Energy harvesting in nanoelectronic devices

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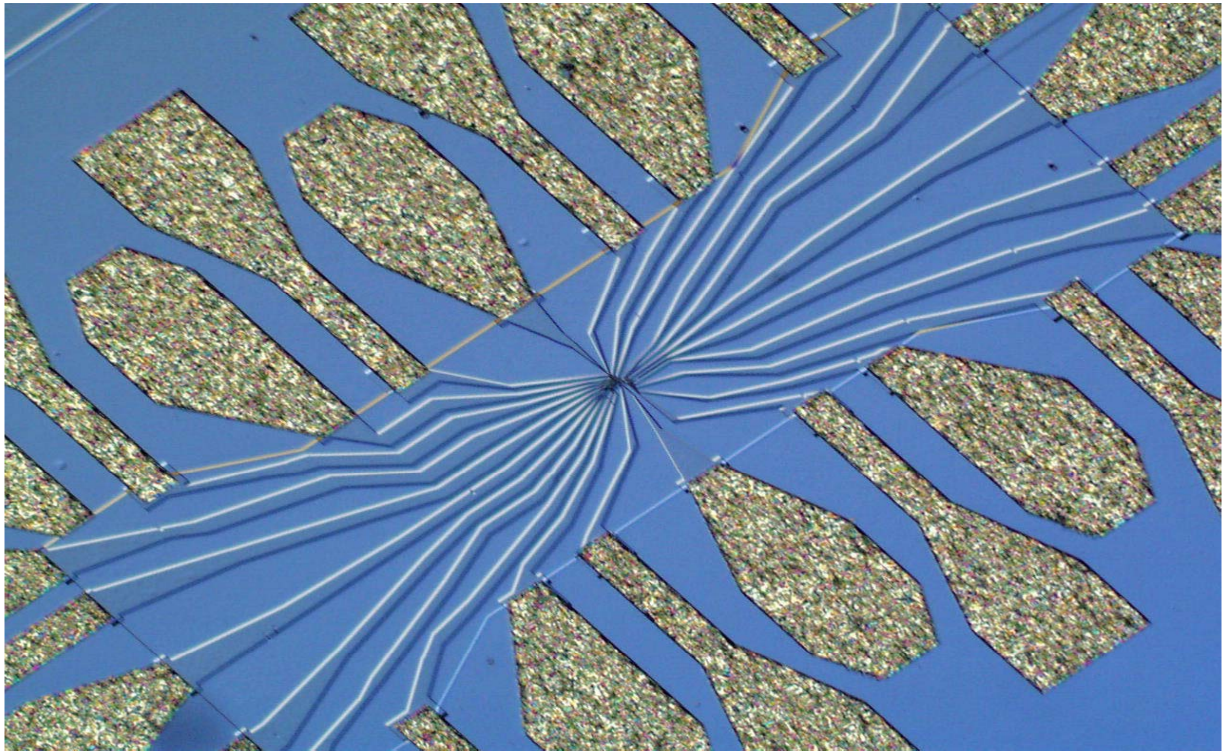

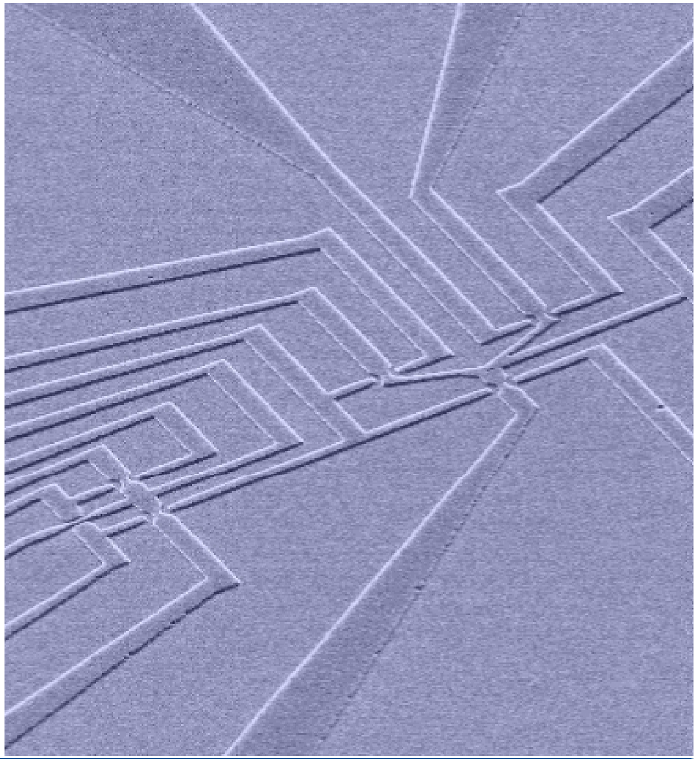

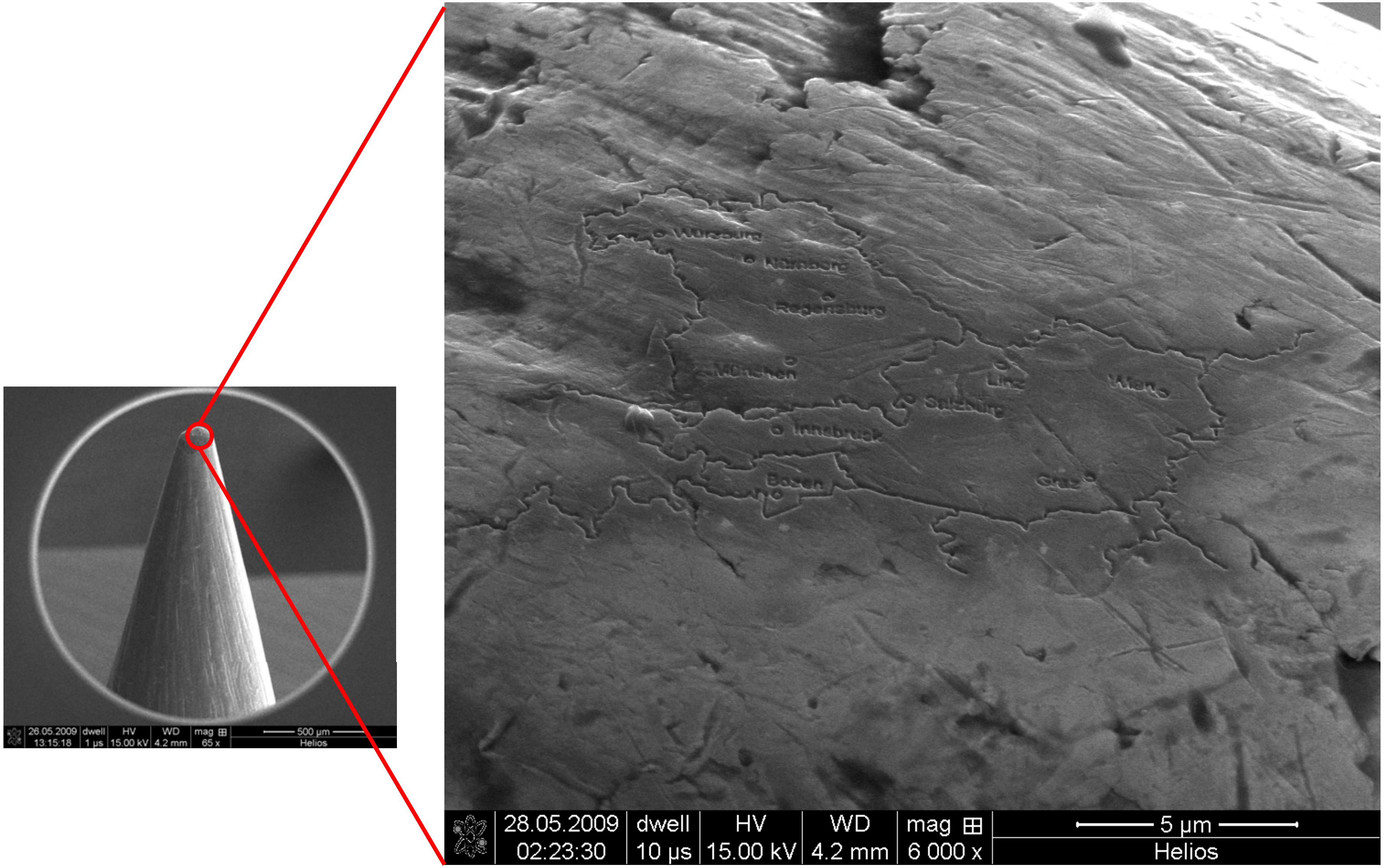
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dwell
1 µs
HV
15.00 kV
WD
4.2 mm
mag
65 x
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Helios
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28.05.2009
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dwell
10 µs
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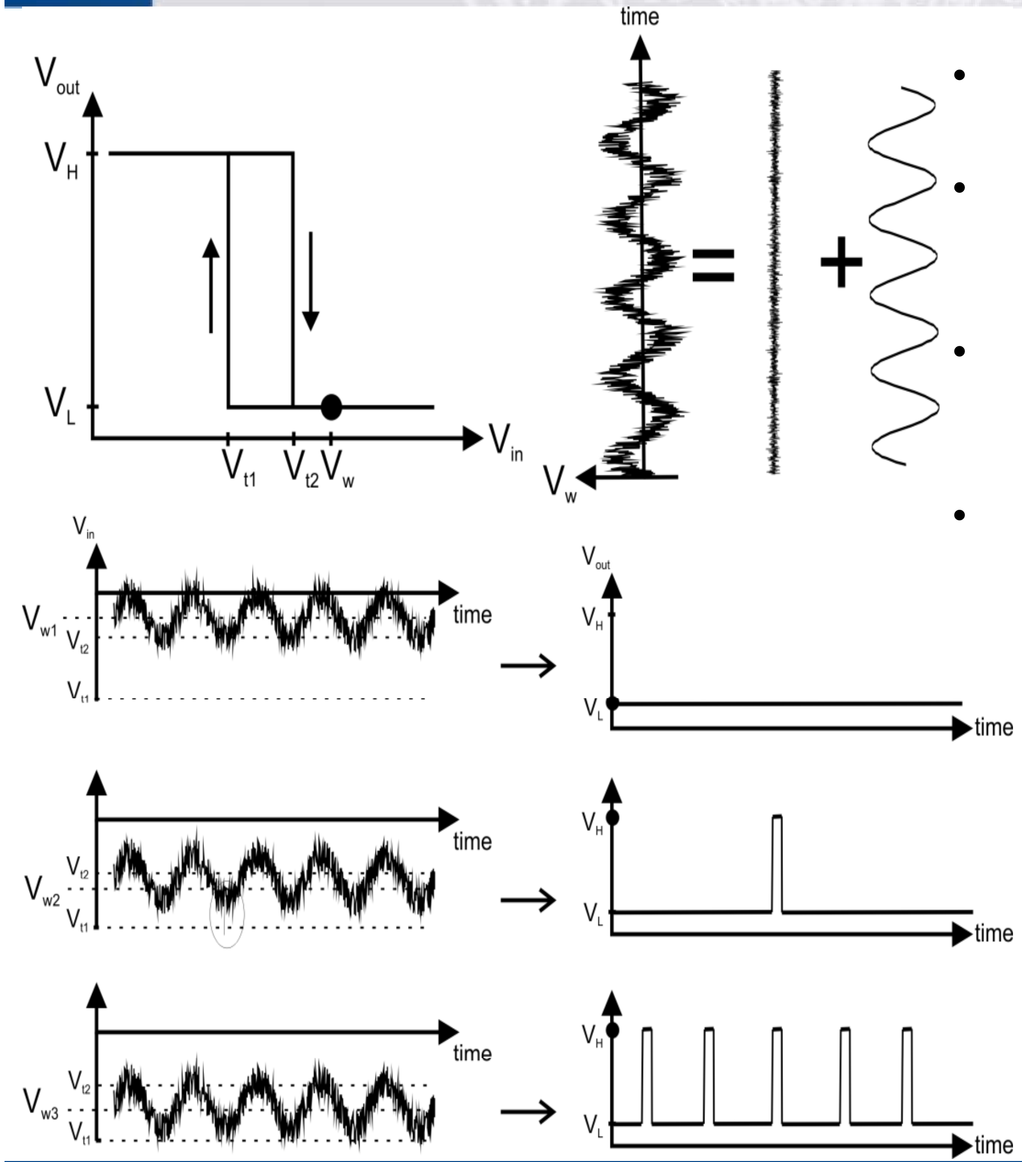
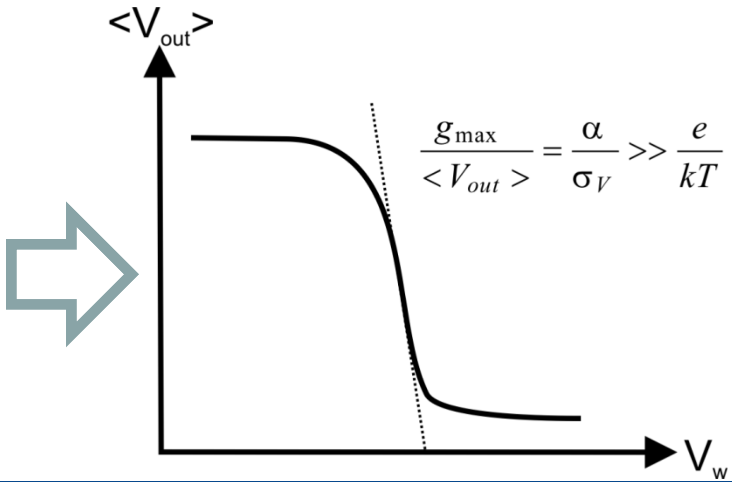
Helios

Energy harvesting with nanoelectronics



- Energy harvesting: Energy provider+Transducer+Rectifier
- Nonlinearities in nanoelectronics: Quantum effects, reduced screening, many devices, bits per volume
- Ultra-miniaturized circuits: Small signal-to-noise ratios (SNR) & feedback between different devices are unavoidable
- Is it possible to exploit ambient noise and feedback action for electronic applications

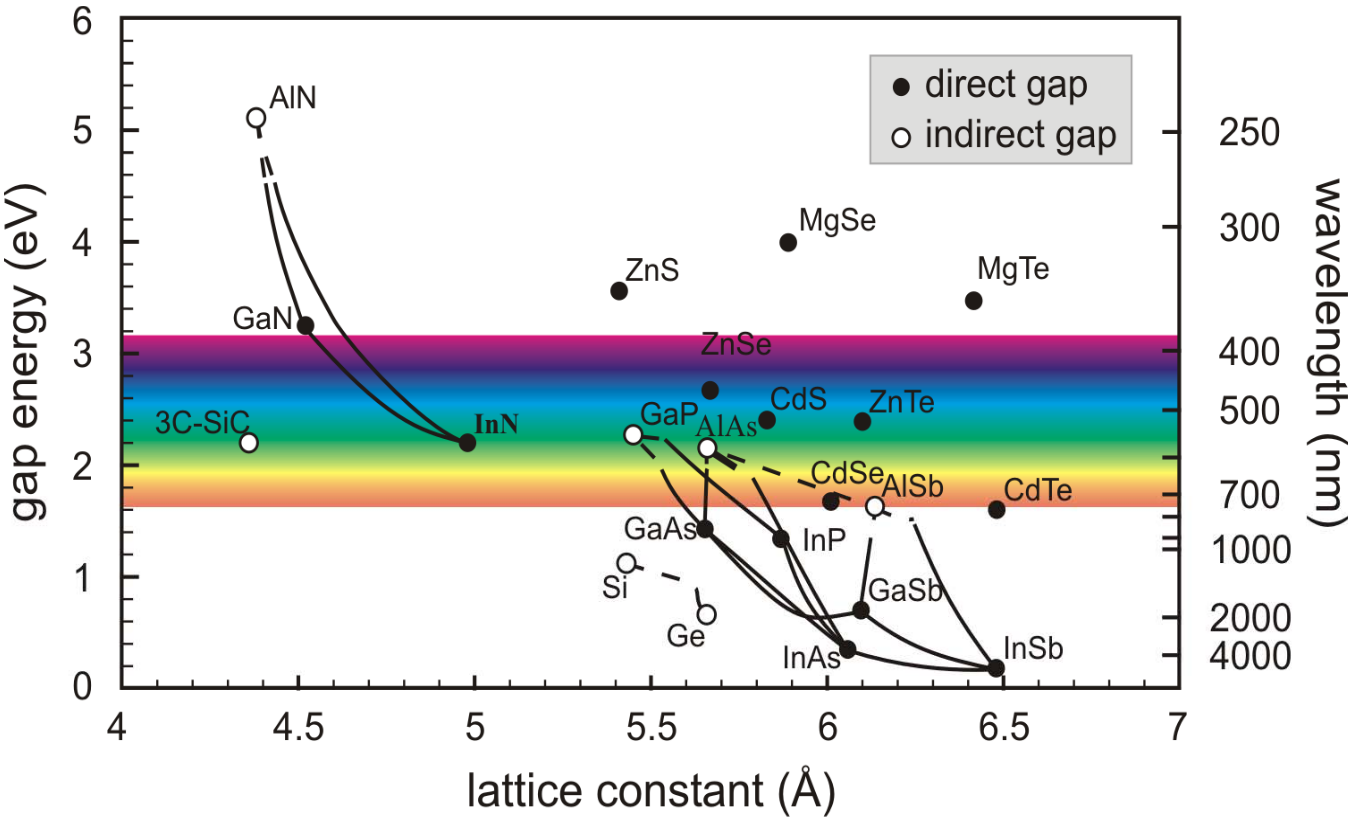


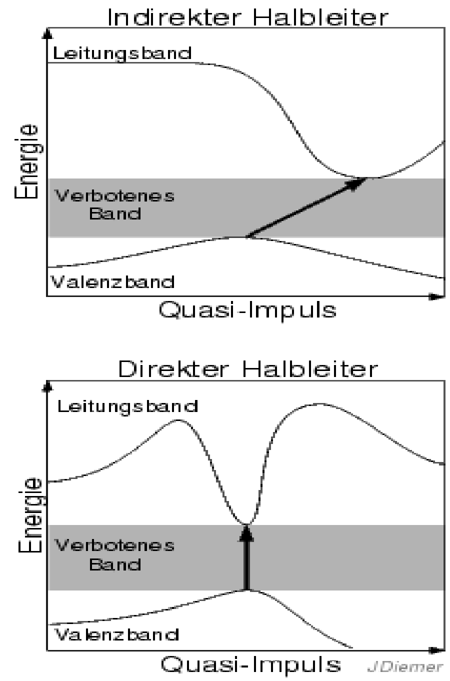
$$\frac{g_{max}}{<V_{out}>} = \frac{\alpha}{\sigma_V} >> \frac{e}{kT}$$

