Characterization and modeling of nano scaled semiconductor devices

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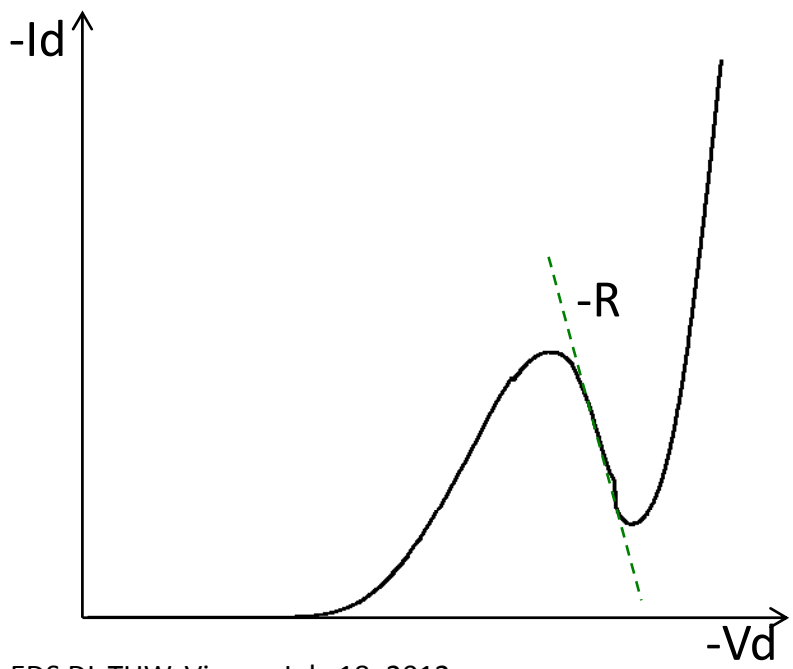
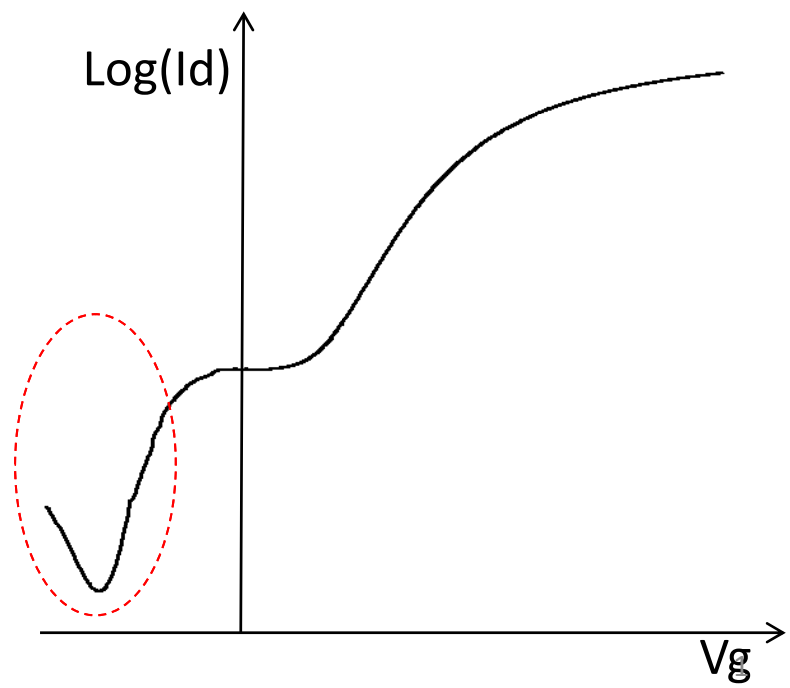


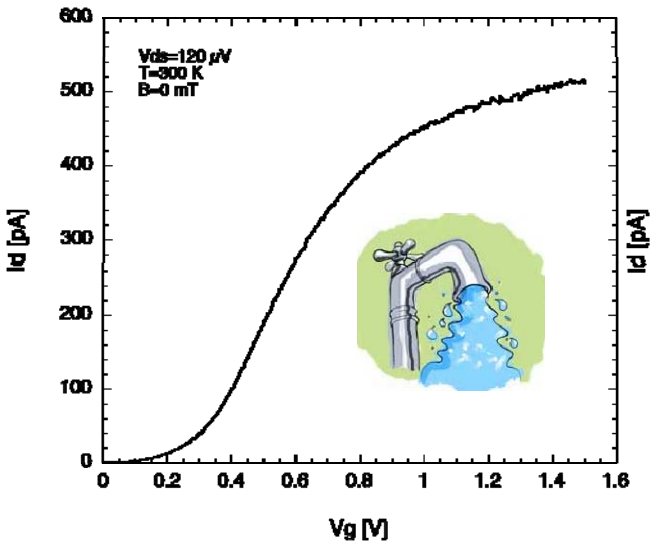


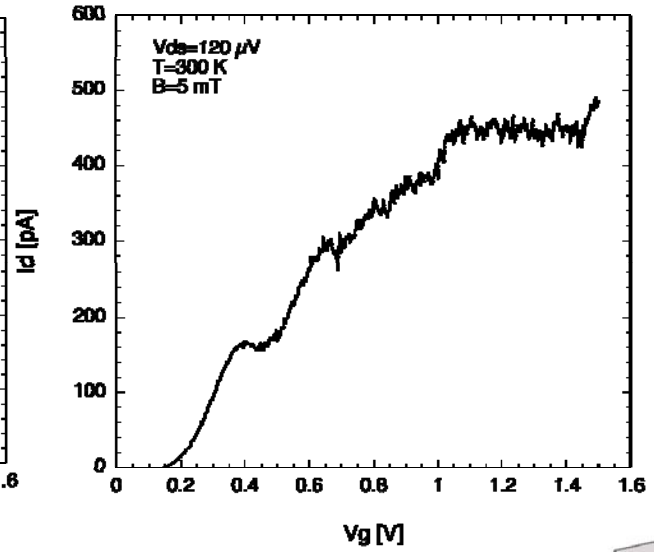
From a "*happy* and continuous" trip to a "discrete journey"

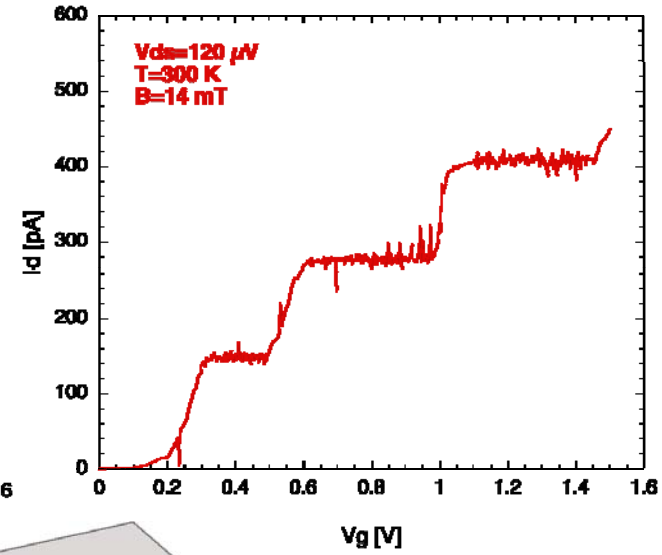
B=0 mT **B=5 mT** **B=140mT**

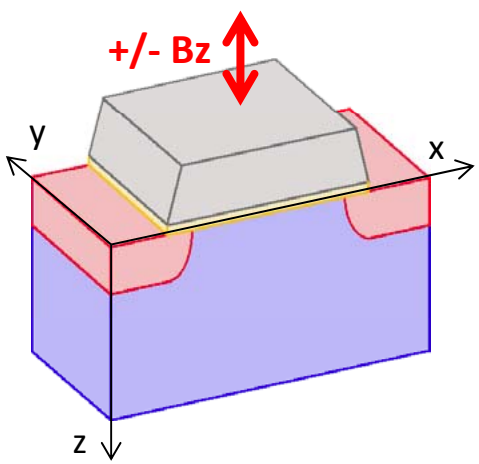
(W/L)=(10nm/44nm)
tri-gate FinFet

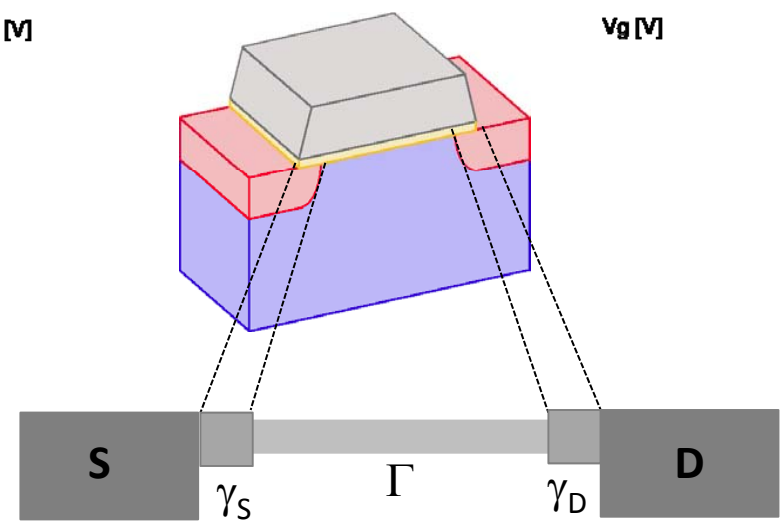
40 x 176 = 7040 atoms!



