Spin currents in two-dimensional electron gases

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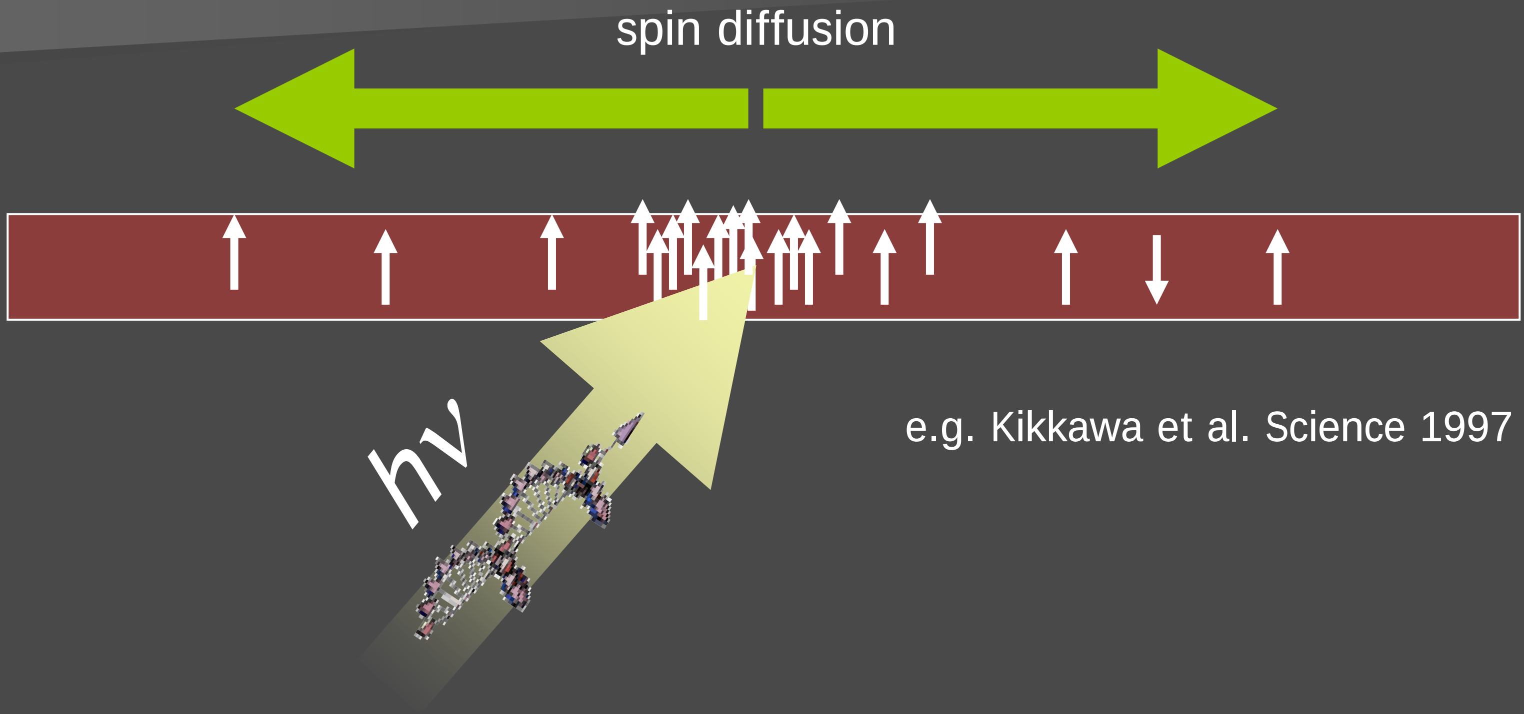
2DEGs provided by:
Werner Wegscheider
ETH Zurich

Main reference: Frolov et al. Phys. Rev. Lett. 2009

(This research was completed between 2005 and 2008)

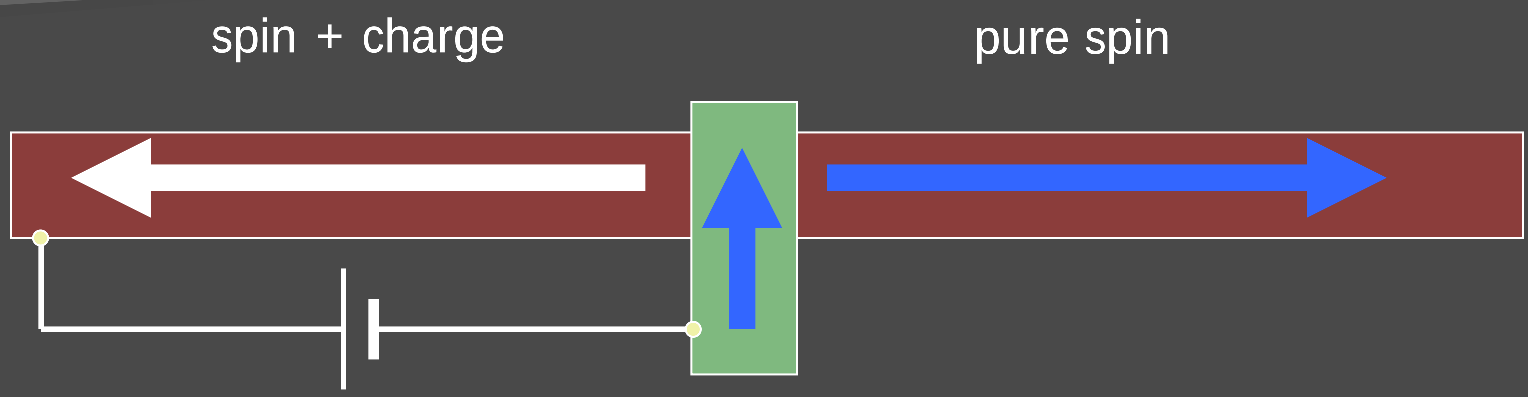
Spin currents



e.g. Kikkawa et al. Science 1997

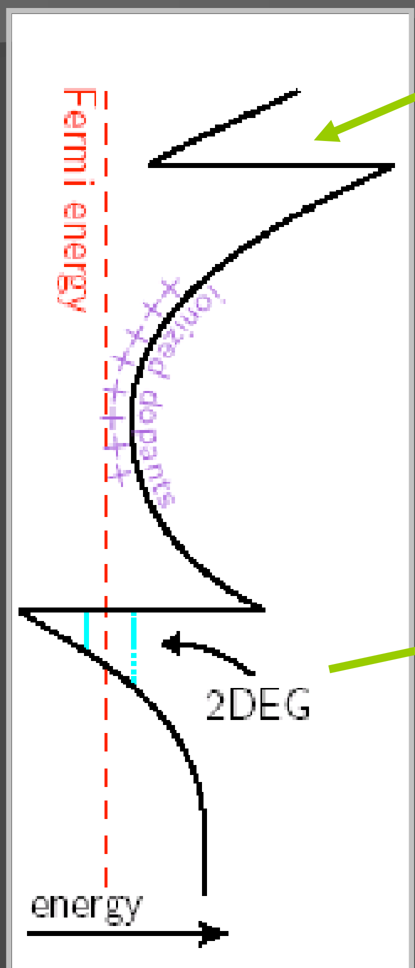
We studied spin currents carried by conduction electrons. Similar to electrical currents, spin currents flow from higher to lower spin chemical potential. The flow of spin current is mediated by the diffusion of electrons. But since electron spin has two values, spin currents are not conserved, i.e. they can relax. To generate a spin current one must create a higher chemical potential for one spin orientation. One prominent way to achieve this is by shining polarized photons on a semiconductor.