Outline

- Nanoelectronic semiconductor electronic devices
  - Technology
  - Nonlinear nanoelectronic transport
    - Magnetic field asymmetry in quantum wire
    - SR in a YBS as B field sensor
    - Y-branch as logic gate and GHz rectifier
    - Logic stochastic resonance in RTDs

semiconductors

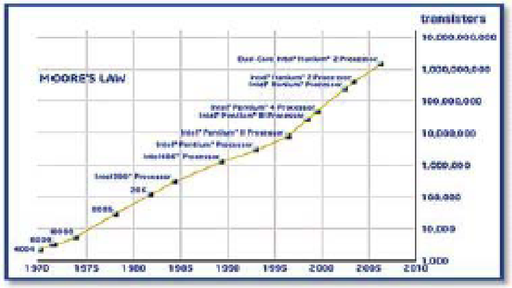


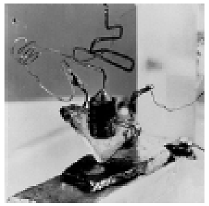


- **Electronics: frequencies Hz – THz**
- **Optoelectronics: wavelengths 0.2 – 100 µm**

Some electronic devices

- Transistors and memories





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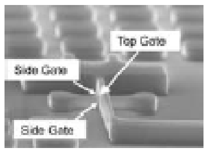
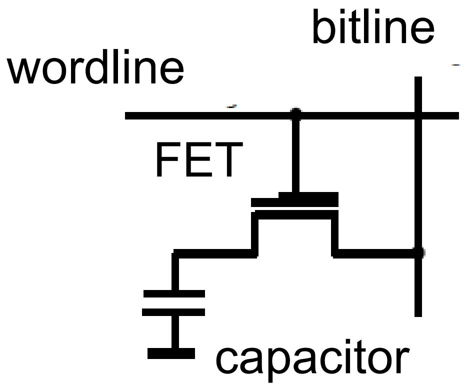
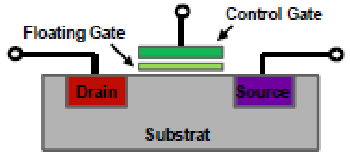


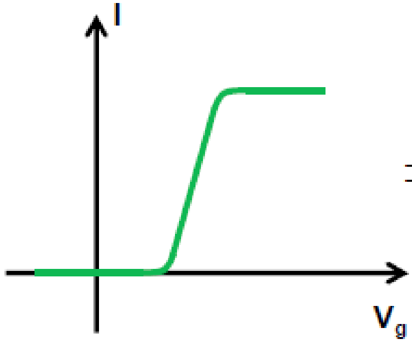
today



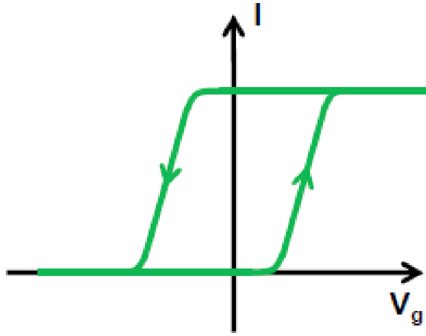
DRAM



FLASH

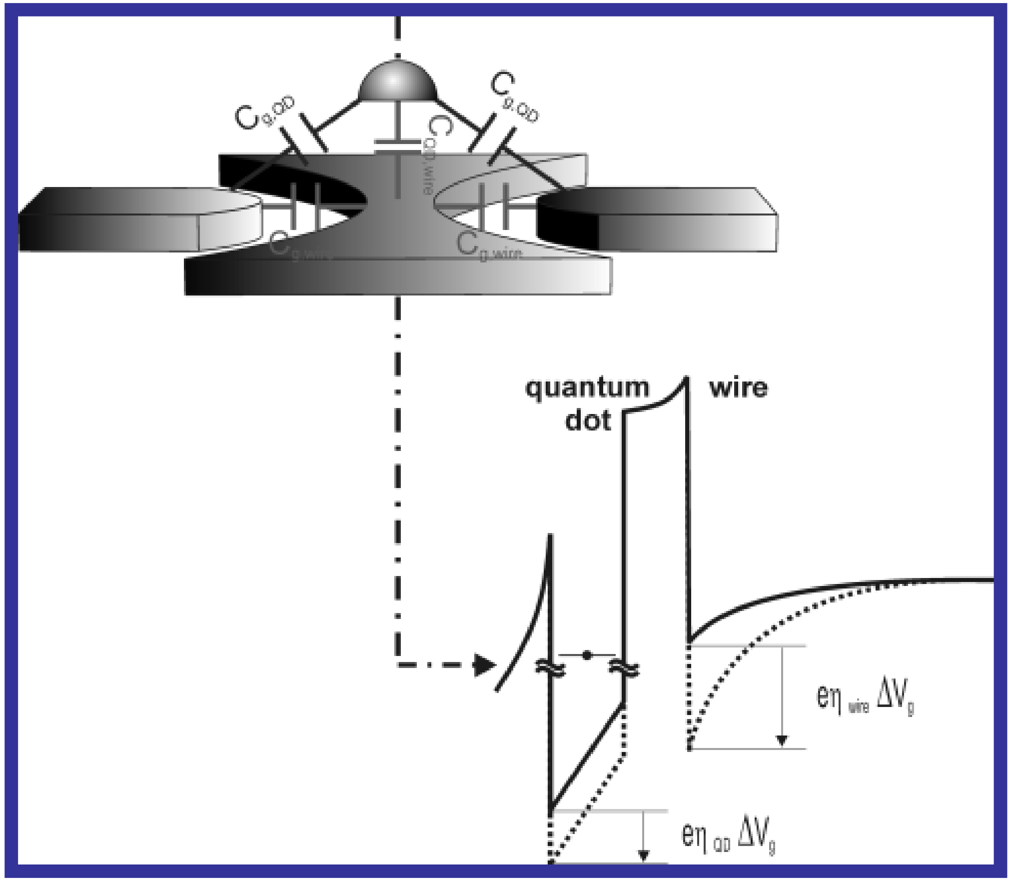


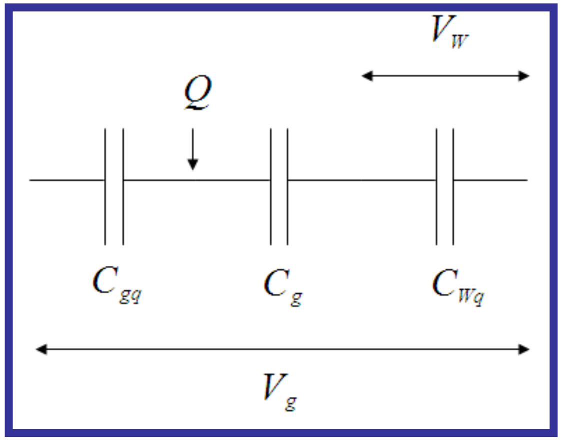
$\Rightarrow$ R (V_g)



$\Rightarrow$ C (Q(t))

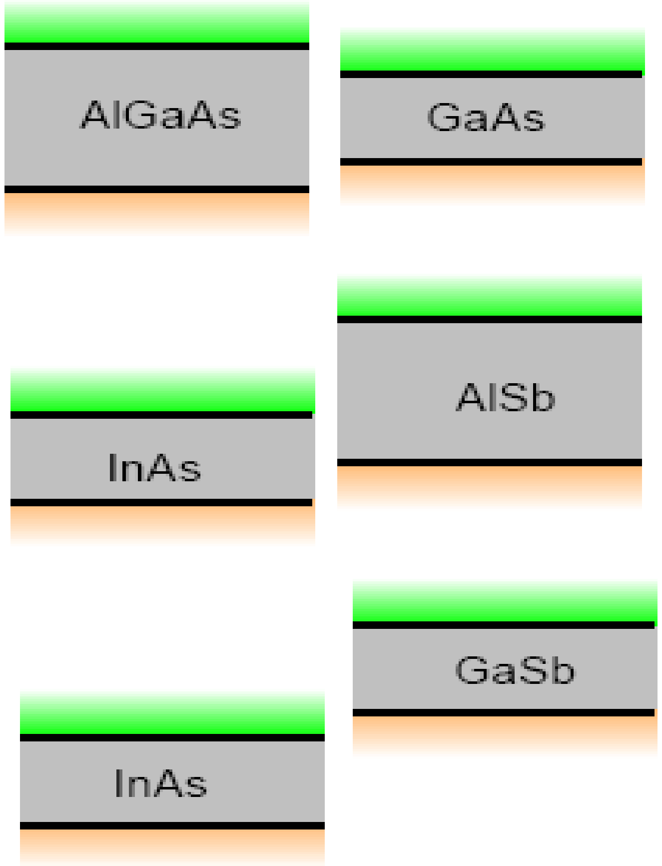
Electrostatics of FETs with nearby charges

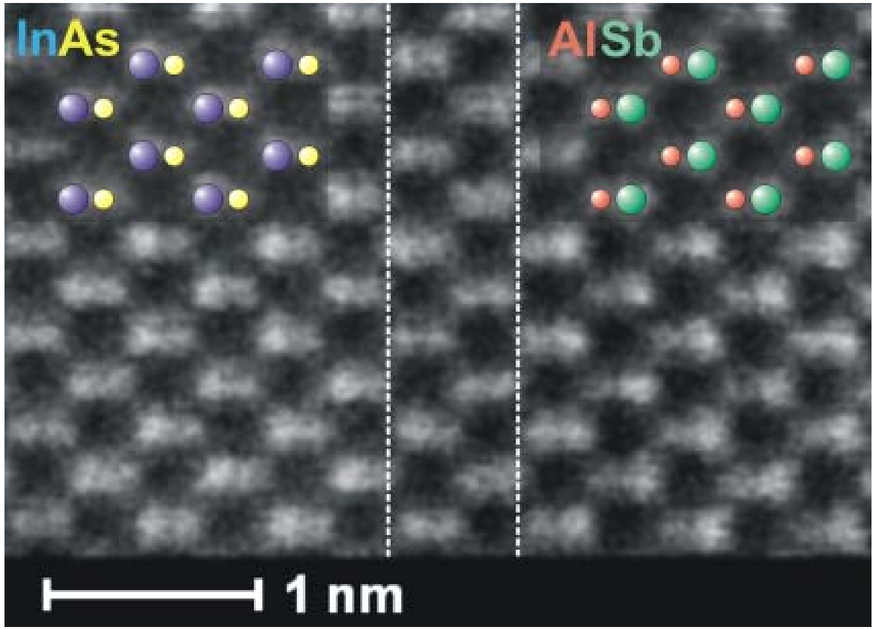




$$\eta(\Delta V_g - V_T) = V_W = \frac{\Delta V_g - \frac{Q}{C_{gq}}}{1+\frac{C_{Wq}}{C_g}+\frac{C_{Wq}}{C_{gq}}}$$

Heterostructures: Band gap engineering

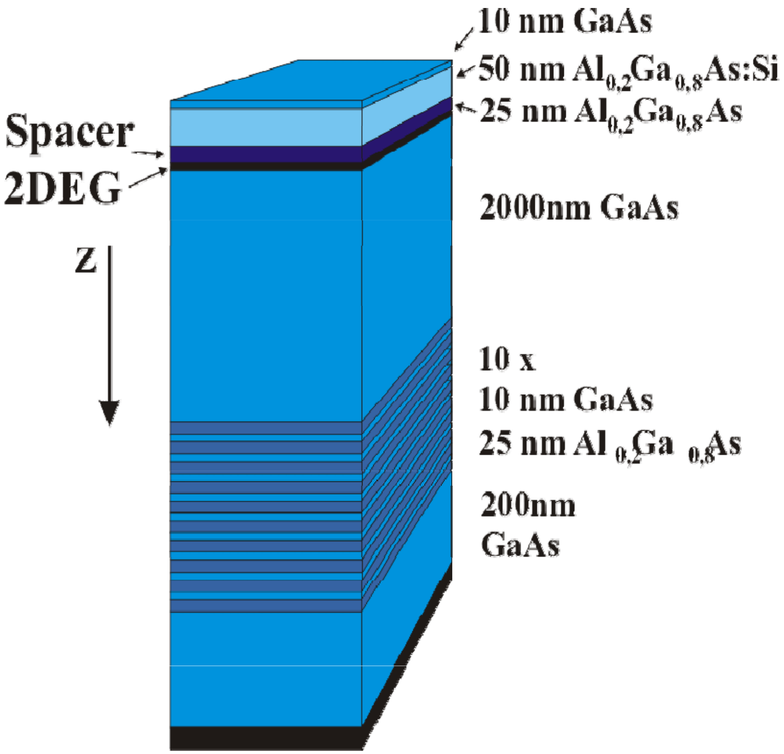


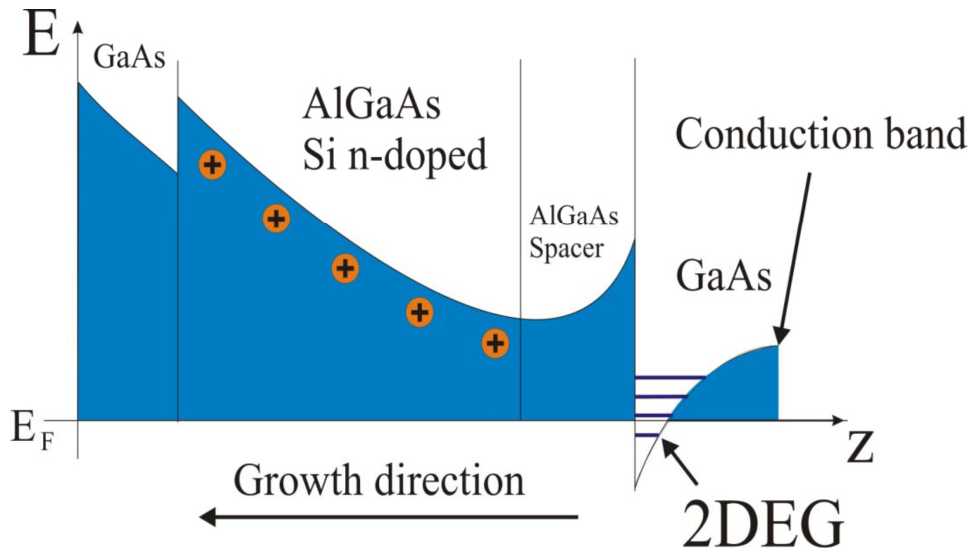


❒ Combination of different semiconductors with atomic precision

❒ Growth techniques: e.g. Molecular beam epitaxy (MBE)

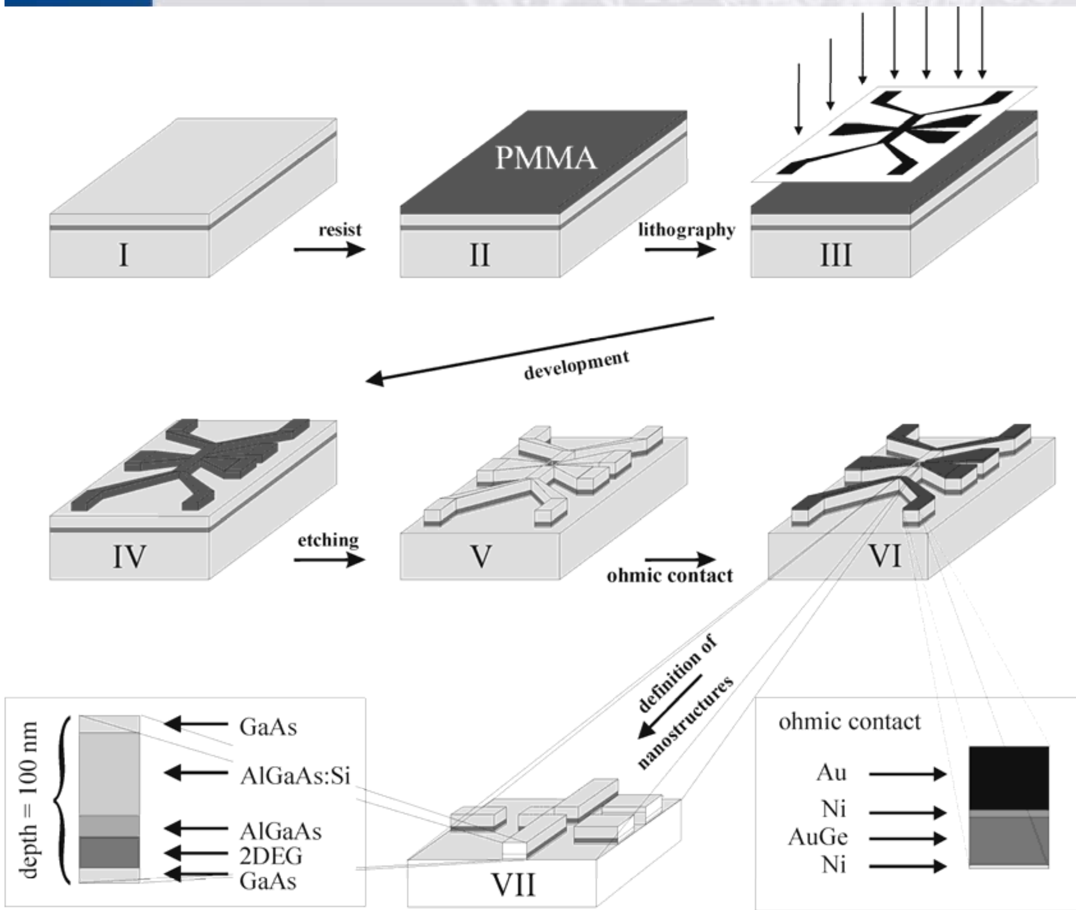
GaAs/AlGaAs HEMT

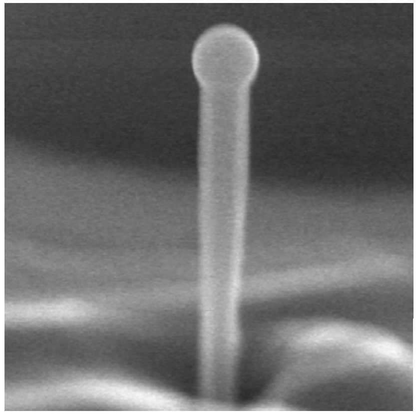


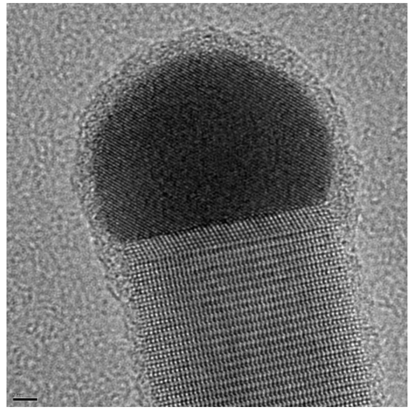


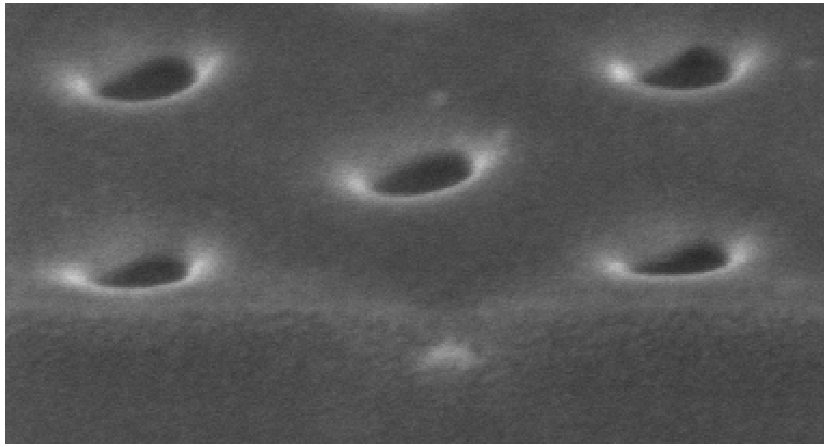
- ❒ Modulation-doped GaAs/AlGaAs heterostruktur (HEMT)
- ❒ Mean free path: ~10µms @ 4,2K / 50 – 200nm @ RT