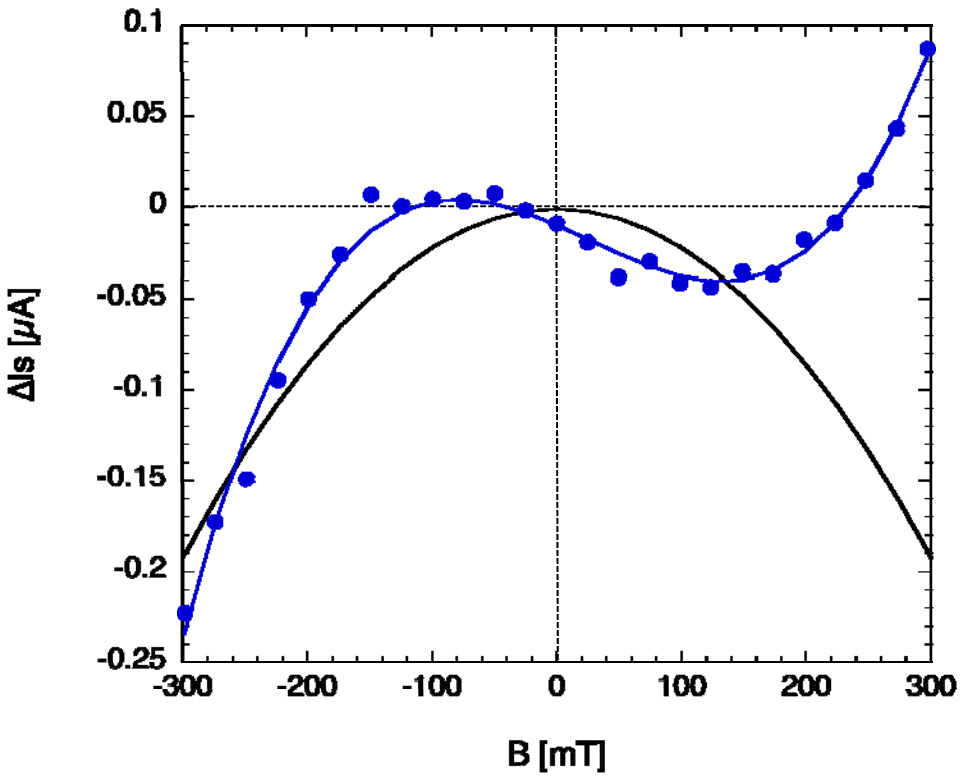


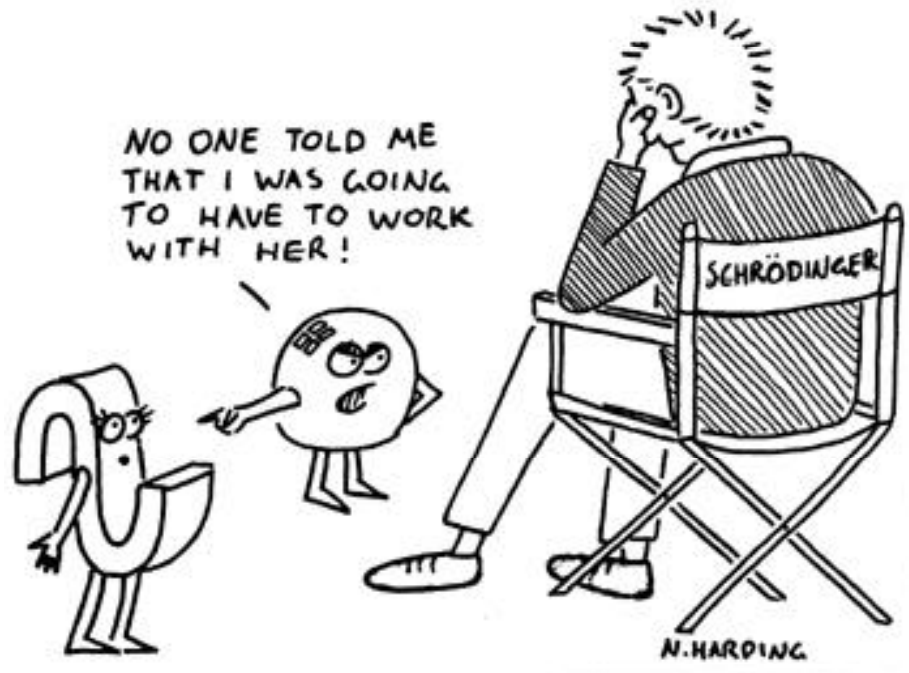




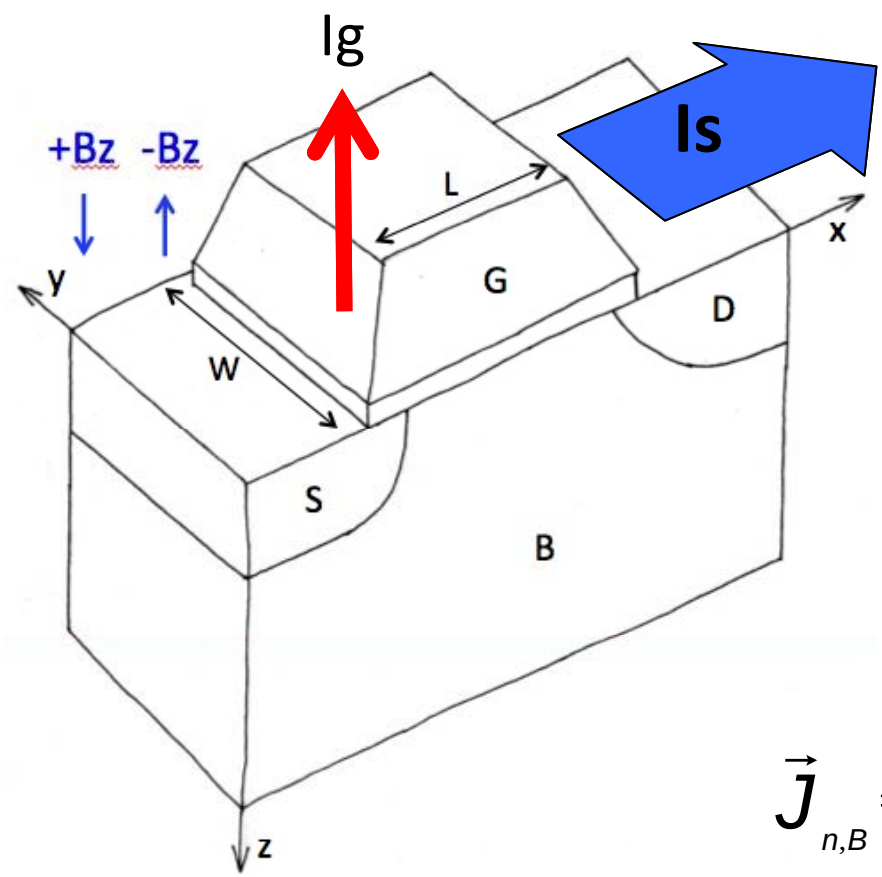


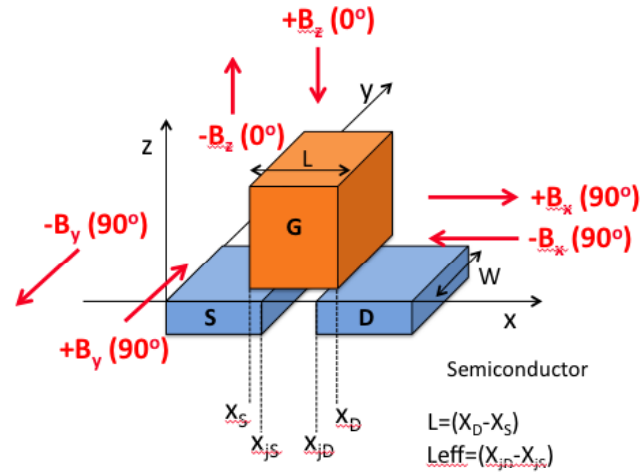
Magneto transport in nanoscopic devices





The experimental setup and the conventional model





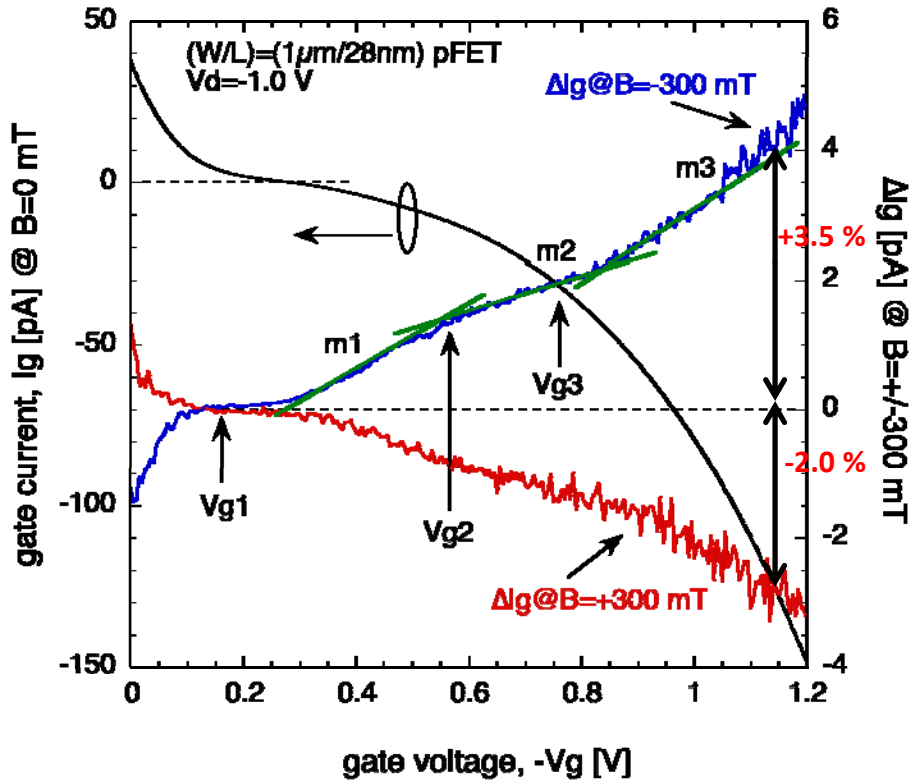
$$\sigma = \frac{\sigma_0}{1+\left(\omega_c \tau\right)^2}\begin{pmatrix} 1 & -\omega_c \tau & 0 \\ \omega_c \tau & 1 & 0 \\ 0 & 0 & 1+\left(\omega_c \tau\right)^2 \end{pmatrix}$$

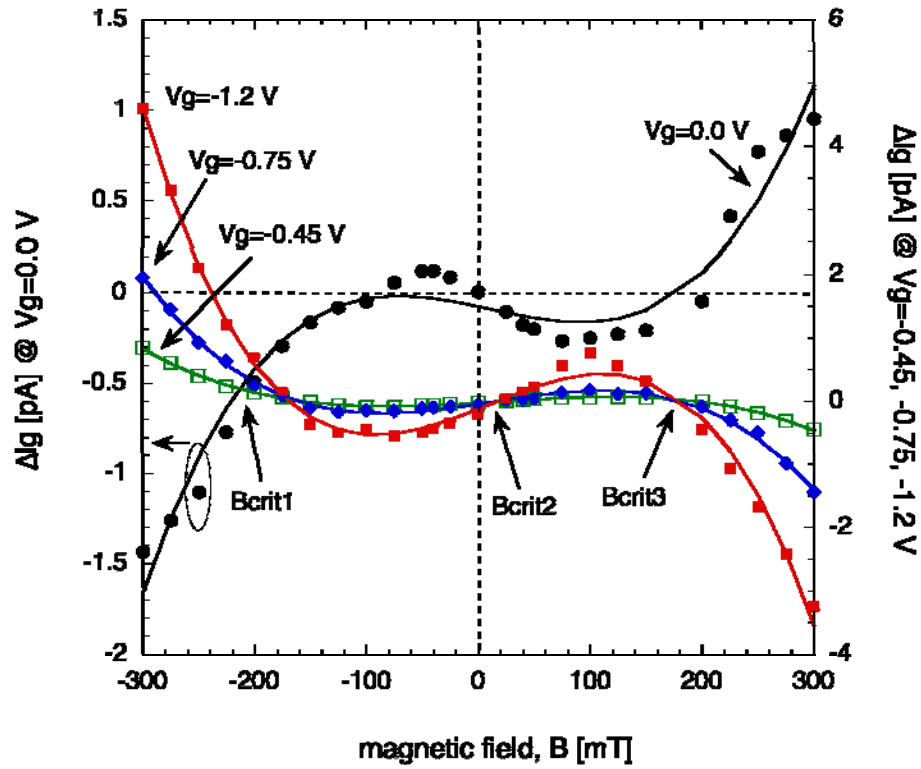
$$\vec{J}_{n,B} = \frac{\vec{J}_{n,0} + \mu_n^*\left(\vec{J}_{n,0} \times \vec{B}\right) + \left(\mu_n^*\right)^2\left(\vec{B} \bullet \vec{J}_{n,0}\right)\vec{B}}{1+\left(\mu_n^* B\right)^2}$$

