Shot noise induced by spin accumulation

Graduate School of Science, Osaka University

Tomonori Arakawa

Collaborators;

Collaboration started since 2011

Japan

J. Shiogai (Institute for Materials Research, Tohoku University)

K. Kobayashi, M. Maeda (Osaka University)

T. Ono (Kyoto University)

M. Kohda, J. Nitta (Tohoku University)

Germany

M. Ciorga, M. Utz, D. Schuh, D. Bougeard , D. Weiss (University of Regensburg)

Acknowledgment;

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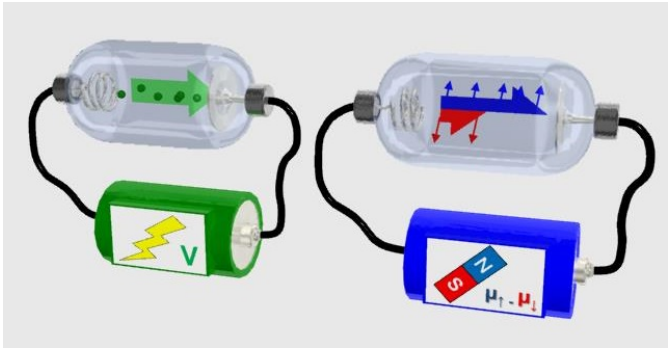
First experimental demonstration of shot noise induced by spin accumulation

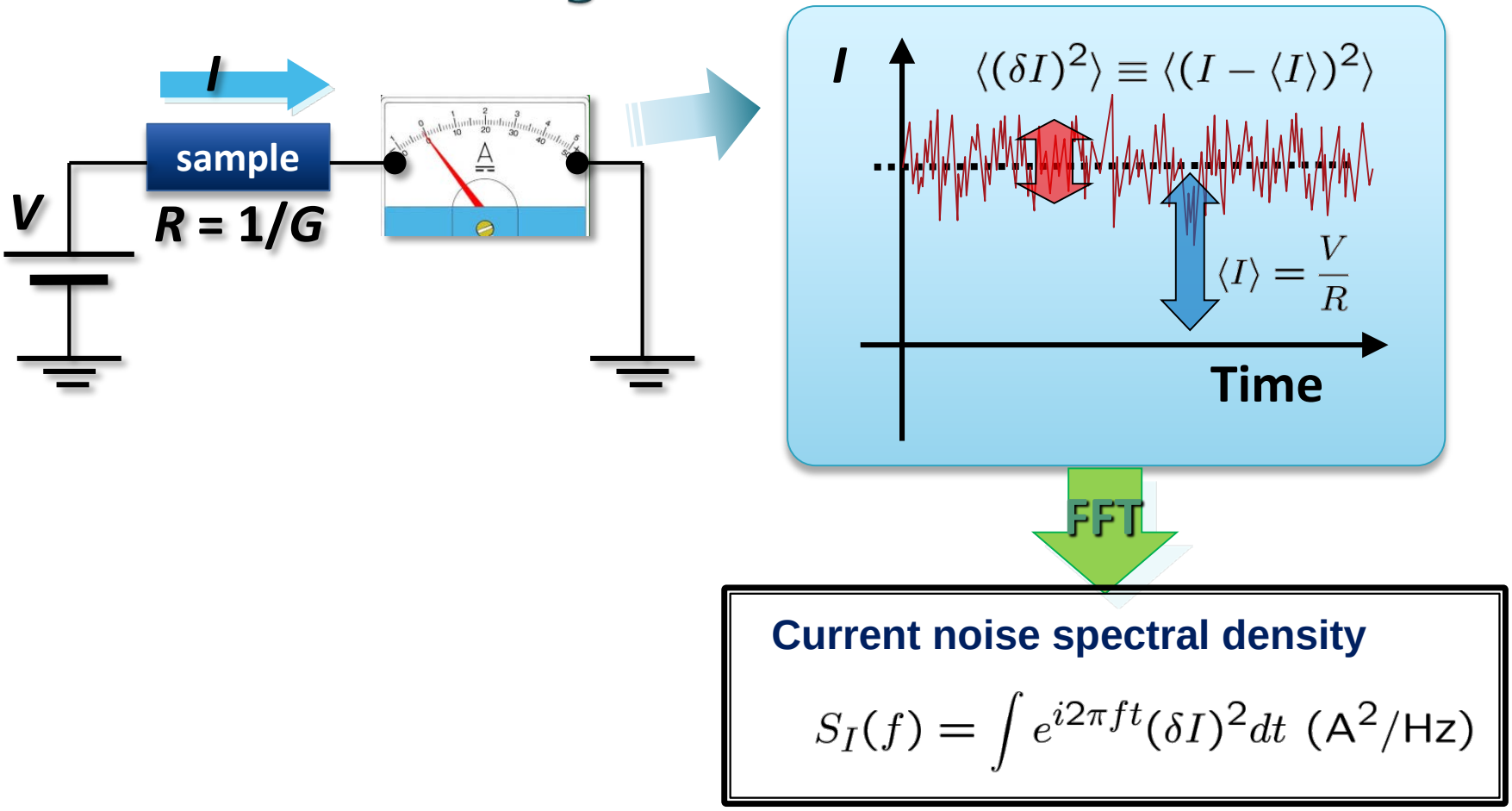
- Introduction
  - What is Shot noise and how to measure it
  - Shot in mesoscopic system
  - Potential of Shot noise in spintronics

- Our result
  - Remind for spin current
  - Experimental results



- Conclusion and future plan

Measuring Noise
=Measuring Current fluctuation

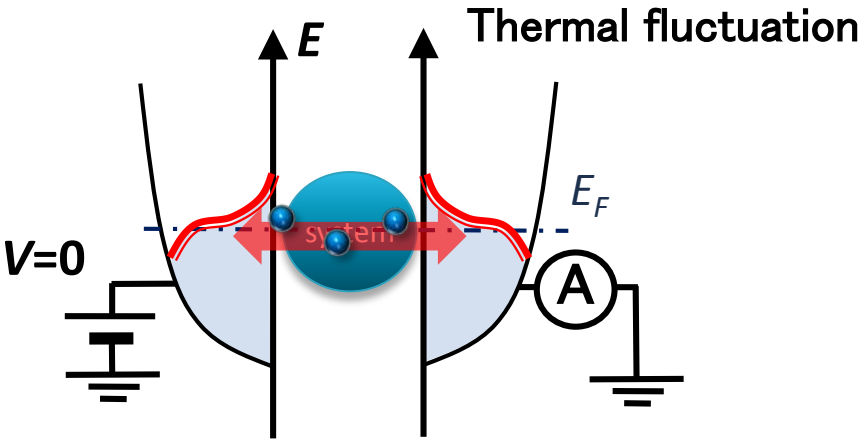


Y. M. Blanter and M. Büttiker, *Phys. Rep.* **336**, 1 (2000).

The noise is the signal

Thermal noise

Johnson-Nyquist (1928)

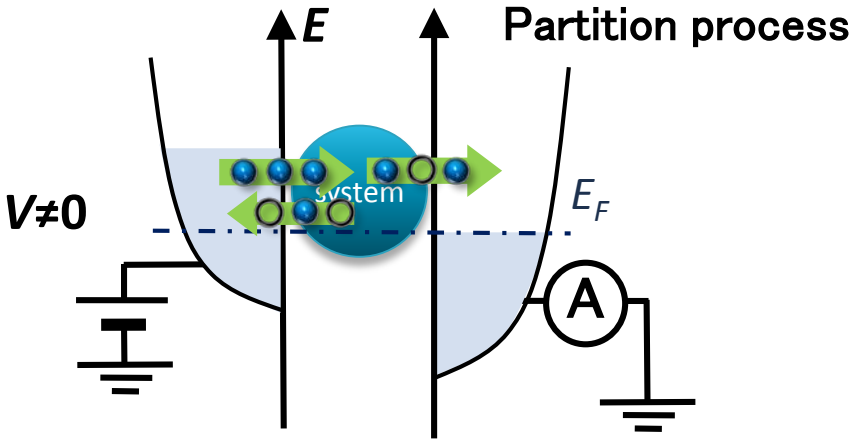


$$S_{\text{thermal}} = 4k_B T_e G$$

Electron Temperature

Shot noise

Schottky (1918)



$$S_{\text{shot}} = 2e^* \langle I \rangle F$$

Effective charge

Fano factor

Powerful tool to investigate transport processes

Review: Y. M. Blanter and M. Büttiker, *Phys. Rep.* **336,** 1 (2000).