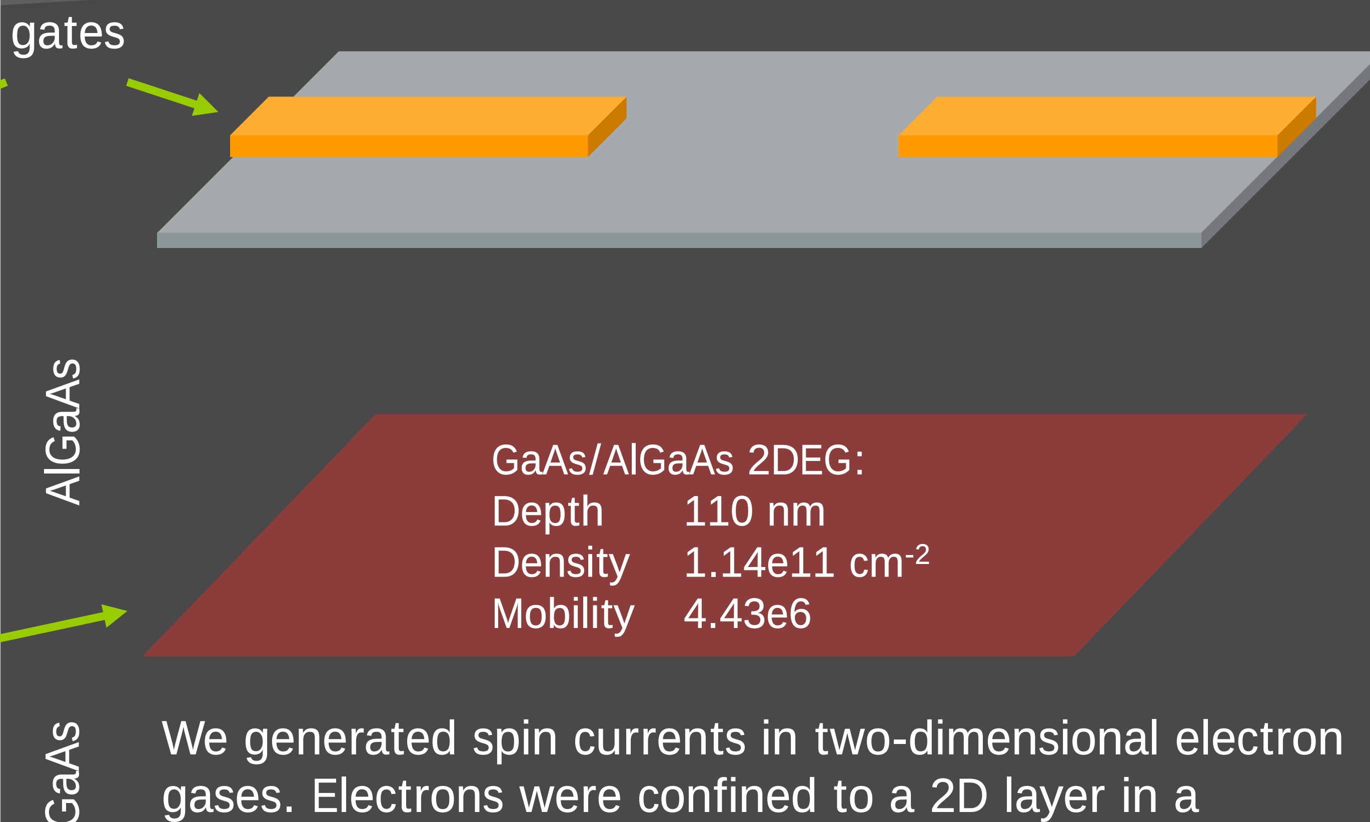
Electrical generation of spin currents



We generated spin currents electrically. The principle is illustrated above. An electrical current is passed through a spin-polarizing contact. This contact only passes spin-up (most commonly ferromagnets are used as spin injectors). Beneath the contact a higher spin-up concentration is accumulated. Extra charge is also injected along with spin, the charge current is sunk on the left side which is electrically grounded. Importantly, spin-up population diffuses to the left as well as to the right. Therefore, a spin current free of charge current, a 'pure spin current' flows to the right end of the device.

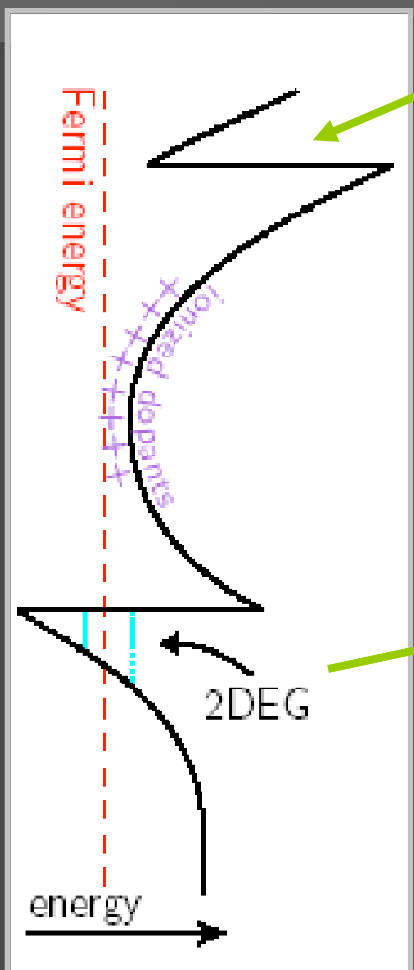
GaAs/AlGaAs heterostructures

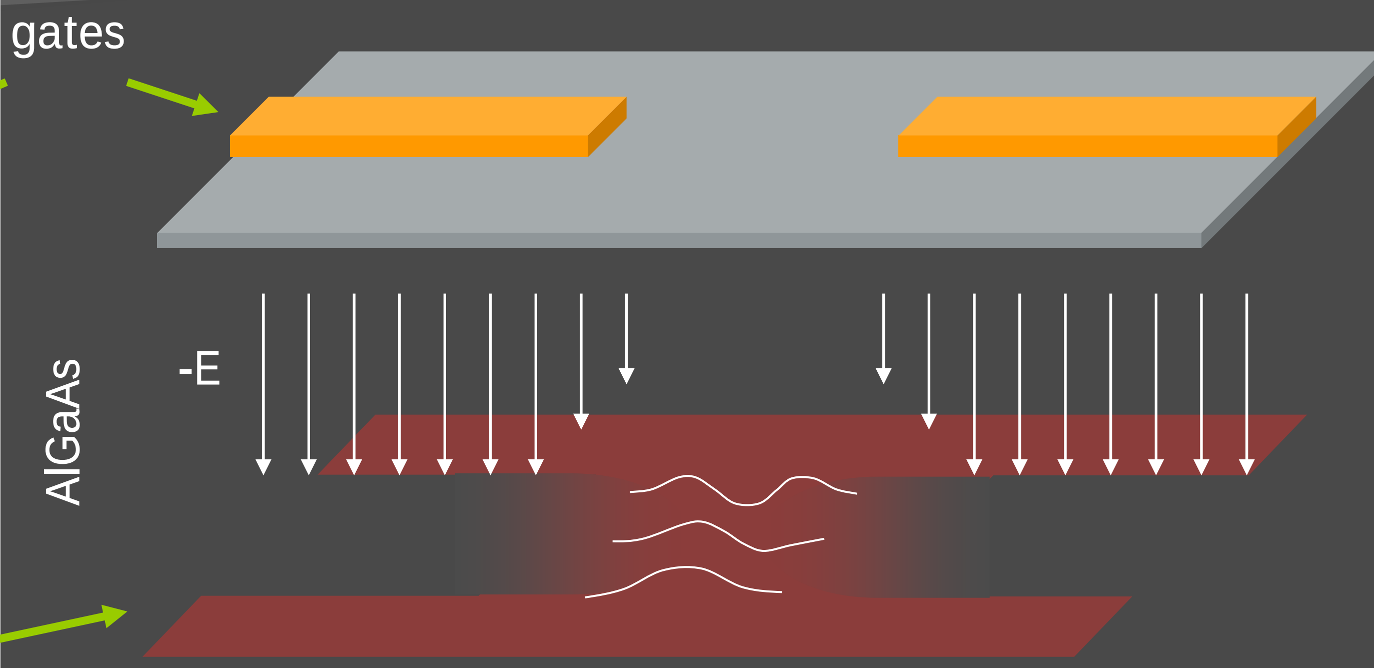




We generated spin currents in two-dimensional electron gases. Electrons were confined to a 2D layer in a GaAs/AlGaAs heterostructure of high mobility (mean free path 25 microns!)