Experimental results

Magneto modulated gate tunneling current

$$\Delta Ig = (Ig_{B\neq 0} - Ig_{B=0})$$

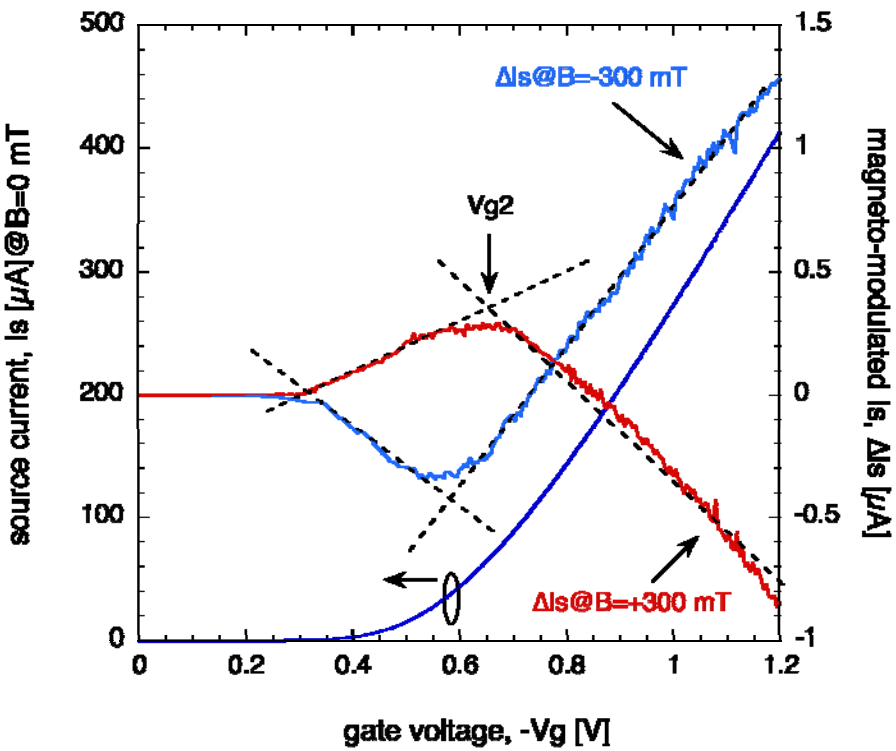


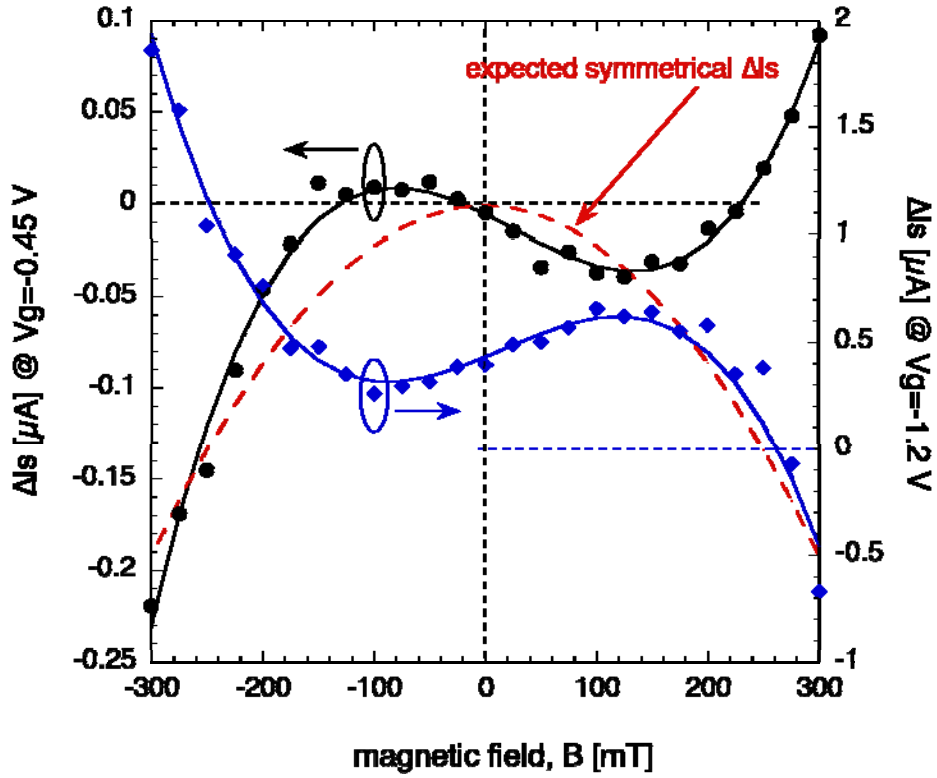


Experimental results

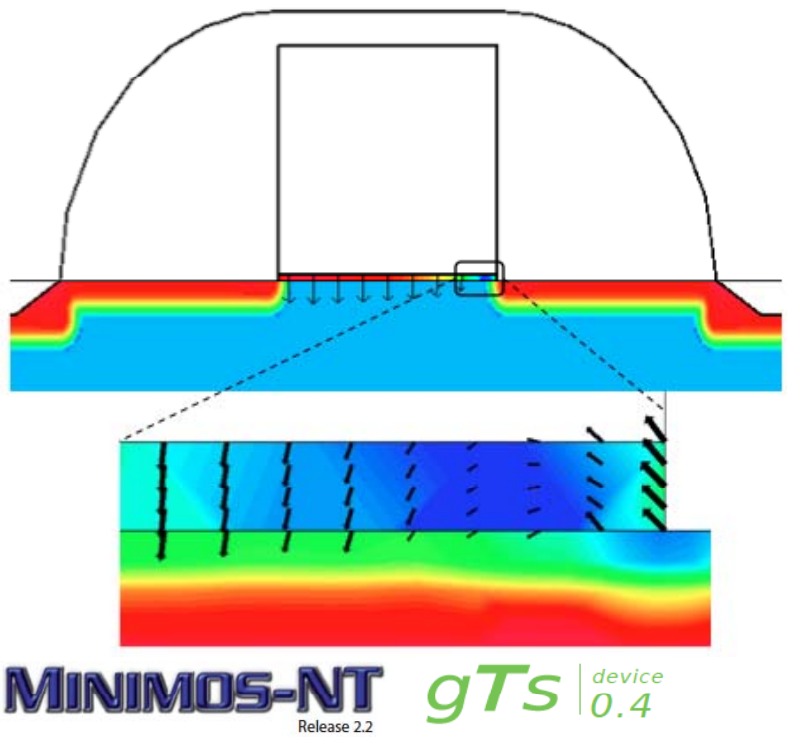
Magneto modulated channel current

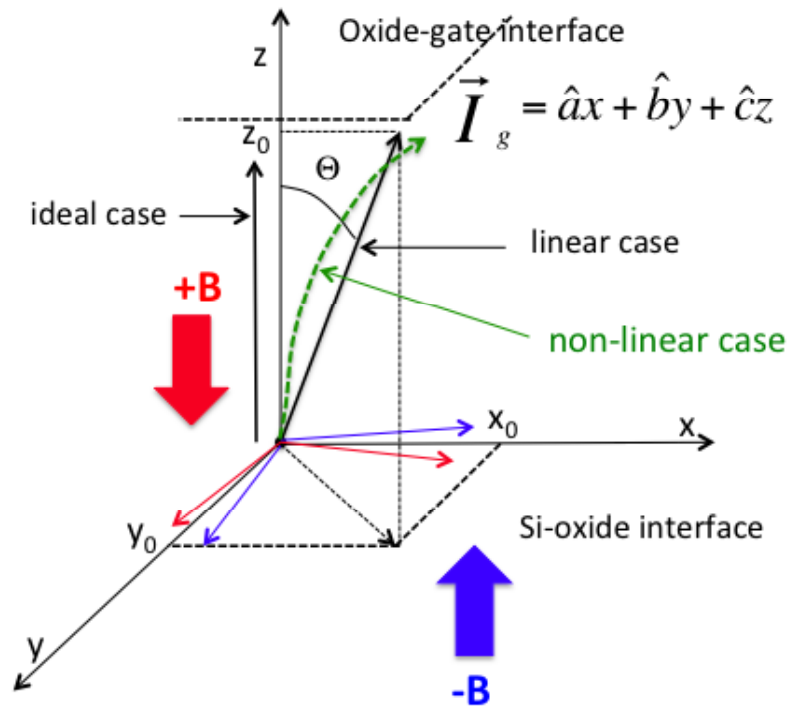
$$\Delta Is=(Is_{B\neq 0}-Is_{B=0})$$





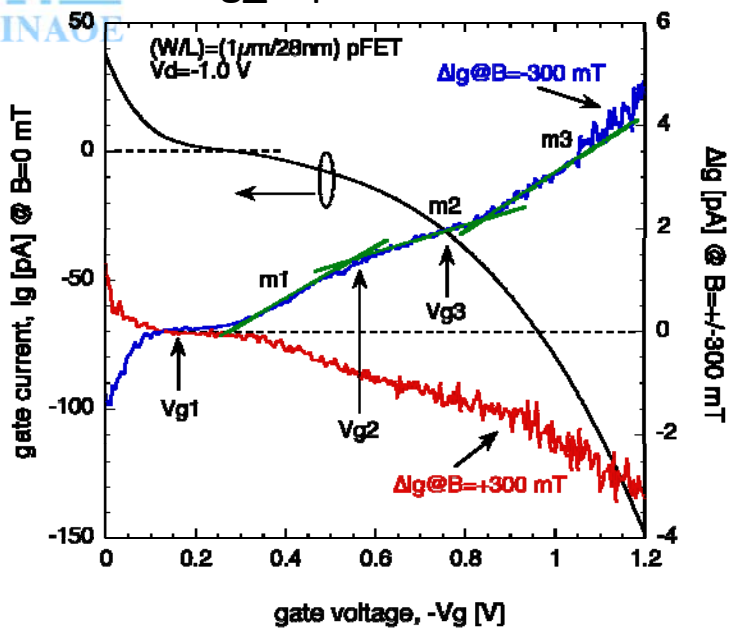
Modeling & simulation



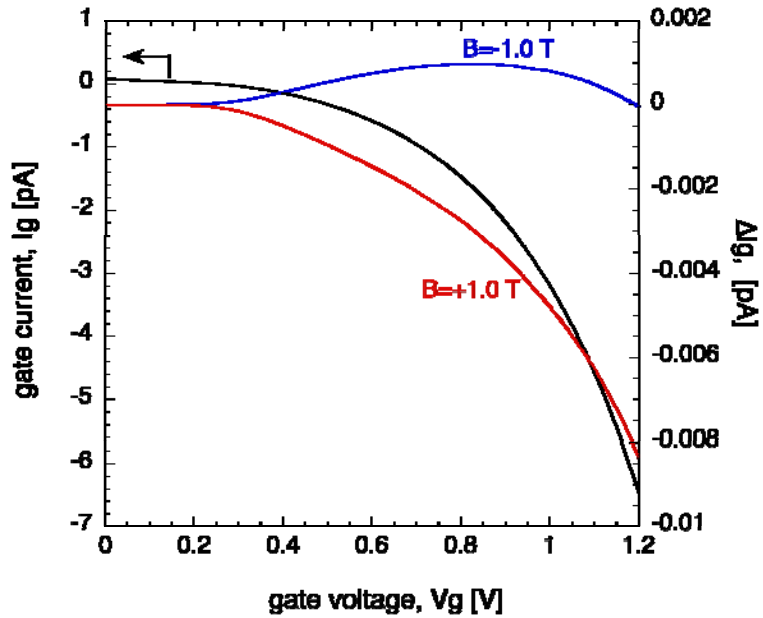


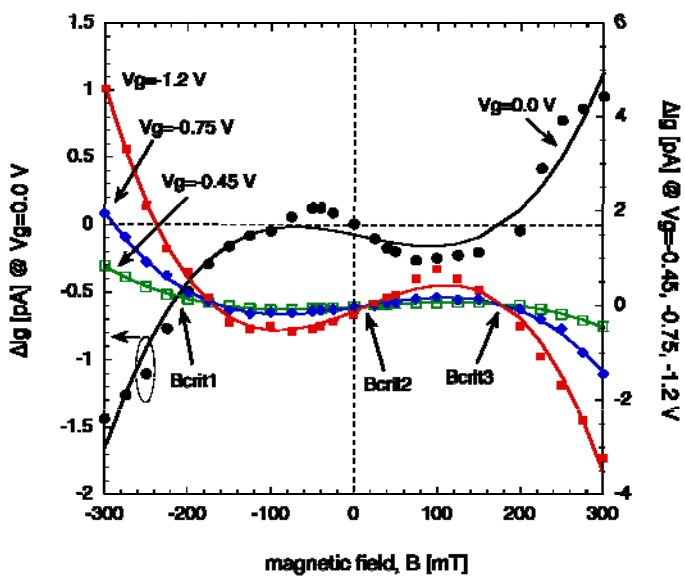