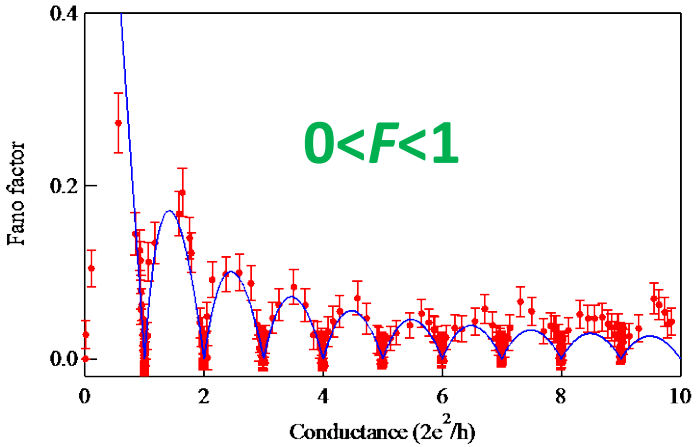
Shot noise in mesoscopic field

Statistical properties of quantum channels

A. Kumar *et al.*, PRL **76** 2778 (1996).

$$G = \frac{2e^2}{h}\sum_n T_n$$

$$F = \frac{\sum_n T_n\left(1-T_n\right)}{\sum_n T_n}$$



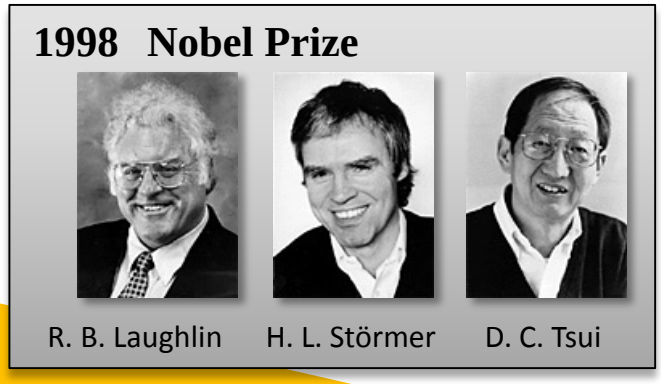
Fractional quantum Hall effect

L. Saminadayar *et al.*, PRL **79**, (1997).

R. de-Picciotto *et al.*, Nature **389**, (1997).

M. Hashisaka *et al.*, PRL **114**, (2015).

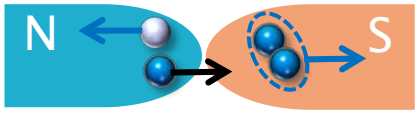
e*/e=1/3



Cooper pair transport

X. Jehl *et al.*, Nature **405**, 50 (2000).

e*/e=2



Teruo
Ono

Target

Spin transport

SPINTRONICS

Motivation

Spin dependent transport probed by Shot noise measurement

MESOSCOPICS

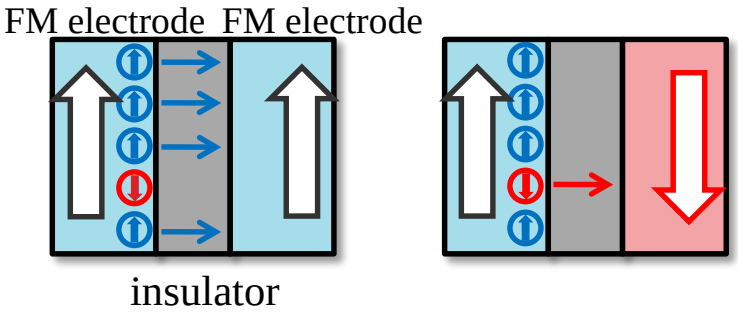
Probe

Shot noise measurement

Kensuke
Kobayashi

Spintronics via Shot noise

◆ Tunnel Magnetresistance effect



Experiment

T. Arakawa *et al.*, *Appl. Phys. Lett.* **98**, (2011).

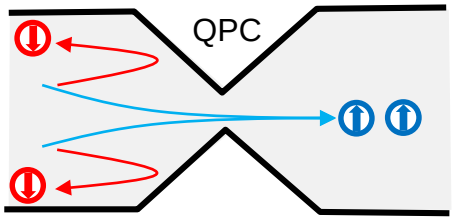
T. Tanaka, T. Arakawa *et al.*, *APEX* **5**, (2012).

Theory

Kai Liu *et al.*, PRB **86**, (2012).

Direct proof for Coherent tunneling theory

◆ Spin filter effect



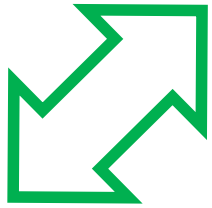
Experiment

M. Kohda *et al.*, *Nat. Commun.* **3**, (2012).

Estimation of Spin polarization

Spintronics via Shot noise (Theory)

A few experimental reports



A lot of theoretical predictions

- **Spin flip process in diffusive conductor**

  E. G. Mishchenko, PRR B **68**, (2003).

  W. Belzig and M. Zareyan, PRB **69**, (2004).

  A. Lamacraft, PRB **69**, 081301 (2004).

- **Shot noise of spin current**

  B. Wang *et al.*, PRB **69**, (2004).

  O. Sauret and D. Feinberg, PRL **92**, (2004).

- **Spin accumulation**

  J. Meair *et al.*, PRB **84**, (2011).

- **Spin Hall effect**

  R. L. Dragomirova *et al.*, EPL **84**, (2008).

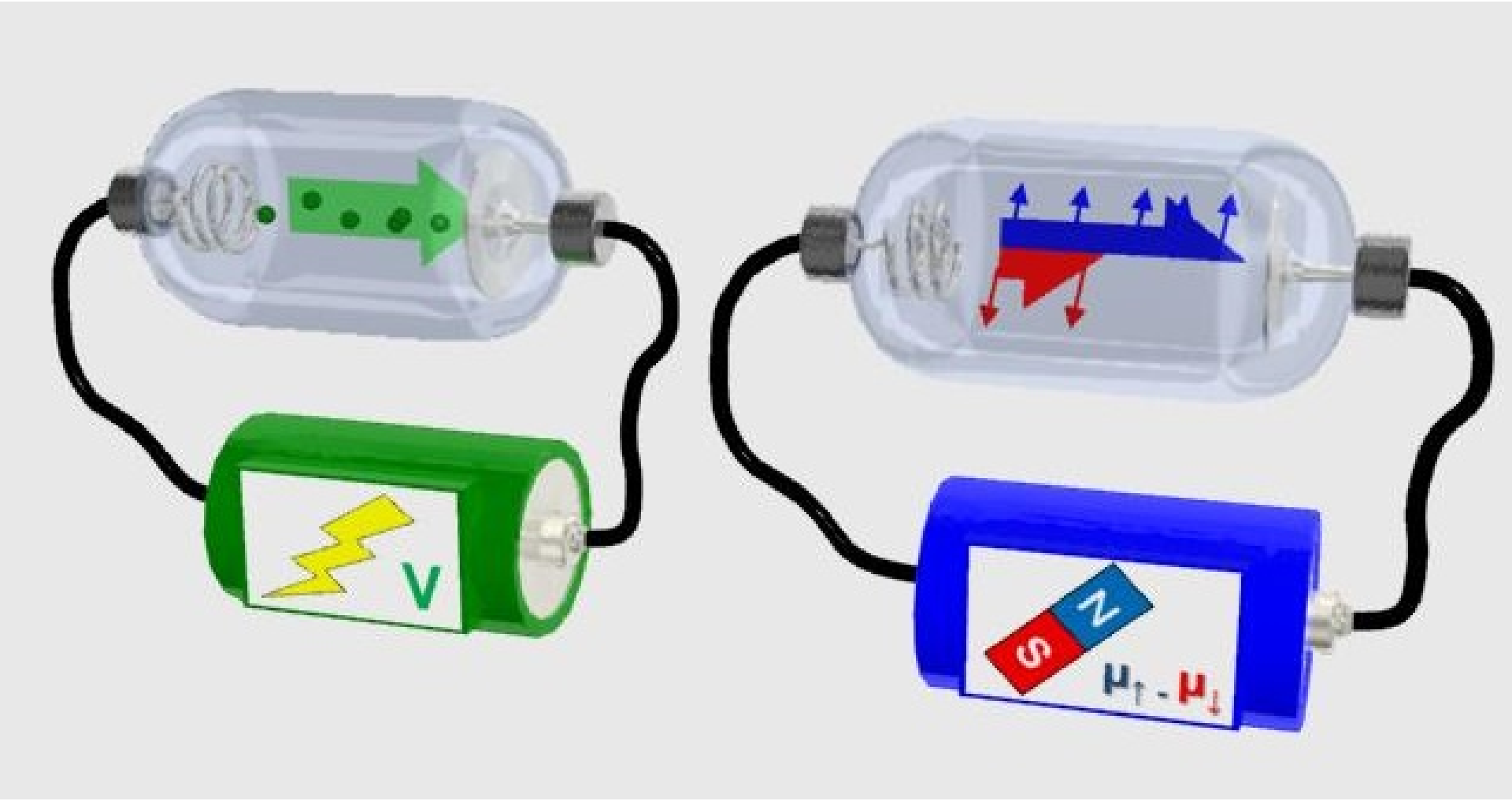
  S. I. Erlingsson and D. Loss, PRB **72**, (2005).

- **Spin torque phenomenon**

  A. Chudnovskiy *et al.*, PRL **101** (2008).

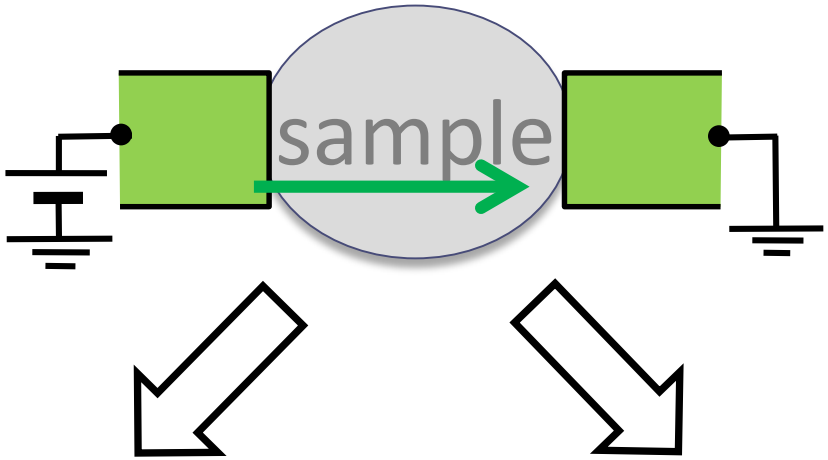
etc….

