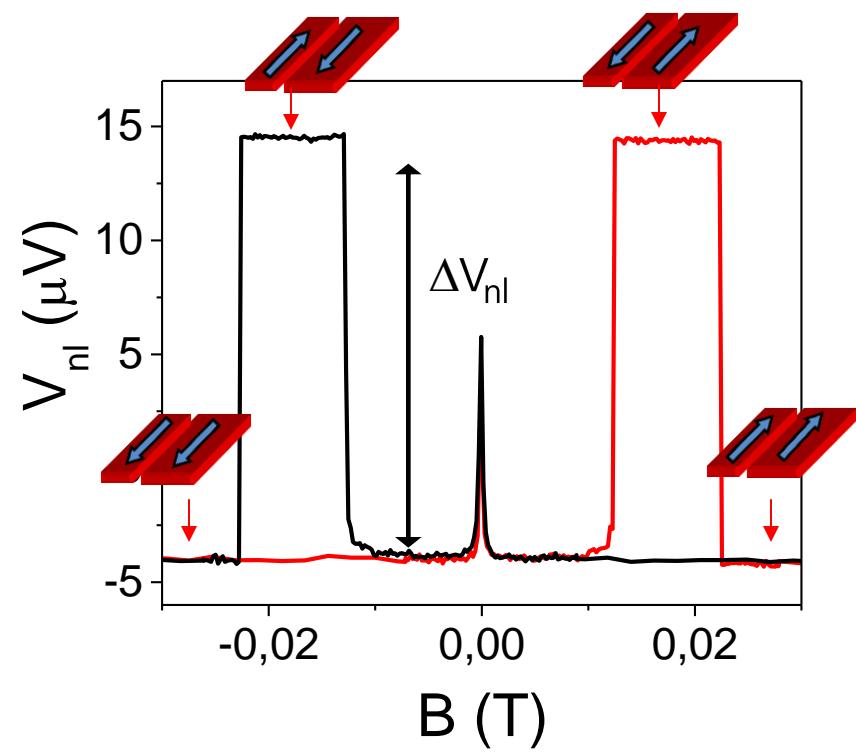
$$V_{nl} = \pm \frac{P_{inj} P_{det} I_{inj} \lambda_s \rho_N}{2S} \exp\left(-\frac{x}{\lambda_s}\right)$$

M. Johnson & R.H. Silsbee
PRL **55**, 1790 (1985)

Non-local injection/detection (here bulk GaAs)



$$\Delta V_{nl} = \frac{P_{inj} P_{det} I_{inj} \lambda_s \rho}{S} \exp\left(-\frac{L}{\lambda_s}\right)$$



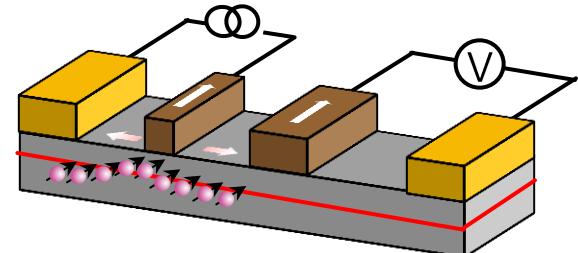
X. Lou et al., Nat. Phys. **3**, 197-202 (2007)

M. Ciorga et al., Phys. Rev. B **79**, 165321 (2009)

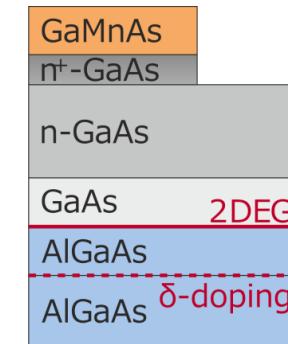
M. Ciorga et al., Phys. Rev. B **88**, 155308 (2013)

From $\Delta V_{nl} \Rightarrow P_{inj} \cdot P_{det} \sim P^2 \rightarrow P \sim 75\%$

- Sample design, Spin-injection/detection principle using non-local geometry

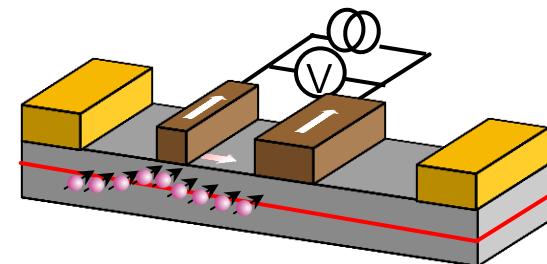


- Spin-injection/detection in 2DES

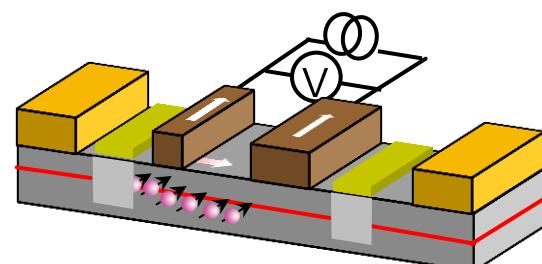


- Local (spin valve) measurements using 2DES: principle and experiments

$$\Delta R / R \sim 80\%$$

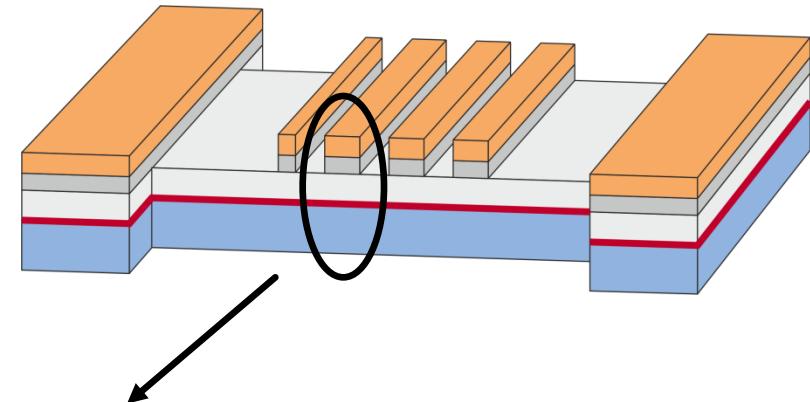
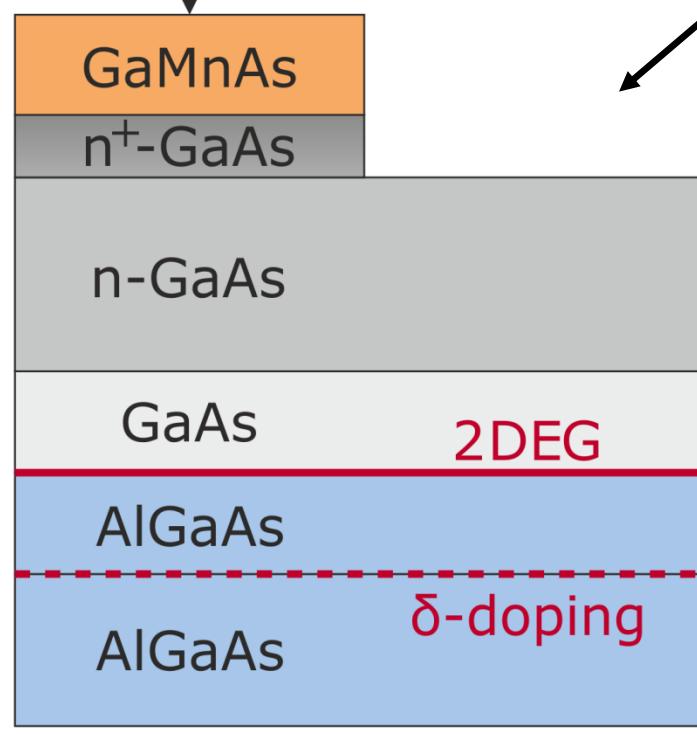
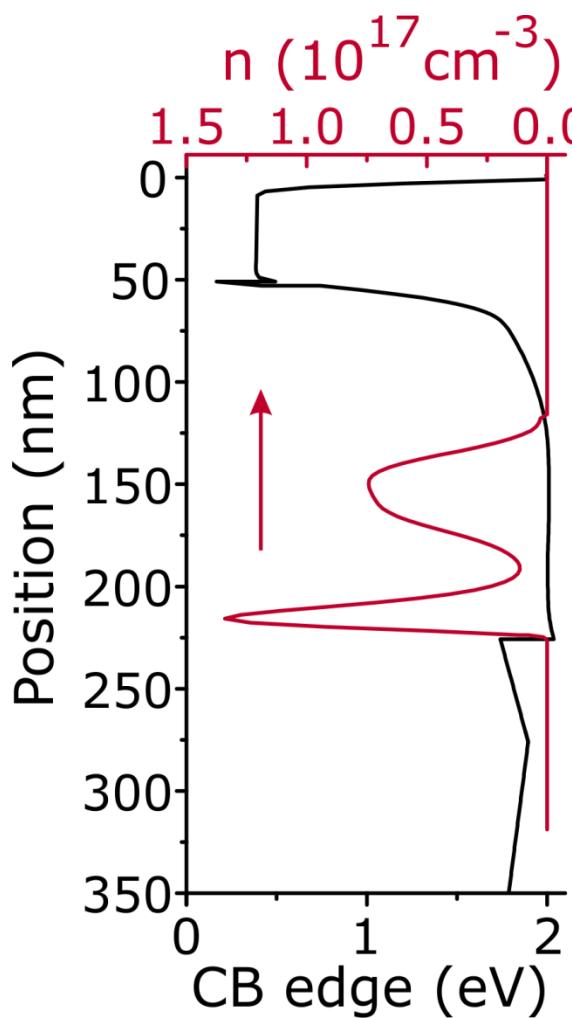


- Tuning the spin valve signal

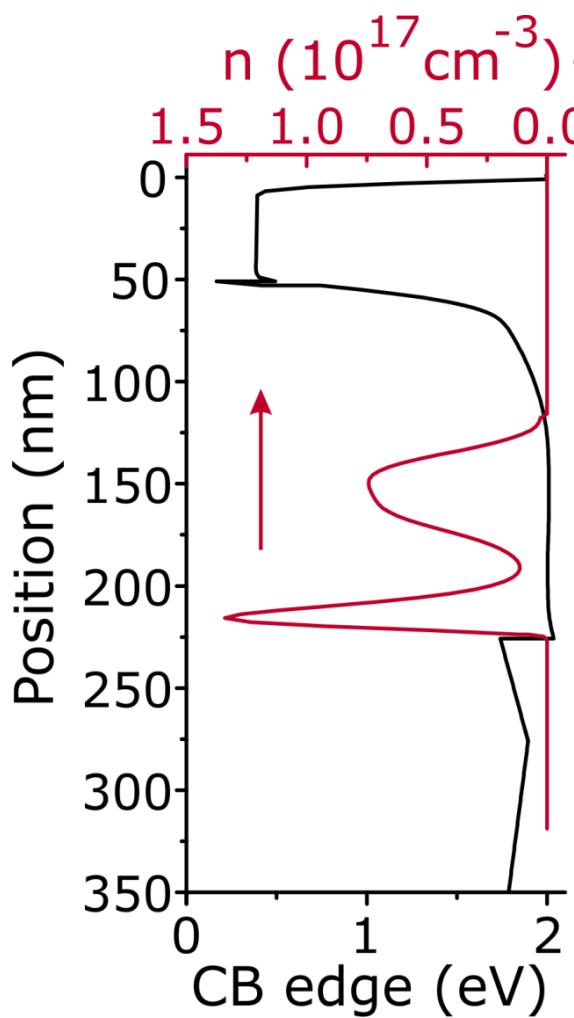


Structure with inverted AlGaAs/GaAs 2DEG

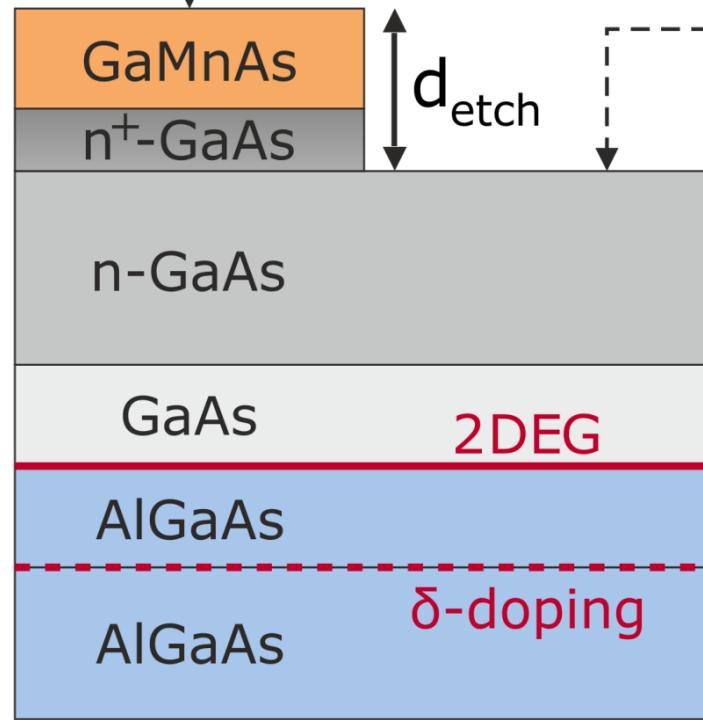
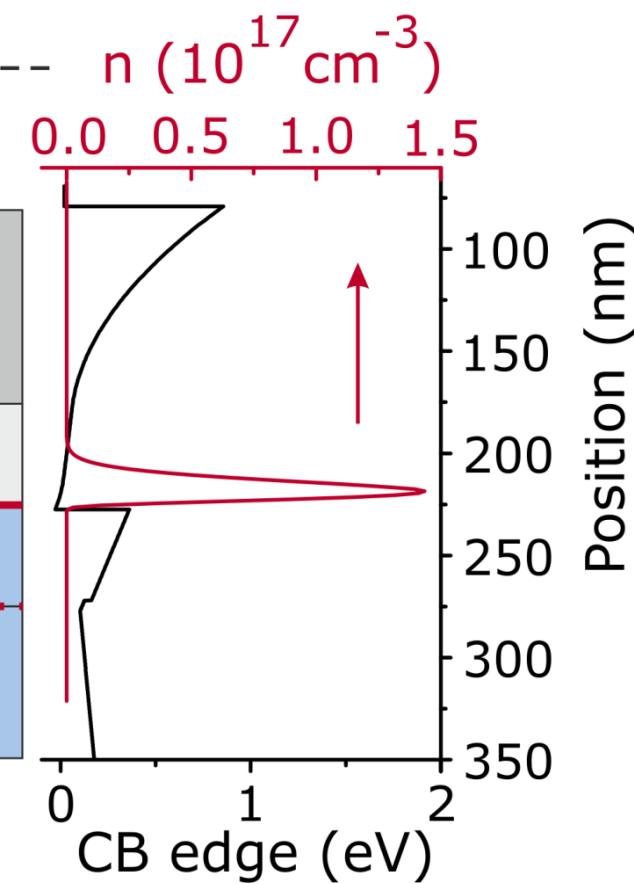
Conduction band & **electron density**
underneath the contacts