Model versus experiment

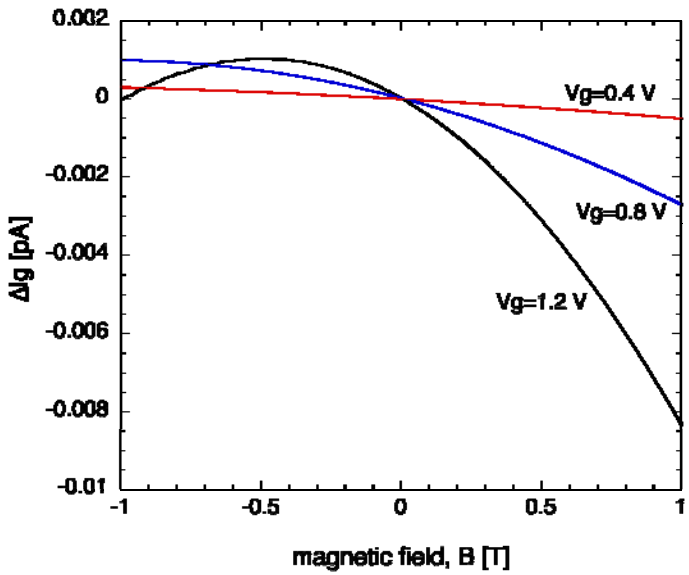
ΔIg_experimental



model

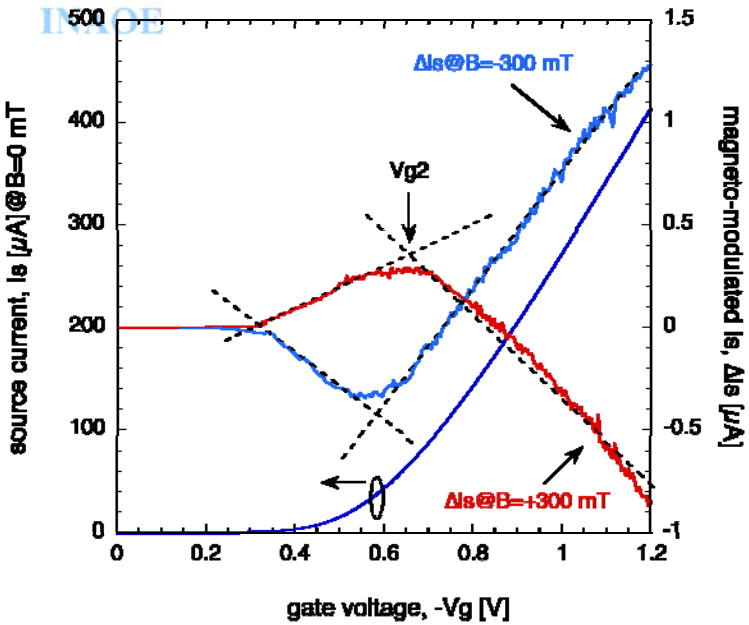




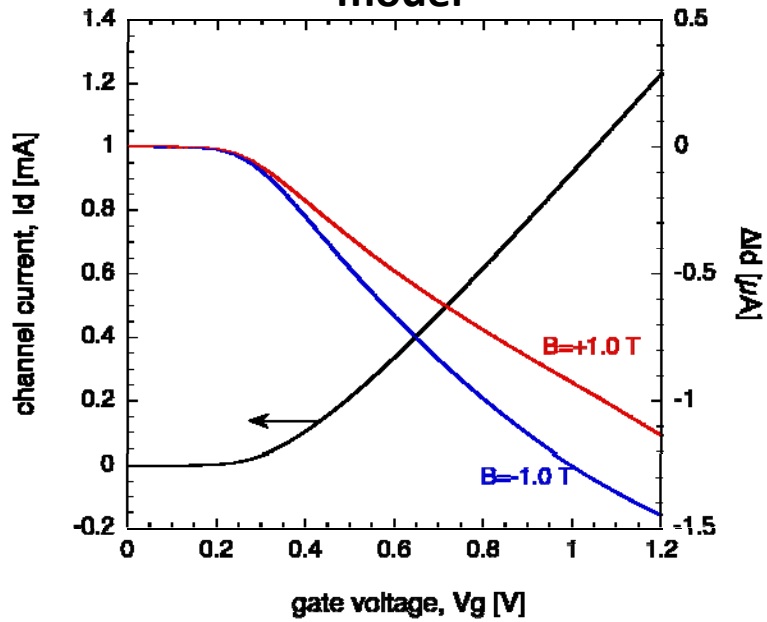


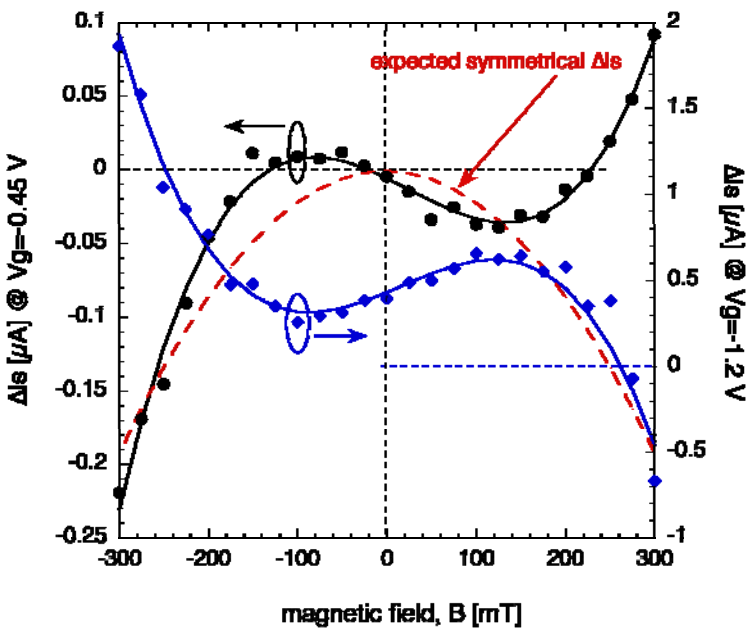
Model versus experiment

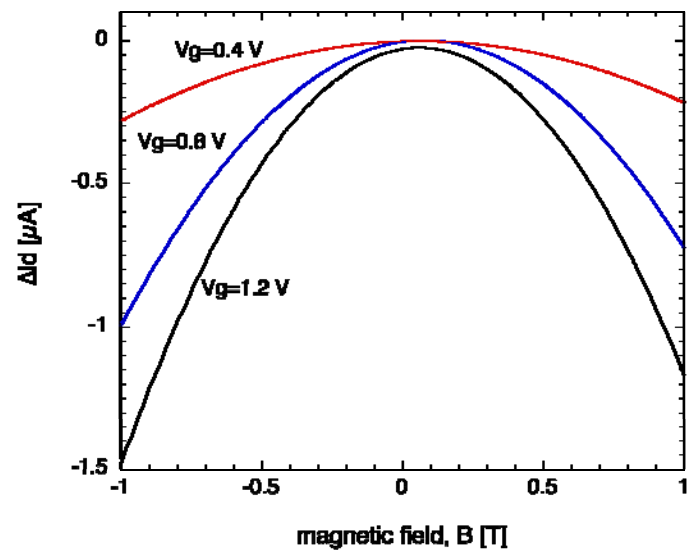
ΔId_experimental



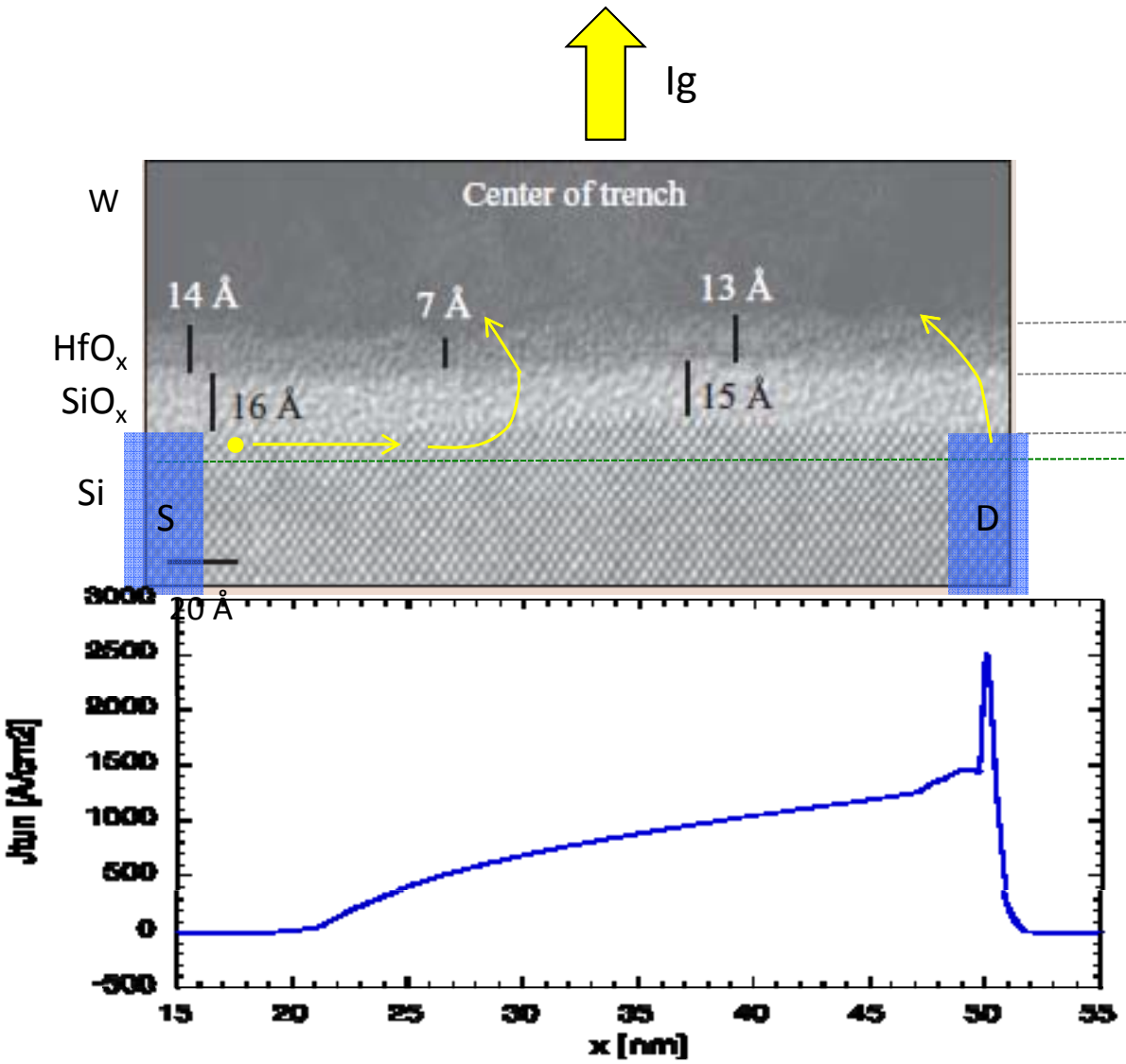
model

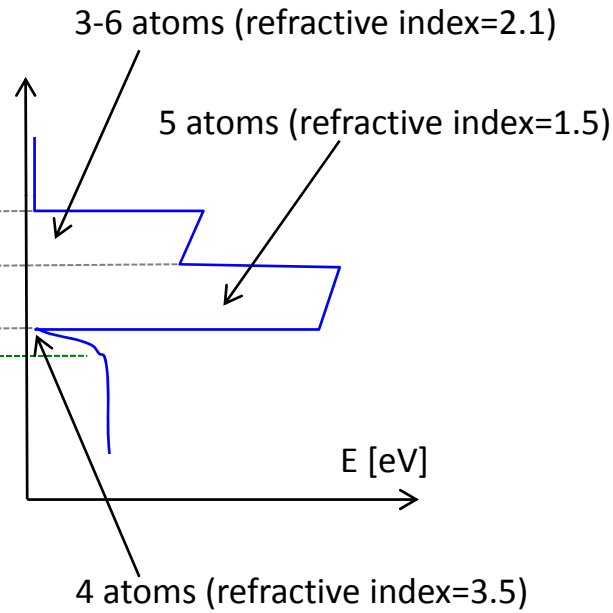






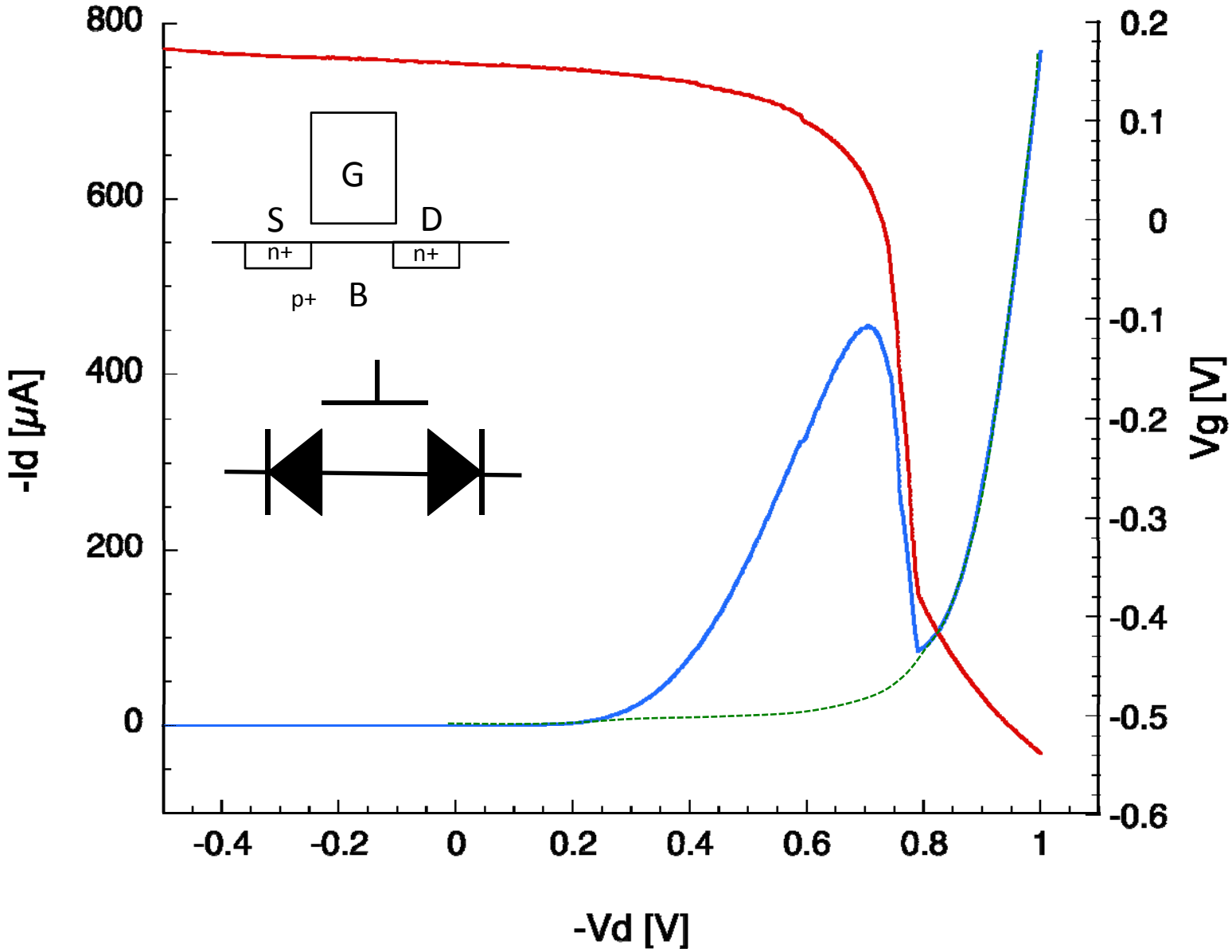
The oxide potential needs to be adapted