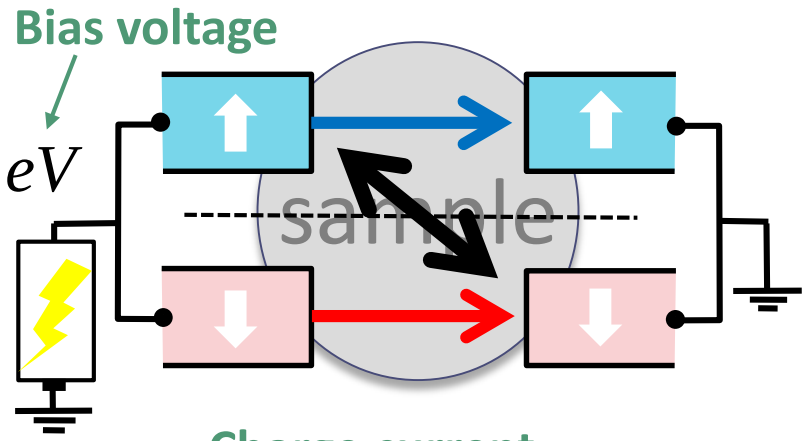
Shot noise induced by spin accumulation

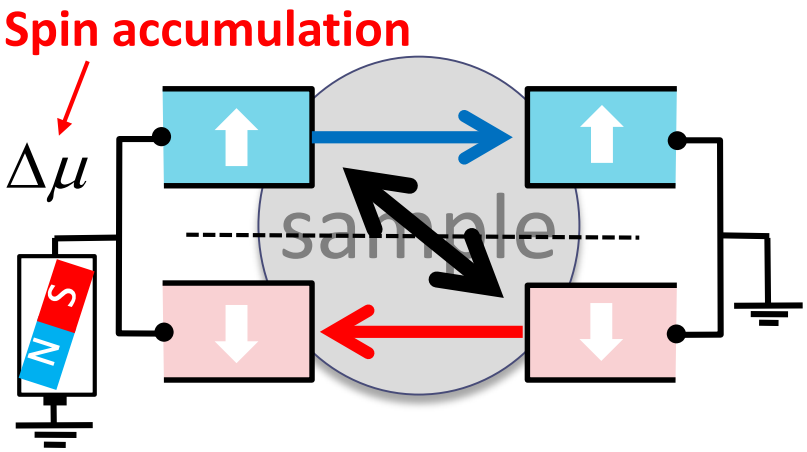


T. Arakawa *et al.*, PRL **114**, 016601 (2015).

What is Spin current







Charge current

$$I_C = I_\uparrow + I_\downarrow$$

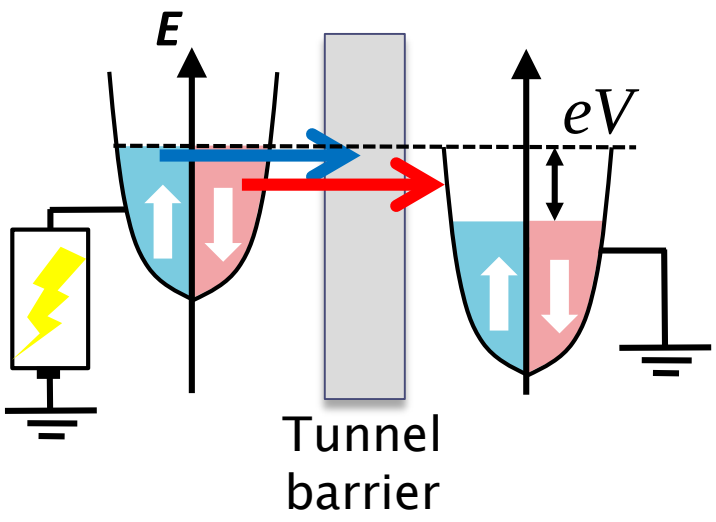
independent

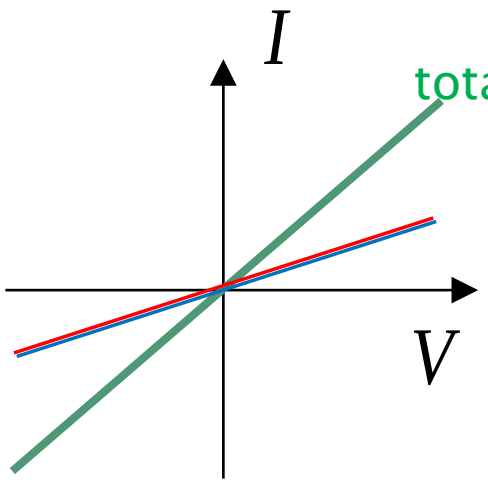
Spin flip process

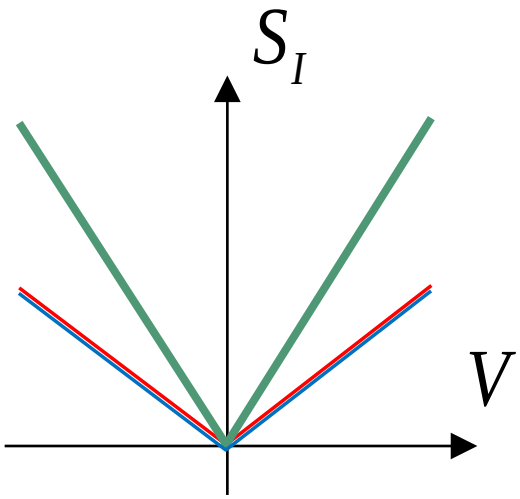
Spin current

$$I_S = I_\uparrow - I_\downarrow$$

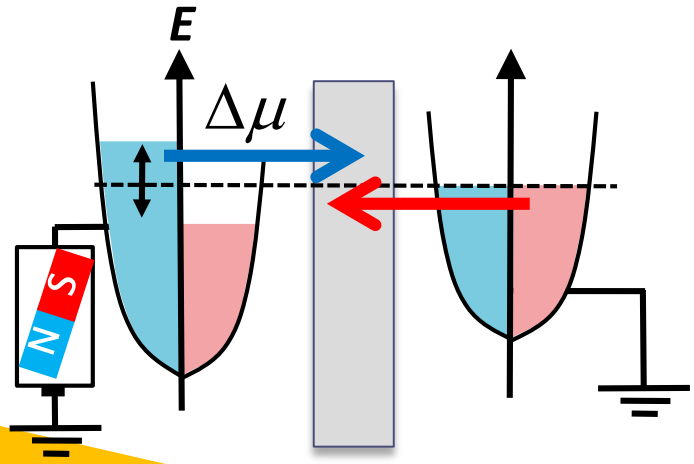
What's happen in the Shot noise

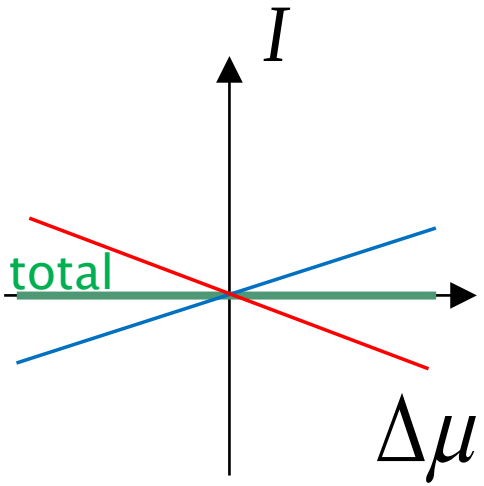


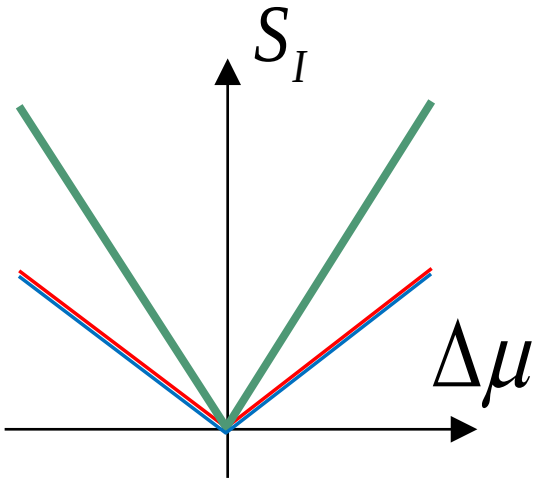




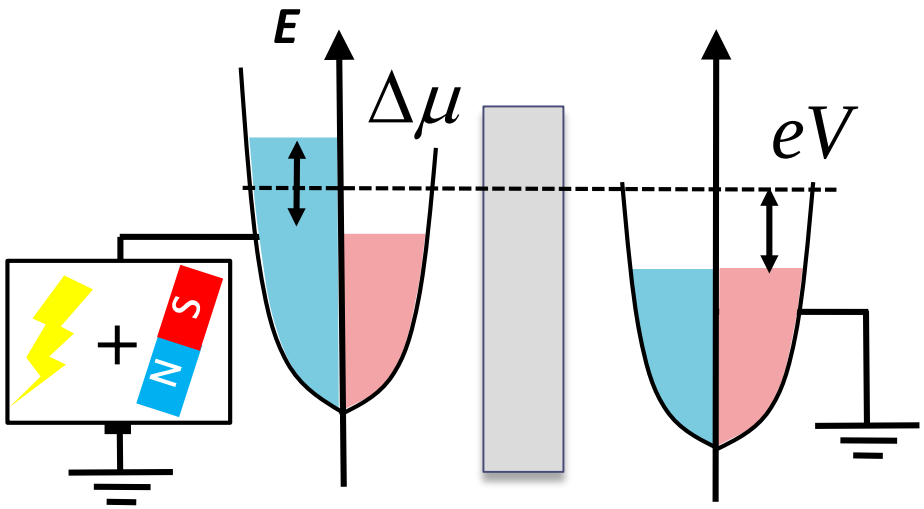
$$S_I = 2e\left(\left|I_\uparrow\right| + \left|I_\downarrow\right|\right)$$