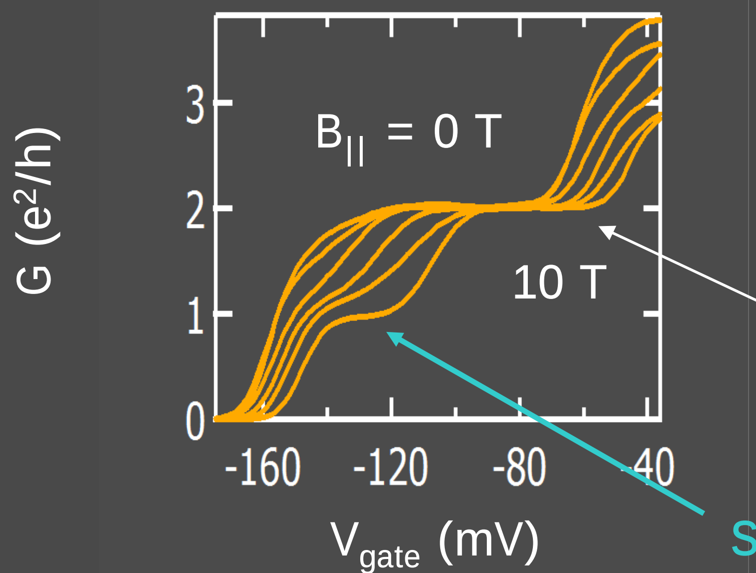
Quantum Point Contacts

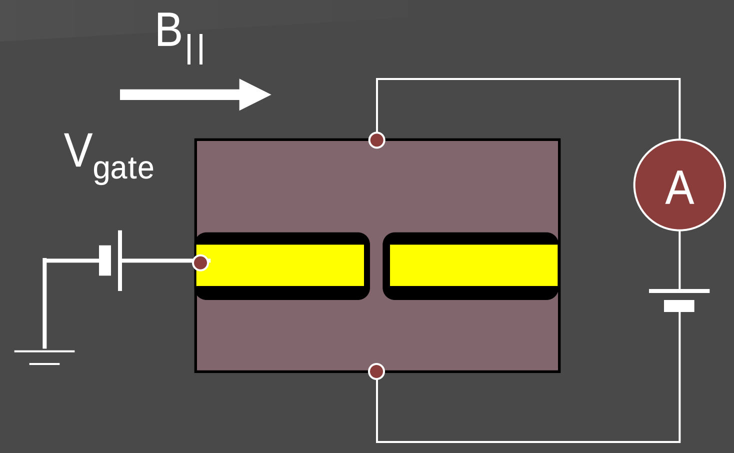




Our spin injectors were quantum point contacts. We applied negative voltages to two metallic gates on the heterostructure surface until the 2DEG was depleted under the gates. A narrow channel of 2DEG remained comparable to the electron wavelength.

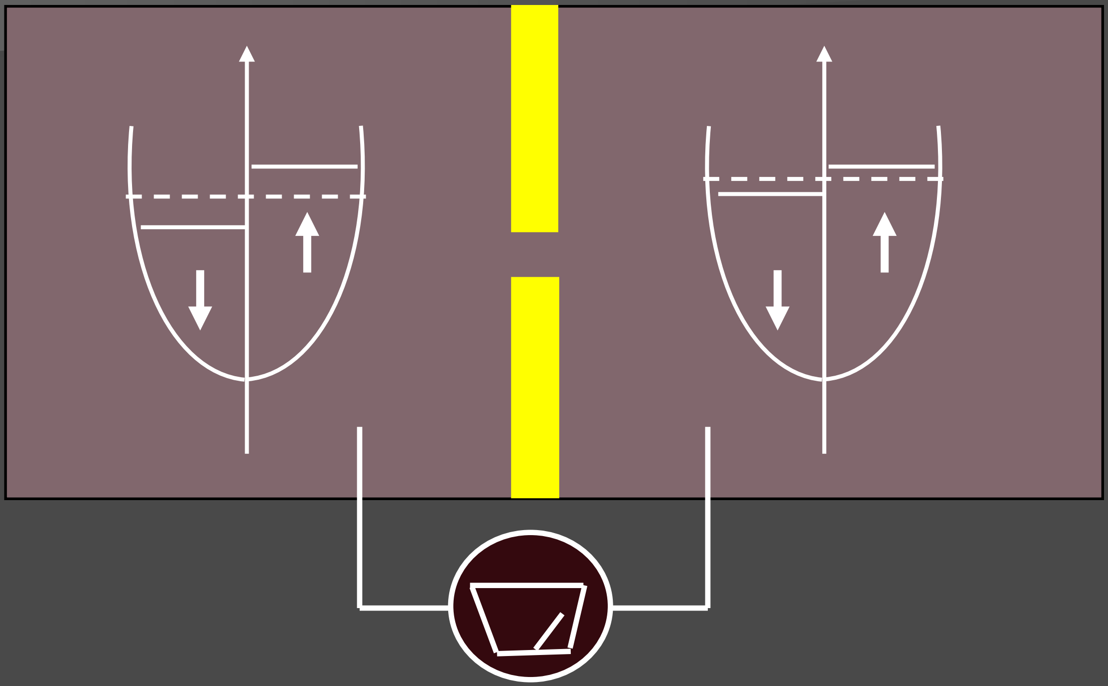
Quantum point contacts as spin injectors





The conductance of a quantum point contact (QPC) shows plateaus that are quantized in the units of $2e^2/h$, the factor 2 comes from spin degeneracy. We applied magnetic field to lift spin degeneracy, a plateau at $1e^2/h$ appeared in the conductance trace. By tuning gate voltages to that plateau we only allow electrons with spins oriented along the field to pass through the QPC.