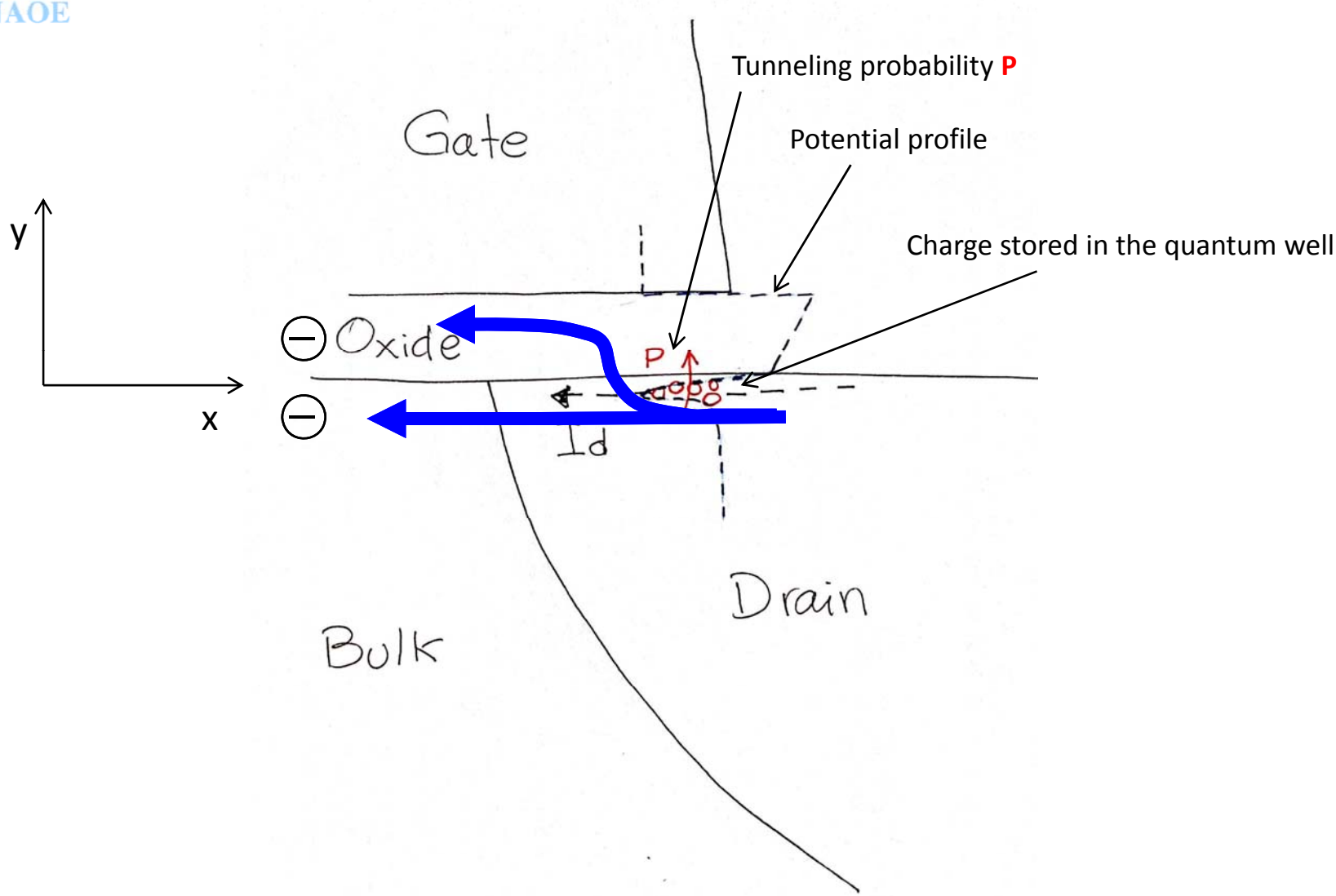


$$J_{tun} = J_0 \int_{Ei}^{Ef} T(E) \cdot N(E) dE$$

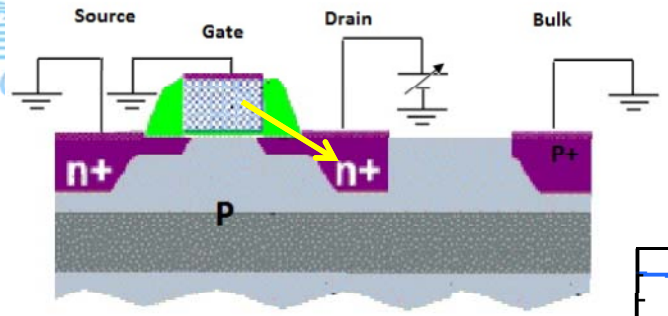
Floating gate nFET*

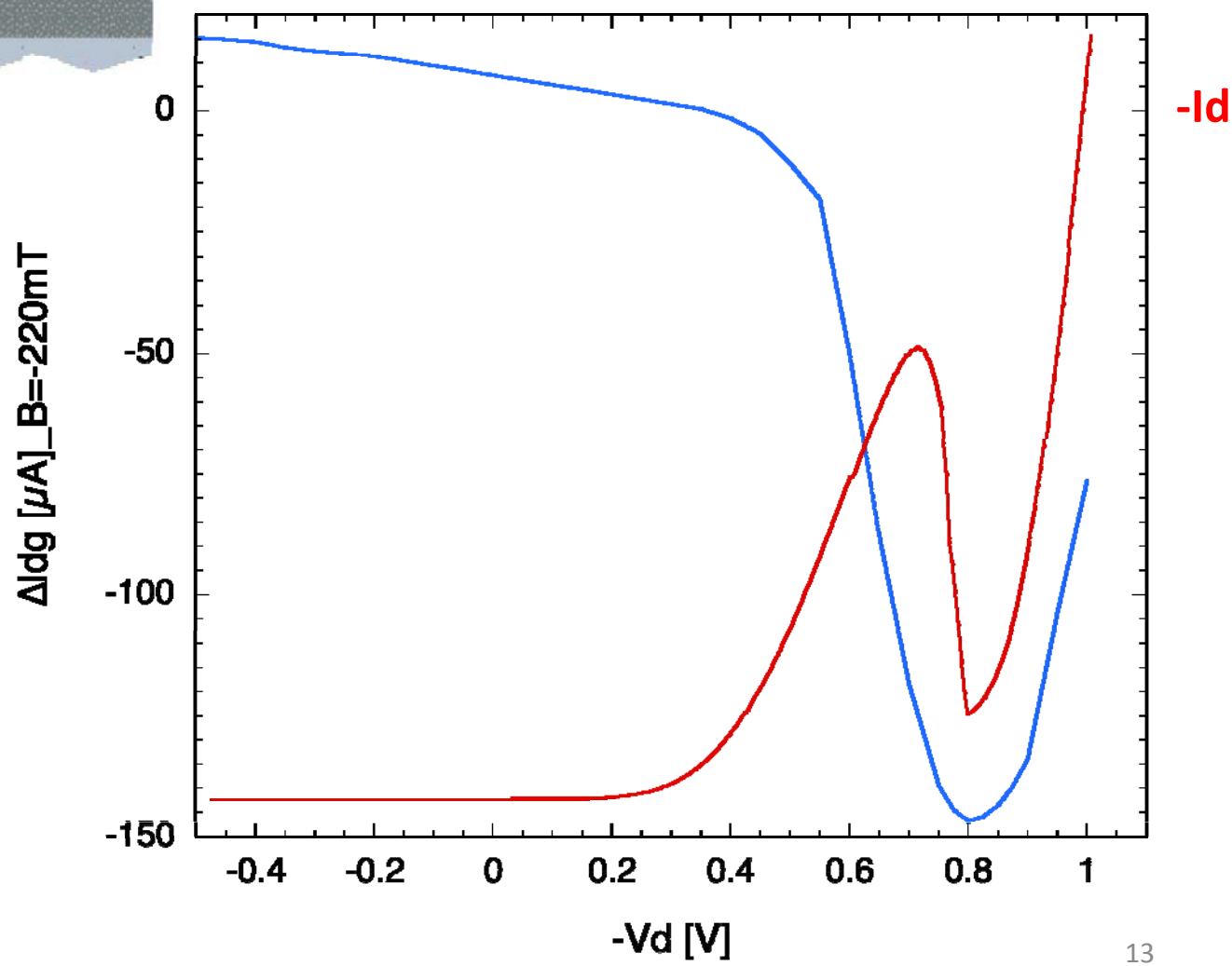


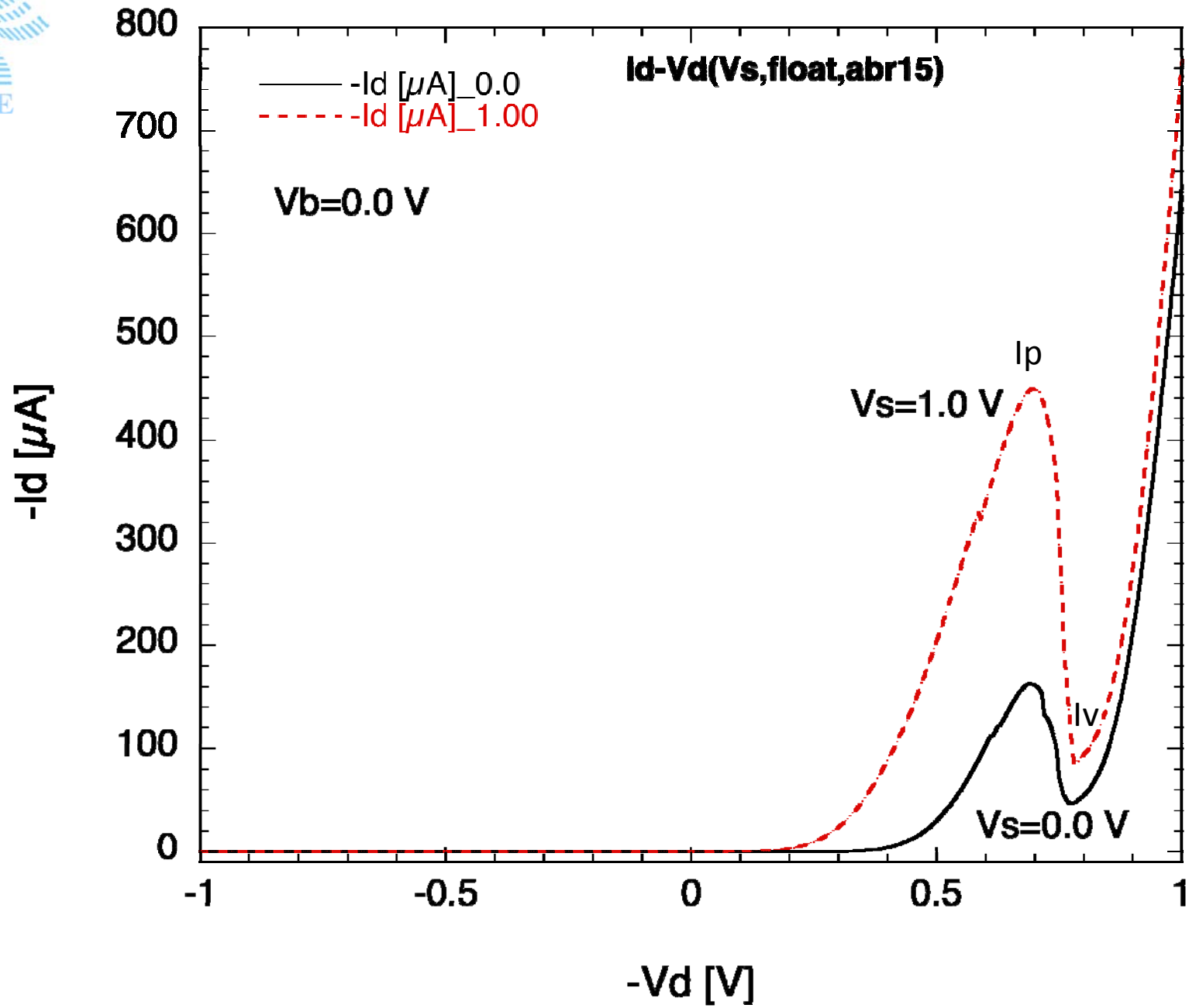
*A Silicon Wave Field Effect Transistor **WaveFET** patent FIS820120227 in process


Tunneling probability P
Potential profile
Charge stored in the quantum well
Gate
y
x
Oxide
P
Id
Drain
Bulk

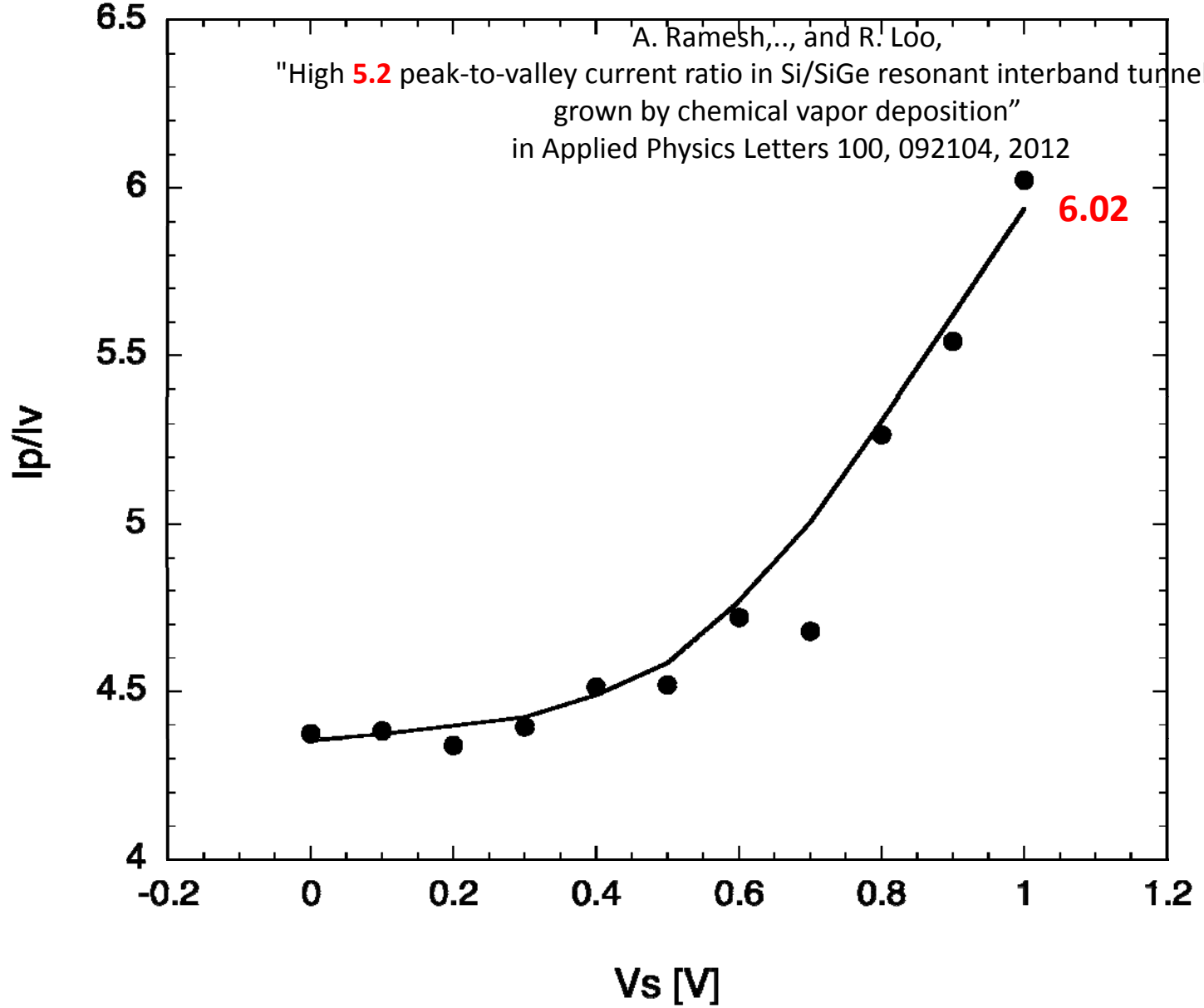
Gate-to-drain magneto modulated tunneling current