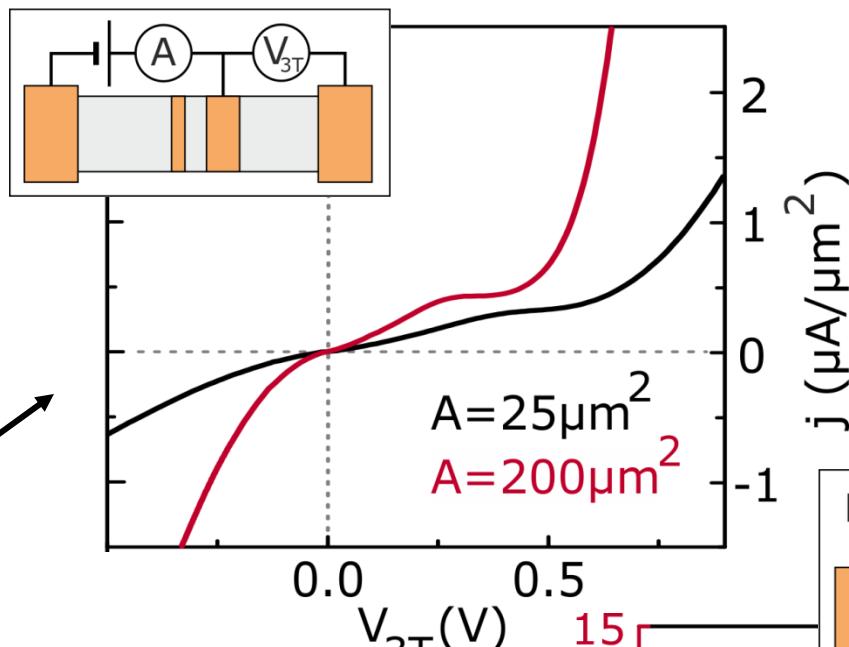
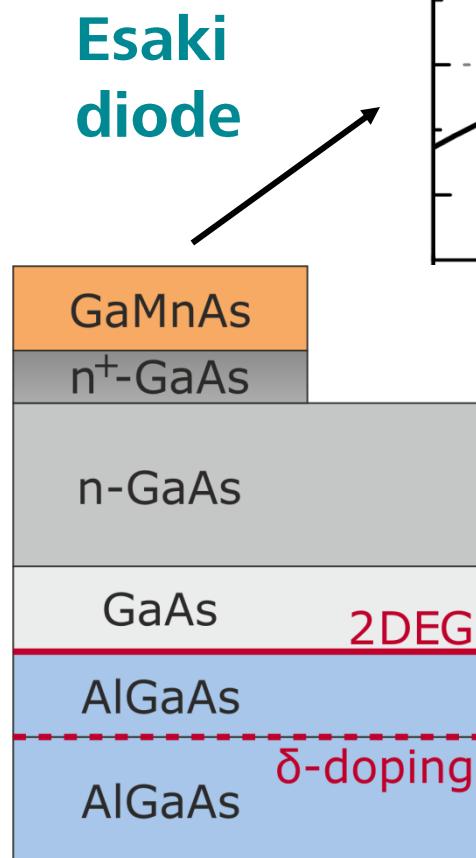
Conduction band & **electron density**
underneath the contacts



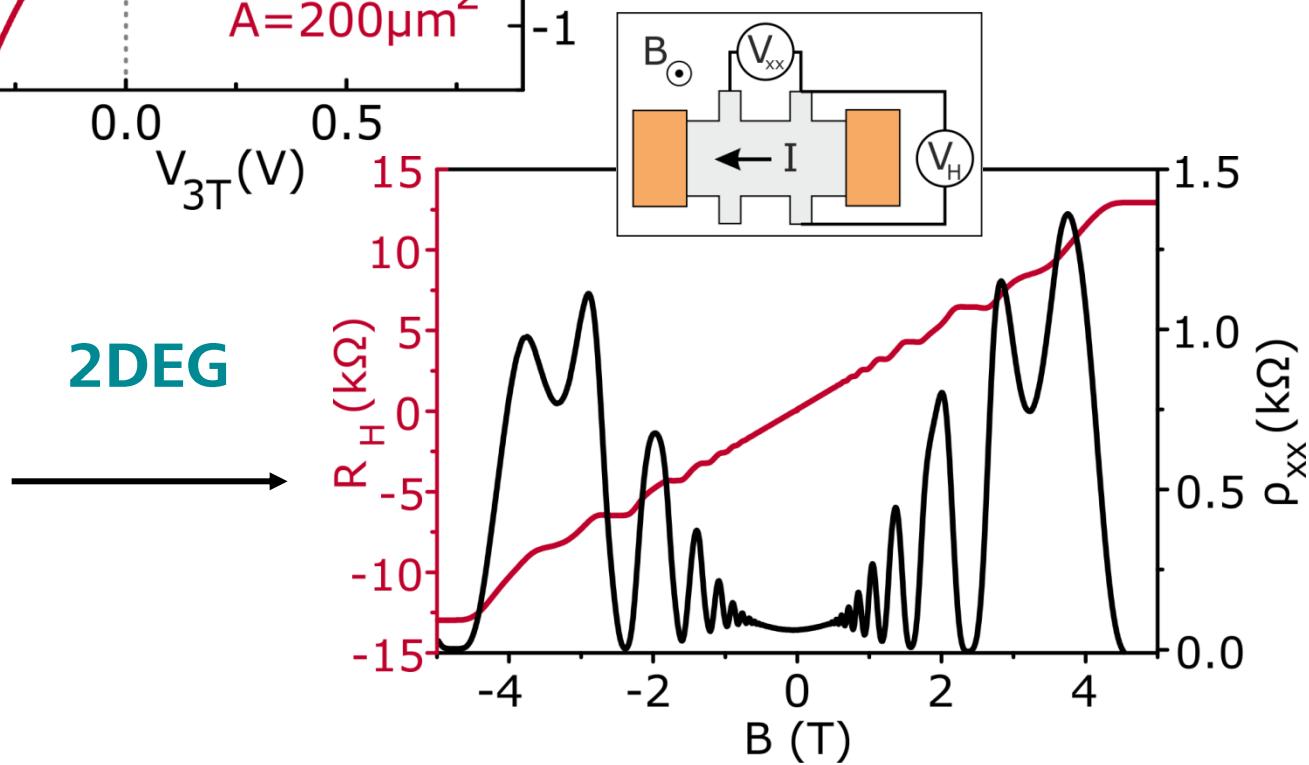
Conduction band & **electron density**
in between contacts

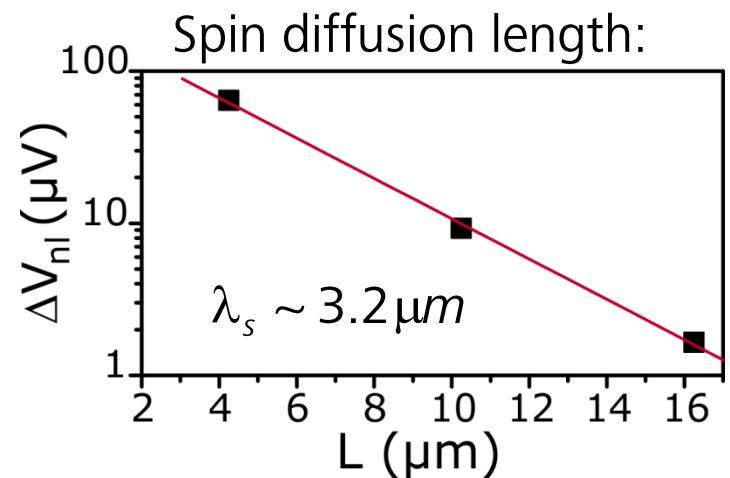
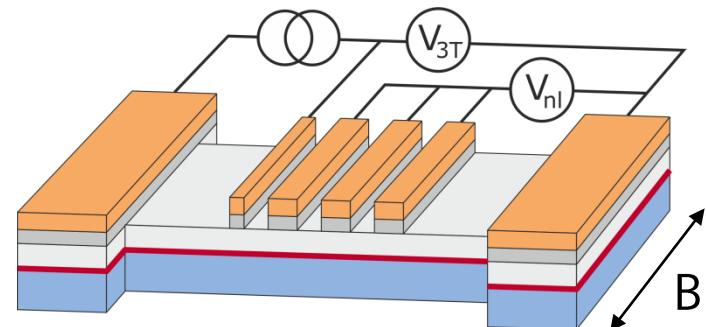
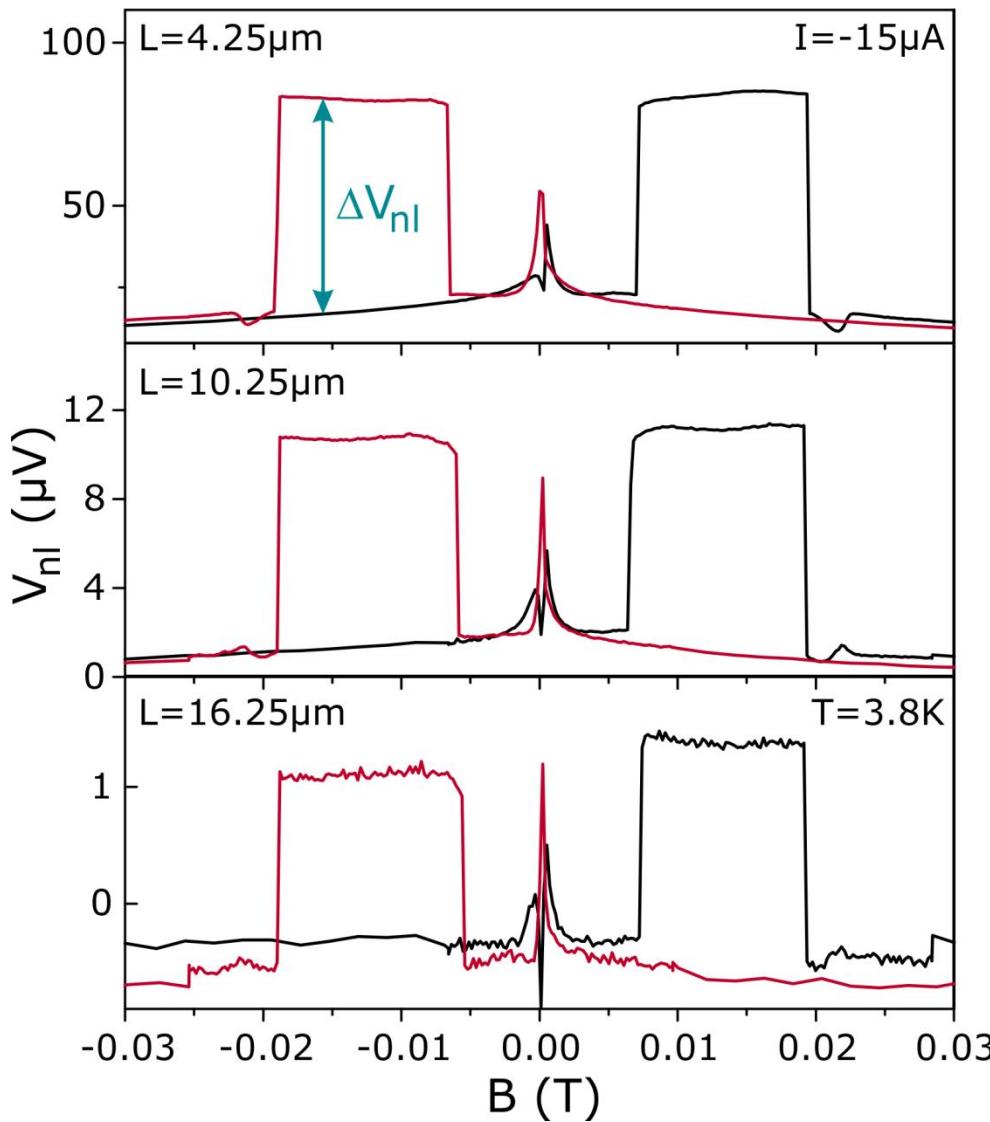


Wafer with inv. 2DEG – device parameters



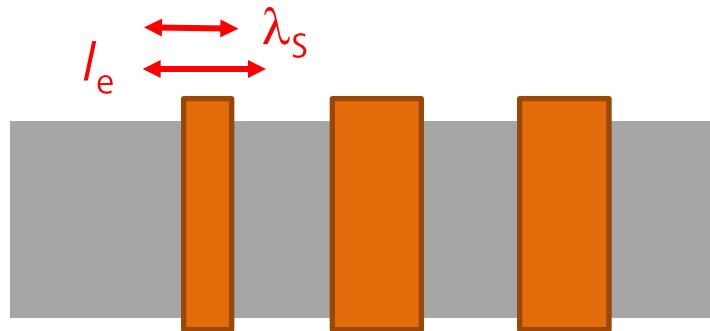
- $R_s = 53.5\Omega$
- $\mu = 5.1 \times 10^5 \text{ cm}^2/\text{Vs}$
- $I_{mf} \approx 4 \mu\text{m}$





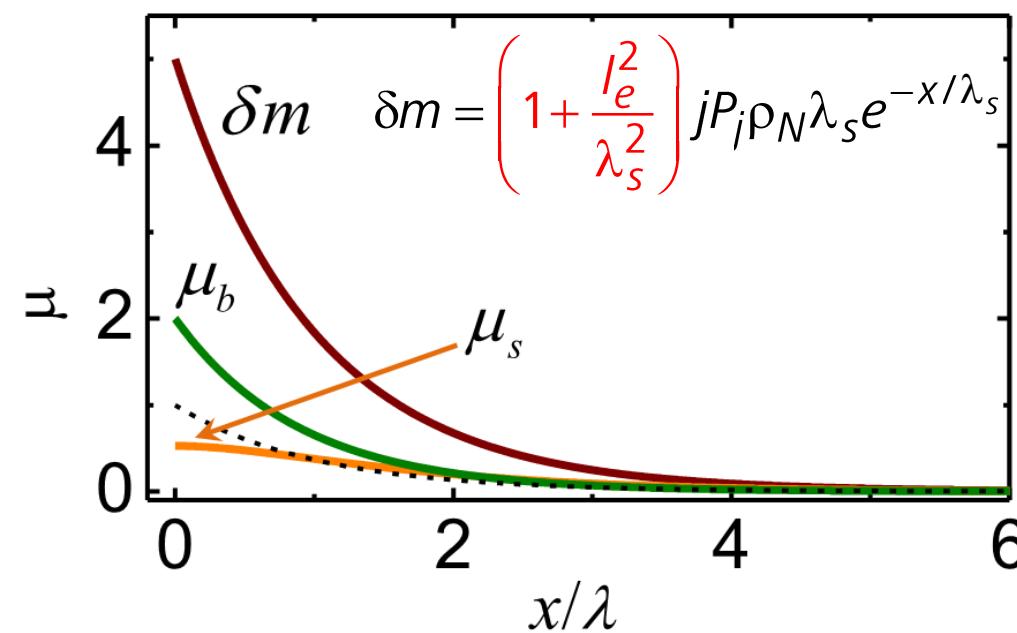
Spin signal ΔV_{nl} at negative bias much higher as expected from drift diffusion model. See:

Ballistic effects enhance spin-signal



$I_e >$ contact width
 $I_e \sim$ contact separation

Theory by Kai Chen and Shufeng Zhang [PRB 92, 214402 (2015)] takes into account that electro-chemical potential depends on electrons' k-vector

