GRAPHENE . . . 7 AUGUST, BENASQUE, SPAIN

CSABA JÓZSA, GRONINGEN, THE NETHERLANDS

Spintronics in Graphene

Netherlands Organisation for Scientific Research

University of Groningen
Zernike Institute
for Advanced Materials

FOM

The Next 45 Minutes:

The next 45 minutes:

- ~~Introduction: graphene~~ last talk of a graphene workshop...
- Introduction: (4-terminal) lateral spin valves
- Making graphene based devices
- RT spin valve/precession measurements on graphene
- Spin vs charge diffusion; relaxation mechanism, anisotropy
- Carrier drift: controlling the transport / injection
- And finally: transport through p-n junctions

Google says:

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- graphene: “about 592.000” hits
- carbon nanotube: 834.000
- fullerene: 1.920.000
- graphite: 16.800.000
- diamond: 182.000.000
- Michael Jackson: 254.000.000

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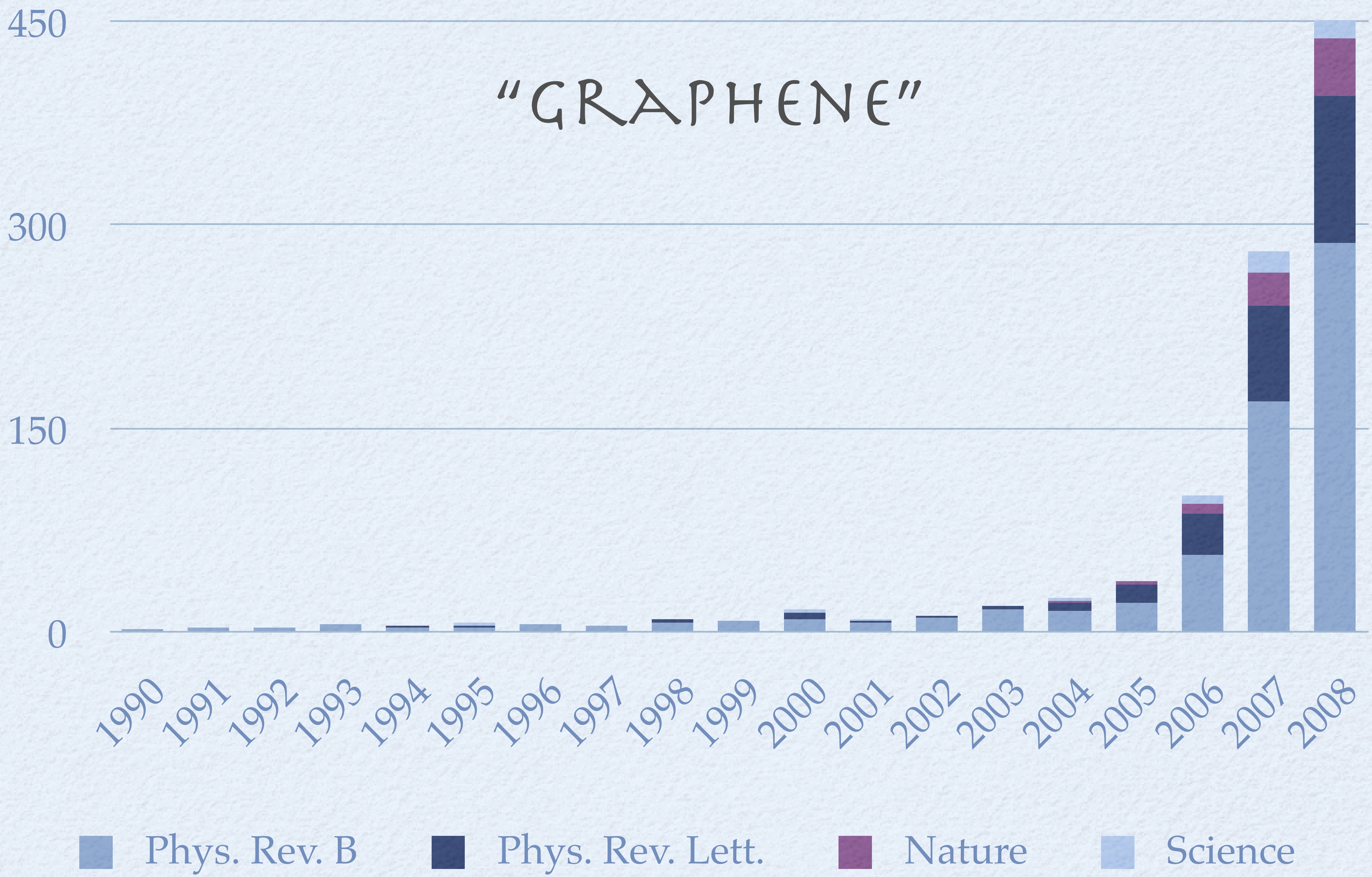
- Michael Jackson: 254.000.000

BUT

of all these,

graphene is the youngest!

(and very much alive)



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"GRAPHENE"
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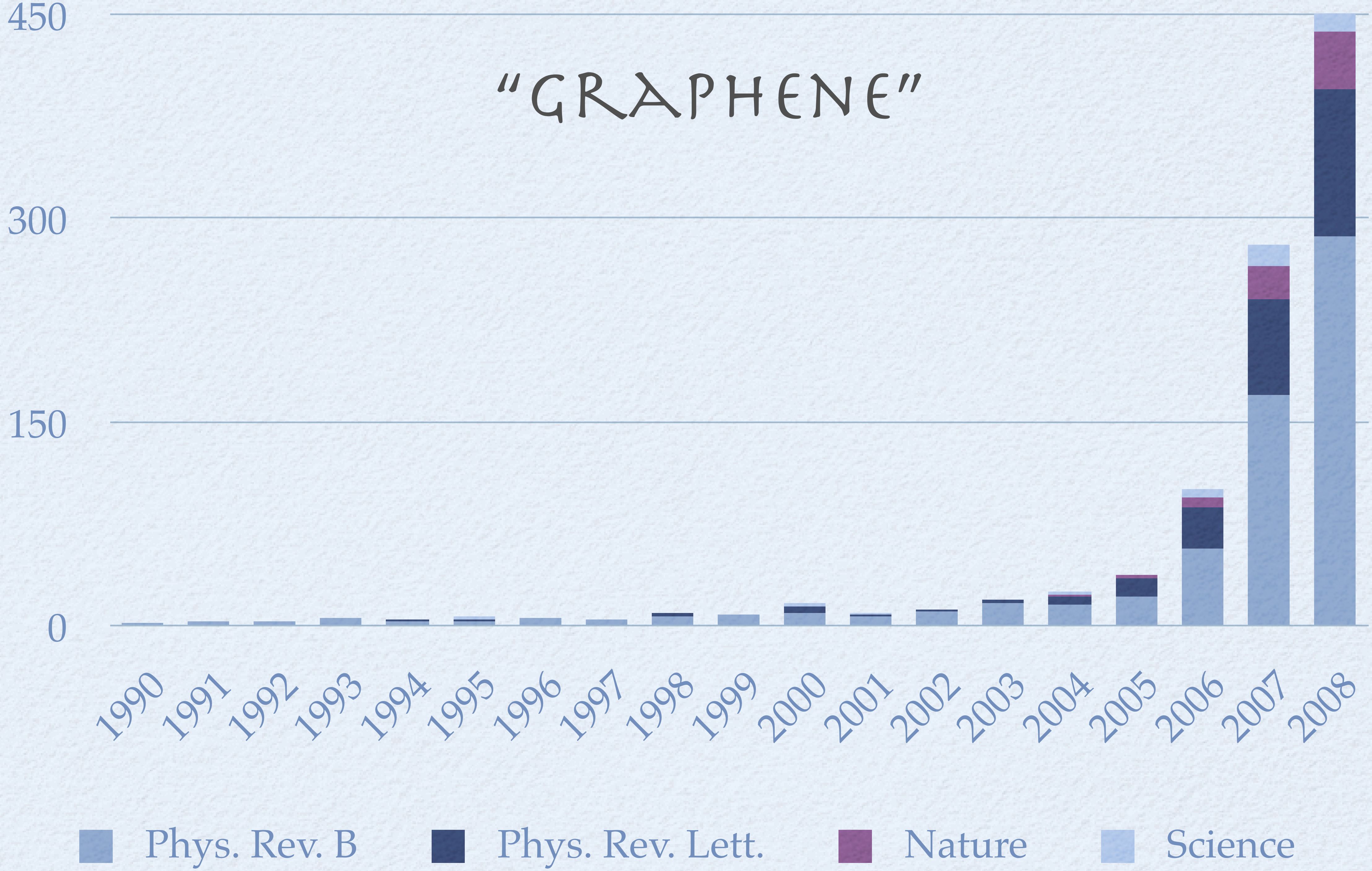
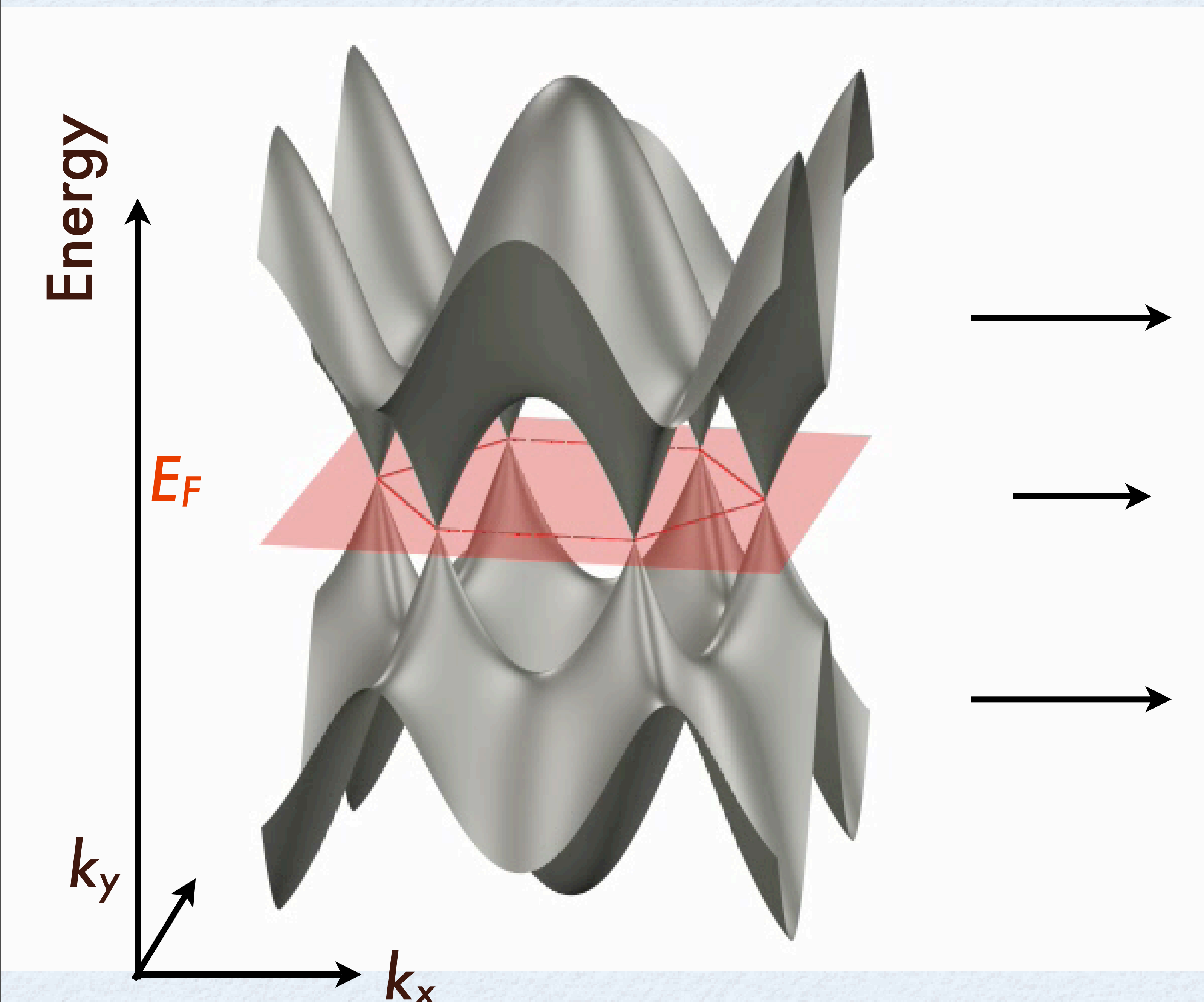
2008
Phys. Rev. B
Phys. Rev. Lett.
Nature
Science

Best thing since sliced bread?



Graphene Bandstructure



electron states

Dirac neutrality points

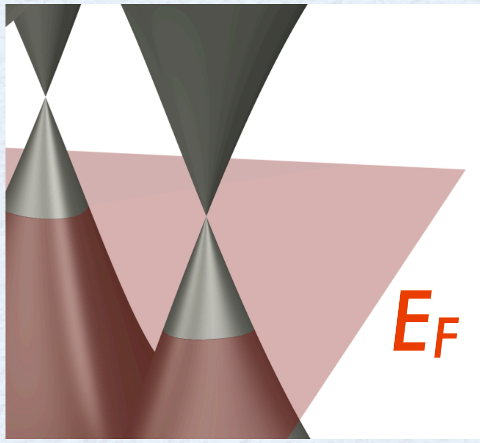
hole states

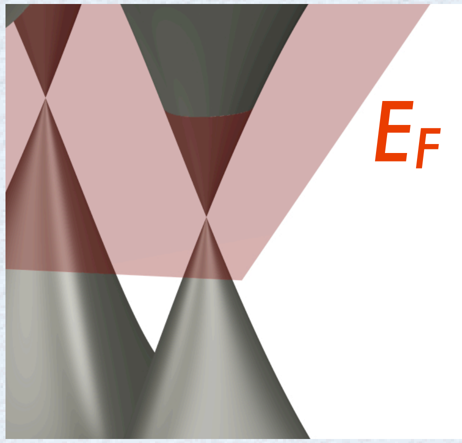
Dispersion relation:

$$E(k_x,k_y) = \pm t\sqrt{1 + 4\cos\left(\frac{\sqrt{3}}{2}\,k_x\,a\right)\cos\left(\frac{1}{2}\,k_y\,a\right) + 4\cos^2\left(\frac{1}{2}\,k_y\,a\right)}$$

Gate Voltage Dependence

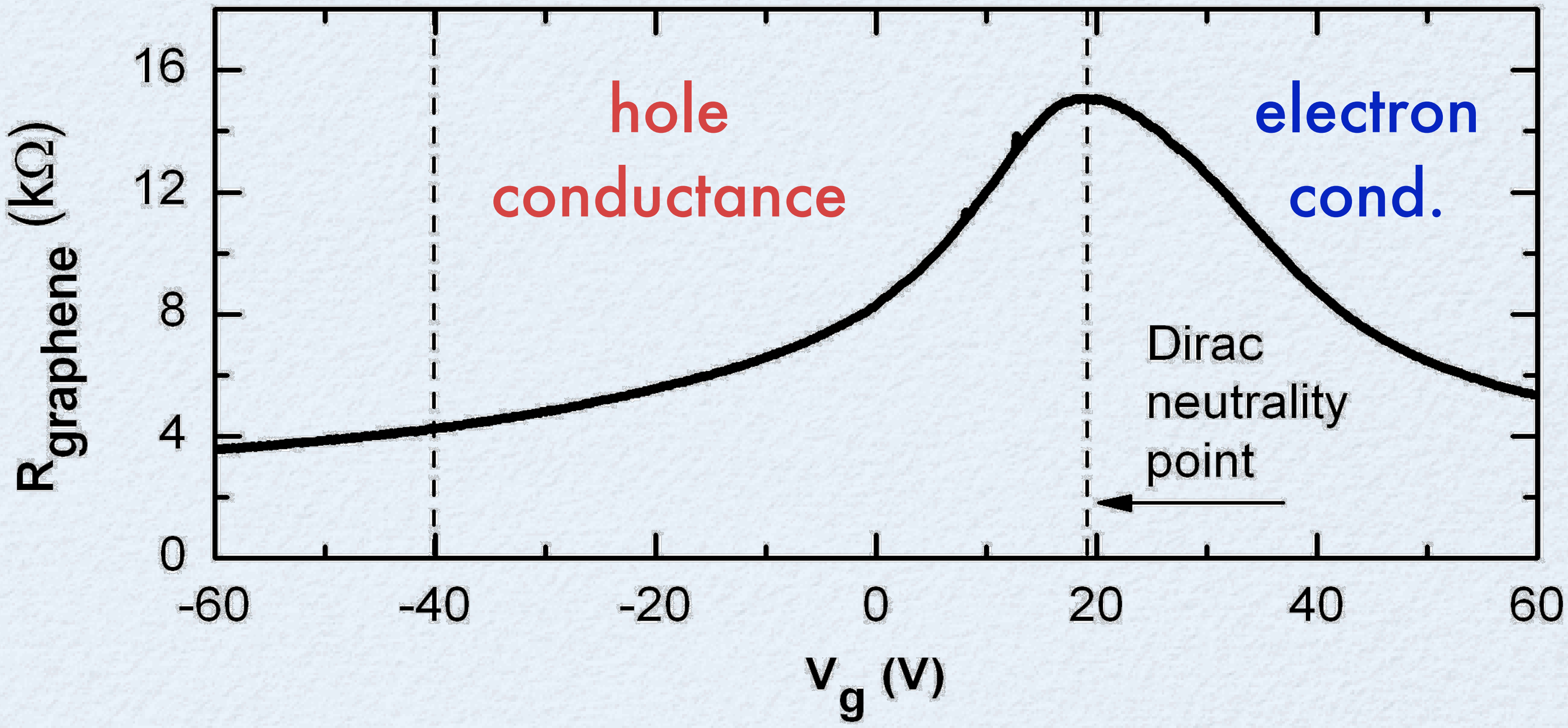
4-terminal electrical measurement of graphene resistance:





Einstein relation:

$\sigma(E) = \nu(E)\, e^2\, D(E)$



Existence of minimum conductivity: *A.K. Geim & K.S. Novoselov, Nature Materials 6, 183 (2007)*
and everybody else who does CHARGE transport...

Spin transport in graphene?

Spin transport in graphene?

Theory predicted ("folklore"?):

- Weak spin-orbit + hyperfine interactions
- Long spin relaxation T_1 and dephasing T_2 times (5-50 ns)
  → spin qubit, quantum computation?

With high mobilities:

- spin-flip length up to 100 μm at RT?
- low power non-volatile spin logic devices, p-n junctions
- robust, thin (=high integration density)

Spin injection / transport literature

Theory of SO in graphene:

- Trauzettel et al., Nat. Phys. 3 (2007)
- C.L. Kane and E.J. Mele, PRL 95 (2005)
- Y. Yao et al., cond-mat/0606.3503
- D. Huertas-Hernando et al., PR B74 (2006)
- M. Gmitra et al., cond-mat/0904.3315
- C. Ertler et al., cond-mat/0905.0424
- Honki Min et al., PR B 74 (2006)

Experimentally: electrically, through FM contacts:

- E.W. Hill et al., IEEE Trans. Magn. 42 (10), 2694 (2006)
- N. Tombros, C. Józsa et al., Nature 448, 571 (2007)
- S. Cho et al., Appl. Phys. Lett. 91, 123105 (2007)
- M. Nishioka et al., Appl. Phys. Lett. 90, 252505 (2007)
- M. Ohishi et al., Jpn. J. Appl. Phys. 46 (25), L605-L607 (2007)
- W.H. Wang et al., Phys. Rev. B 77, 020402(R) (2008)

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- W.H. Wang et al., Phys. Rev. B 77, 020402(R) (2008)
- and more ...

About Spin Relaxation

i: Elliott-Yafet:

spin flip induced by scattering;

$\tau_s \sim \tau_d$

ii: D'yakonov-Perel:

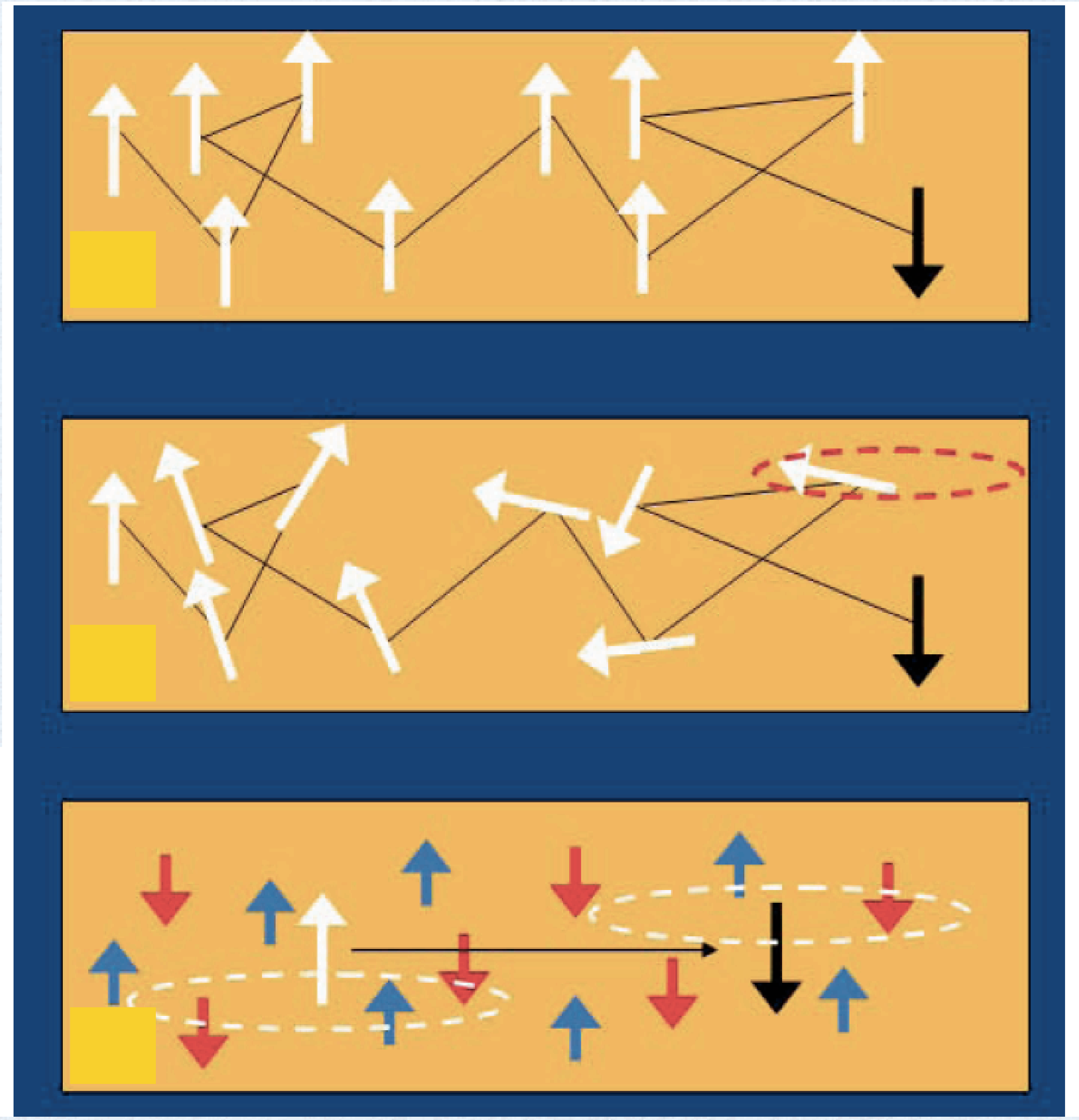
spin precession around fluctuating effective magnetic field;

$\tau_s \sim 1/\tau_d$

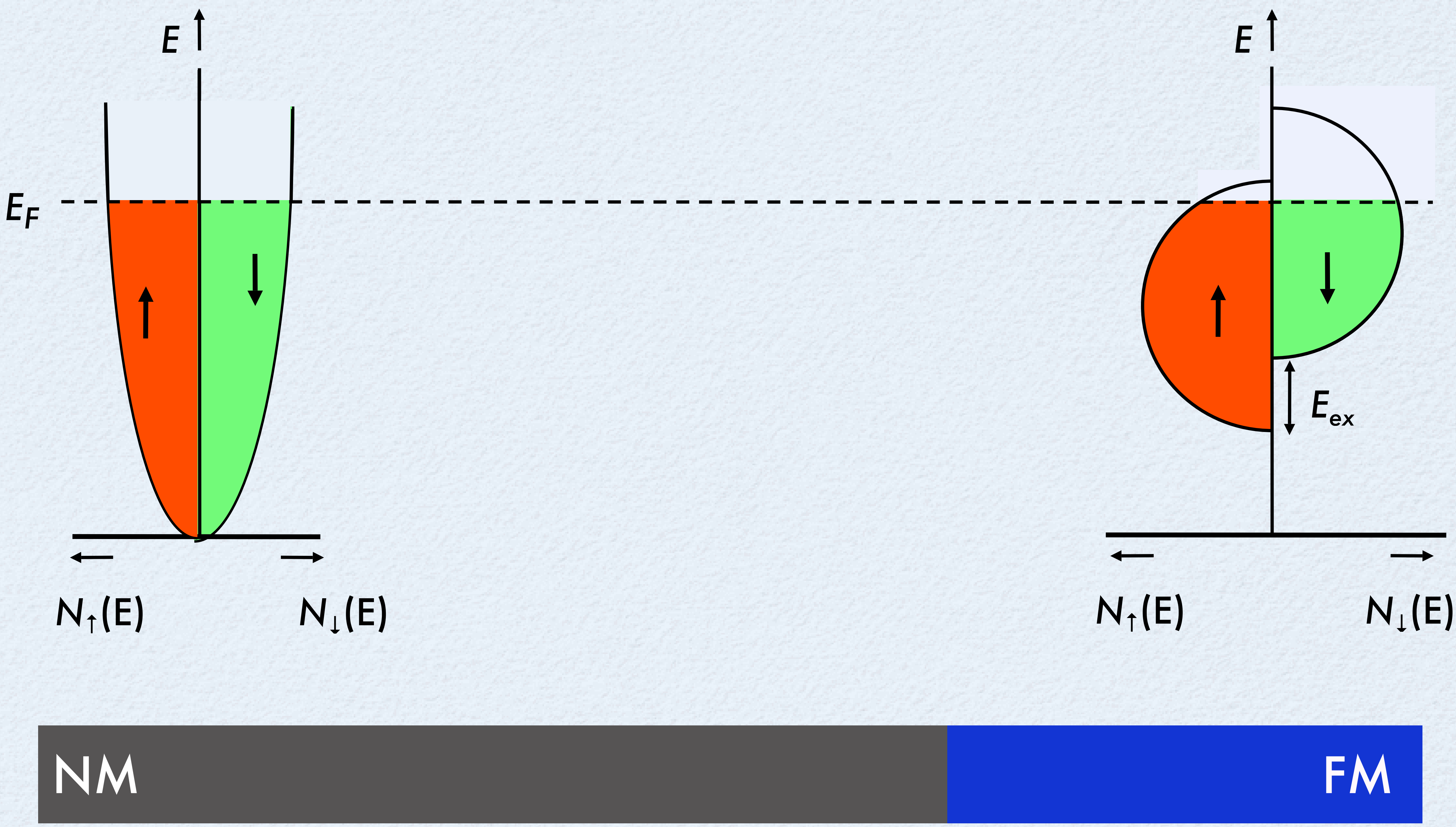
iii: hyperfine:

interaction with nuclear spin;

1% ^{13}C



Spin injection: the basic picture



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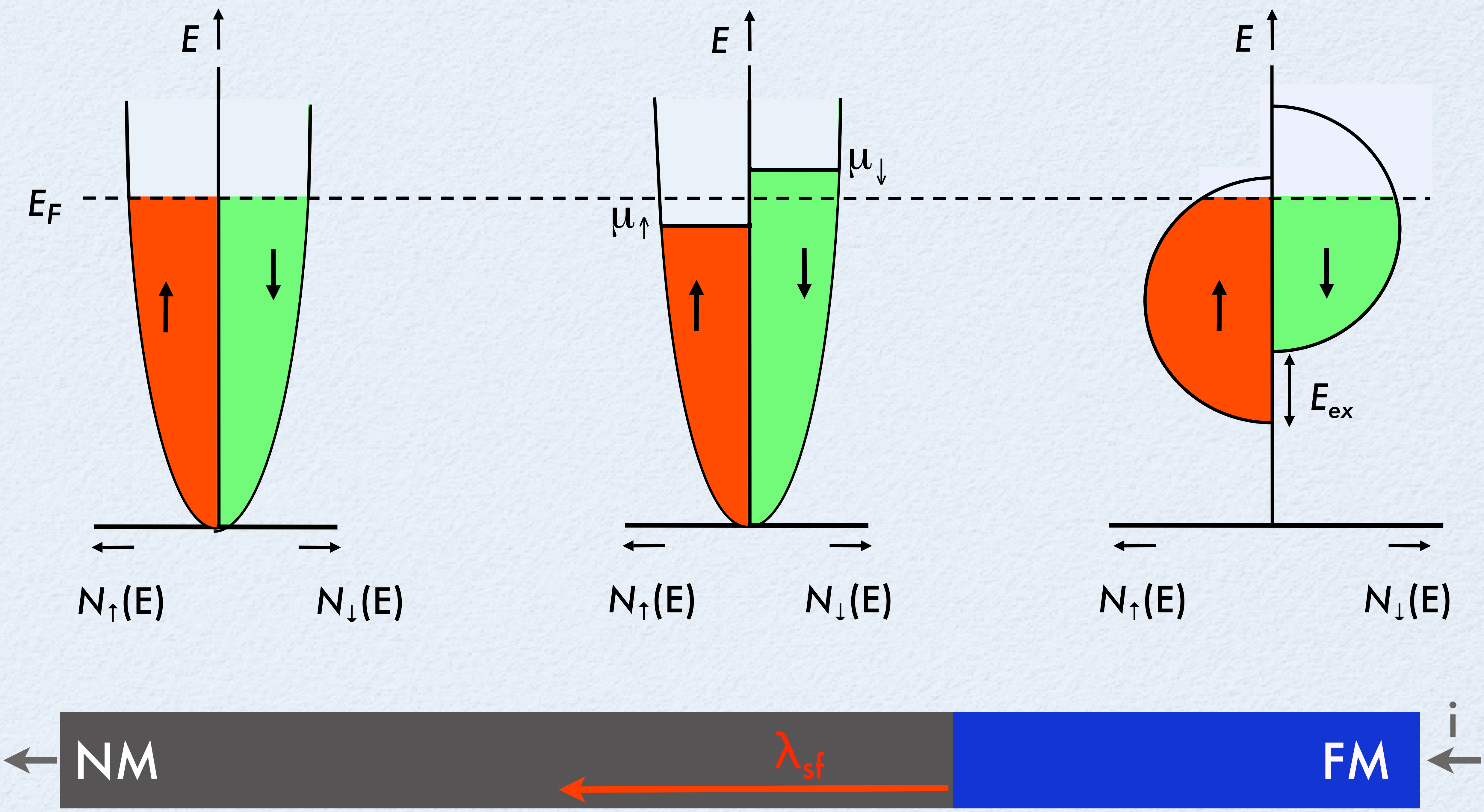
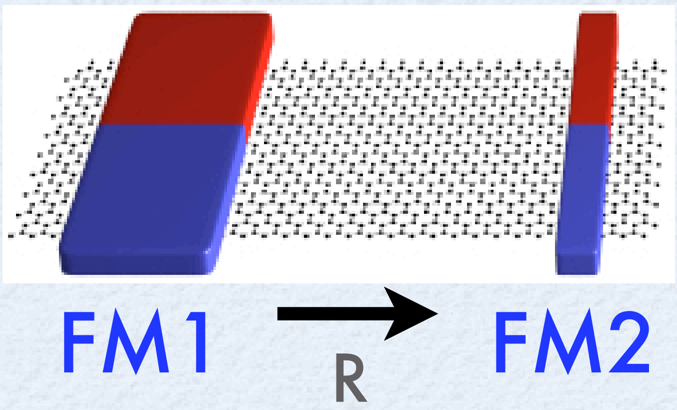


Spin Detection: Lateral Spin Valve



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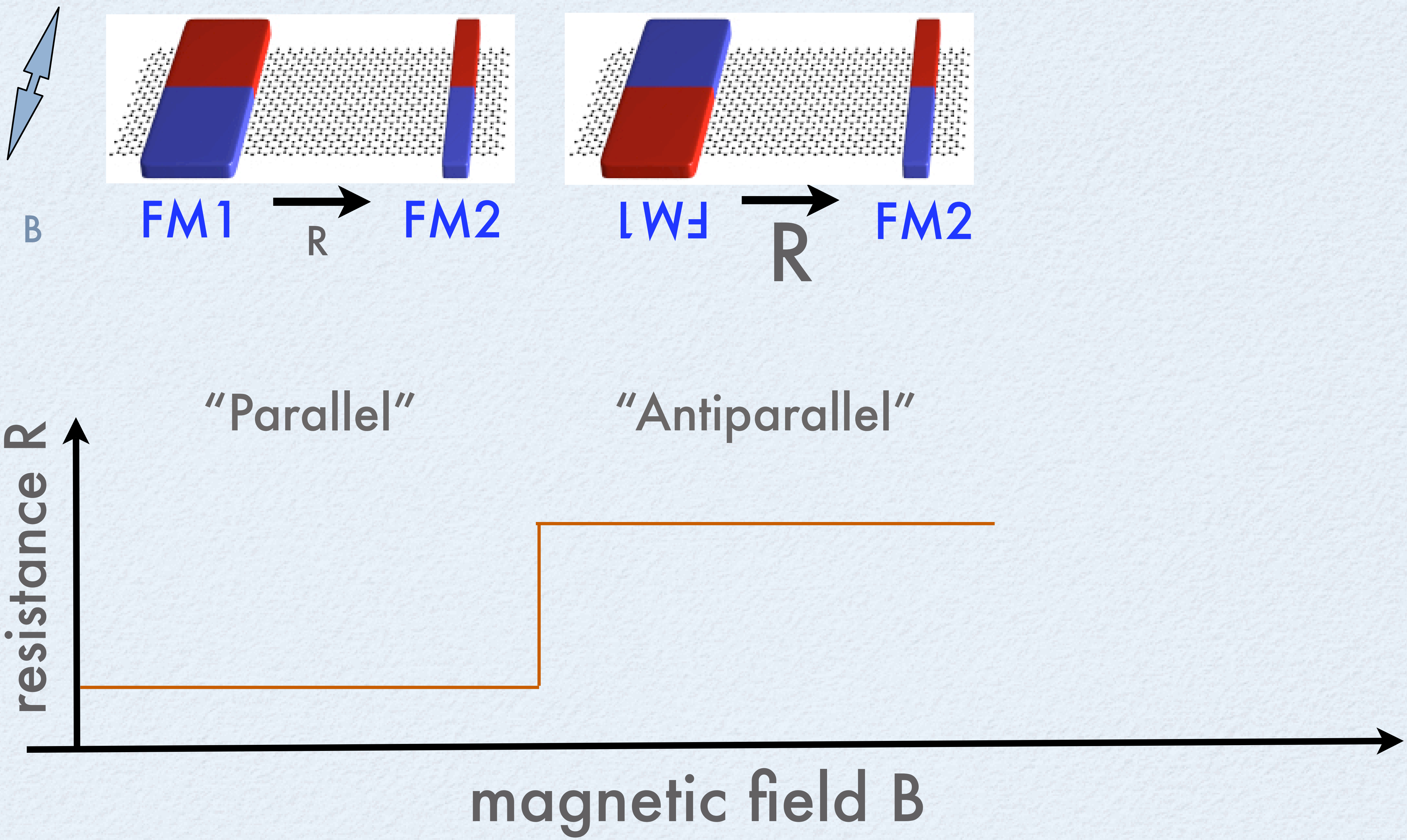

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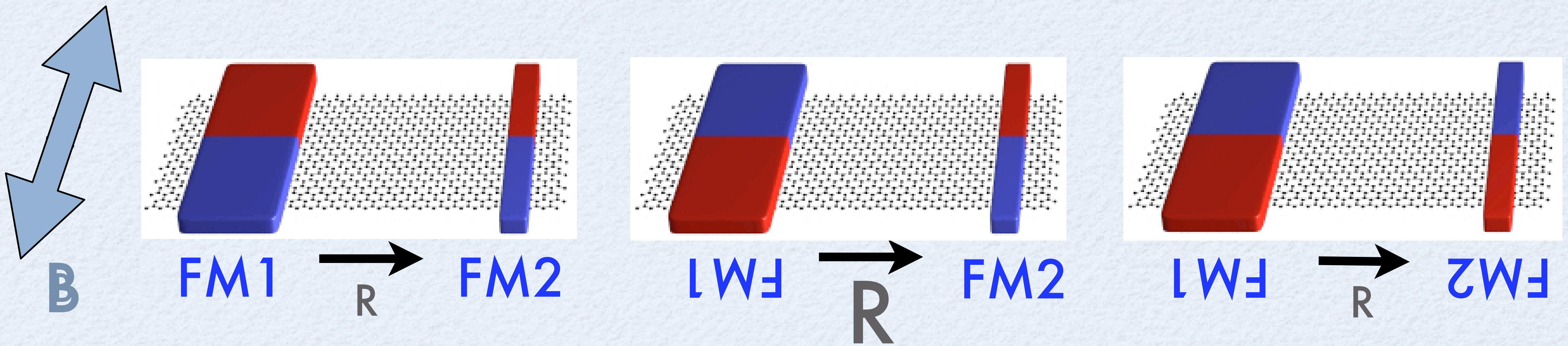
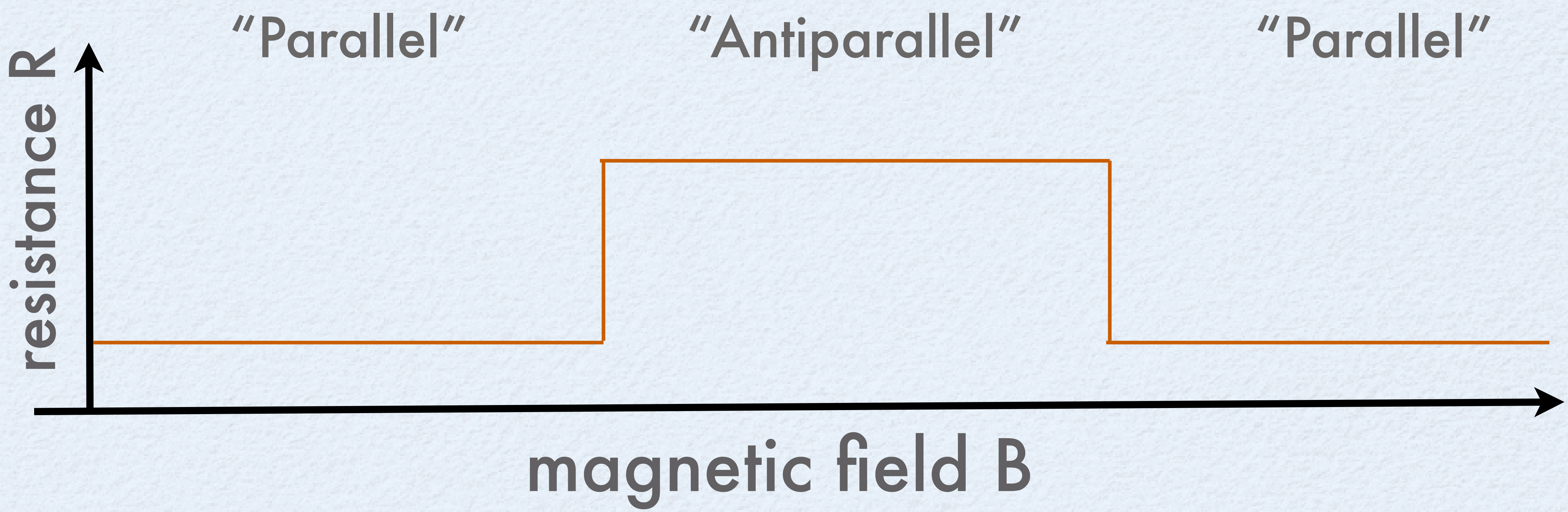
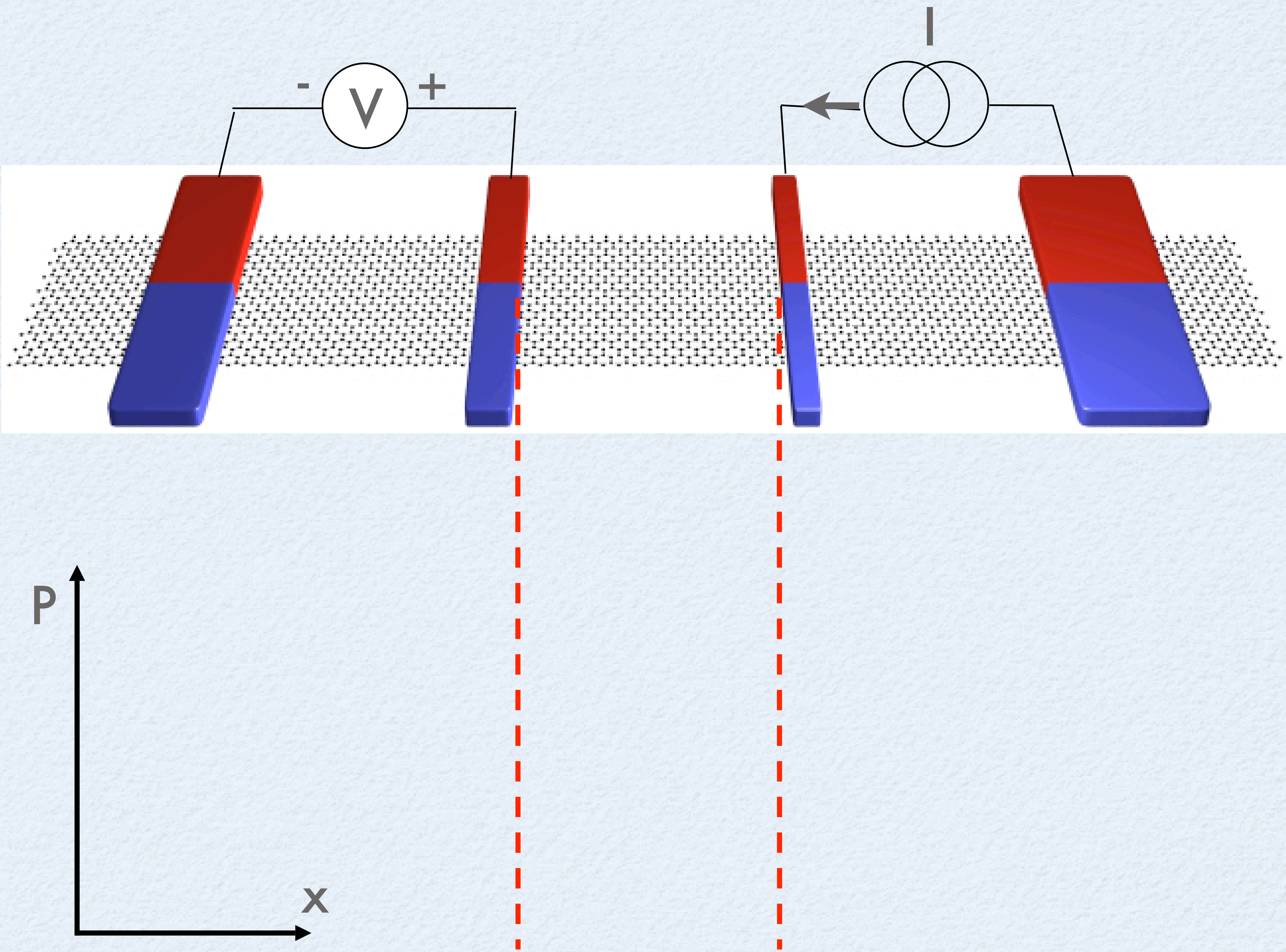