Structuring







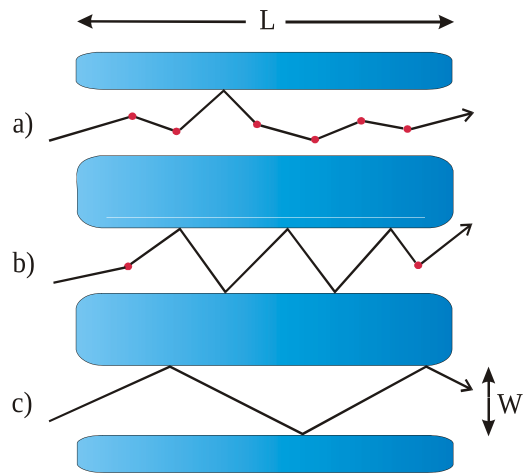


- ❒ Top-down route: lithography, etching,…
- ❒ Bottom-up route: self-assembly, seeded growth,…
- ❒ Different geometries: wires, dots, rings, splitters…

Characteristic lengths

- De Broglie wavelength: $l_{deBroglie} = h / p$
- Fermi wavelength: $l_F = l_{deBroglie} \,|_{E=E_F}$
- Mean free path: $l_m = v\tau = \frac{p}{m}\tau = \frac{\hbar k}{e}\frac{e\tau}{m} = \frac{\hbar k}{e}\mu$
- Phase coherence length: $l_\phi = h / \sqrt{2mkT}$

a) Diffusive
b) Coherent
c) Ballistic



Linear mesoscopic transport

- Conductance quantization in 1D wires

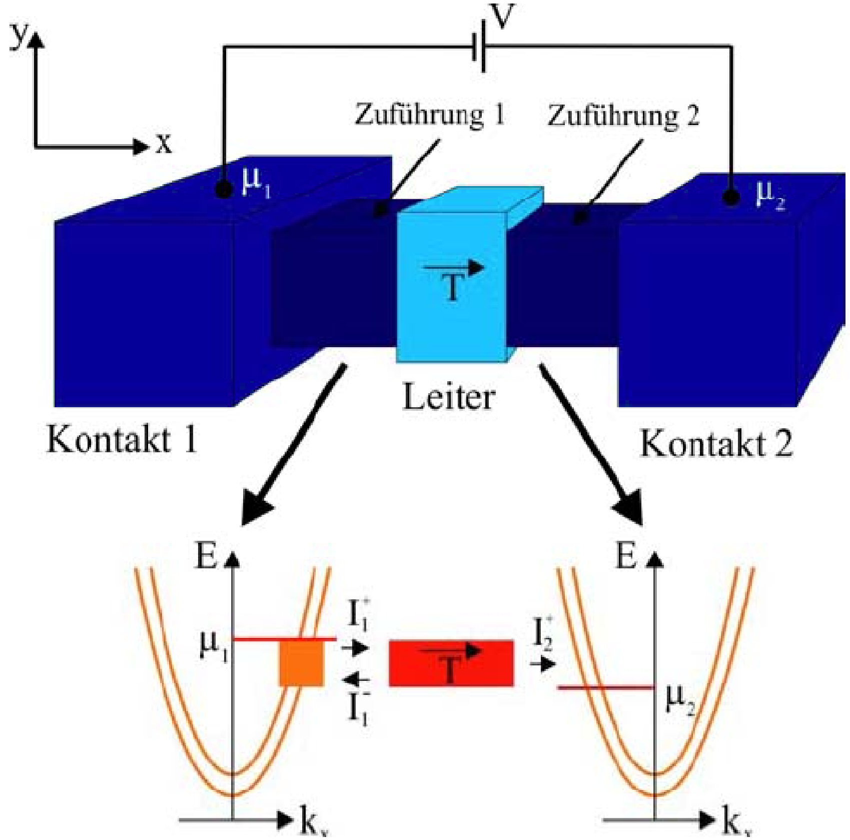
$$I_{2T} = I_{L\to R} + I_{R\to L} =$$

$$\frac{2e}{h}\sum_{\alpha}\int dE \underbrace{\sqrt{E}}_{\sim v} * \underbrace{1/\sqrt{E}*}_{D_{1D}} \underbrace{\left[f^{L} - f^{R}\right]}_{\sim \frac{\partial f}{\partial \mu}(eV)} * T_{\alpha}$$

$$G = I/V = \frac{2e^2}{h}\sum_{\alpha} T_{\alpha}$$

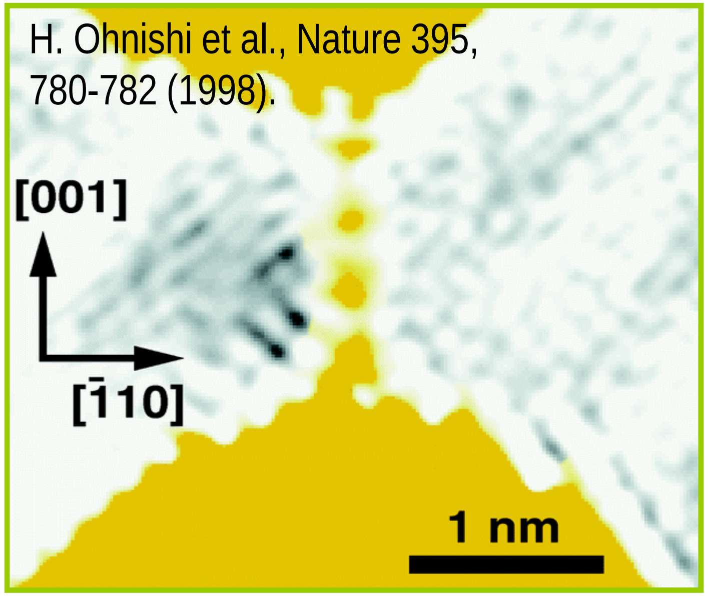
- Multi-terminal conductor: Landauer-Büttiker formula

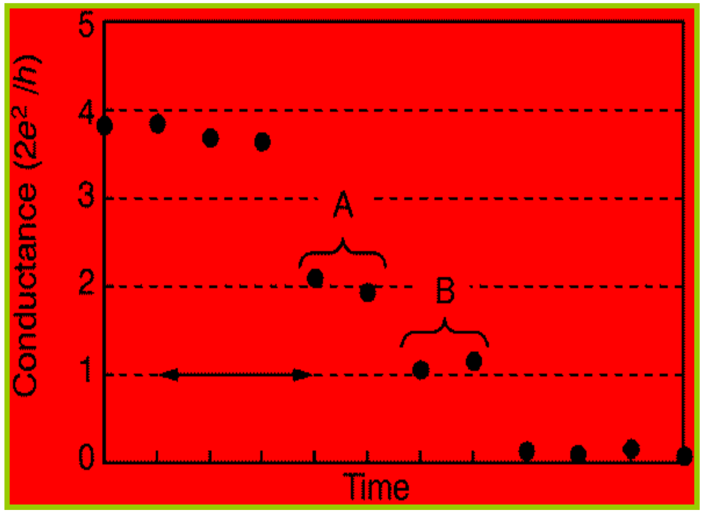
$$I_i = \frac{2e}{h}\left[\mu_i - \sum_j T_{ij}\mu_j\right]$$



What is nano? A comparison: metals vs semiconductor

H. Ohnishi et al., Nature 395, 780-782 (1998).





Metal:
Gold film

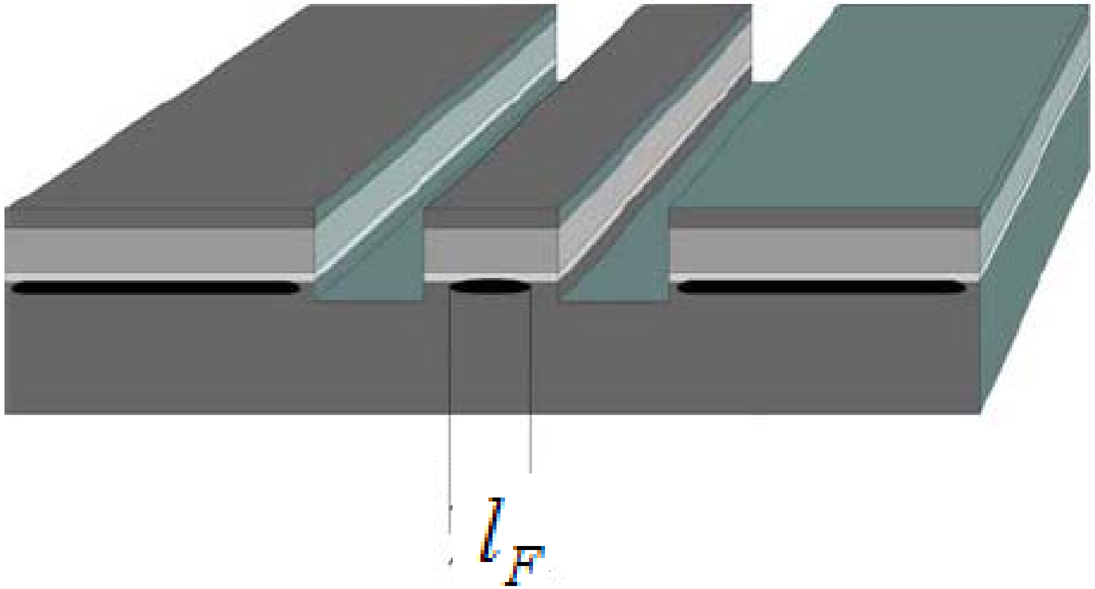
$n = 2.3 \times 10^{15}/cm^2$
$l_F = 0.52$ nm, E_F=5.5 eV
$l_m \sim$ 1-10 nm
$l_\phi \sim$ 1-100 μm

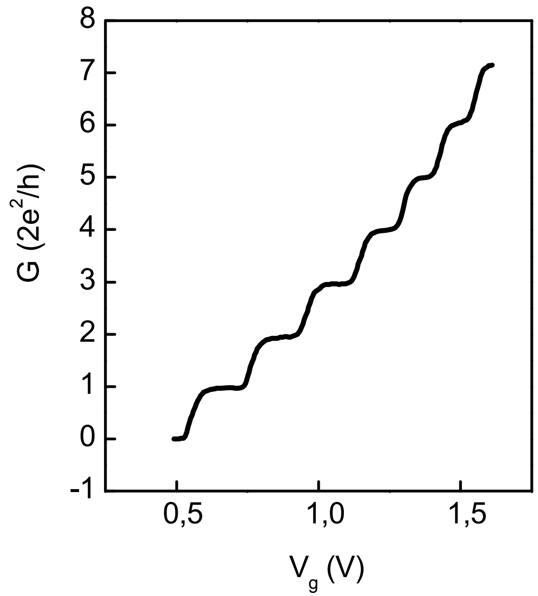
Semiconductor:
2 dimensional electron gas (2DEG)

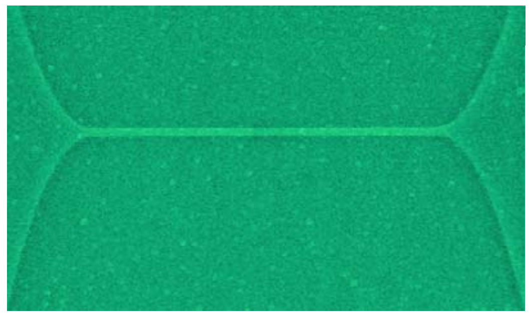
$n = 3.0 \times 10^{11}/cm^2$
$l_F = 46$ nm, E_F= 11 meV
$l_m \sim$ 1-100 μm T < 4 K
$l_\phi \sim$ 1-100 μm

Quantum wire

- Electron wave propagation: each occupied subband contributes with $2e^2/h$ to the conductance ➔ conductance quantization







Outline

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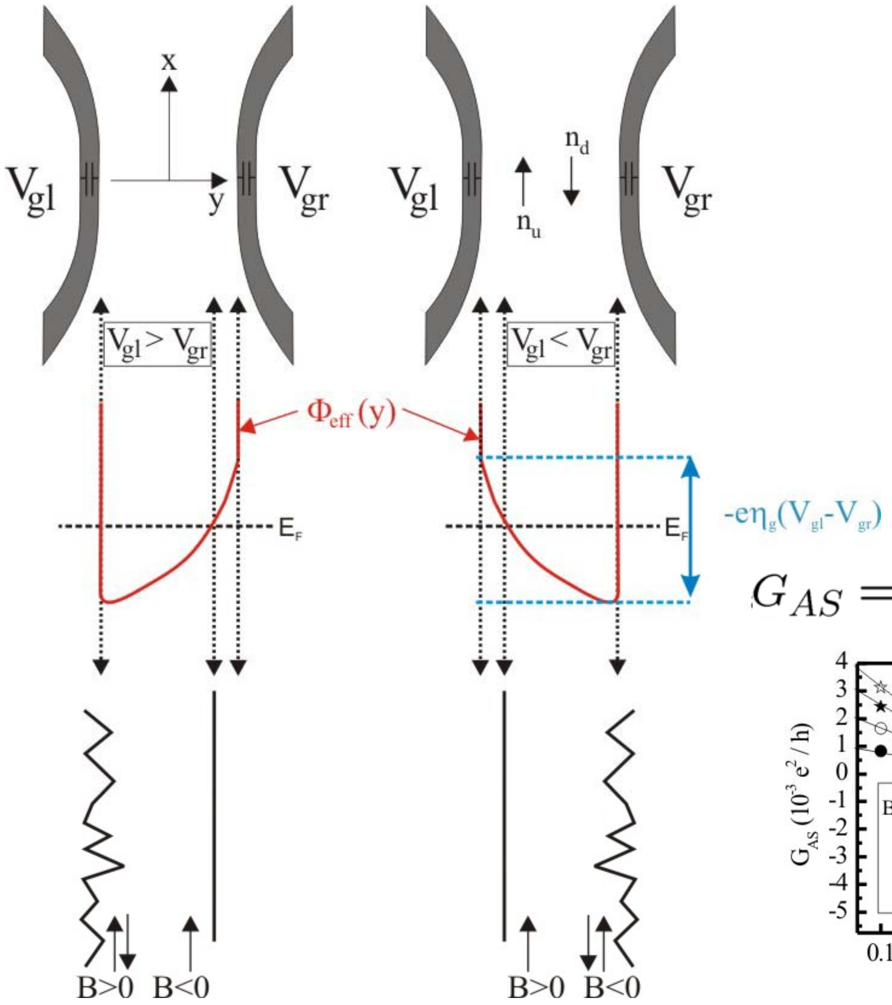
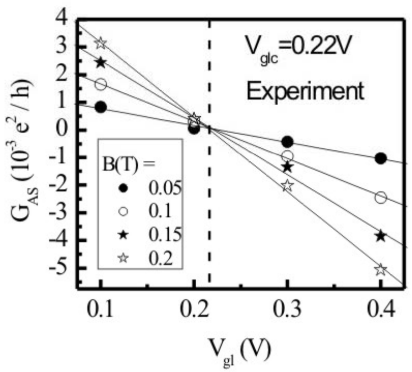
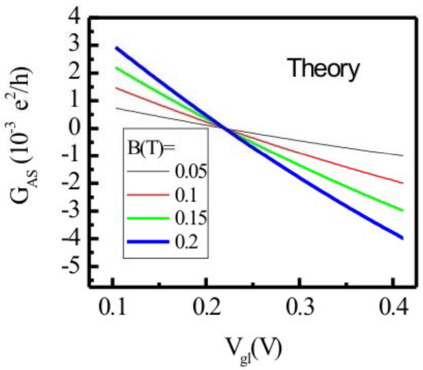
Asymmetric scattering

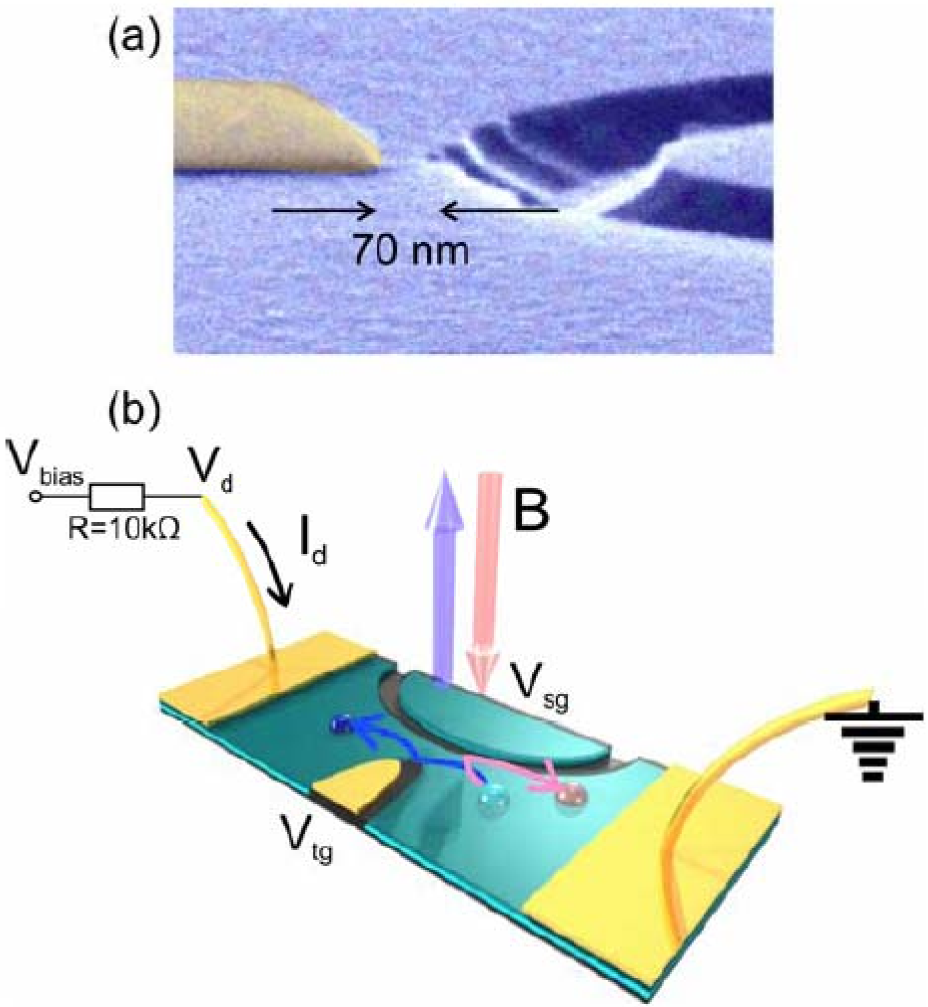


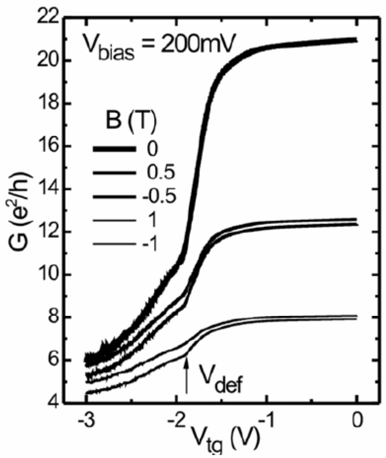
$$G_{AS} = (1/2)(G^{(2)}(B) - G^{(2)}(-B))$$