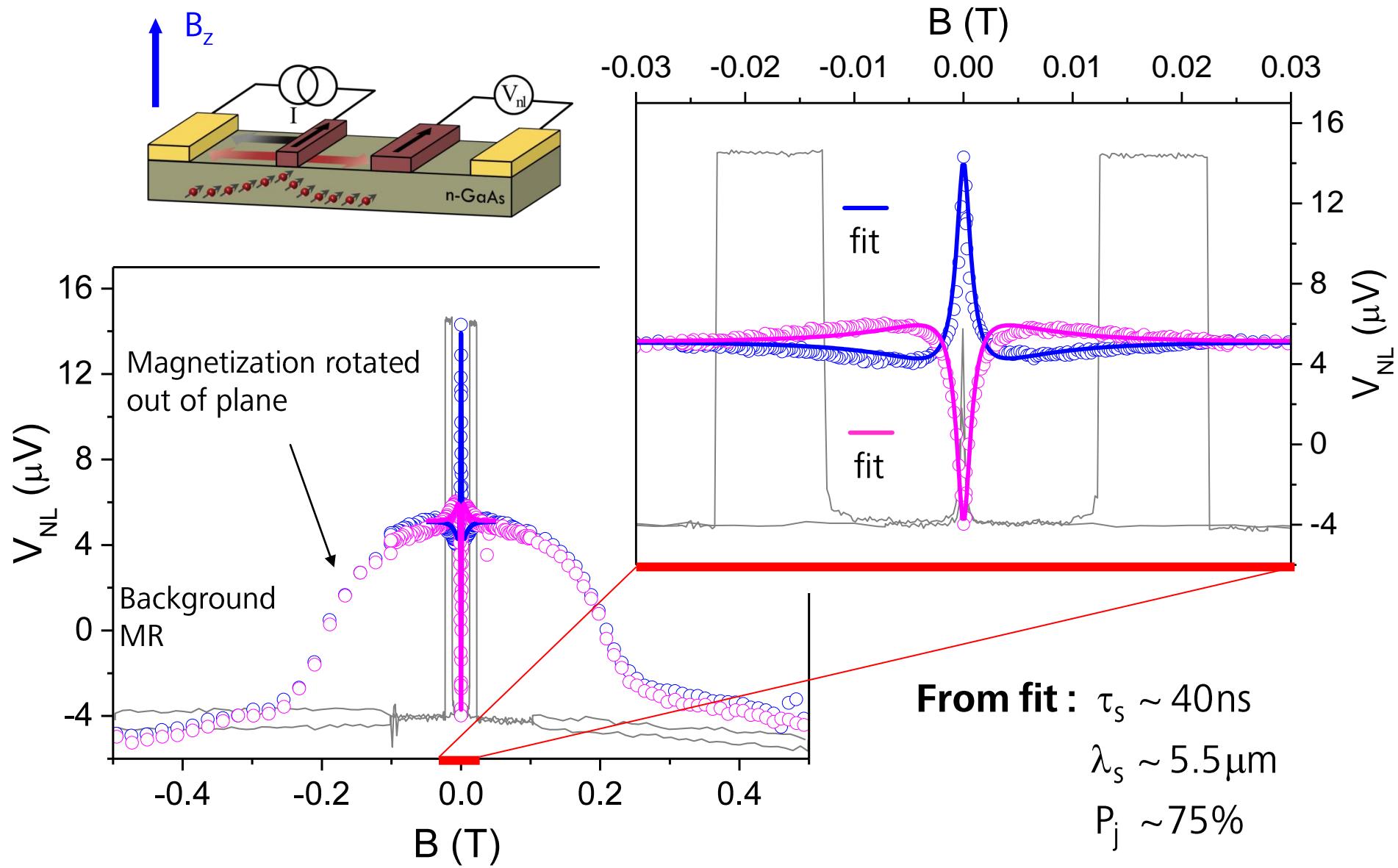


Enhancement of "diffusive" spin-accumulation by factor

$$\left(1 + \frac{I_e^2}{\lambda_s^2}\right);$$

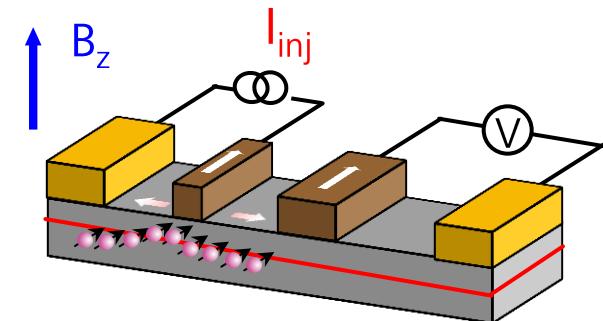
I_e = electron mean free path

Hanle curves (bulk)

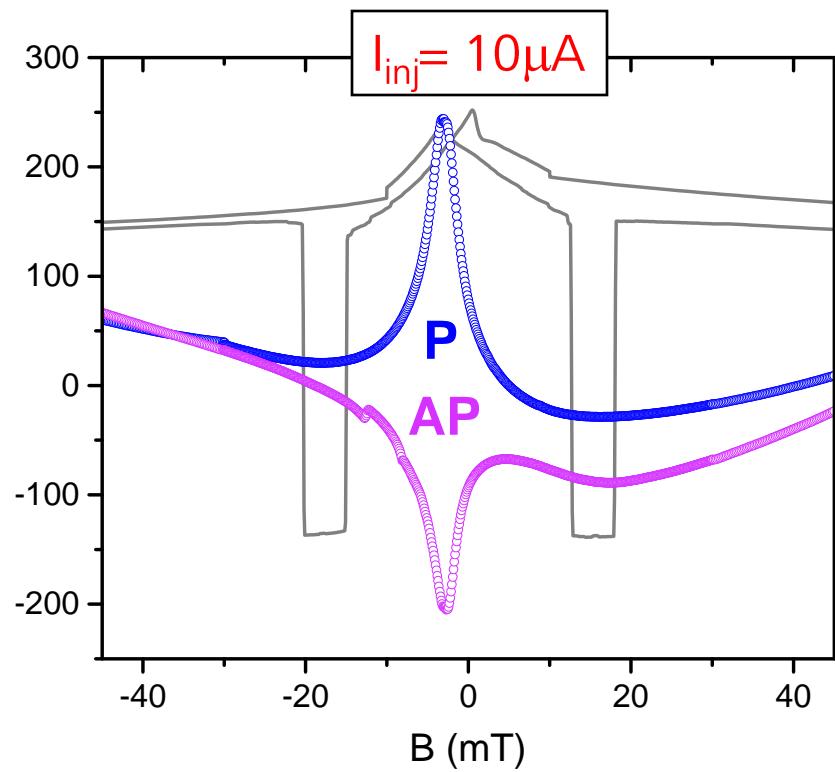
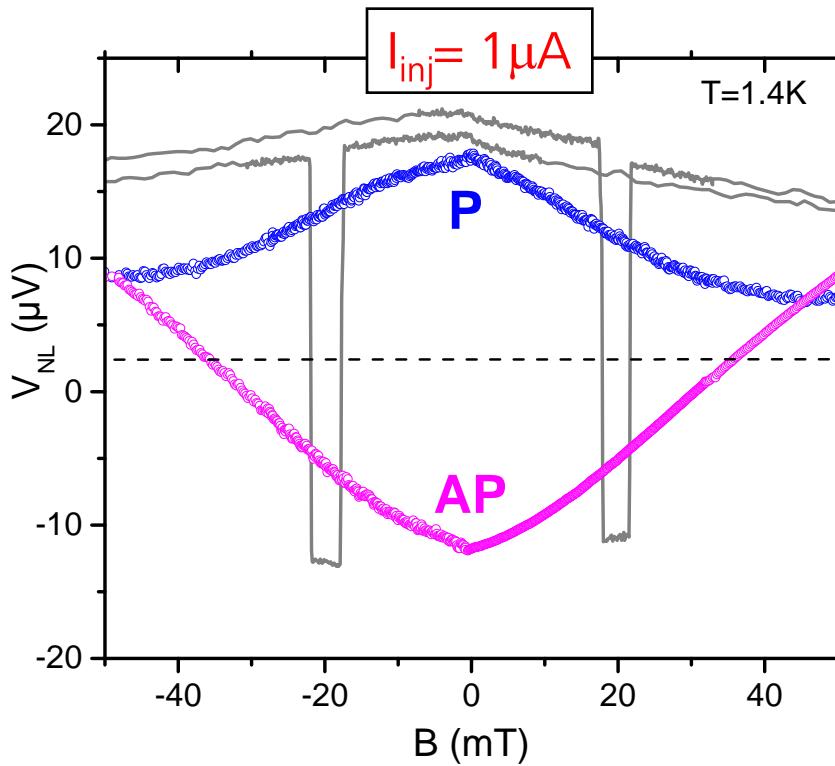


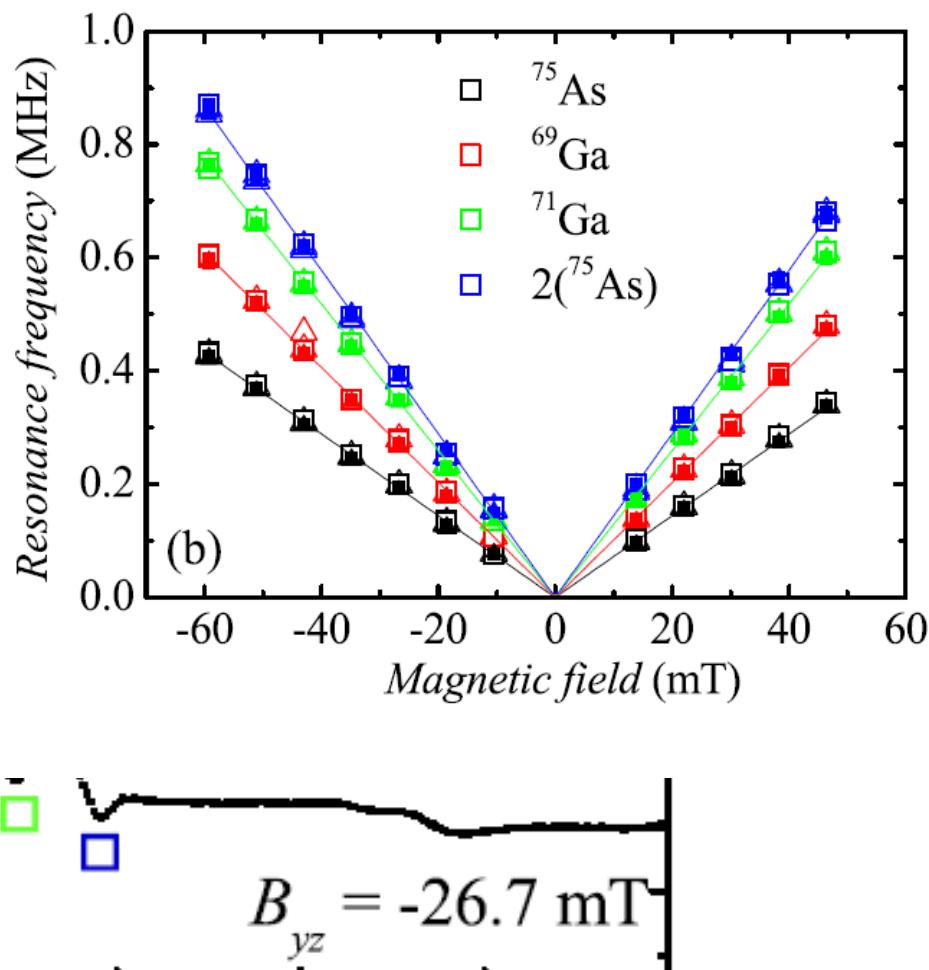
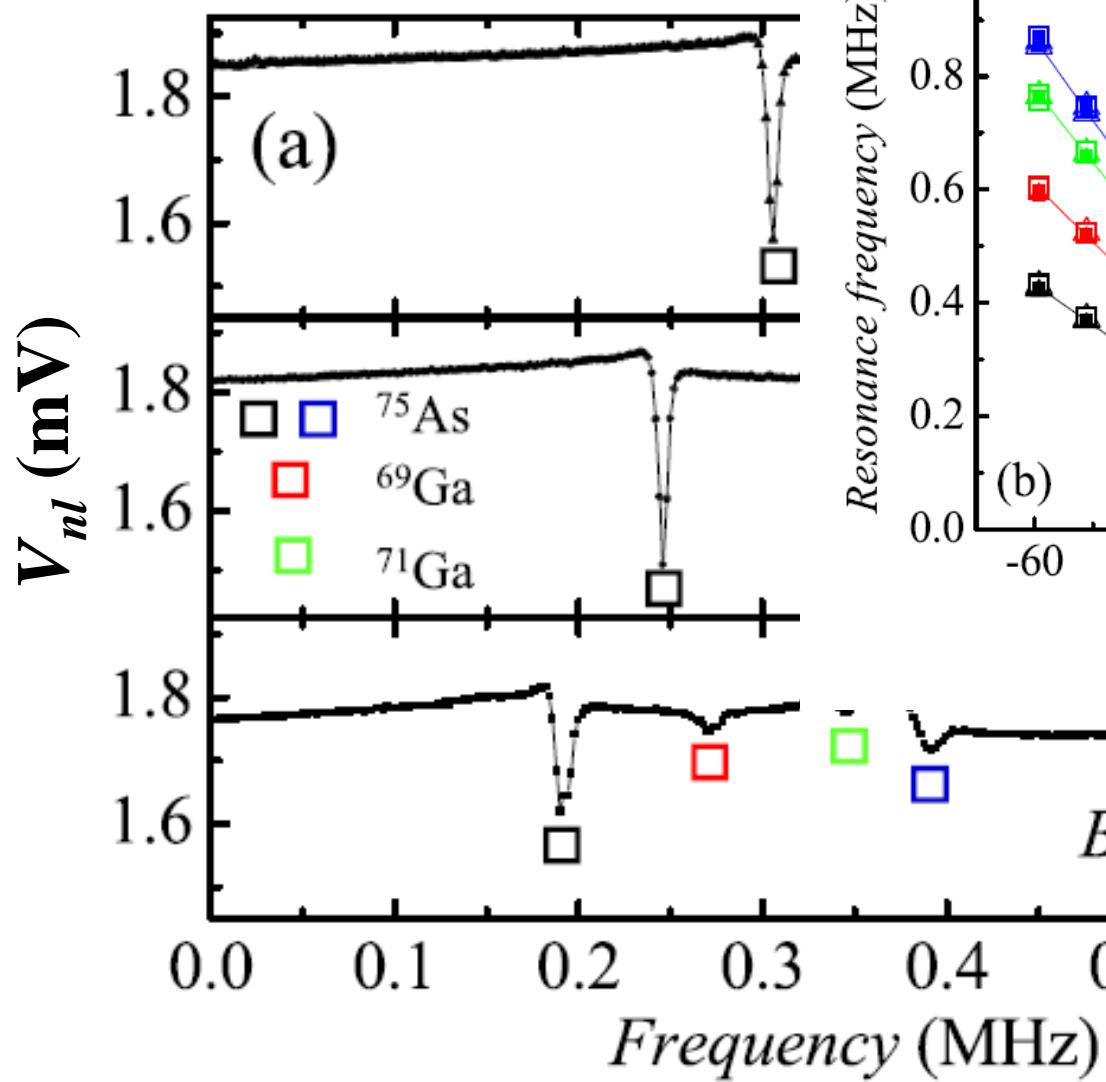
Hanle precession in 2DEG devices