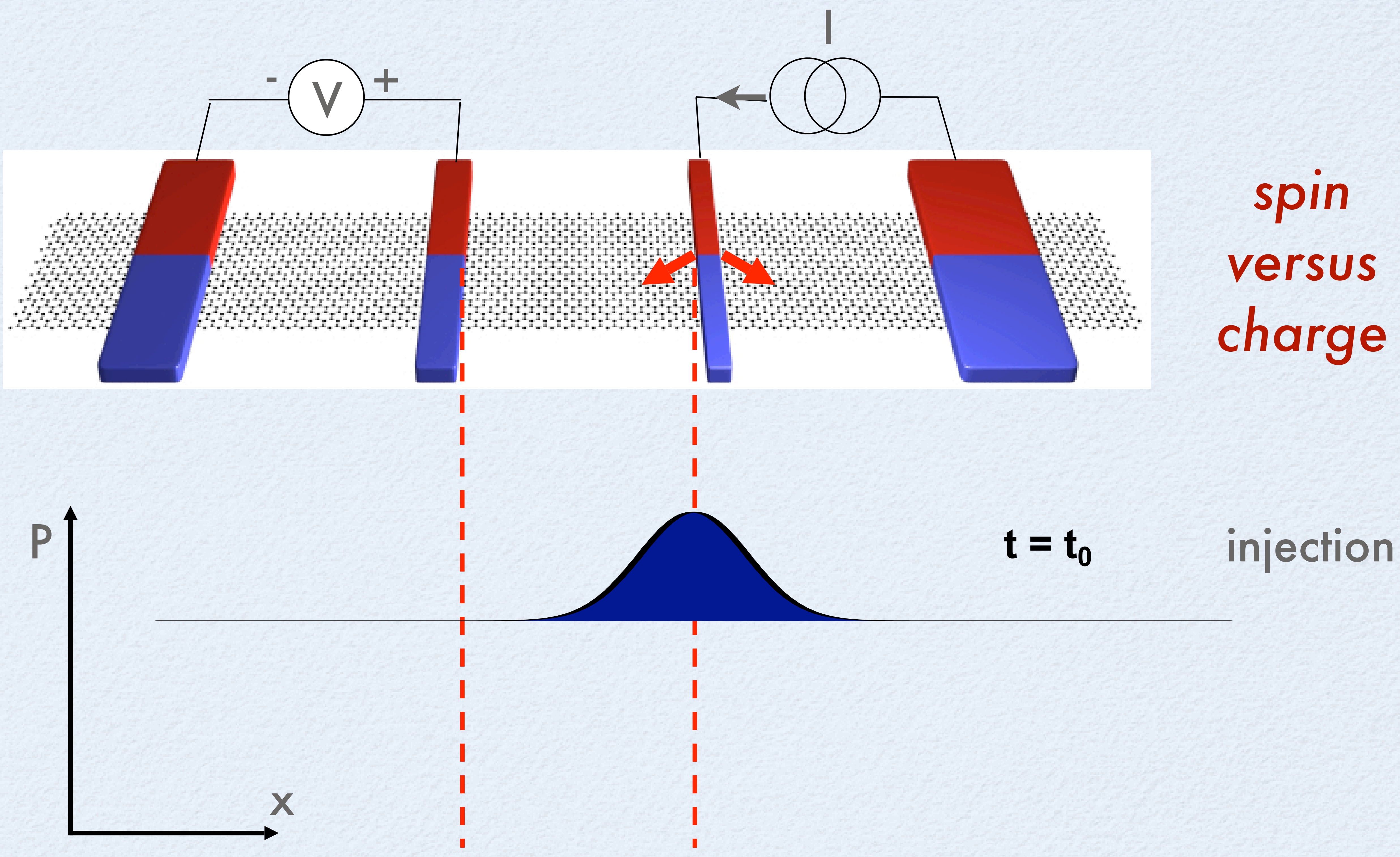


Non-local 4-terminal spin valve



spin versus charge

Non-local 4-terminal spin valve



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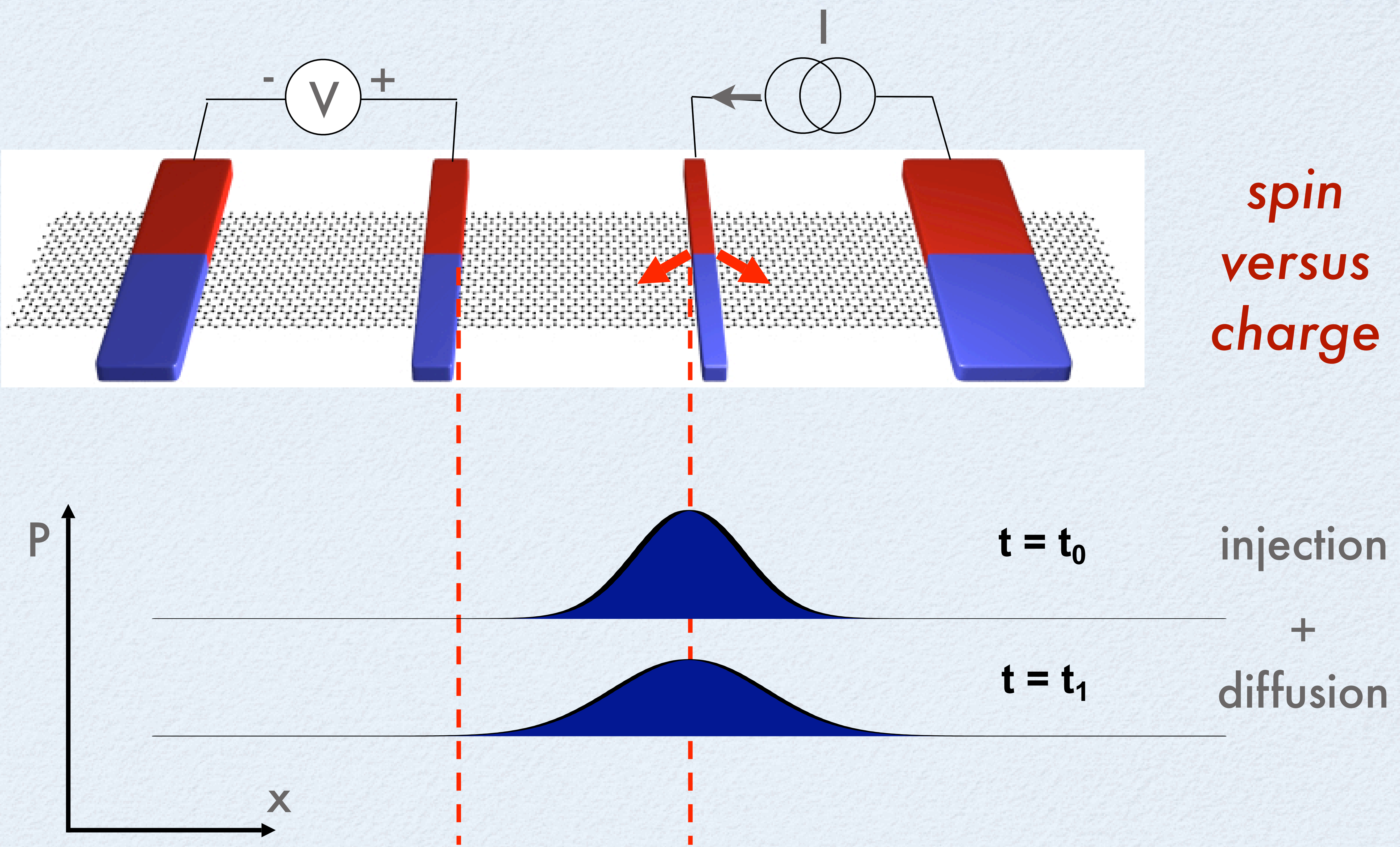
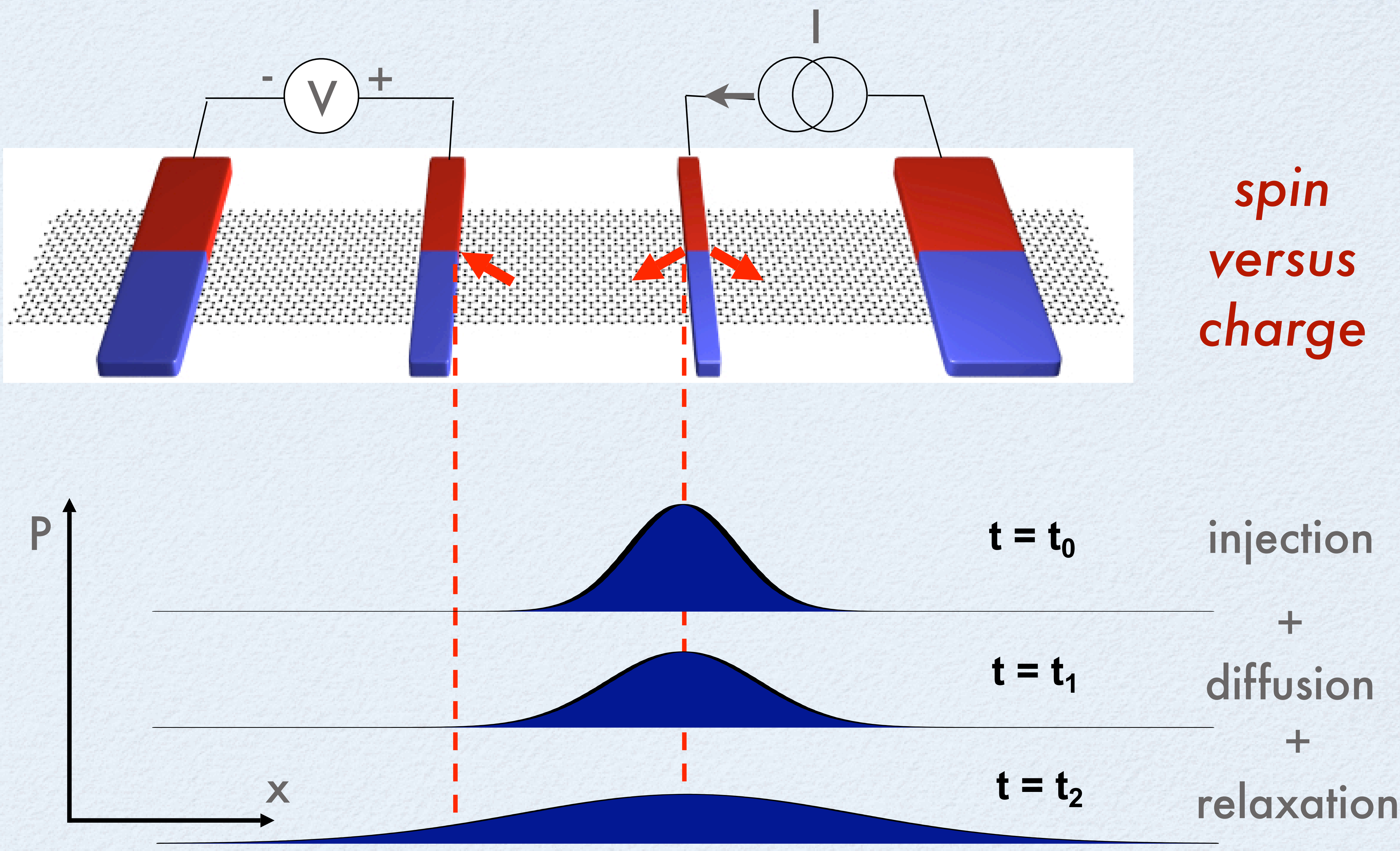
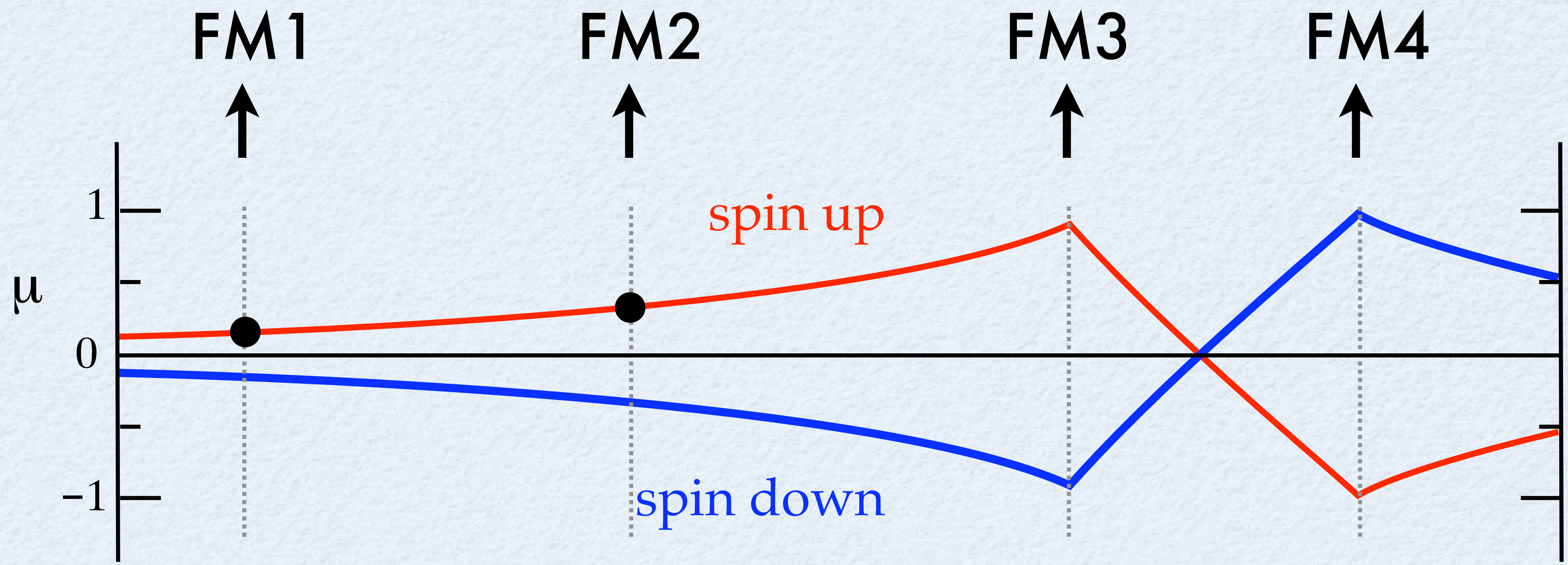


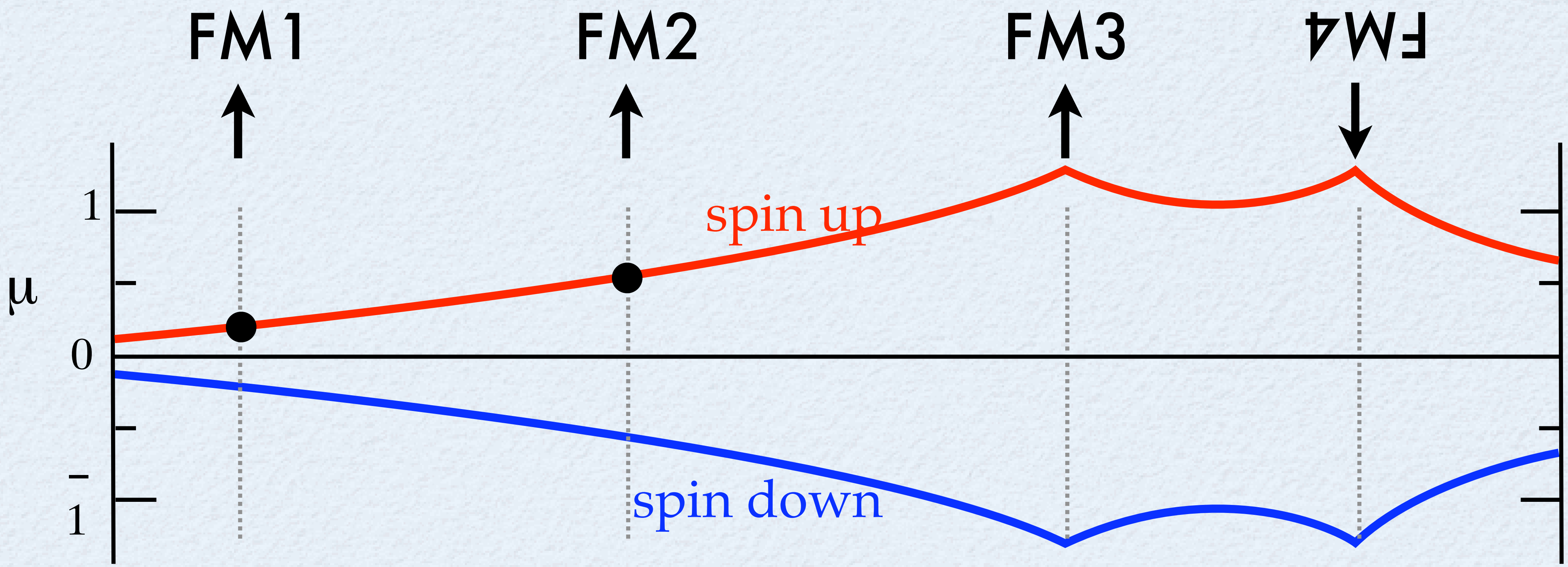
NON-LOCAL 4-TERMINAL SPIN VALVE



Electrochemical Potential



Electrochemical potential



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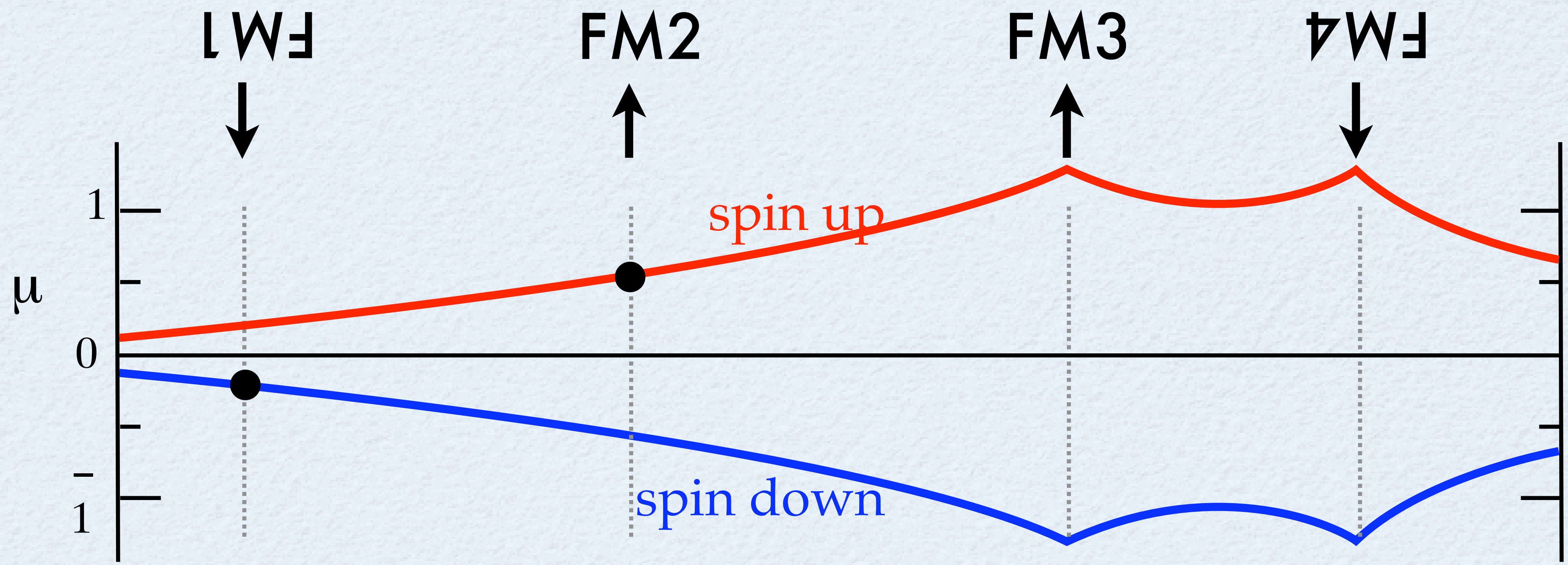
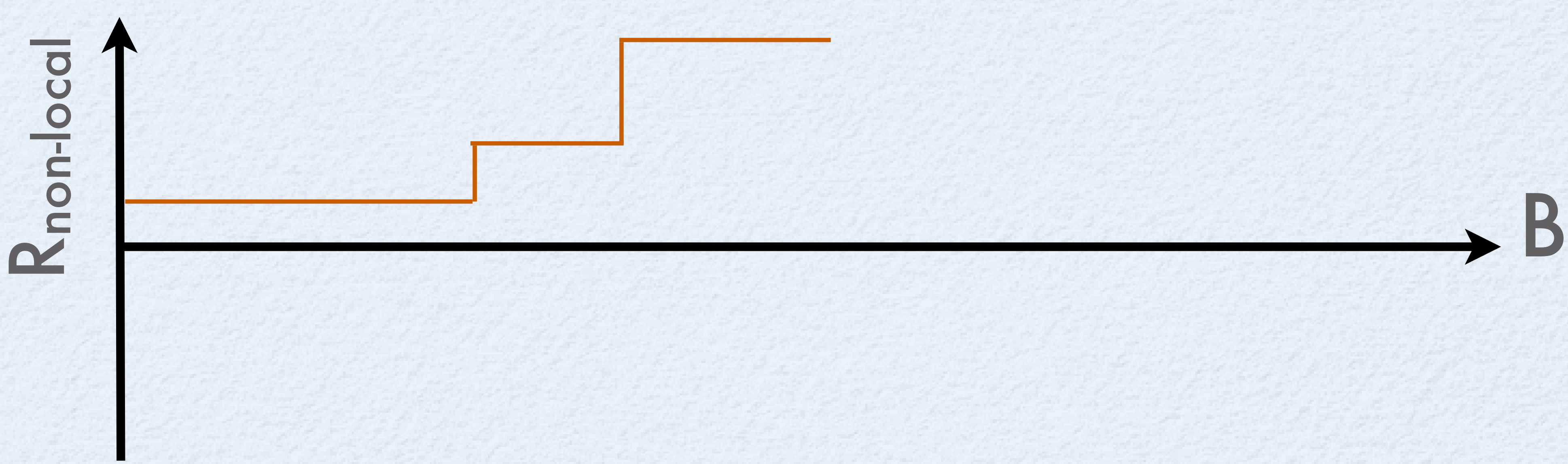
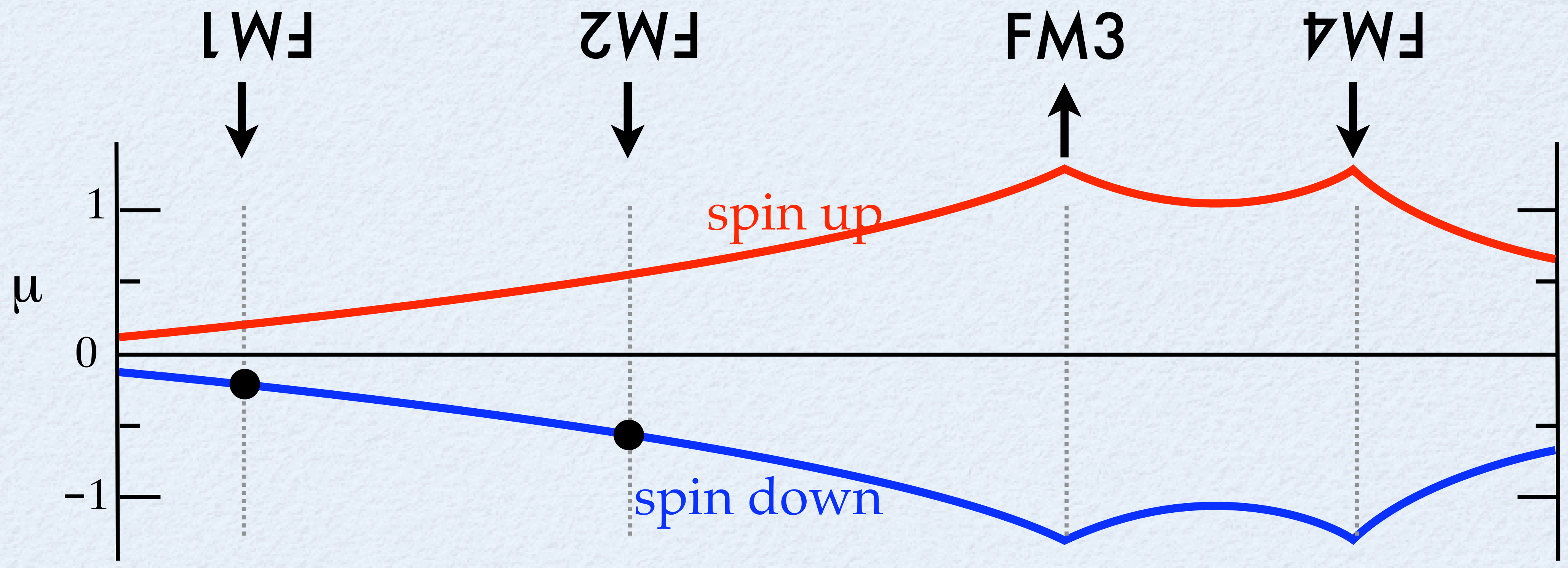
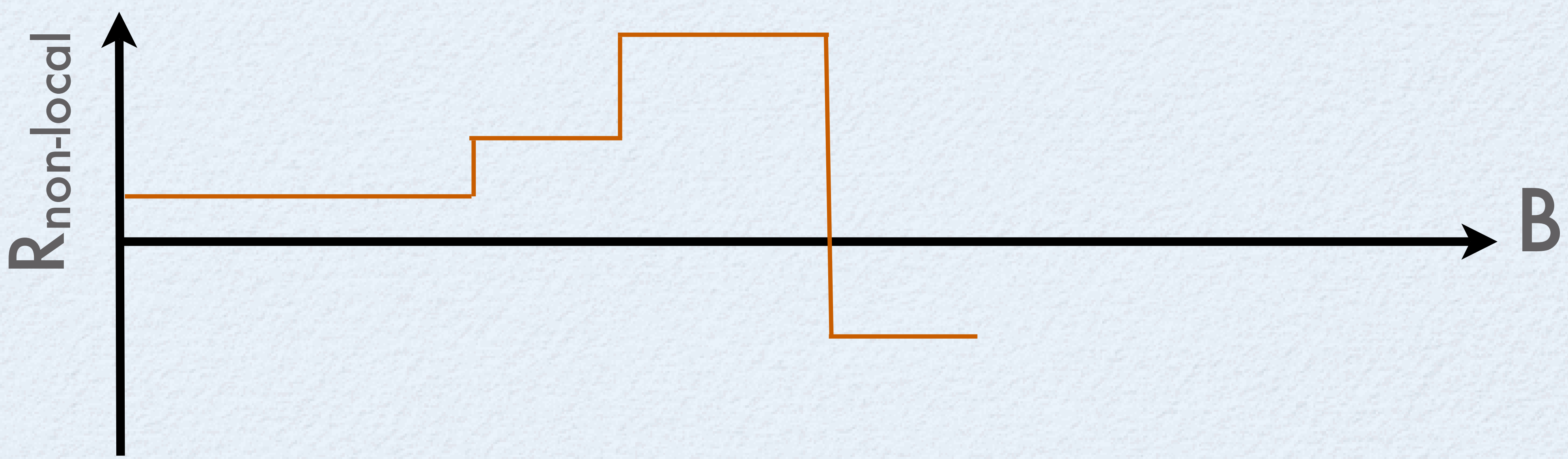


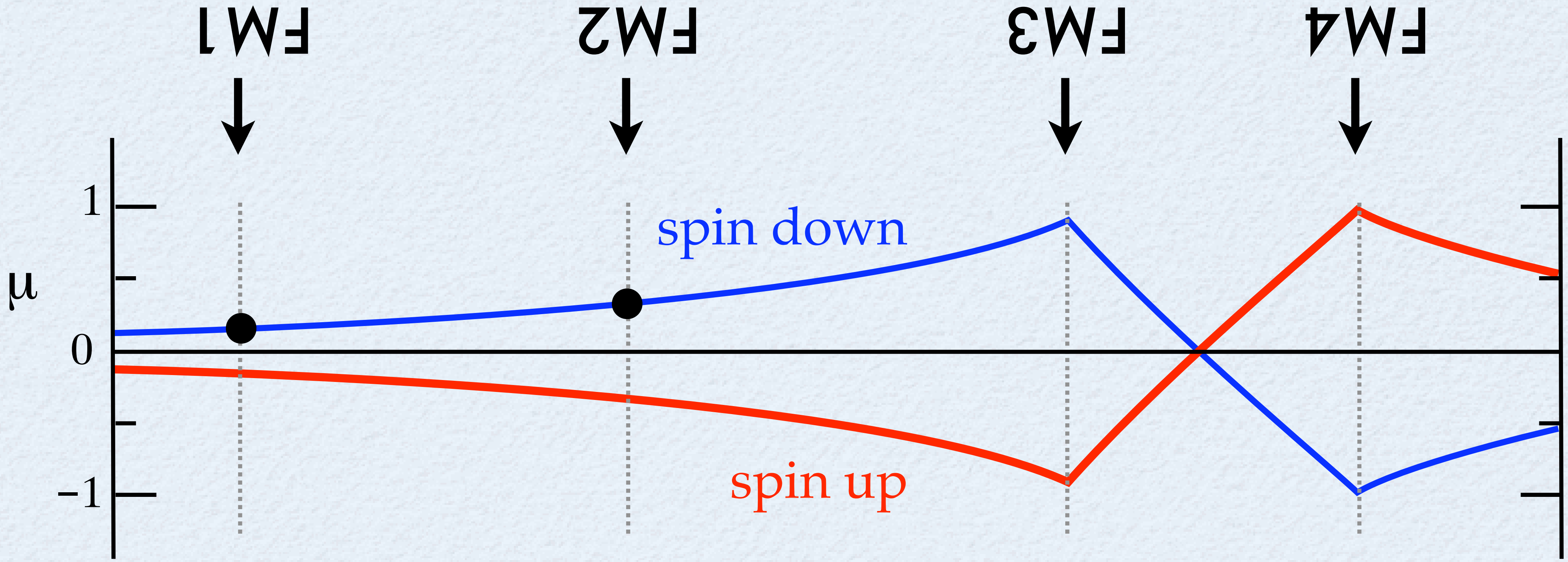


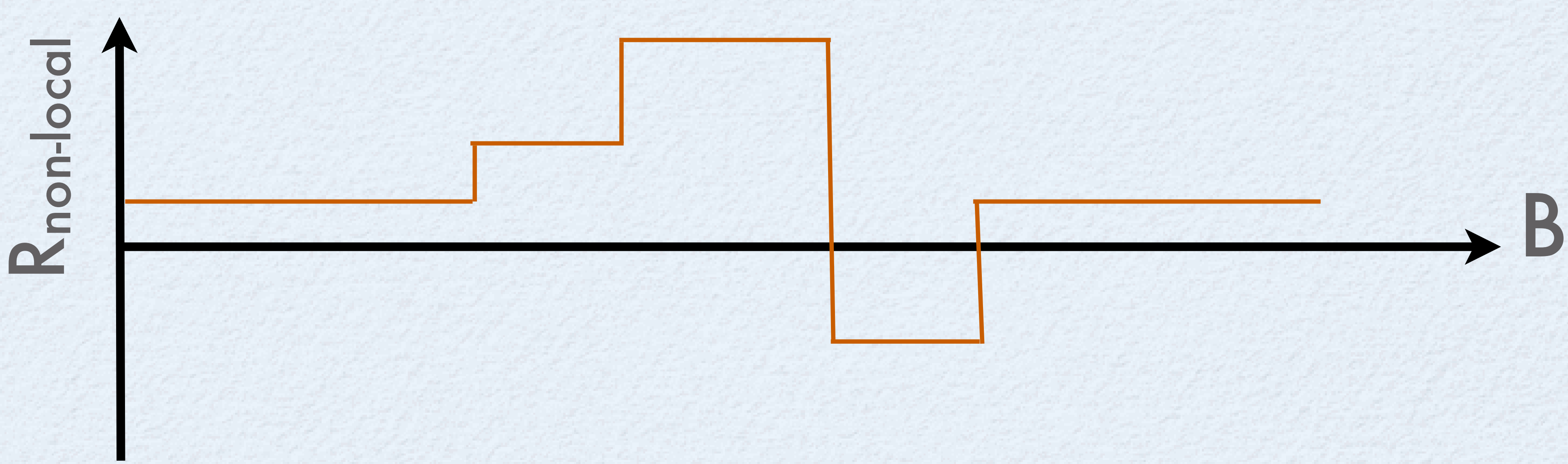
ELECTROCHEMICAL POTENTIAL





Electrochemical potential





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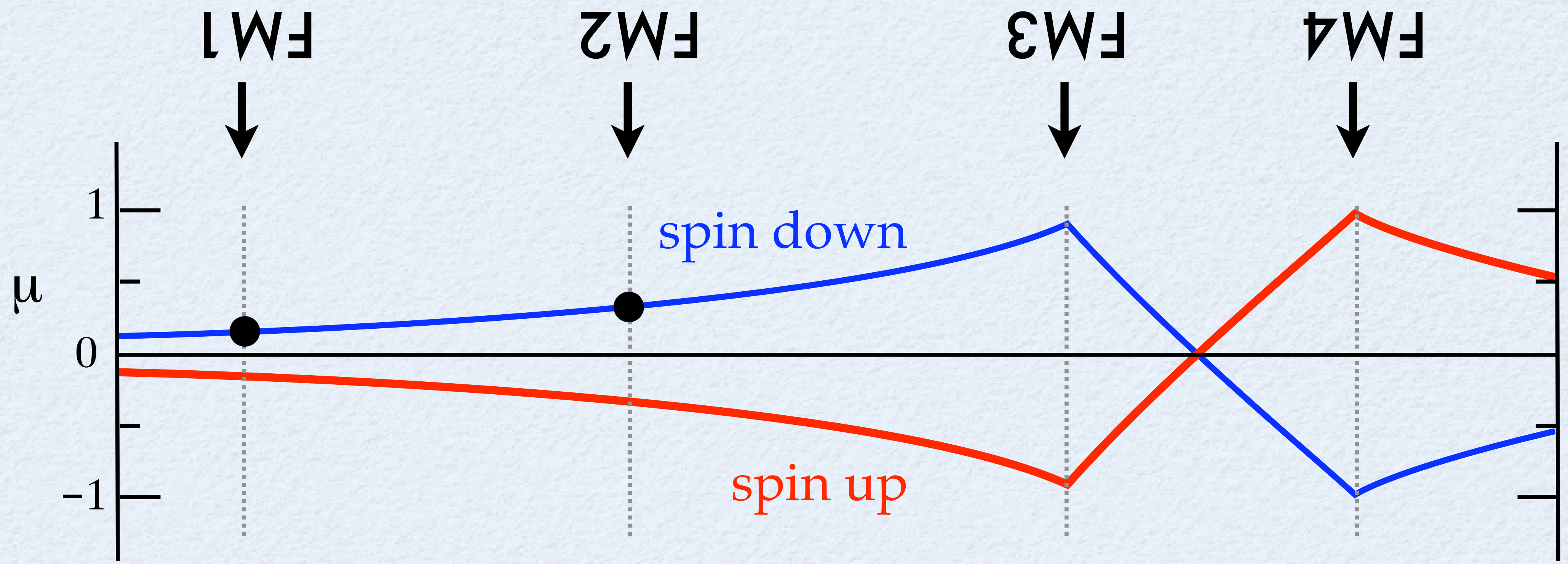
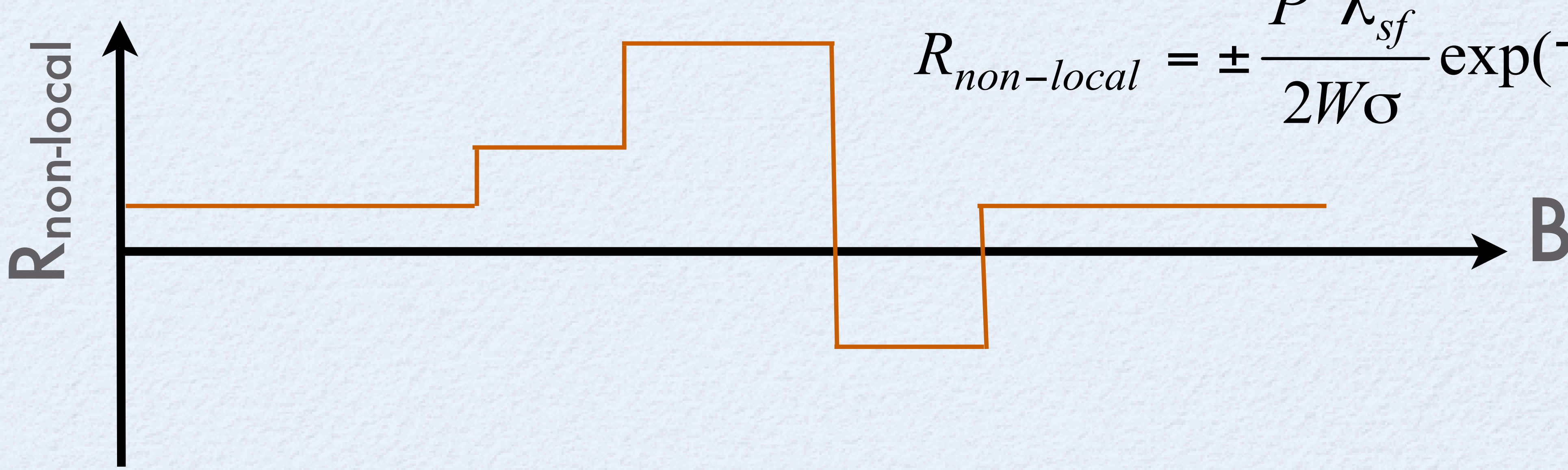
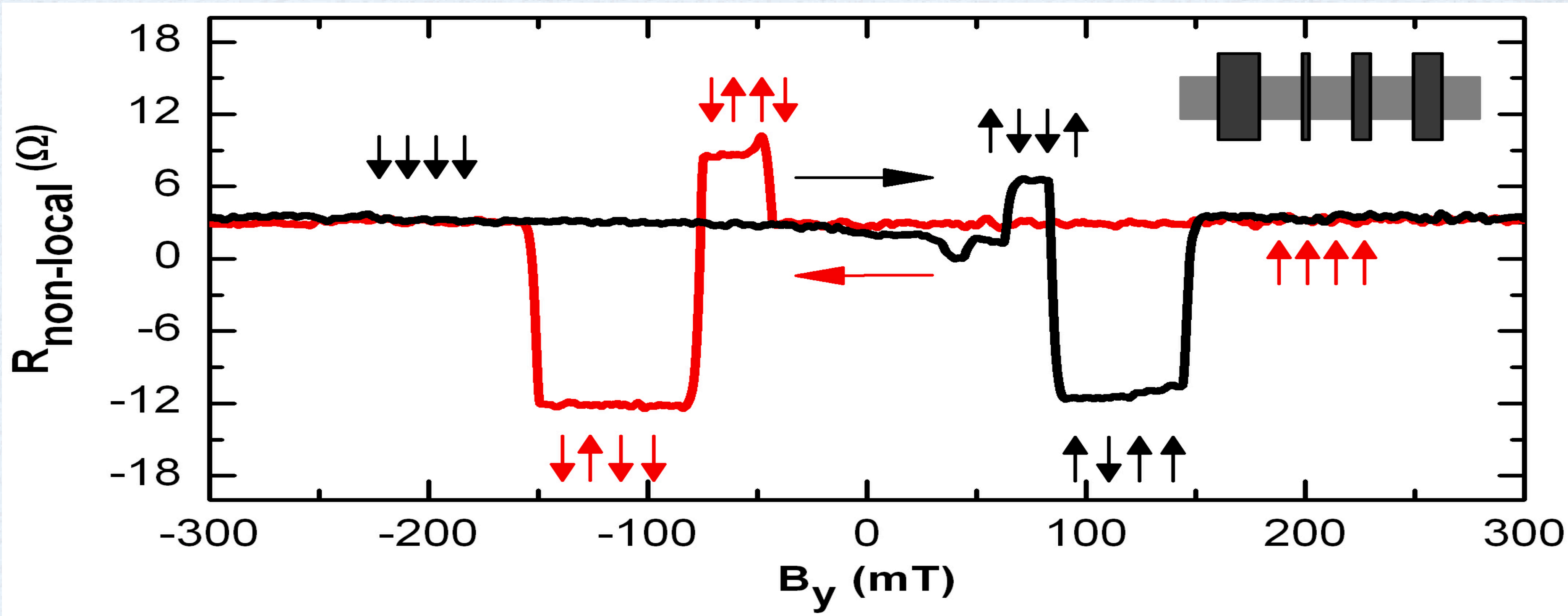
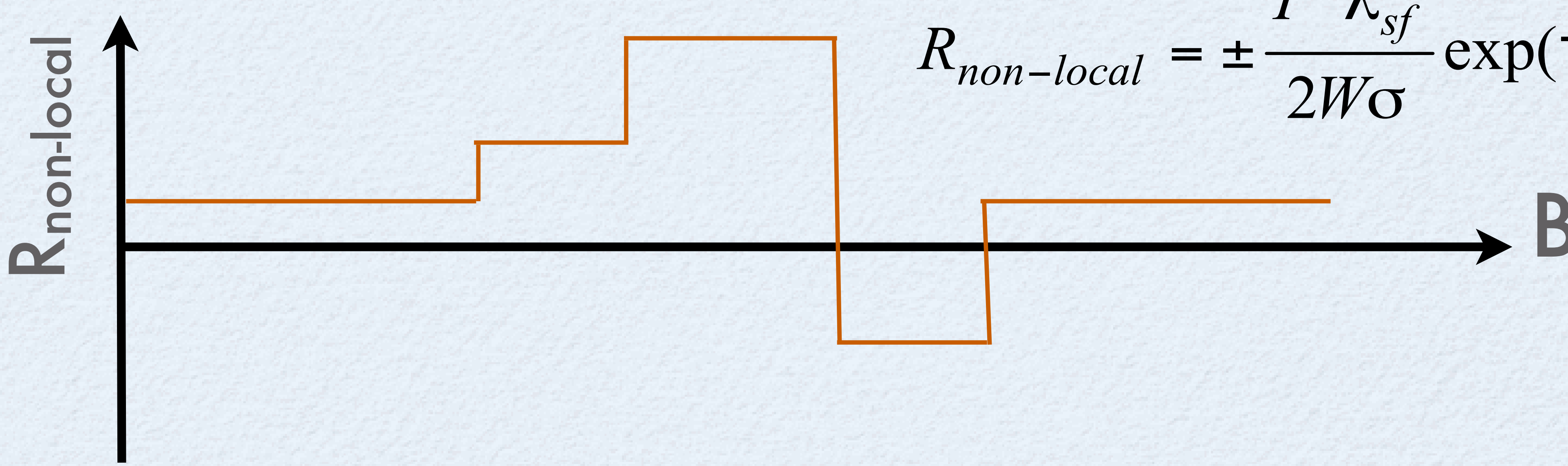




$$R_{non-local} = \pm \frac{P^2 \lambda_{sf}}{2W\sigma} \exp(-L/\lambda_{sf})$$

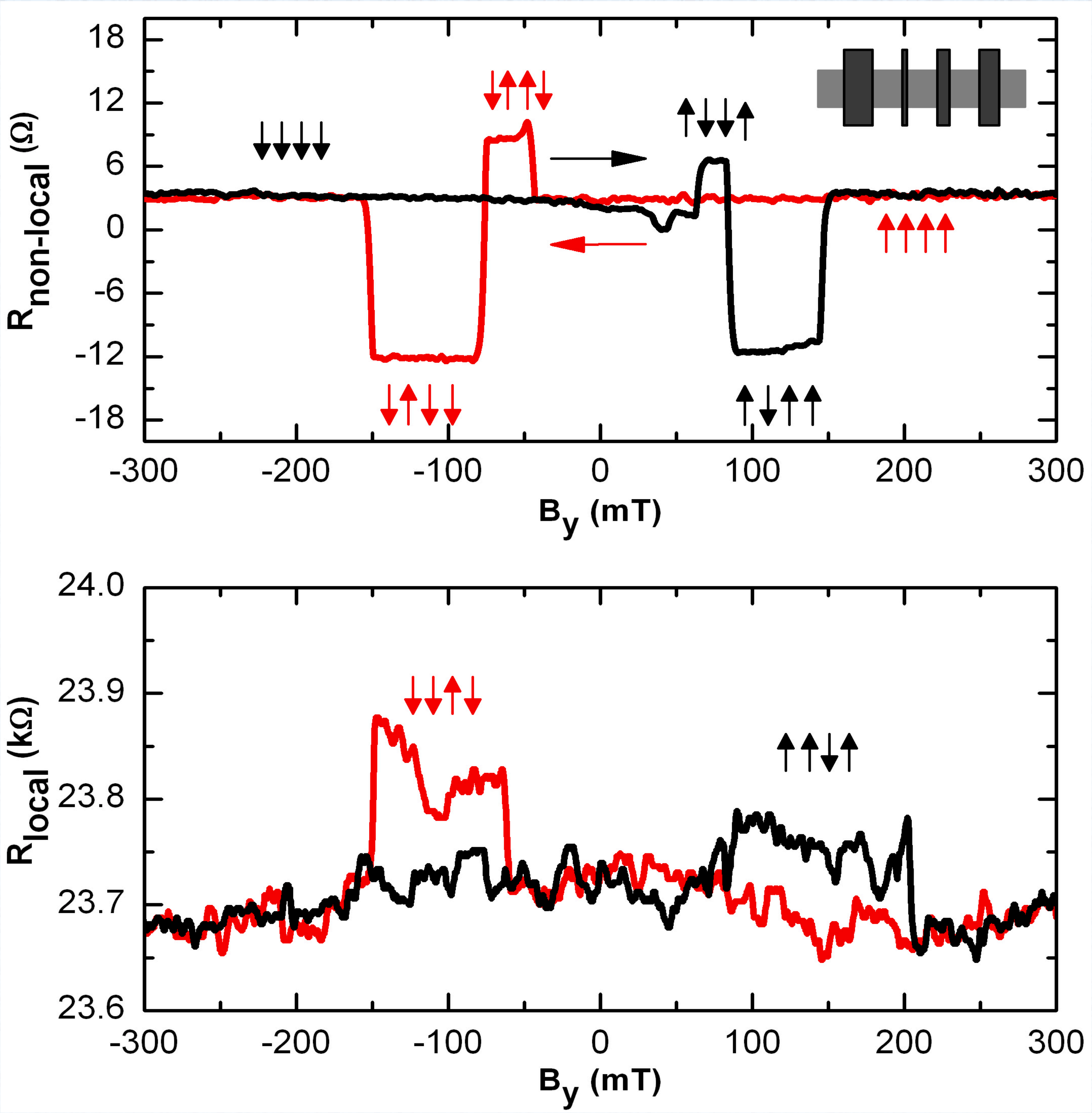
Electrochemical potential





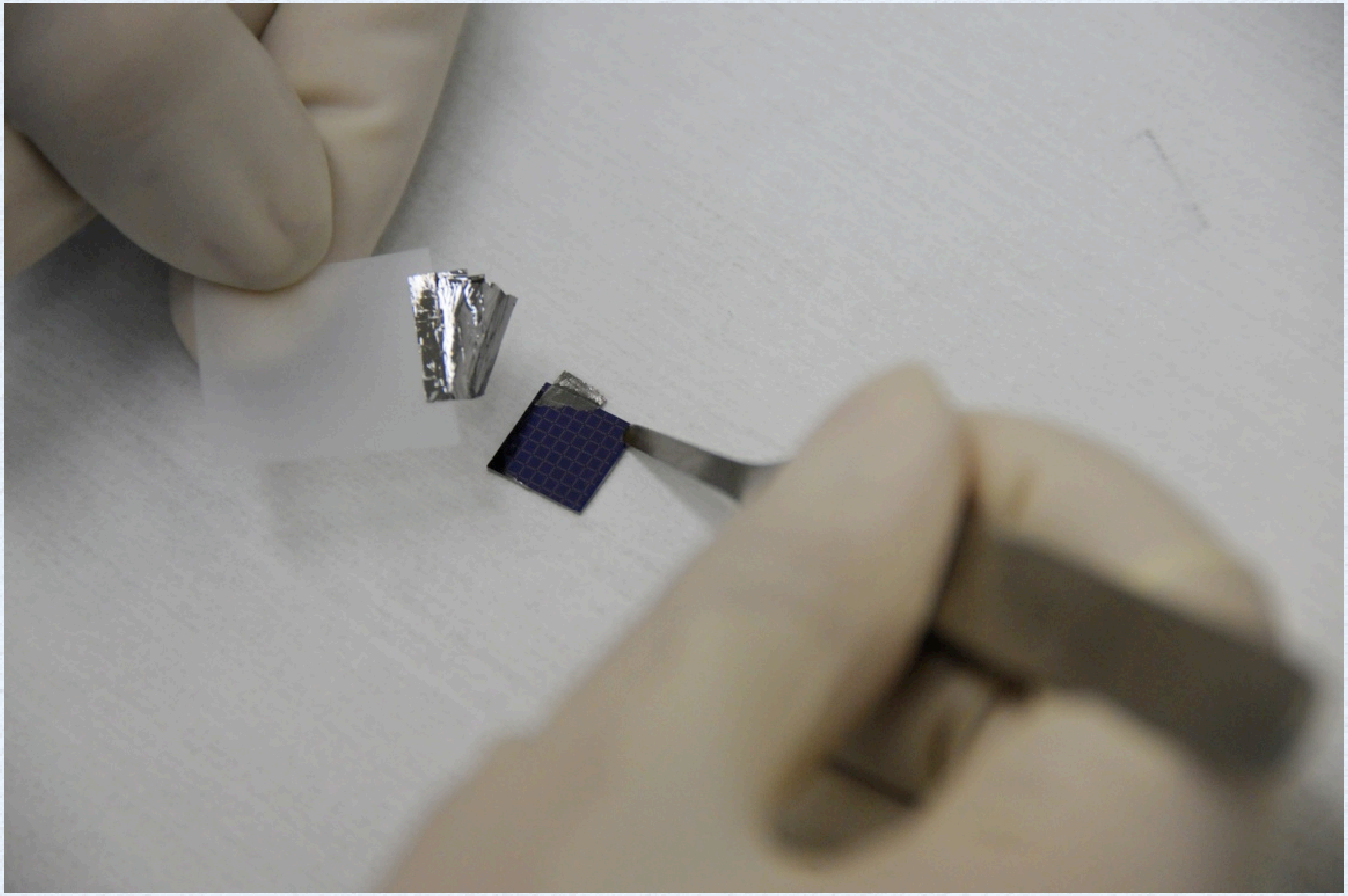
$$R_{non-local} = \pm \frac{P^2 \lambda_{sf}}{2W\sigma} \exp(-L/\lambda_{sf})$$