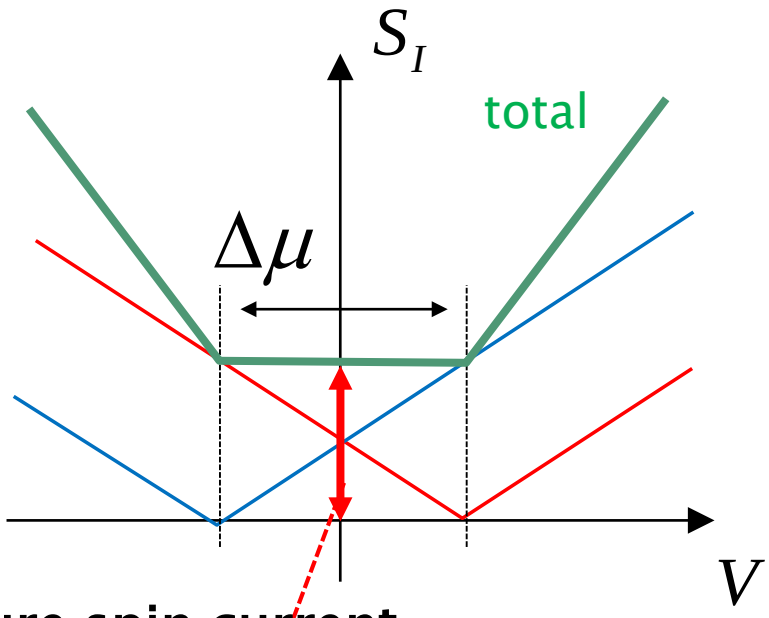






More general case





◆ Pure spin current

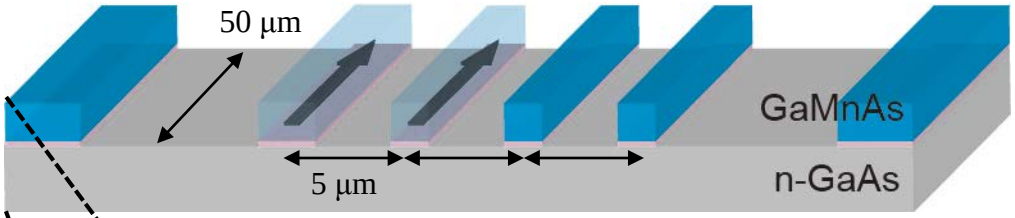
$$I_\uparrow = -I_\downarrow \Rightarrow I_C = 0 \quad I_S \neq 0$$

$$S = 2e|I_S|F$$

Direct measurement of Spin current and Δμ without ferromagnet or Invers spin Hall effect

Sample structure

lateral all-semiconductor spin valve device



50 nm	$(Ga_{0.945}Mn_{0.055})As$
2.2 nm	$(Al_{0.35}Ga_{0.65})As$
8.0 nm	n^+-GaAs (n^+=5-6 × $10^{18}cm^{-3}$)
15 nm	$n^+ \rightarrow$n-GaAs
1 μm	n-GaAs (n=2-4 × $10^{16}cm^{-3}$)
500 nm	$[AlGaAs/GaAs]_{50}$
300 nm	GaAs
GaAs substrate	

P–type (FM)

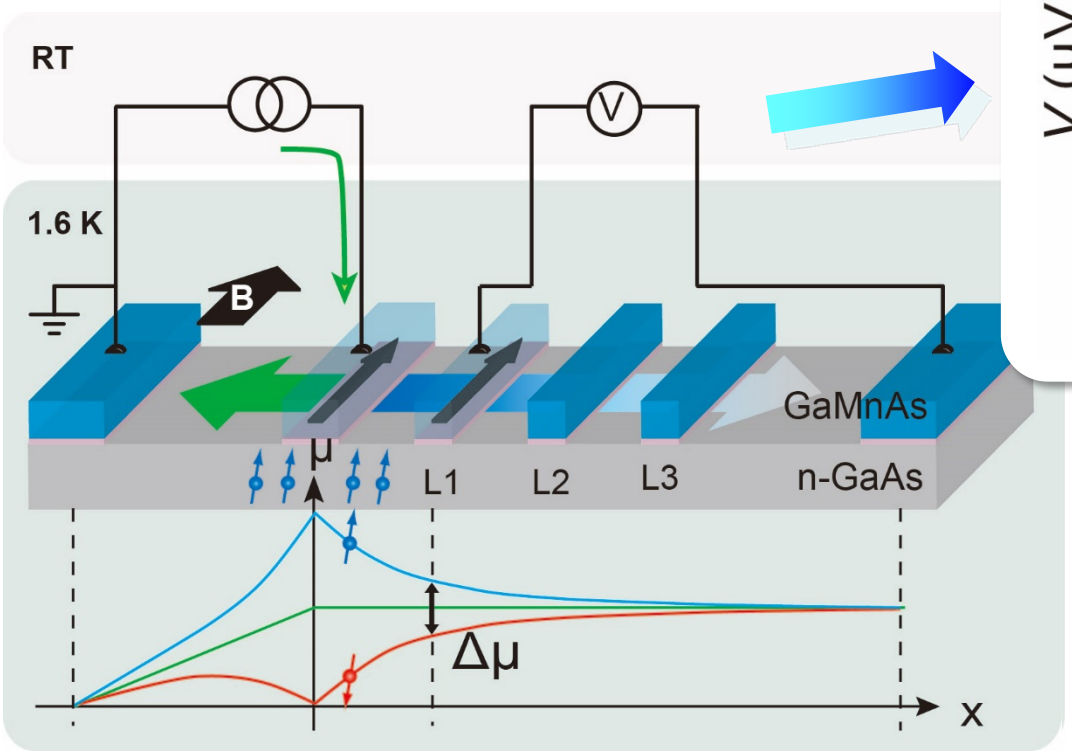
Tunnel barrier

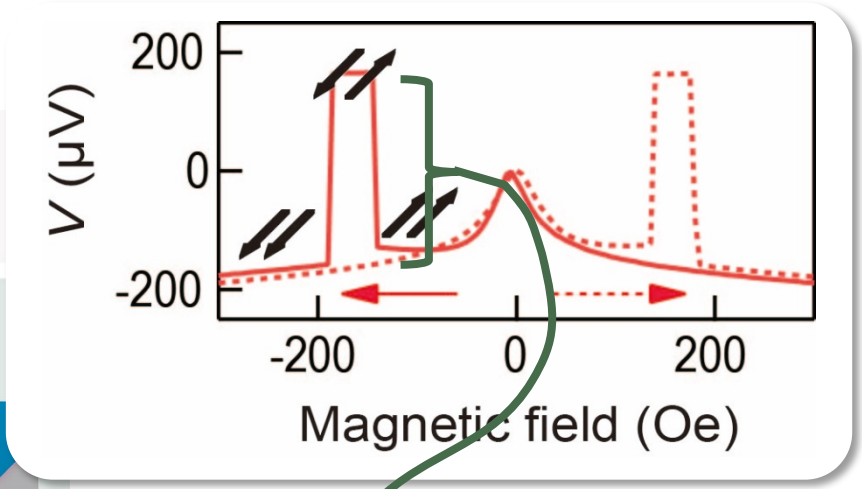
n–type (Normal)