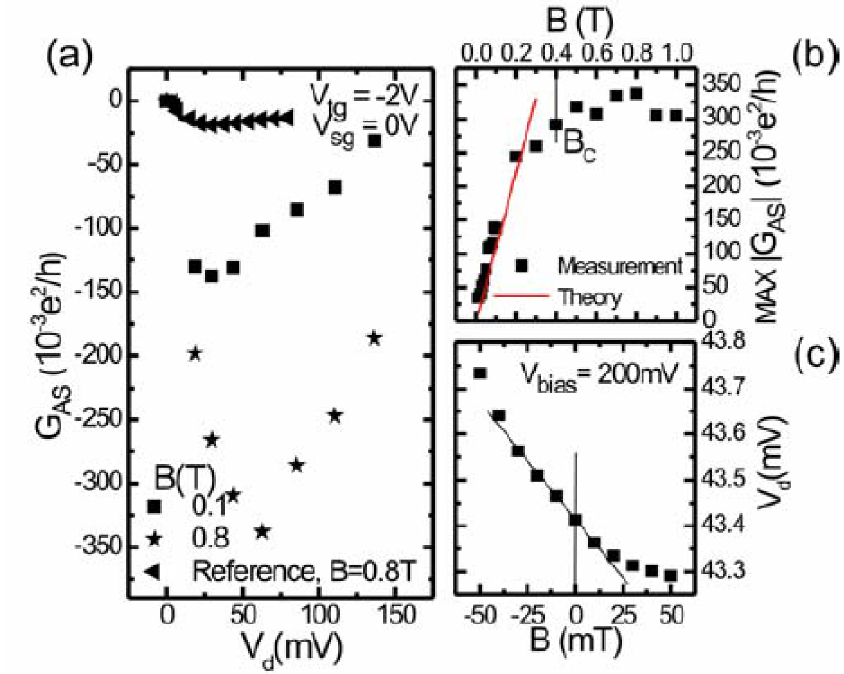




Deterministic asymmetry







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Stochastic resonance

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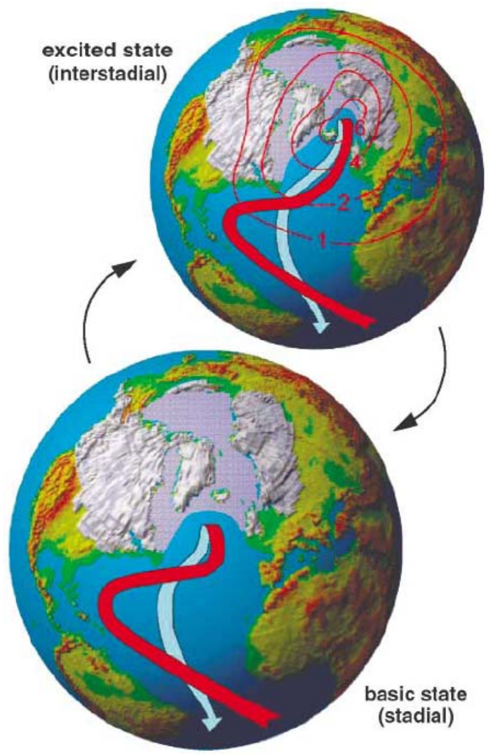
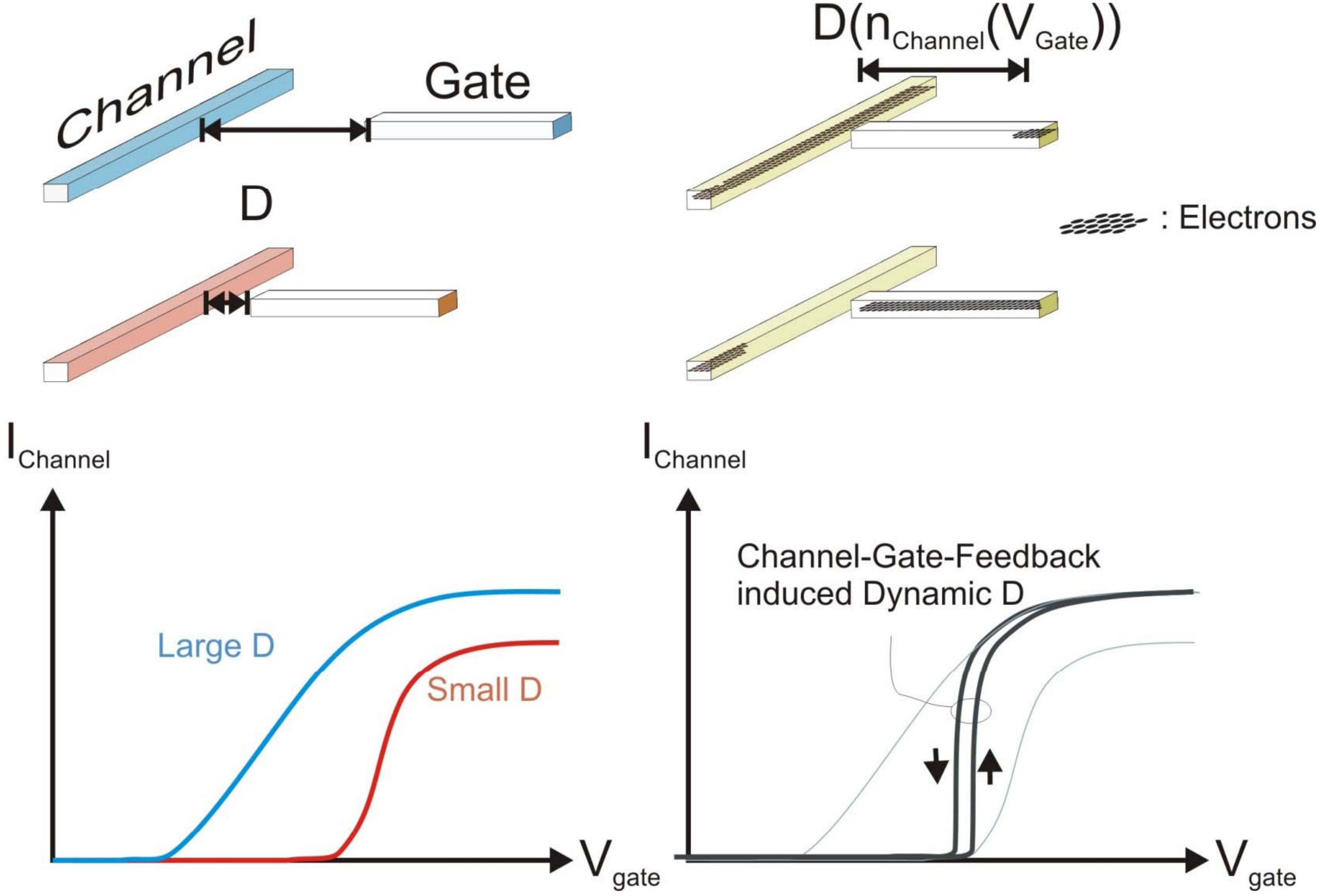
Abrupt Glacial Climate Changes due to Stochastic Resonance

Andrey Ganopolski and Stefan Rahmstorf*
Potsdam Institute for Climate Impact Research, Box 601203, 14412 Potsdam, Germany
(Received 5 July 2001; published 4 January 2002)

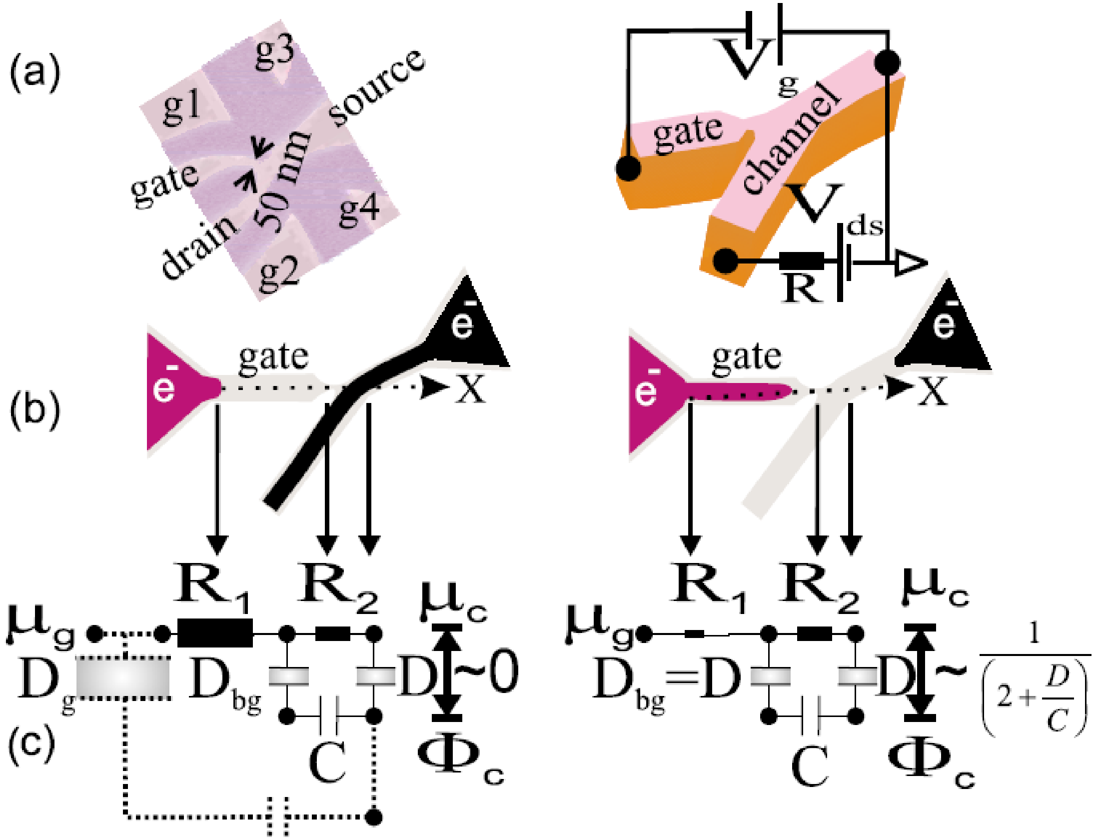
- **SR: weak signals can be amplified by fluctuations**
- **SR conditions**
  - **non-linear system (threshold)**
  - **Subthreshold signal**
  - **noise**
- **SR was introduced as model for explanation of the periodic ocurrence of ice ages: Benzi, Parisi, Sutera, Vulpiani**

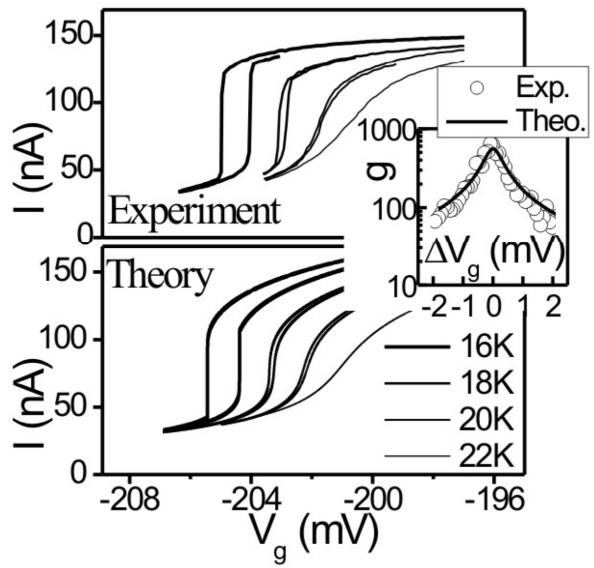


Dynamical gate operation in a YBS



Bistable selfswitching:
γ depends on the bias voltage

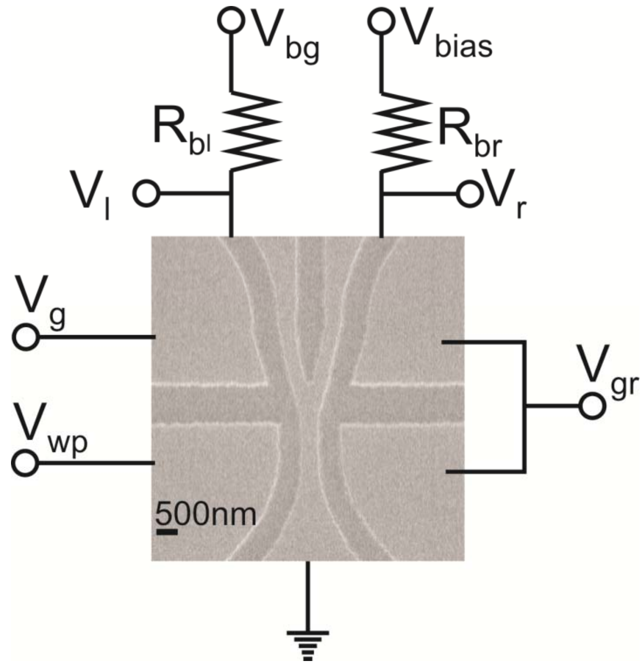


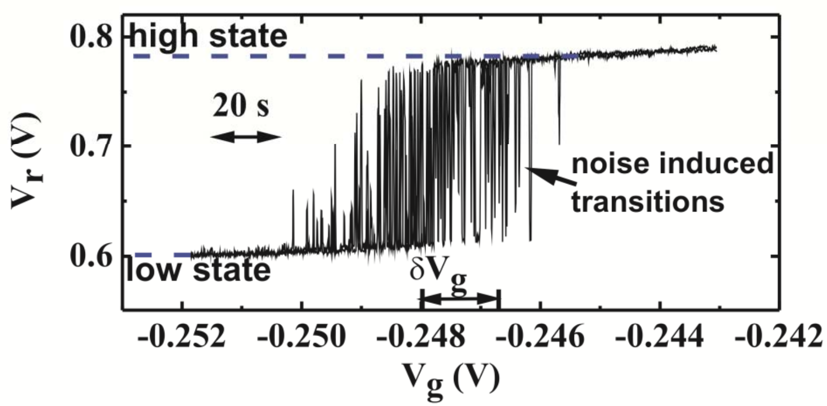


❒ YBS as amplifier and rectier ➔ logic operation

SR: Working principle

- self-gating leads to a bistable transfer characteristic
- the input and the working point voltages were set to bistable switching controlled by noise
- all measurements @ 20K





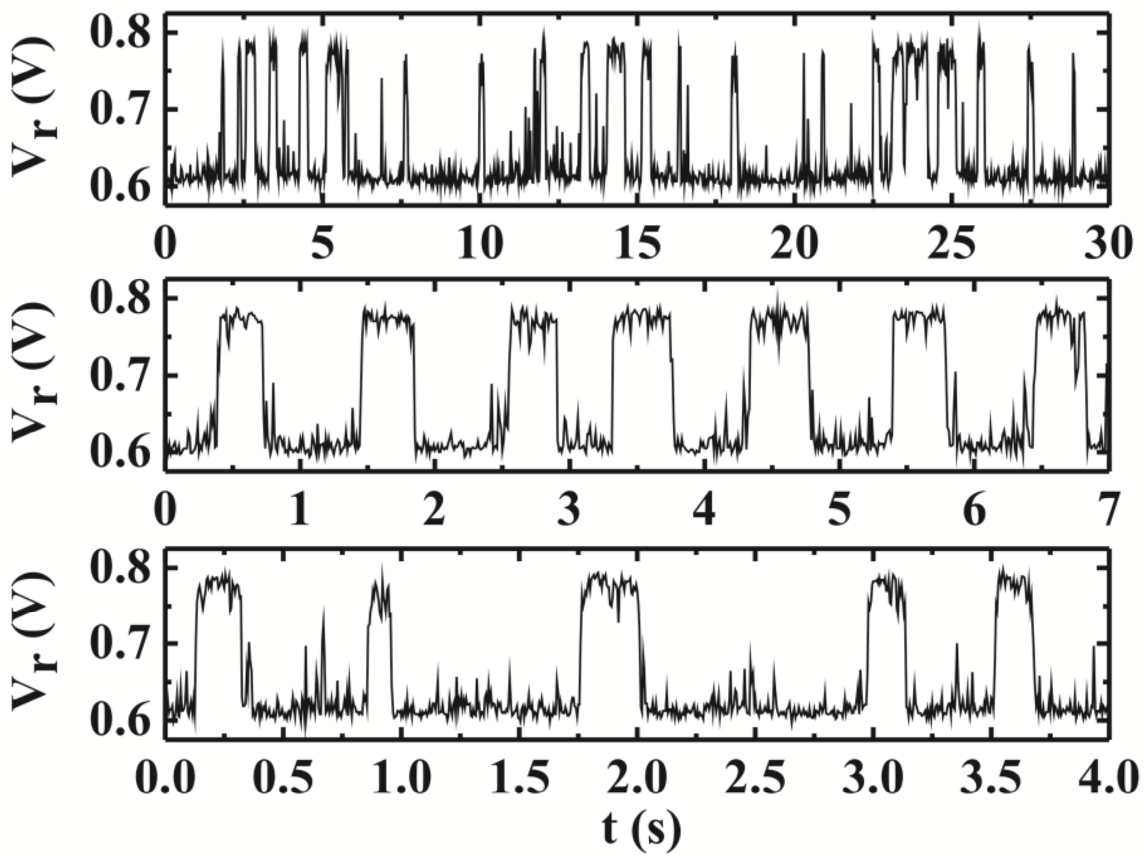
Input signal:

$$V_g(t) = V_{g,0} + \delta V_g \bullet \sin(\omega t)$$

Weak periodic signal:

$$\delta V_g = 1.3mV$$

SR: Signal traces



f = 0.1 Hz

f = 1 Hz

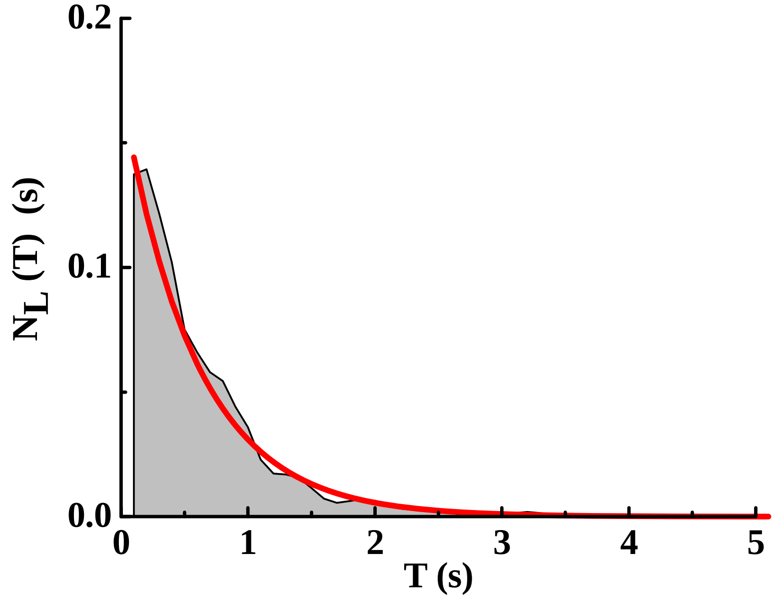
f = 1.8 Hz

At f = 1 Hz the noise dynamics follow directly the frequency of the external input forcing and a maximum synchronization is found.