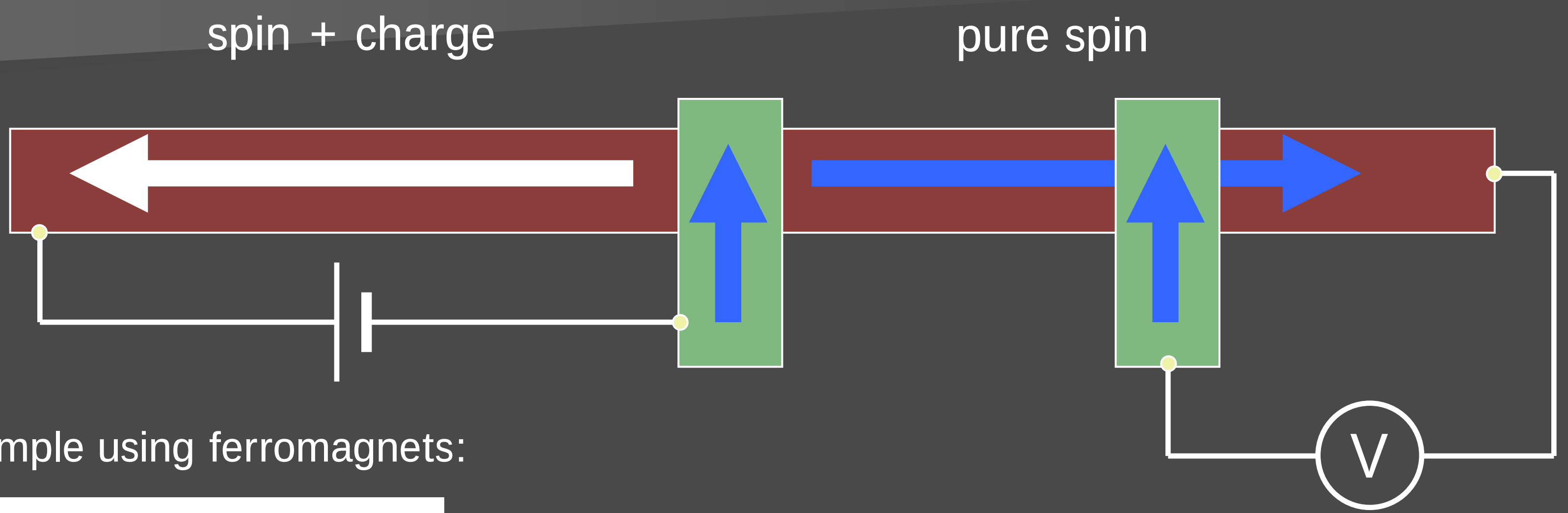
Spin injectors are also spin detectors



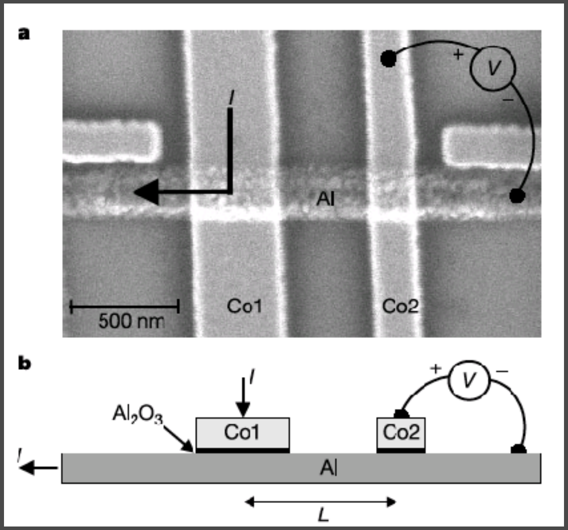
QPCs can also detect nonequilibrium spin populations, and through this probe spin currents. Suppose there is a excess of spin-up on the left side of a spin-polarized QPC, i.e. the chemical potential of spin-up is higher than the average (dash). Those spin-up electrons will travel through the QPC and increase the net chemical potential on the right. A voltmeter hooked up to the QPC will measure a net voltage, a difference in the average chemical potentials on the left and on the right!

Nonlocal Spin Valve

Technique: Johnson and Silsbee, PRL 1985



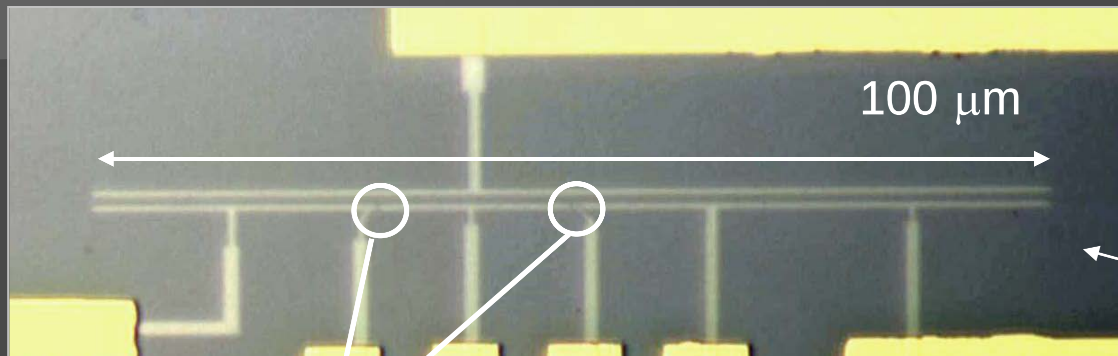
An example using ferromagnets:

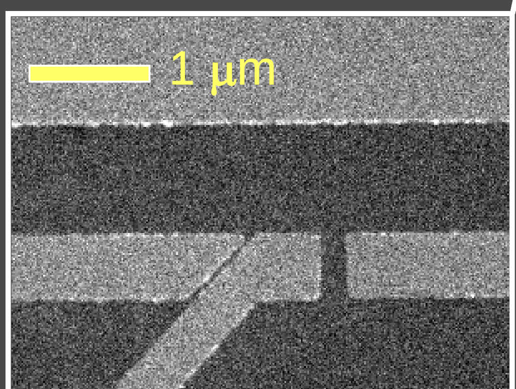


Jedema, van Wees et al. Nature 2002

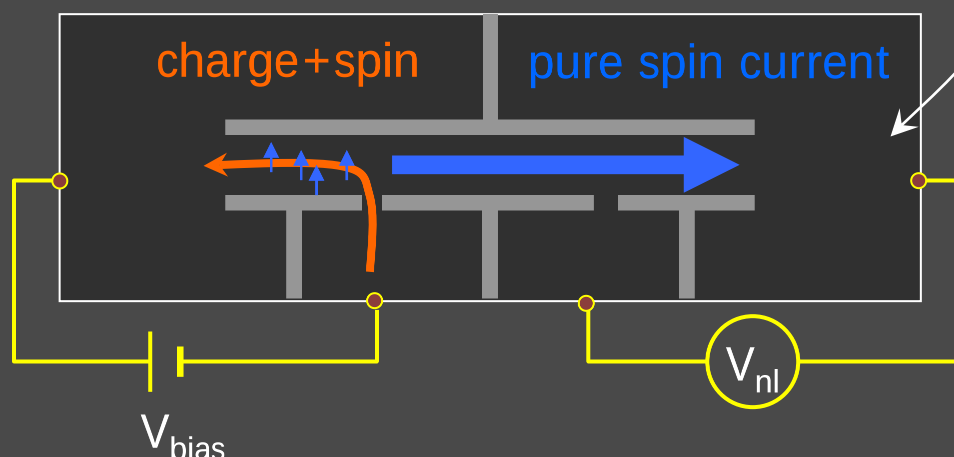
Pure spin current can be monitored if a spin-selective detector contact is placed right of the injector. This measurement geometry is sometimes called ‘nonlocal spin valve’.

Nonlocal Spin Valve in a 2DEG





Quantum Point Contacts
(injector and detector)