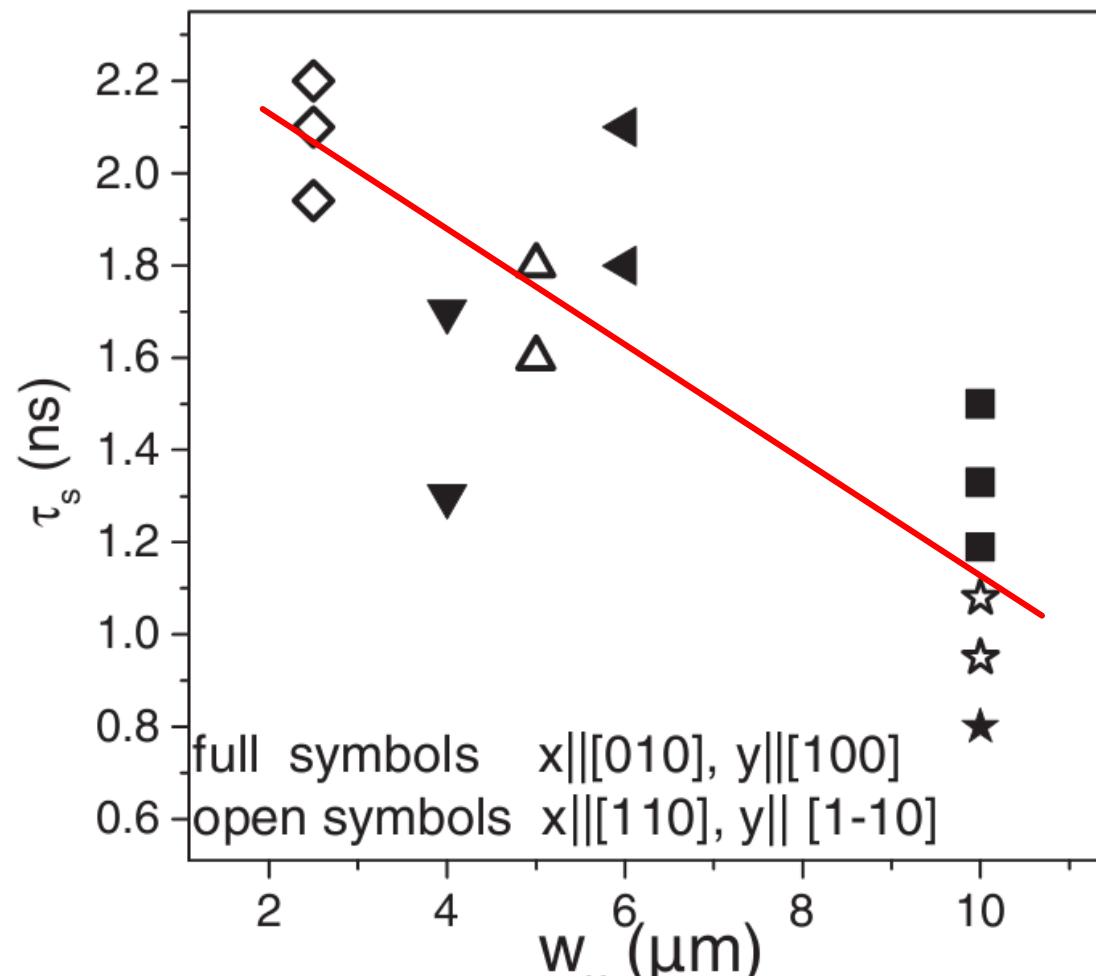
Hanle curve gets narrower with increasing current (ac), due to dynamical nuclear polarization (DNP)



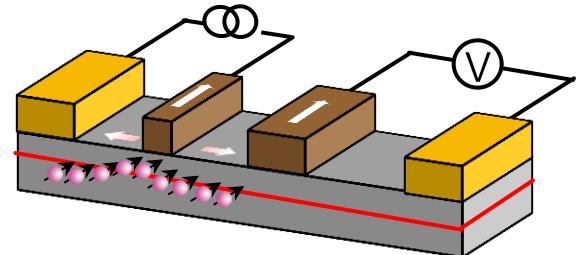
Spin current between fm contacts polarizes nuclei!



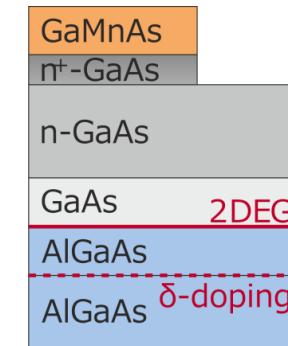




- Sample design, Spin-injection/detection principle using non-local geometry

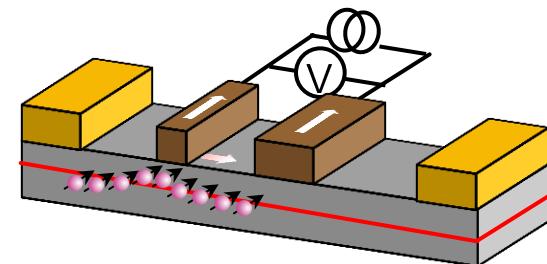


- Spin-injection/detection in 2DES

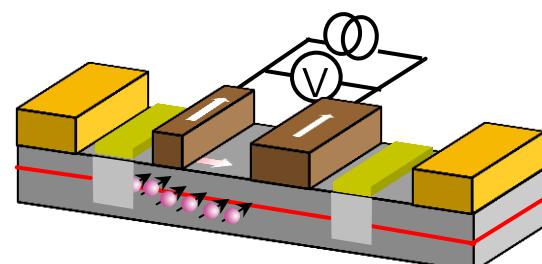


- Local (spin valve) measurements using 2DES: principle and experiments

$$\Delta R / R \sim 80\%$$



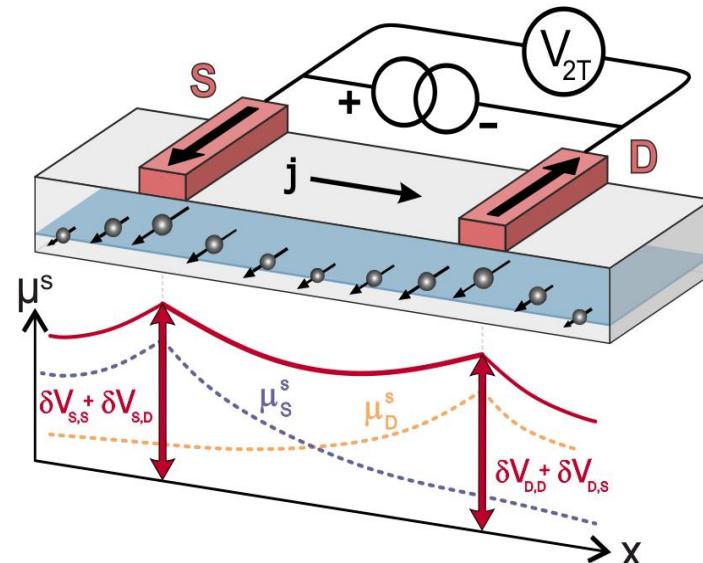
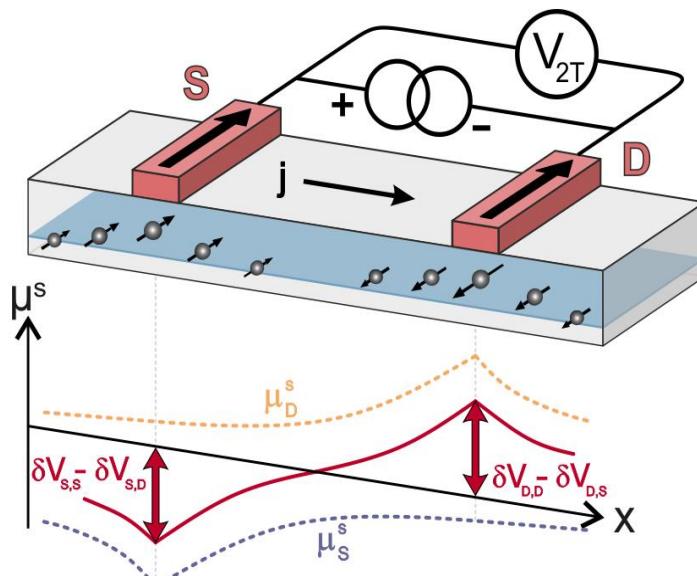
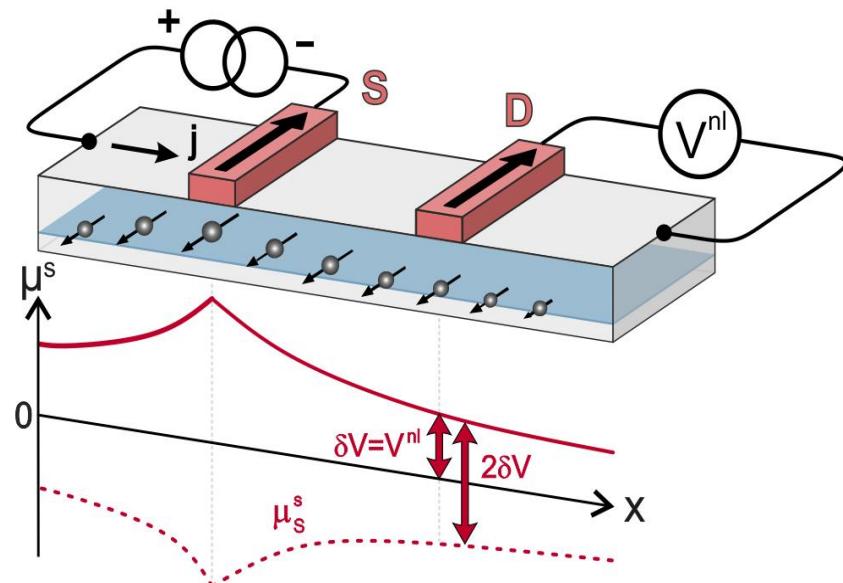
- Tuning the spin valve signal

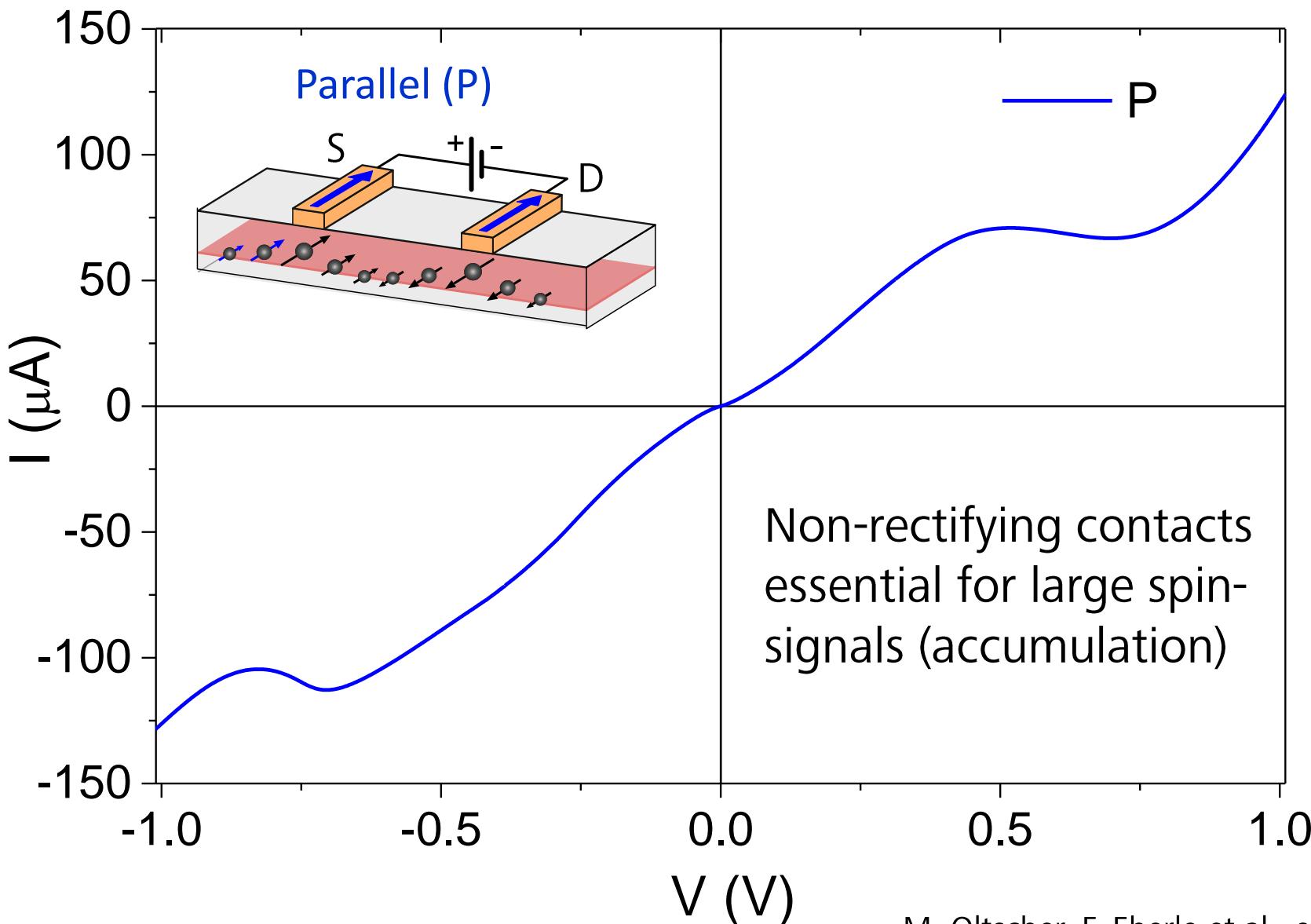


Spin-accumulation: local vs. non-local measurement

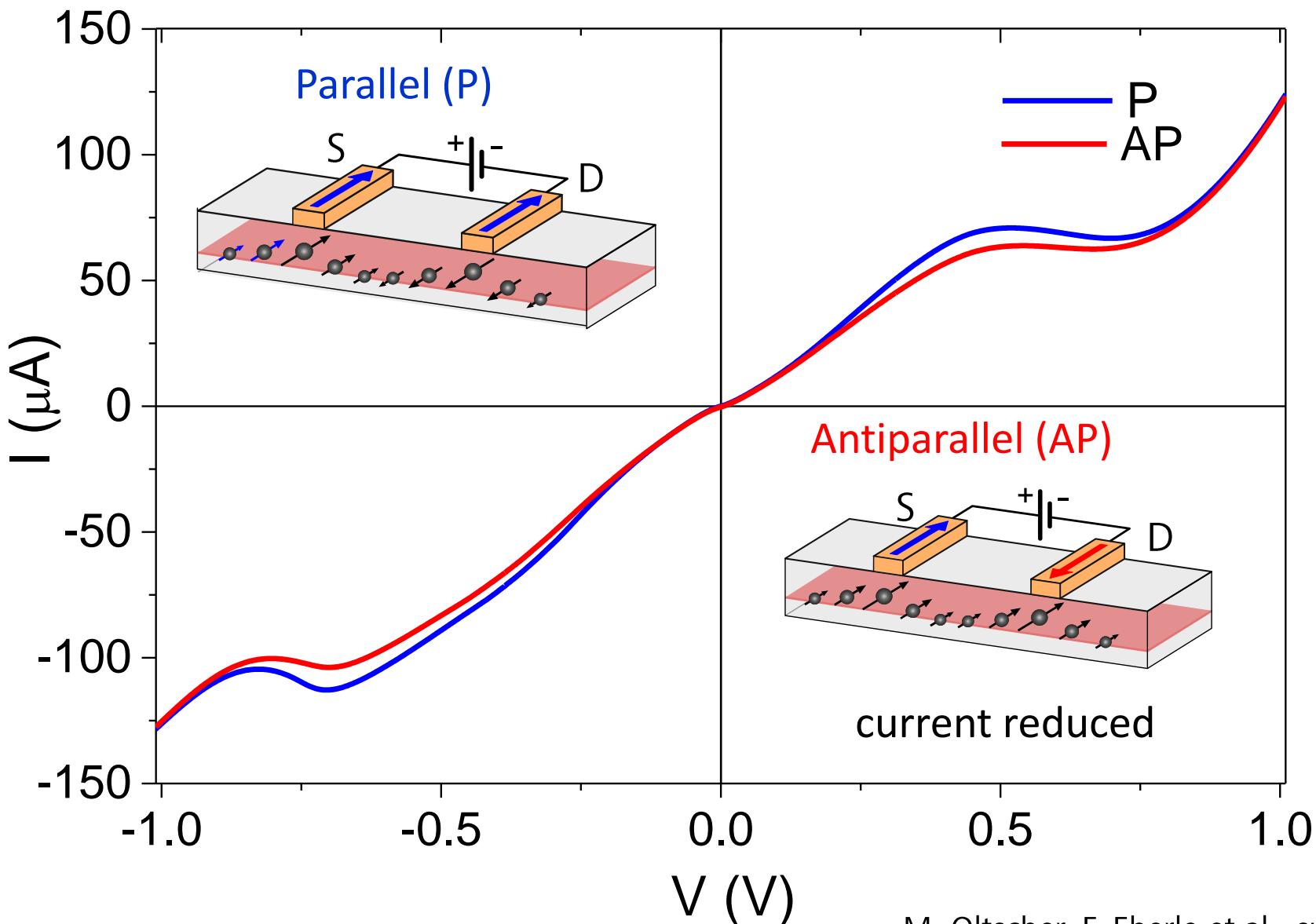
expectation :

$$\begin{aligned}\Delta V^{loc} &= V^{AP} - V^P \\ &= 2V_{1,2}^S + 2V_{21}^S \\ &= \Delta V_{1,2}^{nl} + \Delta V_{2,1}^{nl} \\ &\approx 2\Delta V^{nl}\end{aligned}$$