Recording SR: Residence Time

For the unmodulated system with f = 0 Hz the residence time distribution decays exponentially with the inverse of the Kramer's rate

$$N_{L,H}(T) \propto \exp(-\frac{T}{T_K})$$



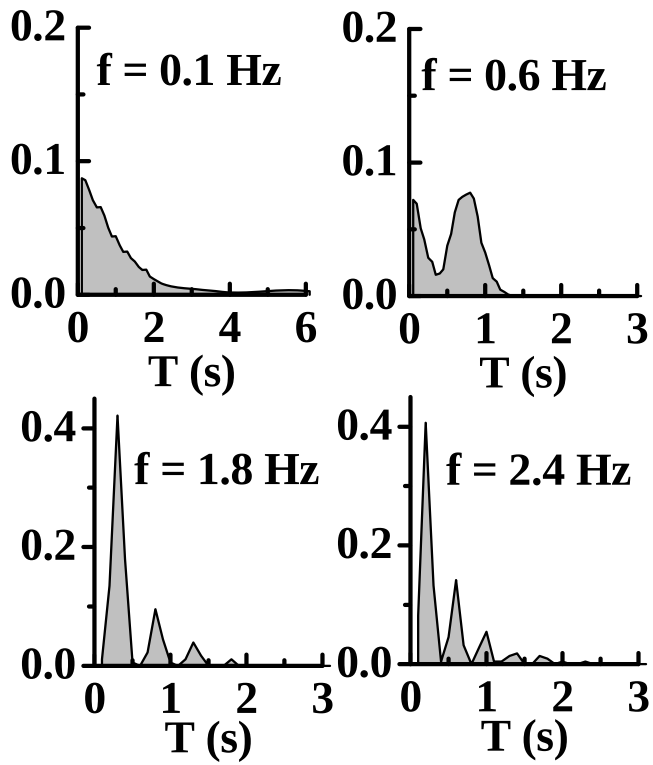
From fitting:

$$T_K = (0.502 \pm 0.044)s$$

Time matching condition of SR: $T_\omega = 2T_K$

Recording SR: Residence Time

- For $f < f_{SR}$ the residence time distribution is strongly controlled by the noise

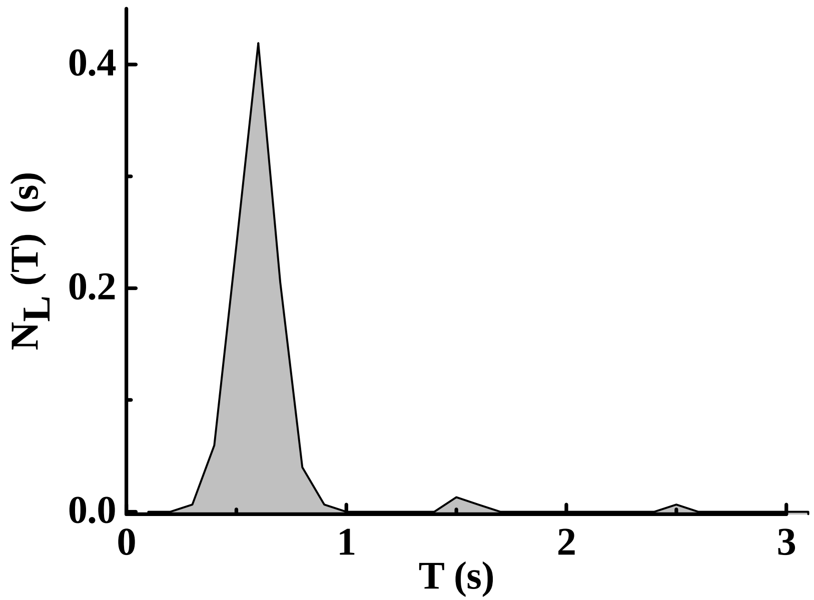


- For $f > f_{SR}$ odd multiples of the periodic forcing T_ω occur:

$$T_n = (2n-1)T_\omega / 2$$

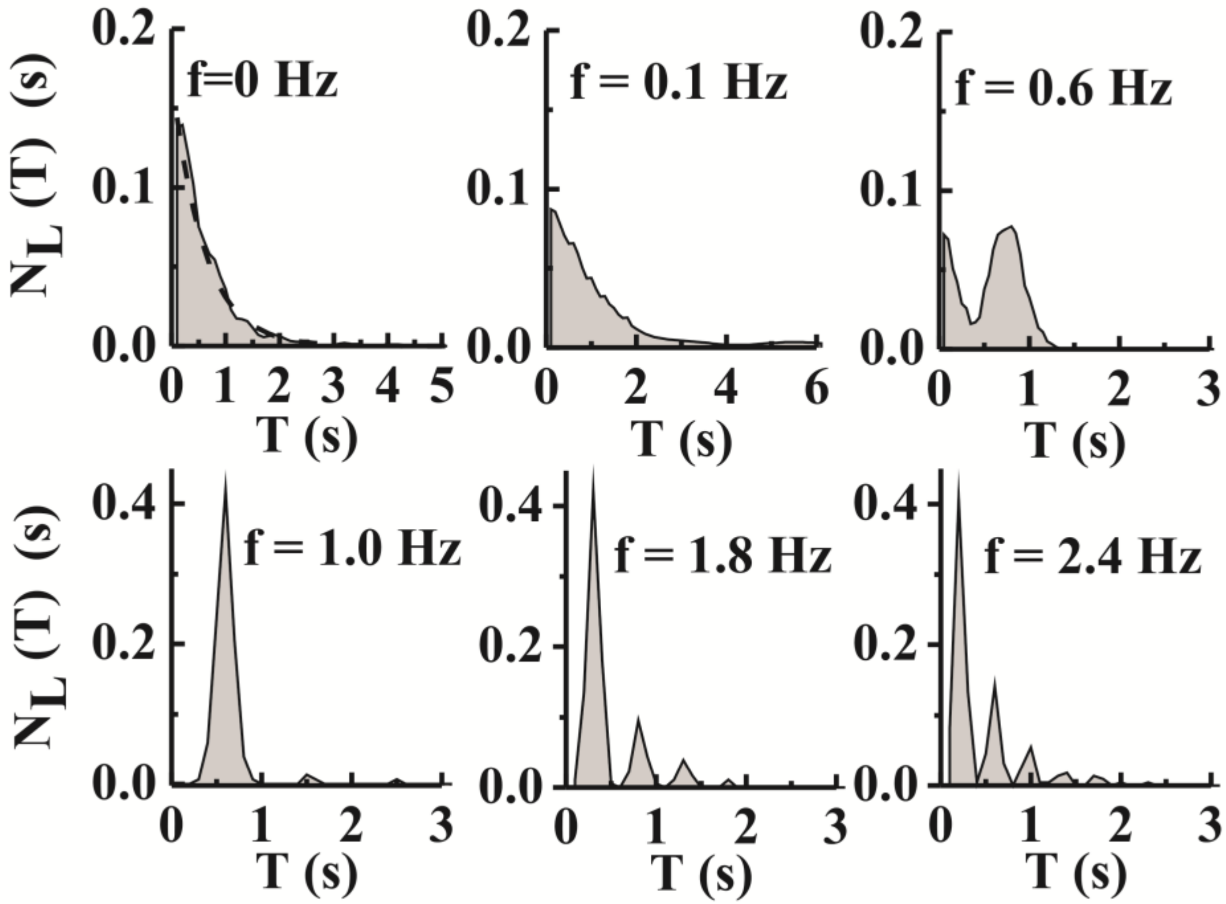
Recording SR: Residence Time

At the optimum frequency f = 1 Hz the residence time distribution is almost perfectly restricted to the first peak.



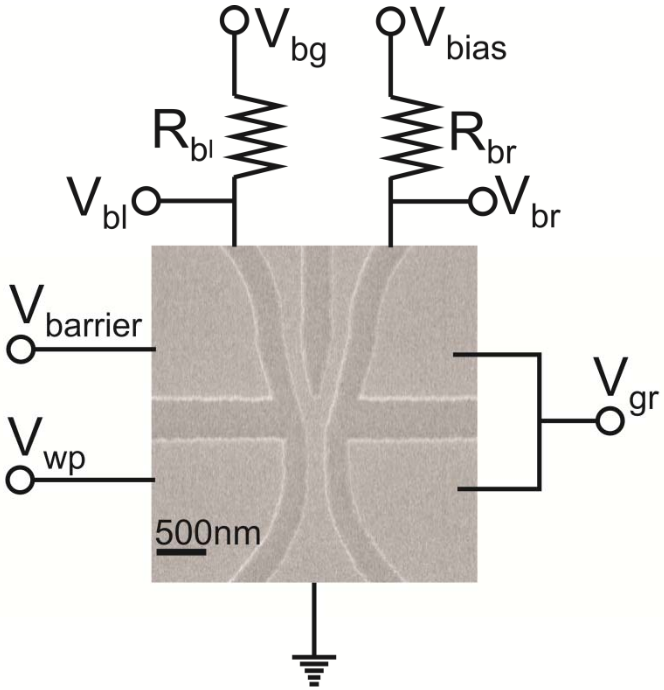
The time scale condition of SR is fulfilled by tuning solely the frequency of the periodic forcing.

SR: Residence Time Distribution

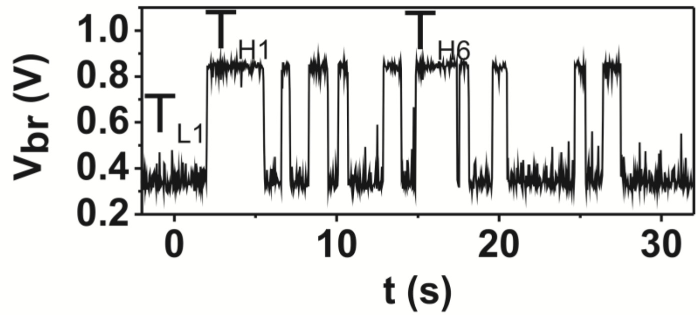


Application: Magnetic field sensor

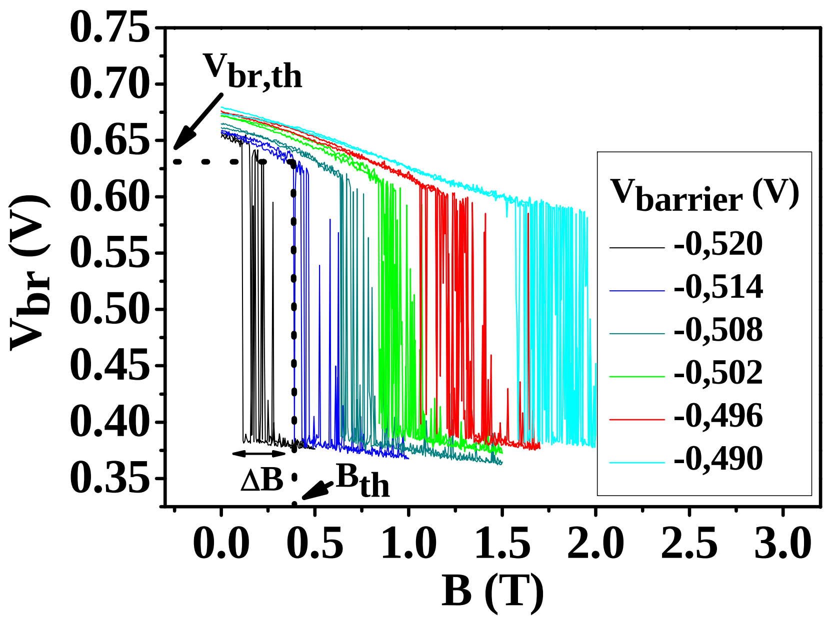
- Set the detector in the strongly noise activated regime
- Magnetic field applied perpendicular to the motion of electrons either in or out of the plane



$$T_{H,L} = \frac{1}{n_{H,L}} \sum_{i=1}^{n_{H,L}} T_{H_i,L_i}$$

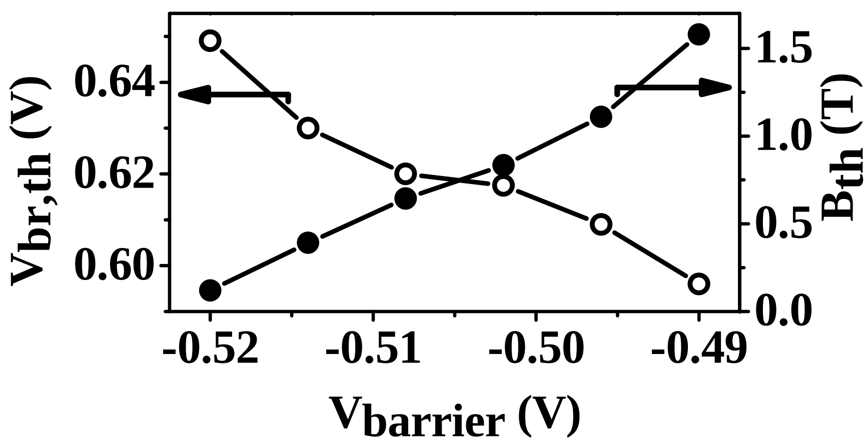


Application: Magnetic field sensor



- V_{br} decreases down to a magnetic field threshold B_{th}
- Transitions between the two states occur between ΔB

The magnetic-field induced switching is associated with a scattering asymmetry at the boundaries



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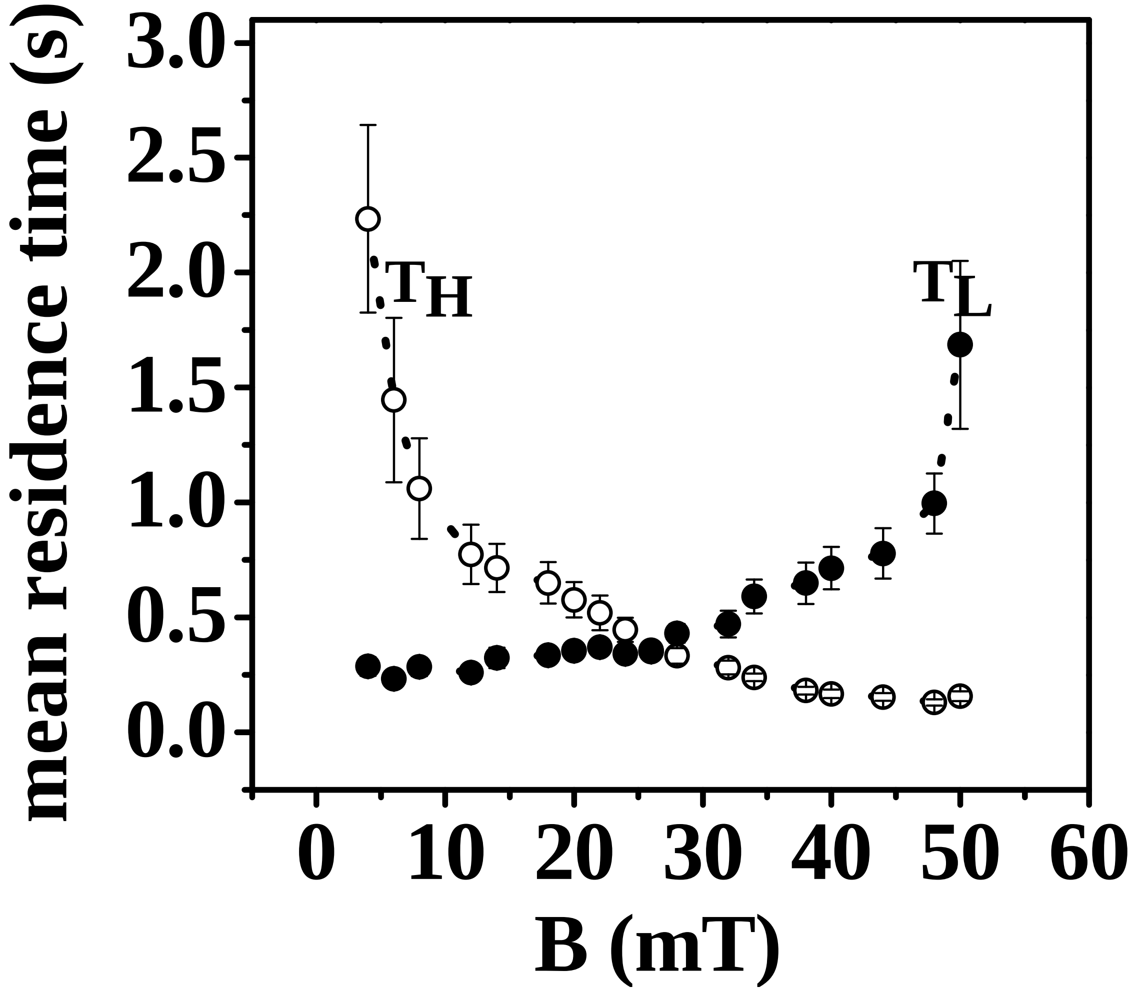
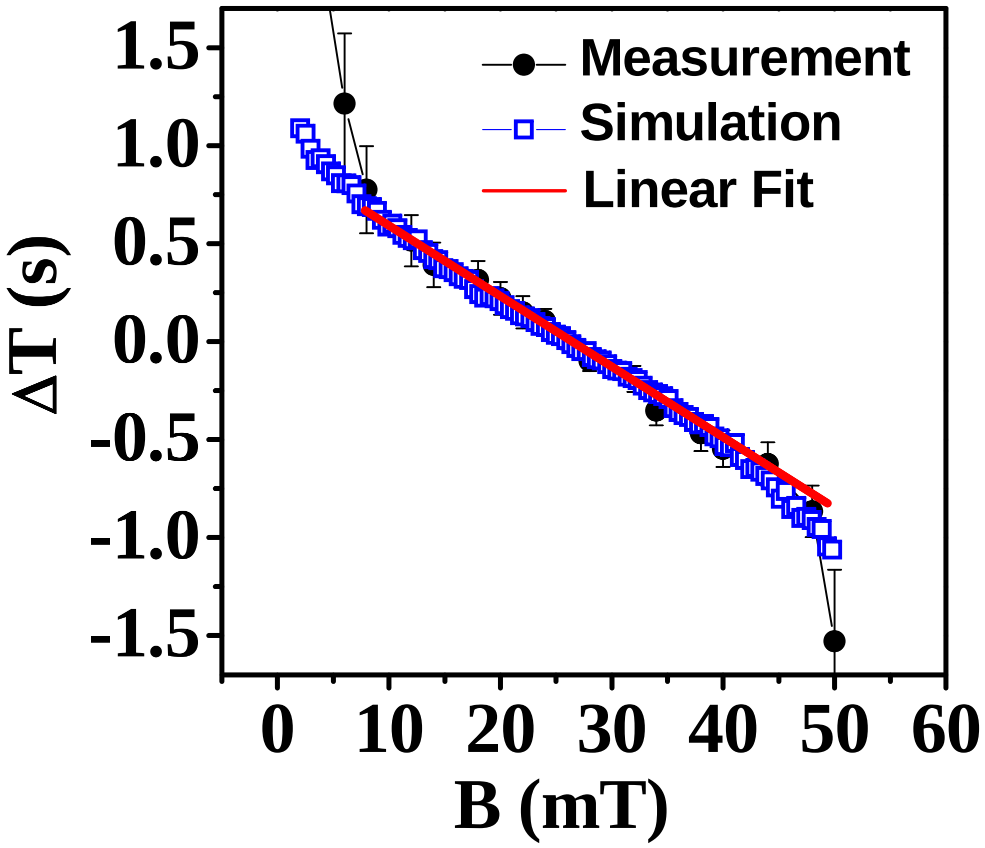