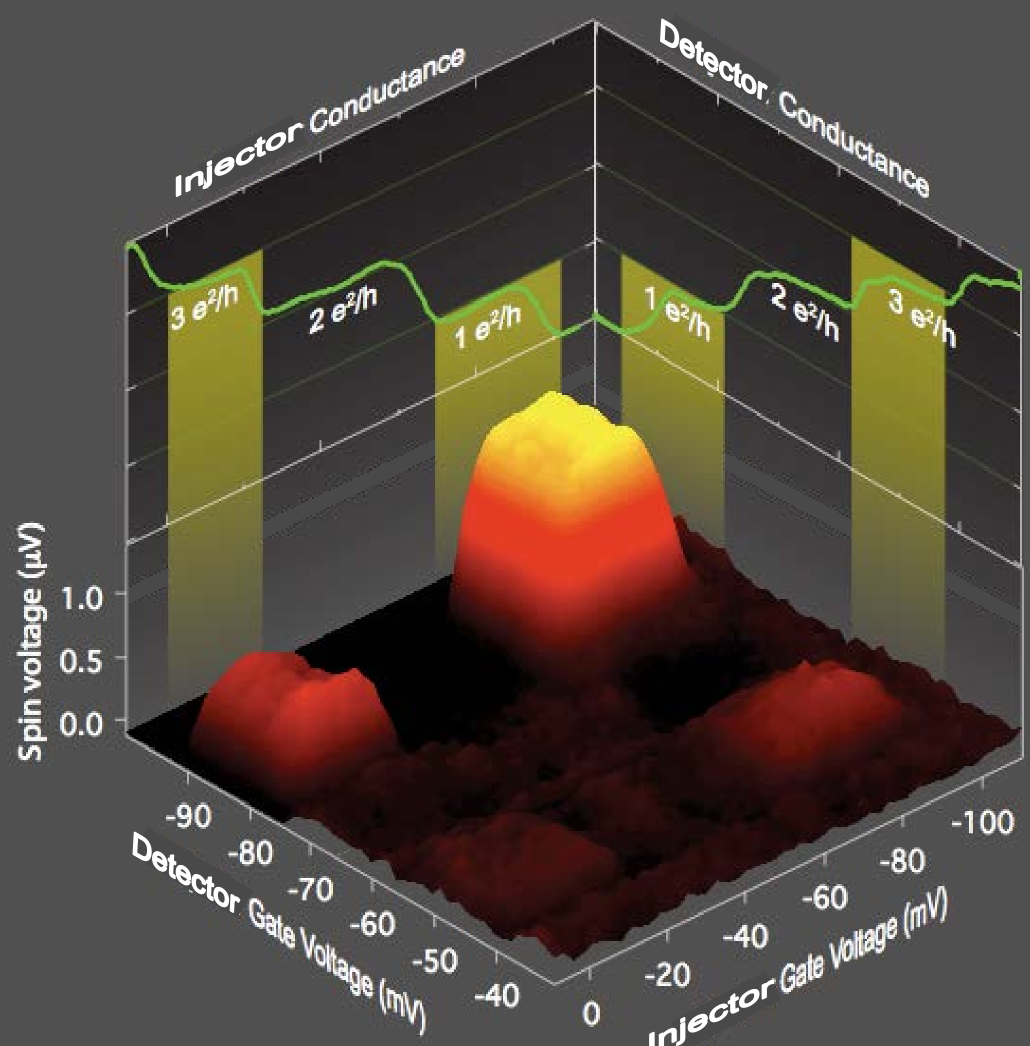


Spin current signal in the nonlocal spin valve

The 3D plot shows the pure spin current signal measured as the conductance of the injector and detector QPCs is swept over several conductance plateaus. When both the injector and the detector are spin polarized, the signal is positive. The signal depends on QPC polarization

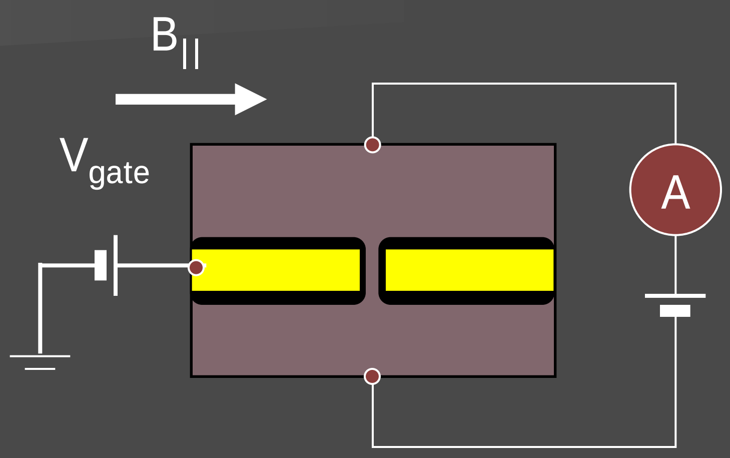
$$V_{nl} \propto P_{inj} P_{det}$$

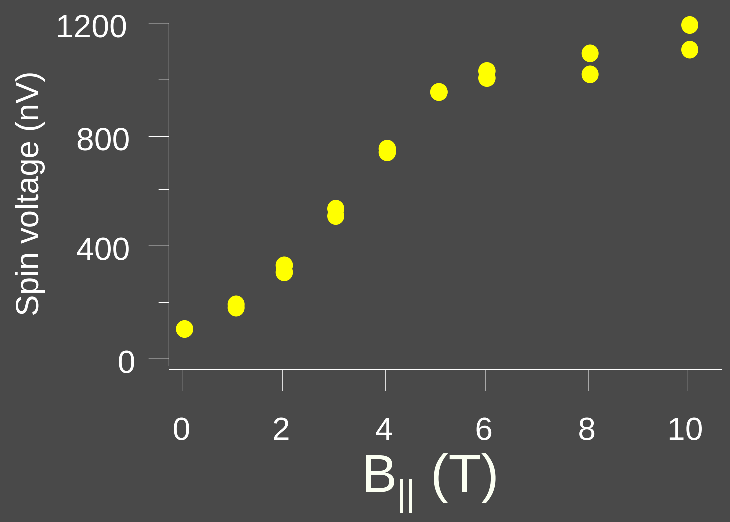
P = 1 at the first plateau (e^2/h)
P = 0 at the second plateau ($2e^2/h$)
P = 1/3 at the third plateau ($3e^2/h$)

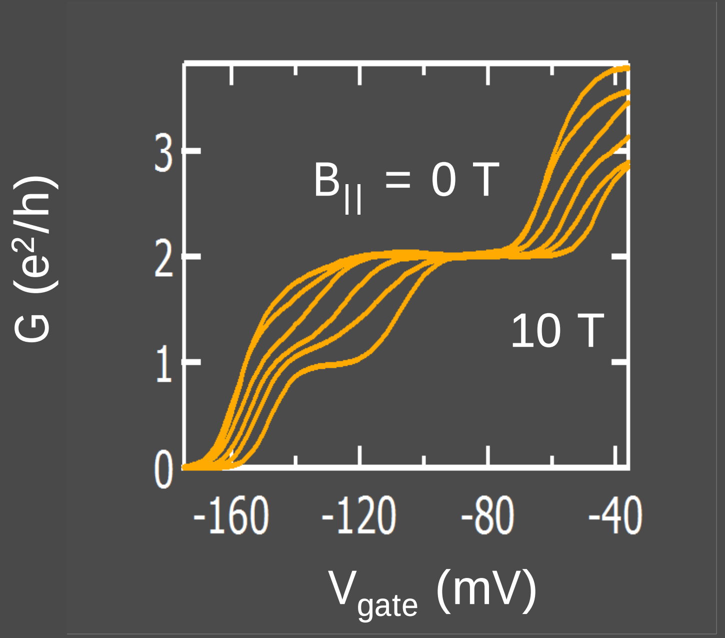


QPCs only polarize at high magnetic fields

The spin signal in the nonlocal spin valve increases with magnetic field and reaches saturation above B=5T. At this field quantum point contacts develop a robust spin-polarized plateau at e^2/h.