NON-LOCAL VS. LOCAL



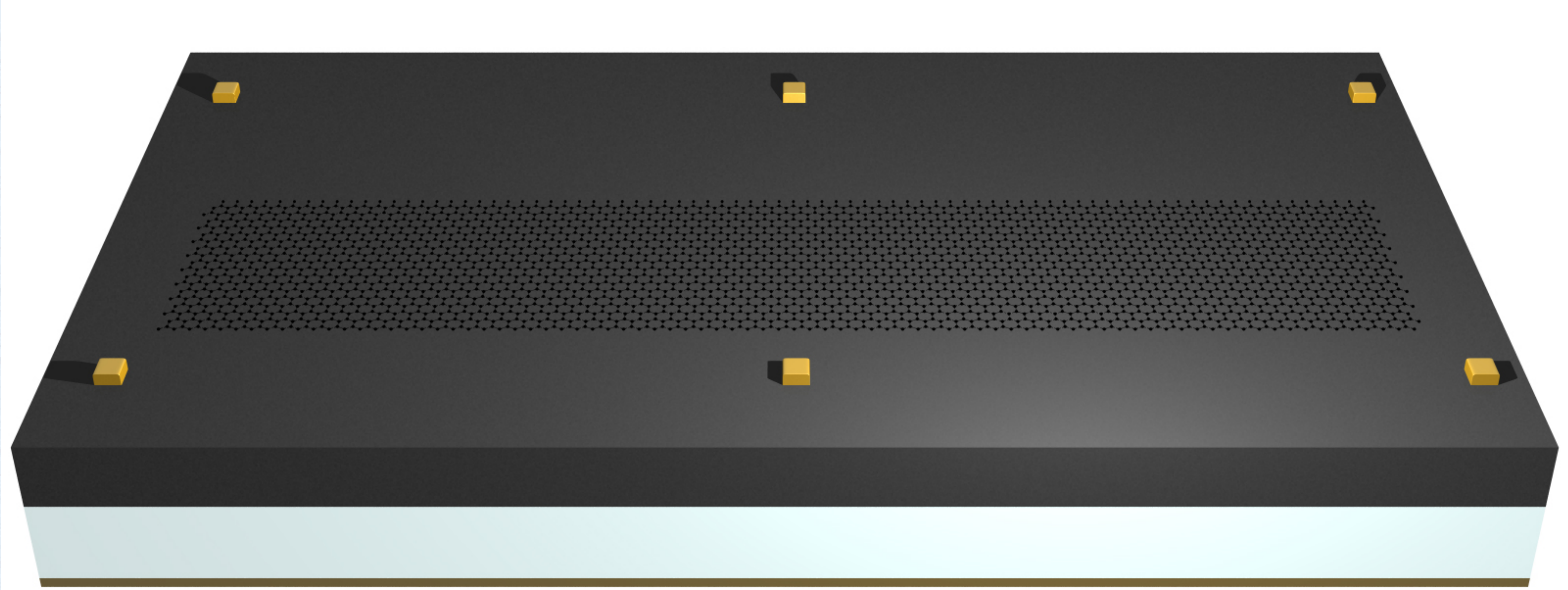
THE BIRTH OF A GRAPHENE SPIN VALVE DEVICE

The Scotch Tape Method



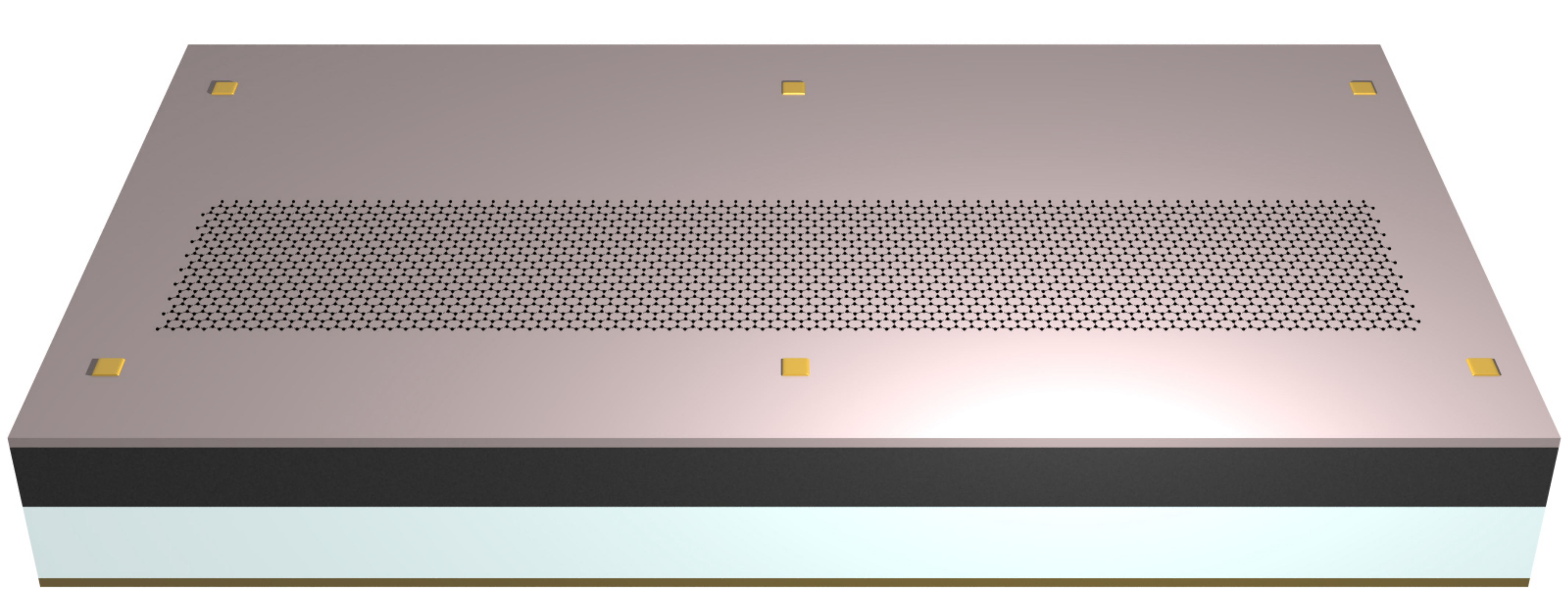
Graphene spin valve device

Graphene flakes: localization (optical + AFM)
Ti/Au (40nm) markers
Si(n++) / SiO_2 (300 nm)substrate
Ti/Au (100 nm) gate electrode



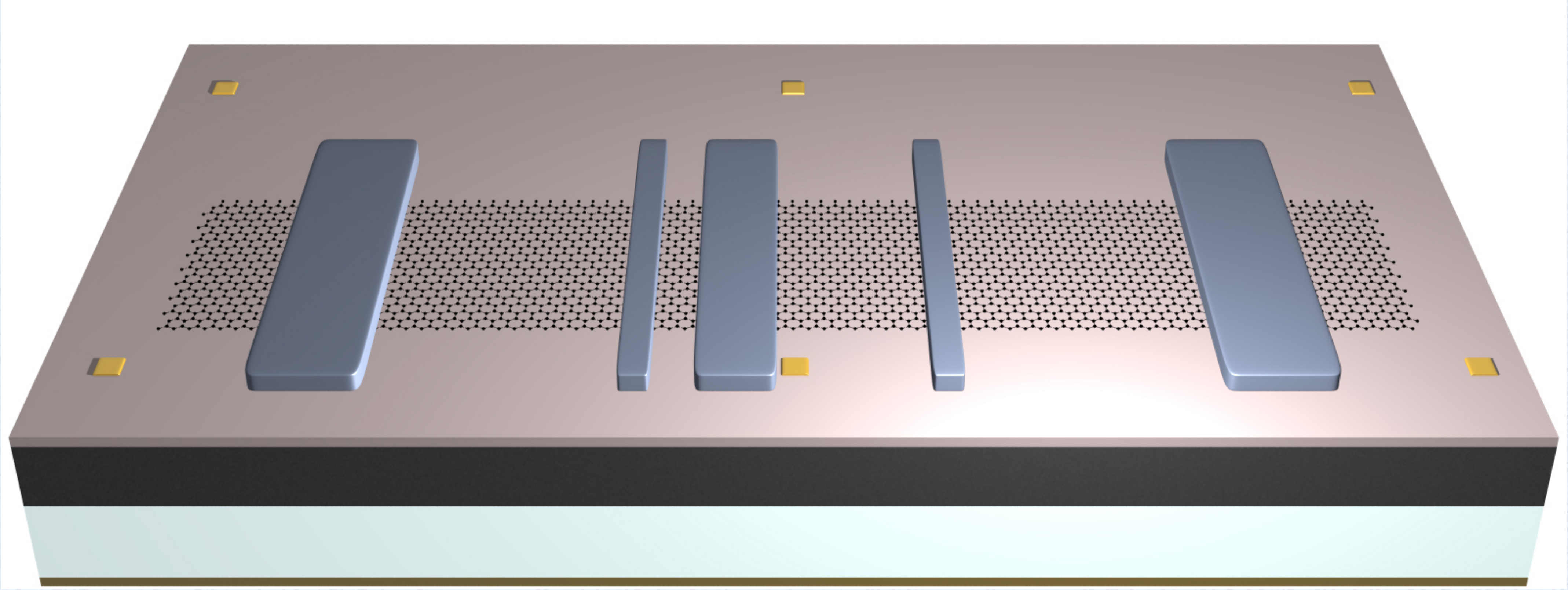
Graphene spin valve device

key ingredient: Al (0.6 nm) UHV evaporation + oxidization



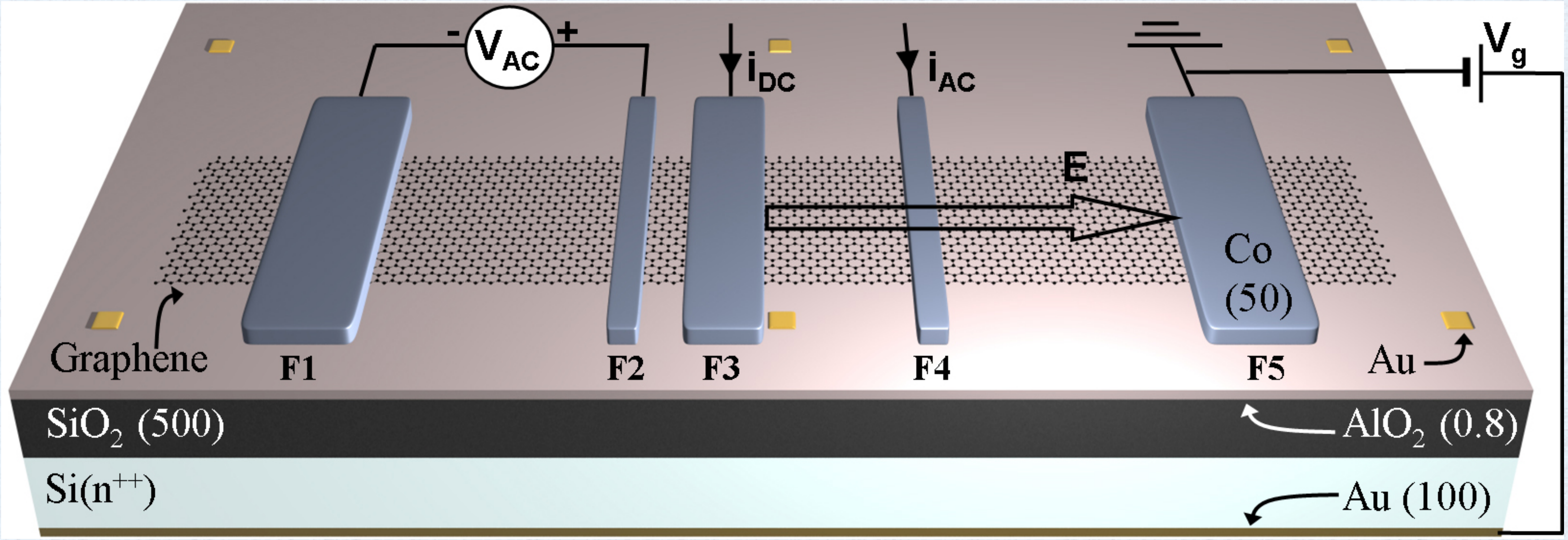
Graphene Spin Valve Device

Electron beam lithography + Lift-off: Co contacts

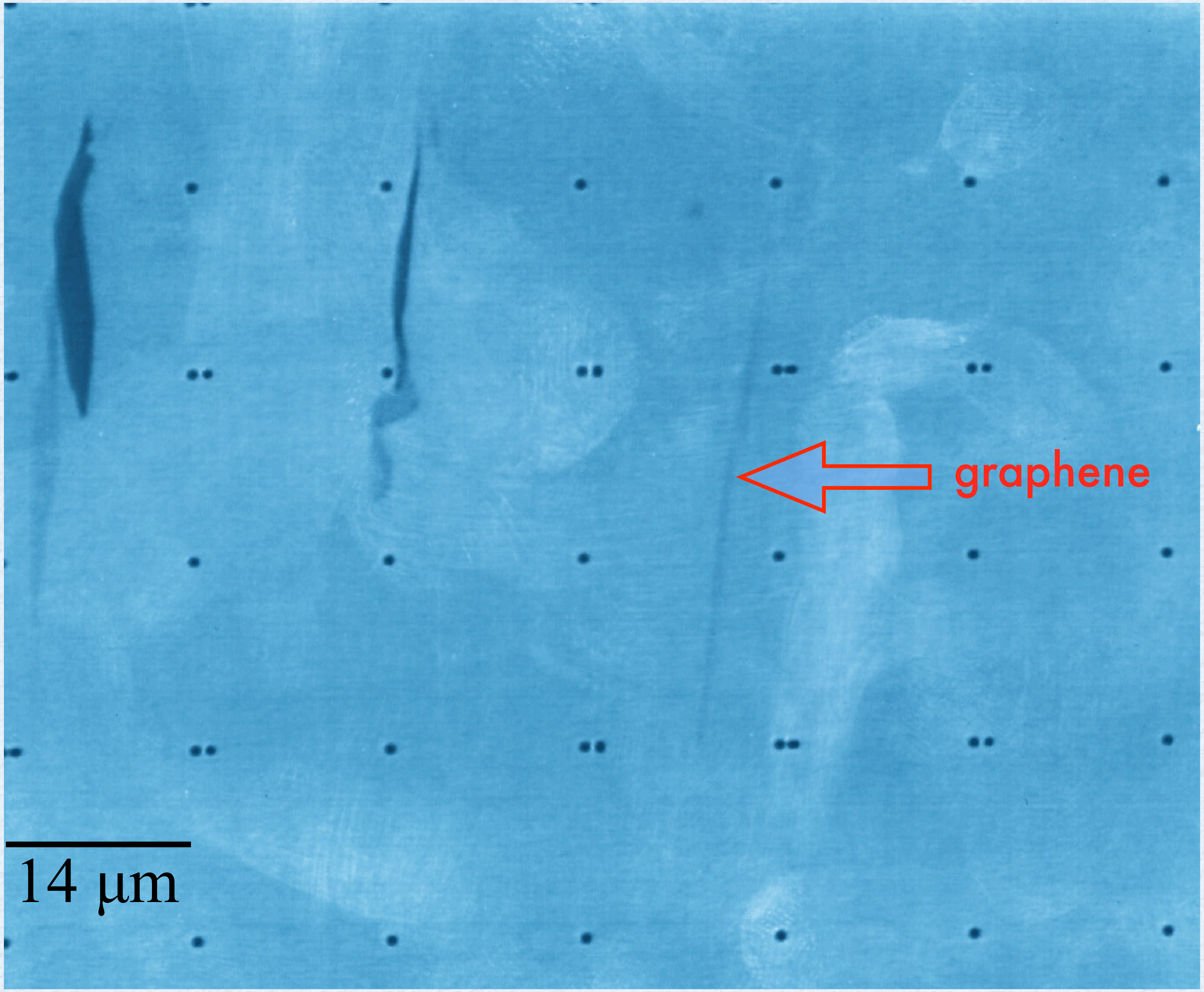


Graphene Spin Valve Device

And ready to be measured

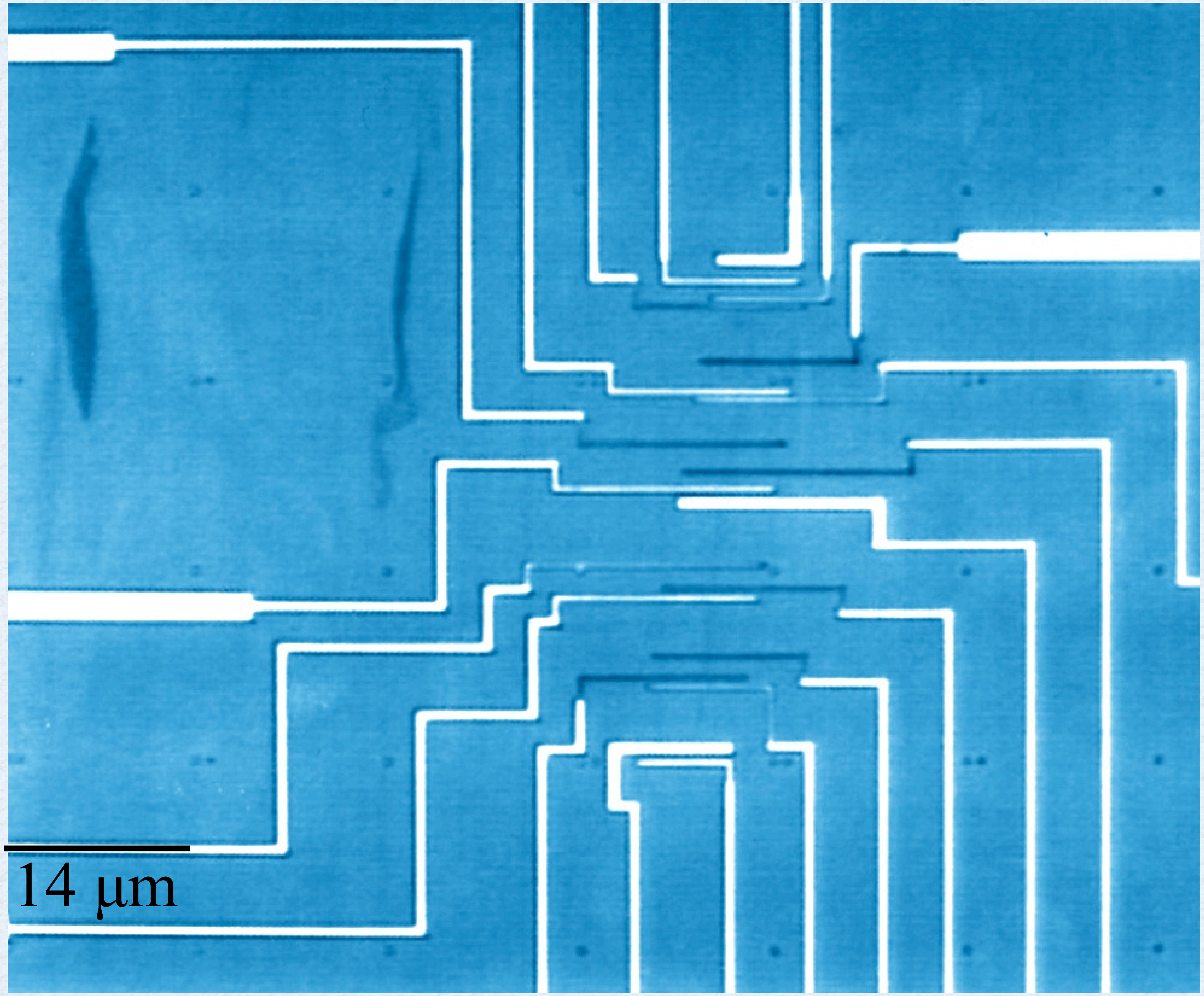


A suitable graphene flake



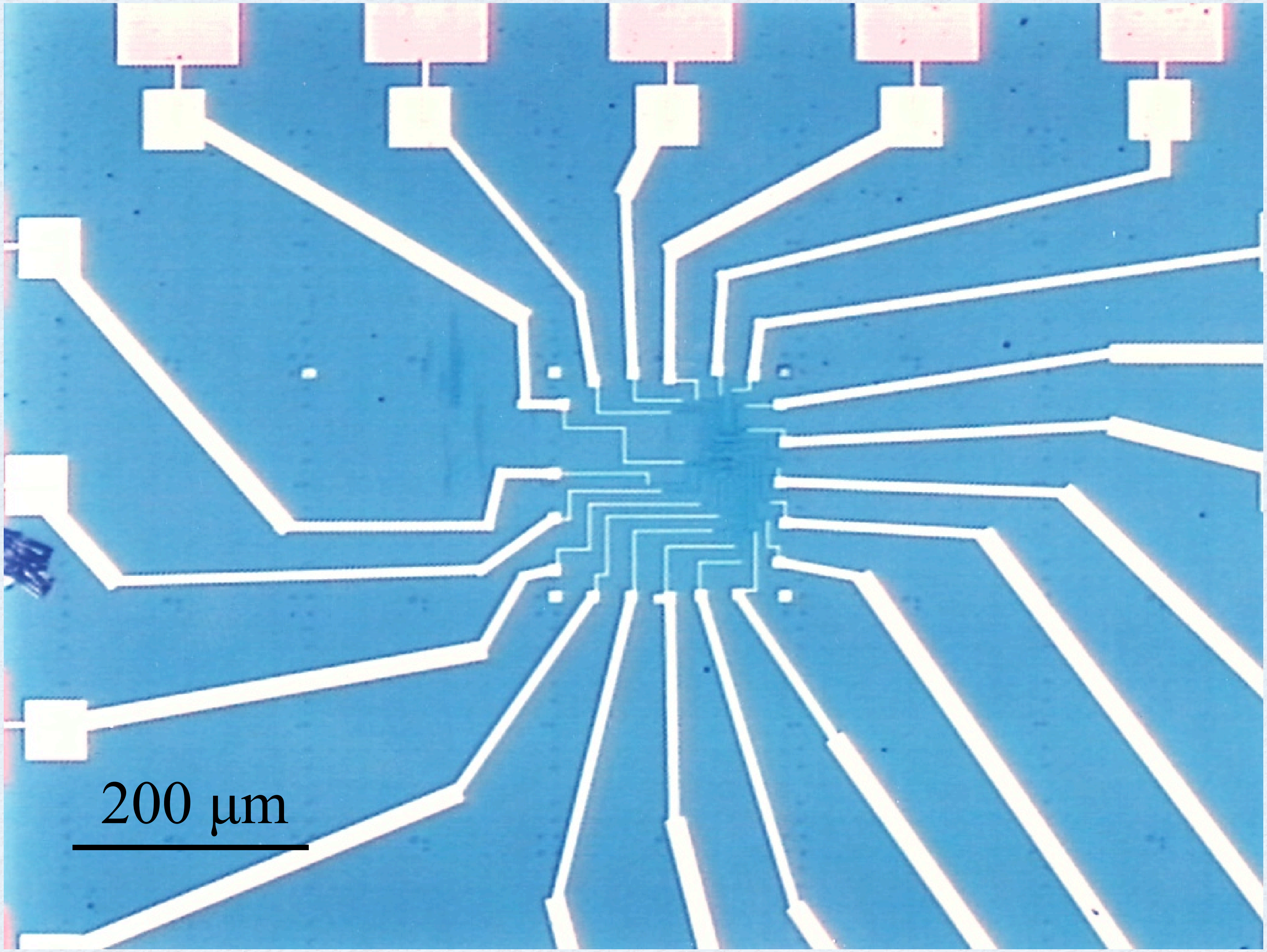
optical microscope image

Cobalt contacts on the flake



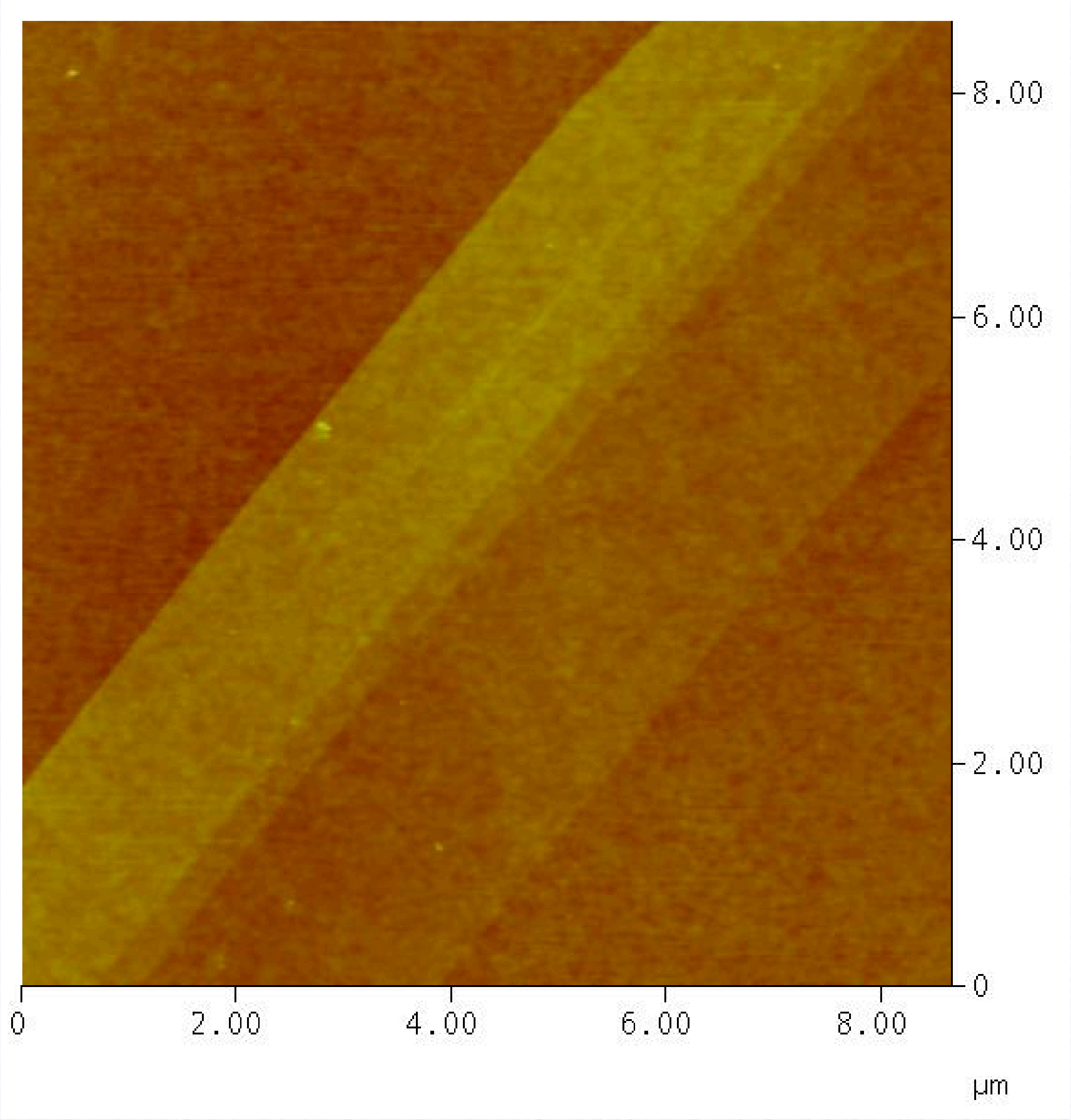
optical microscope image

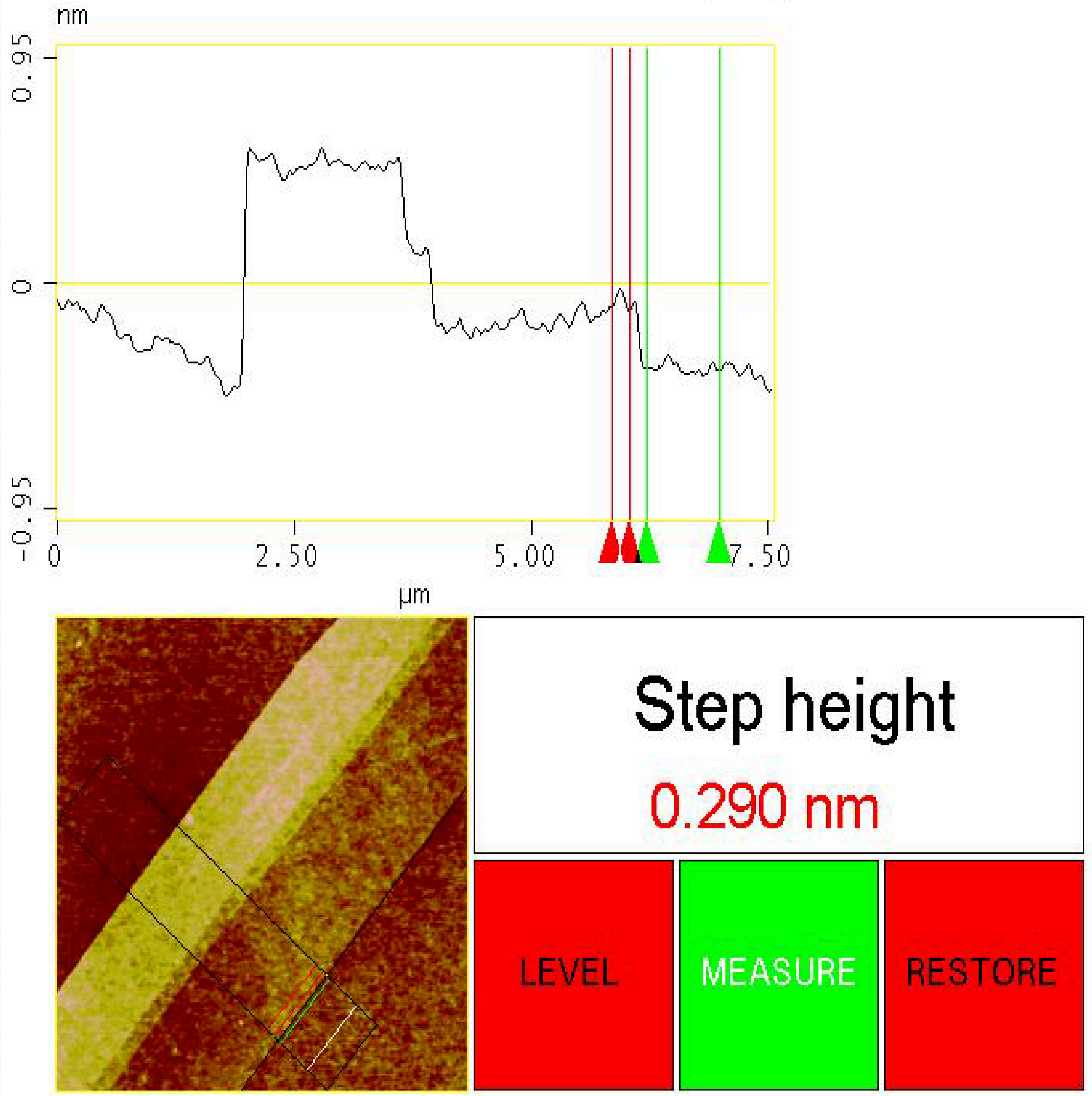
Cobalt contacts on the flake



optical microscope image

HOPG samples, AFM imaging





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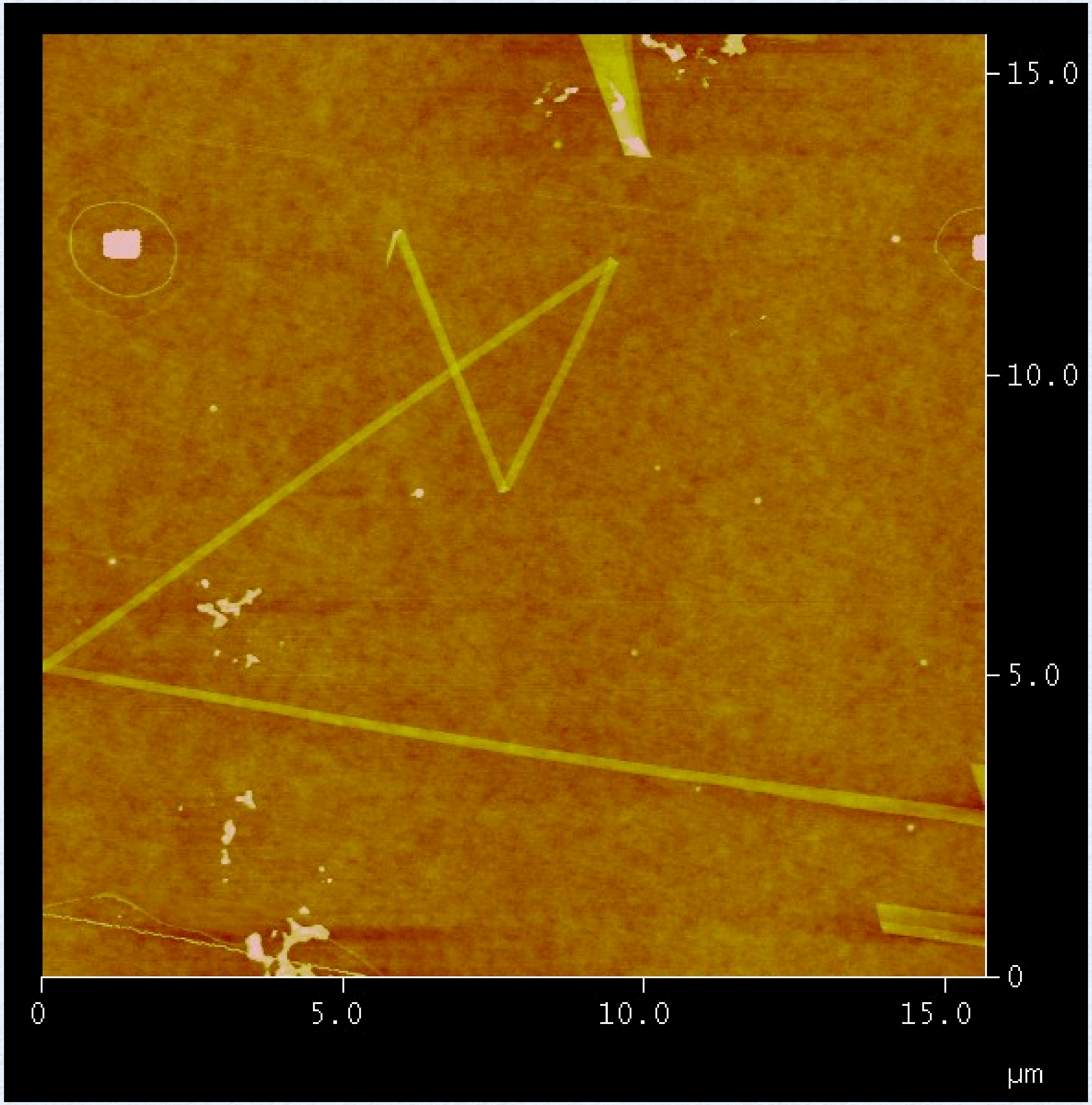
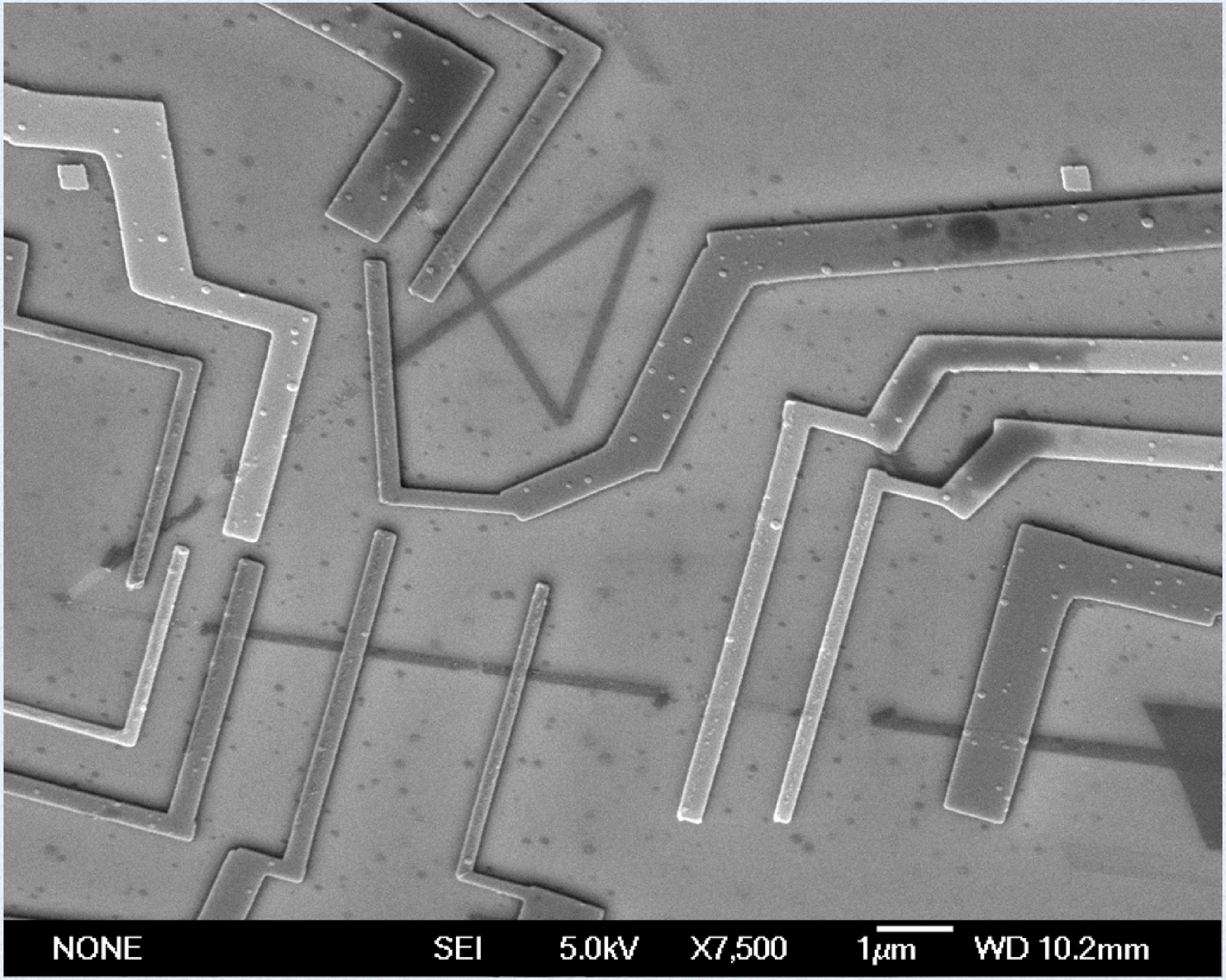


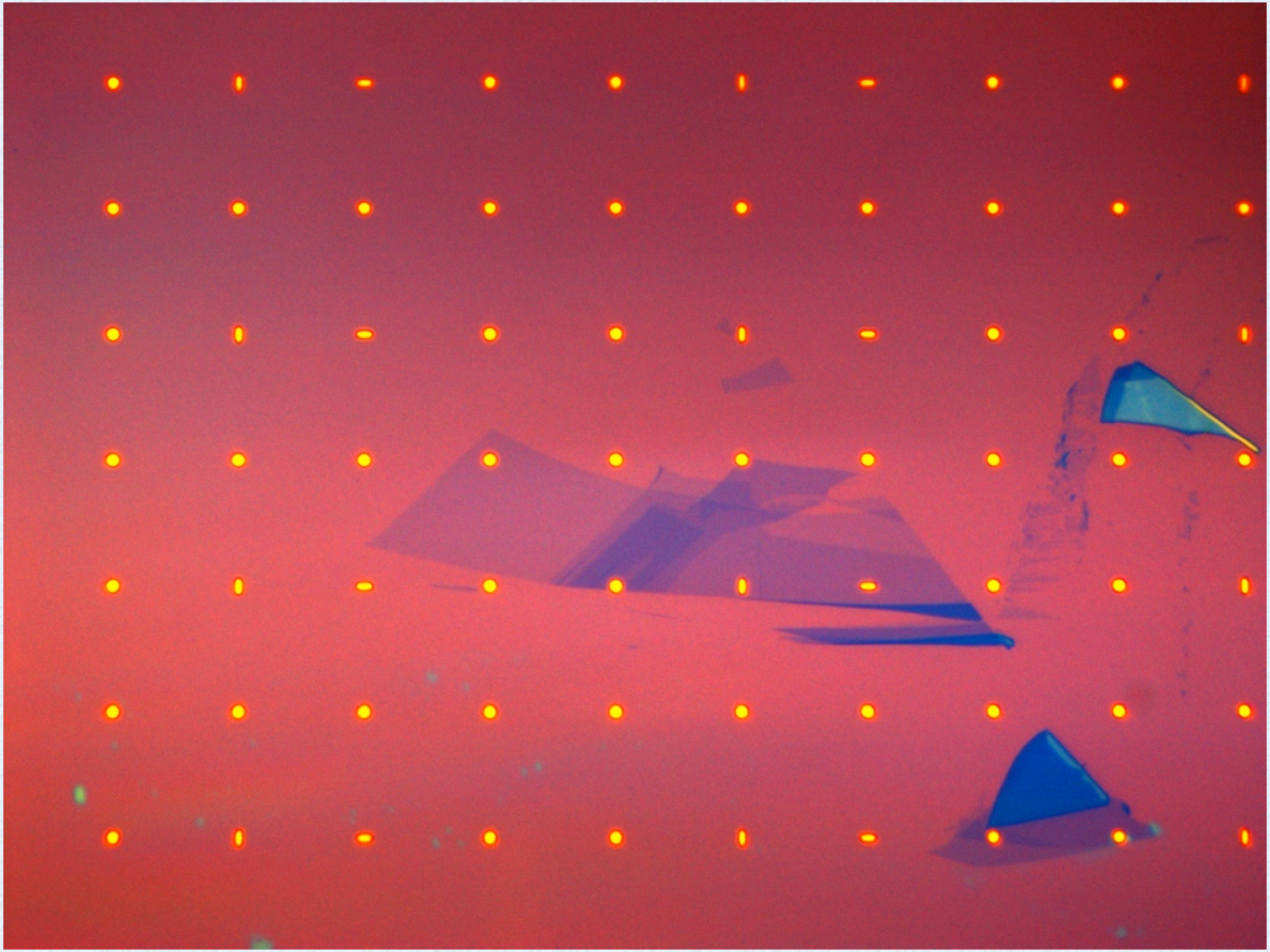
before...