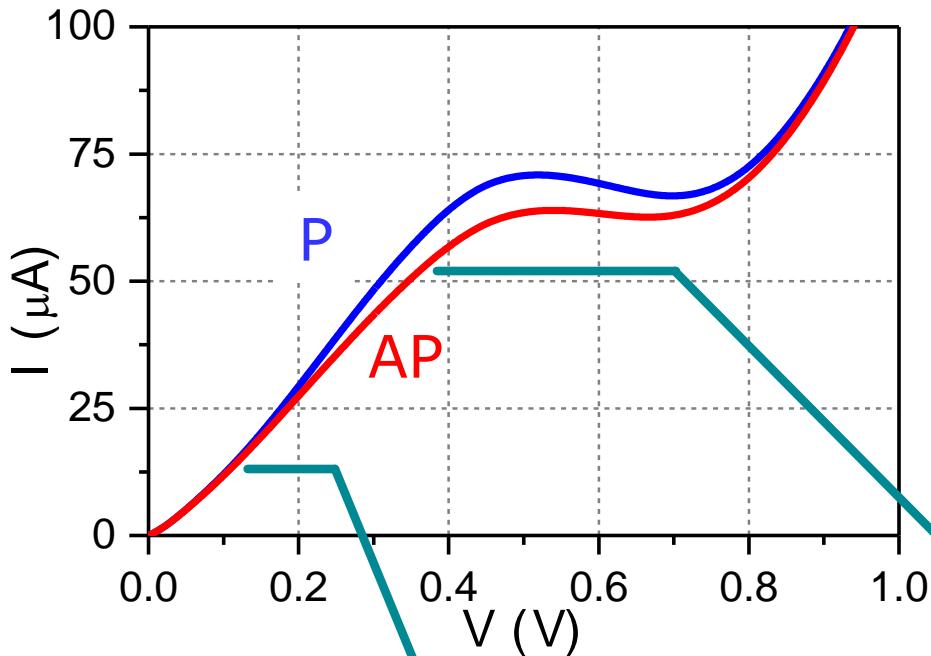




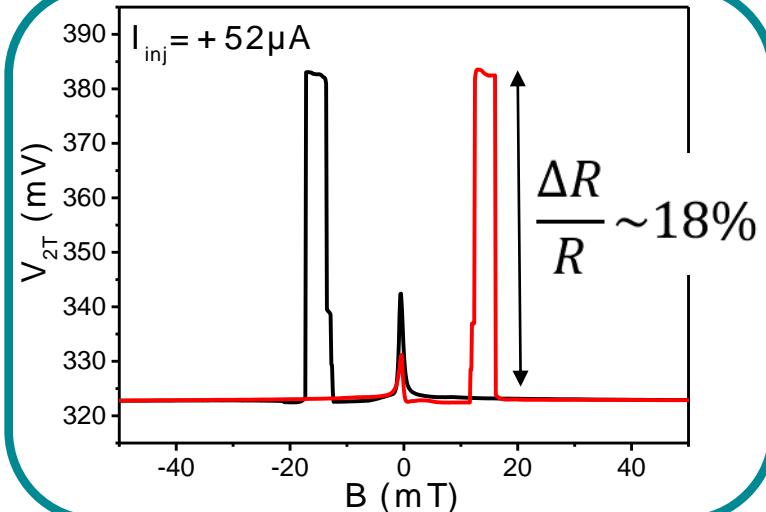
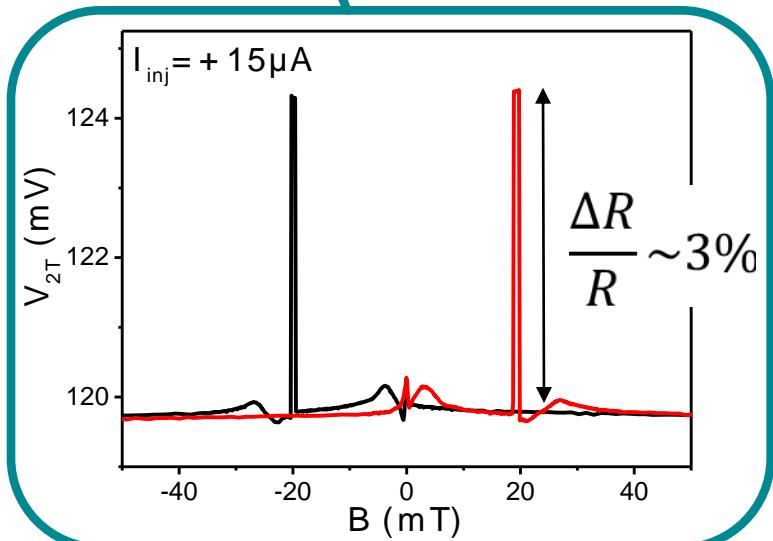
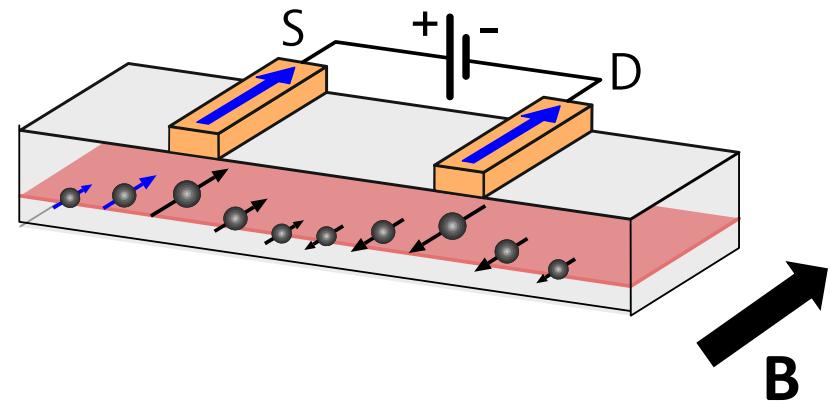
Two-terminal I-V curves



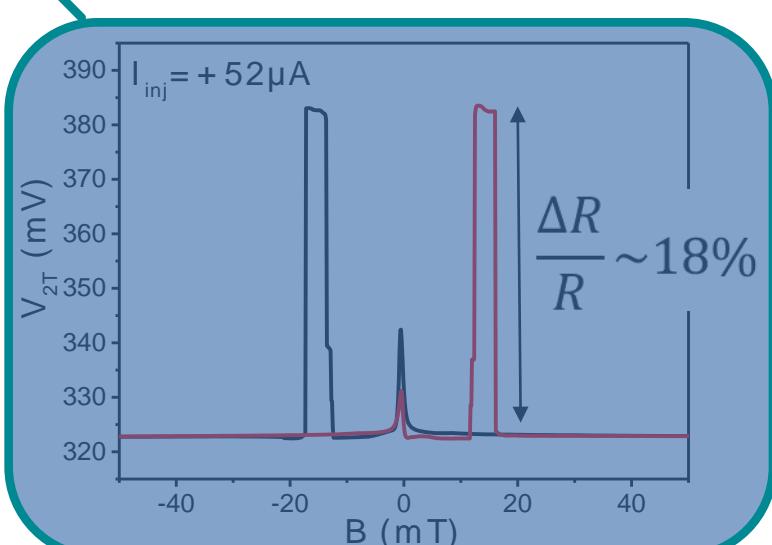
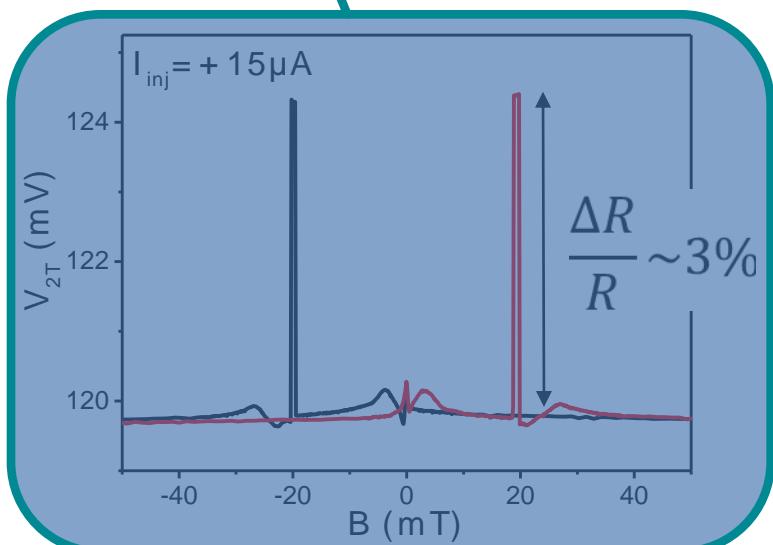
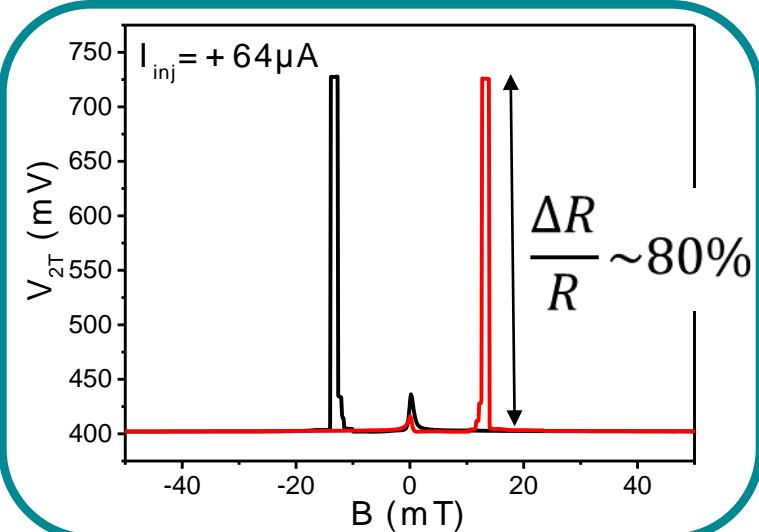
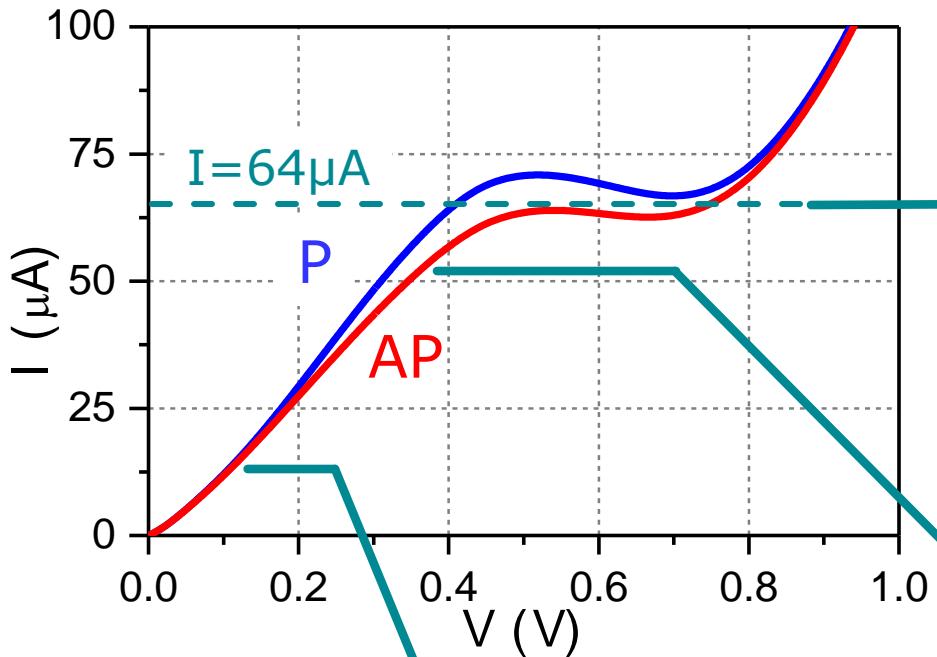
Local 2T spin valve signals

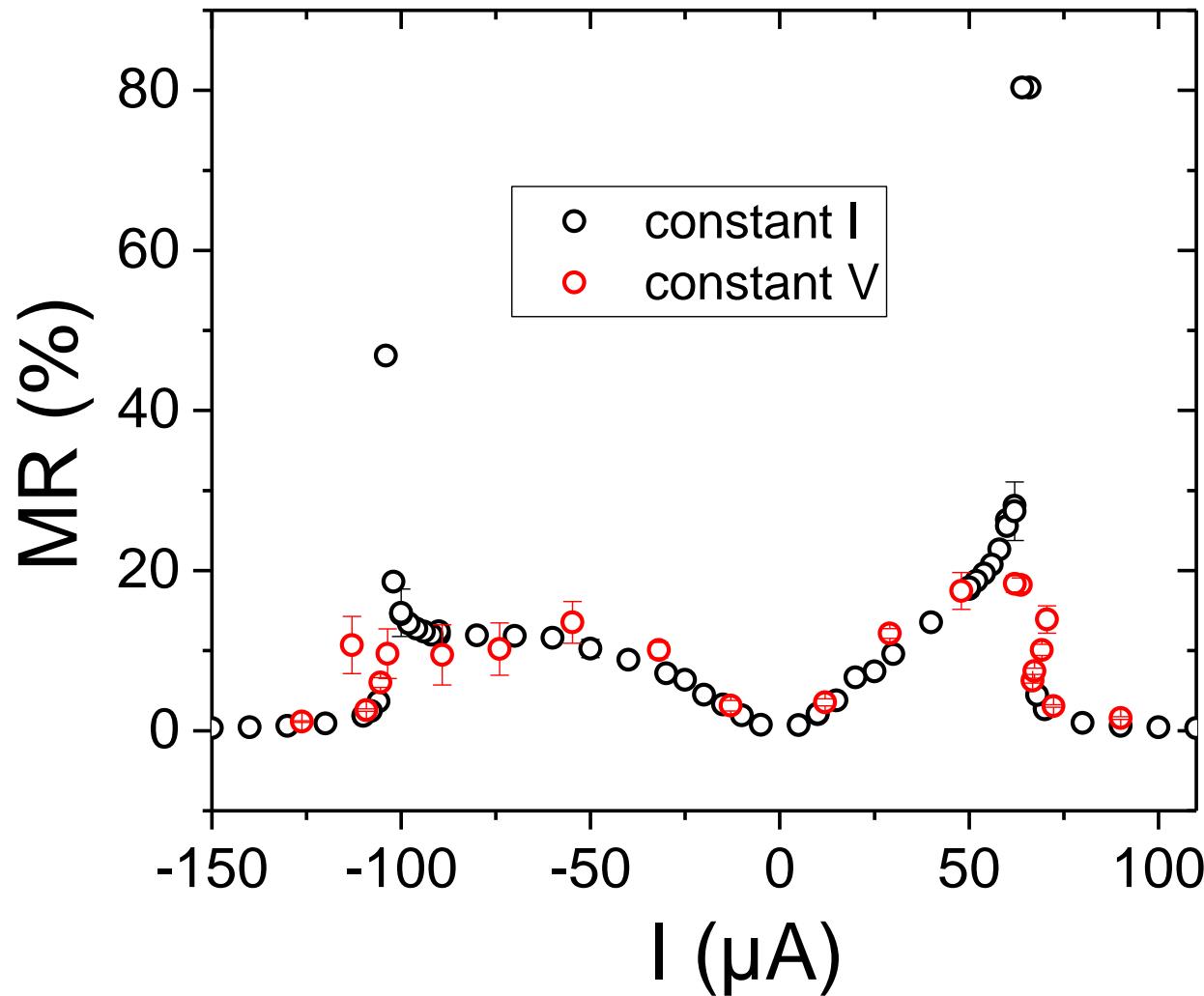


M. Oltsscher, F. Eberle et al., submitted



Giant MR signal at the nonlinear region

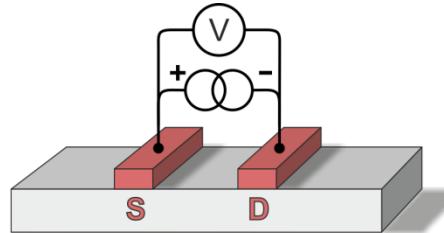




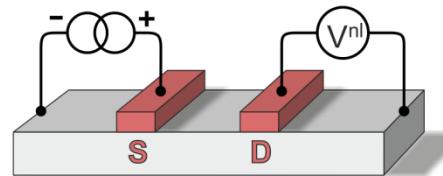
Local vs. non-local signal

Local signal for given bias current much larger than non-local signal!