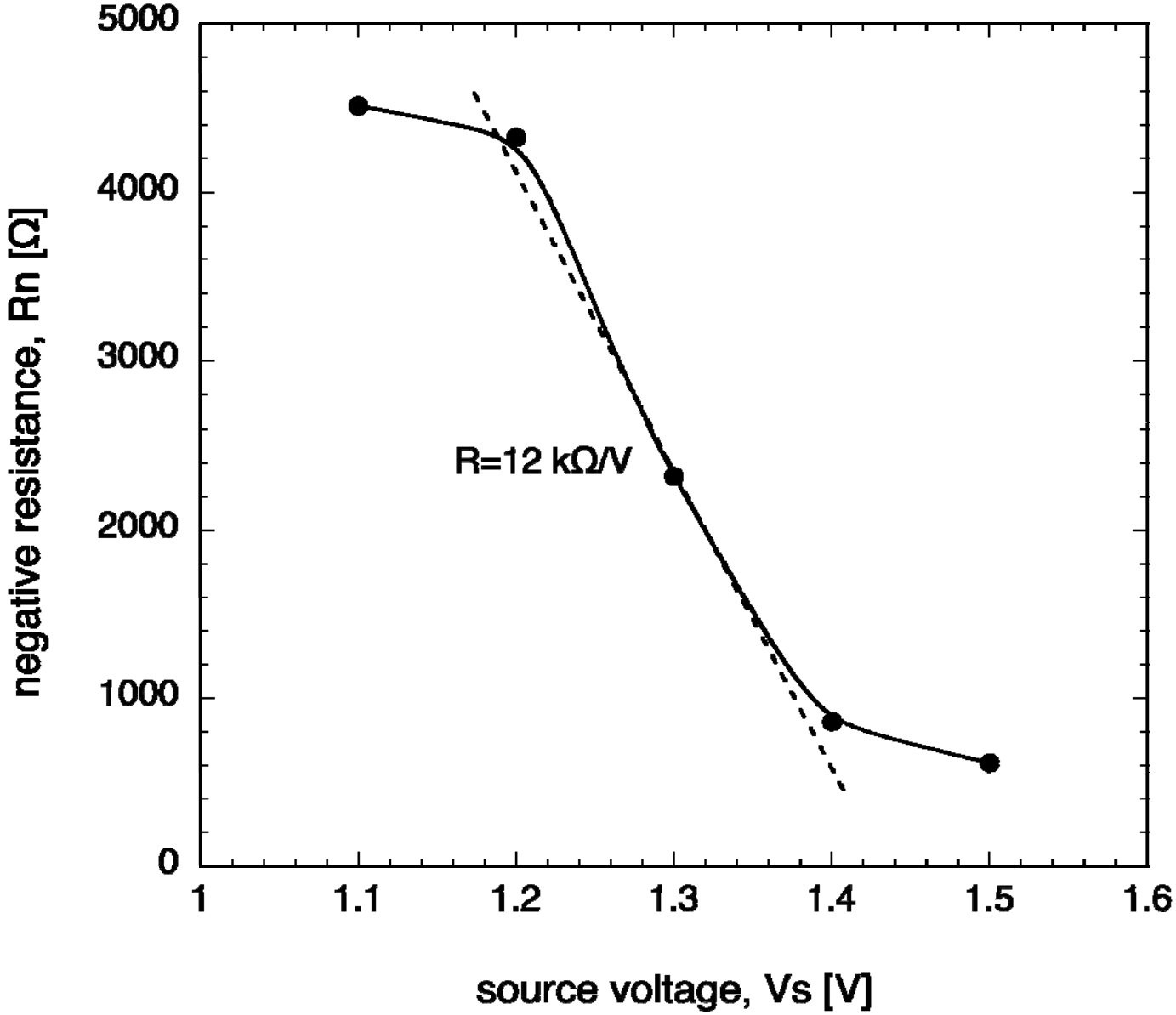




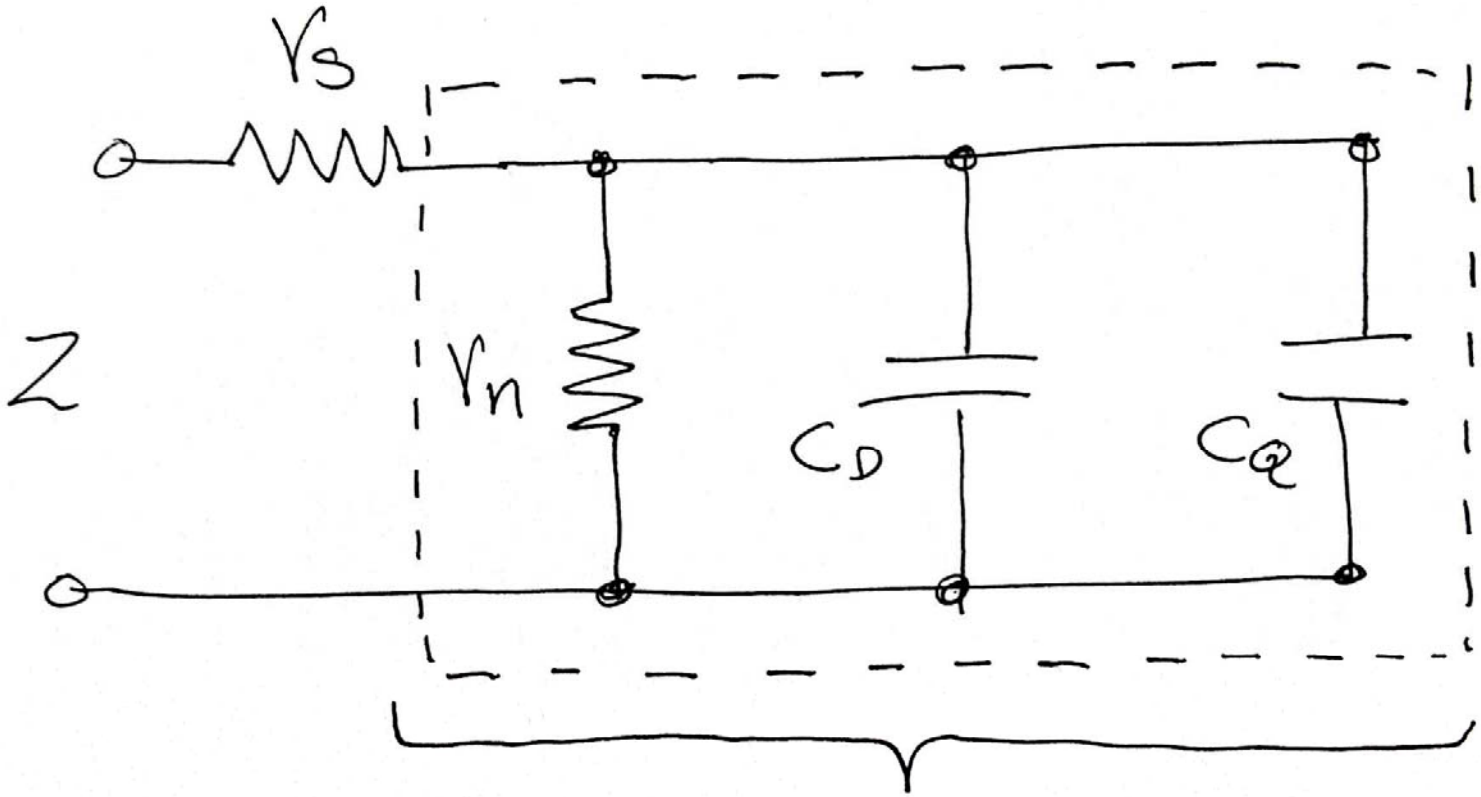

Id-Vd(Vs,float,abr15)
-Id [μA]_0.0
-Id [μA]_1.00
Vb=0.0 V
Ip
Vs=1.0 V
Iv
Vs=0.0 V
-Id [μA]
-Vd [V]
800
700
600
500
400
300
200
100
0
-1
-0.5
0
0.5
1

Peak-to-valley current ratio Ip/Iv



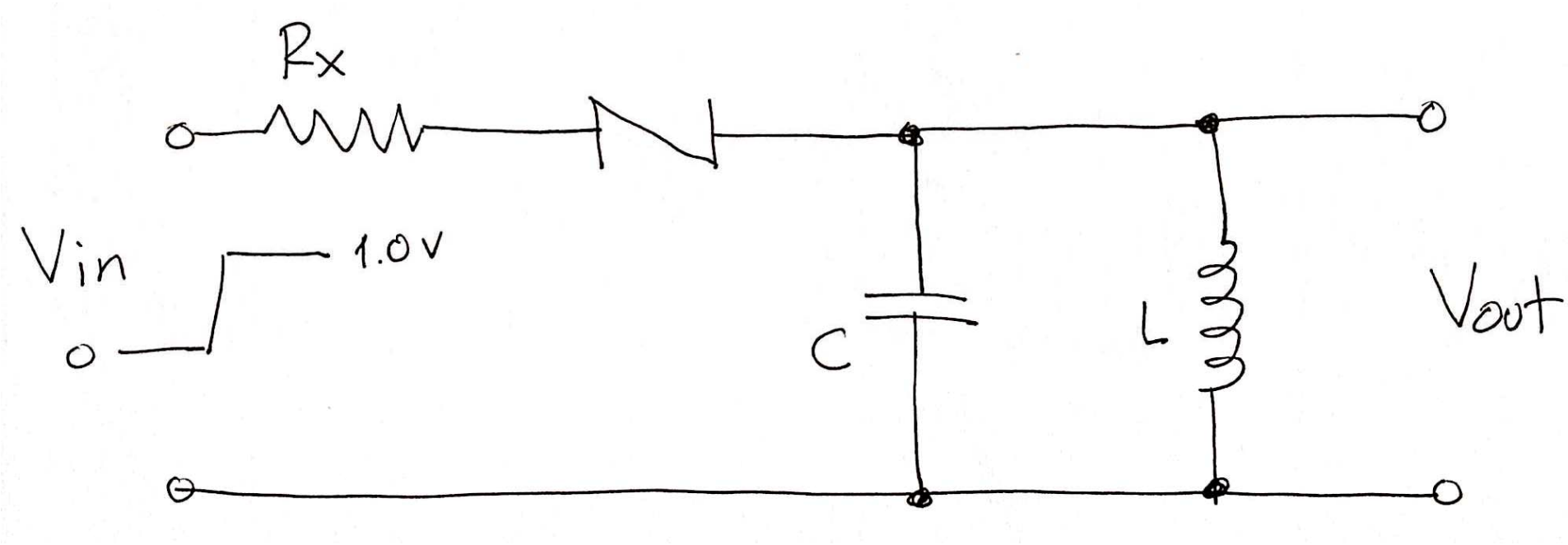

5000
4000
3000
2000
1000
0
1
1.1
1.2
1.3
1.4
1.5
1.6
negative resistance, Rn [Ω]
source voltage, Vs [V]
R=12 kΩ/V

SPICE Macro model



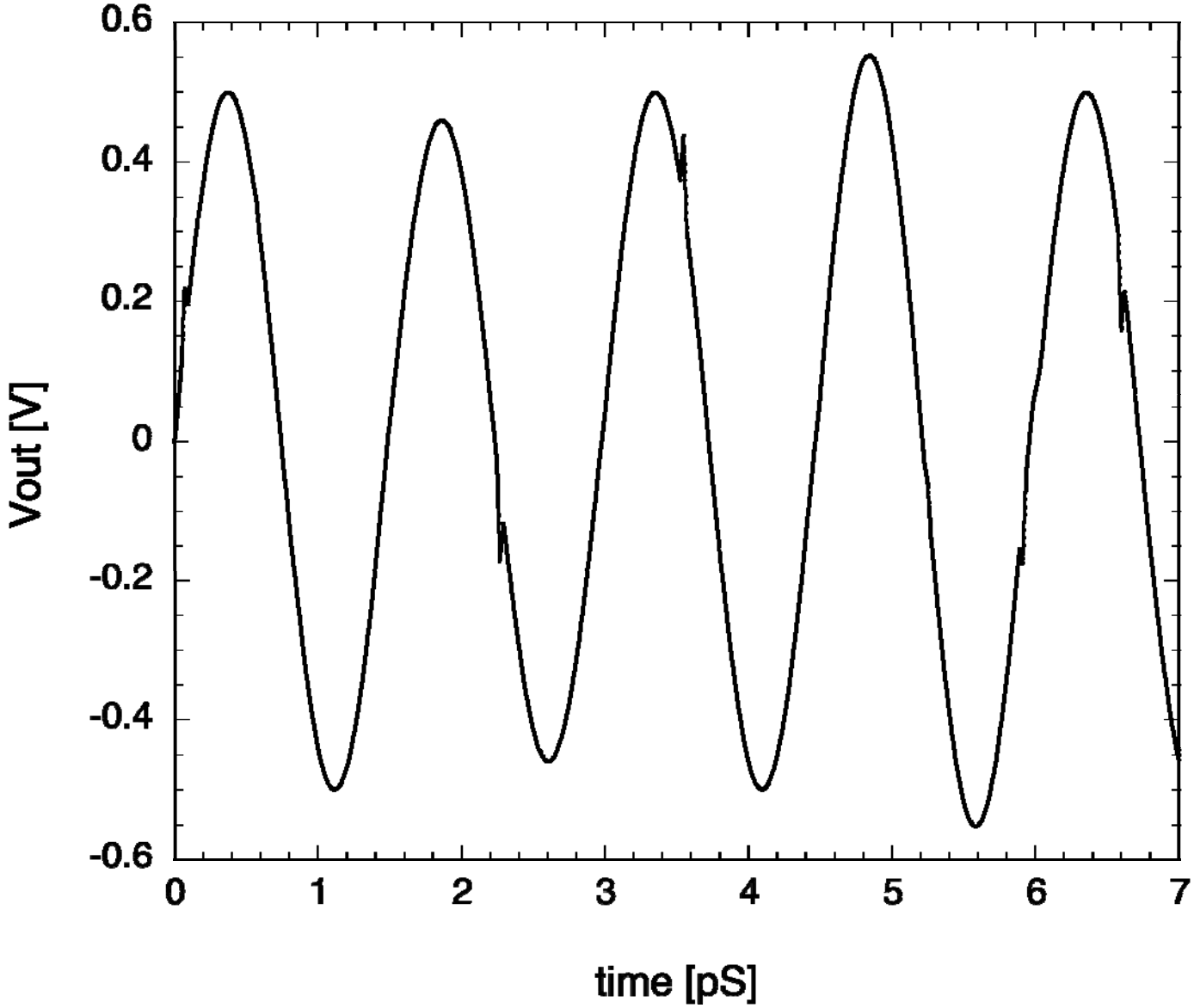
r_n=negative resistance
C_D=depletion capacitance
C_Q=quantum well-barrier capacitance
r_s=external series resistance

Oscillator circuit



R_X=15 Ω, C=1.8 fF, L=50 pH

SPICE simulation



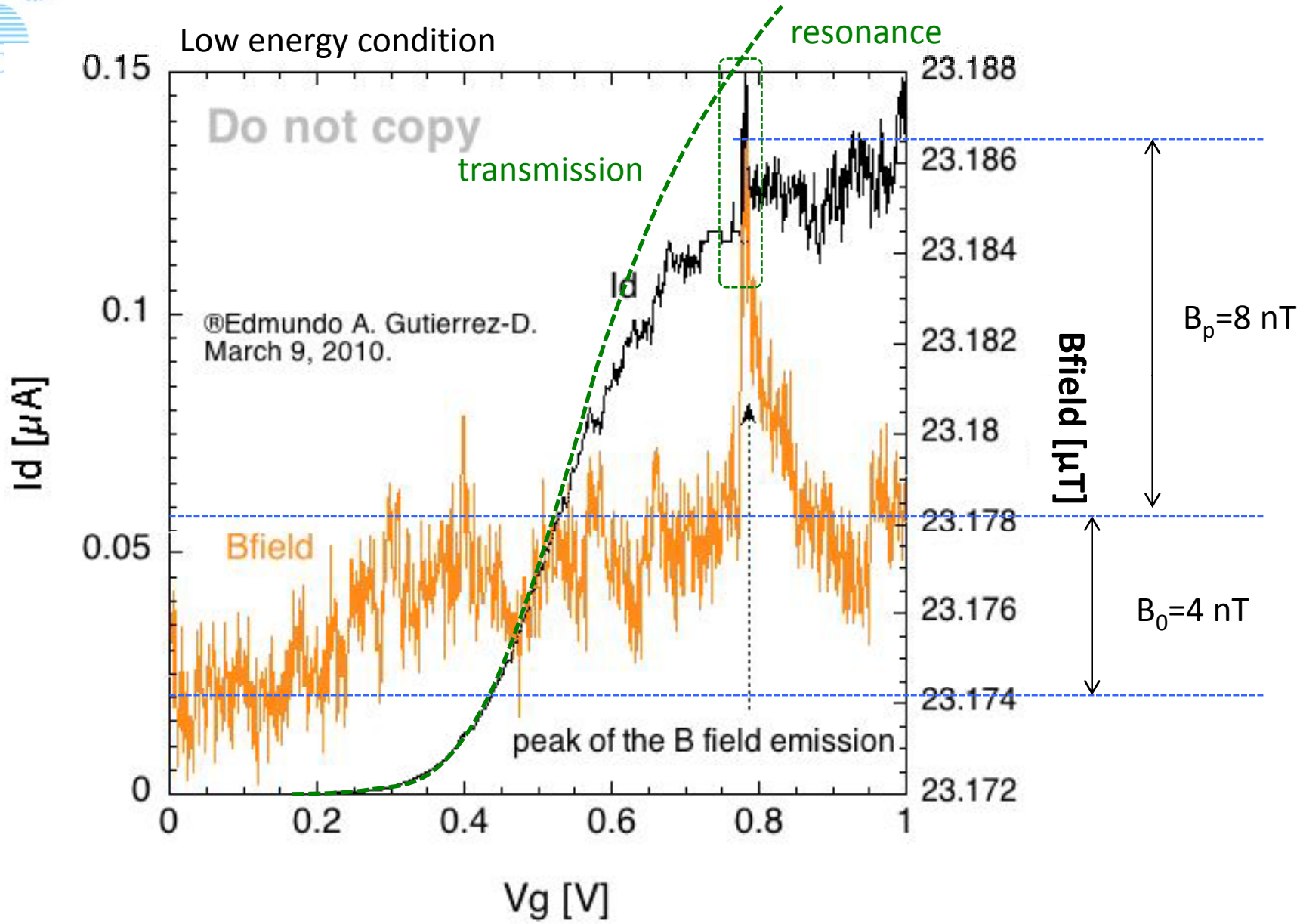
Comments

Distortions of the Vout comes from the quantum well-barrier capacitance system, which is a function of the charge redistribution that in turns is a function of the Vd and Vs voltage.