Same sample, SEM image

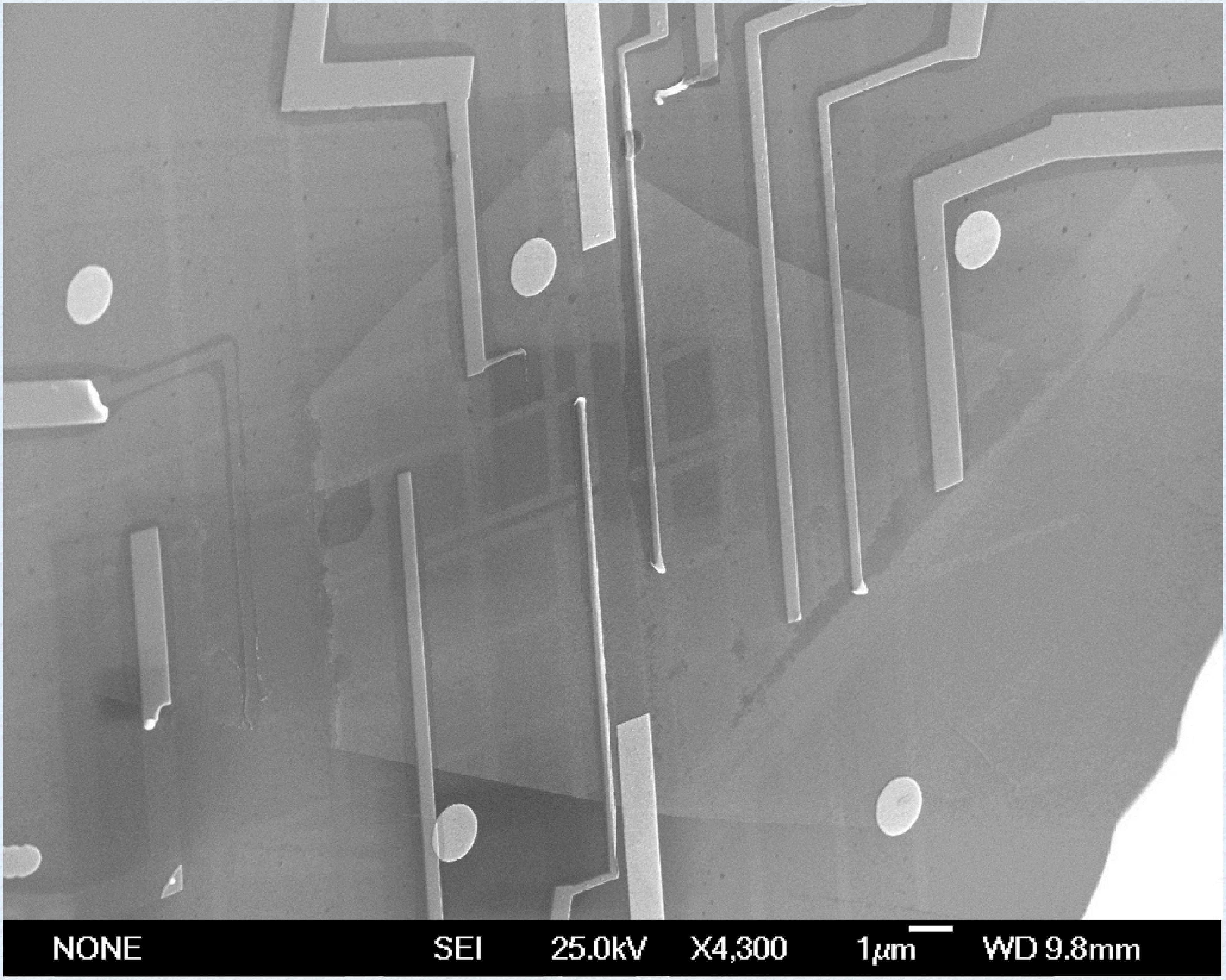


...and after

Kish samples, optical imaging

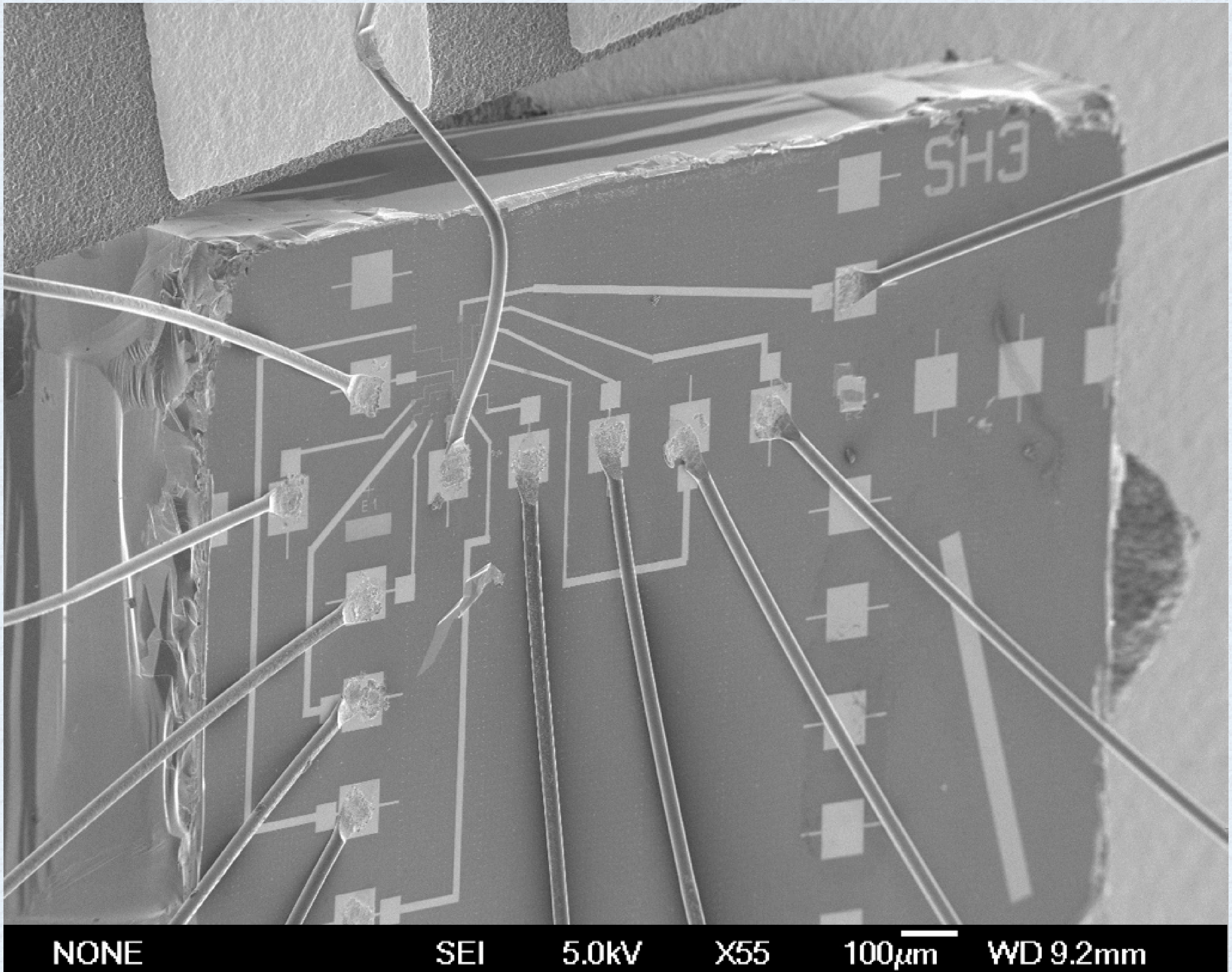


Same sample, SEM imaging

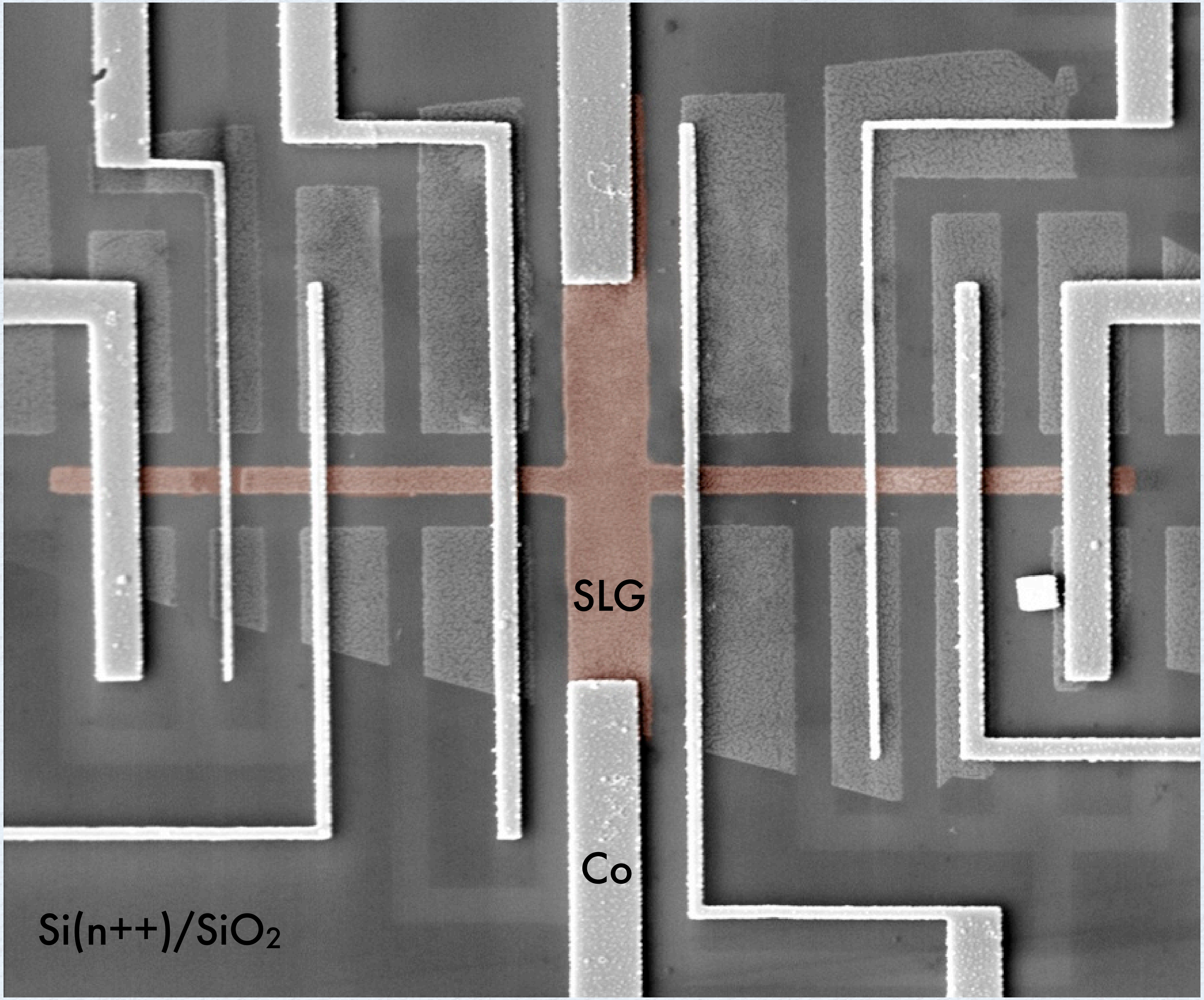


tilted

Sample overview, SEM imaging

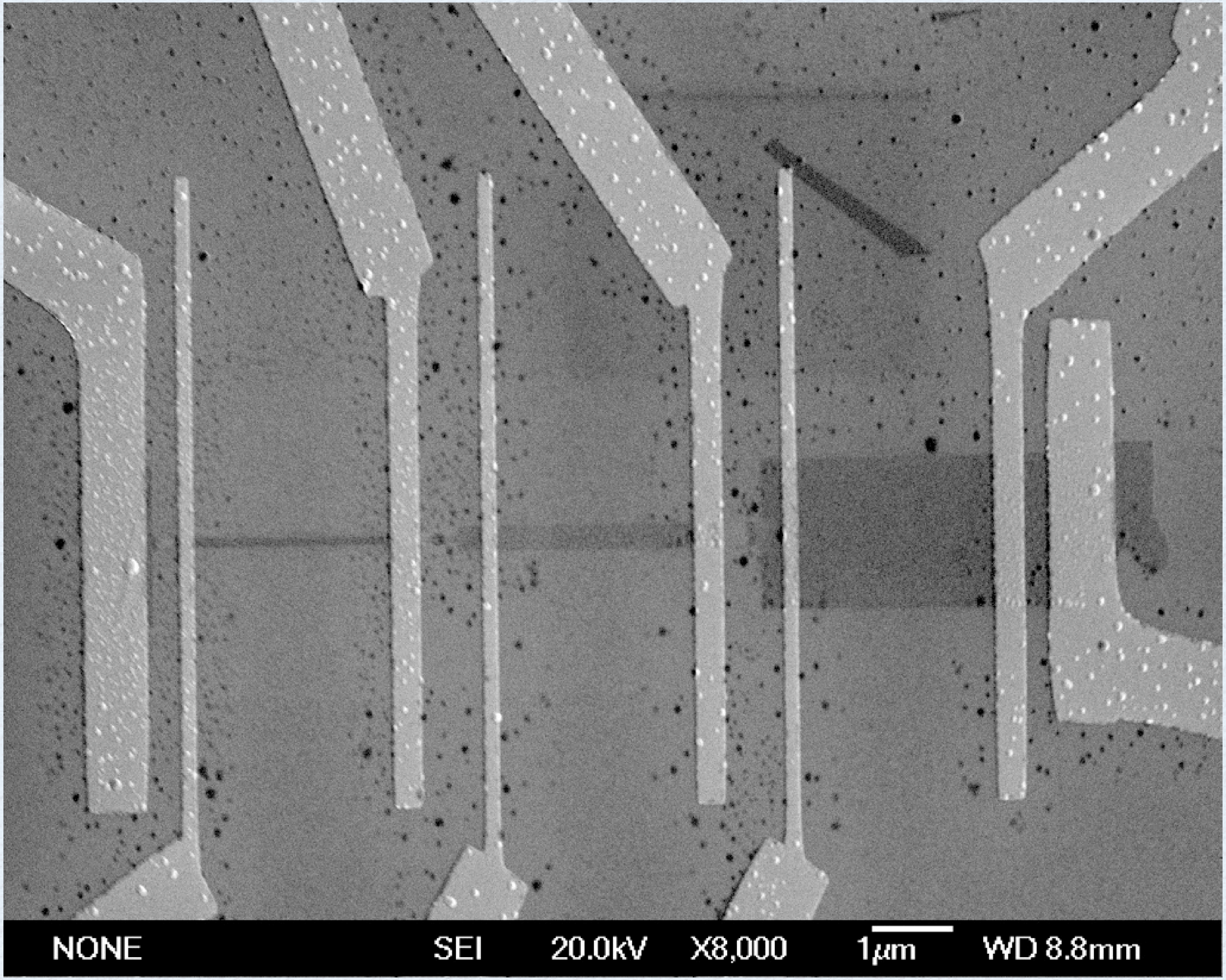


Shape control: plasma etching



artificially coloured SEM image

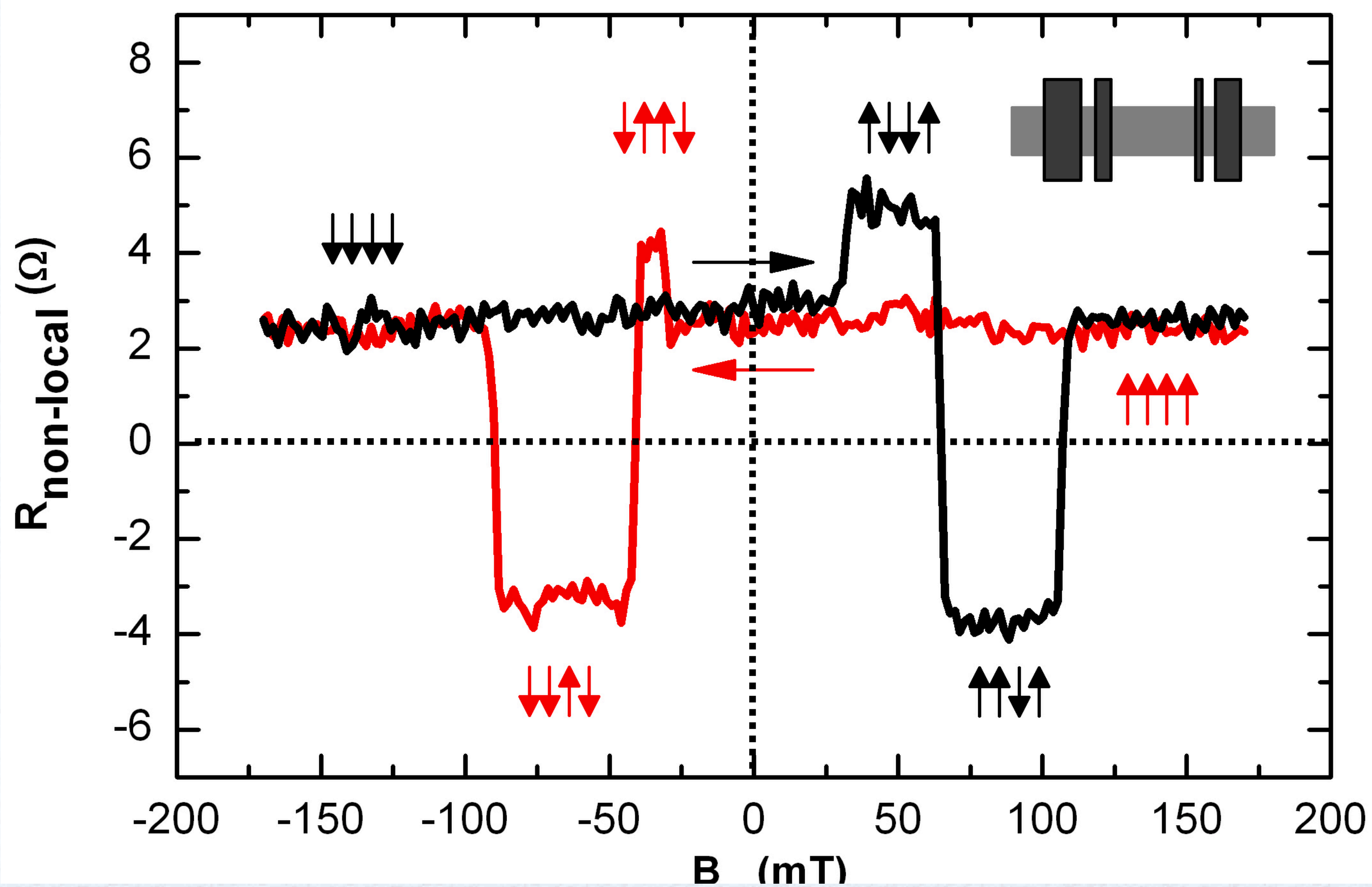
Width control: plasma etching



dirty, but it works

Spin Valve and Spin Precession

4-Terminal Spin Valve Measurement

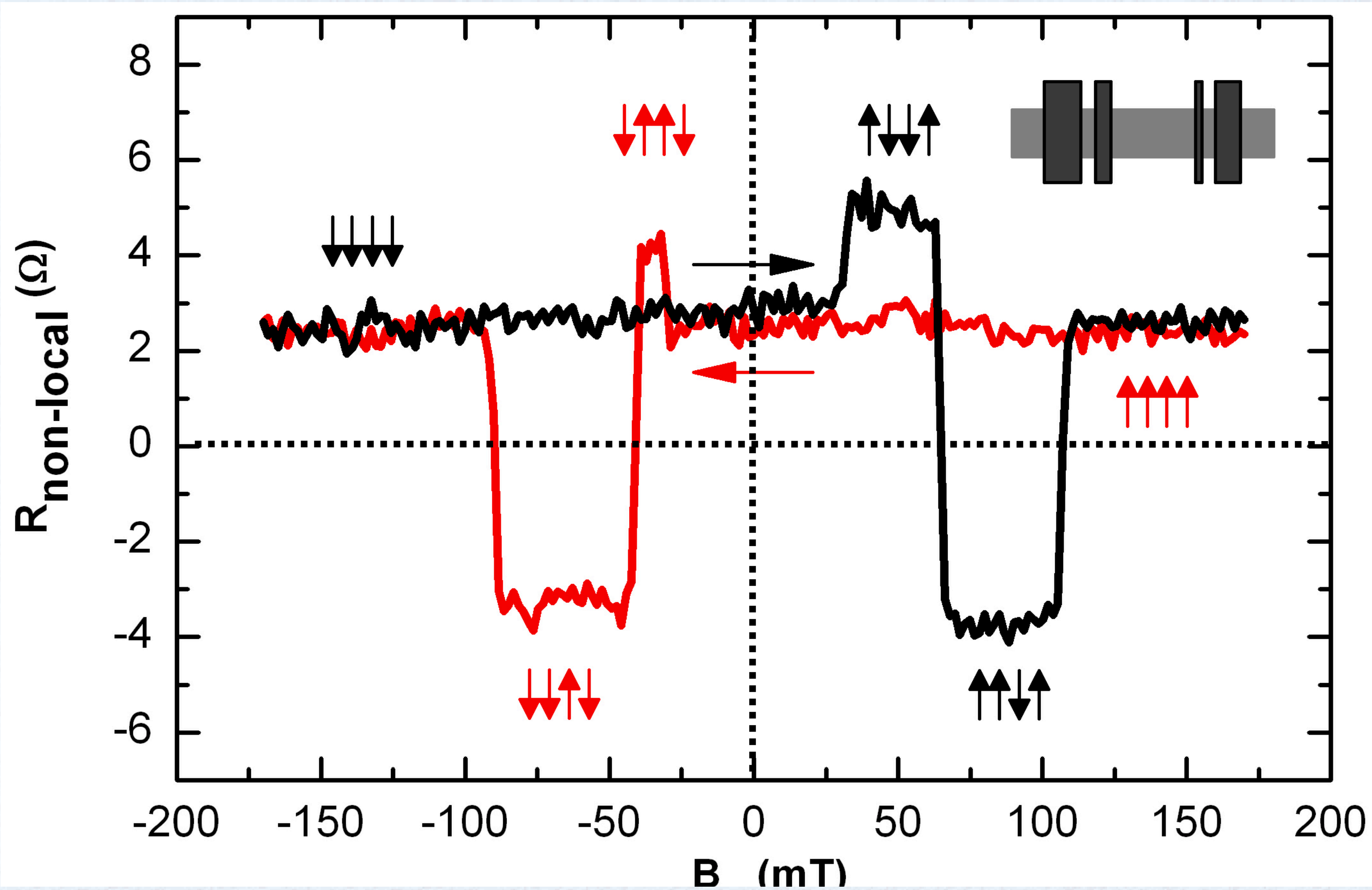


N. Tombros, C.J. et al., Nature ***448****, 571-574 (2007)*

Determining spin transport parameters: length dependence?

$$R_{non-local} = \pm \frac{P^2 \lambda_{sf}}{2W\sigma} \exp(-L/\lambda_{sf})$$

4-terminal spin valve measurement



- diffusion over 6µm
- sign reversal
- low noise
- T = 300K !
- old measurement!

N. Tombros, C.J. et al., Nature ***448****, 571-574 (2007)*

Determining spin transport parameters: length dependence?

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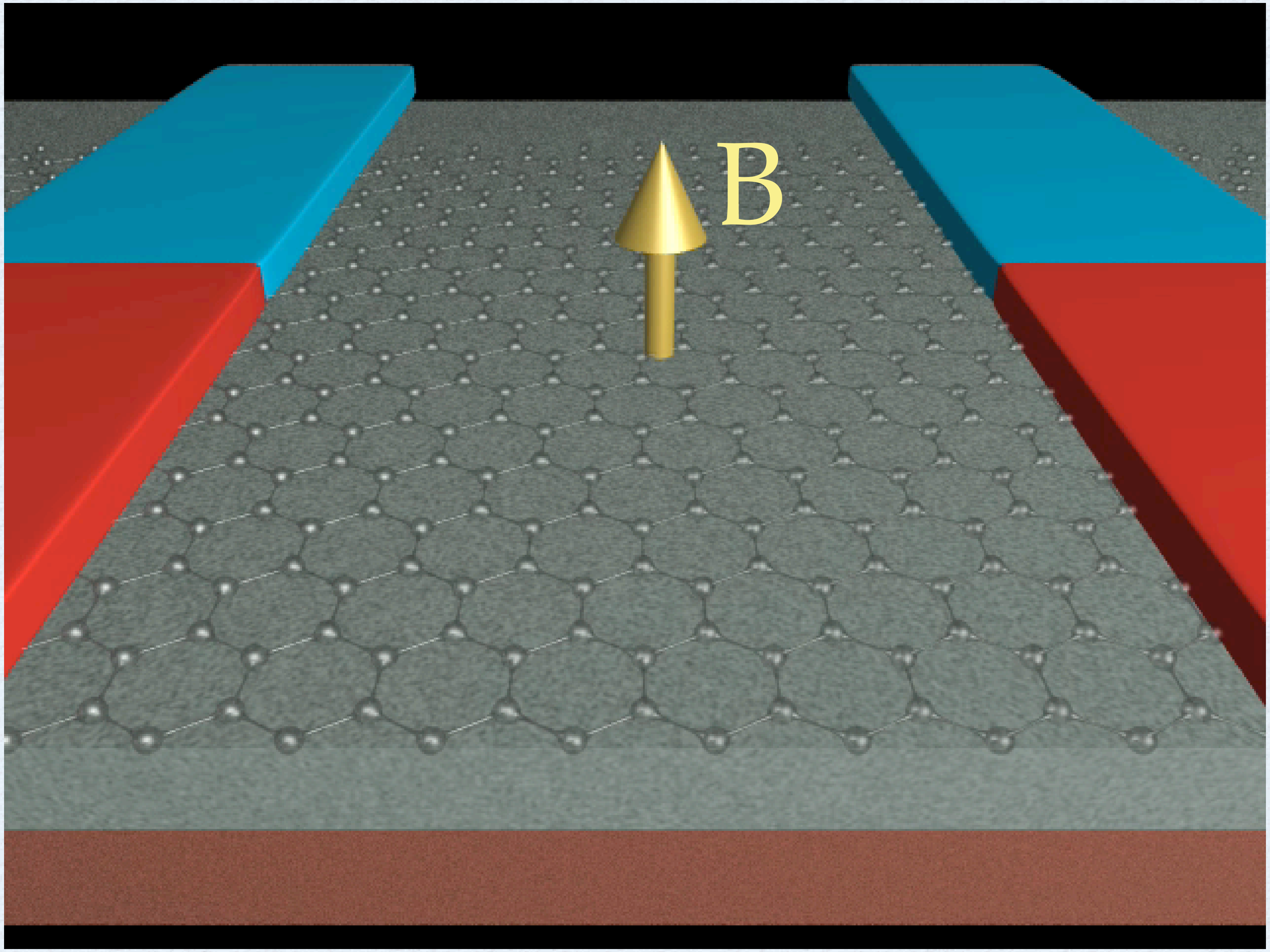
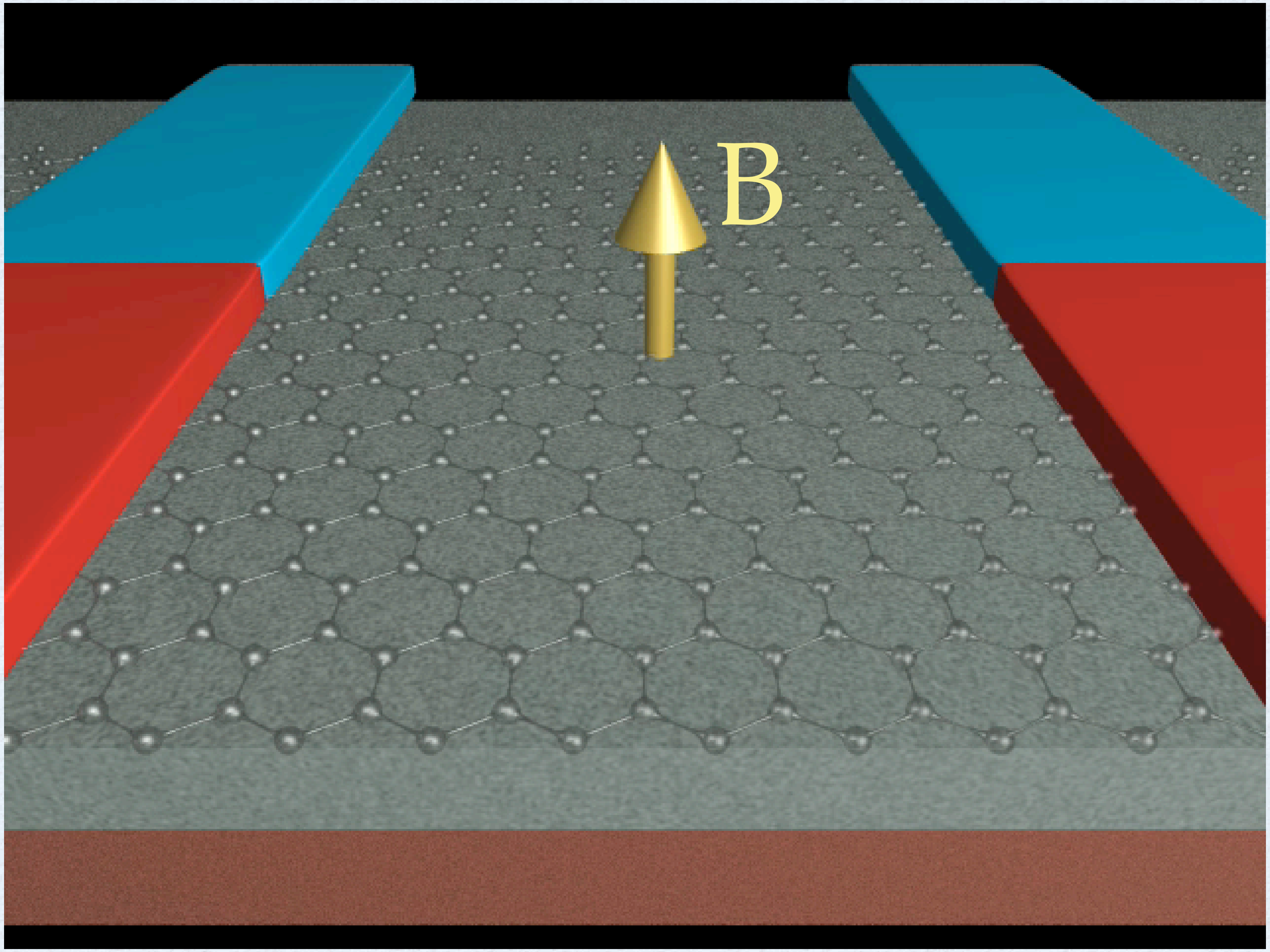
Hanle Precession



spin precession under external magnetic field

Hanle precession

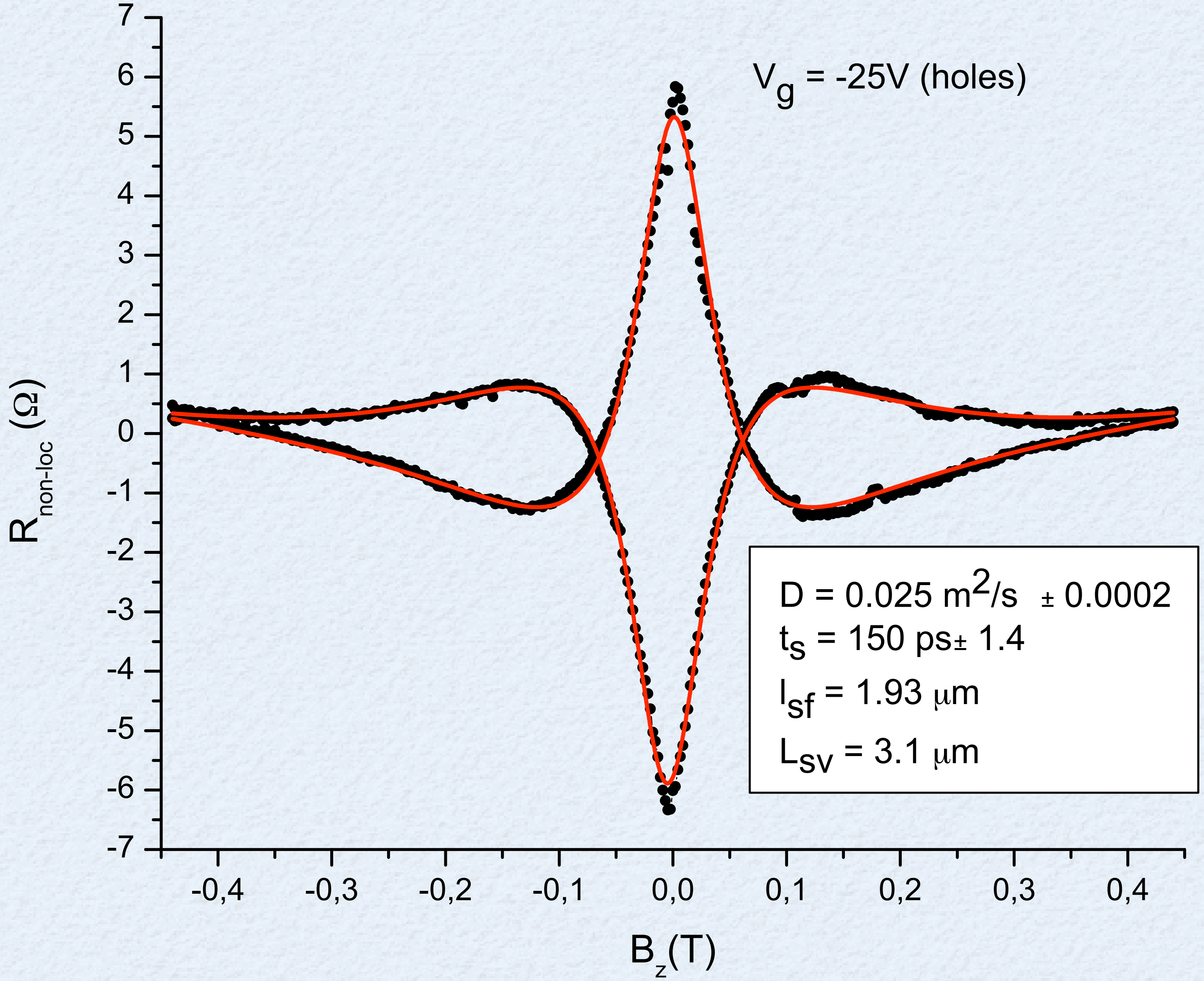


spin precession under external magnetic field

spin signal depends on:

- B strength
- SV length
- spin flip time
- diffusion const
- spin injection

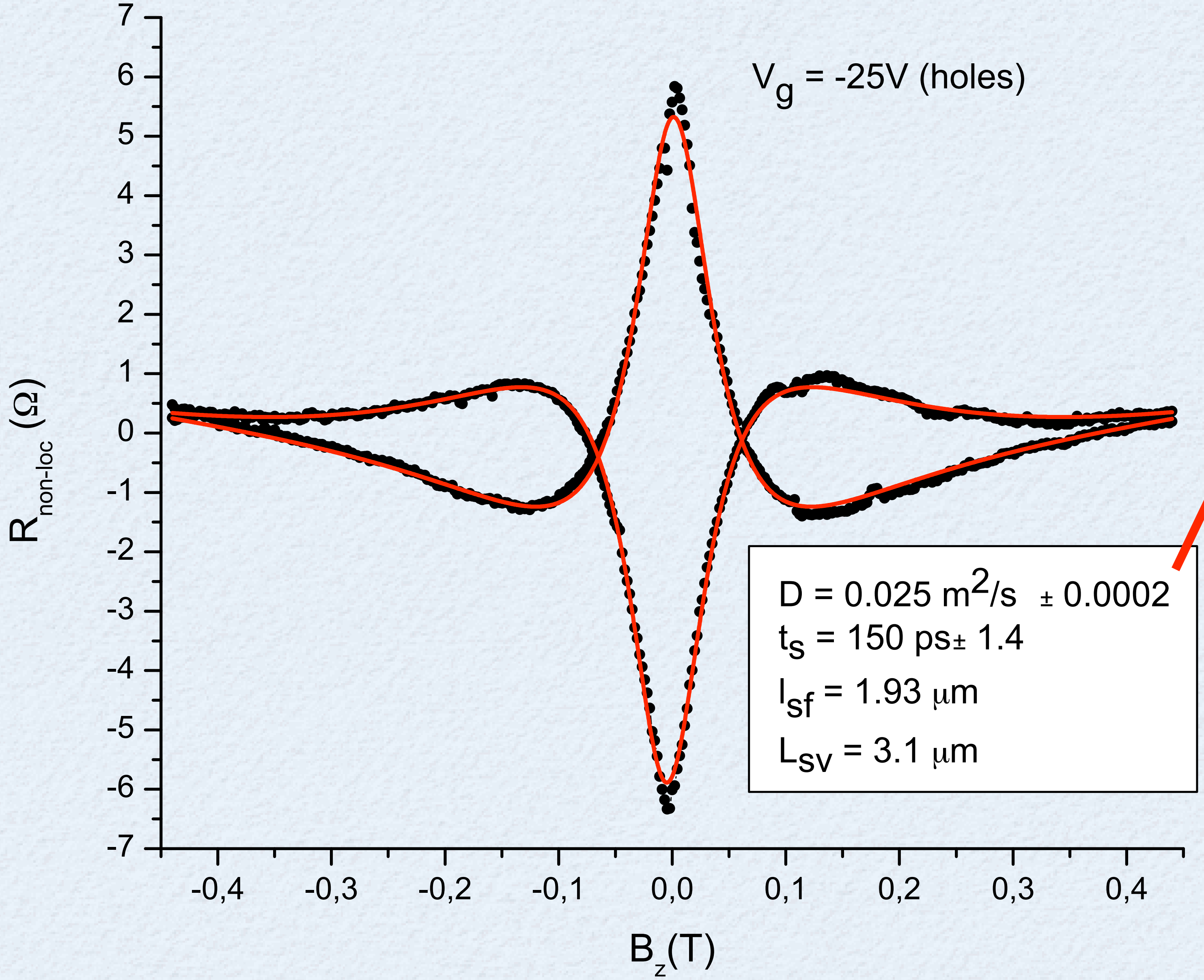
Hanle Precession



Bloch equation for spin accumulation:

$$\frac{\partial \vec{\mu}}{\partial t} = D \nabla^2 \vec{\mu} - \frac{\vec{\mu}}{\tau} + \left(\frac{g\mu_B}{\hbar} \vec{B} \times \vec{\mu} \right)$$

Hanle Precession



Charge diffusion constant:
D= ½ v_F l ≈ 2.5x10^{-2}
- similar to Dspin

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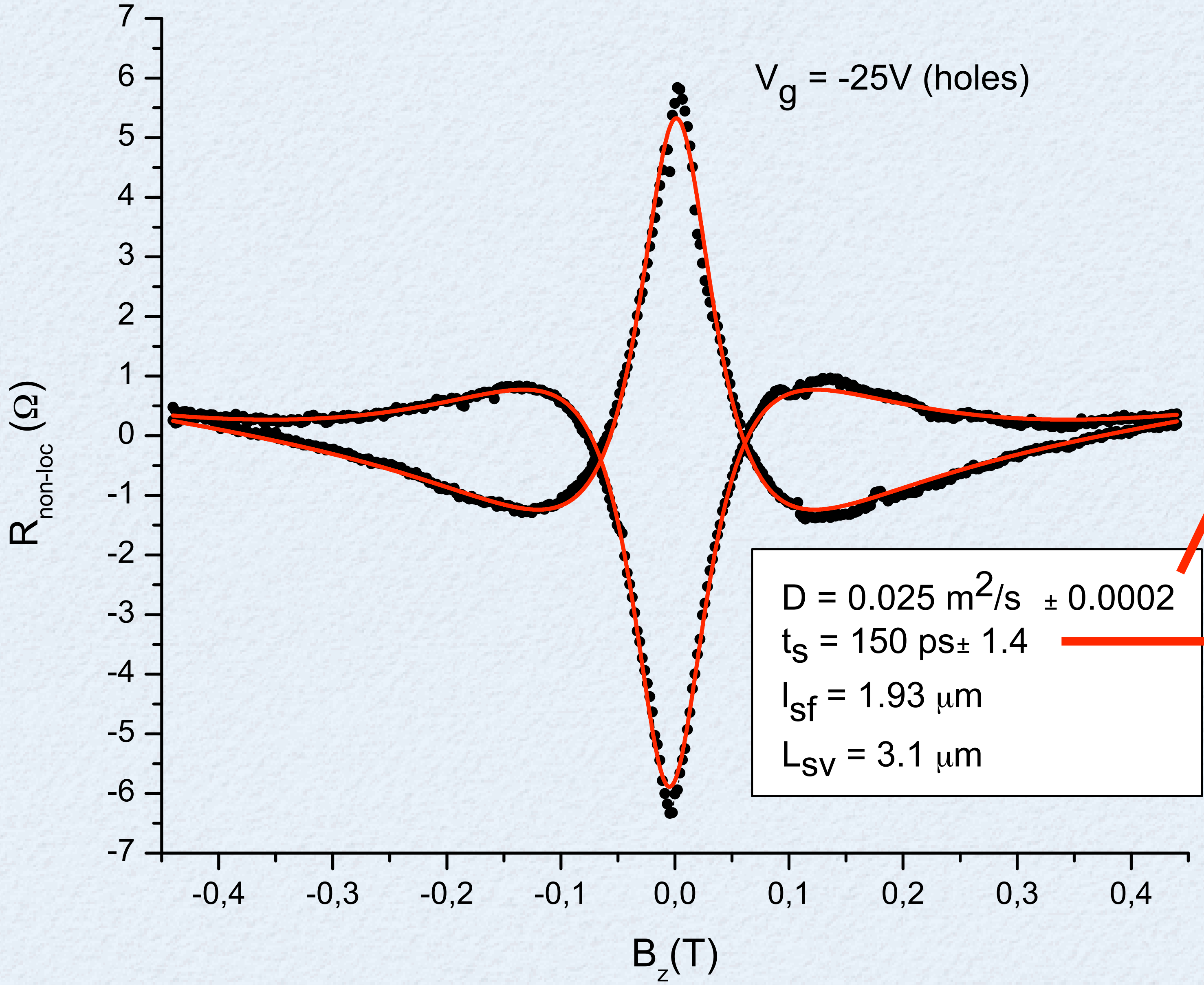
Hanle Precession



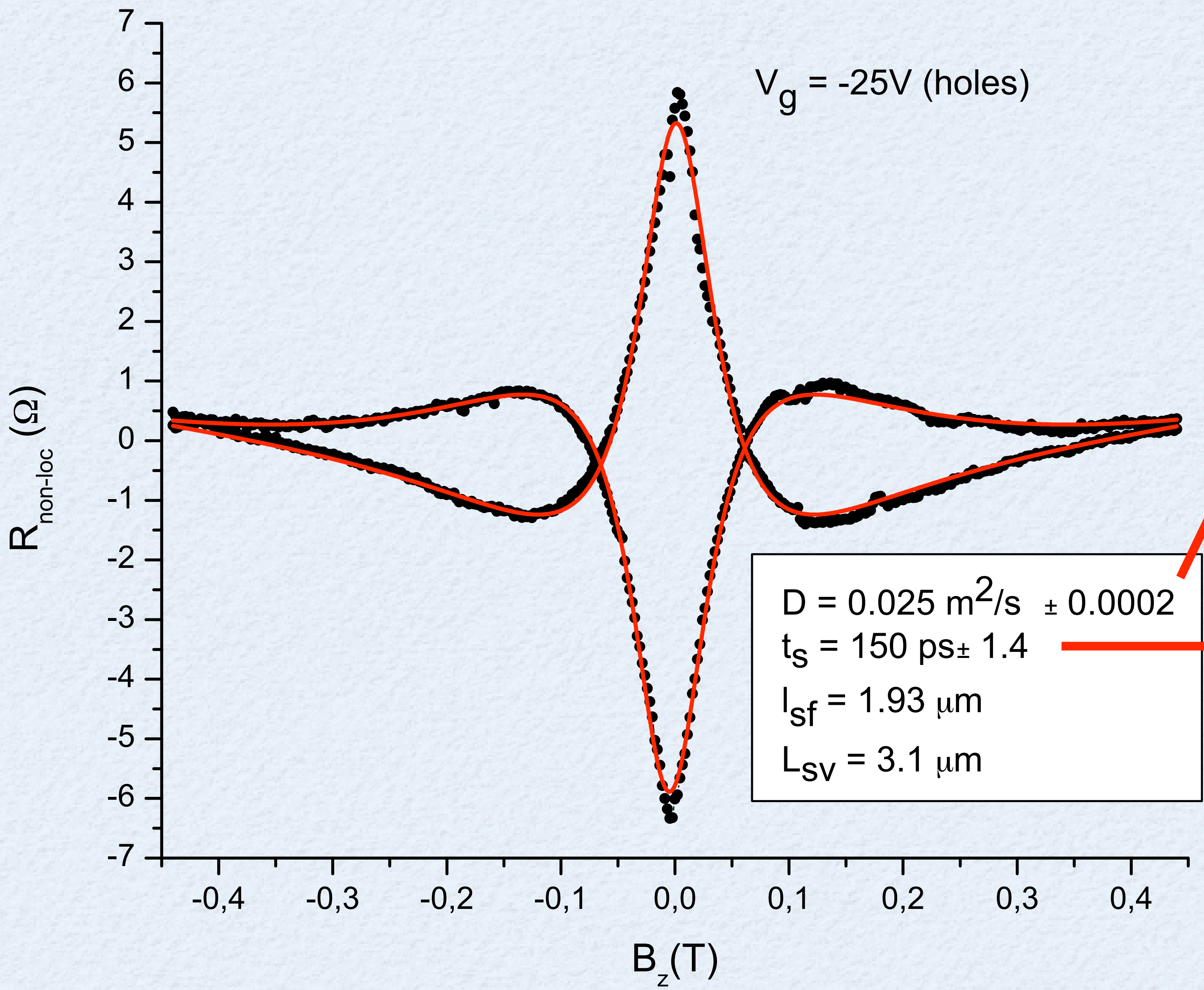
Charge diffusion constant:
D= ½ v_F l ≈ 2.5x10^{-2}
- similar to Dspin