Application: Magnetic field sensor



- Output is a linear function of B around ΔT = 0 s
- Target signal independent sensitivity

$$\Delta T(B) = T_0 - cB$$

$$S(B) = \frac{\partial \Delta T}{\partial B} = c$$

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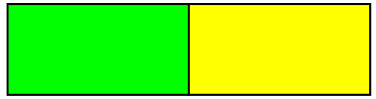
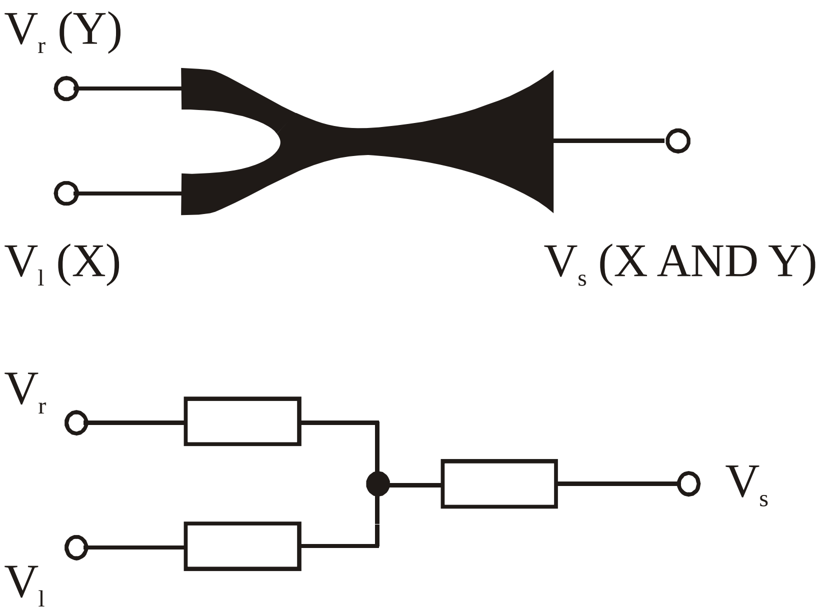
Y-branch as ballistic rectification

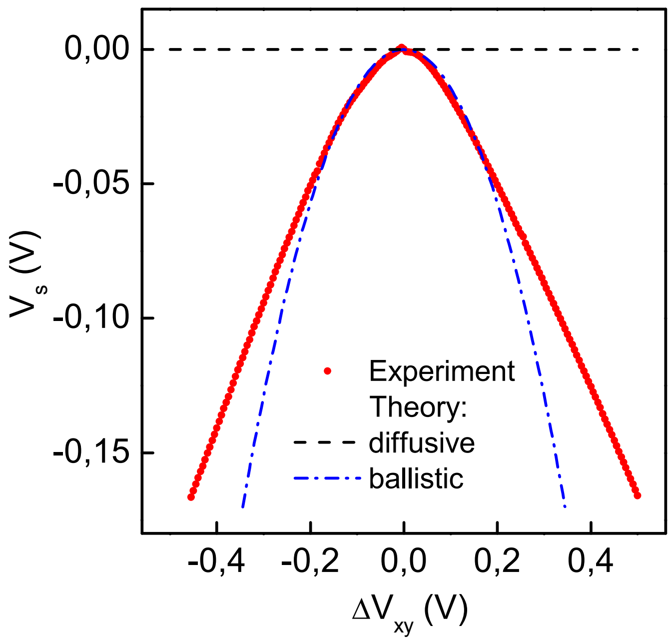
Rectification due to junctions:

- pn-junction
- Metal-semiconductor junction

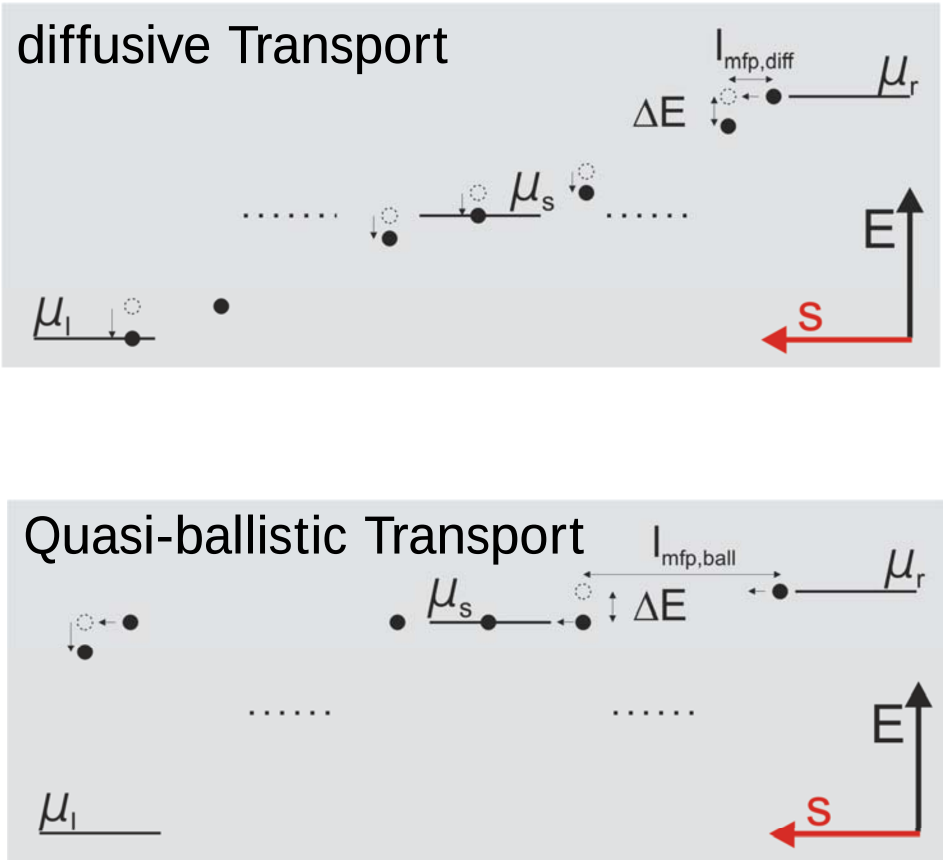


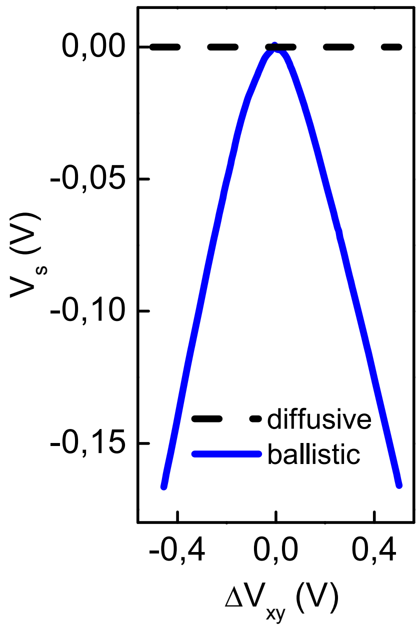
Y-branch junction: no geometrical asymmetry!





Y-branch as ballistic rectification





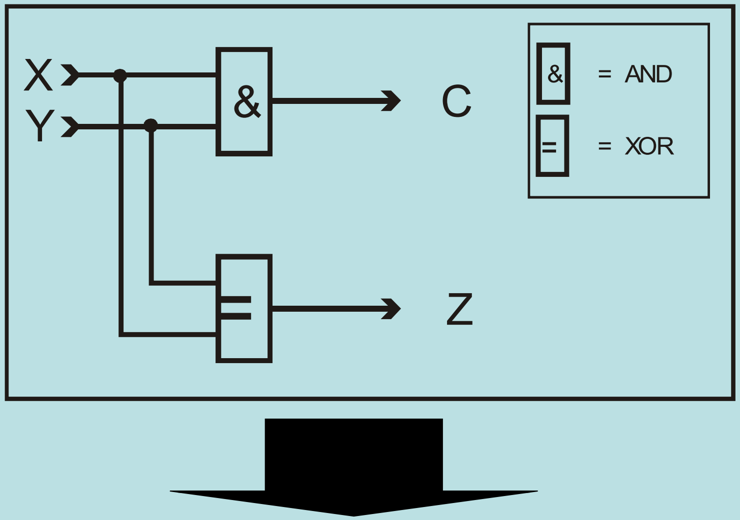
YBS nonlinearity used for a compact adder

Half-Adder: binary addition with carry bit

Truth table

X	**Y**	**Z**	**C**
H	H	L	H
H	L	H	L
L	H	H	L
L	L	L	L

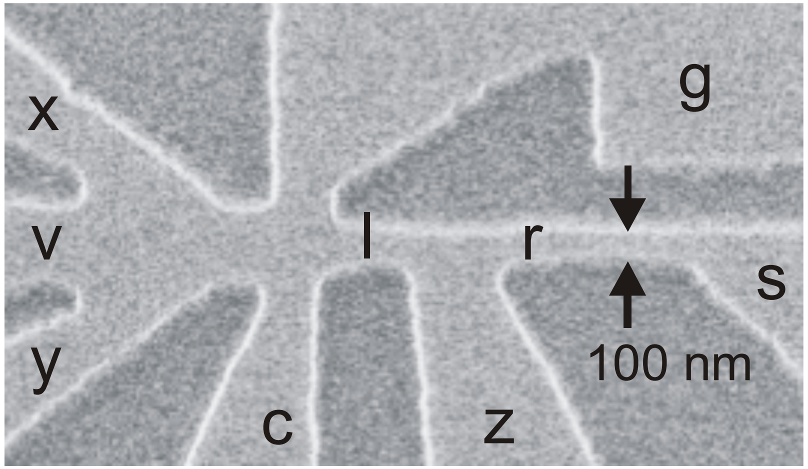
Scheme



> 10 FETs + interconnects

Nanoelectronic Half-Adder

- planar Half-Adder is based on ballistic Y-junctions
- Inputs: x and y
- Outputs: c and z
- Working point: s
- Control: v



L. Worschech et al., Appl. Phys. Lett. 83, 2462 (2003)

Model

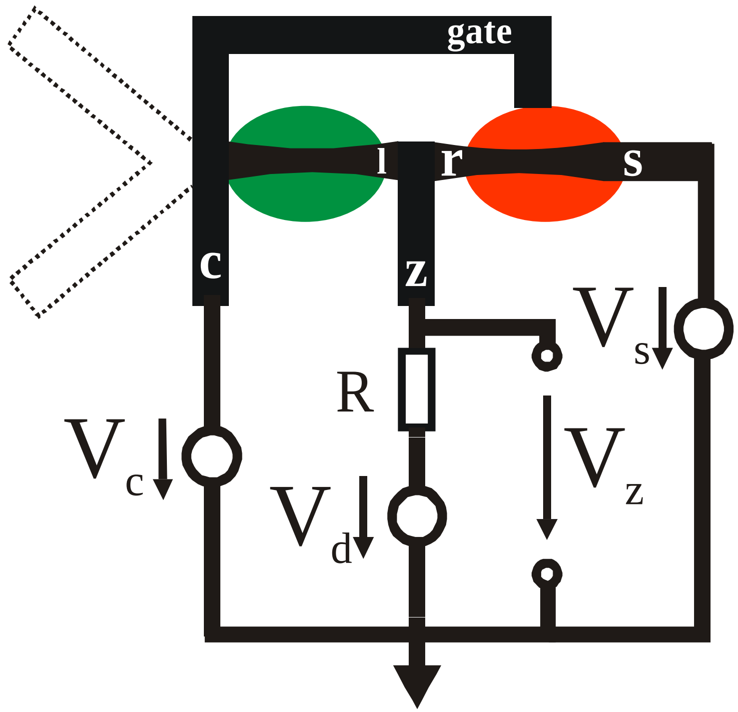
control of V_z via V_c:

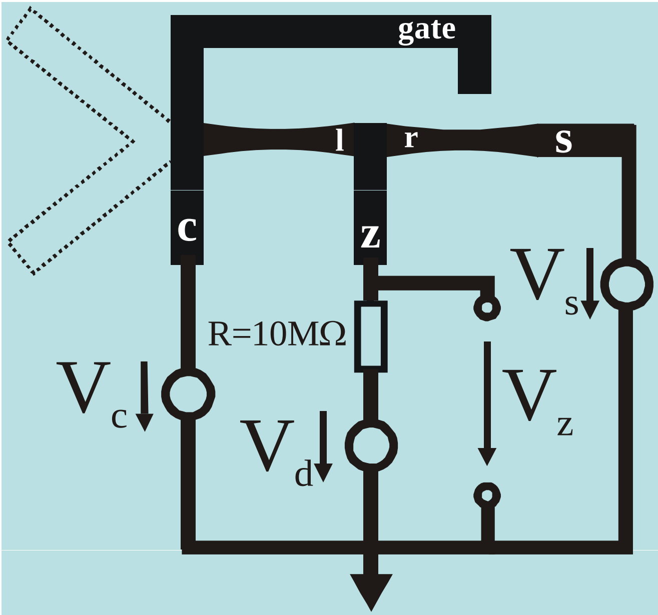
a) Injection of electrons

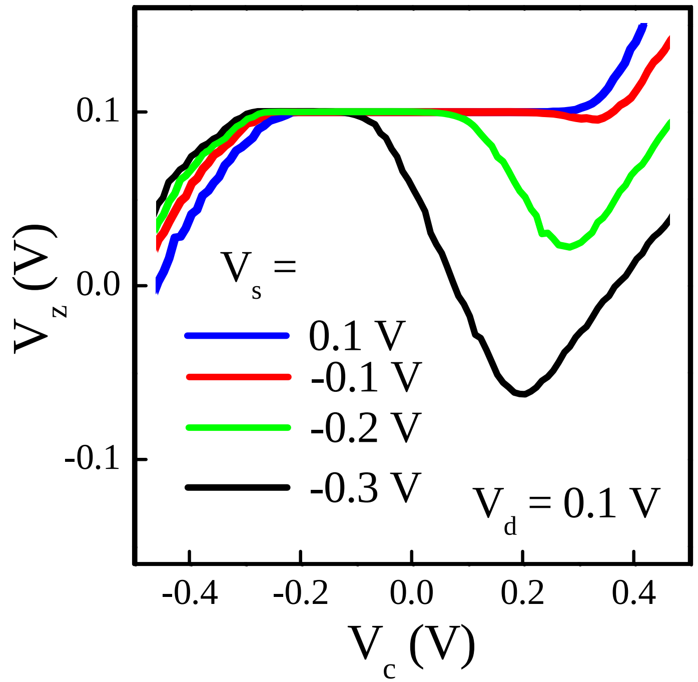
b) Gating

No external gate!