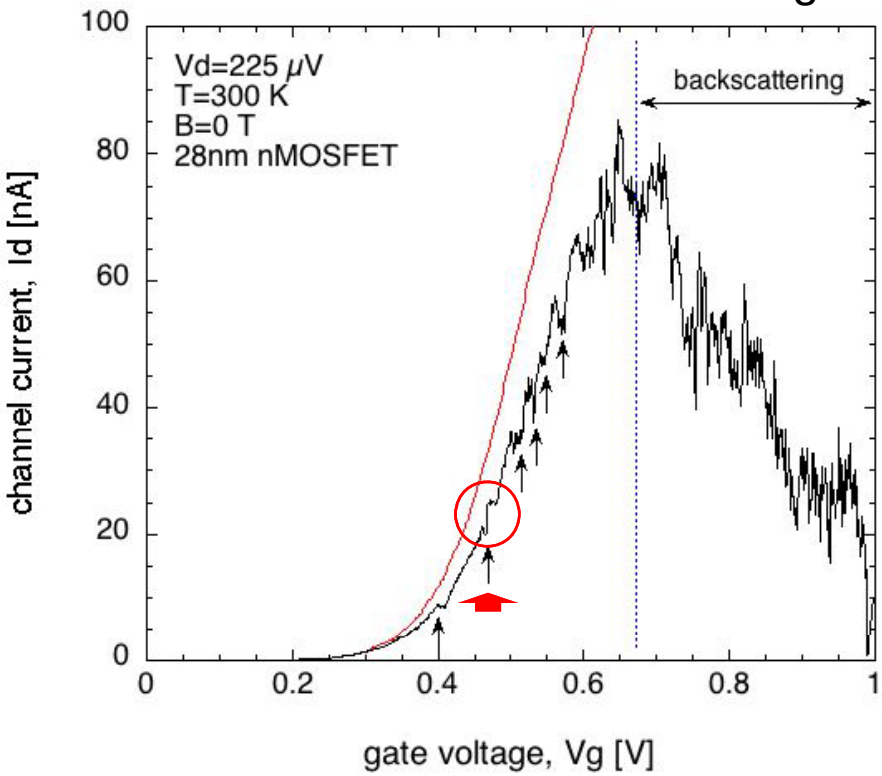
The maximum frequency of oscillation *f* can be, in a simple approach, calculated according to the following model. In our particular case, *f* is close to 0.9 THz, but it can go higher depending on the bias conditions, and the development of a more adequate macro model.

$$f = \frac{1}{2\pi\left(\left|r_n\right| \cdot \left(C_D + C_Q\right)\right)} \cdot \sqrt{\frac{\left|r_n\right|}{r_s} - 1}$$

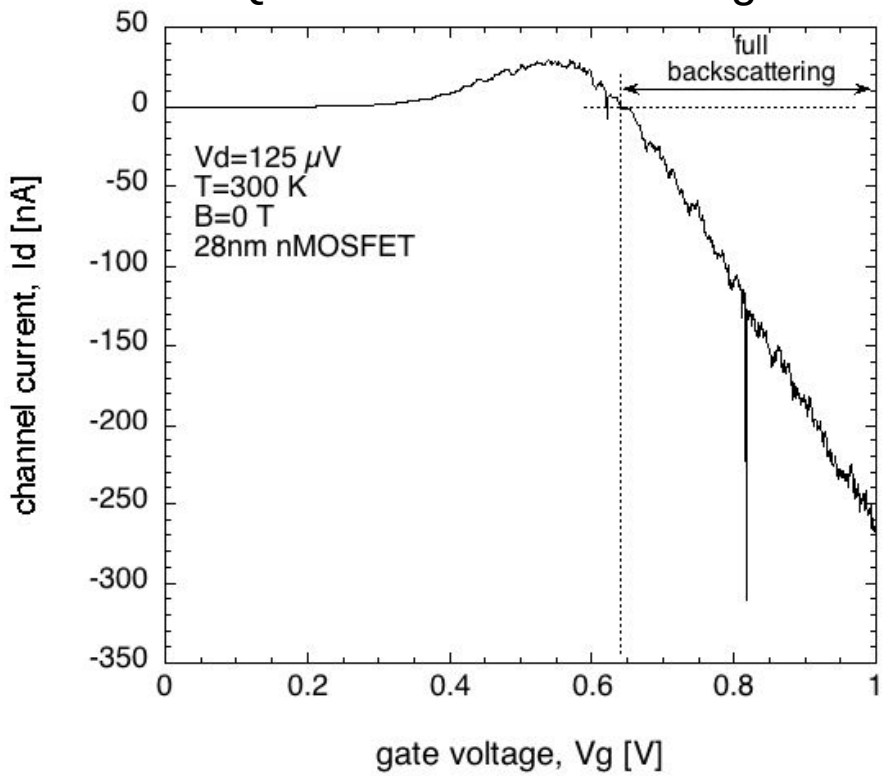
Self-emitted magnetic field



Forward- and back-scattering



Quasi-full backscattering



The Non-Equilibrium Green's Function

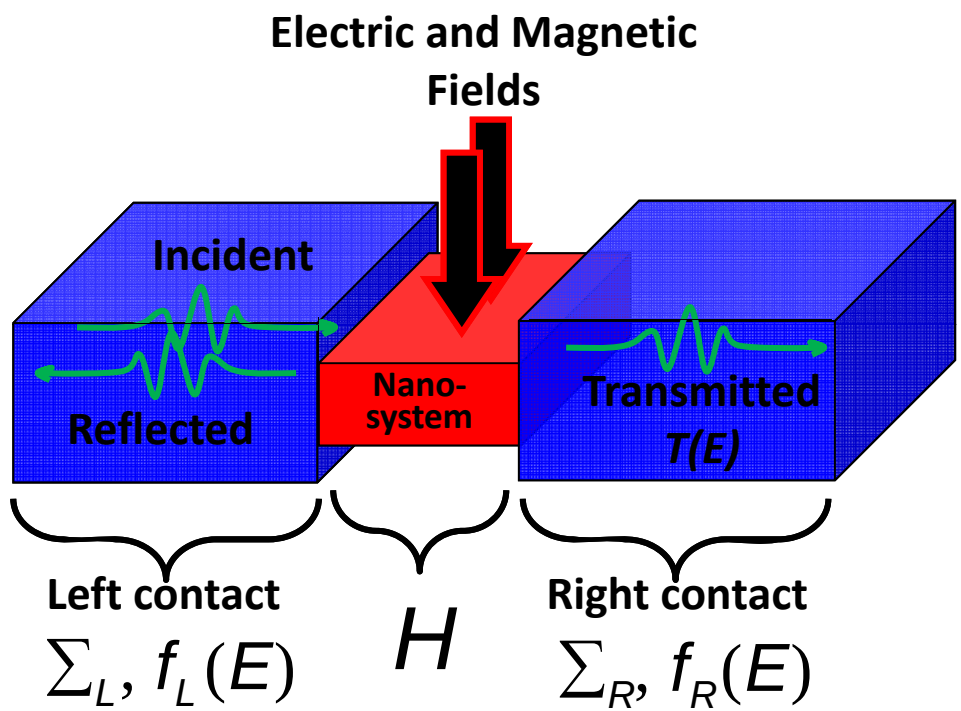
Schrodinger eq.:

$$\left[EI - H - \Sigma_L - \Sigma_R\right]\{\psi\} = \{S\}$$

$$H = \frac{\left(i\hbar\nabla + e\vec{A}\right)^2}{2m^*} + U$$

- Current in terms of transmission:

$$I = \frac{e}{h}\int T(E)\left[f_L(E) - f_R(E)\right]dE$$



The NEGF formalism can be used to analyze the wave nature of the carrier transport in a large variety of nano-scaled electron devices

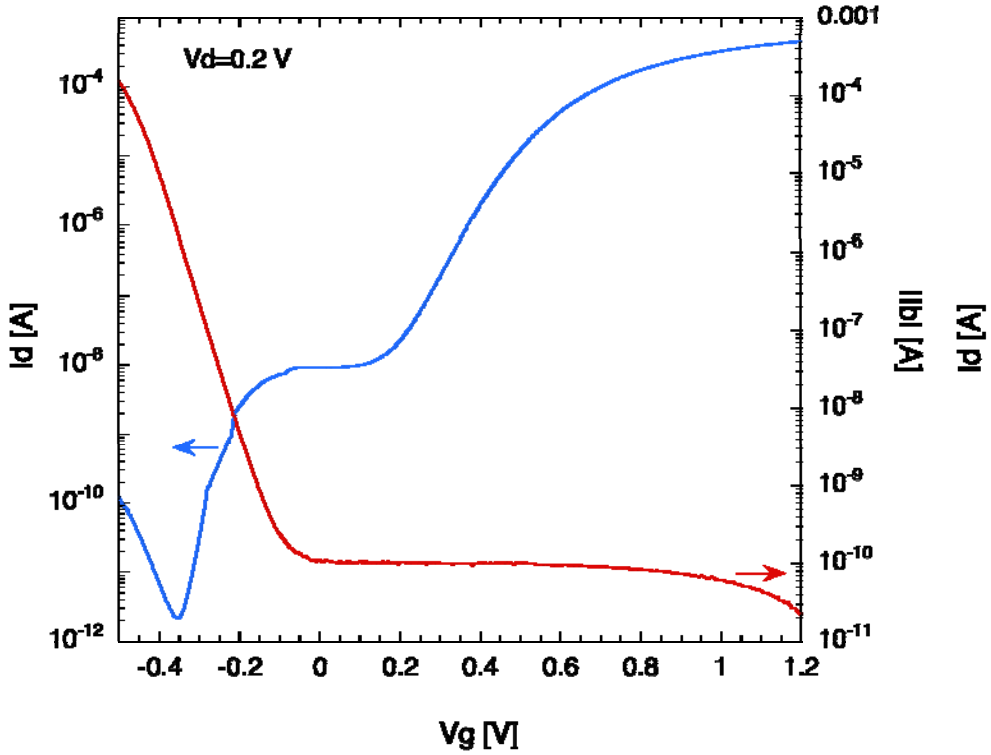
Conclusions

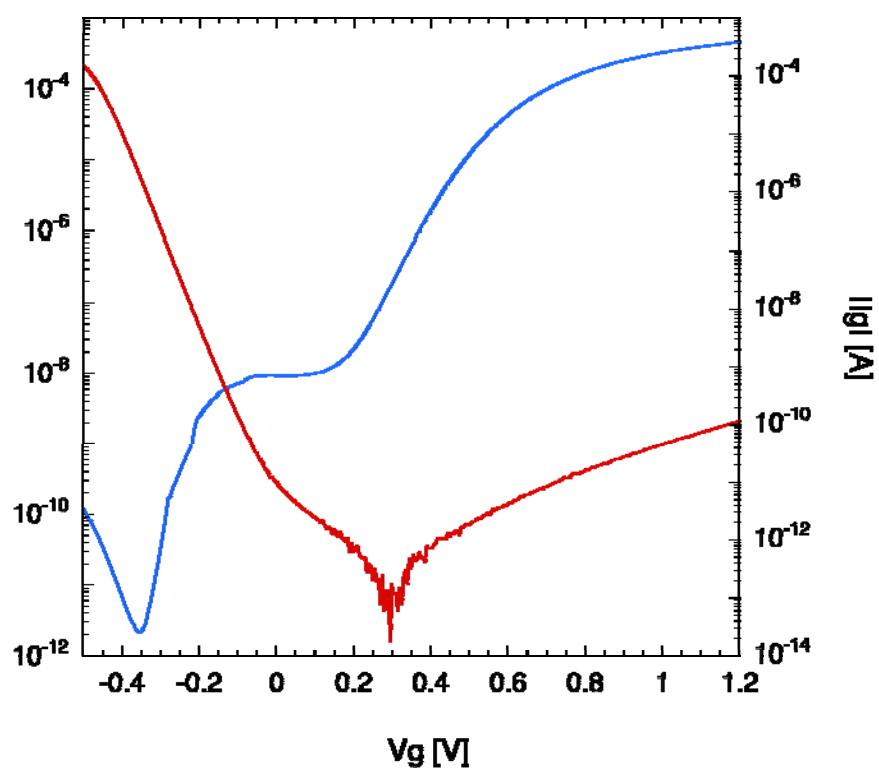
- Nanoscopic semiconductor devices should be considered as a full thermo-electro-magnetic device for modeling purposes.

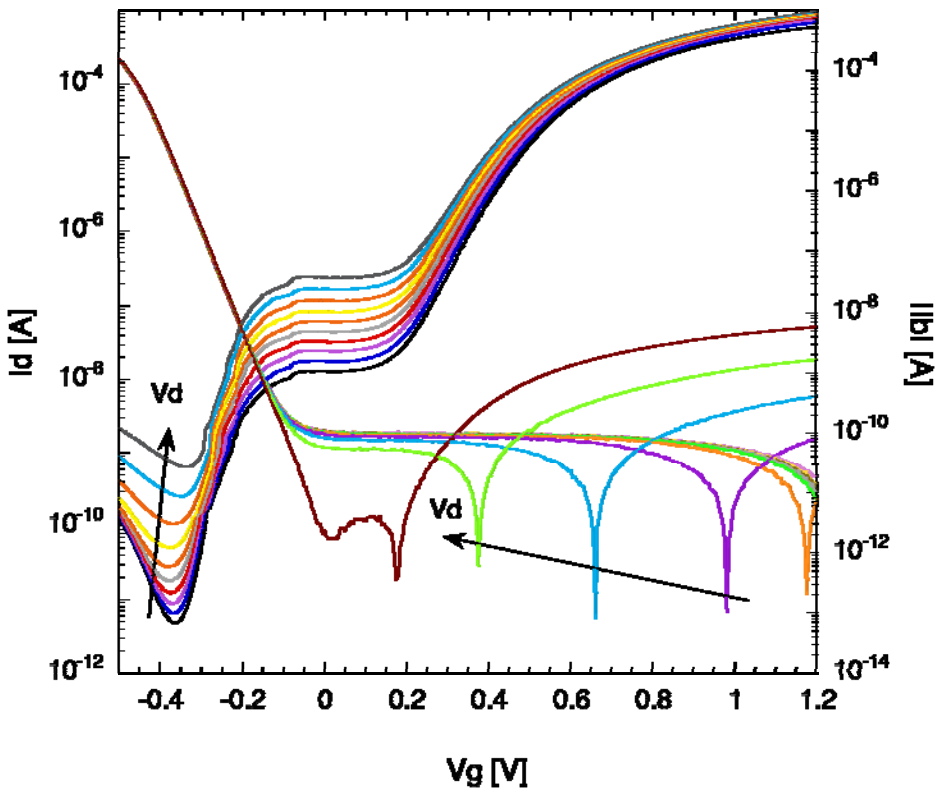
- The wave nature should also be strongly considered when modeling nanoscopic devices.