Relaxation:
100x faster than expected

Bloch equation for spin accumulation:

$$\frac{\partial \vec{\mu}}{\partial t} = D\,\nabla^2 \vec{\mu} - \frac{\vec{\mu}}{\tau} + \left(\frac{g\mu_B}{\hbar}\, \vec{B} \times \vec{\mu} \right)$$

Hanle precession



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- similar to Dspin

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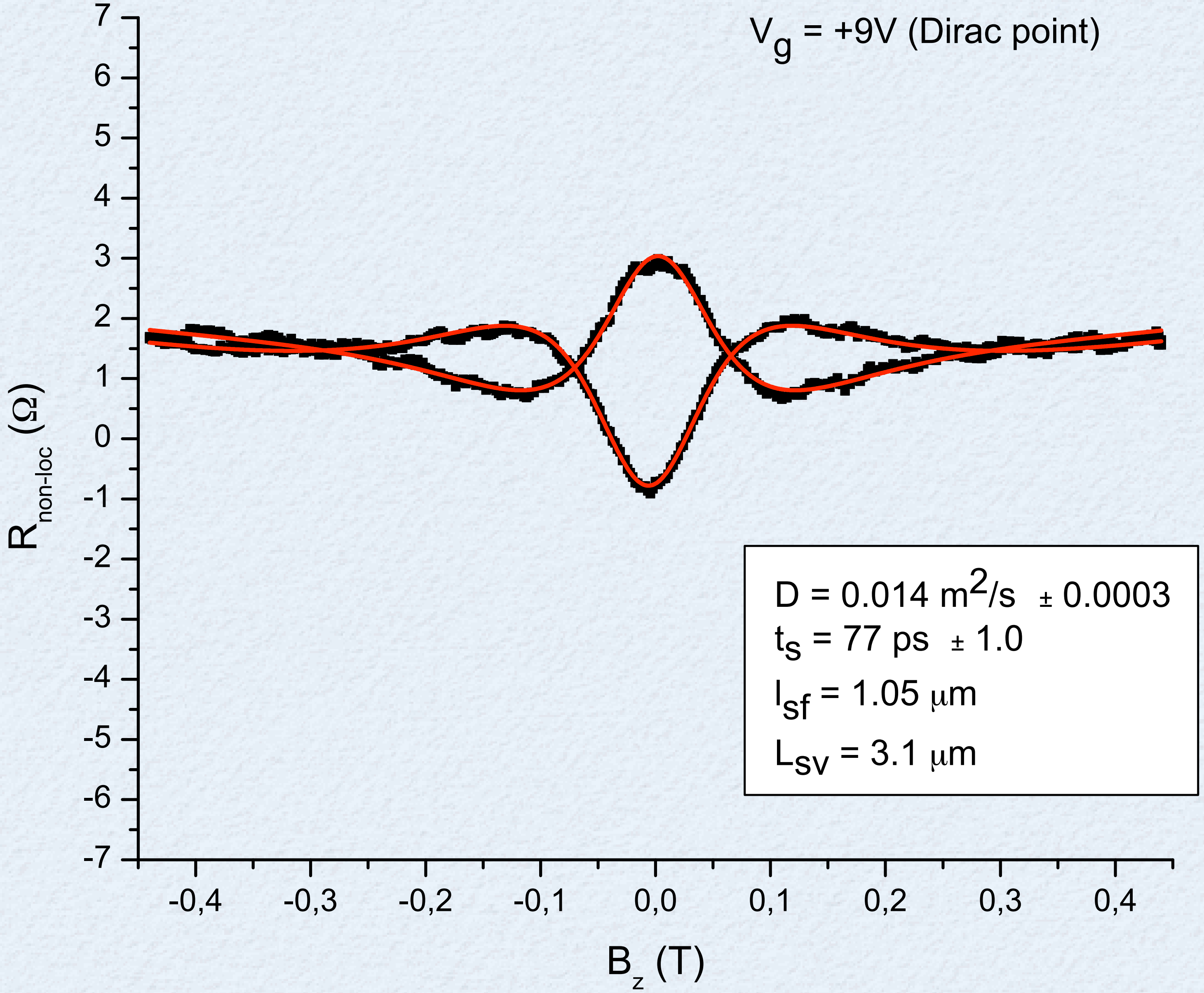
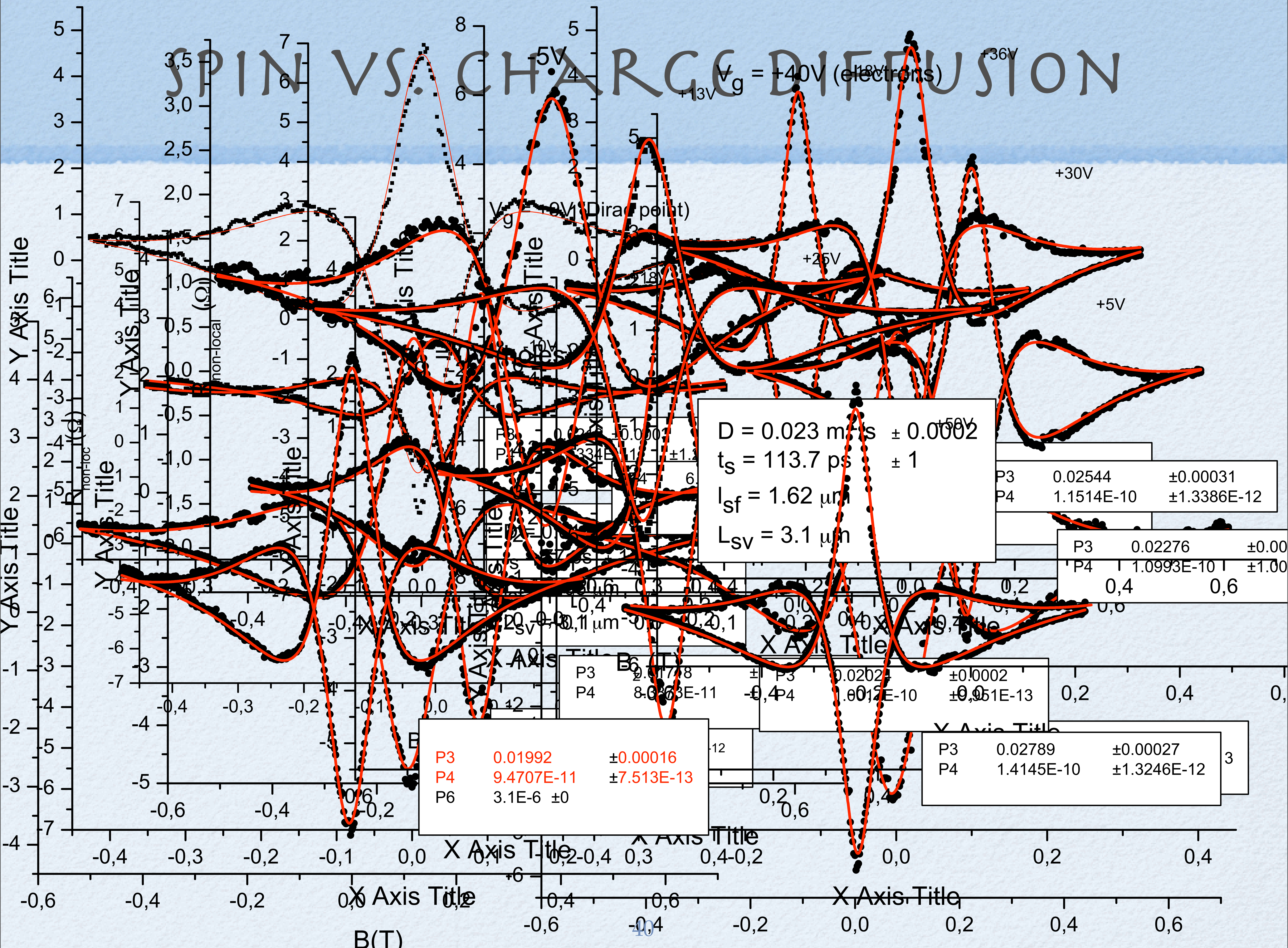
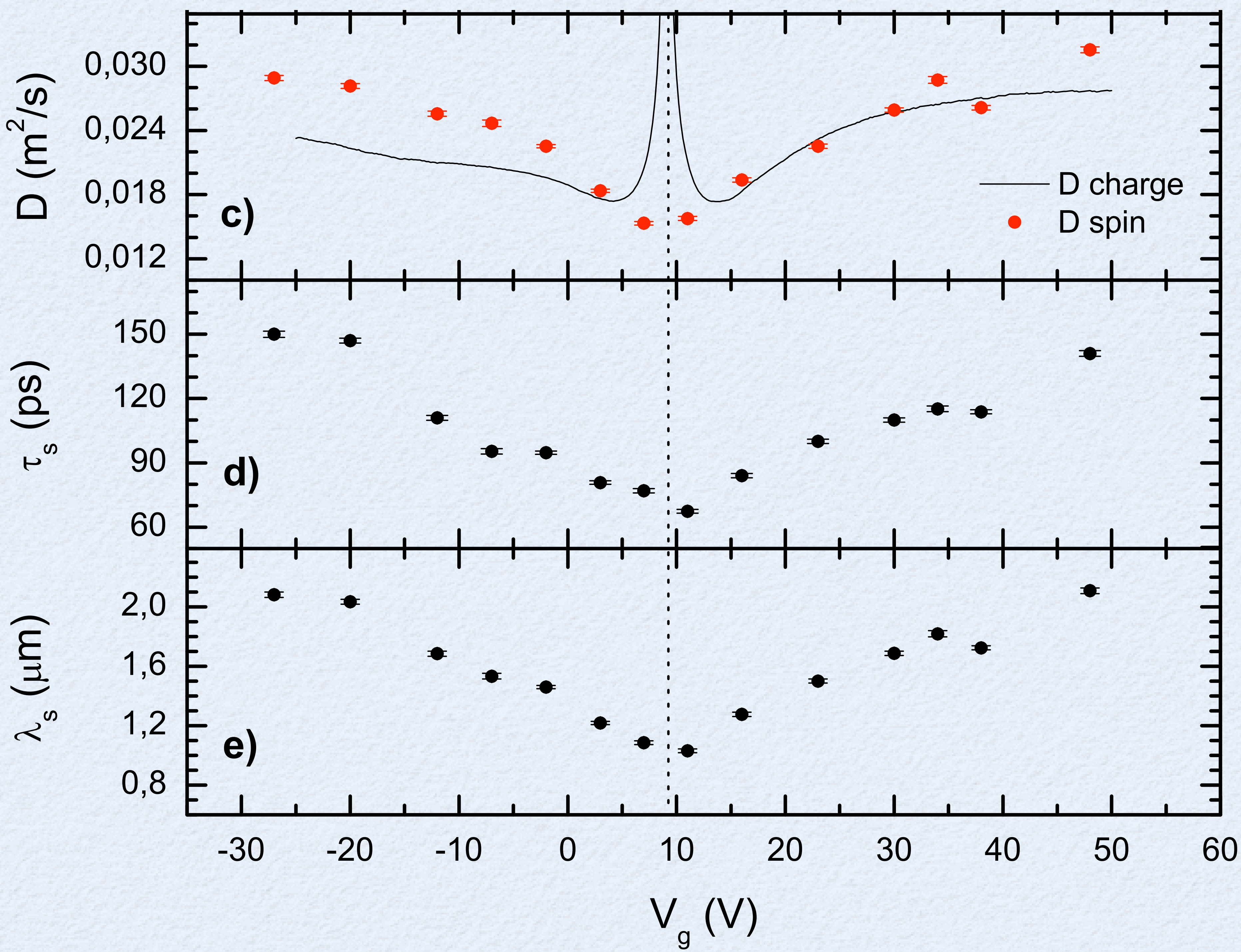
Spin vs. Charge Diffusion



Spin vs. Charge diffusion



Spin vs. Charge diffusion*



spin and charge: similar diffusion

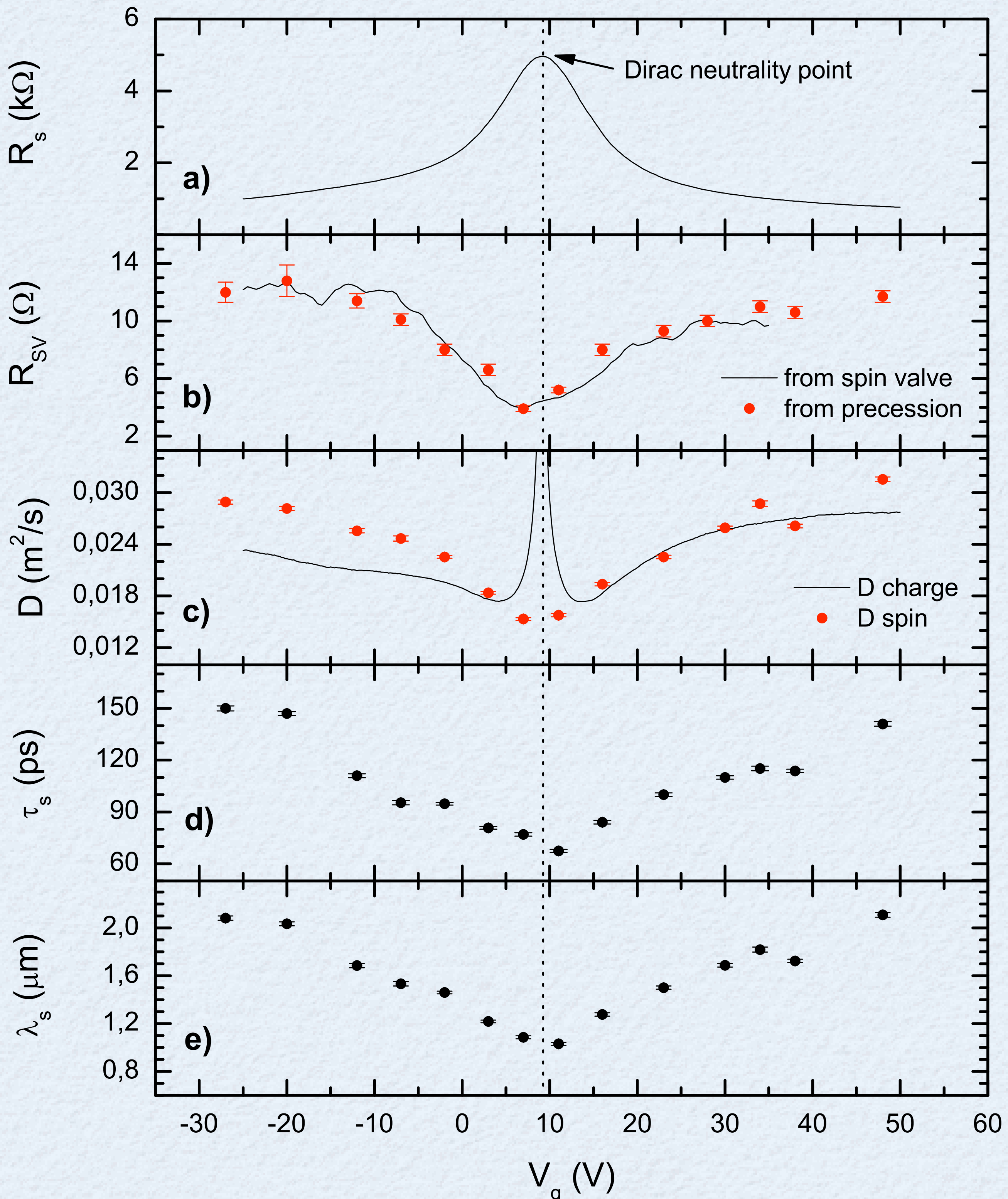
no spin Coulomb drag

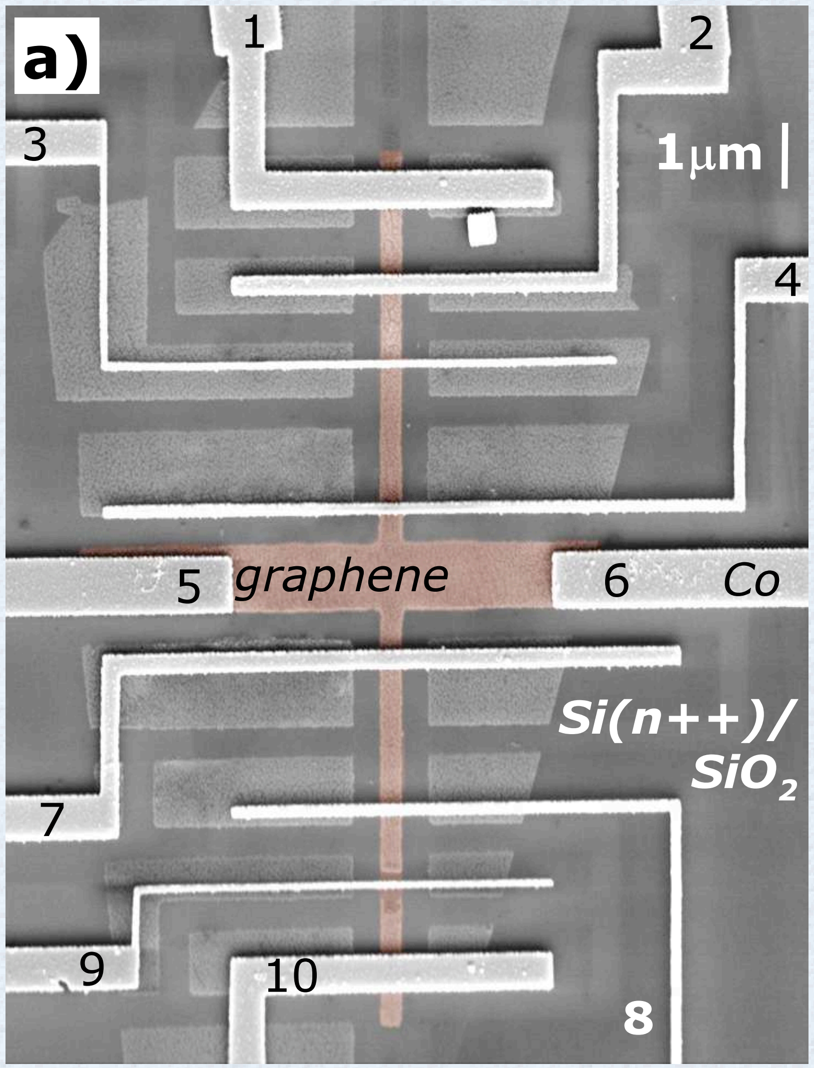
-> e-e interactions too weak!

D, **τ,** λ: the same trend vs. Vg

**C. Józsa, T. Maassen et al., in preparation*

Spin vs. charge diffusion*





D, **τ**, λ: the same trend vs. Vg

*C. Józsa, T. Maassen et al., in preparation

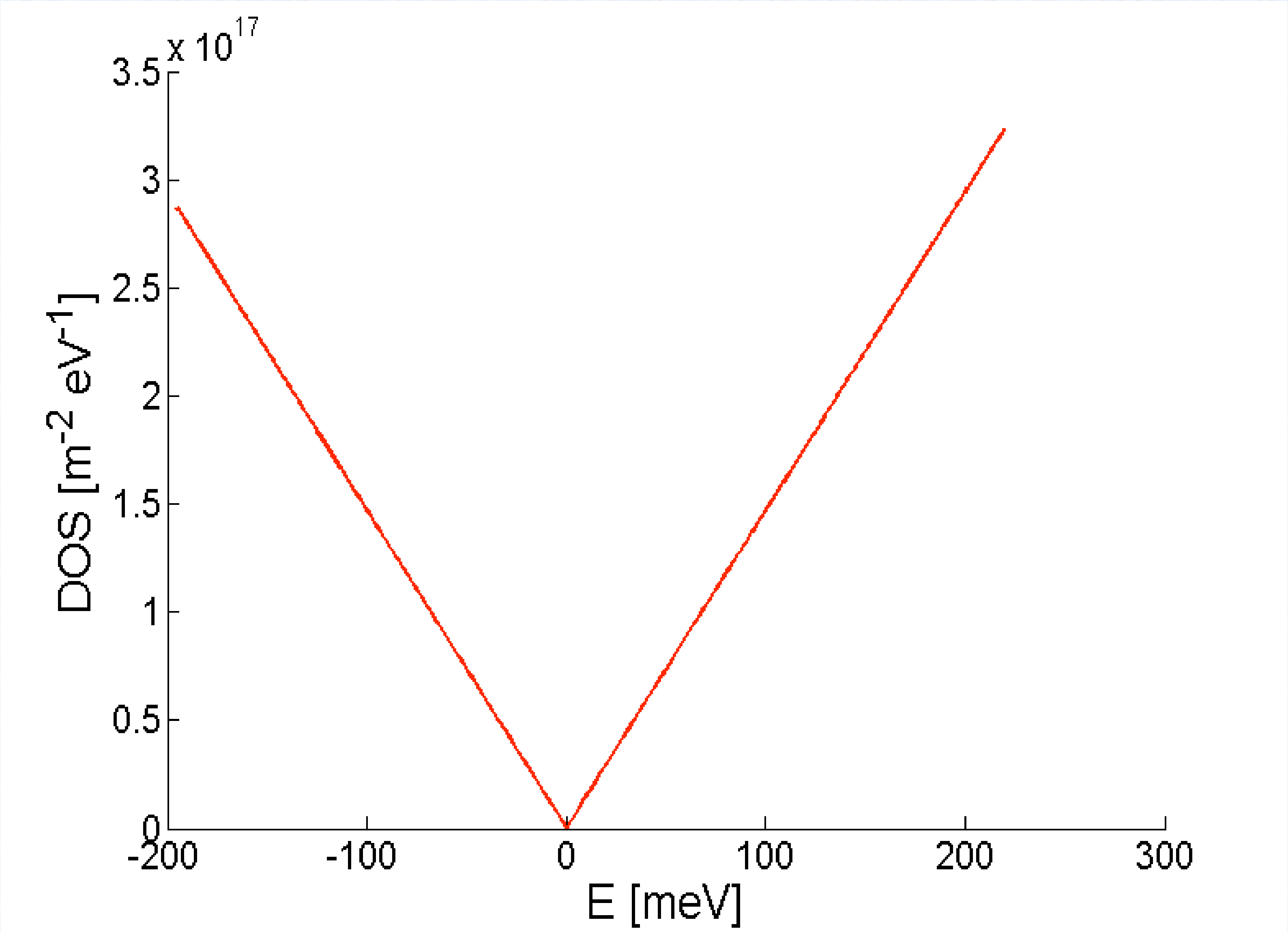
Spin vs. charge diffusion

$$D = \frac{1}{e^2 \nu(E_F)\, R_{square}(V_g)}$$

$\nu(E_F)$: DOS at E_F

$R_{square}(V_g)$: resistivity

singularity at charge neutrality point!



Spin vs. Charge Diffusion

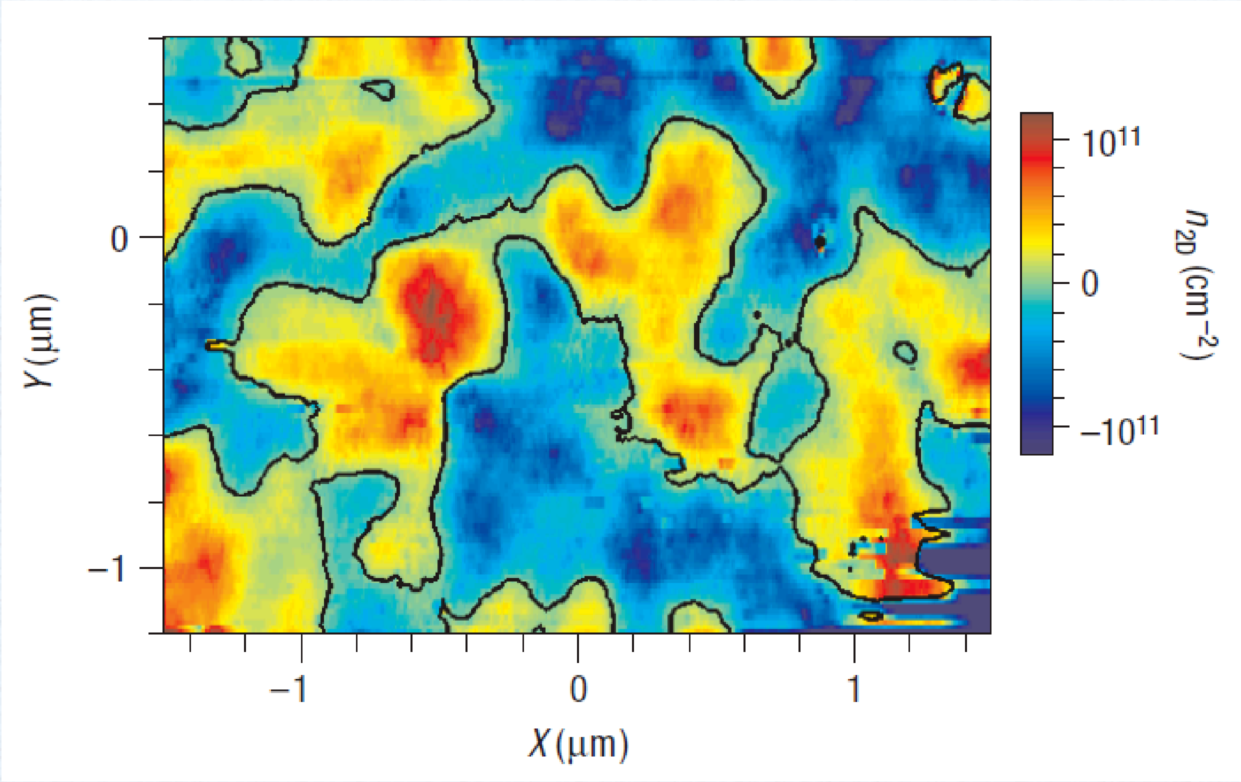
In reality, DOS broadened:

- temperature (300K)
- e-h puddles
- scattering

use Gaussian broadening σ

$$q(E) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\infty} d\epsilon \; e^{-\frac{(\epsilon - E)^2}{2\sigma^2}} \, \nu(\epsilon)$$

electron-hole puddles at the charge neutrality point



J. Martin et al. Nature Physics 2008
X. Du et al. Nature Nanotechnology 2008
Y.W. Tan et al. Phys. Rev. Lett. 2007

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an ignorant experimentalist, i know...

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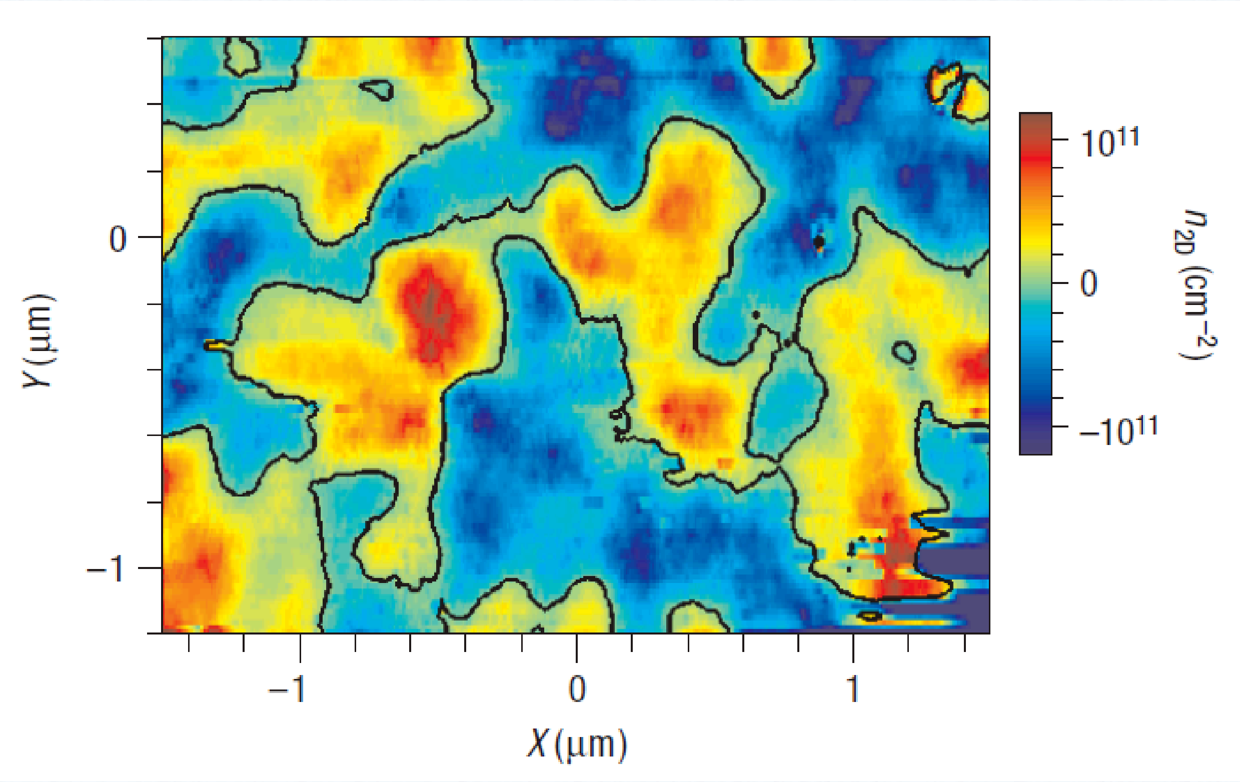

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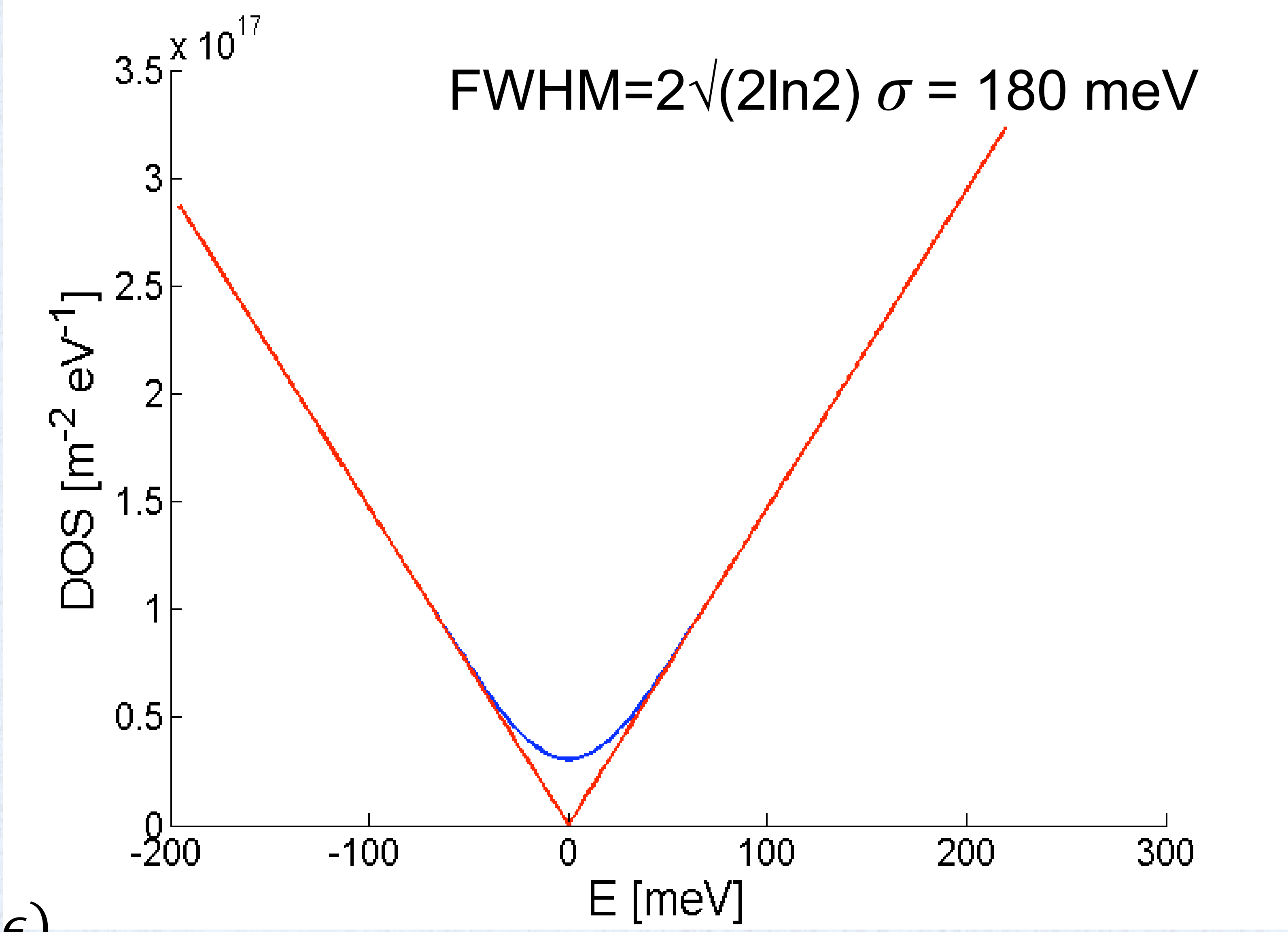


Spin vs. Charge Diffusion

$$q(E) = \frac{4g_s g_v\sqrt{\pi}}{\left(hv_f\right)^2}\left\{\frac{\sigma}{\sqrt{2}}e^{-\frac{E^2}{2\sigma^2}} \quad + \quad \frac{\sqrt{\pi}}{2}E\, erf\left(\frac{E}{\sqrt{2}\sigma}\right)\right\}$$

broadened DOS

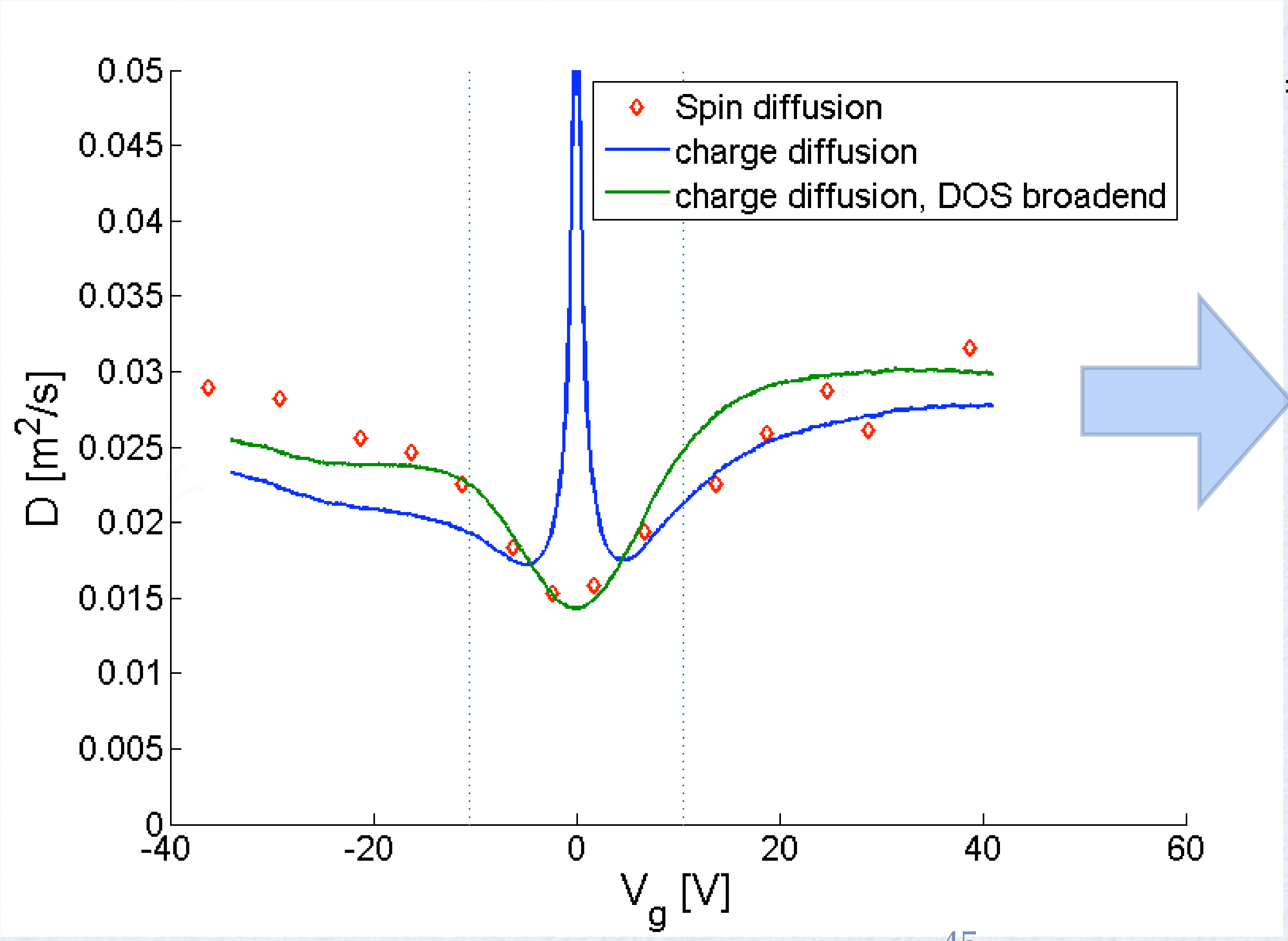
$$\lim_{\sigma\to 0} q(E) = \lim_{\sigma\to 0}\left[\frac{4g_s g_v\sqrt{\pi}}{\left(hv_f\right)^2}\left\{\frac{\sigma}{\sqrt{2}}e^{-\frac{E^2}{2\sigma^2}} \quad + \quad \frac{\sqrt{\pi}}{2}E\, erf\left(\frac{E}{\sqrt{2}\sigma}\right)\right\}\right] = \frac{2g_s g_v \pi E}{\left(hv_f\right)^2}$$

unbroadened

Spin vs. Charge Diffusion

$$q(E) = \frac{4 g_s g_v \sqrt{\pi}}{(h v_f)^2} \left\{ \frac{\sigma}{\sqrt{2}} e^{-\frac{E^2}{2\sigma^2}} + \frac{\sqrt{\pi}}{2} E \, erf\left(\frac{E}{\sqrt{2}\sigma}\right) \right\}$$

broadened DOS



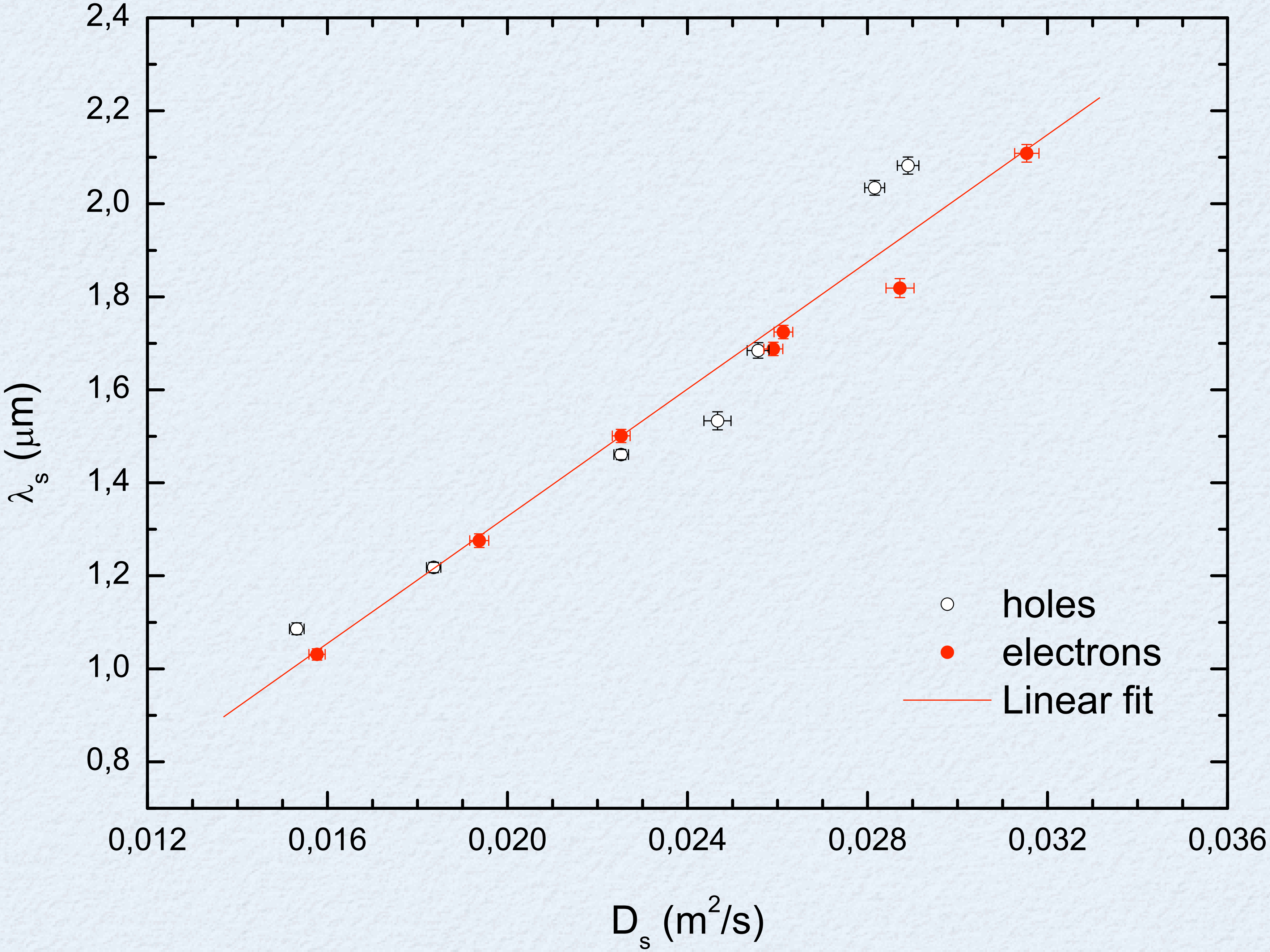
$$= \frac{2 g_s g_v \pi E}{(h v_f)^2}$$

unbroadened

very good agreement from 2 different approaches

no Coulomb drag!
relaxation:
on impurities

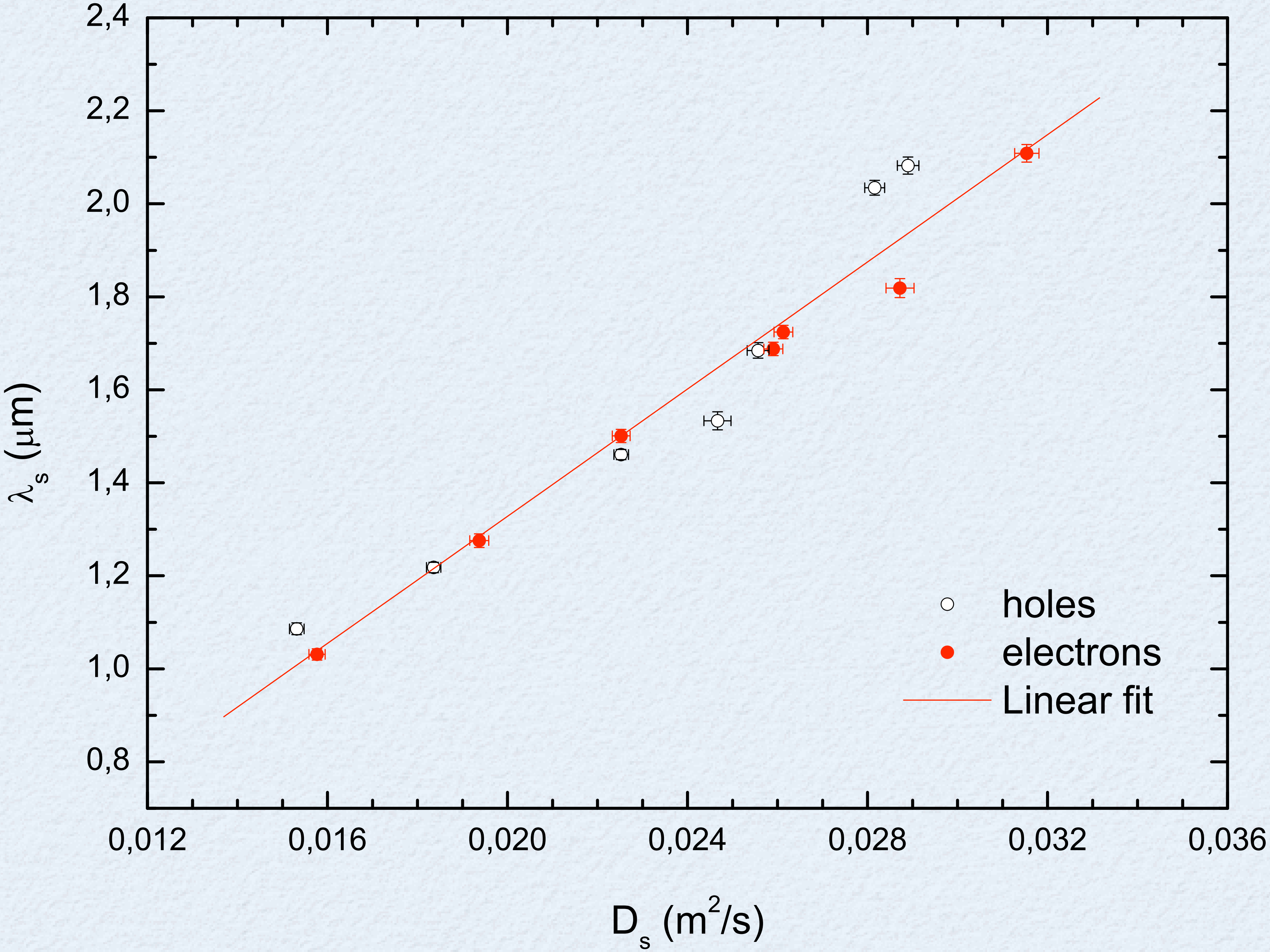
Diffusion length and mobility?*



linear scaling:
fingerprint of
Elliott-Yafet type
impurity scattering
$\lambda_s = \sqrt{D\tau_s}$
$D \sim \tau_d$

**C. Józsa, T. Maassen et al., in preparation*

Diffusion length and mobility?*



linear scaling:
fingerprint of
Elliott-Yafet type
impurity scattering
$\lambda_s = \sqrt{D\tau_s}$
$D \sim \tau_d$

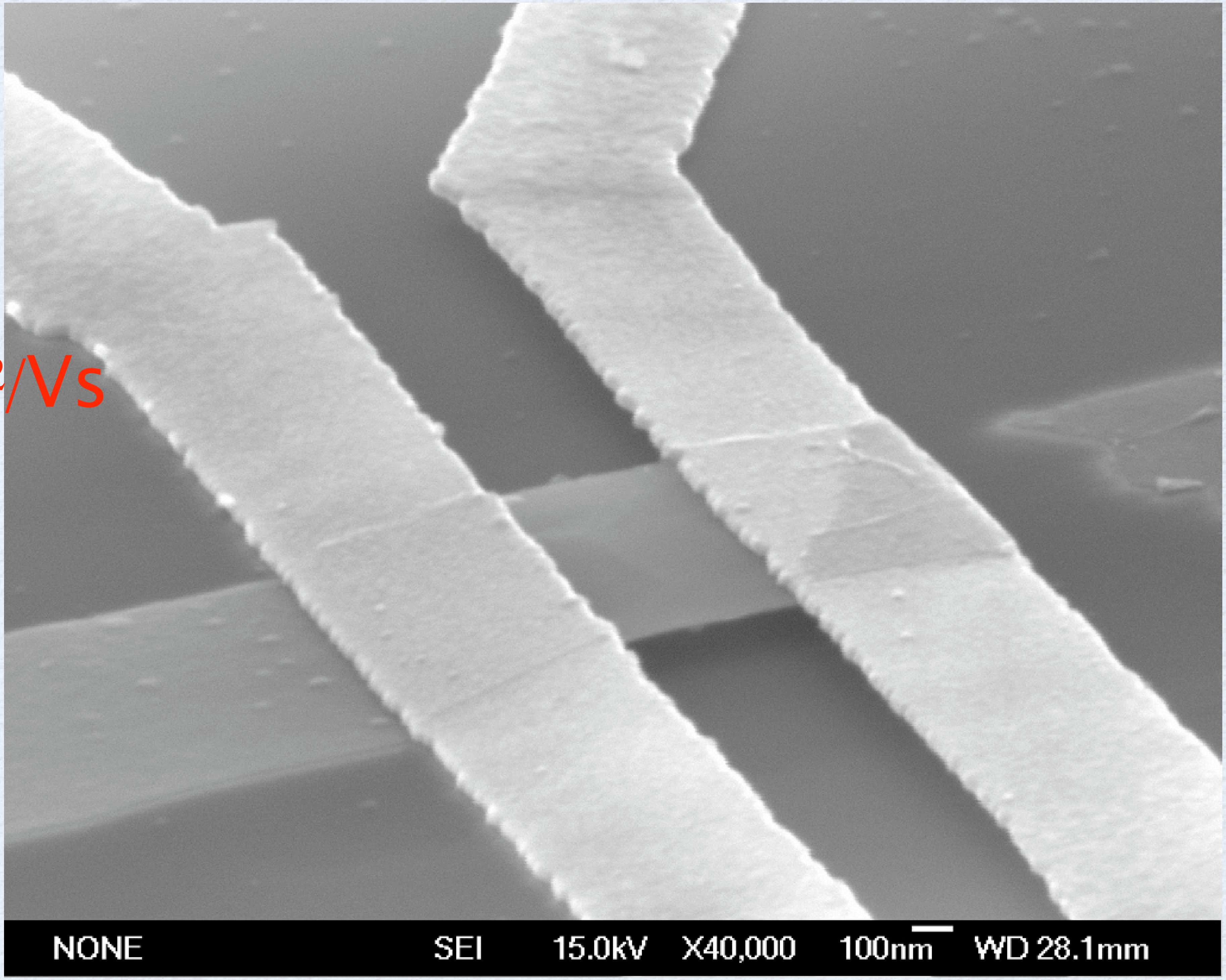
for higher mobilities:
λ_s -> 100 µm
at RT

**C. Józsa, T. Maassen et al., in preparation*

Diffusion length and mobility?