M. Ciorga *et al.*, PRB **79**, 165321 (2009).

J. Shiogai *et al.*, APL **101**, 212402 (2012).

Characteristic of the sample





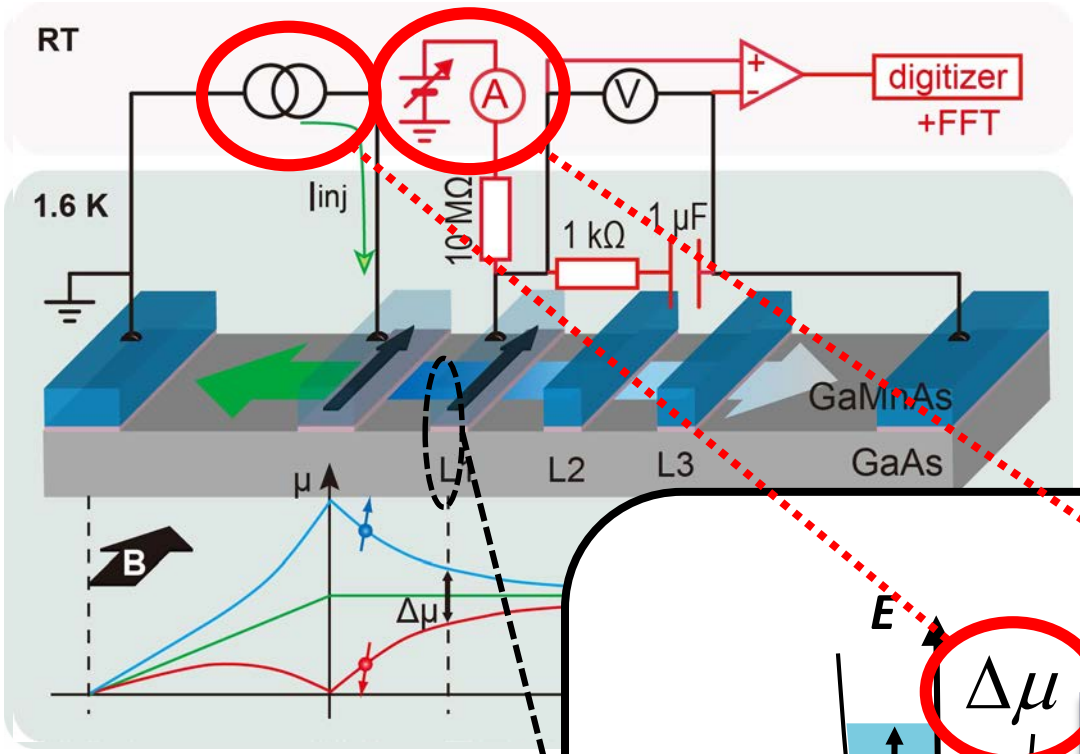
$$\Delta V = P\Delta\mu$$

$$P = \frac{T_1 - T_2}{T_1 + T_2} = 0.82$$

Spin accumulation

F. J. Jedema *et al.*, Nature **410**, 345 (2001).

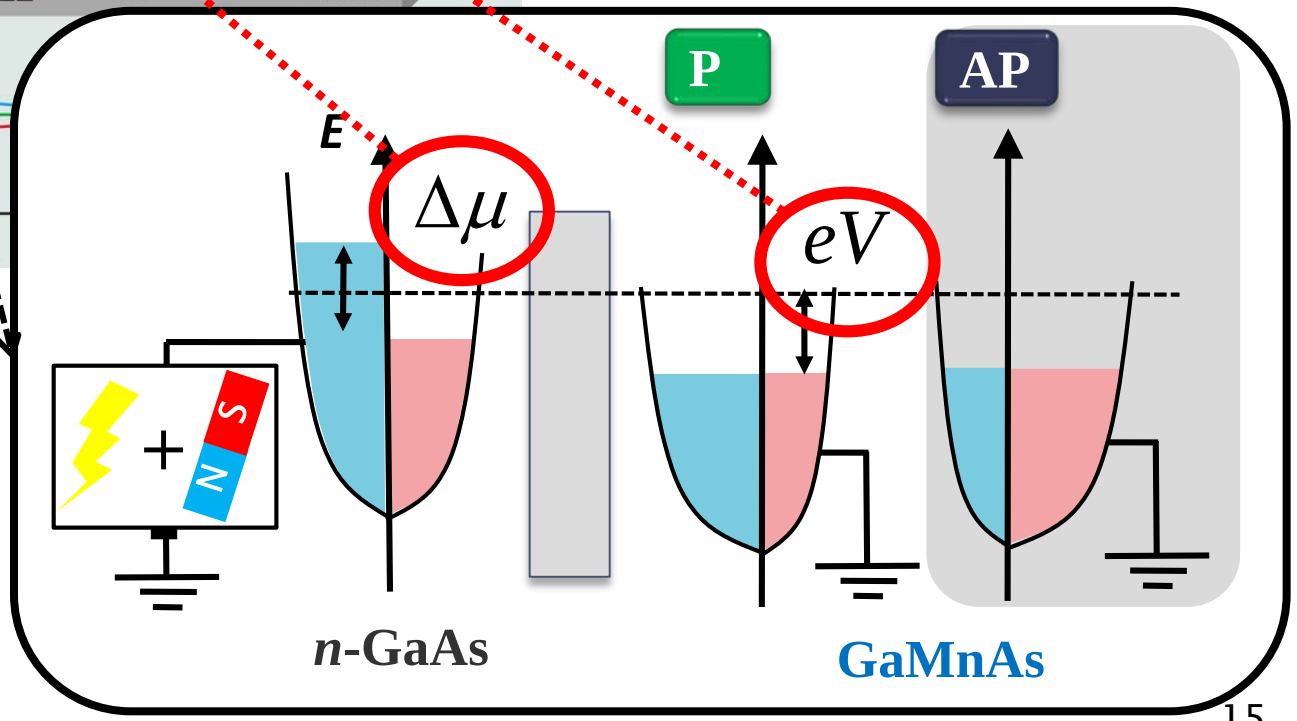
Set up for shot noise measurement



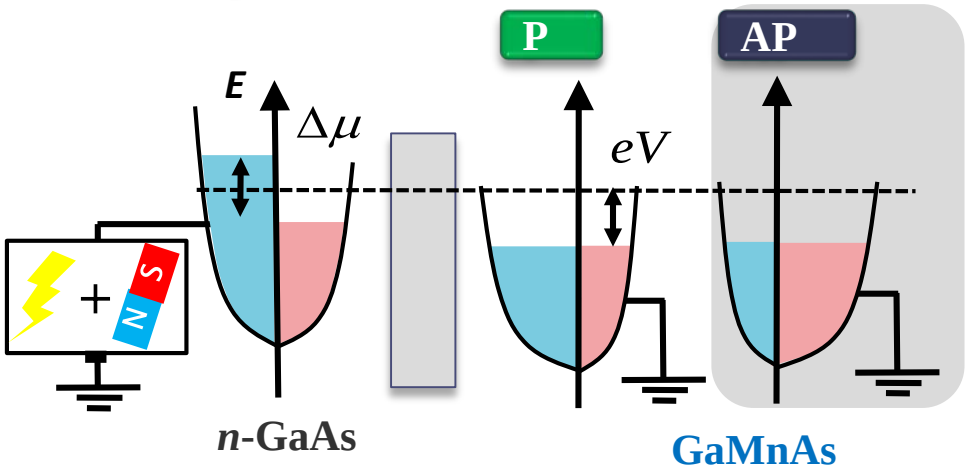
Modulate V and $\Delta\mu$ independently