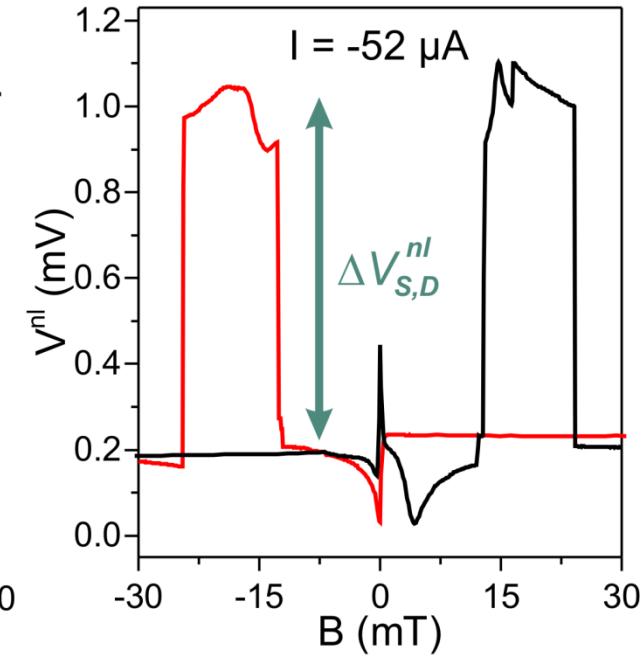
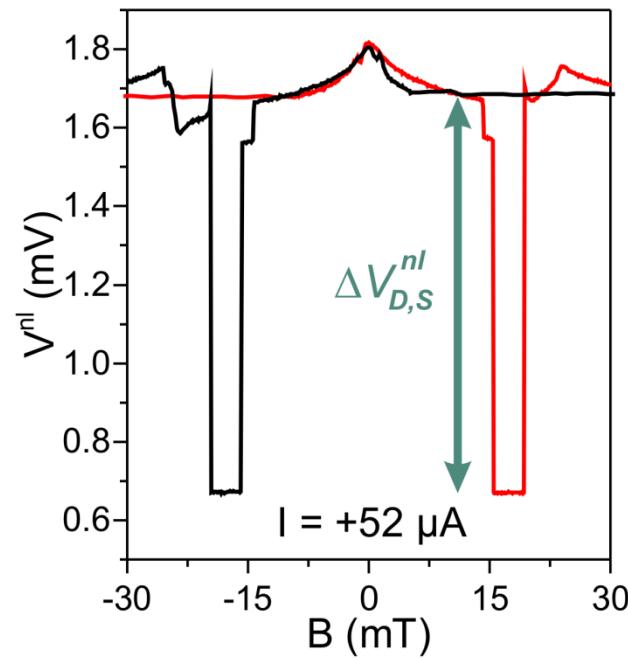
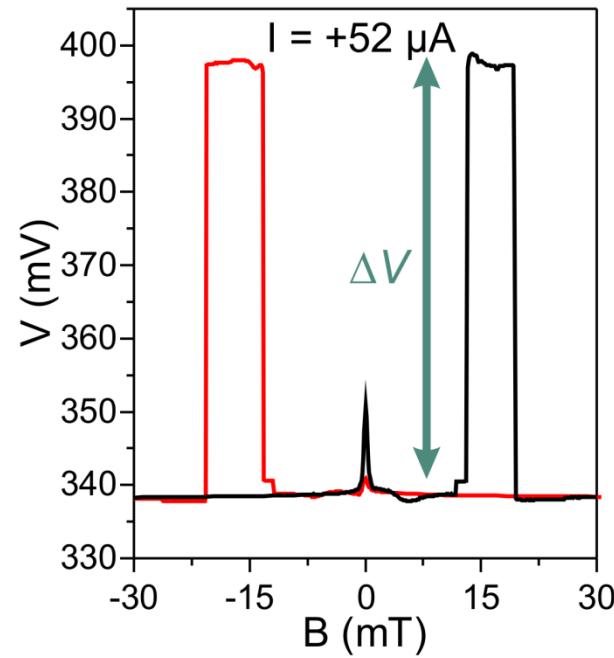
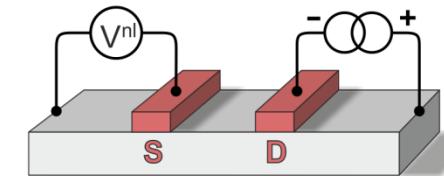
local



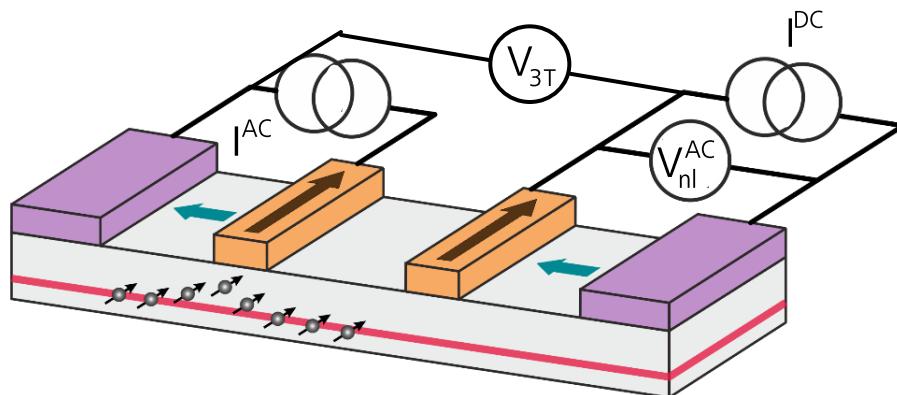
non-local



non-local



Influence of biasing spin detector



Forward bias (extraction)

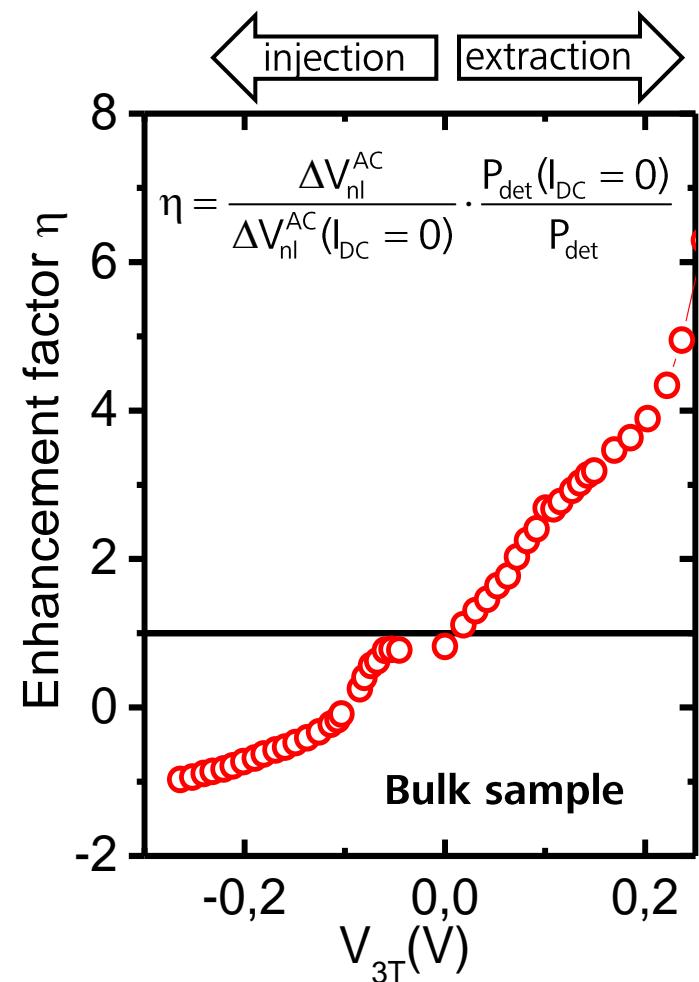
- Enhanced spin detection sensitivity

Reverse bias (injection)

- Suppressed spin detection sensitivity

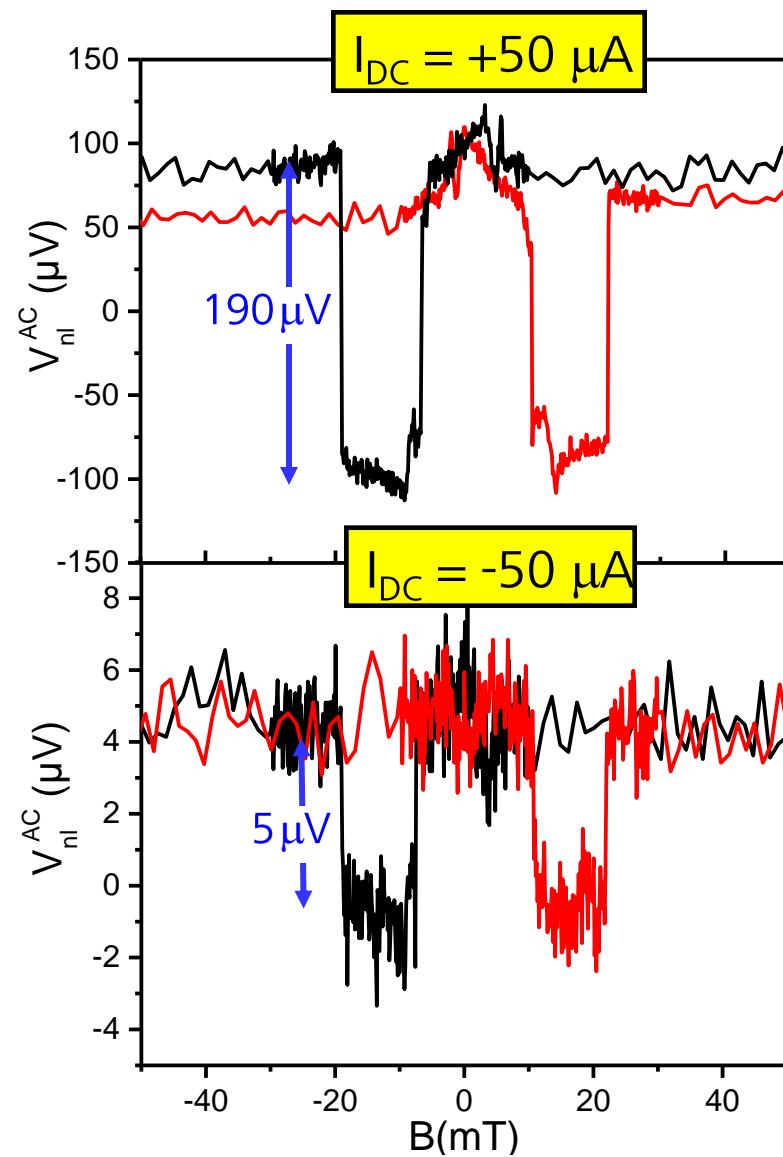
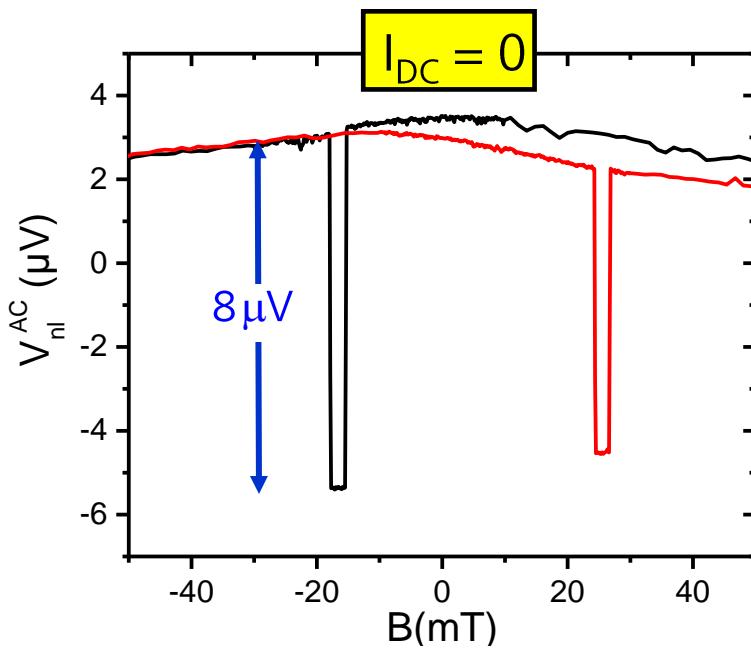
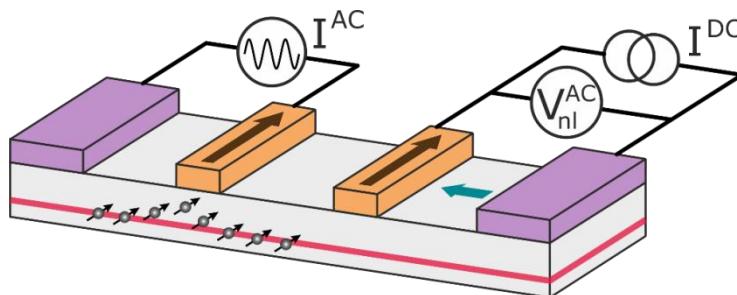
Experiments on GaAs bulk devices:

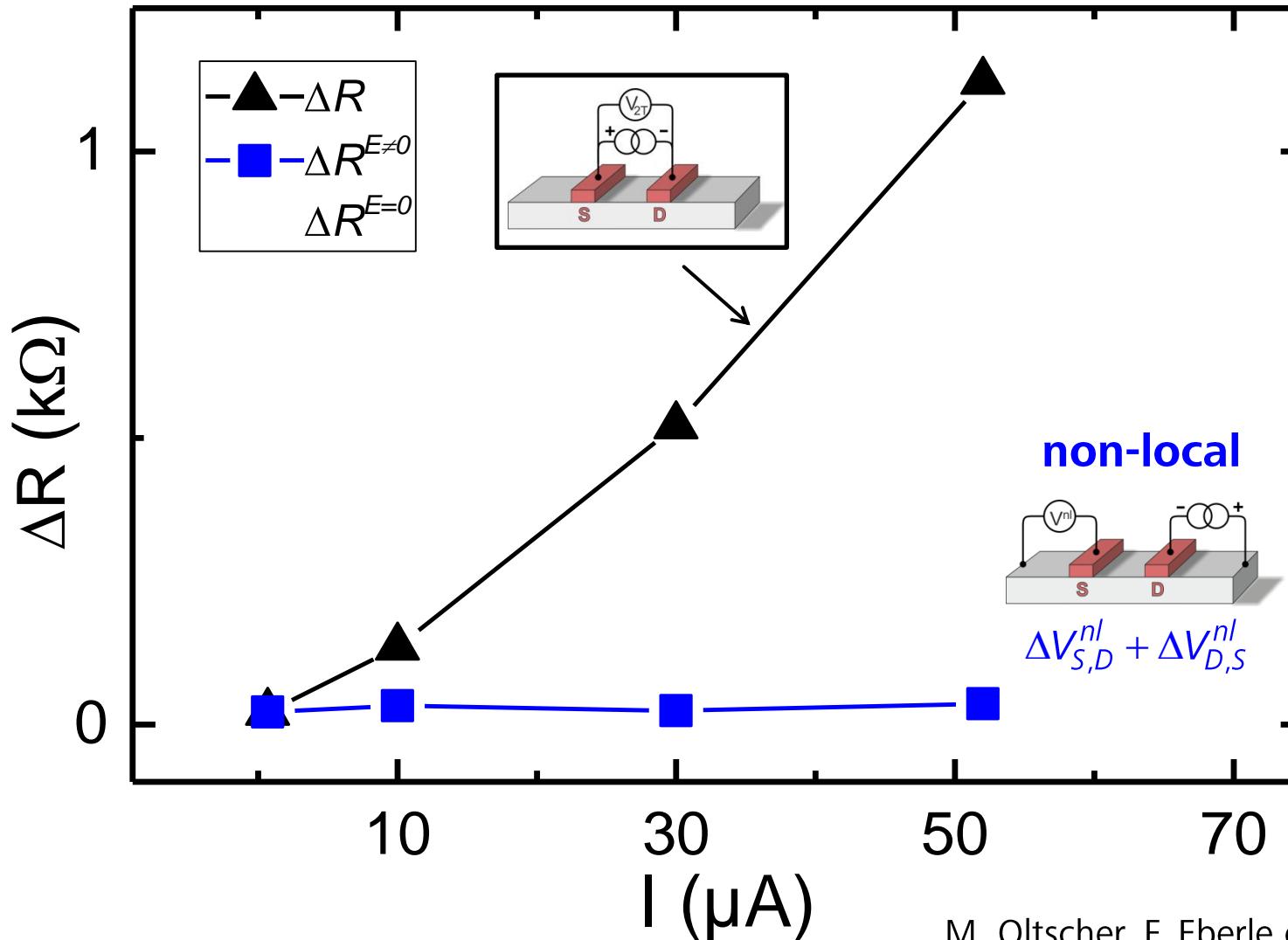
S. Crooker *et al.* Phys. Rev. B **80**, 041305R (2009);
J. Shiogai *et al.* Phys. Rev. B **89**, 081307(R) (2014)



Influence of biasing spin detector

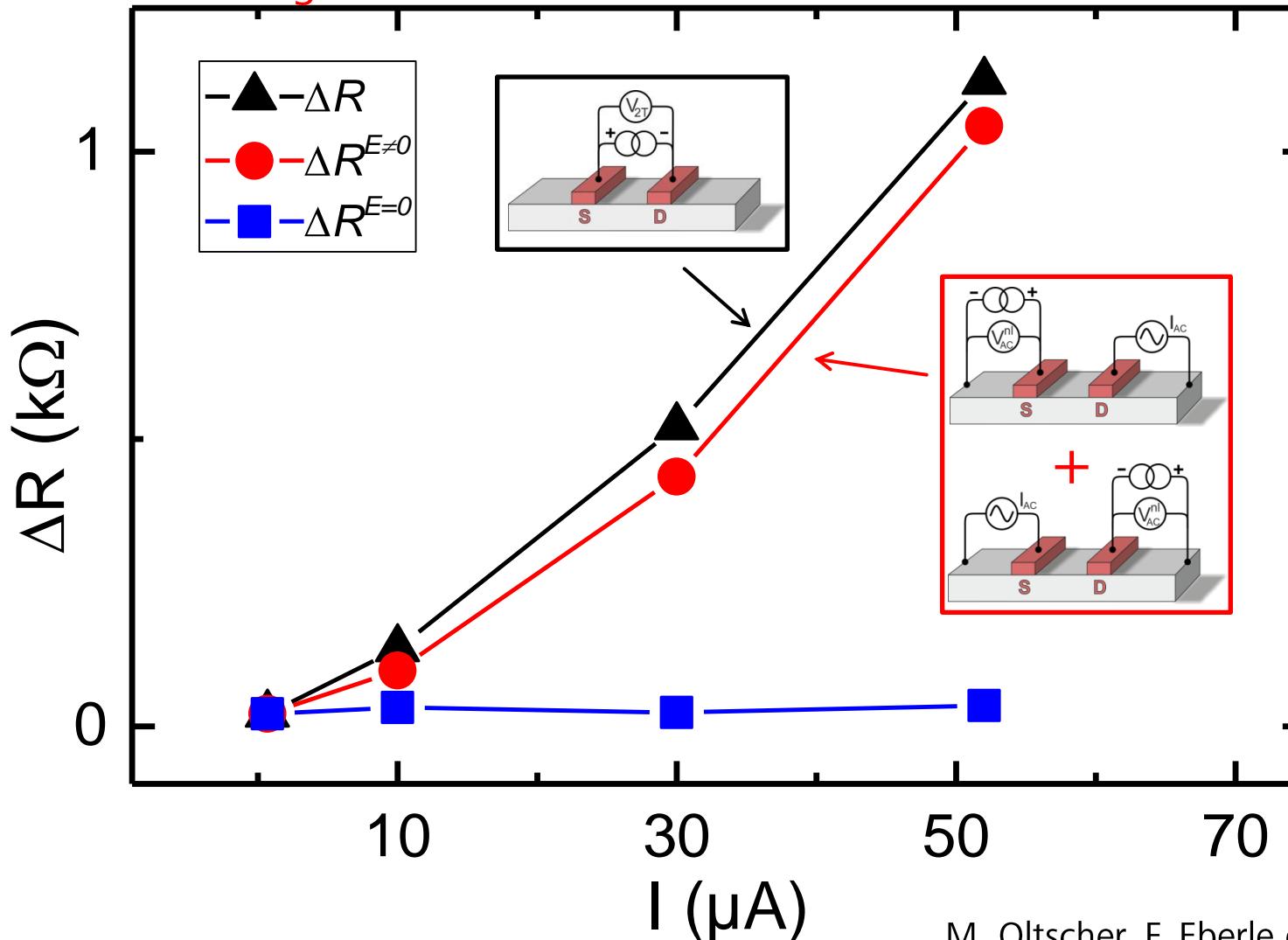
Measurement: AC
Biasing: DC



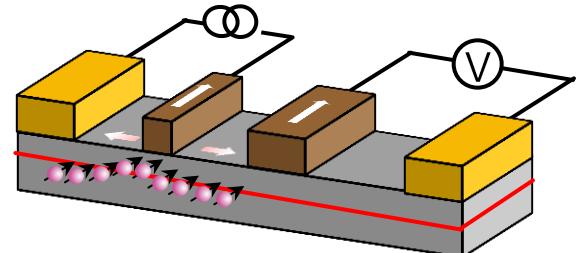


Mimicking local experiments non-locally

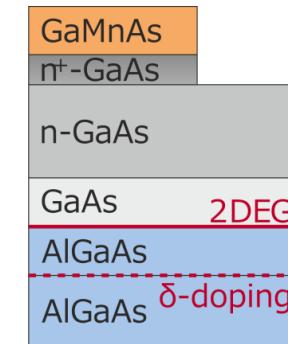
local voltage signal can be reconstructed by non-local voltage with biased detector contacts



- Sample design, Spin-injection/detection principle using non-local geometry

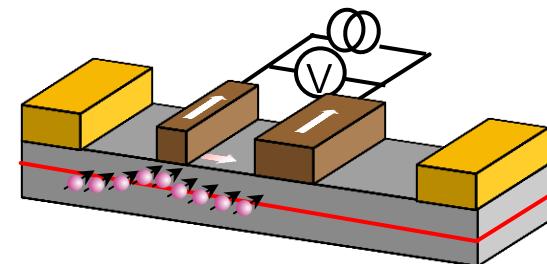


- Spin-injection/detection in 2DES

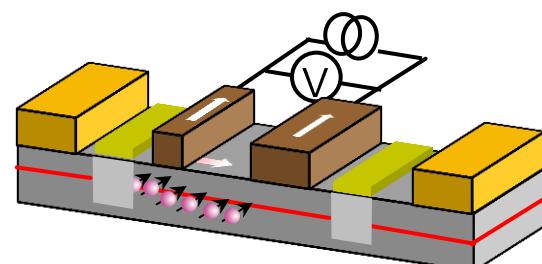


- Local (spin valve) measurements using 2DES: principle and experiments

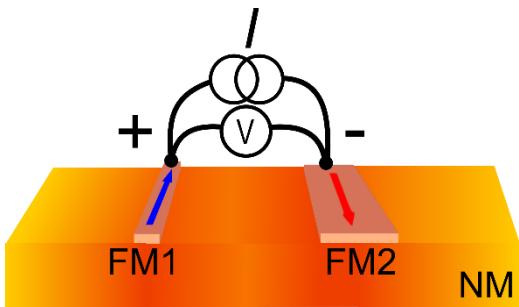
$$\Delta R / R \sim 80\%$$



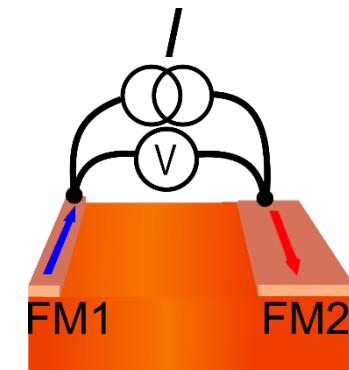
- Tuning the spin valve signal



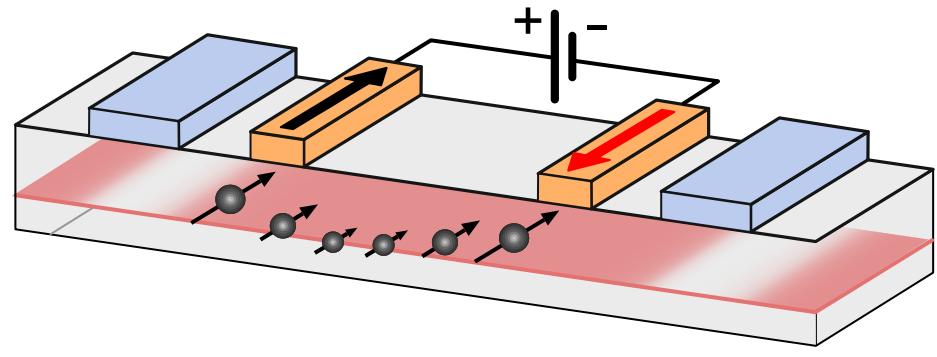
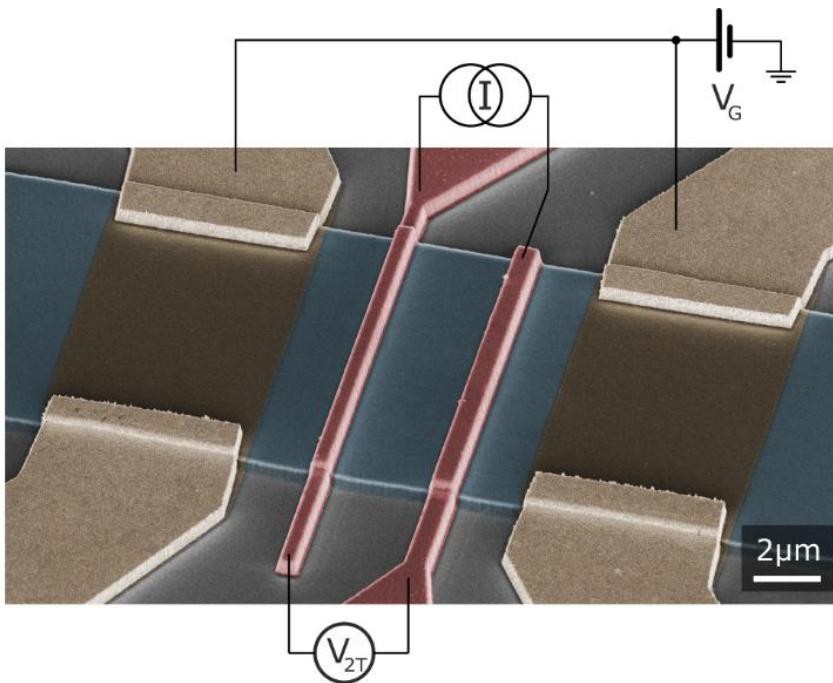
Open vs confined channel



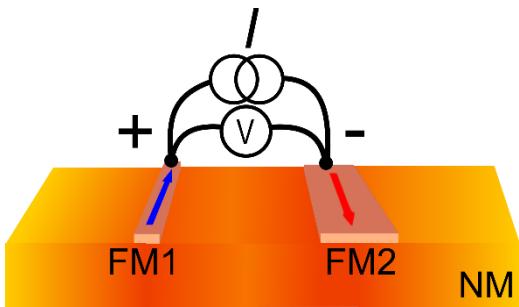
- Confining the spins between the contacts increases the MR ratio
H. Jaffres et al., Phys. Rev. B **82**, 140408 (2010)
H. Dery et al., Phys. Rev. B **73**, 041306 (2006)