Our first suspended (multi)layer; A. Veligura *et al.*

Suspended graphene?



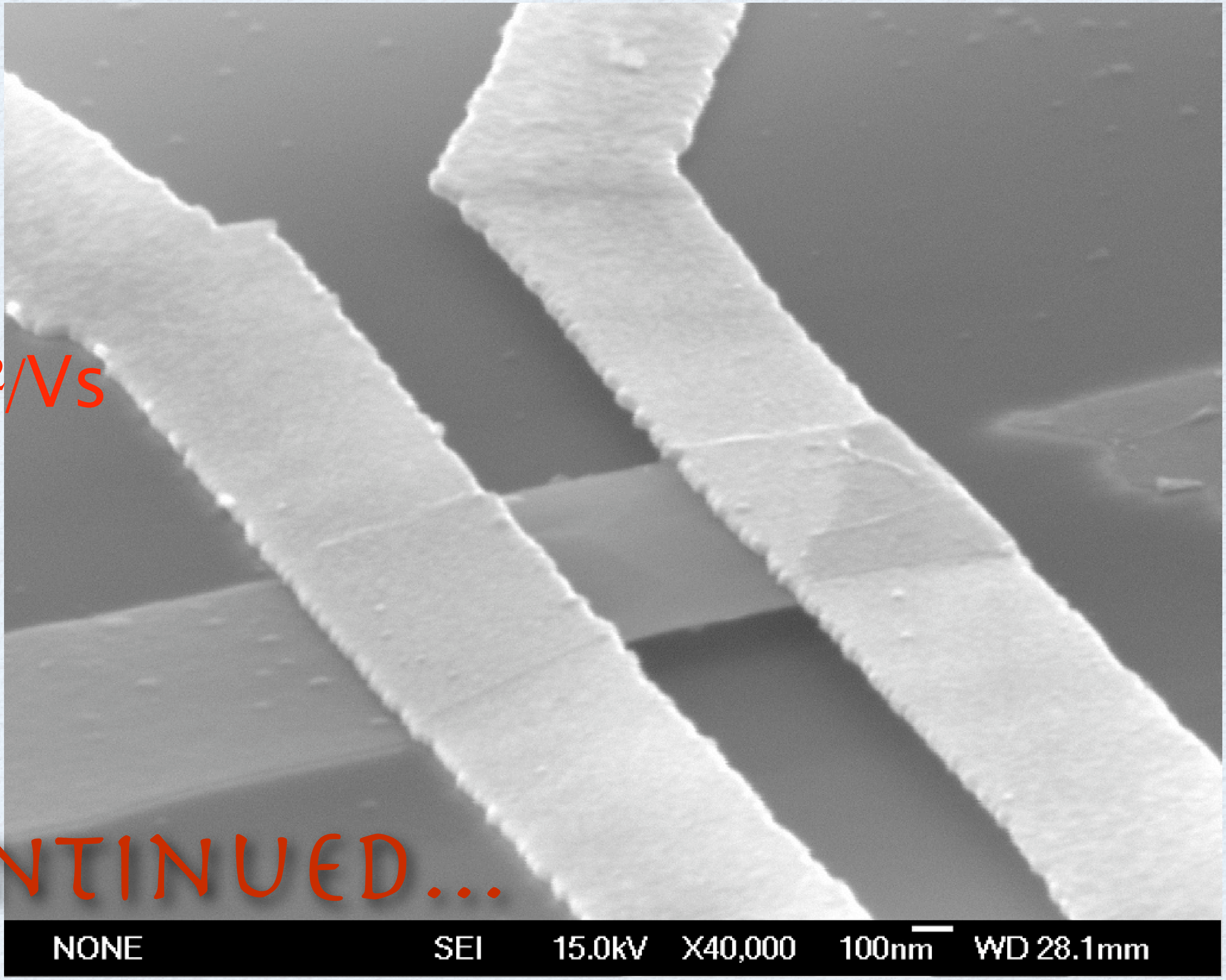
$\mu \approx$ 200 000 cm^2/Vs

as measured by K.I. Bolotin, P. Kim *et al.*

Does λ_s increase?

Diffusion length and mobility?

Our first suspended (multi)layer; A. Veligura *et al.*



Suspended graphene?

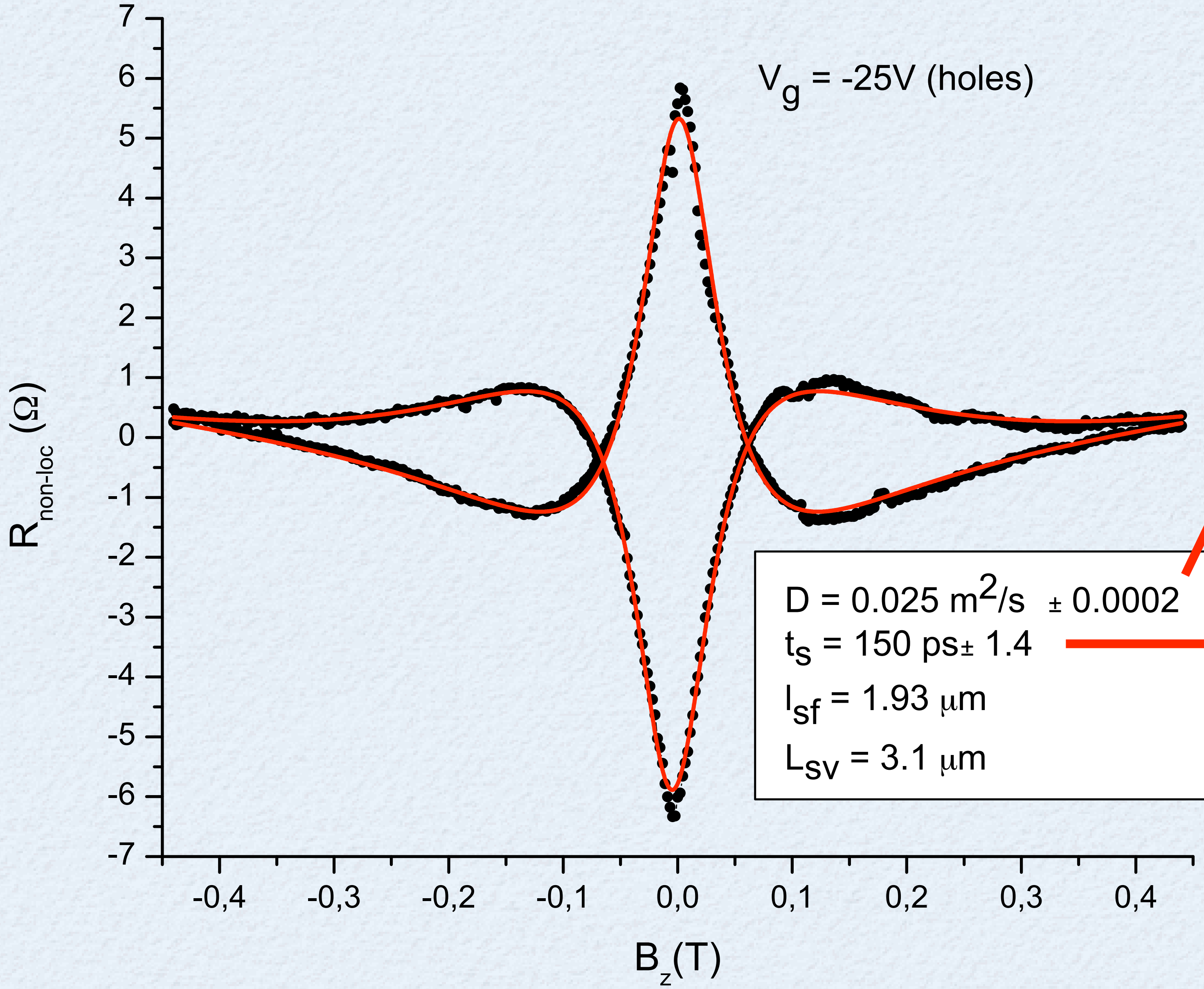
$\mu \approx 200\,000$ cm²/Vs

as measured by K.I. Bolotin, P. Kim *et al.*

Does λ_s increase?

To be continued...

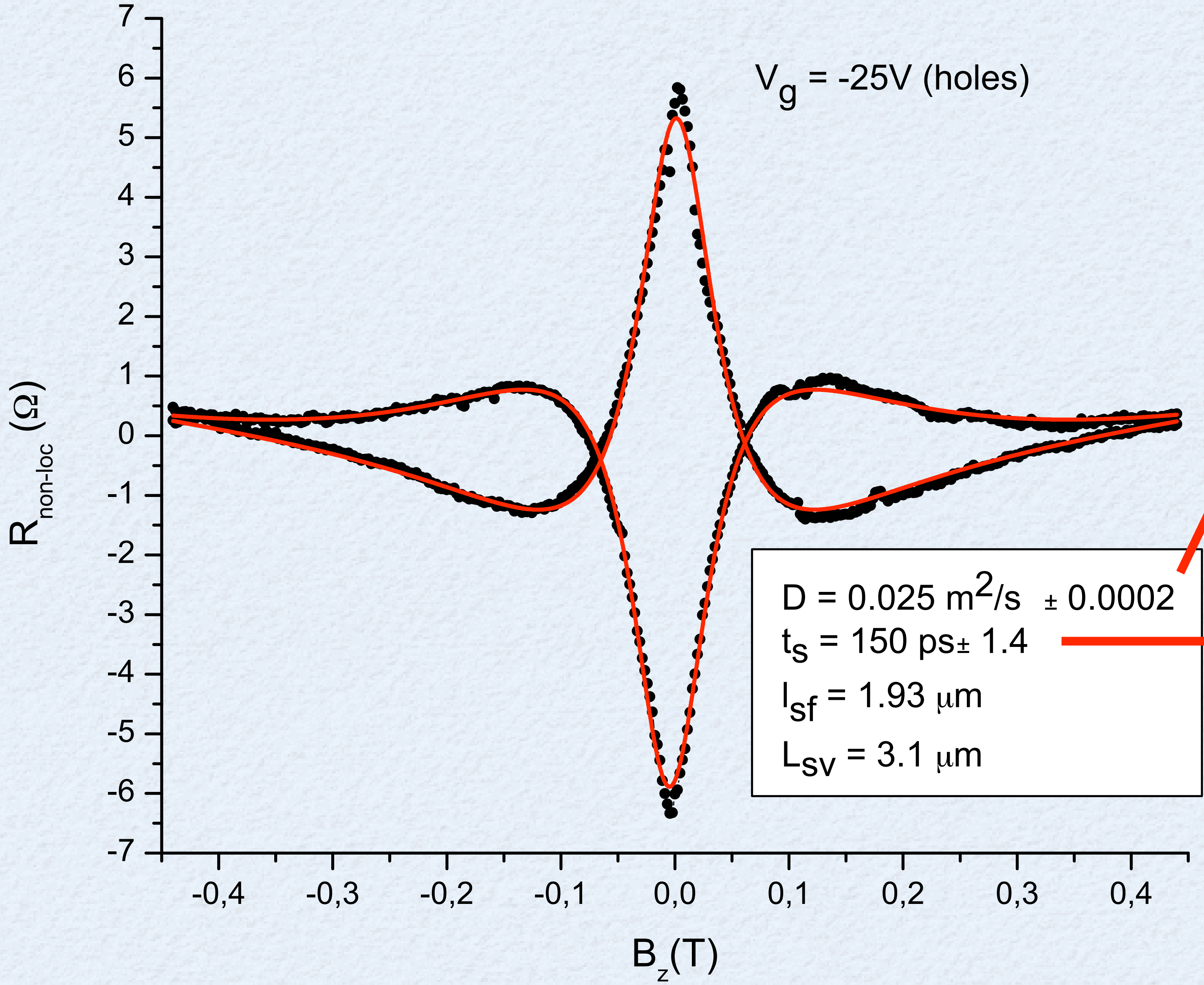
One more thing on Relaxation



Charge diffusion constant:
D= ½ v_F l = 2.5x10^{-2}
- similar to Dspin

Relaxation:
100x faster than expected

ONE MORE THING ON RELAXATION

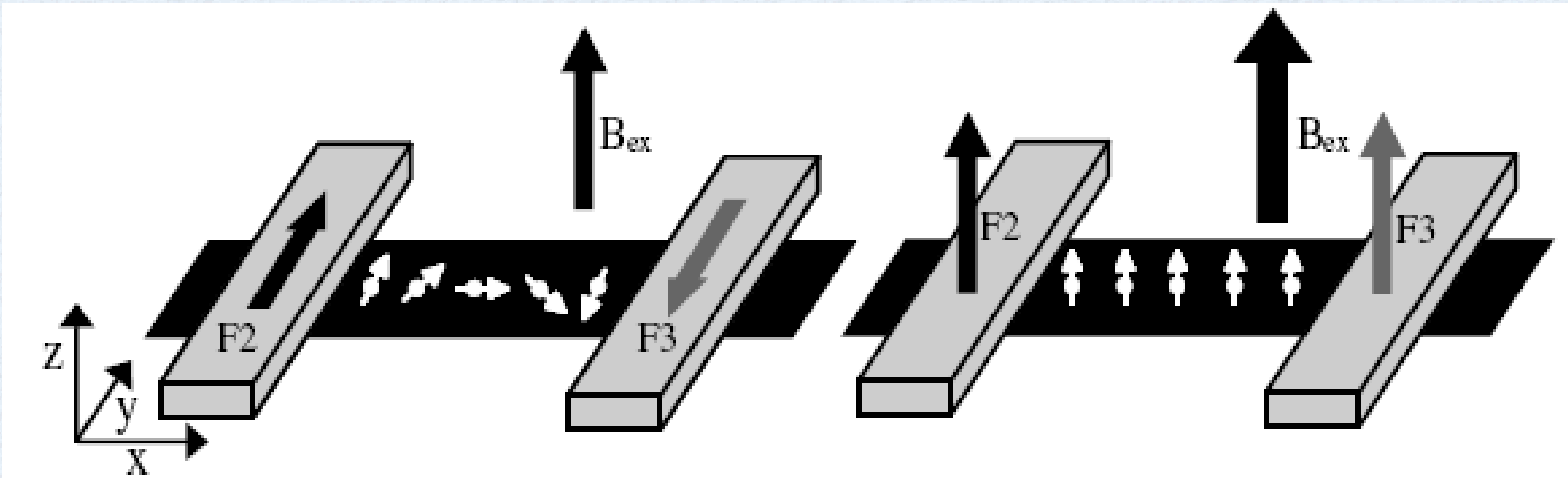


Charge diffusion constant:
D= ½ v_F l = 2.5x10^{-2}
- similar to Dspin

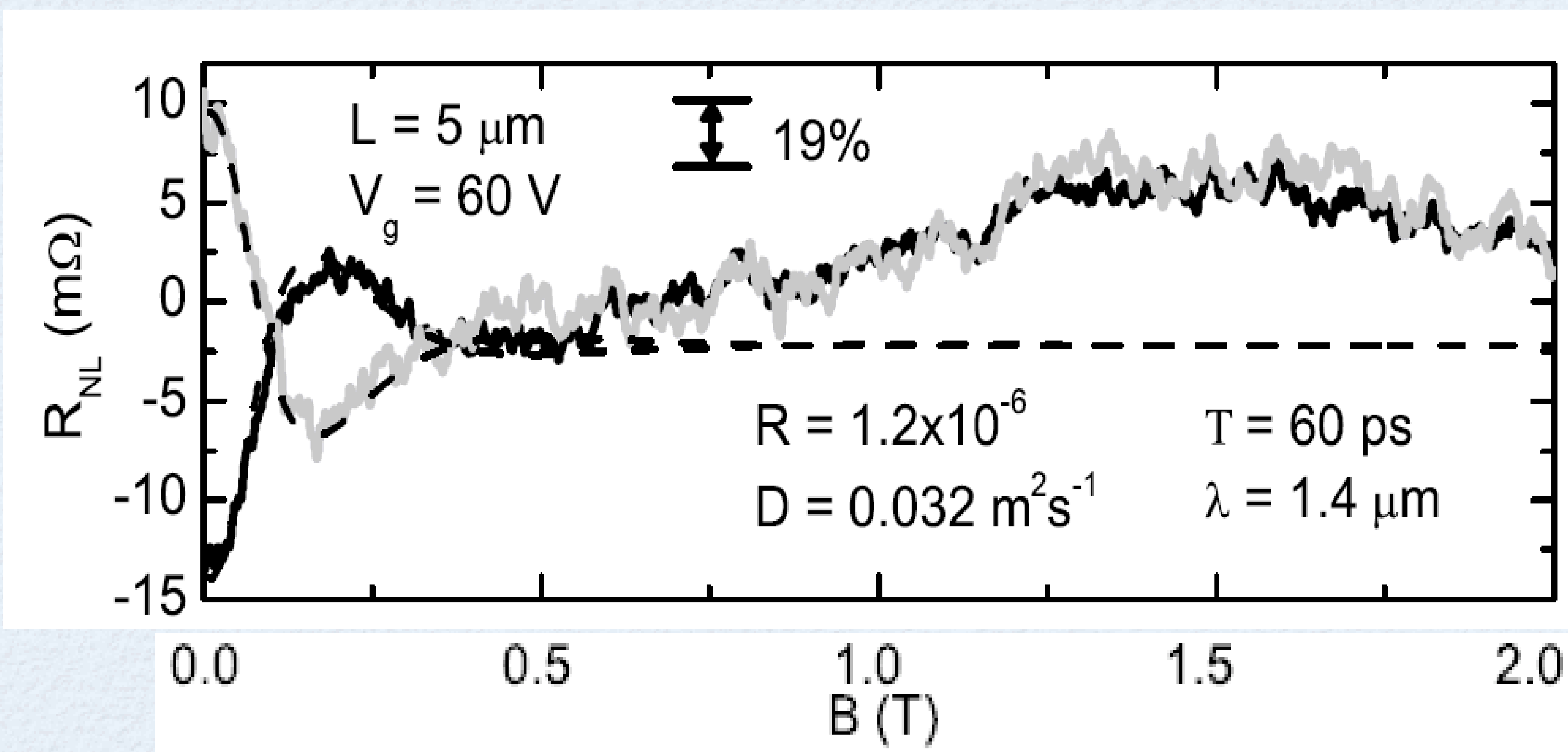
Relaxation:
100x faster than expected

What happens if the spin imbalance is orthogonal to the graphene plane?

Relaxation Anisotropy*

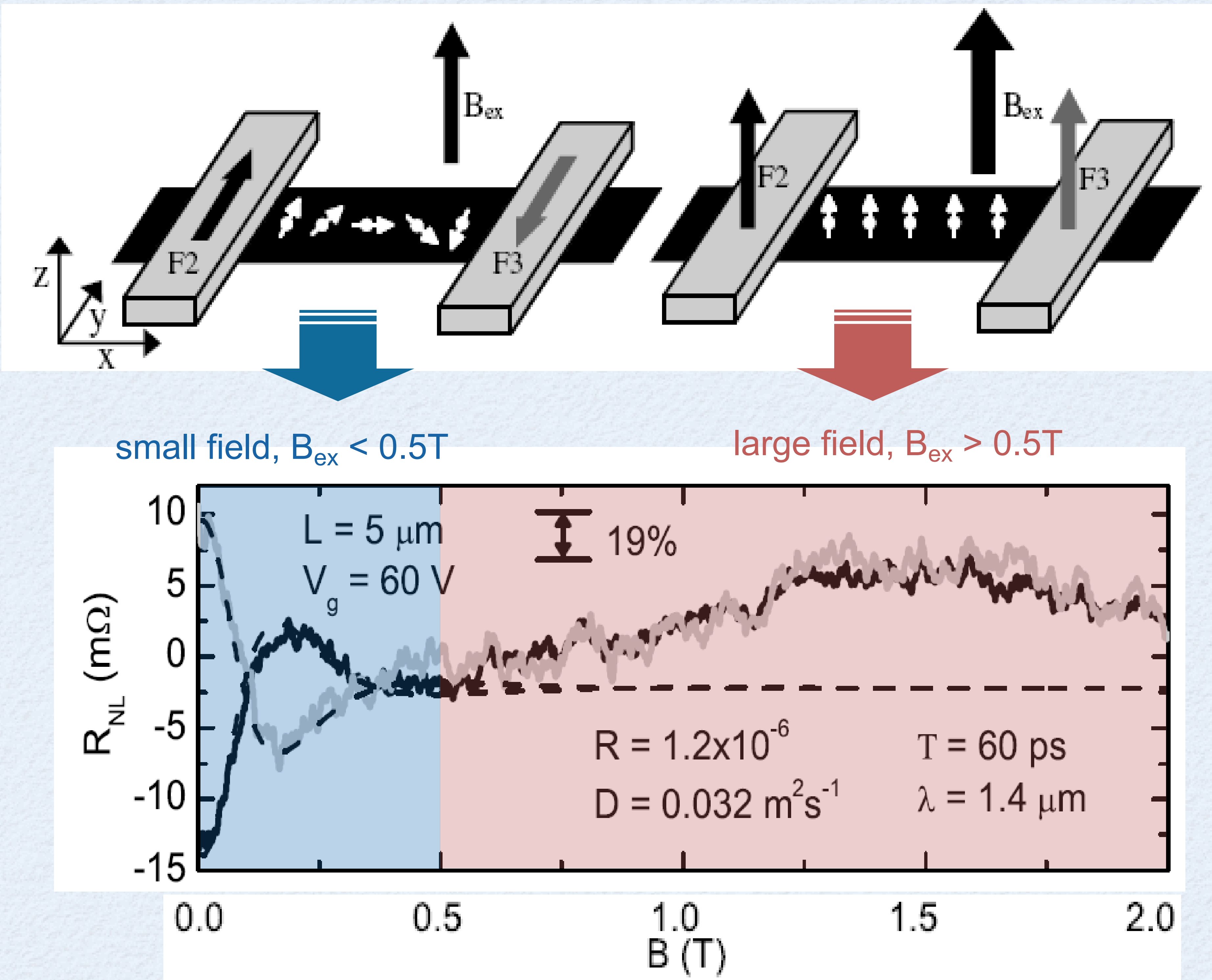


further increase magnetic field



*N. Tombros, C. Józsa et al., Phys. Rev. Lett., **101**, 046601 (2008)

Relaxation anisotropy*



further increase magnetic field

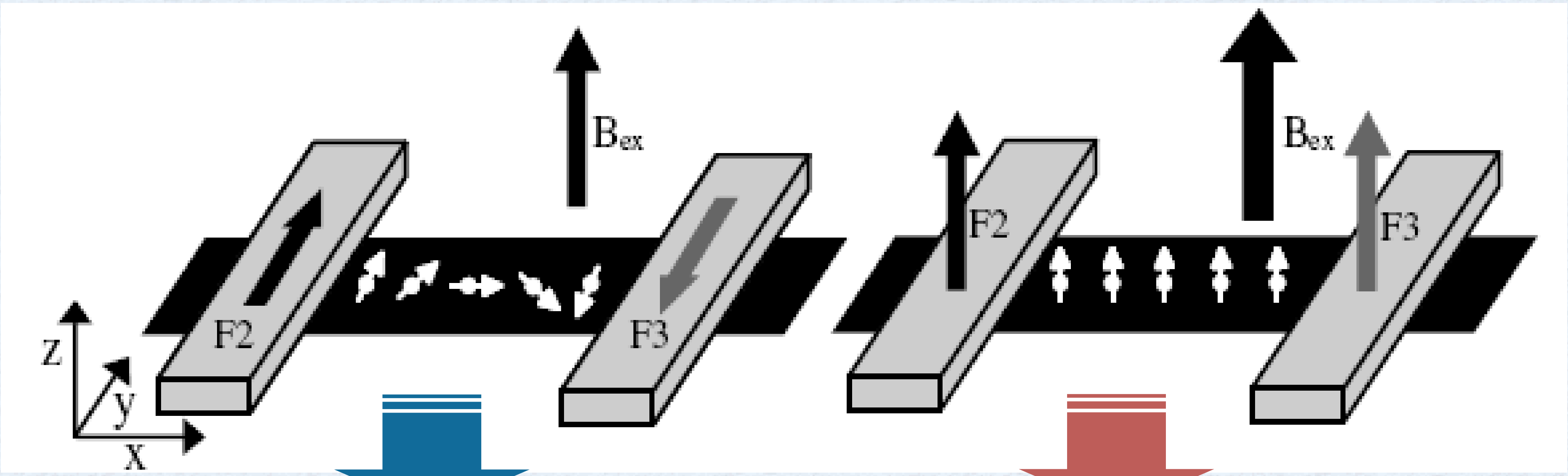
$\tau_\perp \approx 0.8\, \tau_\parallel$

SO fields: predominantly in-plane

Again: Elliott-Yafet is important

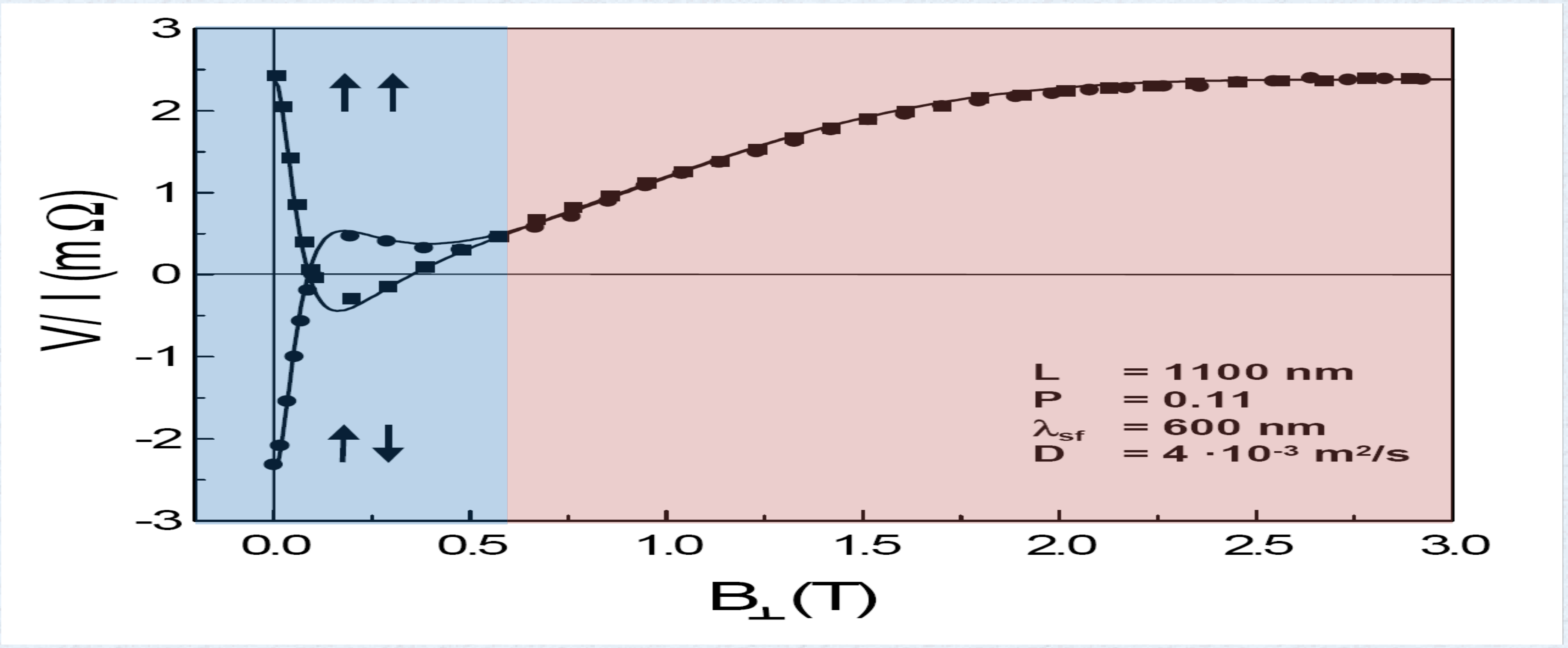
*N. Tombros, C. Józsa et al., Phys. Rev. Lett., **101**, 046601 (2008)*

COMPARED TO METALS



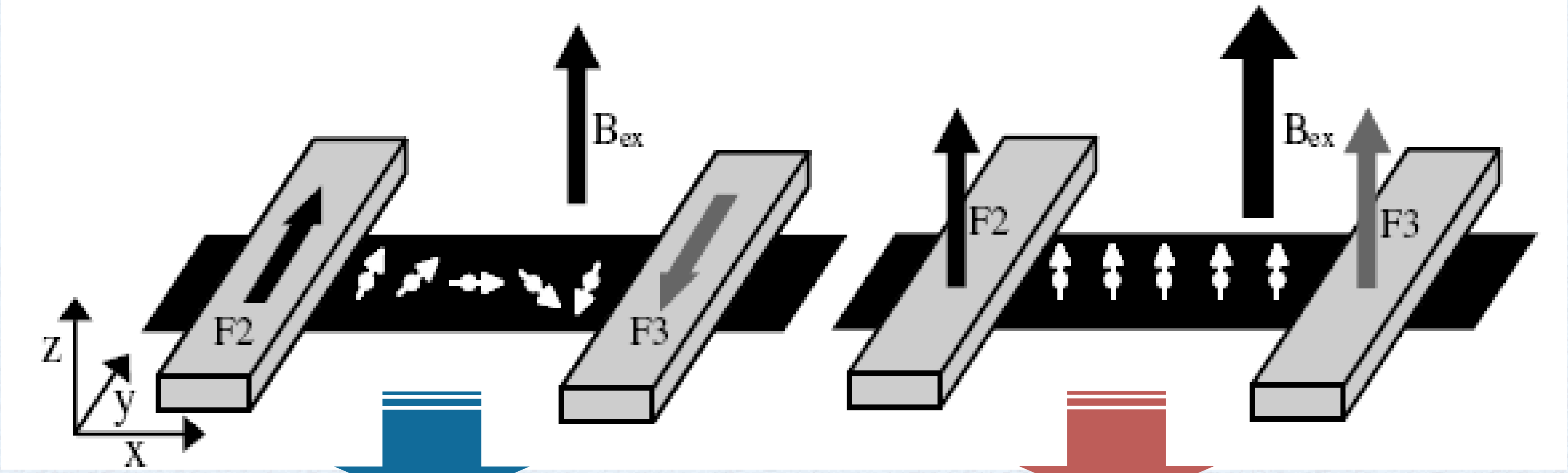
small field, $B_{ex} < 0.5T$

large field, $B_{ex} > 0.5T$



same geometry

Compared to Metals



small field, B_{ex} < 0.5T

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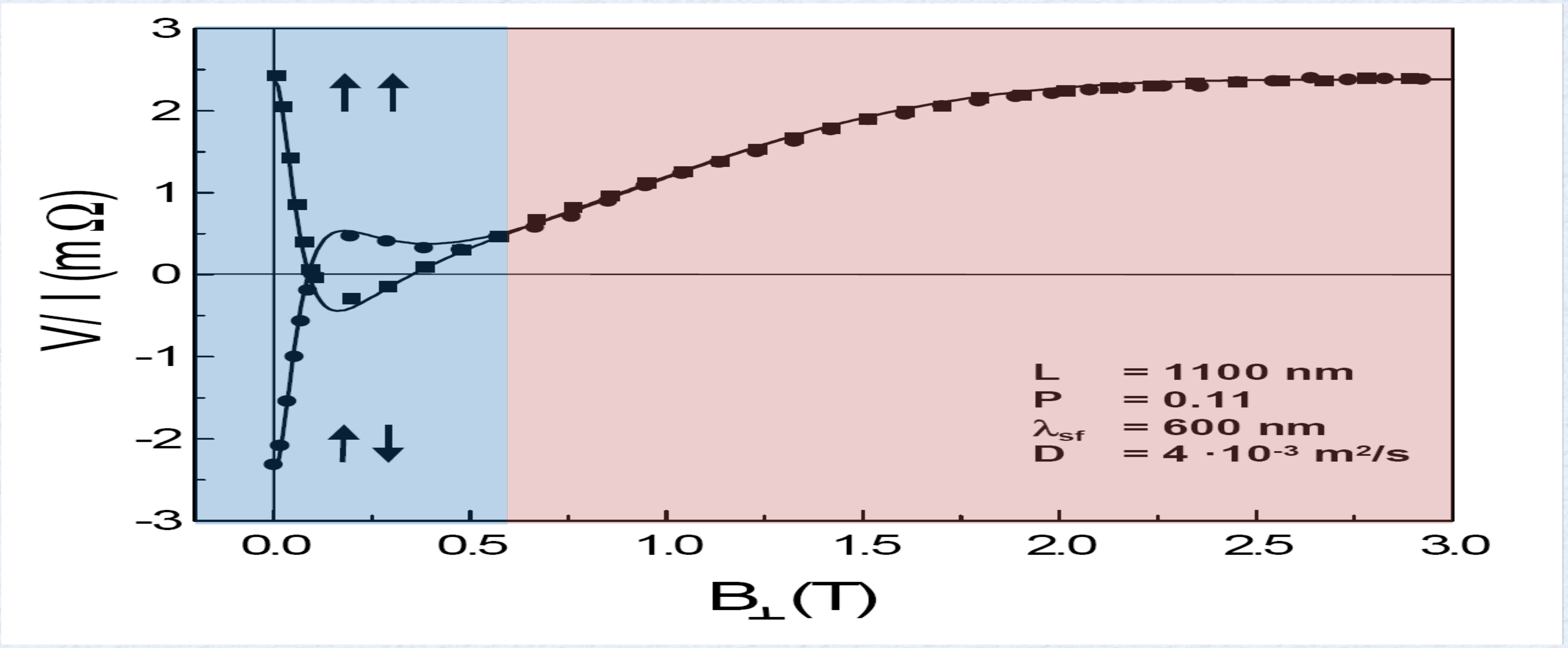


same geometry

$\tau_\perp \approx \tau_\parallel$

Jedema et al., Nature (2002)

spin relaxation is isotropic in Al films!

Carrier drift to control spin transport

Spin drift effects in n-GaAs: X. Lou et al., Phys. Rev. Lett. 96, 176603 (2006)

Drift-Diffusion under an E Field?

- *Yu-Flatté for spin imbalance (degenerate SC):*

$$D\,\nabla^2 \vec{\mu} = \frac{\vec{\mu}}{\tau} - \vec{v}_D\,\nabla\vec{\mu}$$

Z.G. Yu and M.E. Flatté,
Phys. Rev. B ***66****, R 201202 (2002)*

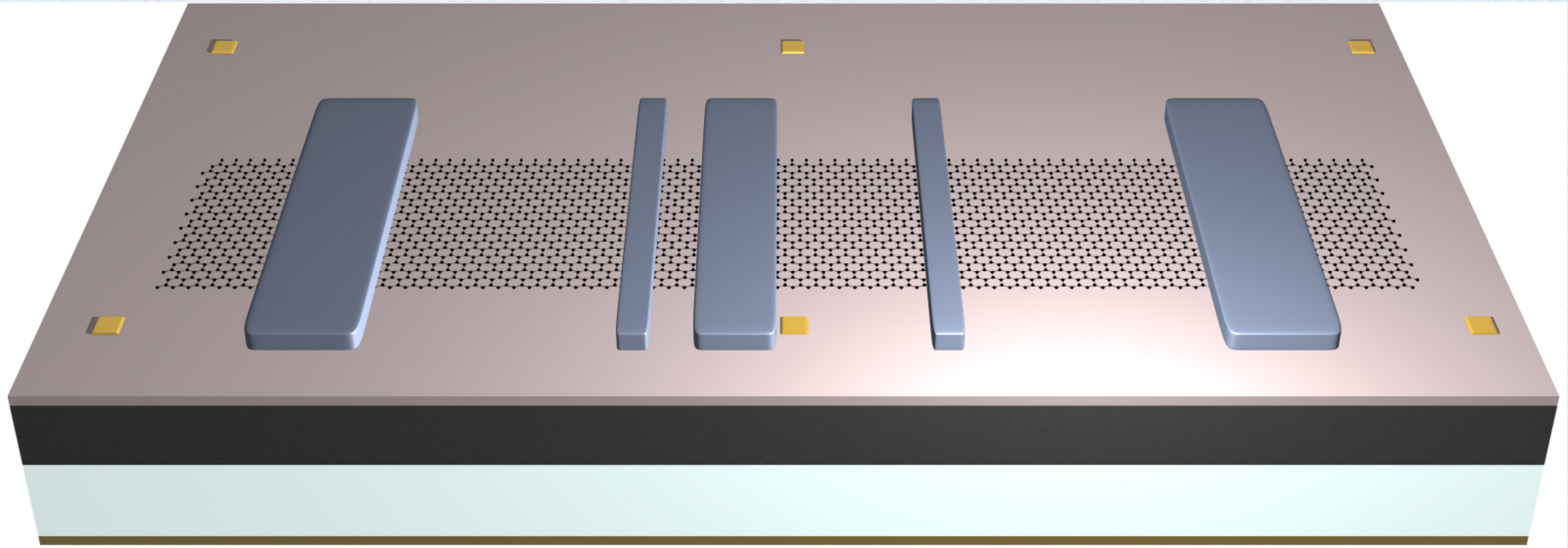
- *Solution along x:* $\mu(x) = A\exp\left(\frac{x}{\lambda_+}\right) + B\exp\left(-\frac{x}{\lambda_-}\right)$

where $\frac{1}{\lambda_\pm} = \pm\frac{1}{2}\frac{1}{\lambda_D} + \sqrt{\frac{1}{4}\frac{1}{\lambda_D^2} + \frac{1}{\lambda_s^2}}$ *= up / downstream spin transport length;*

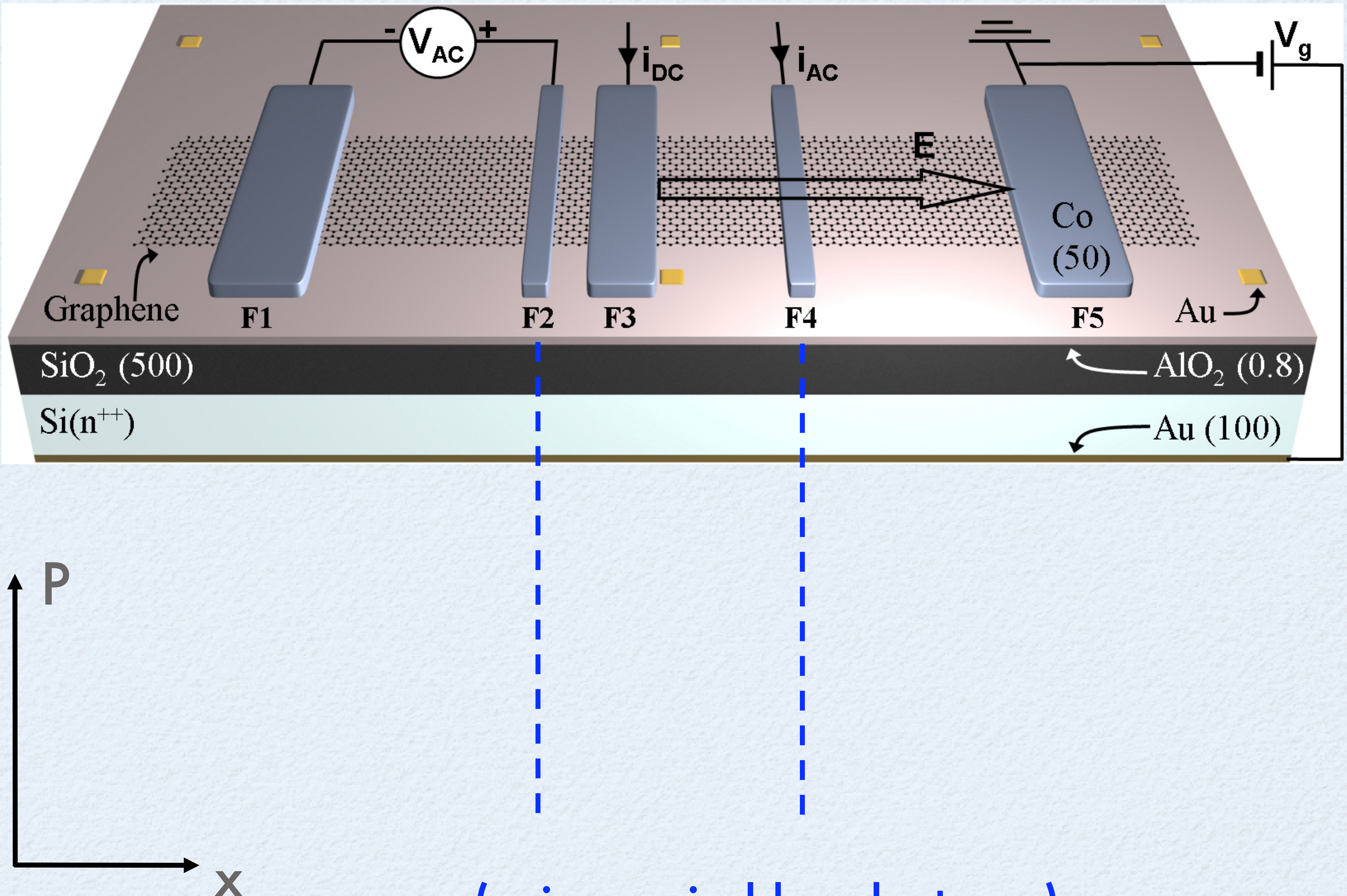
$\lambda_s = \sqrt{D\tau}$ *= spin diffusion length,* ***symmetric*** *in* x

$\lambda_D = \frac{D}{v_D}$ *= "spin drift length" ,* ***asymmetric*** *due to* $v_D = \mu E$