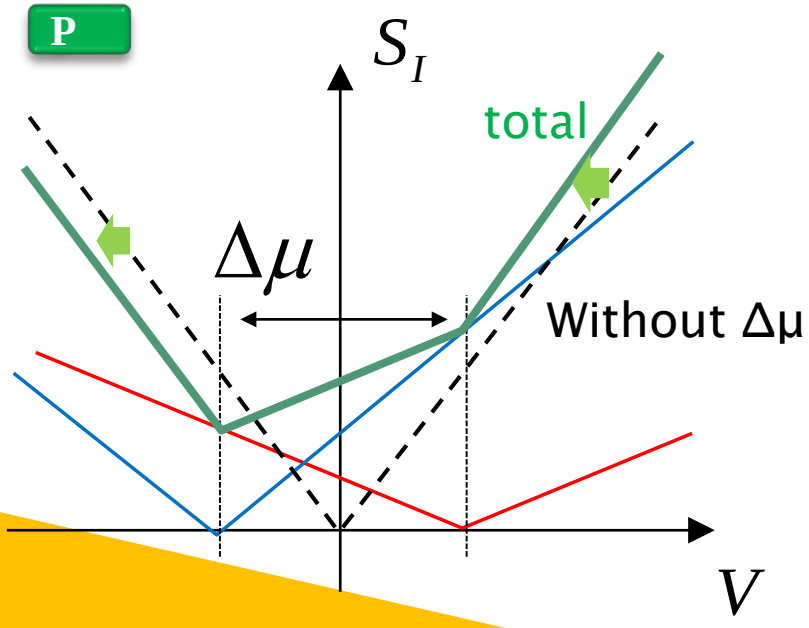
⇩

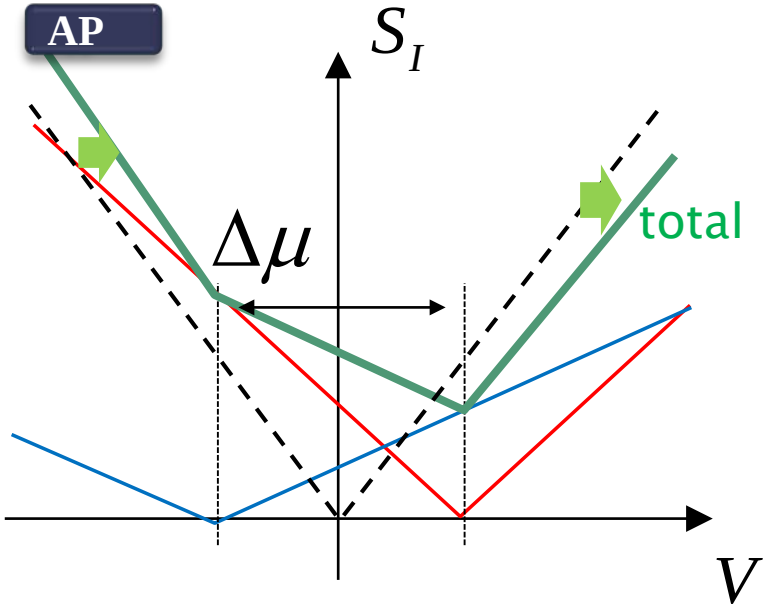
Measure S_I and I



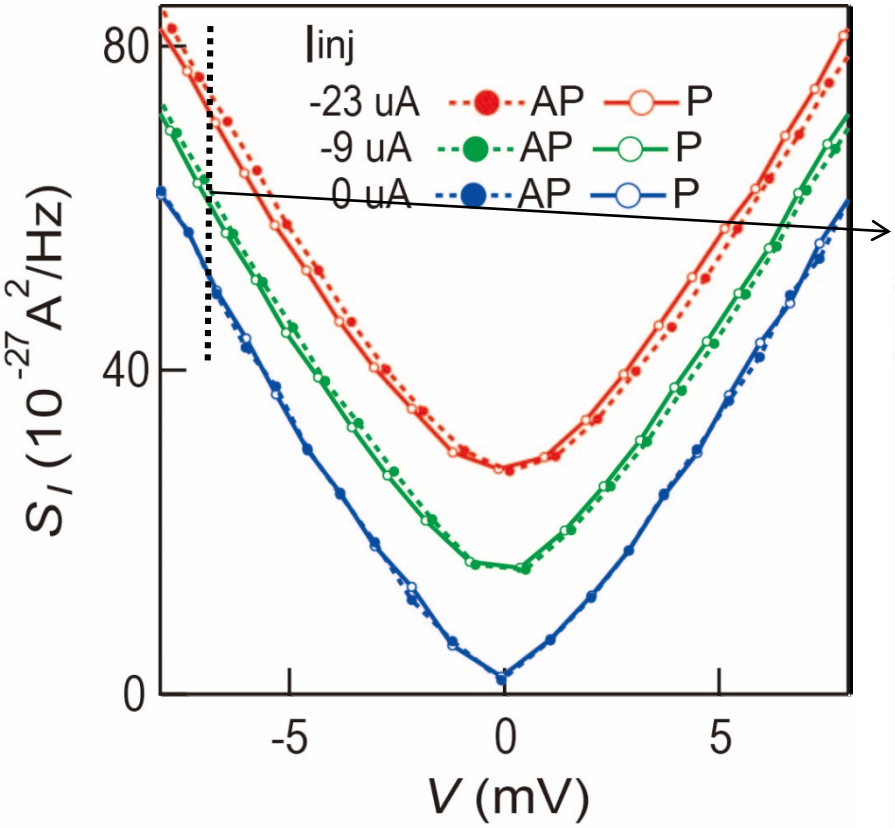
Expected signal

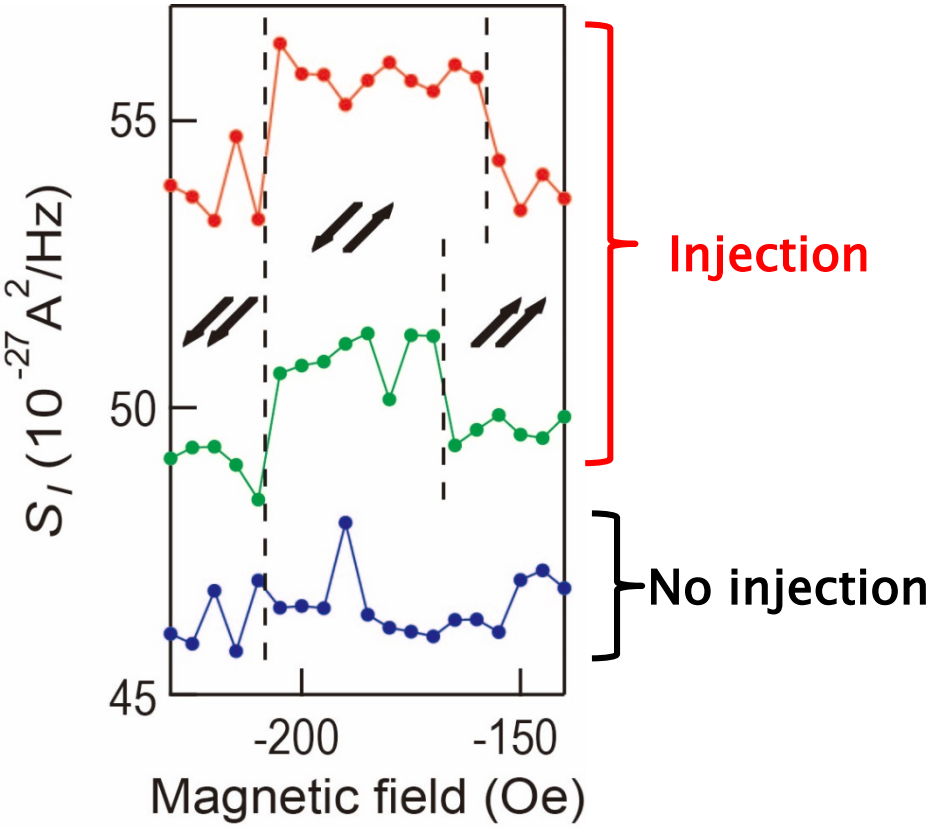






Measured noise S_I





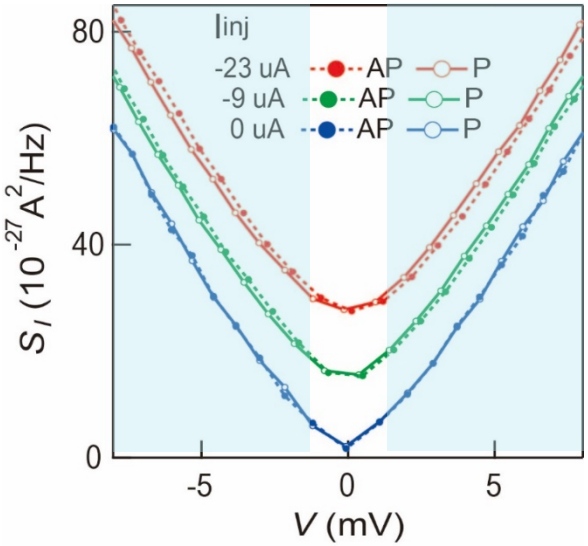
$$S_I = \frac{4k_B T(1-F)}{dV/dI} + \frac{2eIF}{\tanh(eV/2k_B T)}$$

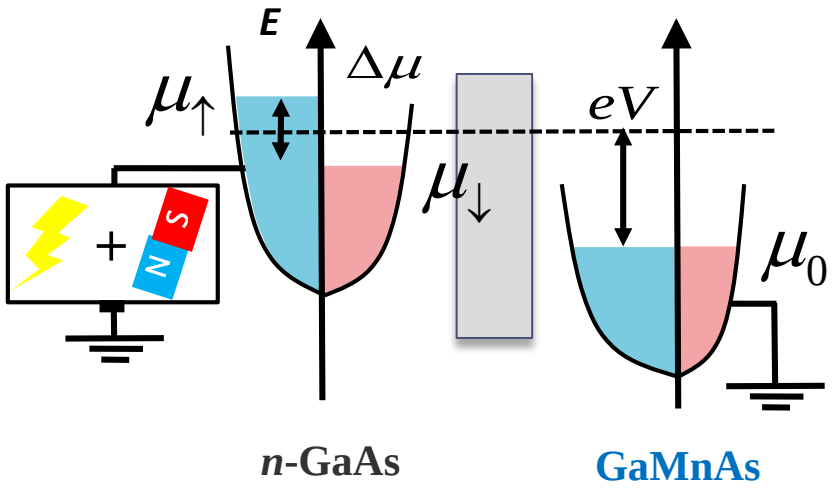
F: Fano factor

T: electron temperature

High bias region

$$|eV| > \Delta\mu, 4k_B T$$





Current

$I_P(V)$ and $I_{AP}(V)$ reconstruct

Noise

$S_P(V)$ and $S_{AP}(V)$

Charge current

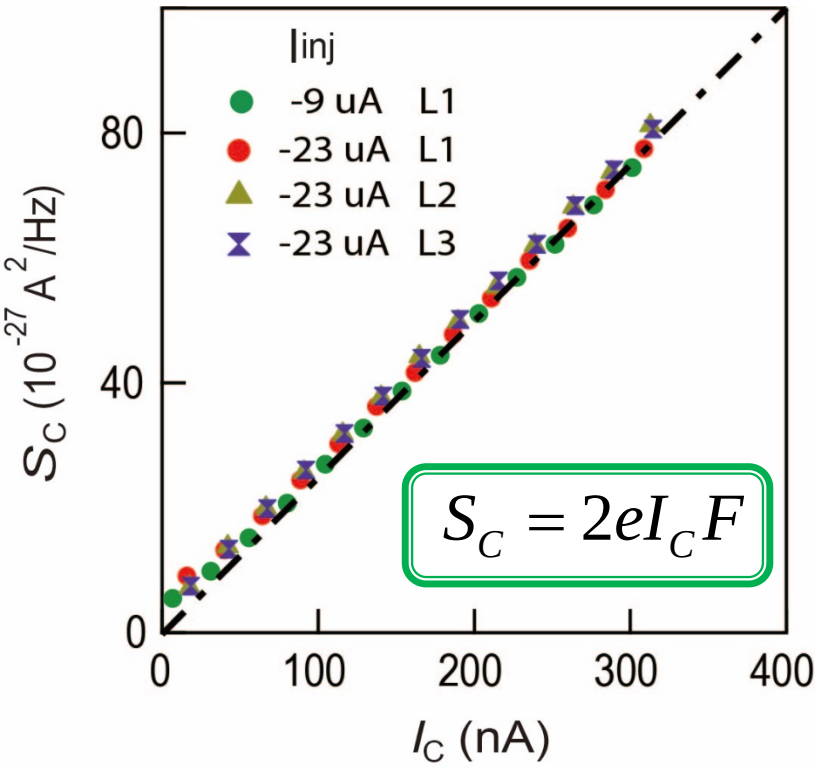
$$I_C = \frac{I_P + I_{AP}}{2} \propto \left(\frac{\mu_\uparrow + \mu_\downarrow}{2} - \mu_0 \right) \qquad S_C \equiv \frac{S_P + S_{AP}}{2}$$