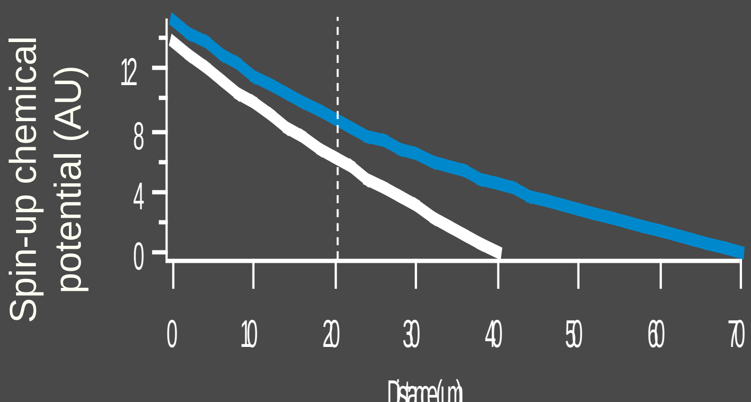
Spin relaxation measurement

Long Channel:

Short channel:

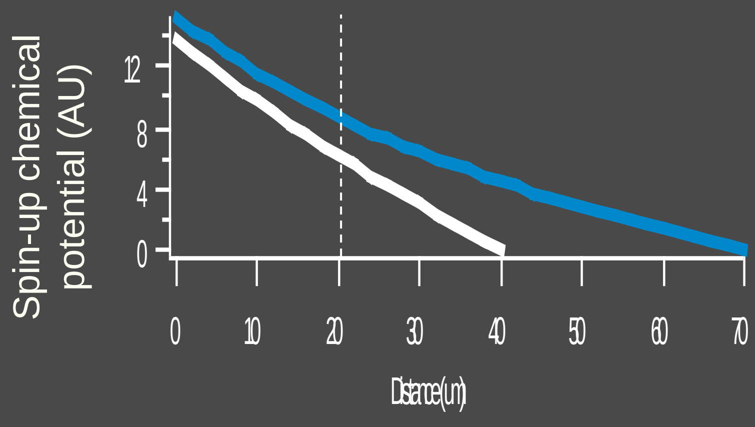
$$V_{spin}(x) \propto \lambda_s sinh(\frac{L-x}{\lambda_s})$$

detector at 20um



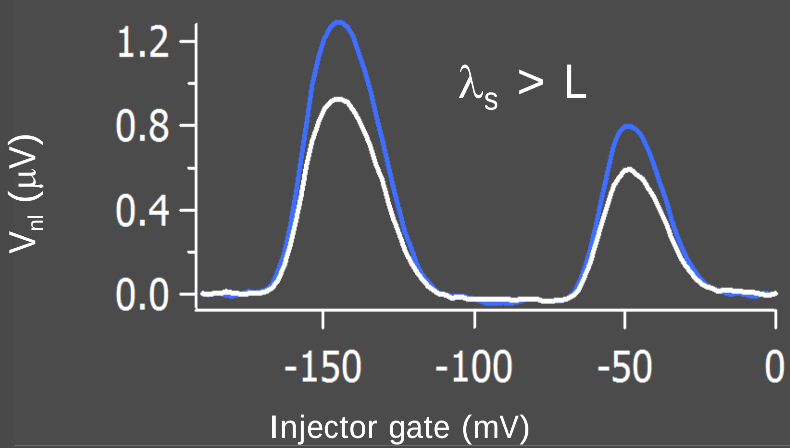
Spin signal also depends on spin relaxation in the diffusion channel, described by the relaxation length λ_S. We can extract λ_S in-situ by changing the length of the diffusion channel L using the blue gate at the right end. Spins are at equilibrium at the channel end. When the channel end is moved closer to the detector the spin signal is reduced – see the 1D diffusion equation solution plotted on the left.

Spin relaxation measurement



The relaxation length λ_s can be extracted from the ratio of spin signals for short and long channels by substituting the spin voltage in the solution of the diffusion equation for two different values of L:

$$V_{spin}(x) \propto \lambda_s sinh(\frac{L-x}{\lambda_s})$$

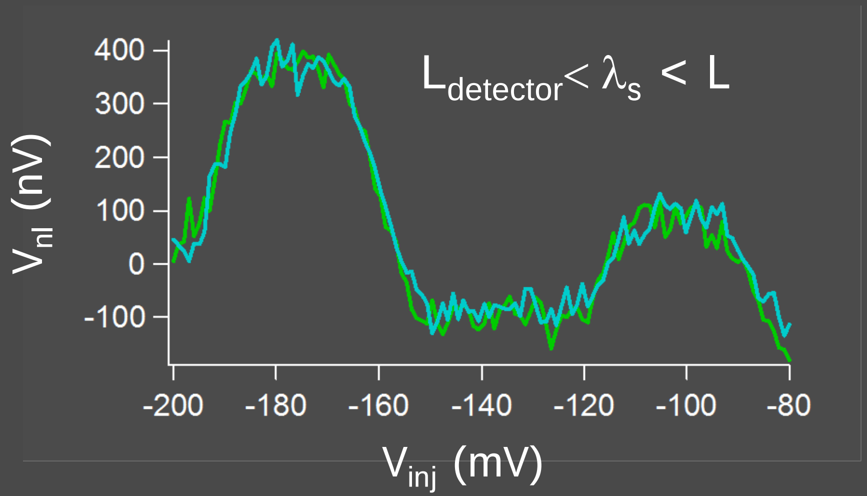


This method is useful because no knowledge of QPC spin polarization is required.

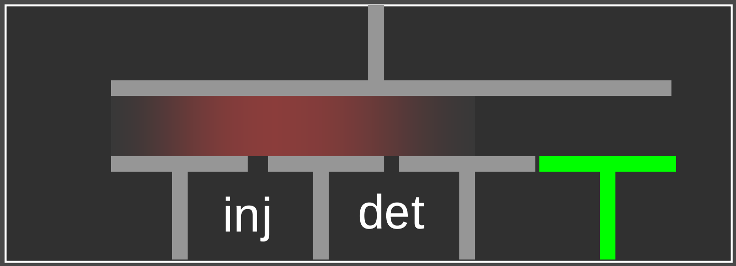
The plot on the left shows the spin signal over the 1,2,3 plateaus of the injector for Long and Short channels.

Spin relaxation measurement

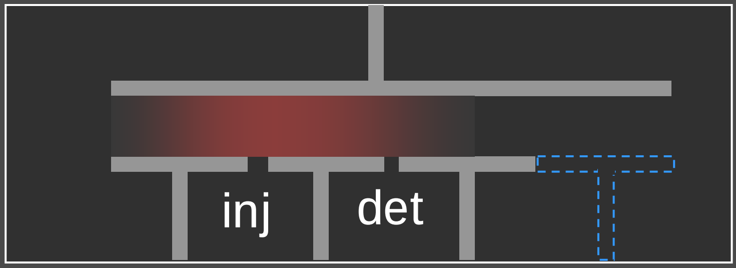
{Note that the method does not work when the spin relaxation length is shorter than the short channel. In this case the signal is not affected by undepleting the end-gate. The spin current has already fully relaxed before reaching the end of the channel.}



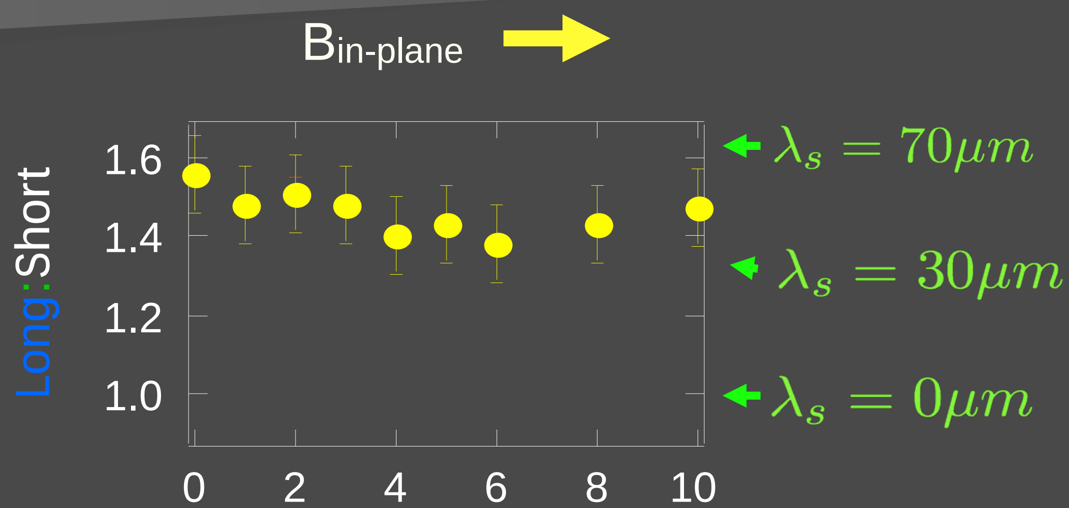
Long channel:

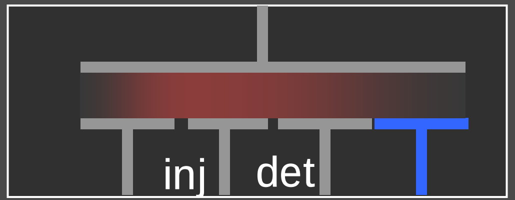


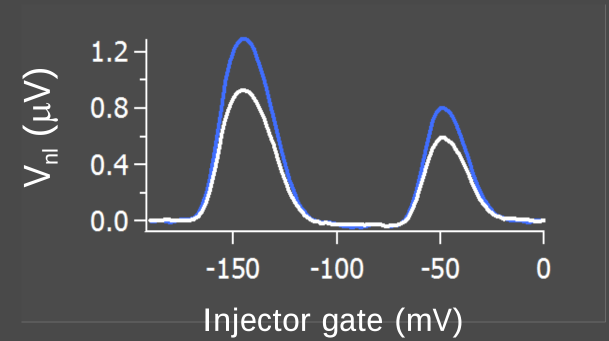
Short channel:

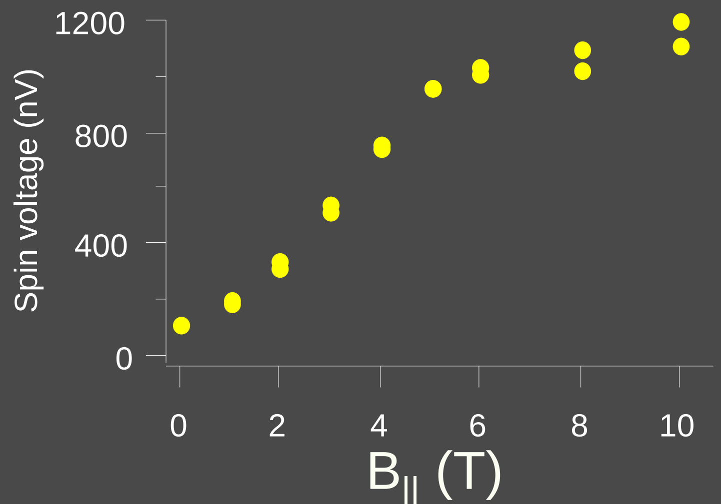


Spin relaxation length: 50 microns







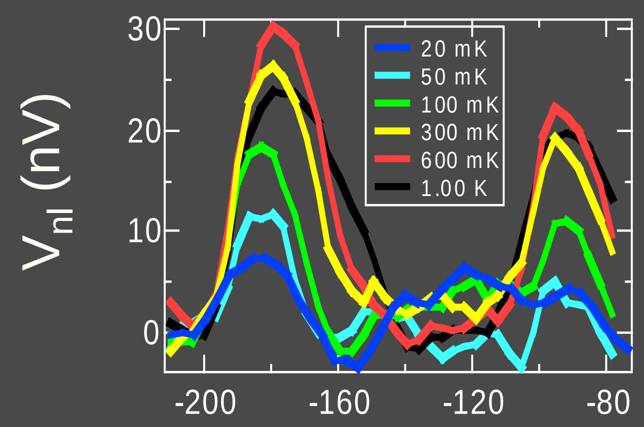


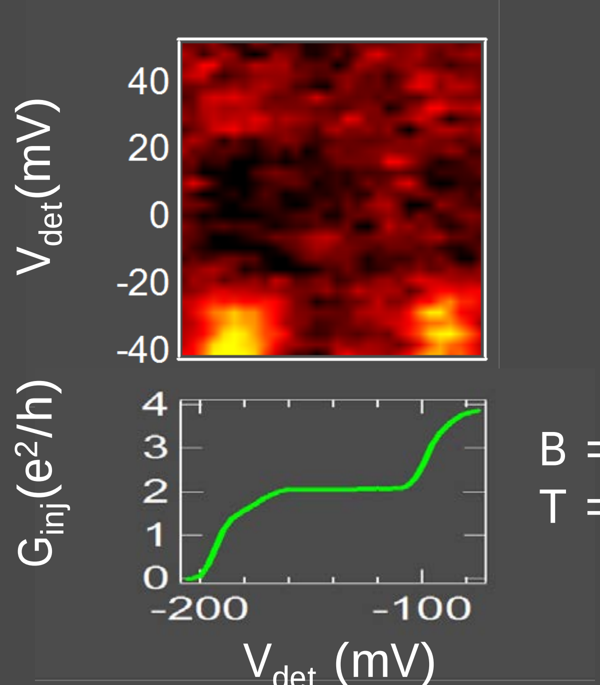
We have measured the ratio of V_{nl}(Long)/V_{nl}(Short) and extracted $\lambda_S \sim 50\ \mu m$ independent of field for B along the channel.

We explained it by suppressed spin relaxation due to motional narrowing in the 1 micron wide diffusion channel. This conclusion was confirmed by the simulations of spin dynamics.

Spin (?) signal at B=0

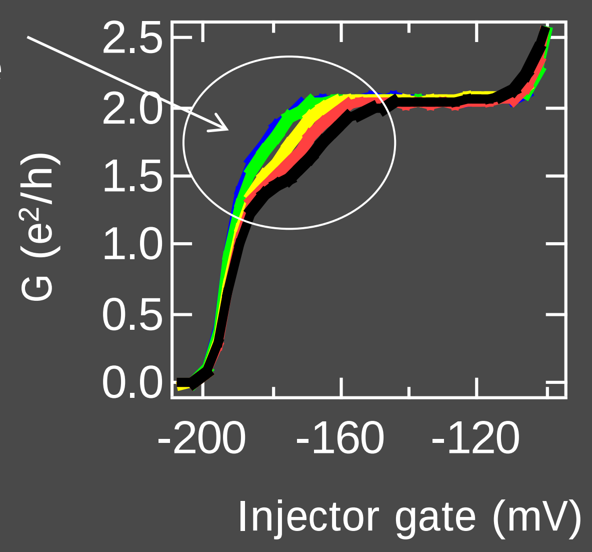
A pattern remarkably similar to spin signal was observed at zero field. Positive voltage coincided with the infamous 0.7 conductance plateau ($0.7*2e^2/h$), which some believe is a sign of spin polarizaion at zero magnetic field – a much sought after effect in semiconductor spintronics!





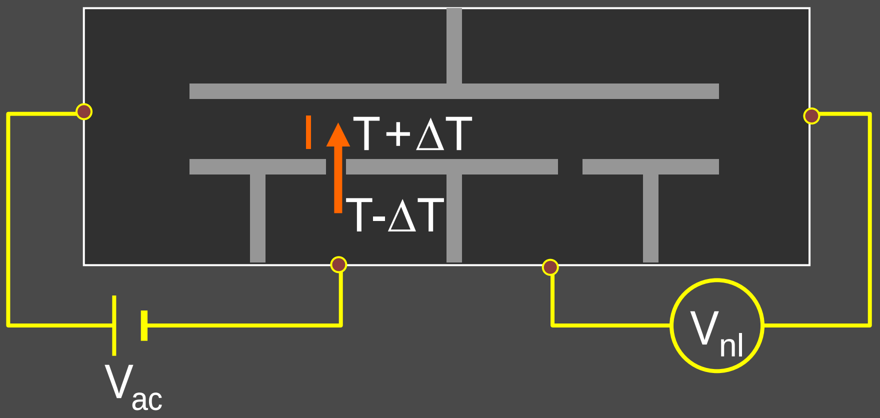
0.7 plateau develops at higher temperature

B = 0
T = 300 mK



No spin polarization at B=0! (Peltier effect)