DRIFT GEOMETRY

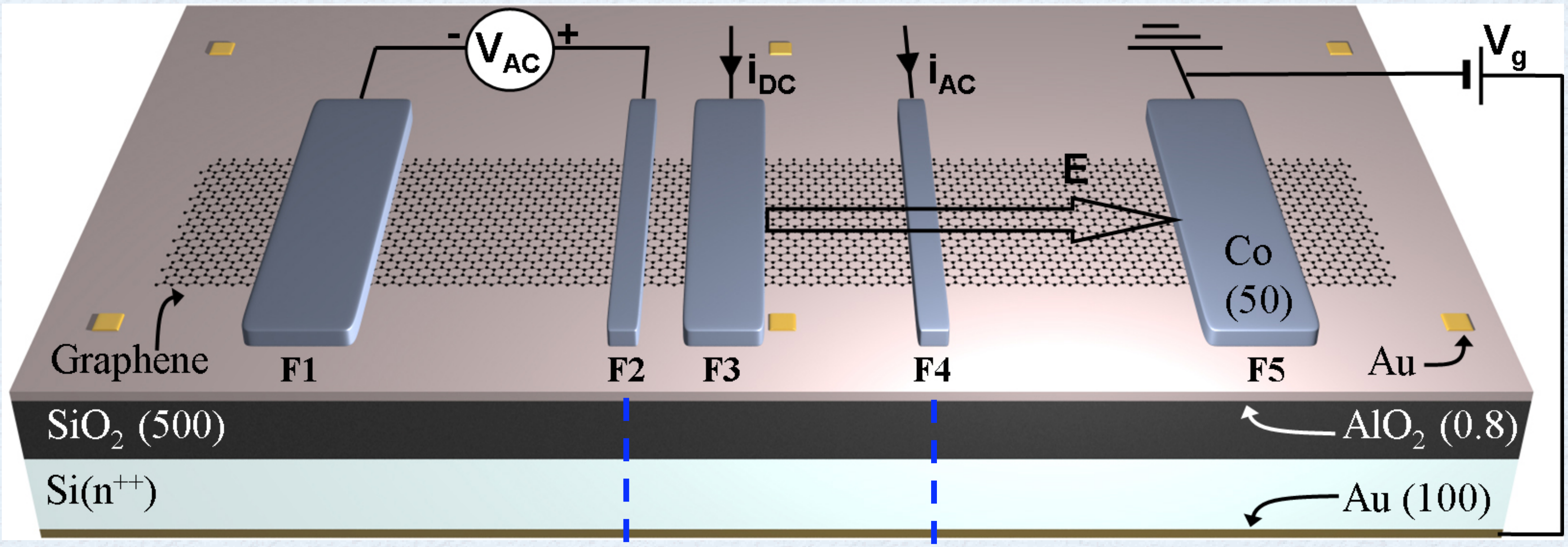


DRIFT GEOMETRY, N-TYPE

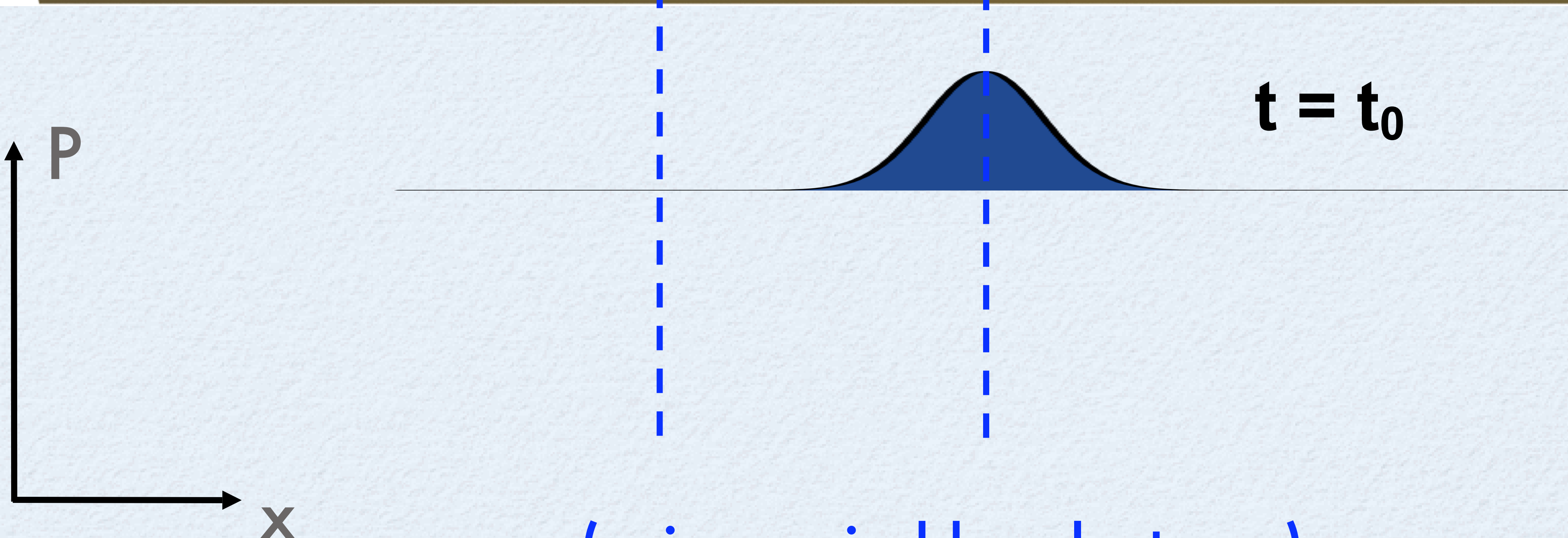


(spin carried by electrons)

DRIFT GEOMETRY, N-TYPE

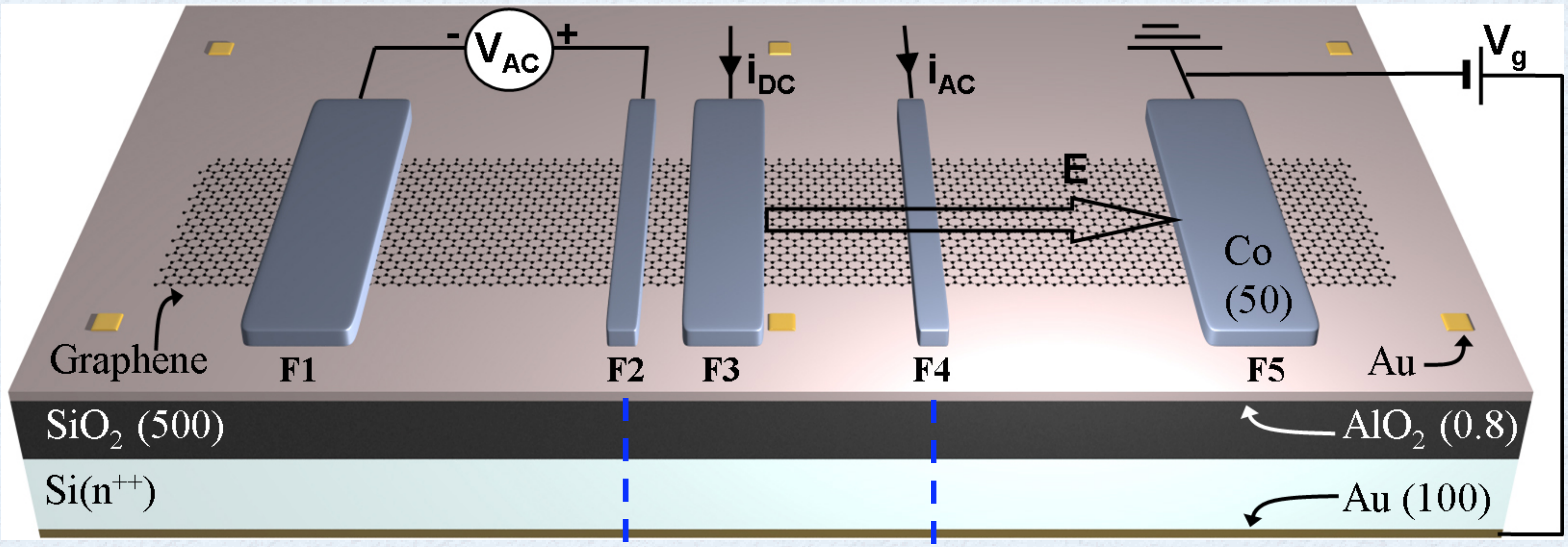


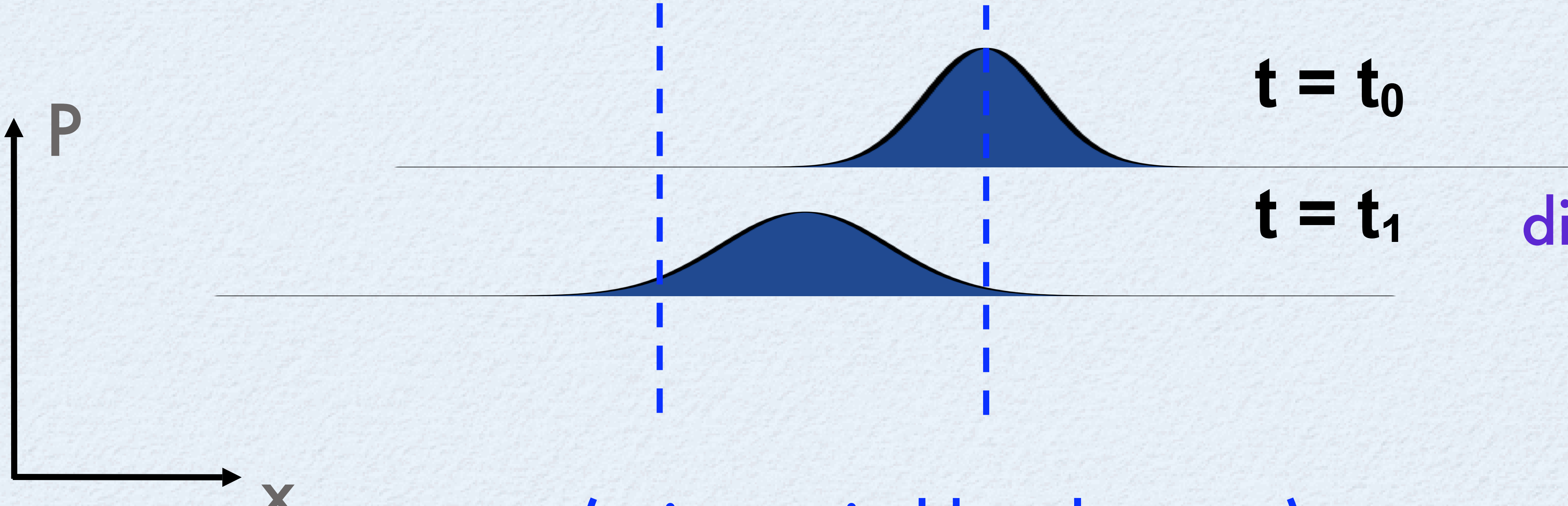
injection



(spin carried by electrons)

DRIFT GEOMETRY, N-TYPE



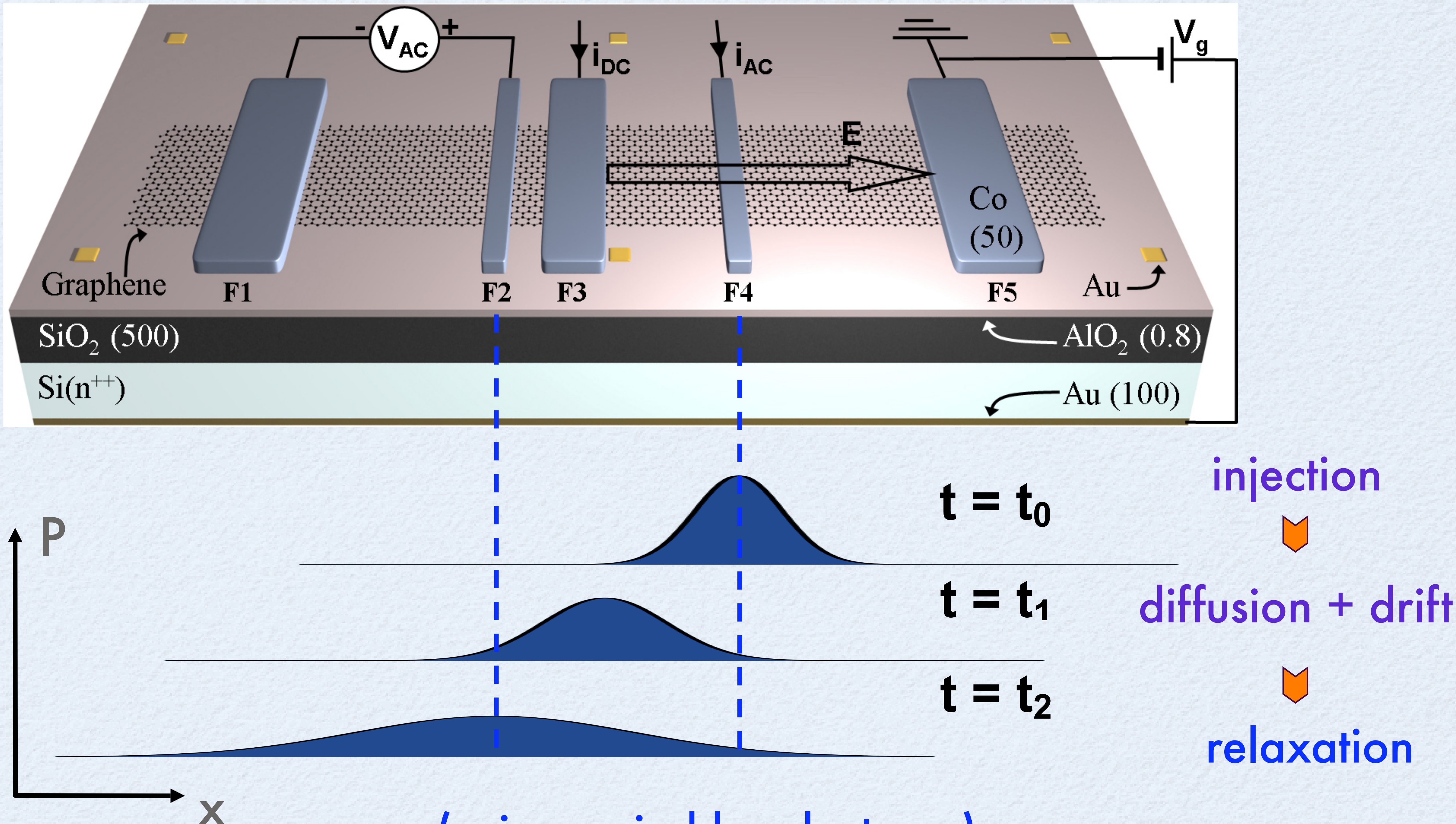


injection

diffusion + drift

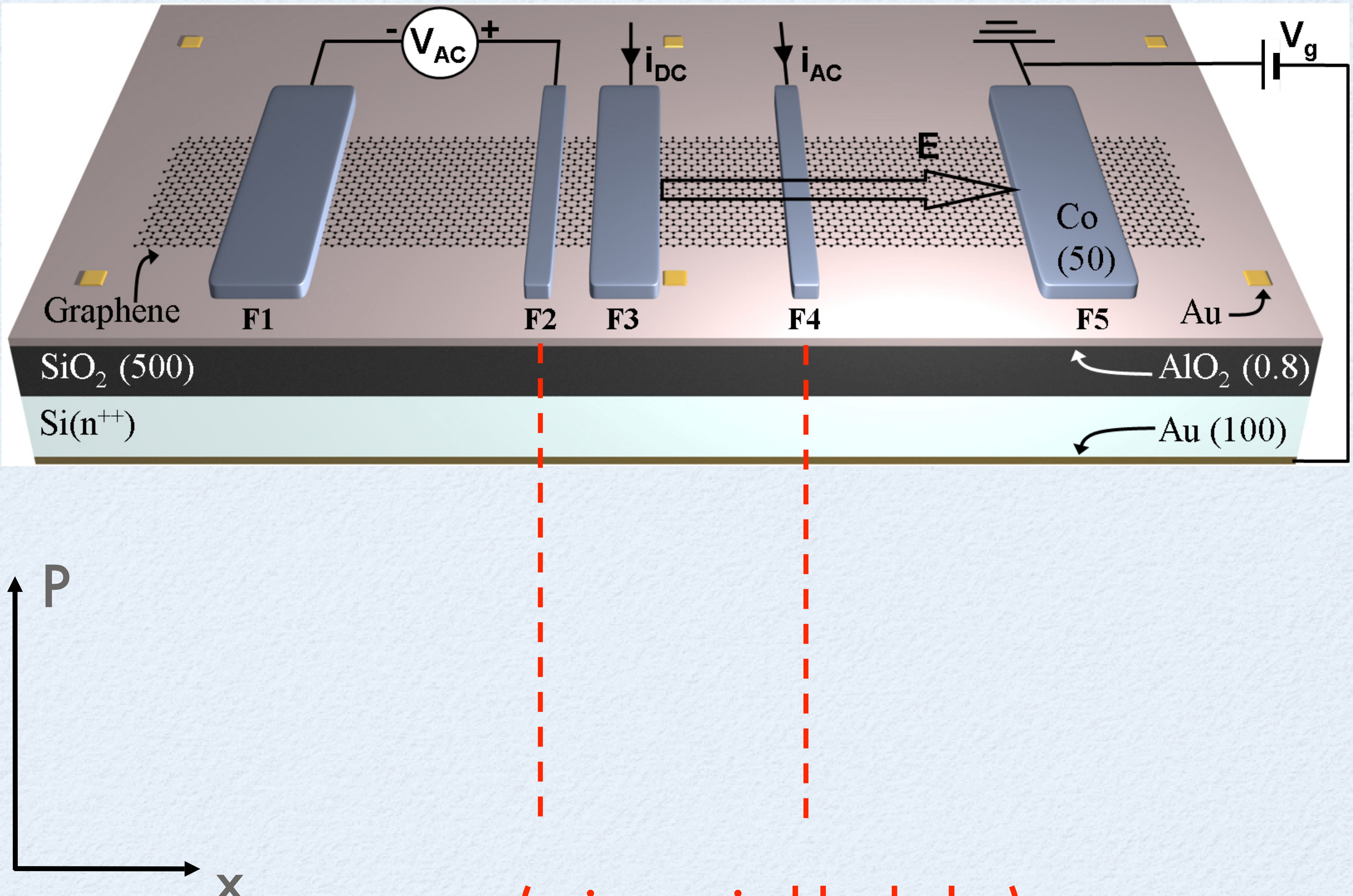
(spin carried by electrons)

DRIFT GEOMETRY, N-TYPE



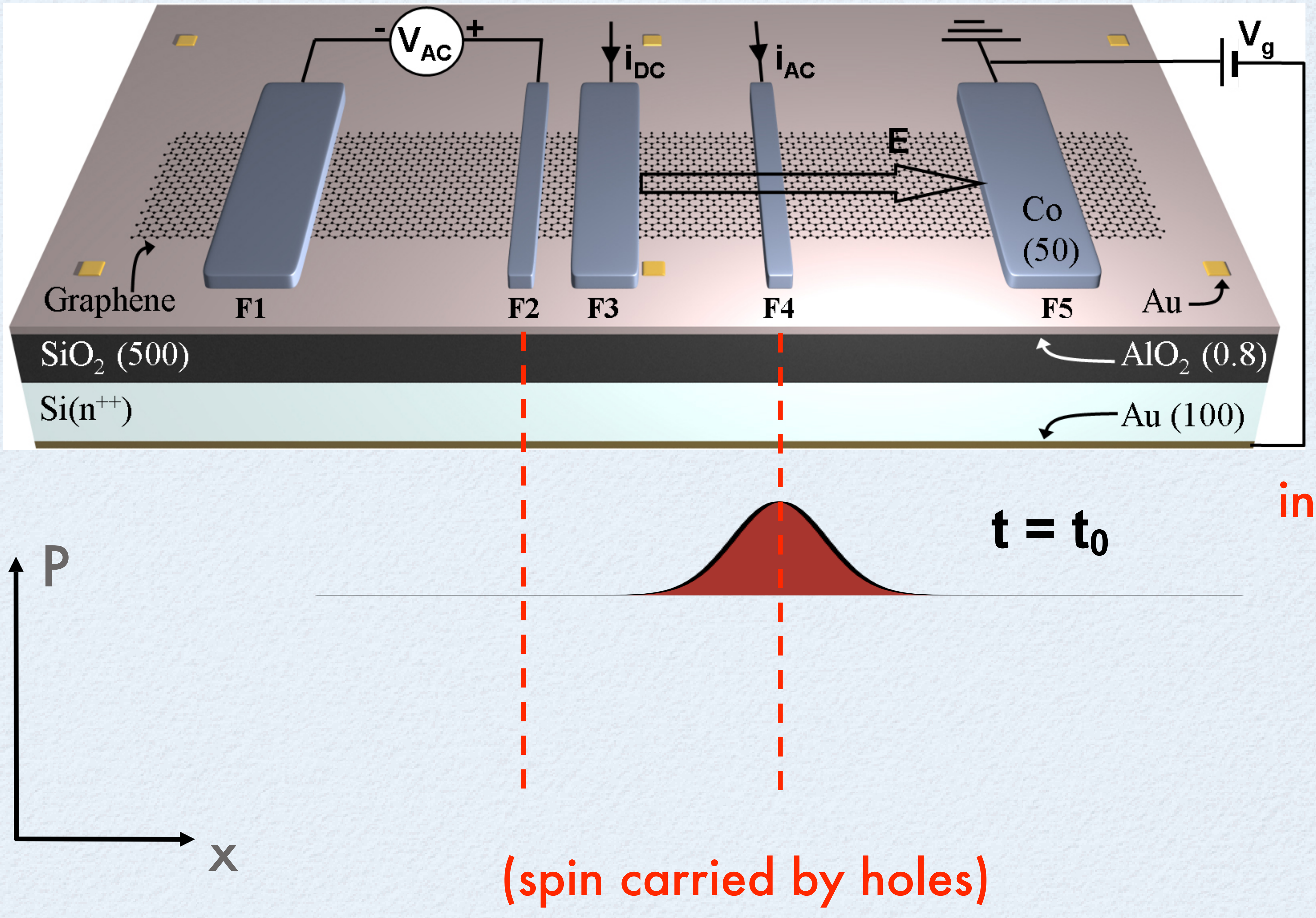
(spin carried by electrons)

DRIFT GEOMETRY, P-TYPE



(spin carried by holes)

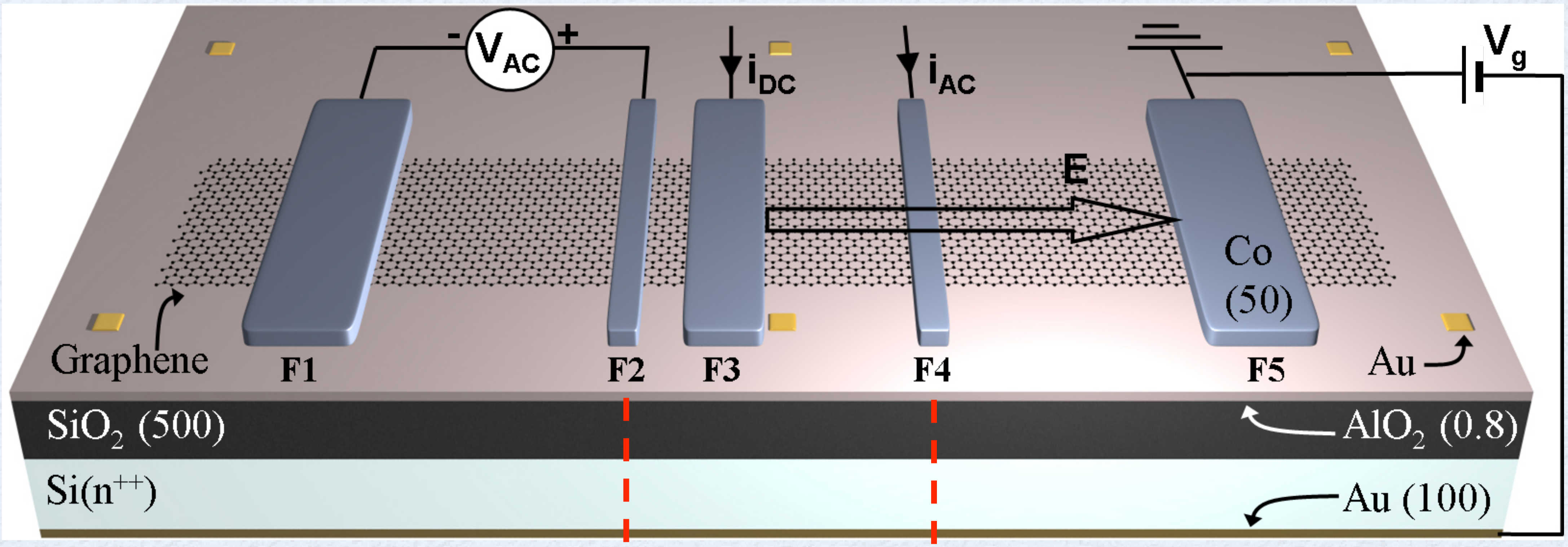
DRIFT GEOMETRY, P-TYPE

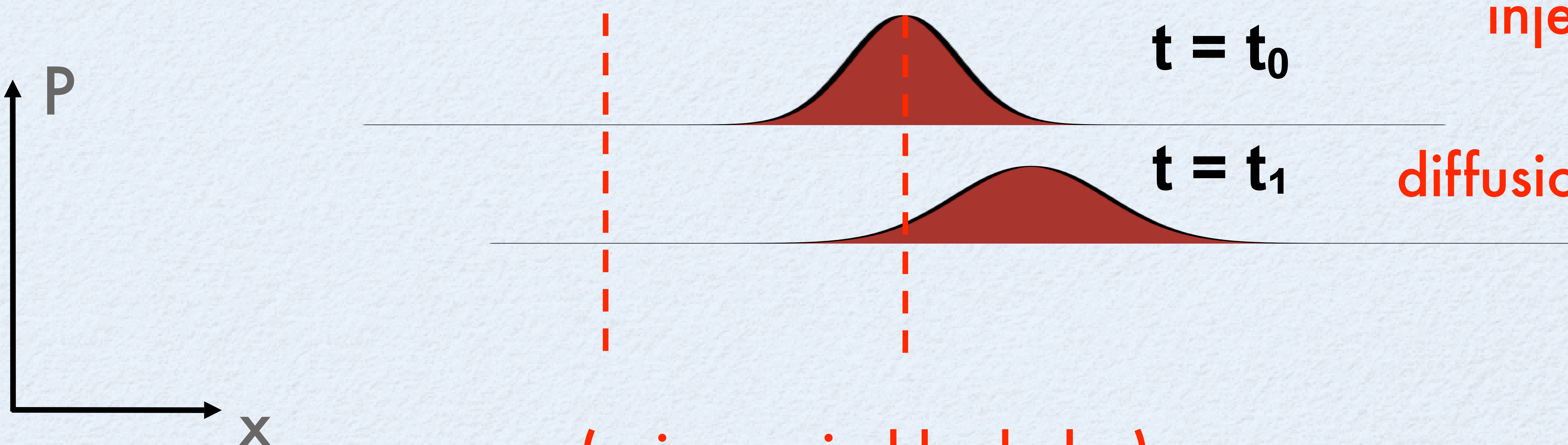


injection

(spin carried by holes)

DRIFT GEOMETRY, P-TYPE





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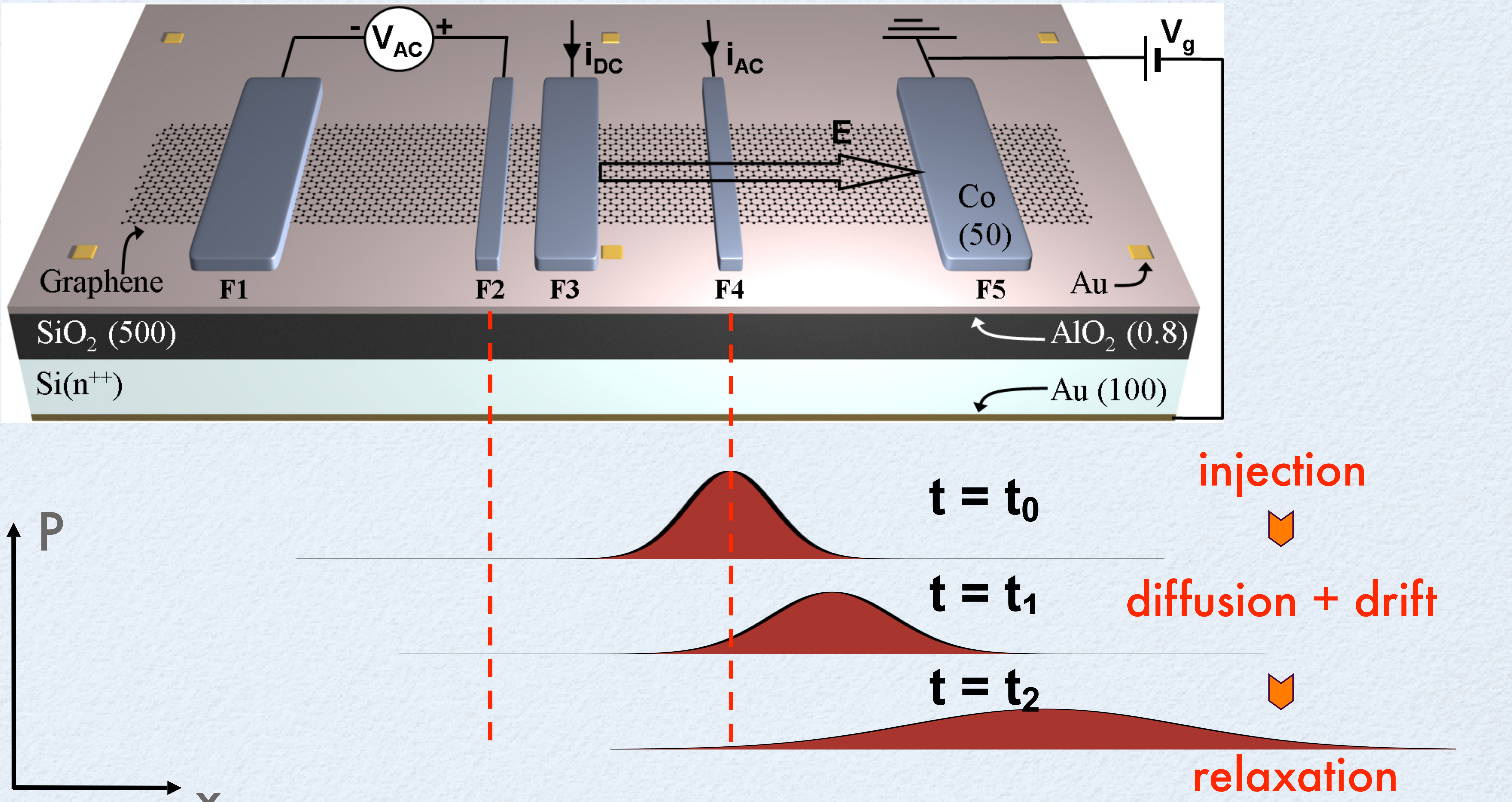
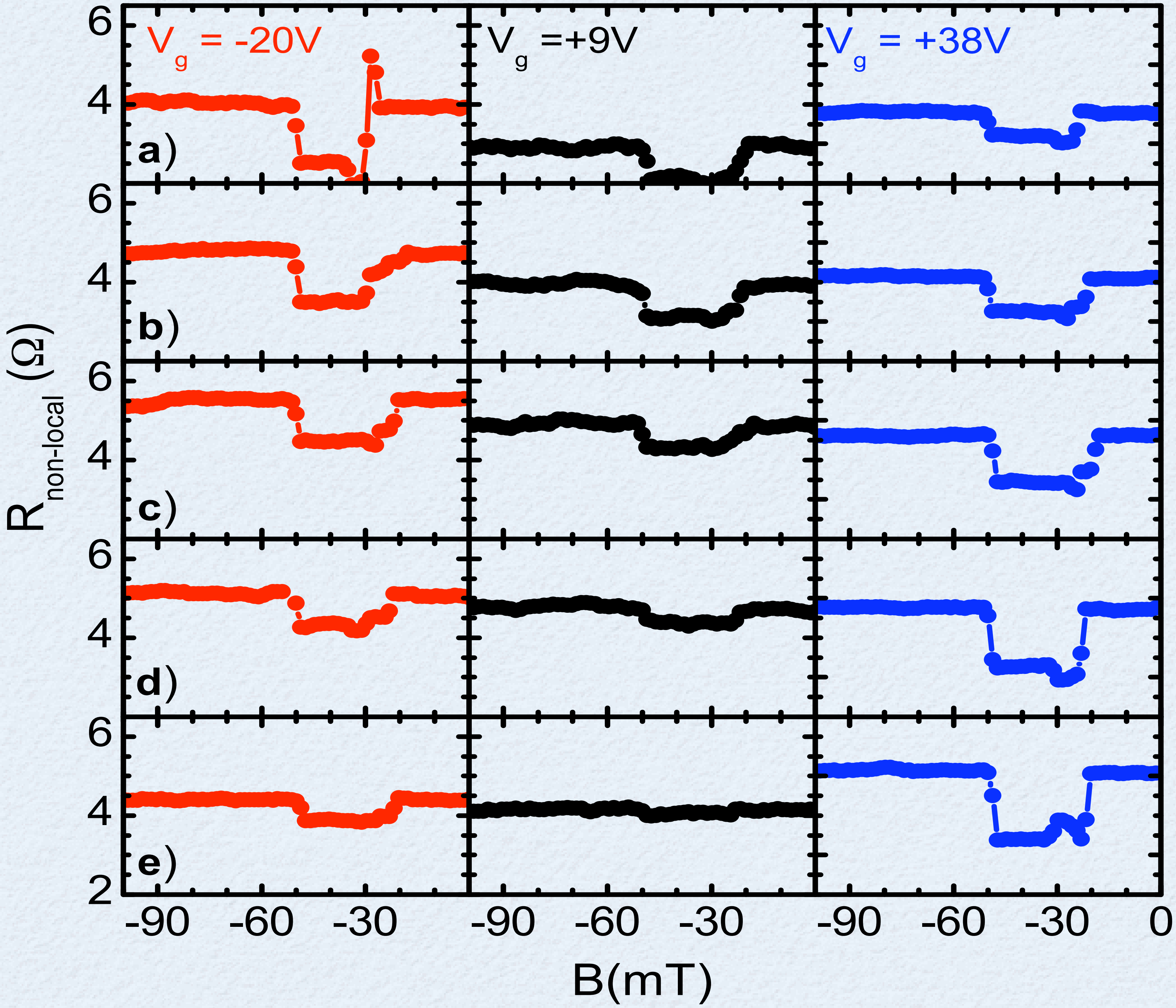


(spin carried by holes)

Spin Drift Measurements*



i_{DC} = -40 μA

i_{DC} = -20 μA

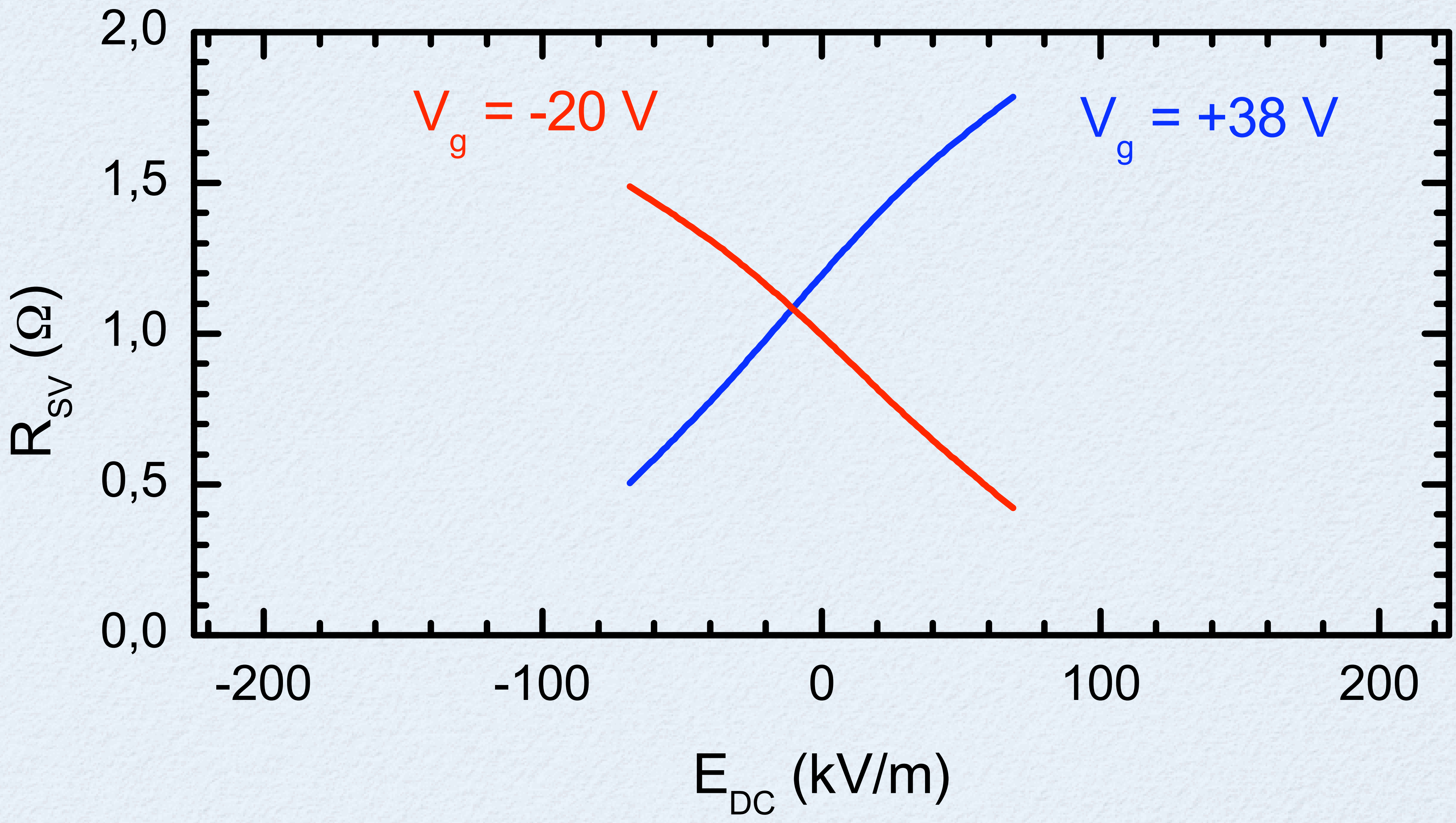
i_{DC} = 0

i_{DC} = +20 μA

i_{DC} = +40 μA

C. Józsa, M. Popinciuc et al., PRL **100, 236603 (2008)*

Comparison with the Yu-Flatté model*



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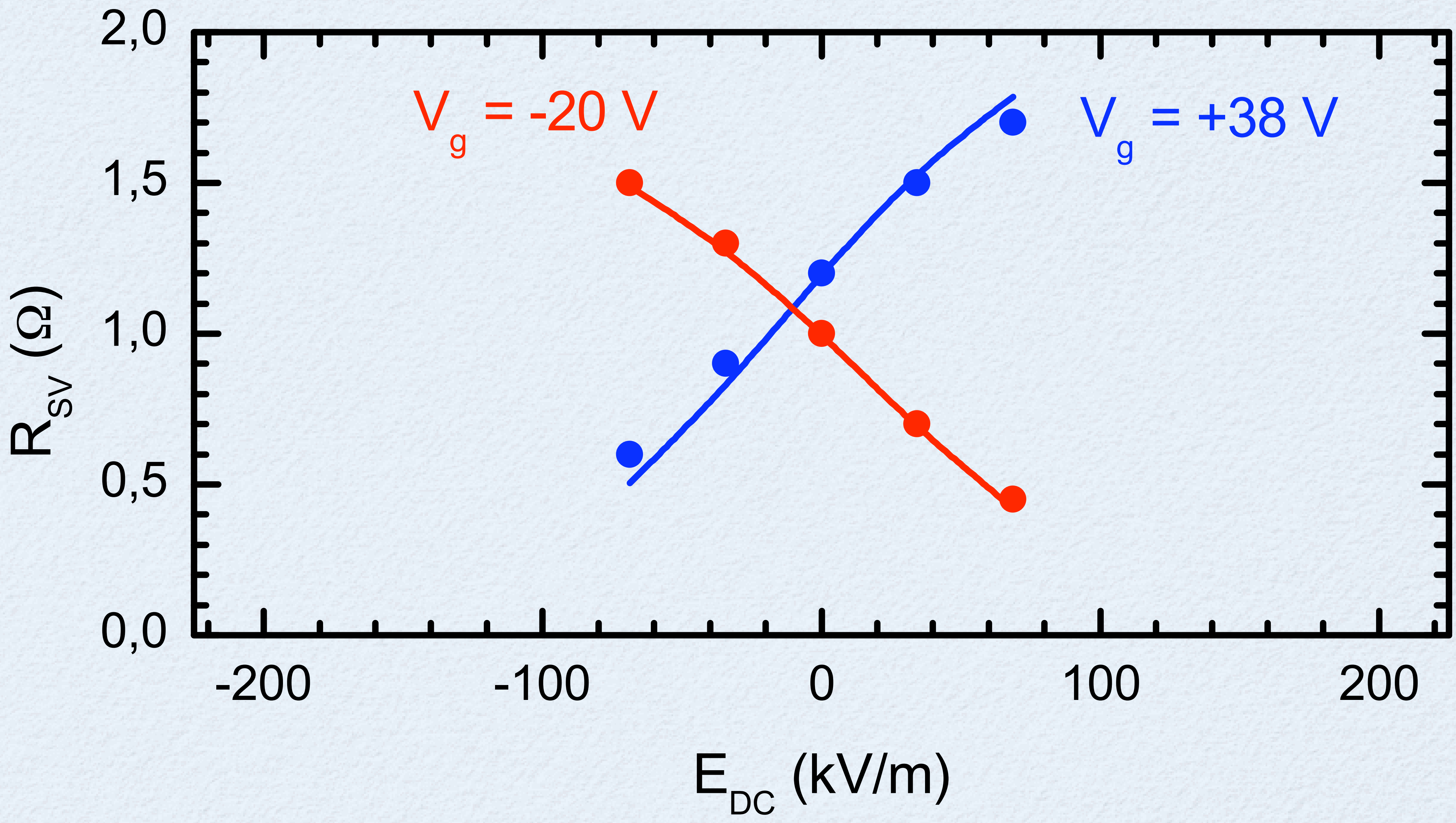
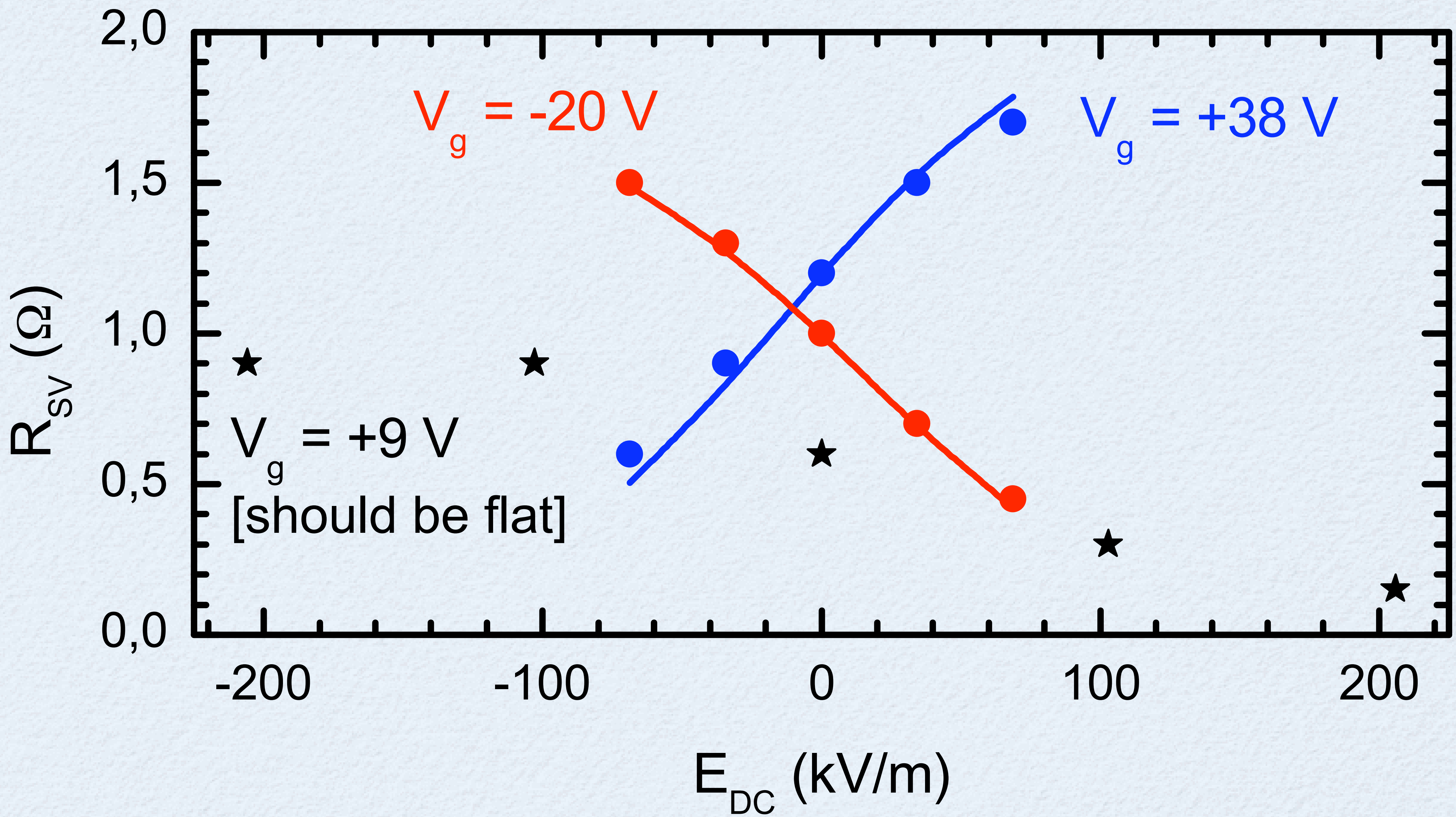


Comparison with the Yu-Flatté model*



Drift and Carrier Mobility

- Spin valve signal: ±50%
- spin "diffusion" length: >200%

Can we get more?