Spin current

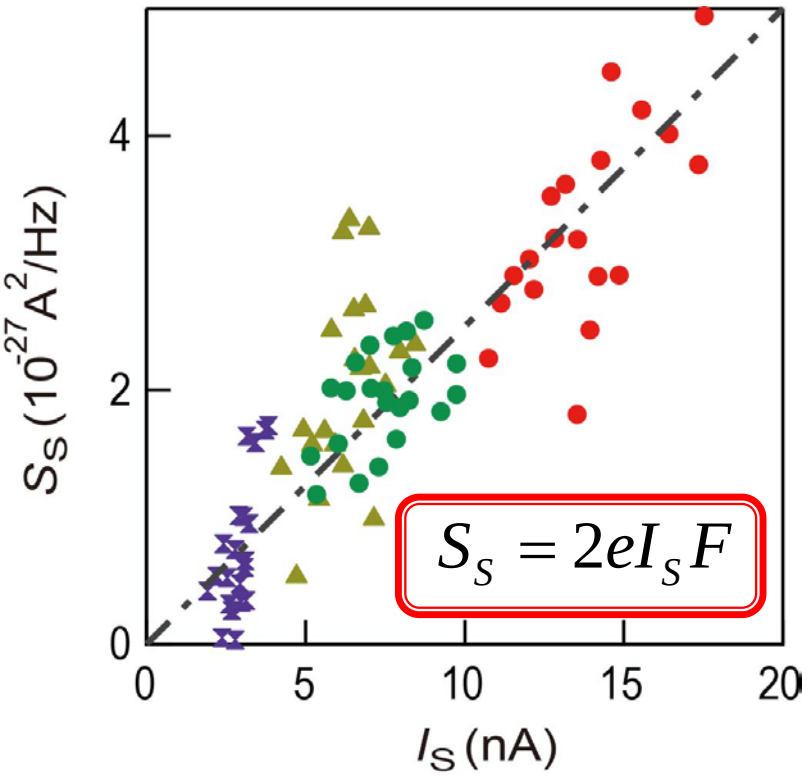
$$I_S = \frac{I_P - I_{AP}}{2P} \propto \left(\mu_\uparrow - \mu_\downarrow \right) \qquad S_S \equiv \frac{|S_P - S_{AP}|}{2P}$$

Relation between Noise and Current

Charge

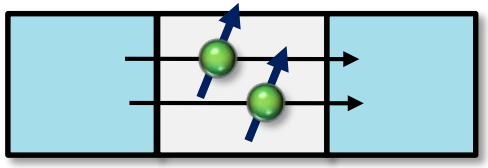


Spin

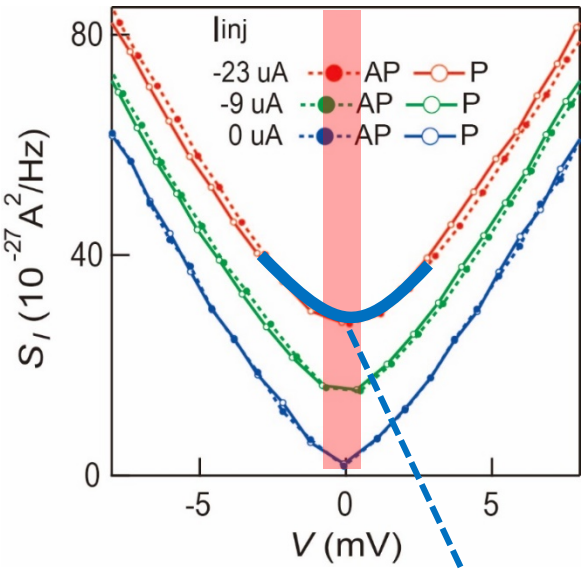


Same Fano factor

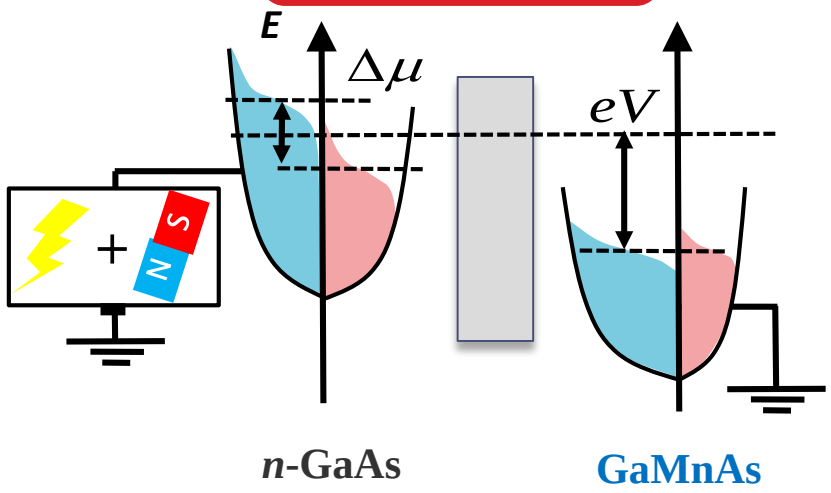
charge and spin tunnel through the barrier as a single object