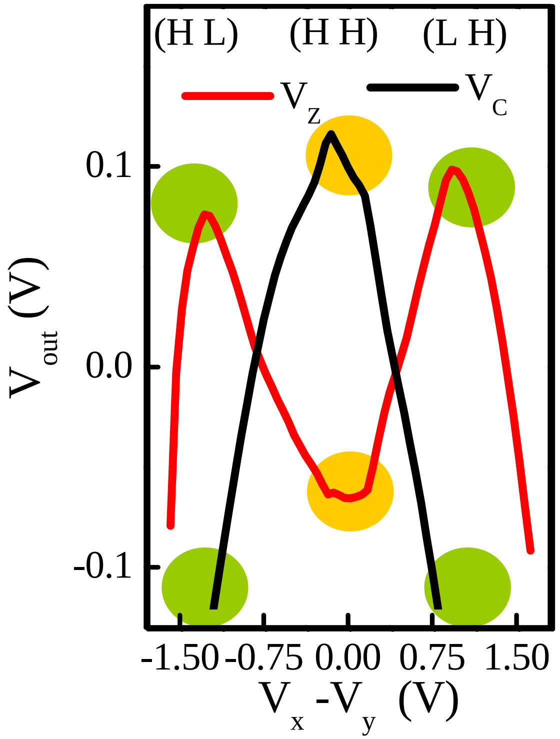
⇒ Self induced switching

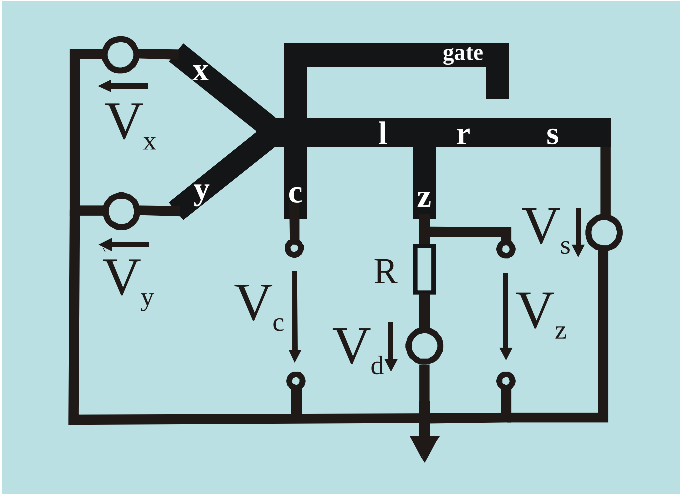


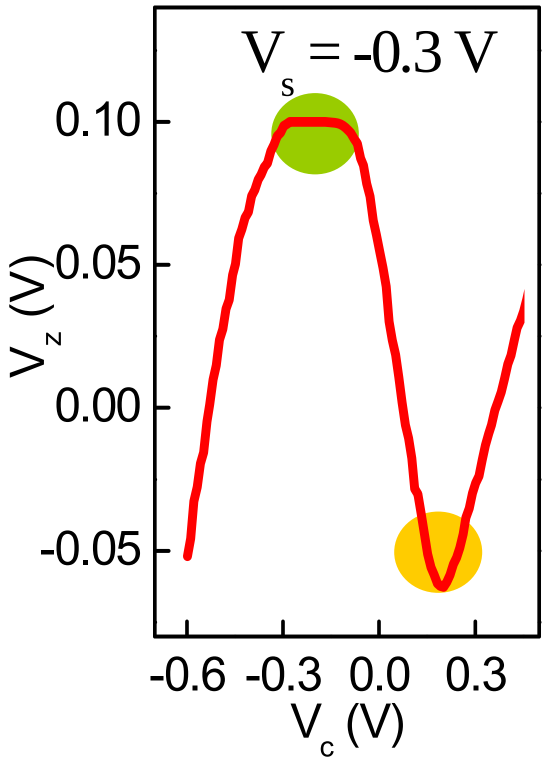




- Self switching ⇒ N-shaped V_z (V_c)-characteristics
- Definition of the working point via V_s

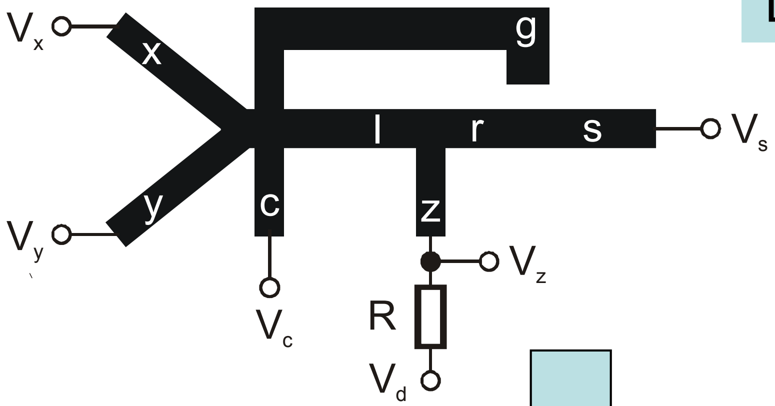




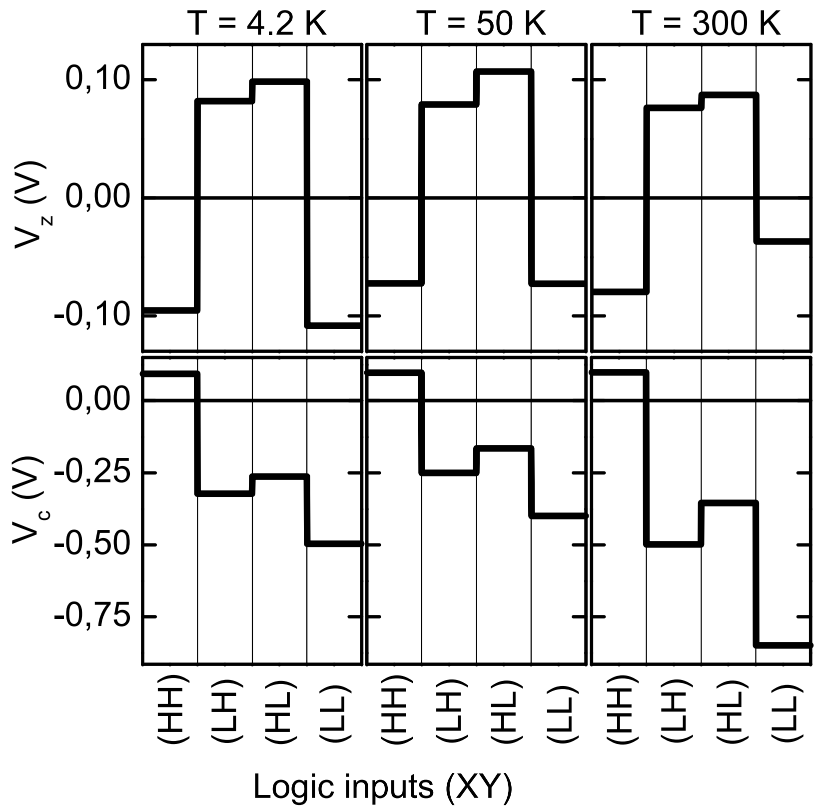


- Push-Pull-Mode:
  $V_x + V_y = 0.3$ V
- Rectification: $V_c < (V_x + V_y)/2$
- Self induced Switching:
  M-shaped V_z-characteristic

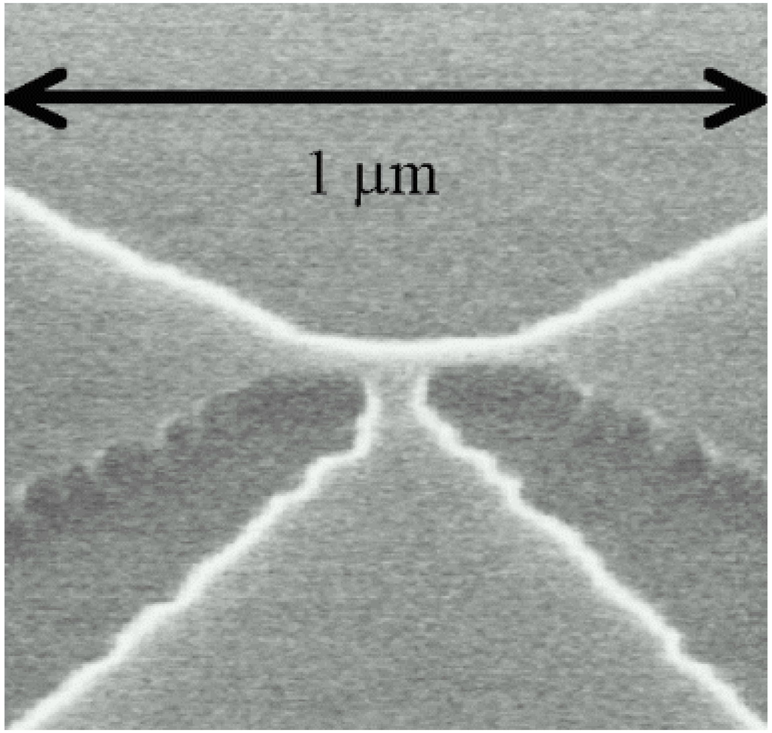
Demonstration of logic function at RT:

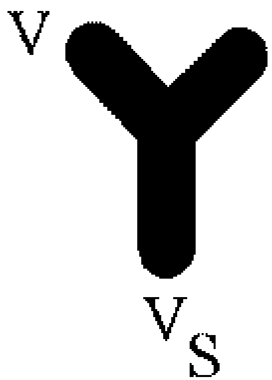


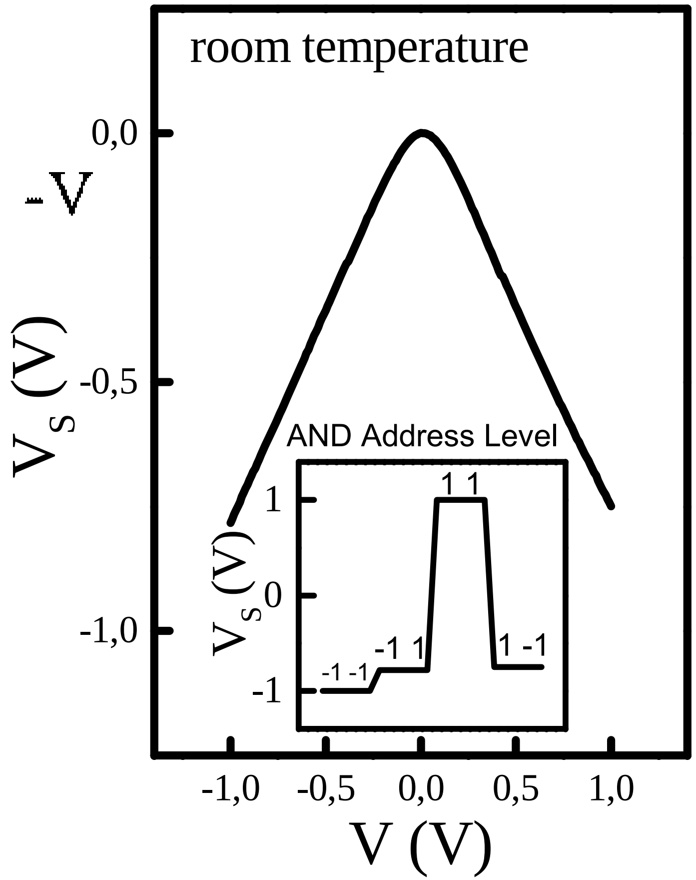
X	Y	Z	C
H	H	L	H
H	L	H	L
L	H	H	L
L	L	L	L



Dynamic properties of rectification







Microwave rectification: energy harvesting

3T ballistic cavity
A. N. Jordan,
Markus Büttiker,
PRB 2009

$$c \sim \frac{1}{2}\frac{e}{\mu_F}$$

- assuming $V_s = c\,V^2$
- with $V = V_\sim \times \sin(\frac{f_1}{2\pi}t)$

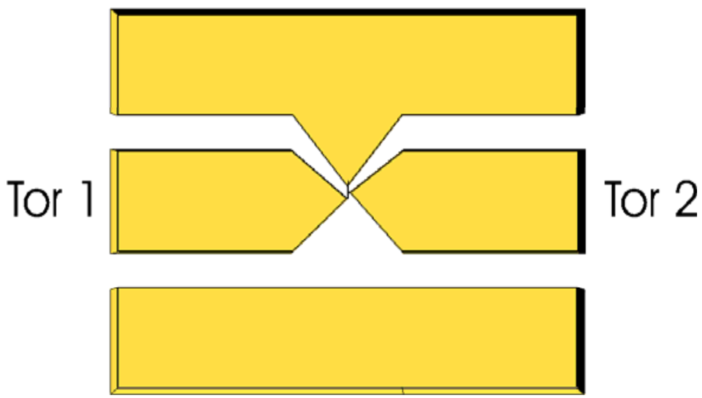
$$\Rightarrow V_s = \frac{c}{2}V_\sim^{\,2} - \frac{c}{2}V_\sim^{\,2} \times \cos(\frac{2\ f_1}{2\pi}t)$$

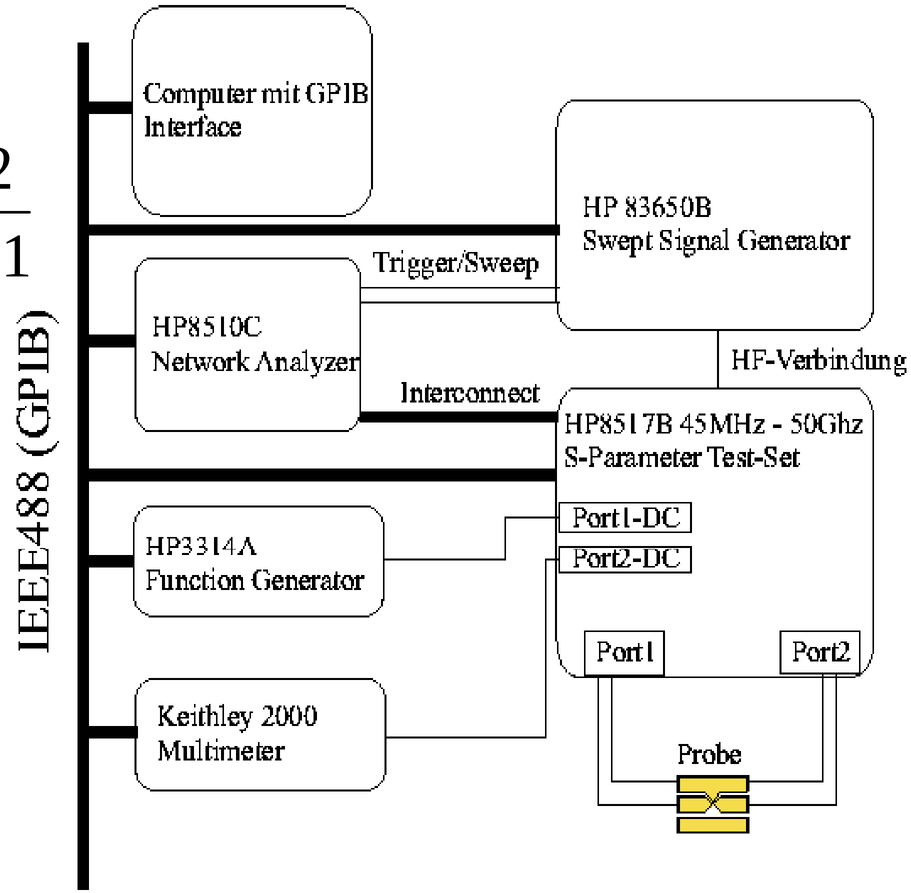
frequency doubling and dc current

High Frequency Setup

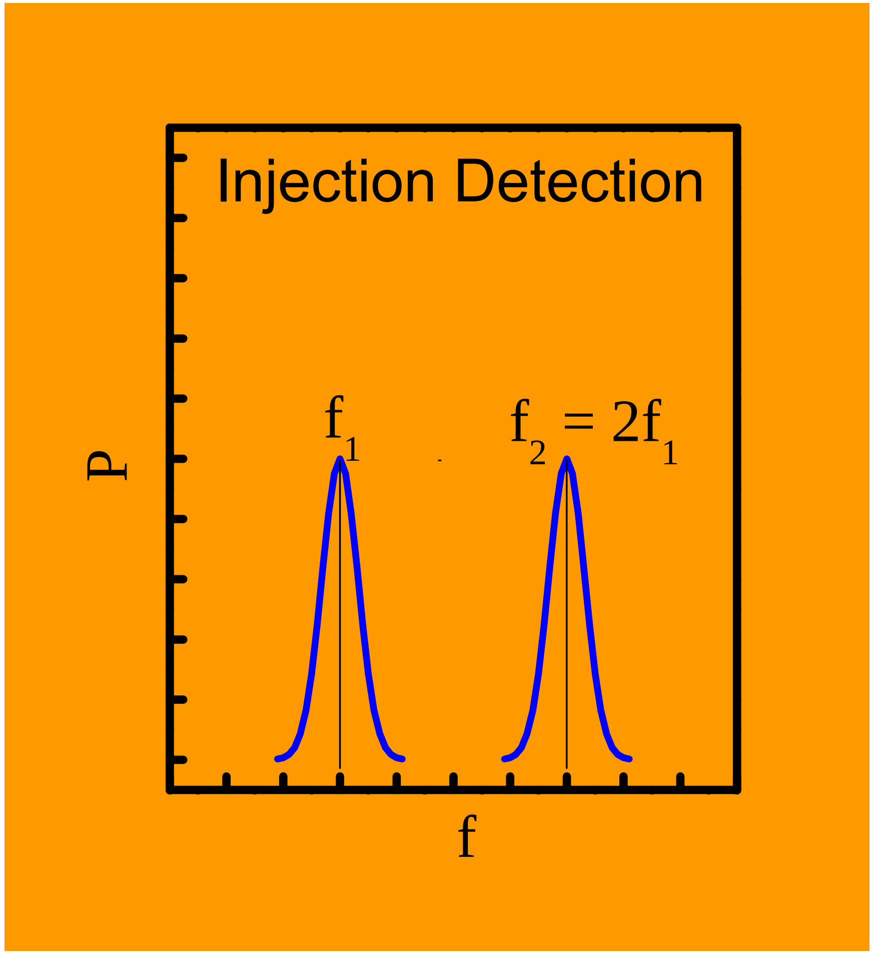
- S-Parameter

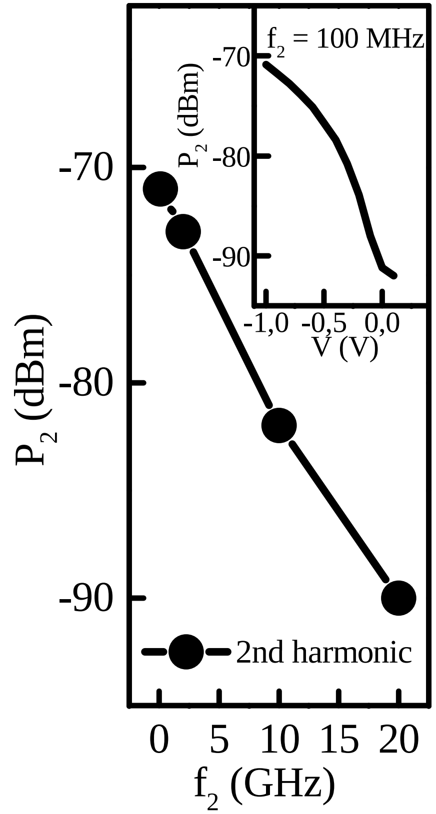
$$S_{21} = \frac{\text{microwave power detected at 2}}{\text{microwave power injected into 1}}$$