We have identified this signal as Peltier heating. Electrons injected into the channel raise the temperature slightly. This temperature difference is picked up by the detector since the QPCs thermopower S is high between conductance steps.



$$\Delta V = R\,I + S\Delta T$$
$$dQ/dt = \Pi\,I - \kappa\Delta T$$

QPC thermopower is peaked between plateaus:

$$S \propto T\, d\,ln G_{QPC}/d\mu$$

And so is the Peltier coefficient:

$$\Pi = S\,T;$$

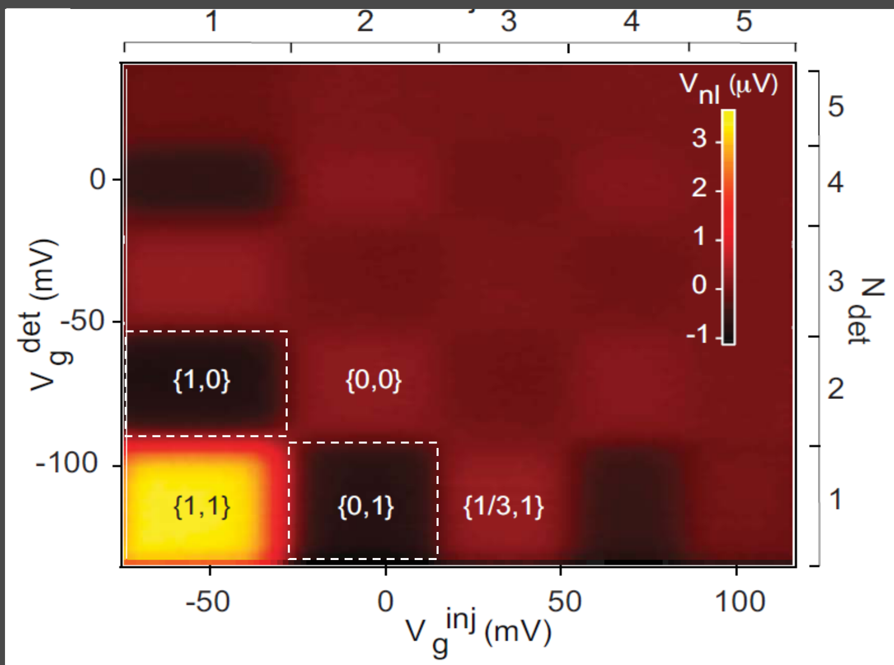
Peltier heating:

$$\Delta T \propto \Pi\, I$$

In a lock-in measurement sinusoidal bias is applied:

$$V_{nl} = S\,\Delta T \propto S\,\Pi\, I_{ac} \sin(\omega t)$$

Negative nonlocal voltage



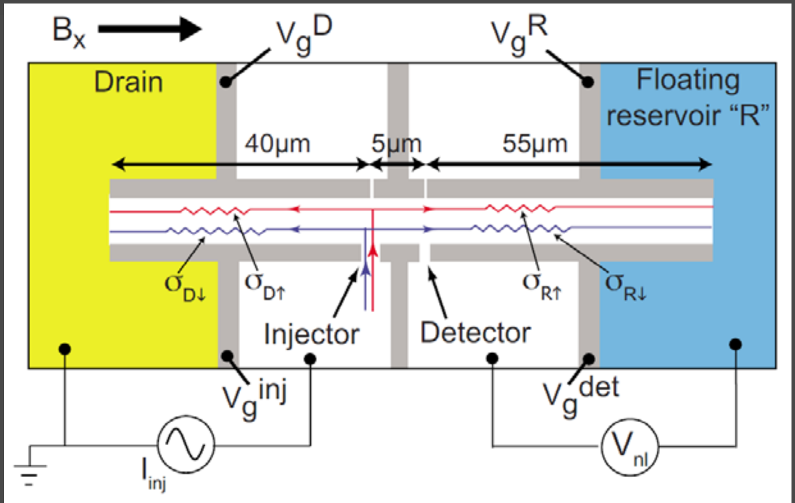
Ebrahimnejad PRB(Rapid) 2010

In additional to positive spin signal when both the injector and the detector are polarized, we often observed a negative nonlocal signal.

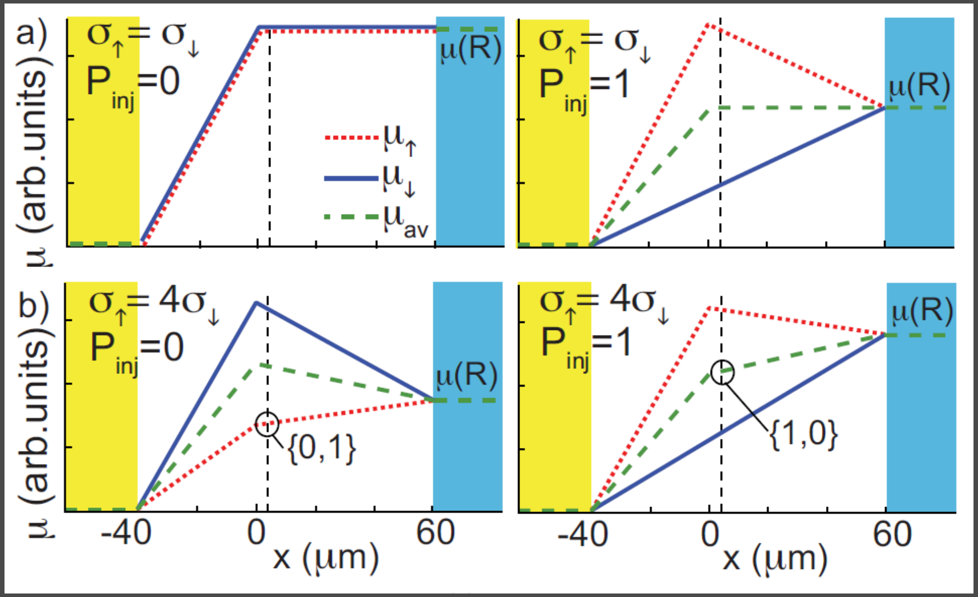
This signal appeared when either only the detector or only the injector were polarized. The field dependence of this negative signal indicated that it has spin origins as well.

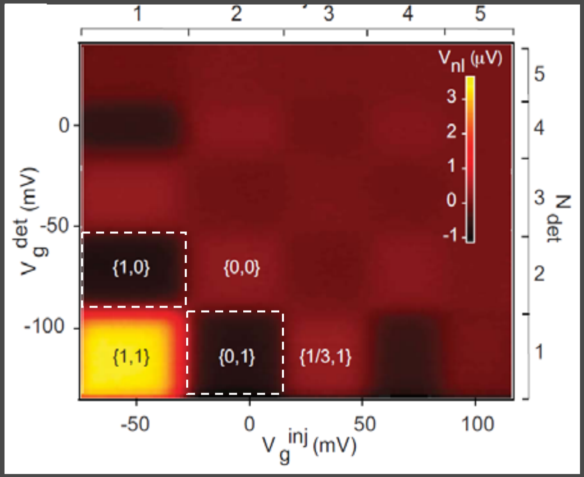
But how can an unpolarized contact detect a spin signal? And how can an unpolarized QPC inject an opposite spin current?

Spin-dependent conductivity in a 2DEG



At large magnetic fields different Fermi velocities for spin up and down lead to different conductivities for the two spin orientations in the bulk of the 2DEG! The opposite spin current is generated in the 2DEG due to this conductivity mismatch as explained below.





We extracted a 4-5 times enhanced spin susceptibility in the 2DEG

Summary

- Electrical generation of pure spin currents in GaAs/AlGaAs 2D electron gas

  Frolov et al. PRL 2009

- Spin-dependent conductivities in a 2DEG

  Ebrahimnejad et al. PRB(Rapid) 2010

- Ballistic Spin Resonance detected using pure spin currents (discussed separately)

  Frolov et al. Nature 2009