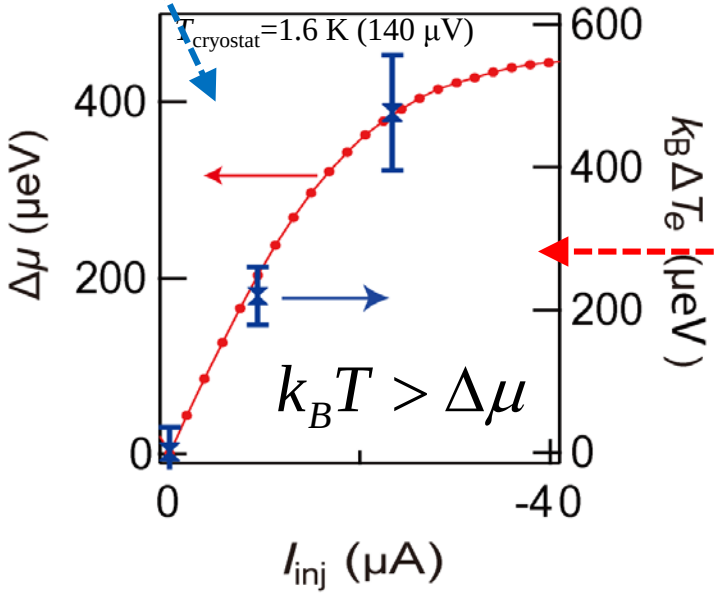


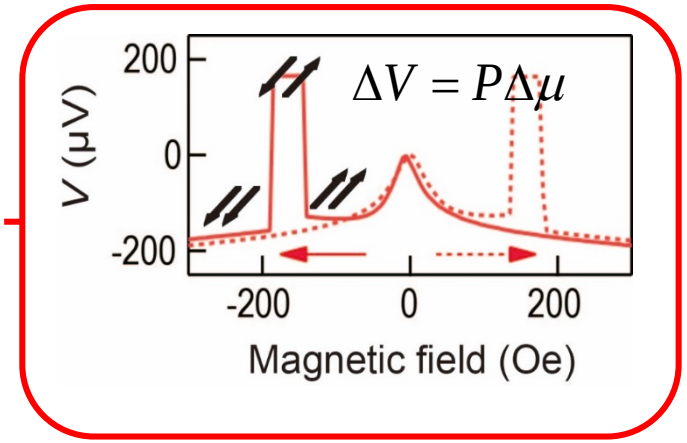
Low bias region



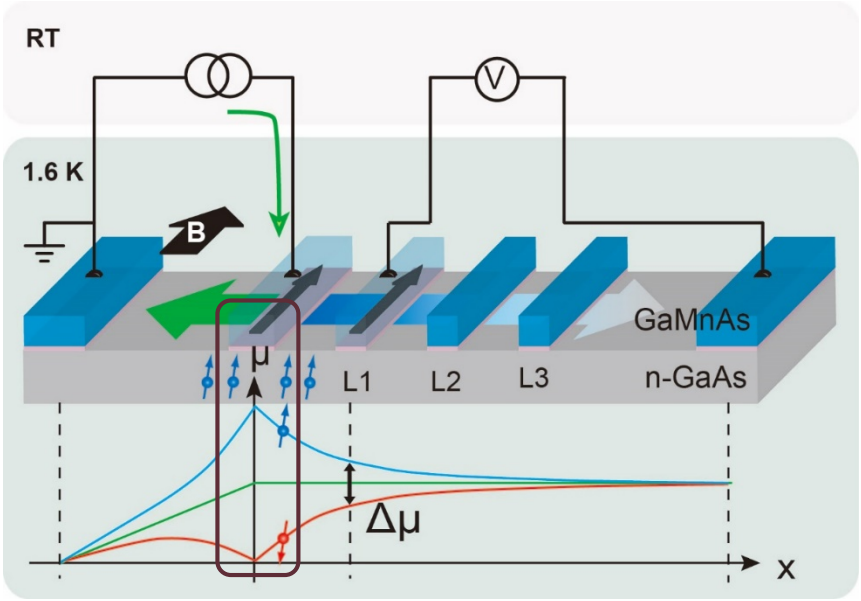
$$|eV| < \frac{\Delta\mu}{2}$$







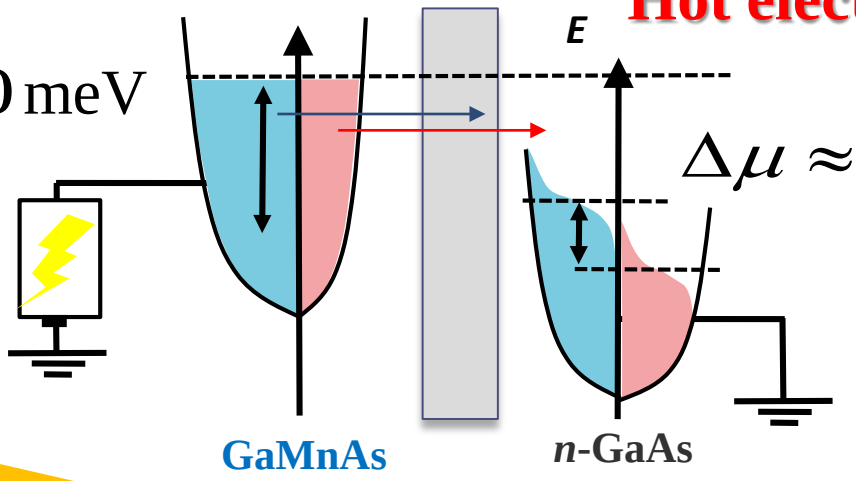
Origin of over heating



Spin injection process

Hot electrons

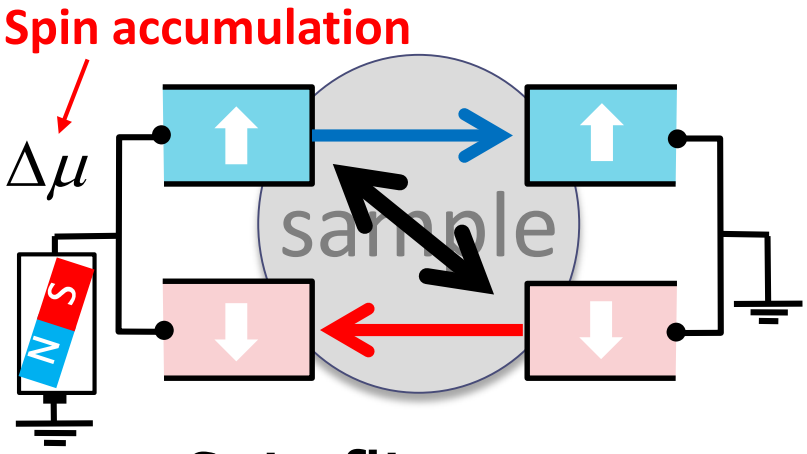
$V > 200\,\text{meV}$



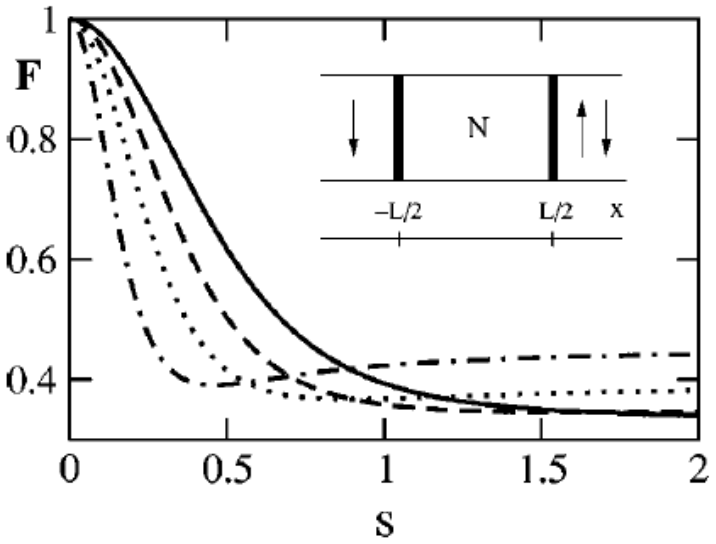
$\Delta\mu \approx 0.2\ \text{meV}$

$V \square \Delta\mu$

What's happen in the presence of spin flip process

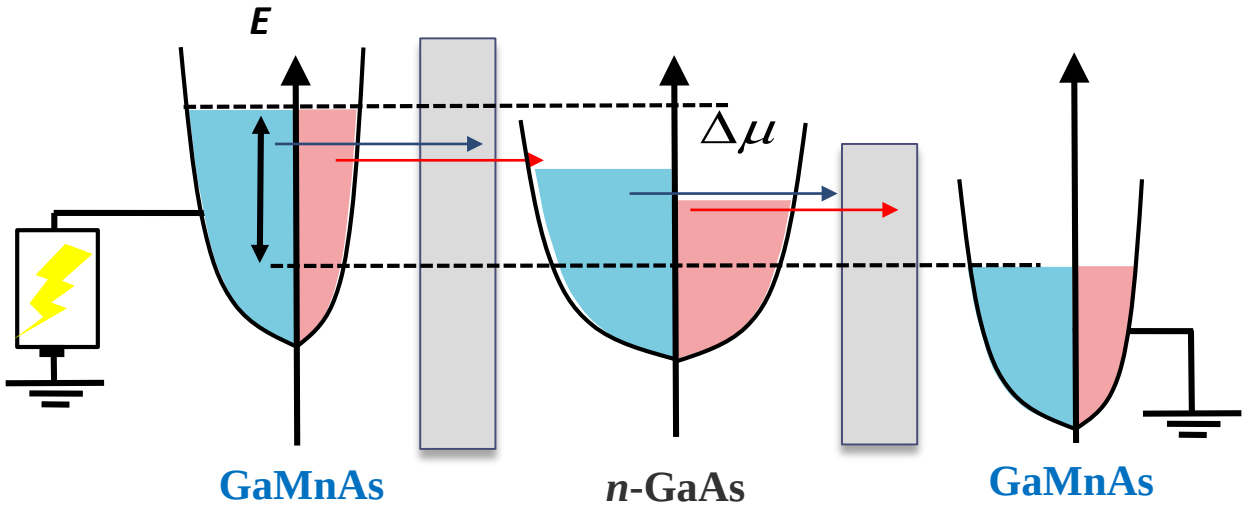


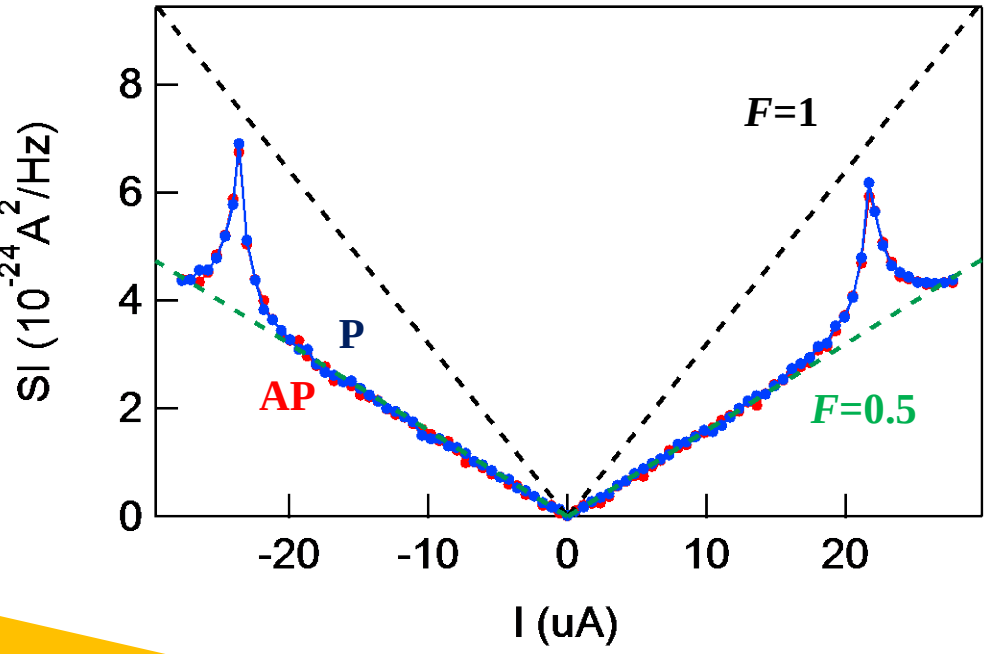
Spin flip process



E. G. Mishchenko, Physical Review B **68**, 100409 (2003).

Brief result





Conclusion

- **Shot noise due to the spin current through a tunnelling barrier was detected**
- **Our result indicates that charge and spin tunnel through the barrier as a single object**
- **The electron temperature increase due to spin injection was quantitatively estimated**

Future vision

- **Spin current shot noise in various systems**

$F_C \neq F_S$?

Spin orbit interaction
Many body effect
etc…

sensitive probe for spin transport

- **Cooling the electron temperature**

Spin injection through metallic contact
Super conductor on the channel

Coherent phenomena of Spin current