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Can we get more?

$v_D = \mu E$;

$\mu \approx 5500\ \mathrm{cm^2/Vs}$

Drift and carrier mobility

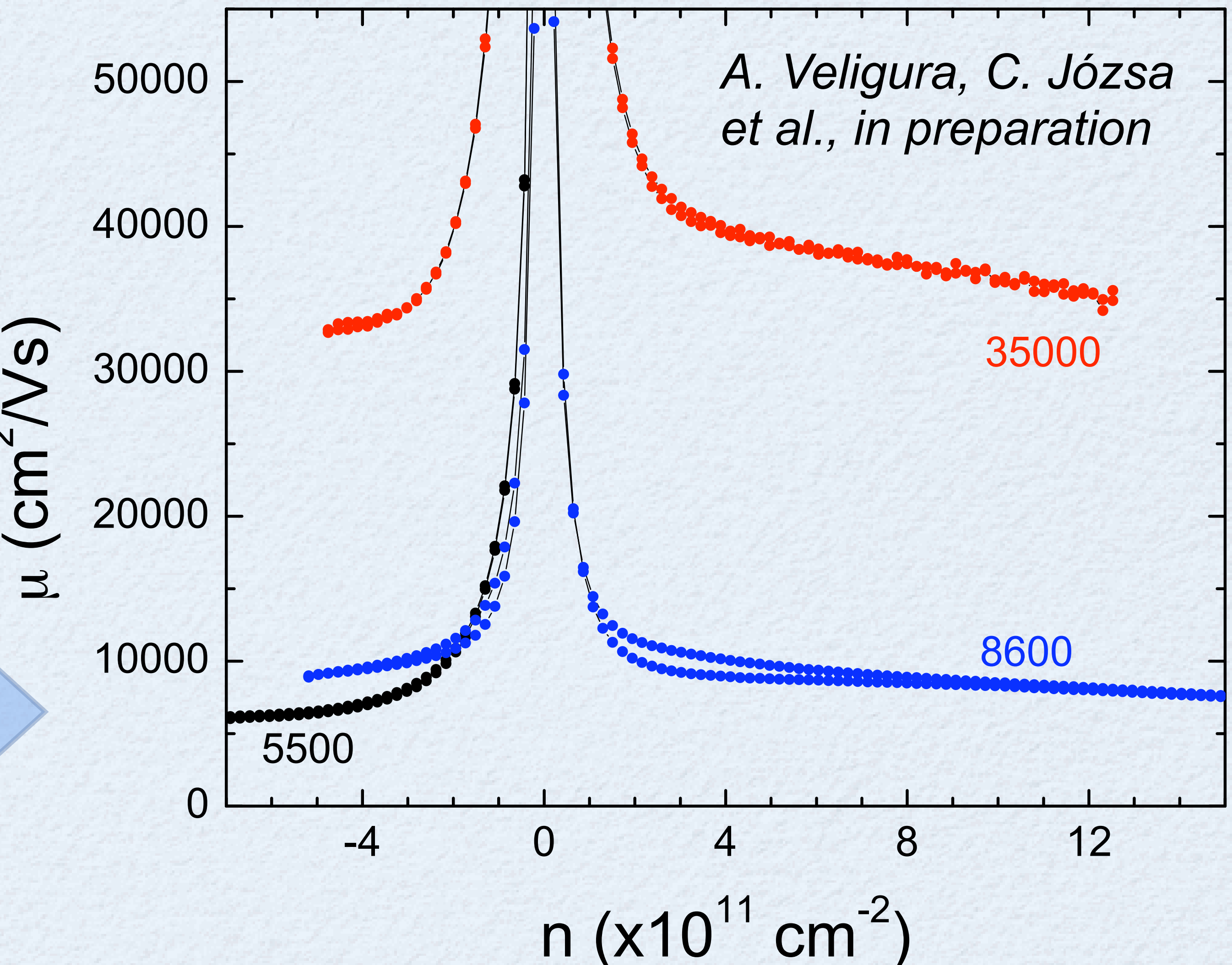
- Spin valve signal: ±50%
- spin "diffusion" length: >200%

Can we get more?

$v_D = \mu E$;

$\mu \approx 5500\ \mathrm{cm^2/Vs}$

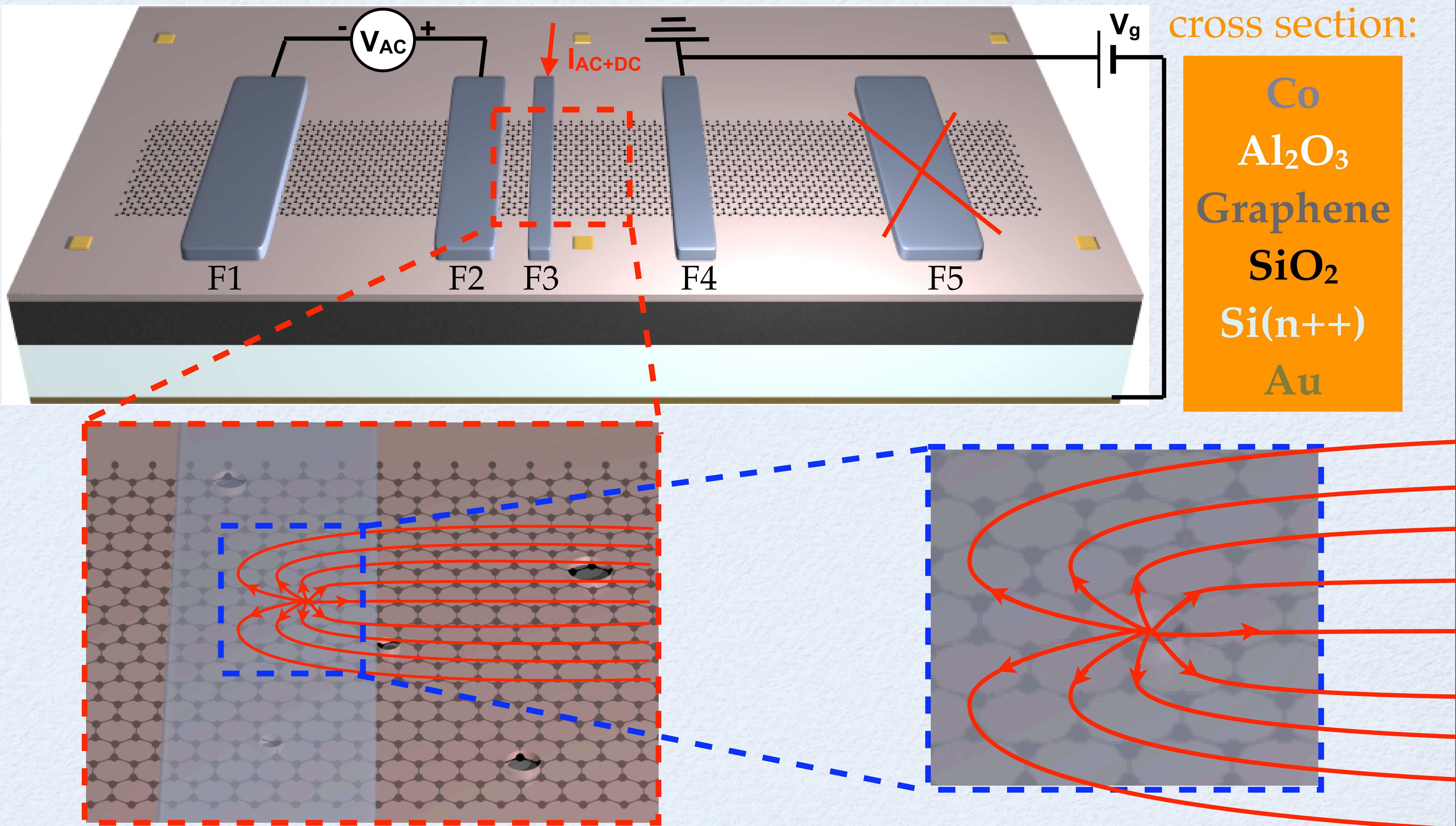
heat treatment:
150°C, 10^{-5} mbar
$\mu \approx 35000\ \mathrm{cm^2/Vs}$



How to combat the impedance mismatch?

DC biasing effects on spin detection in Fe/GaAs junctions:
S.A. Crooker *et al.*, arXiv: 0809.1120v1 (2008)

DC bias on AC spin injectors



cross section:

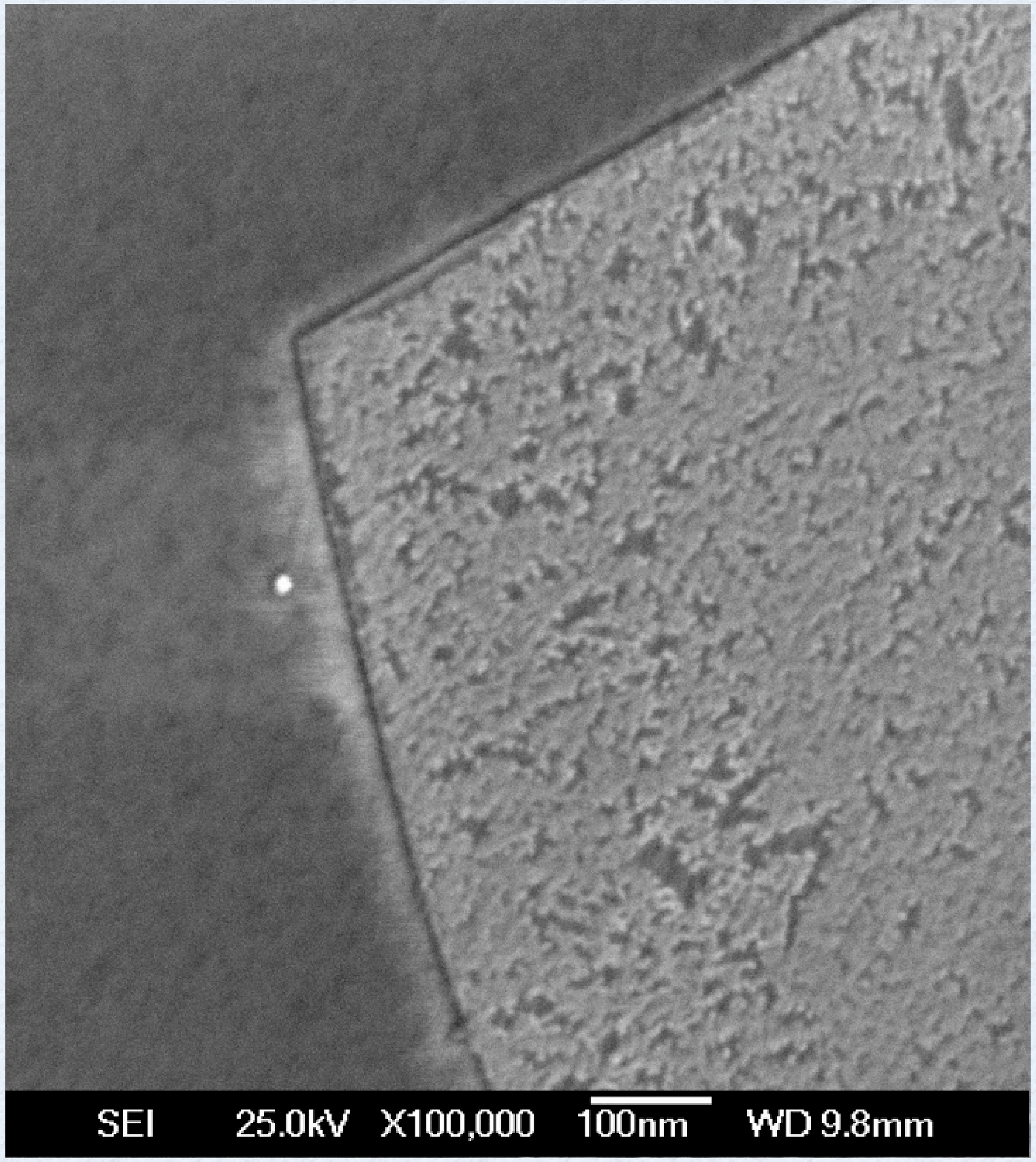
Co
Al_2O_3
Graphene
SiO_2
Si(n++)
Au

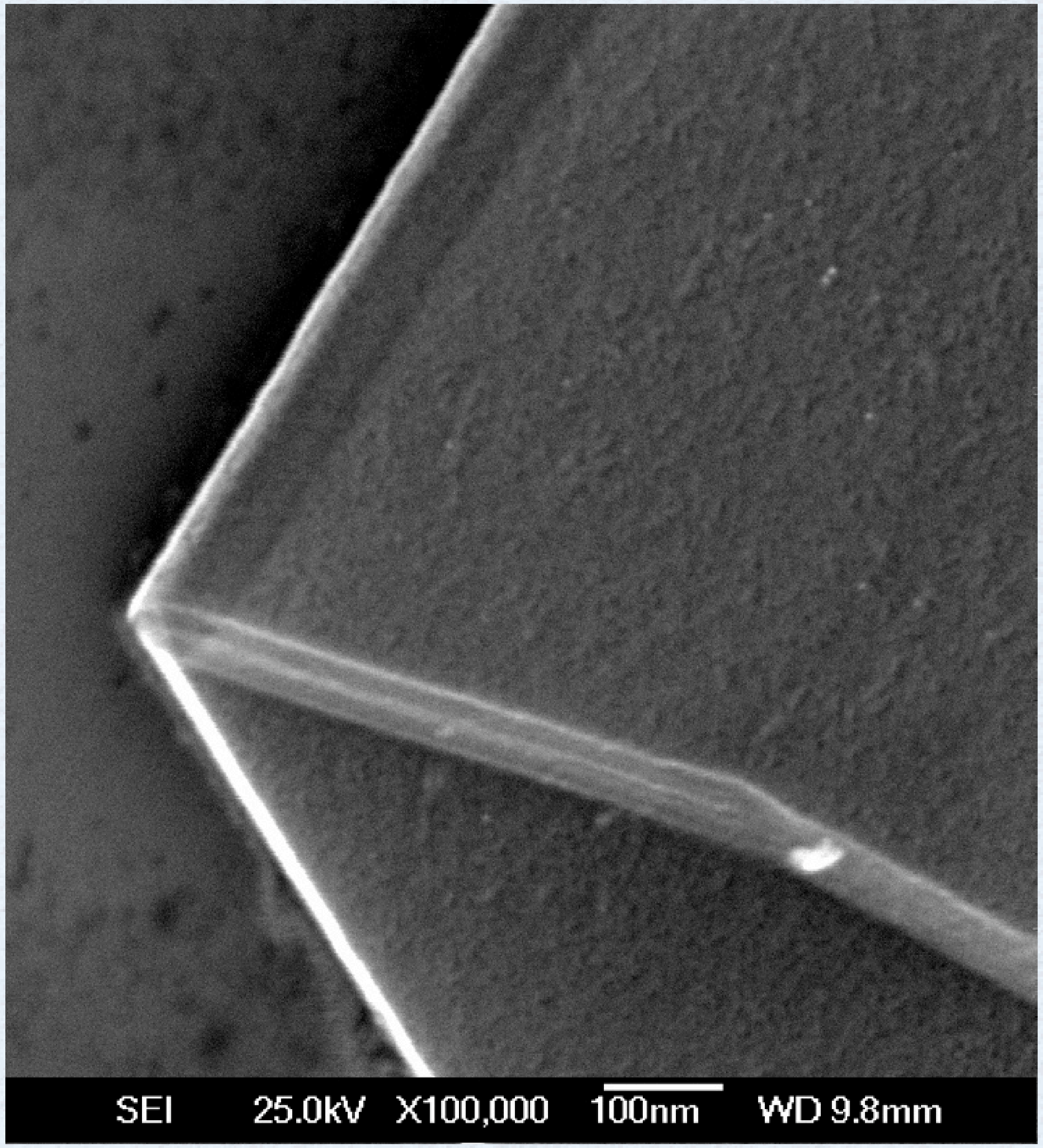
A very "bad" barrier

SEM images:

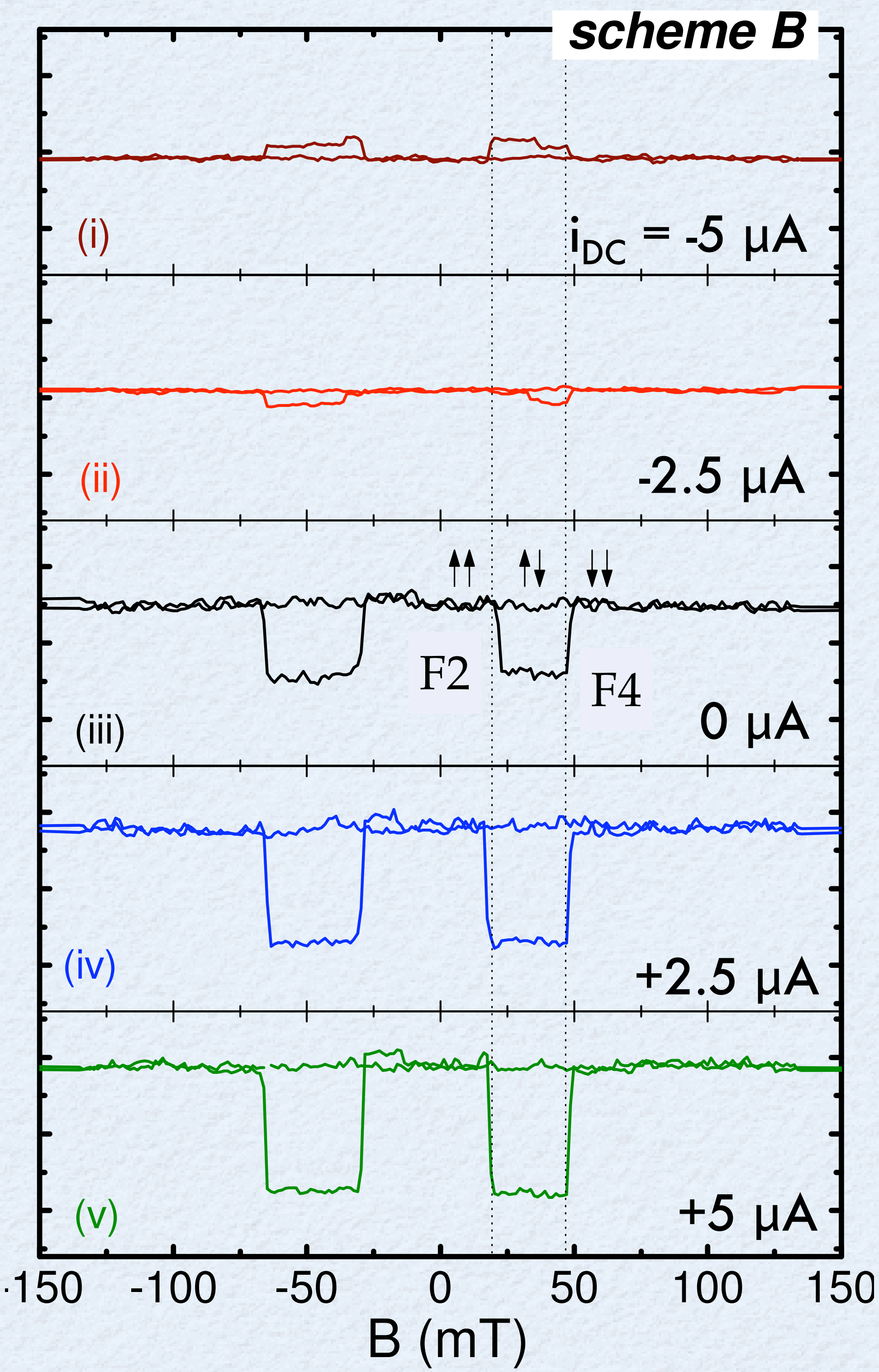
Al_2O_3

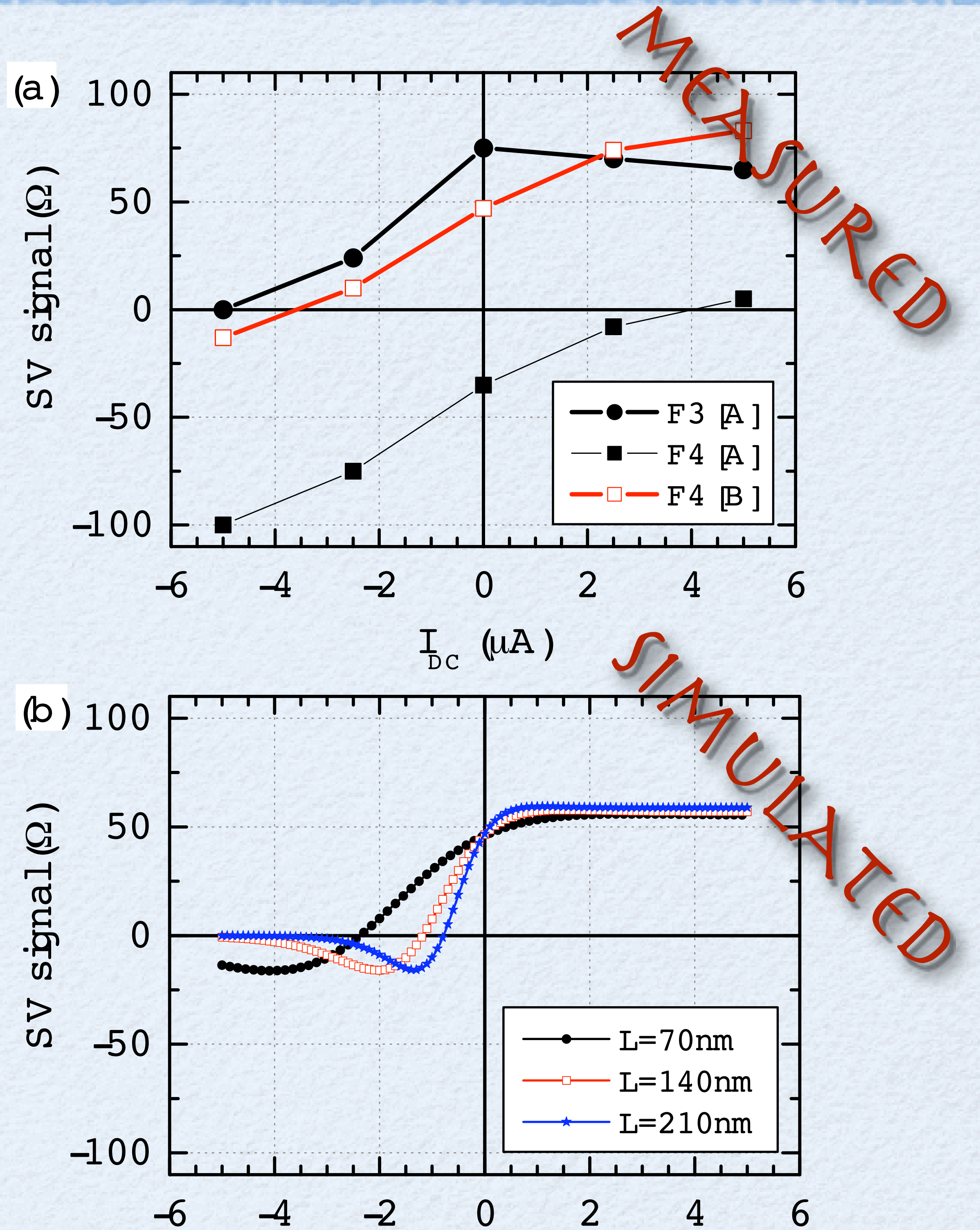
No Al_2O_3





Spin Valve & DC Bias - Measurements*

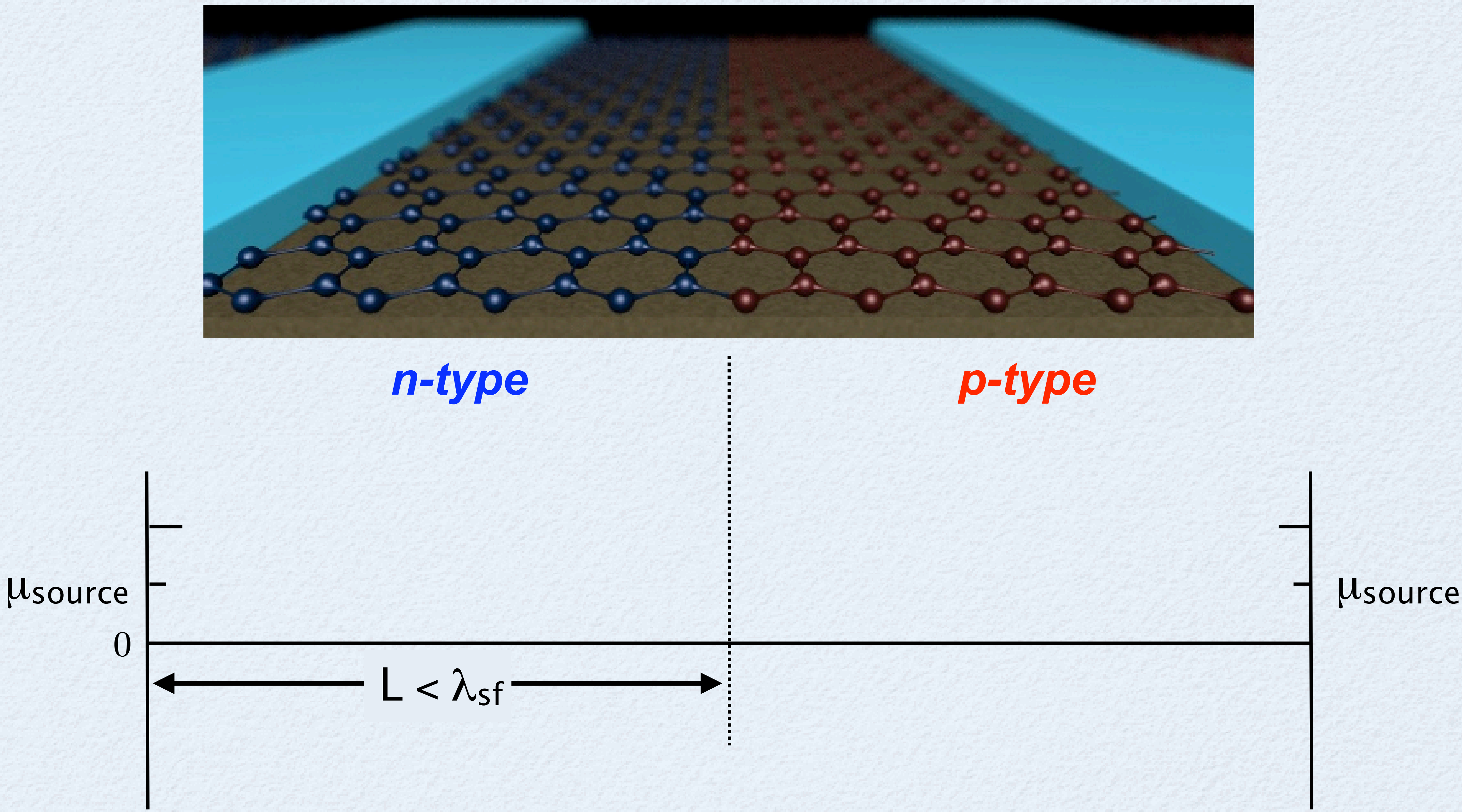




*C. Józsa et al., PRB 79, 081402(R) (2009)

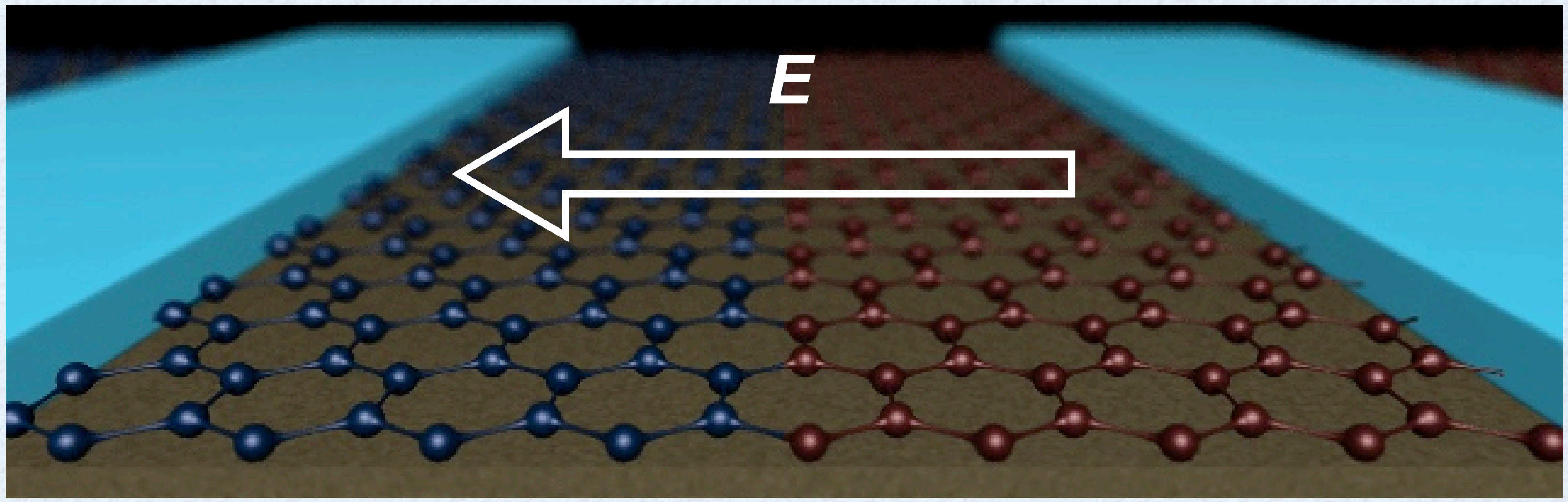
Graphene p-n junction: spin amplification device?

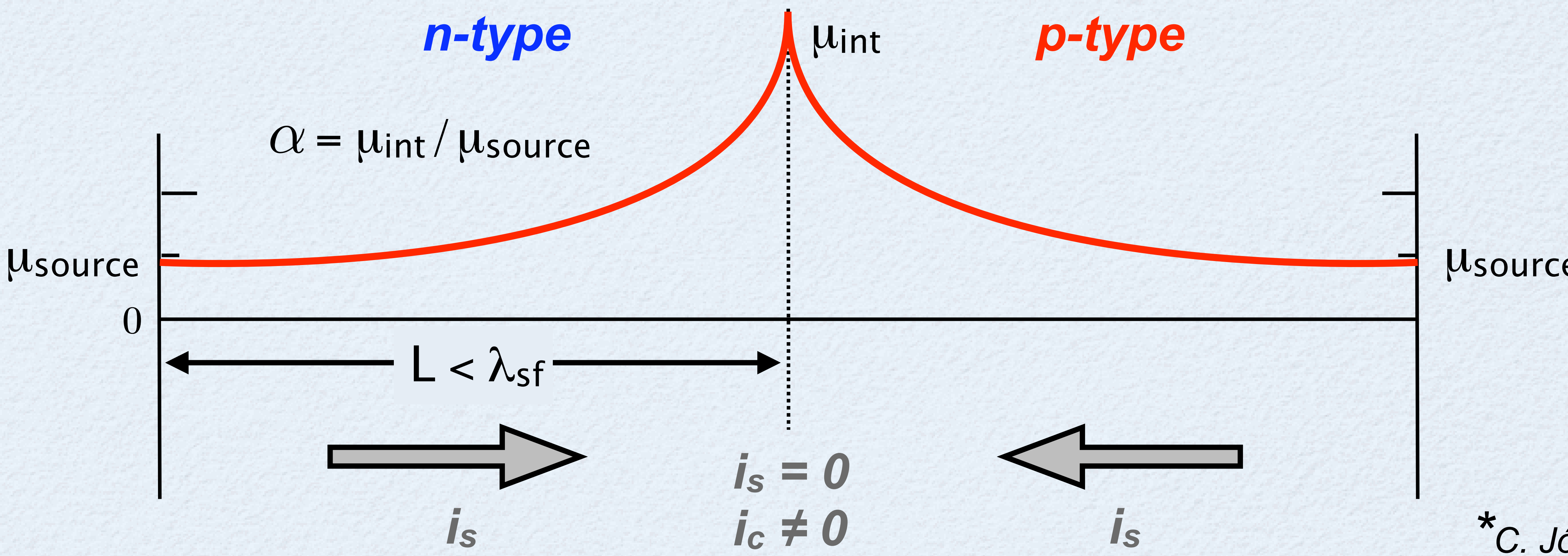
Spin Amplification Device*



*C. Józsa,
S.M. Watts & B.J. van Wees, in preparation

Spin amplification device*

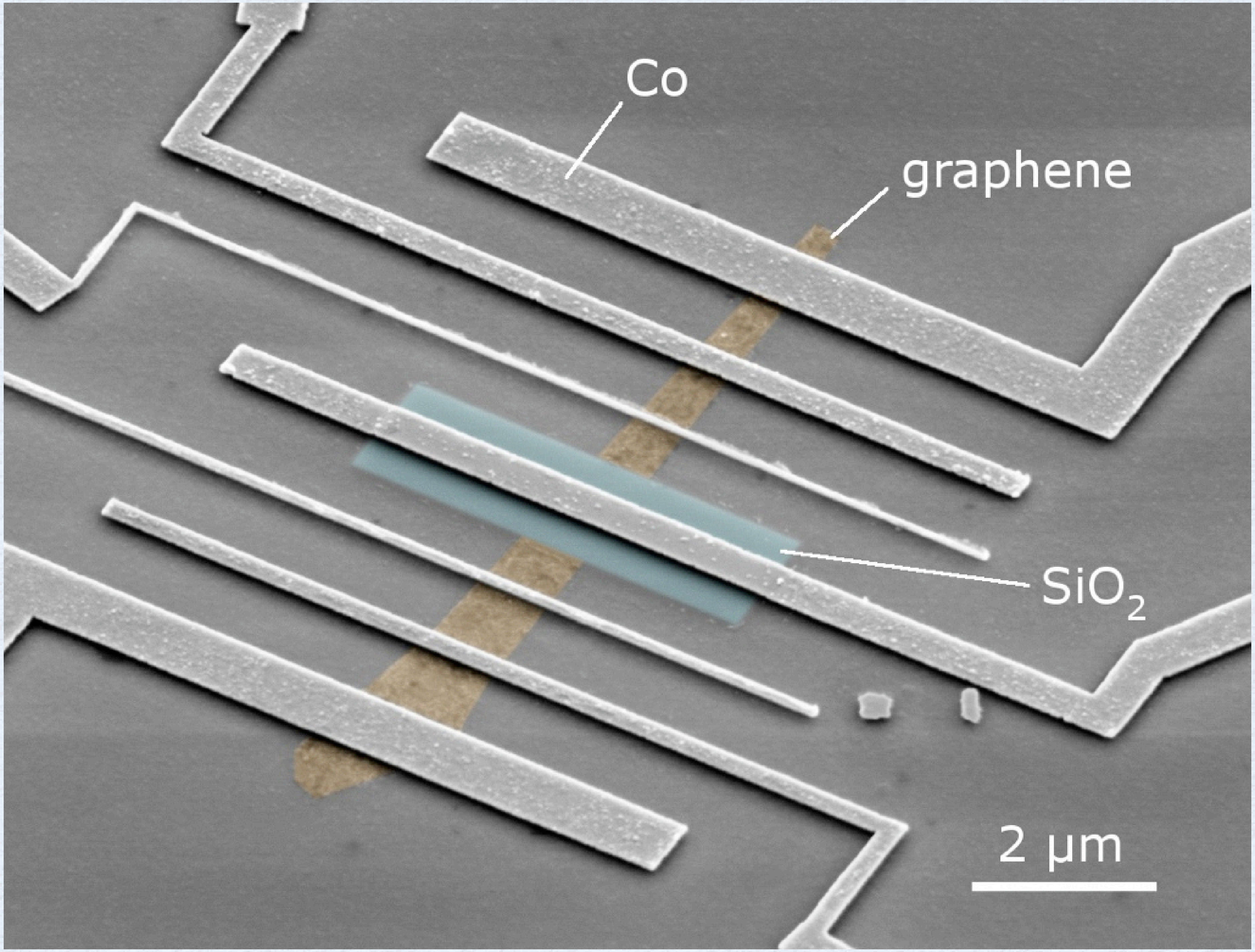




*C. Józsa, S.M. Watts & B.J. van Wees, in preparation

Spin amplification device: top gate?

Our first top-gated SV device; T. Maassen *et al*.



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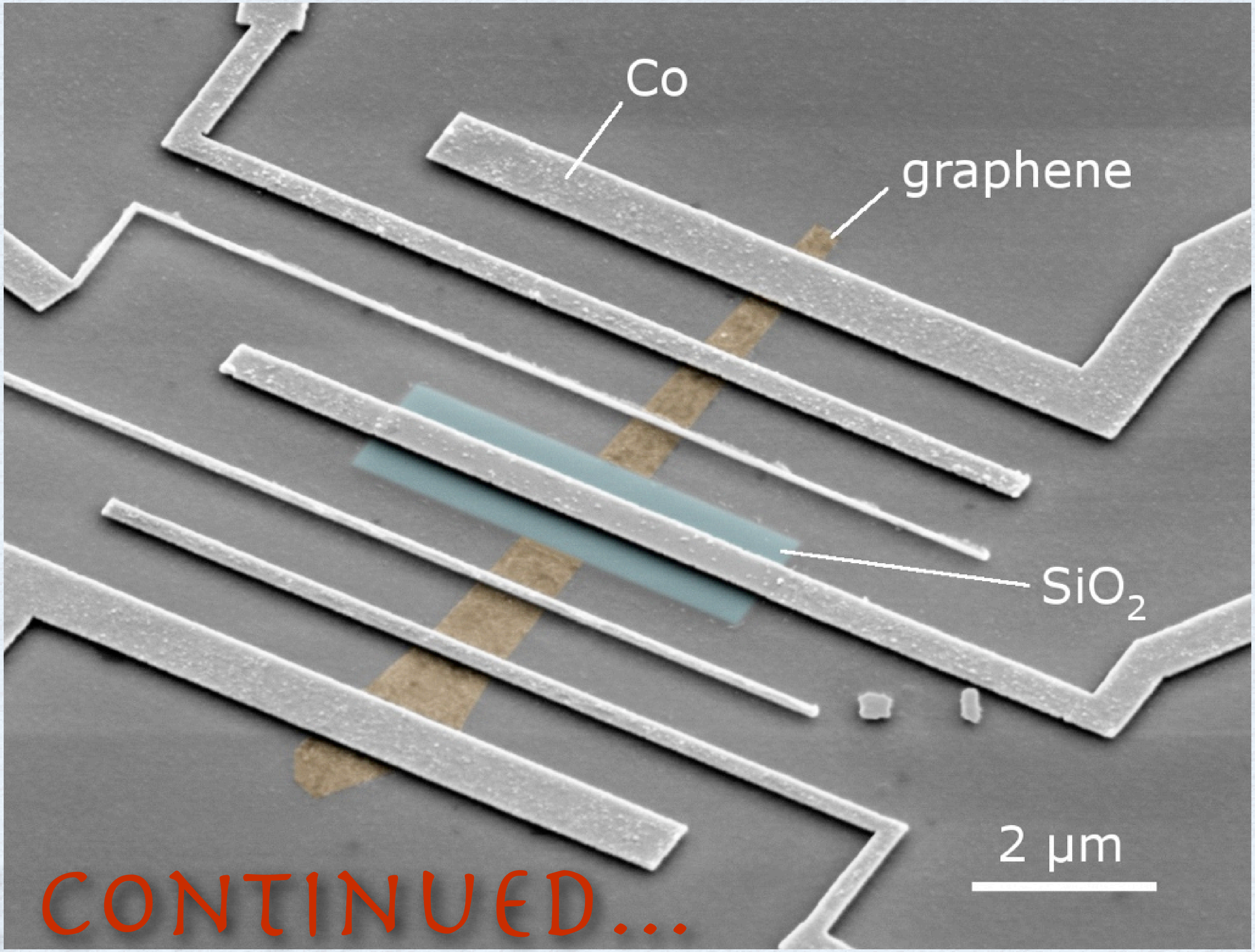

To be continued...

Summary

Spin vs. charge diffusion, relaxation anisotropy:

- No sign of spin Coulomb drag - weak e-e interactions;
- $\tau_s \leq 200$ ps, due to Elliott-Yafet;
- higher μ (cleaner+suspended graphene) -> $\lambda s \approx 100$ μm at RT.

Control on spin injection+transport:

- Carrier drift enhances transport/injection; signals $\approx 100\ \Omega$.

Spin amplification device:

- spin imbalance enhanced by drift in a p-n junction;
- plenty of questions at the neutrality point.

The Place


NETHERLANDS
Wadden Islands
Ameland
Schiermonnikoog
Terschelling
Vlieland
Texel
Harlingen
Groningen
Den Helder
Zwolle
Haarlem
Amsterdam
NORTH SEA
Enschede
Leiden
Utrecht
Den Haag
(The Hague)
Hoge Veluwe
The Randstad
Arnhem
Rotterdam
Breda
Delta Region
GERMANY
Tilburg
Middelburg
Eindhoven
0 30 km
0 20 miles
BELGIUM
Maastricht

THE PLACE


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Terschelling
Vlieland
Groningen

"Graphene team"-
also an acknowledgment

prof. Bart van Wees

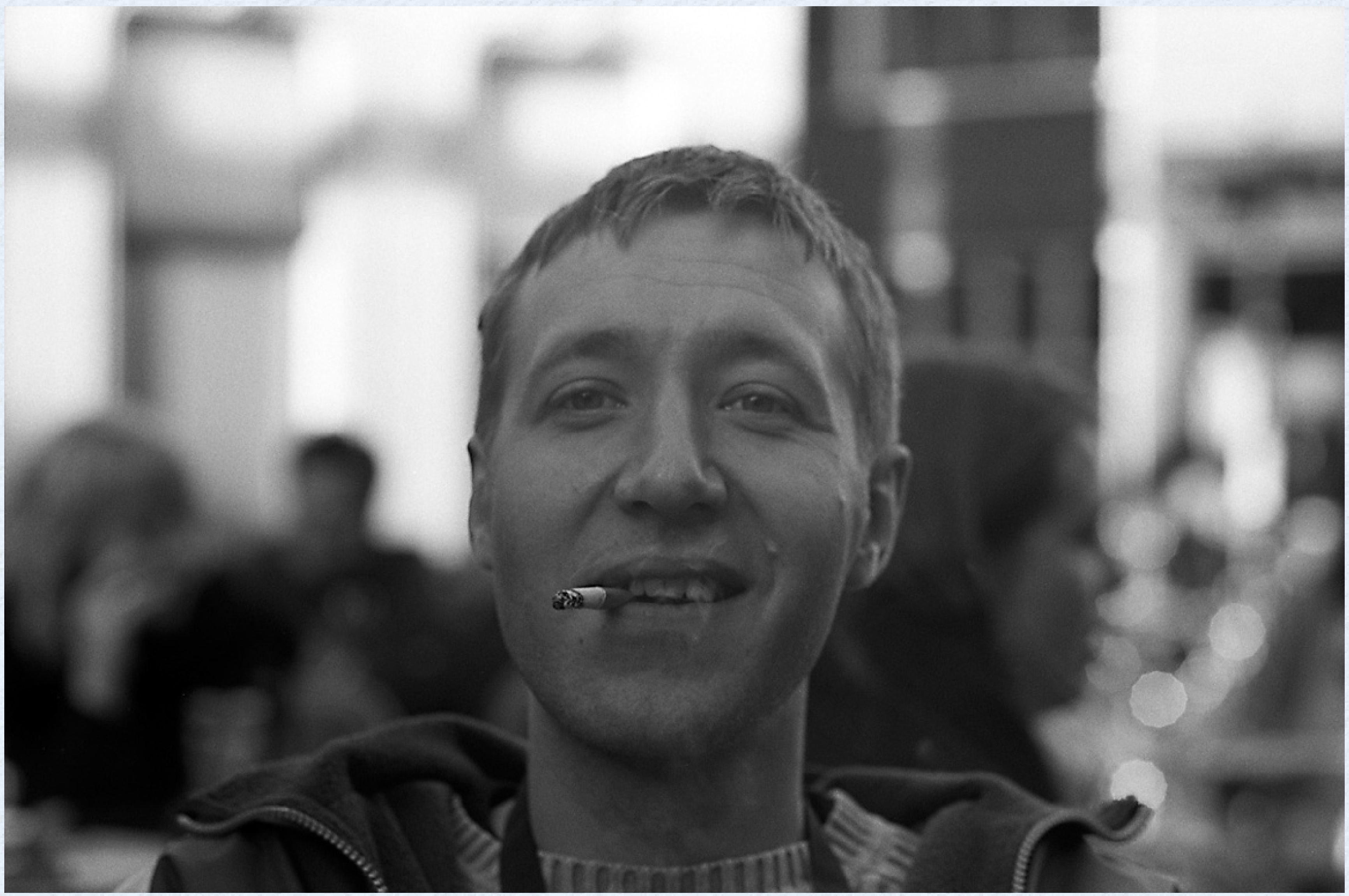
group leader

"Graphene Team"-
also an acknowledgment

Niko Tombros

lately a post-doc

"Graphene Team"-
also an acknowledgment



Mihai Popinciuc

now at RWTH Aachen

"GRAPHENE TEAM"-
ALSO AN ACKNOWLEDGMENT

Alina Veligura

somewhere in this room

"Graphene team"- also an acknowledgment

Thomas Maassen

somewhere in this room

"Graphene Team"-
also an acknowledgment

Steve Watts

now at Grandis Inc.
selling the spin

"Graphene team"-
also an acknowledgment

Paul Zomer

Shinichi Tanabe, now at NTT

THANK YOU.

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