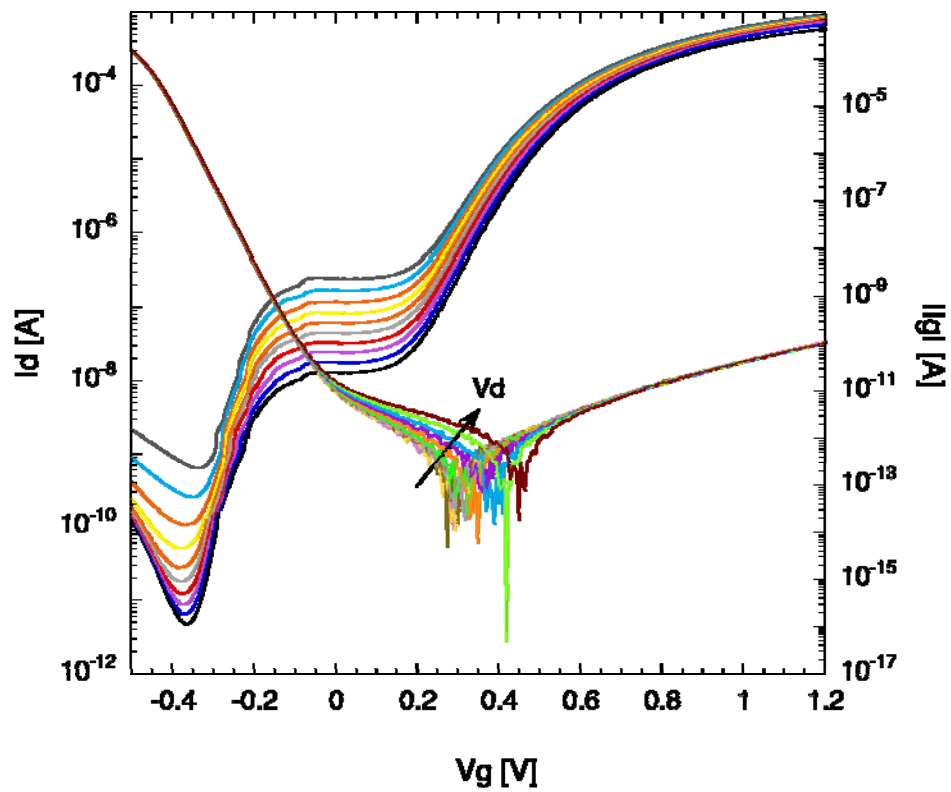
- The magnetic components should not be neglected anymore when analyzing "transport or transfer" device properties.

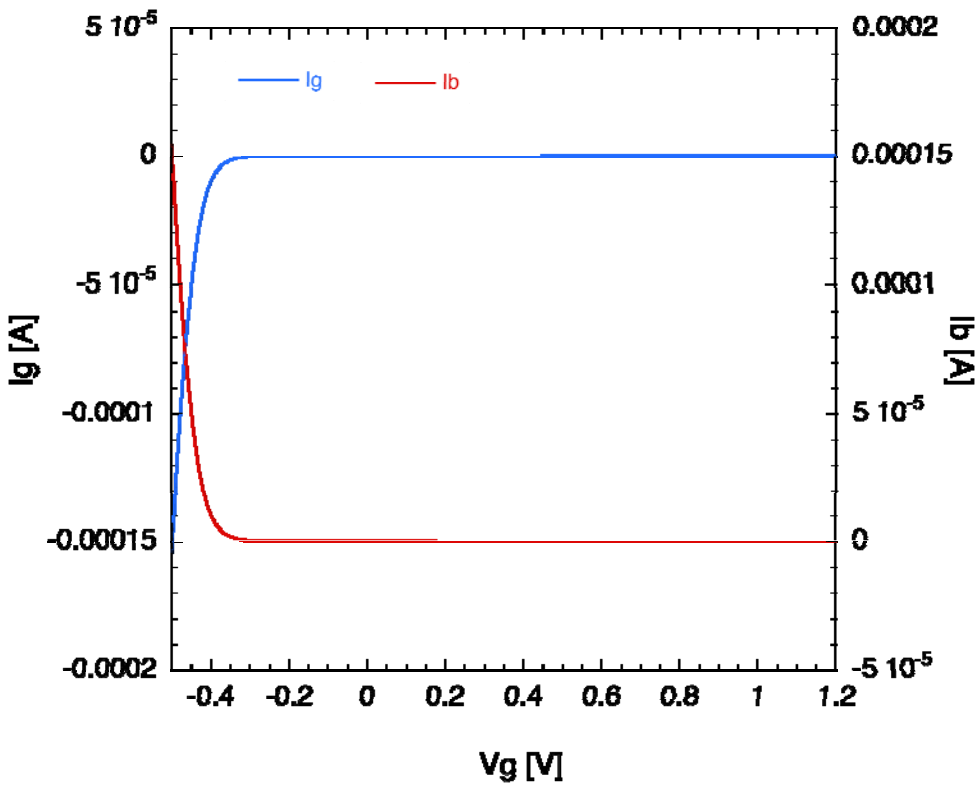
nFET under accumulation condition

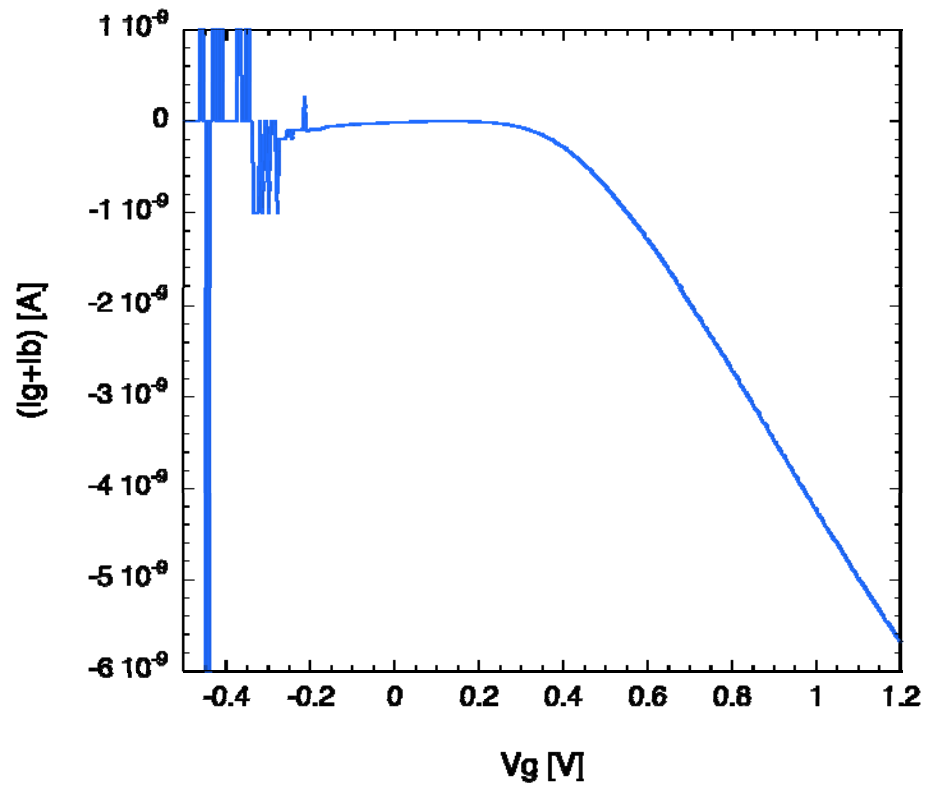




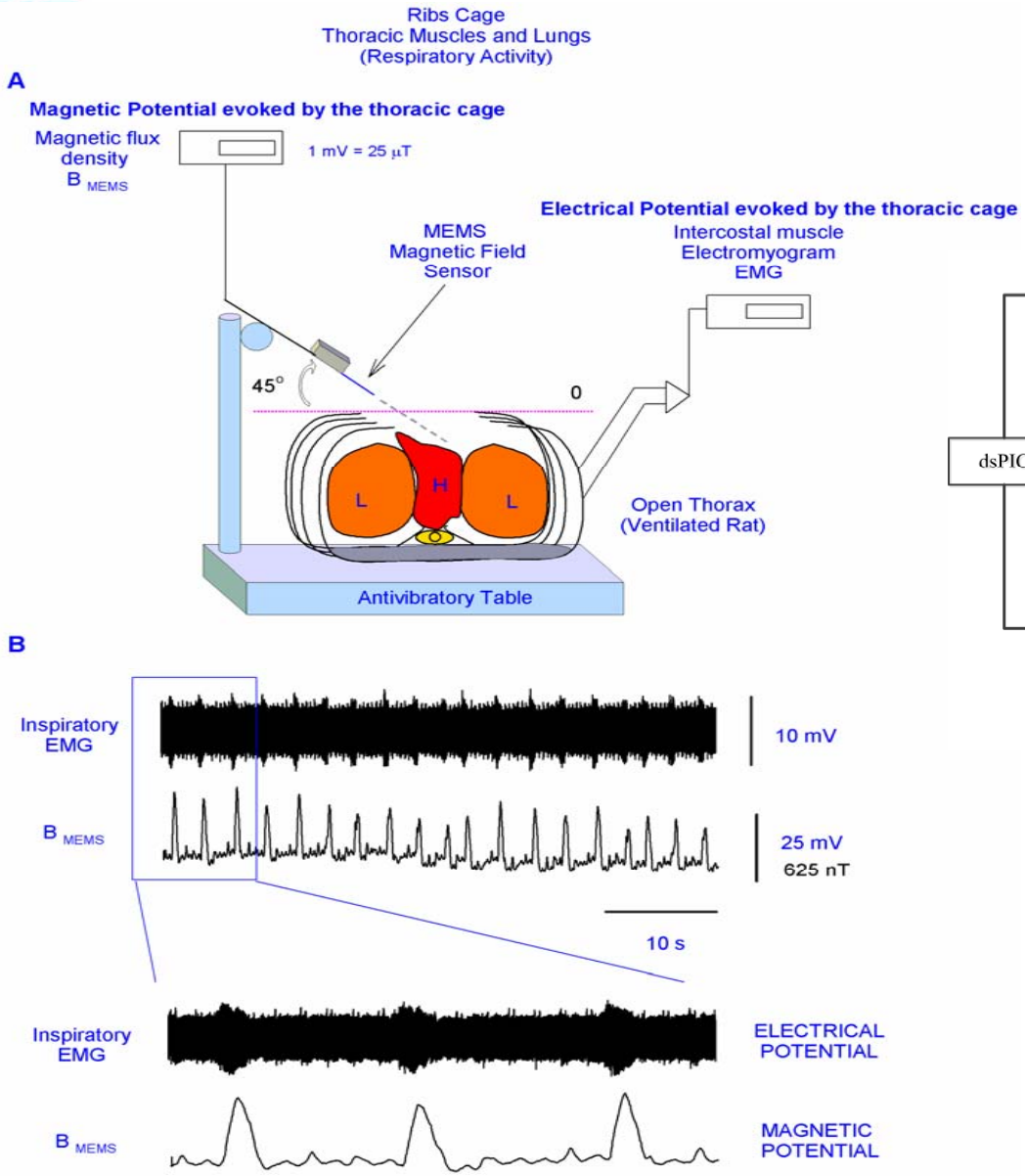

Id [A]
|Ib| [A]
Vg [V]
Vd
Vd


Id [A]
|Ig| [A]
Vg [V]
Vd

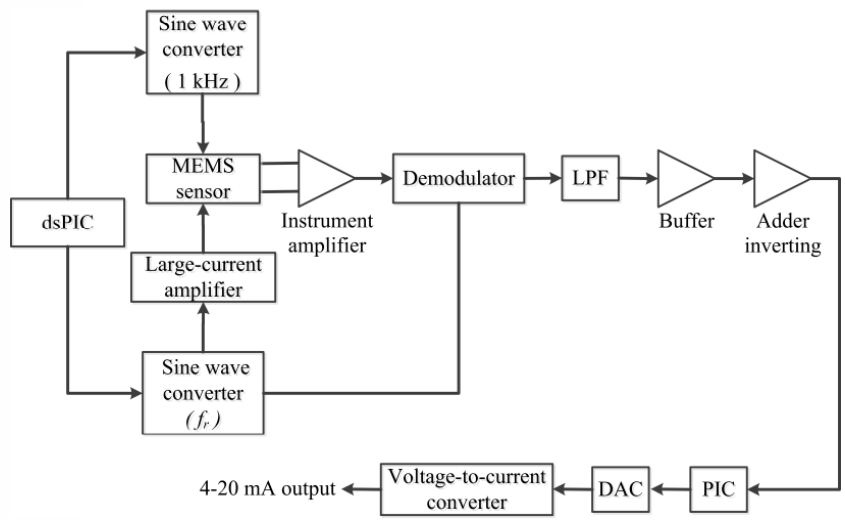

Ig
Ib
Ig [A]
Ib [A]
Vg [V]
5 10-5
0
-5 10-5
-0.0001
-0.00015
-0.0002
0.0002
0.00015
0.0001
5 10-5
0
-5 10-5
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2


(Ig+Ib) [A]
Vg [V]
1 10-9
0
-1 10-9
-2 10-9
-3 10-9
-4 10-9
-5 10-9
-6 10-9
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2

Experimental setup of an open-thoracic cage and anesthetized and ventilated rat



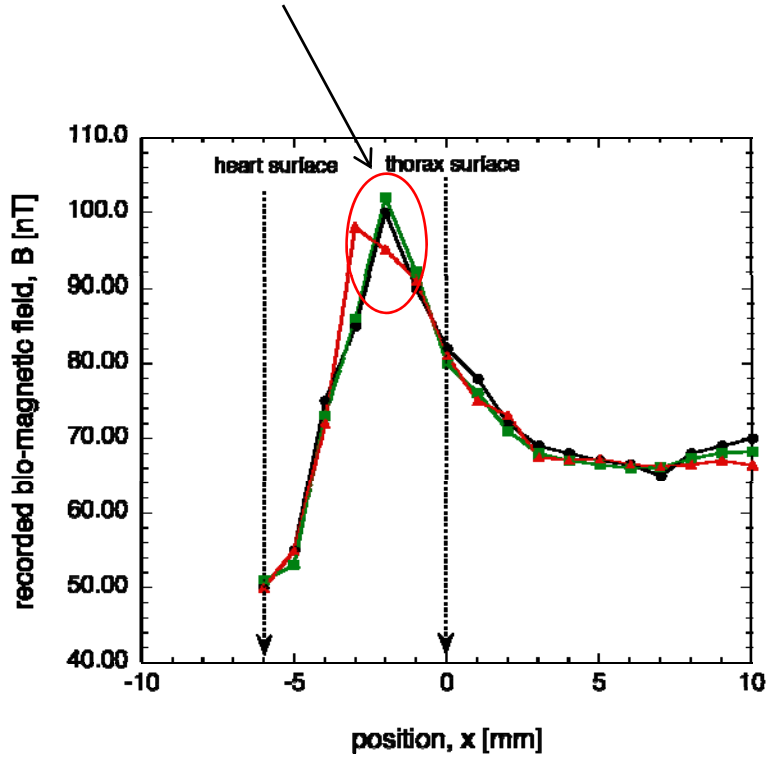
Signal conditioning and noise cancellation system



It increases minimum detectable B field from 1 µT down to 50 nT

Open thorax of the rat reports from 2,000 to 10,000 stronger MCG than the typical 50 pT human chest or 10 pT for rats.

Inside thoracic cage resonance



A 90nm nFET at 45º with respect to the normal to the open thorax