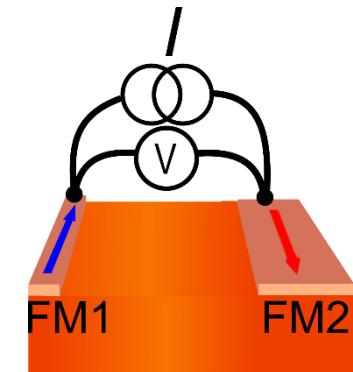
For a 2 DEG channel



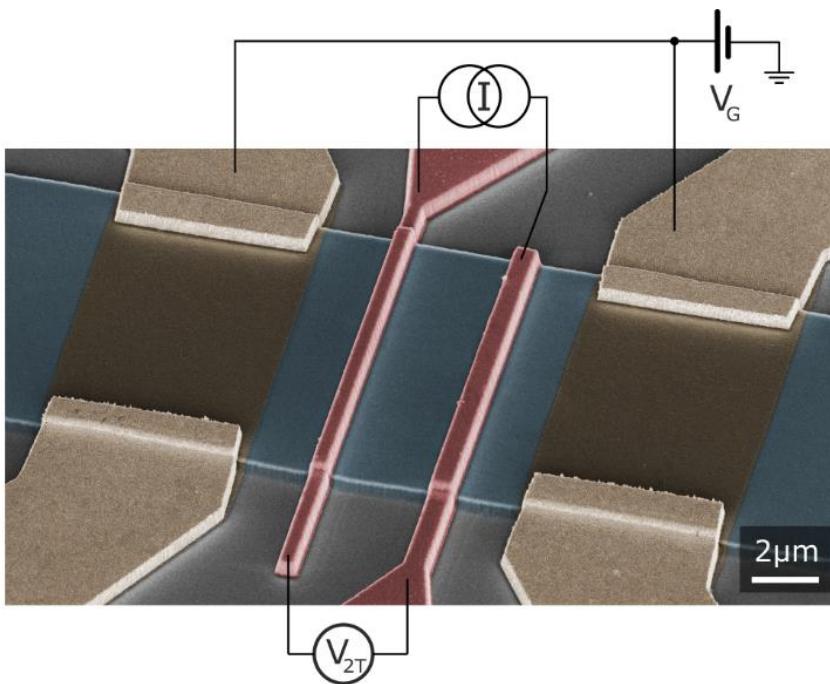
Open vs confined channel



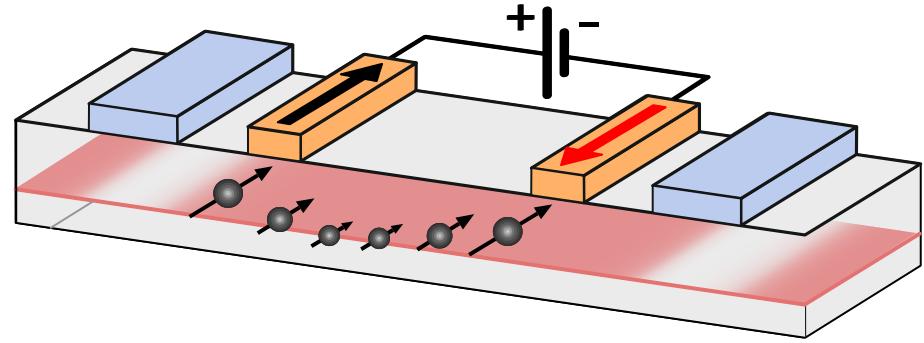
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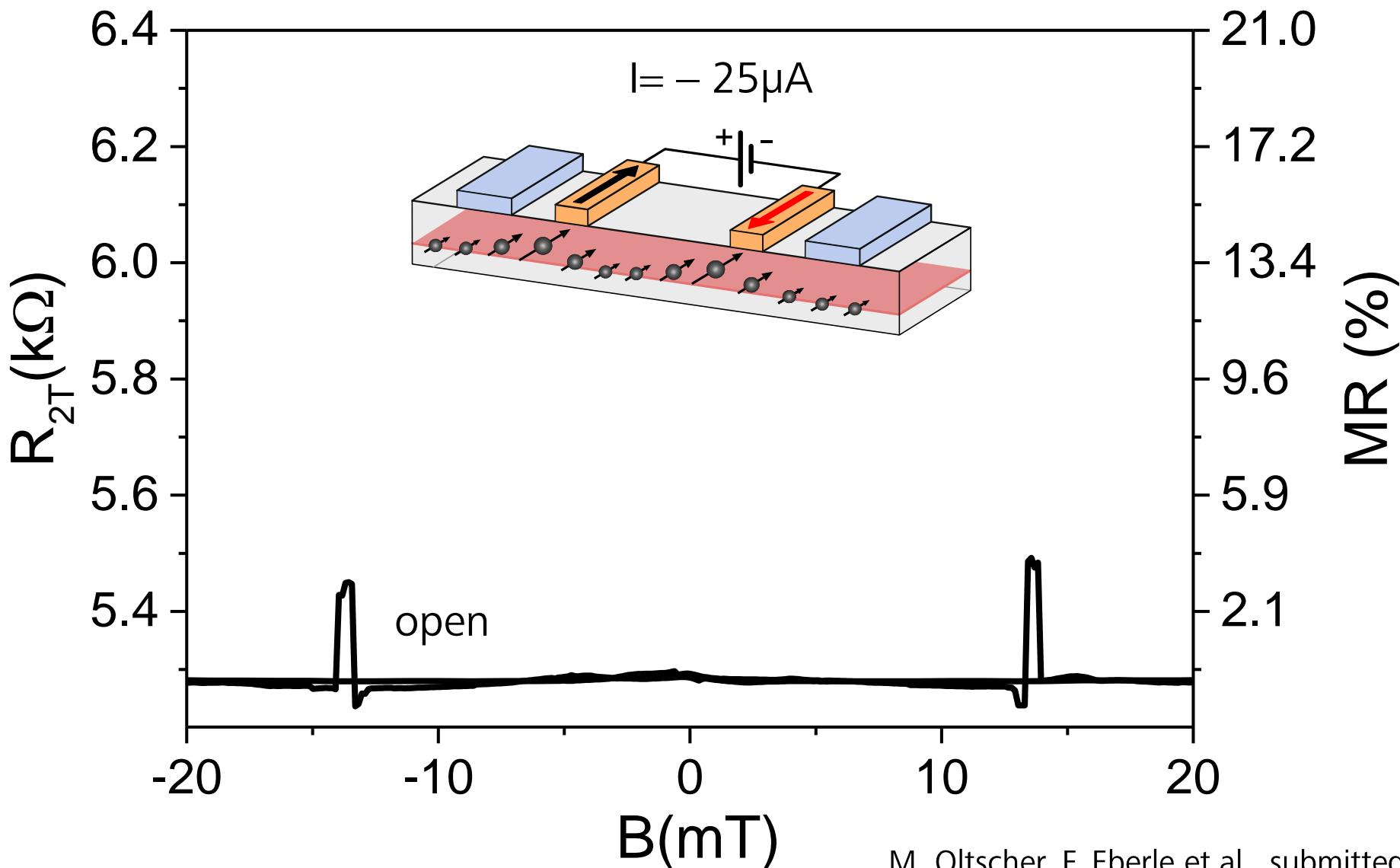
For a 2 DEG channel



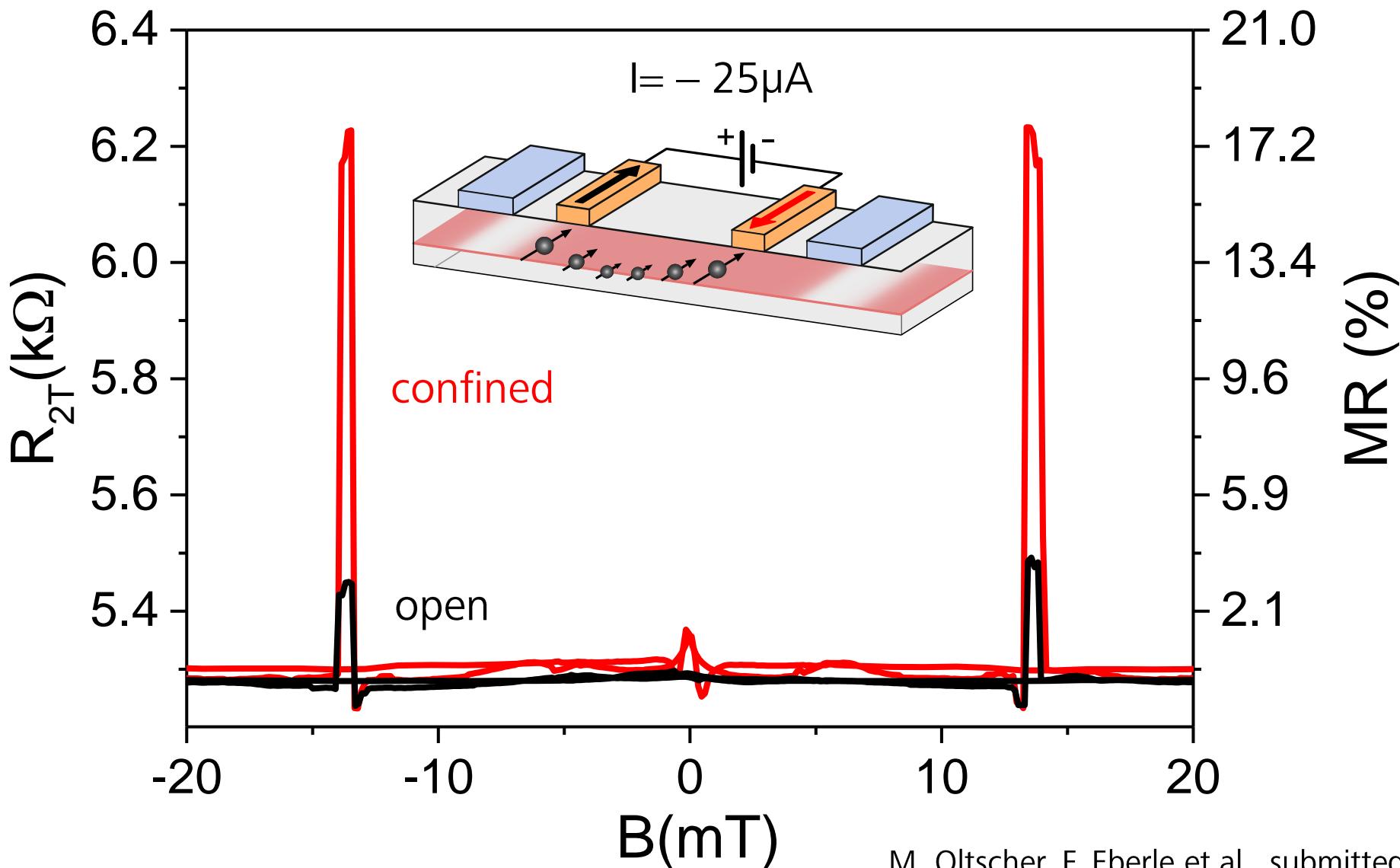
$$\Delta R_{open} = 2P^2 R_{ch} \exp(-d / \lambda_s)$$



Open vs confined channel

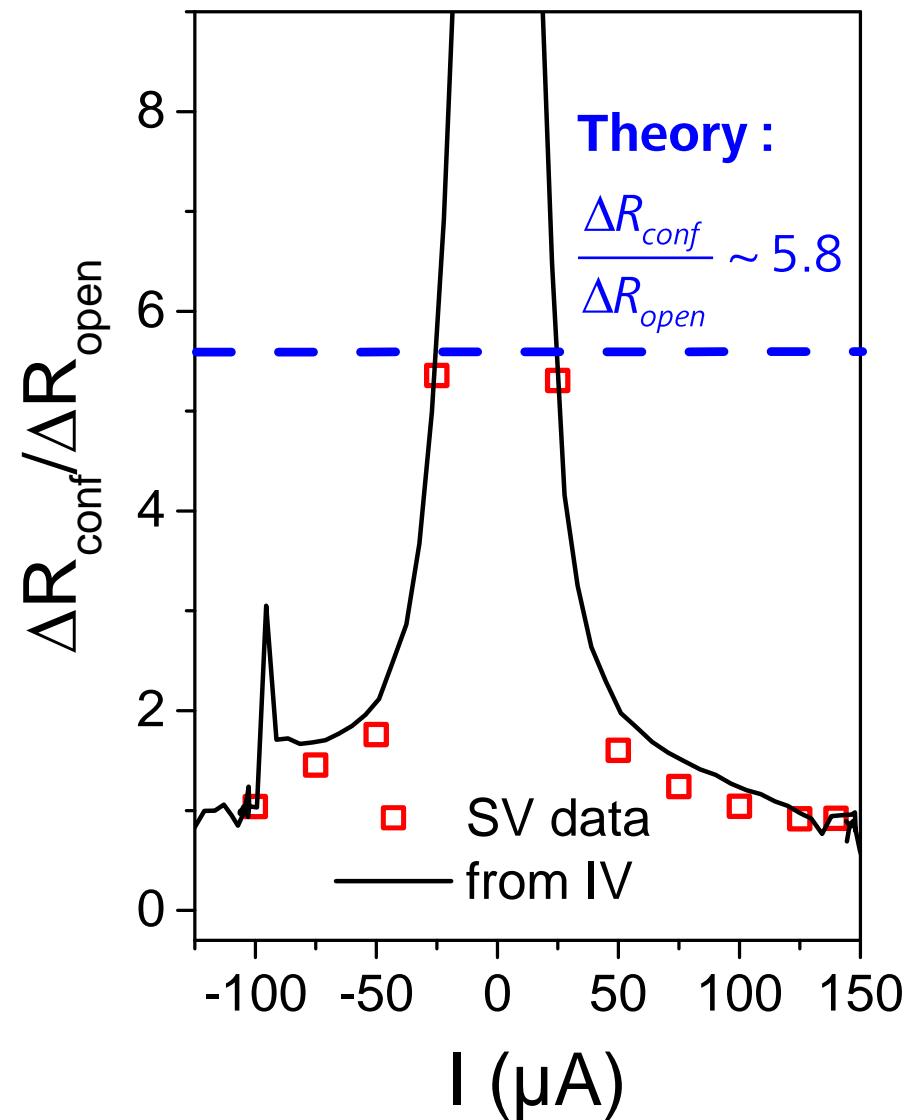
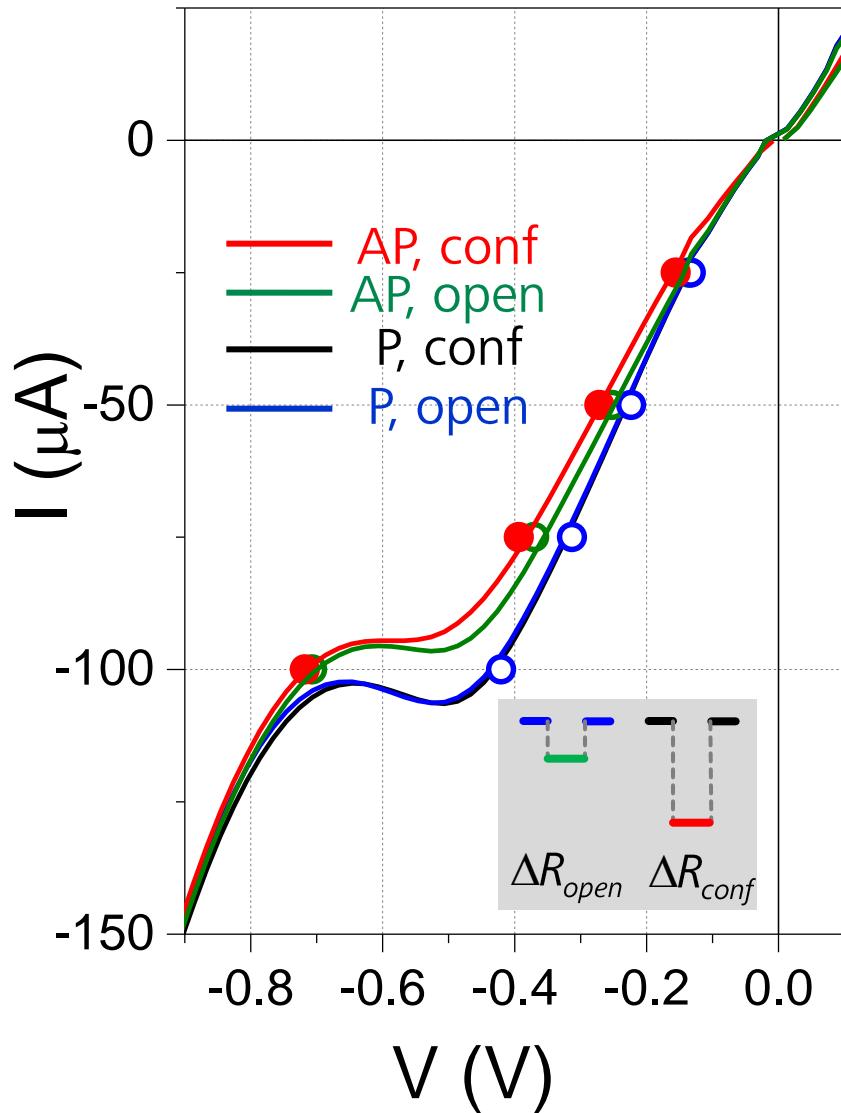


Open vs confined channel



Bias dependence of the confinement

M. Oltscher, F. Eberle et al., submitted



Some take home messages

(Ga,Mn)As/GaAs-2DEG model system to study electrical spin-injection, manipulation, and detection

- Efficient spin injection into high mobility 2DEGs
- Large local spin valve signals observed; $\Delta R/R$ up to 80%
- Bias dependence of detection sensitivity causes large local signals
- MR in FM/2DEG/FM samples can be tuned by gate

Funding



THANK YOU VERY MUCH FOR YOUR ATTENTION