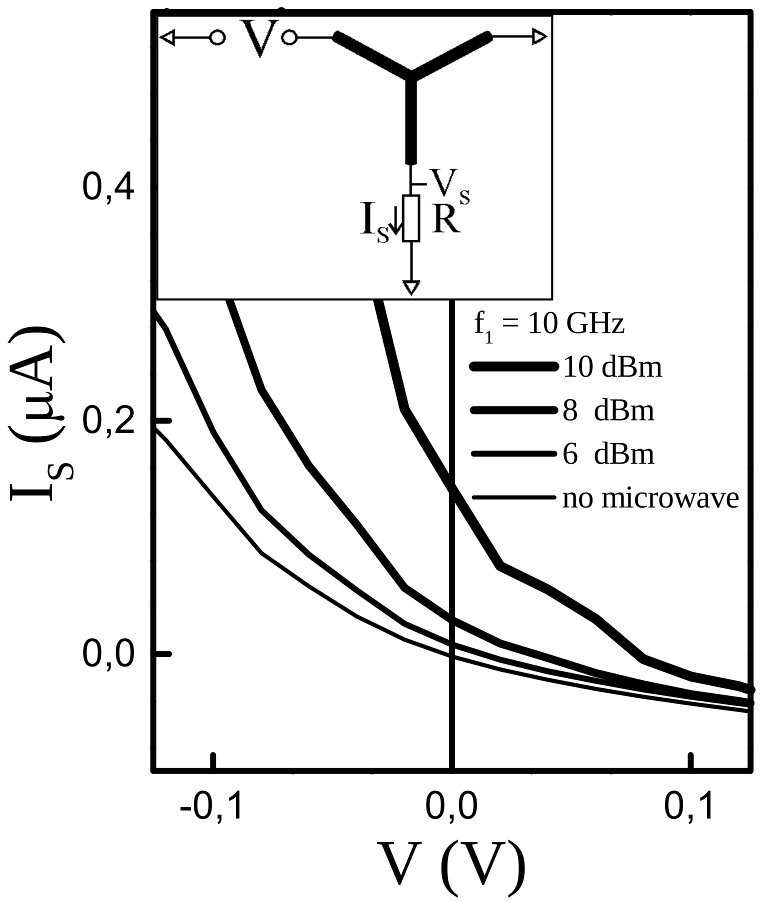


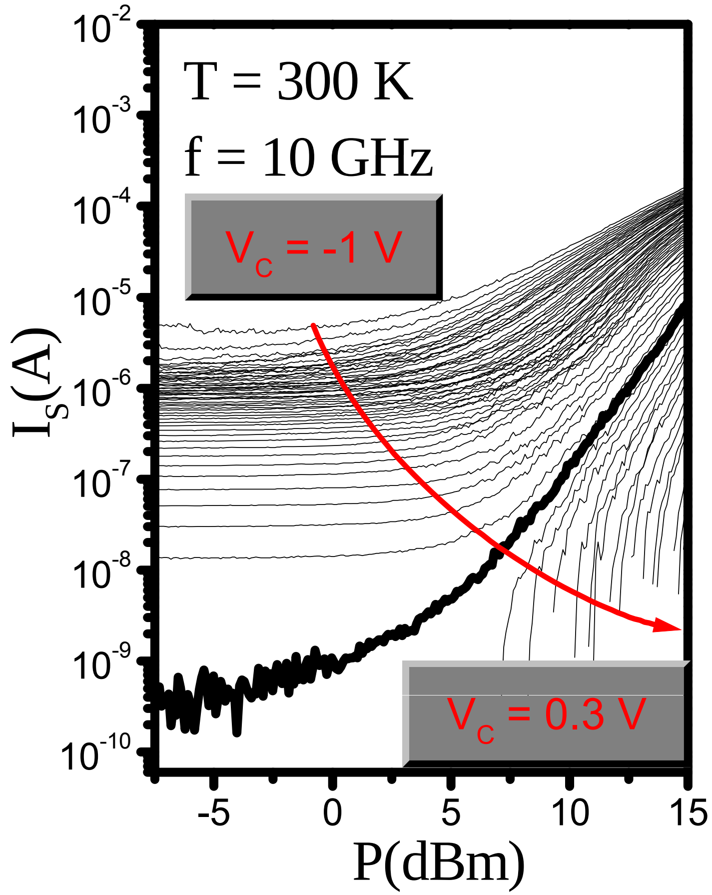
Frequency doubling





Microwave generates a DC current

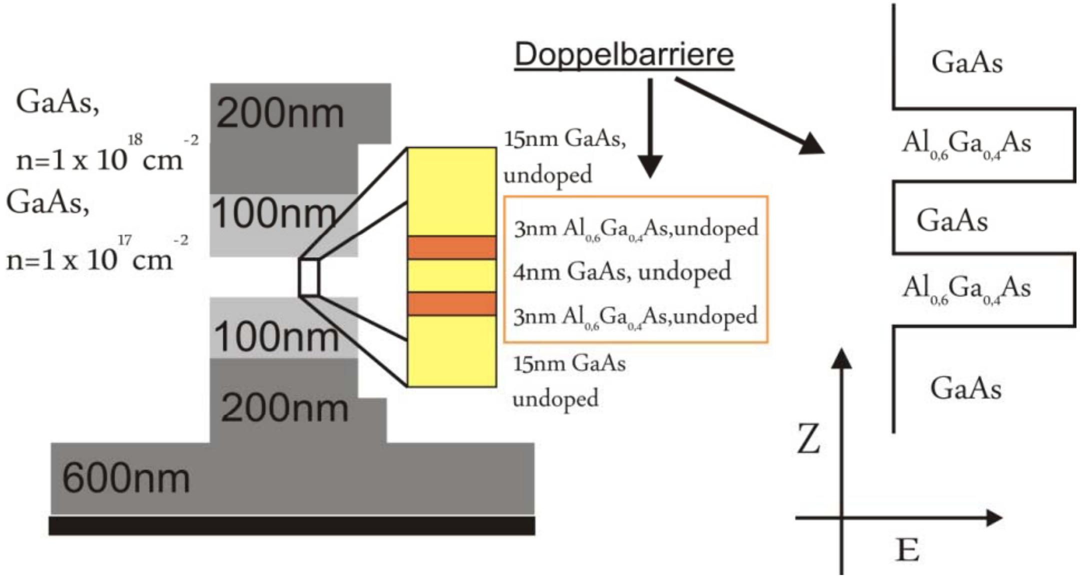




Outline

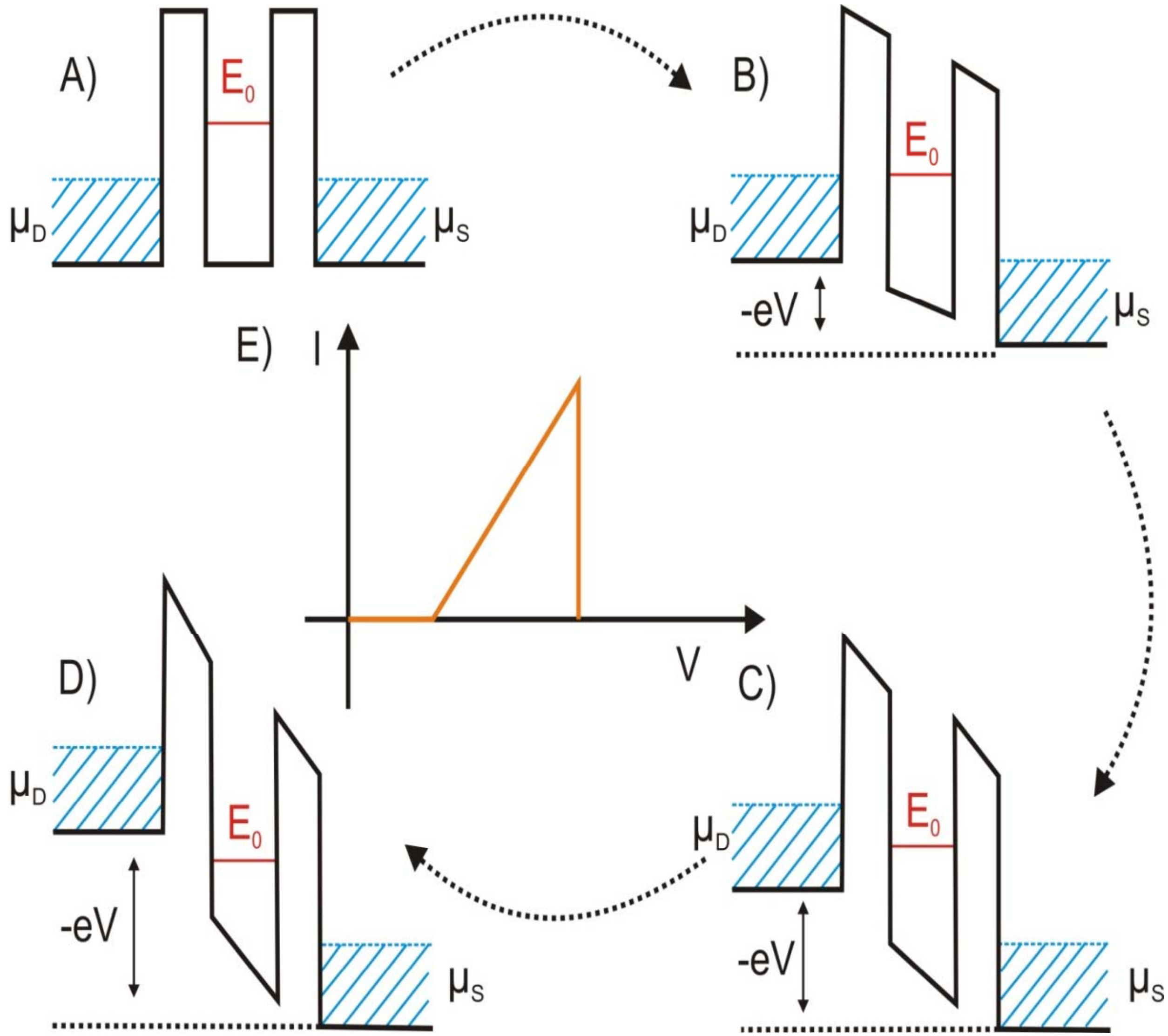
- Nanoelectronic semiconductor electronic devices
  - Technology
  - Nonlinear nanoelectronic transport
    - Magnetic field asymmetry in quantum wire
    - SR in a YBS as B field sensor
    - Y-branch as logic gate and GHz rectifier
    - Logic stochastic resonance in RTDs

Resonant-tunneling diode

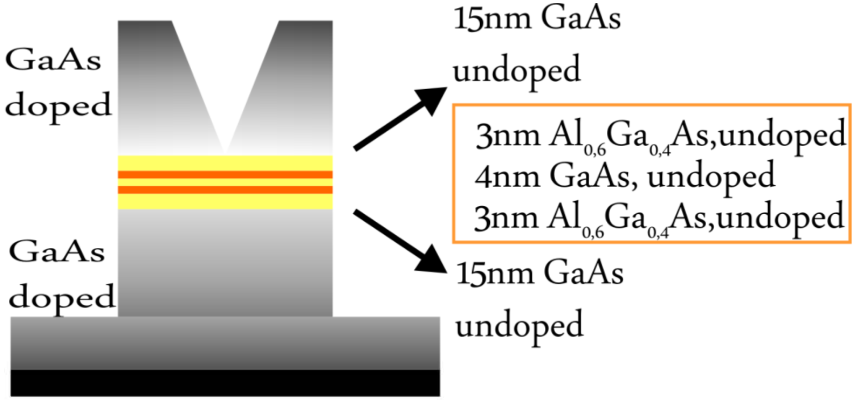


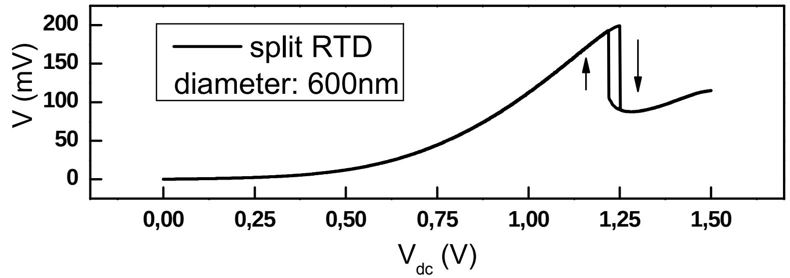
- fast operation ~THz
- negative differential resistance
- ballistic operation at room temperature

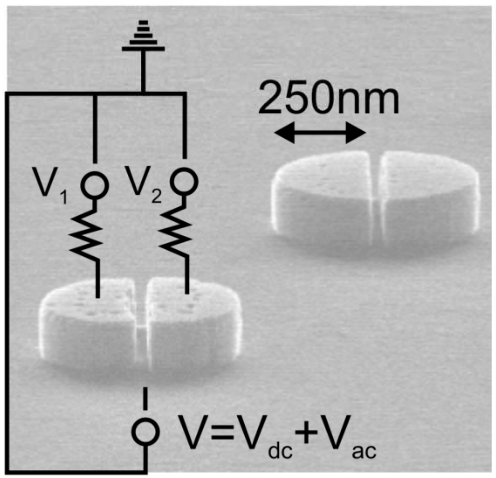
RTD operation

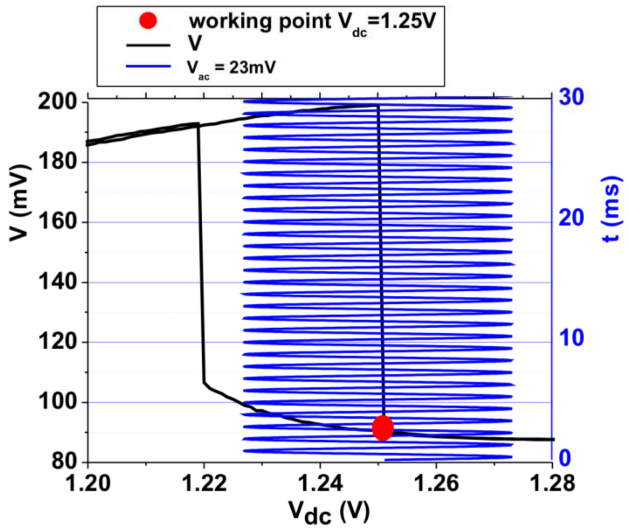


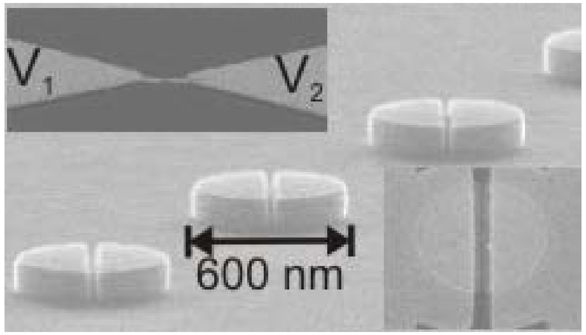
Logic operation with RTD mesas

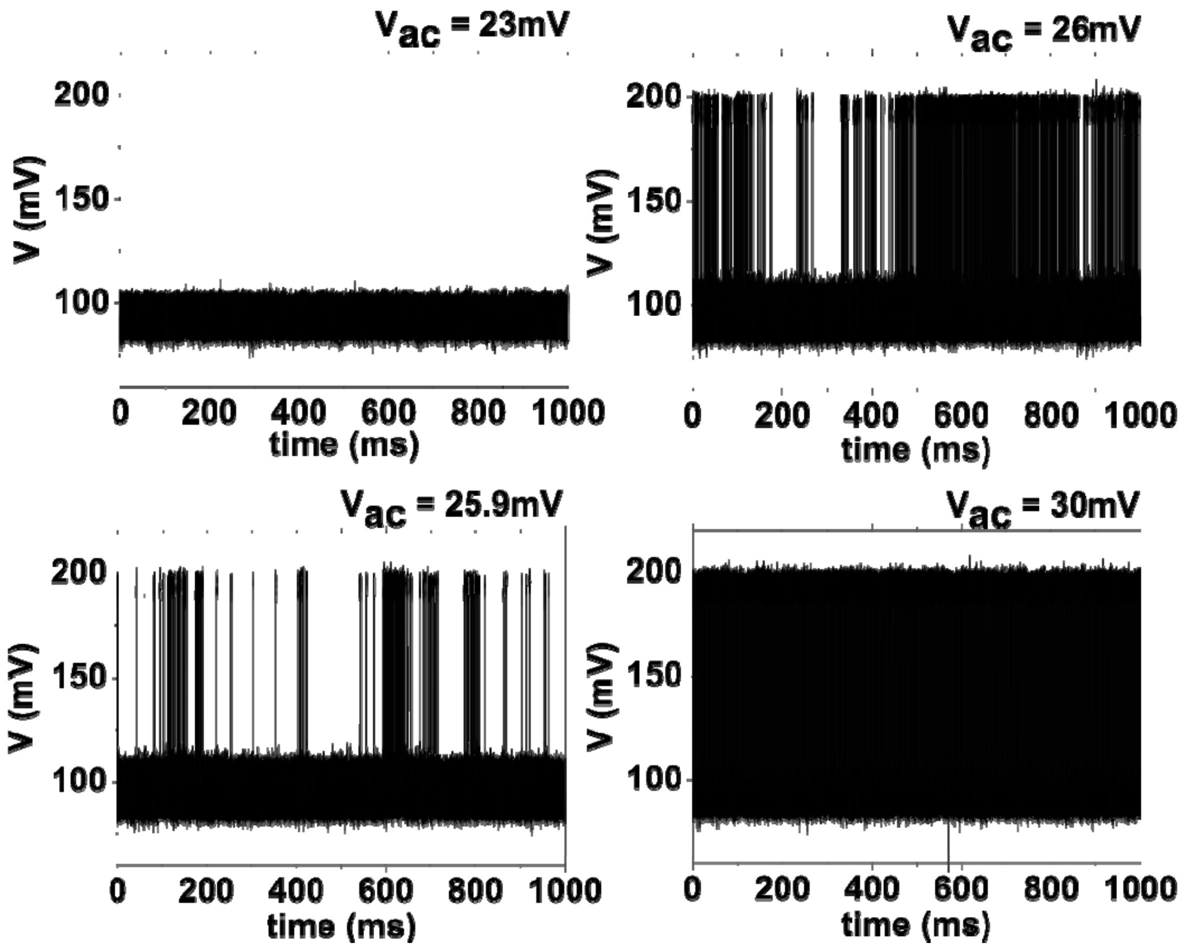






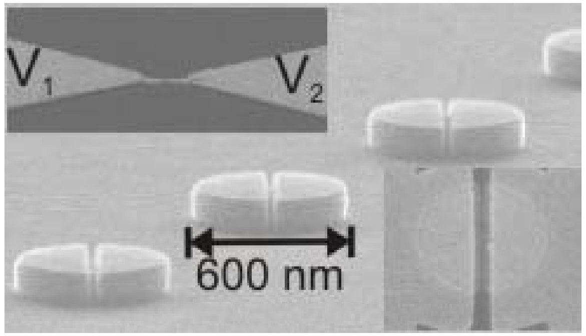


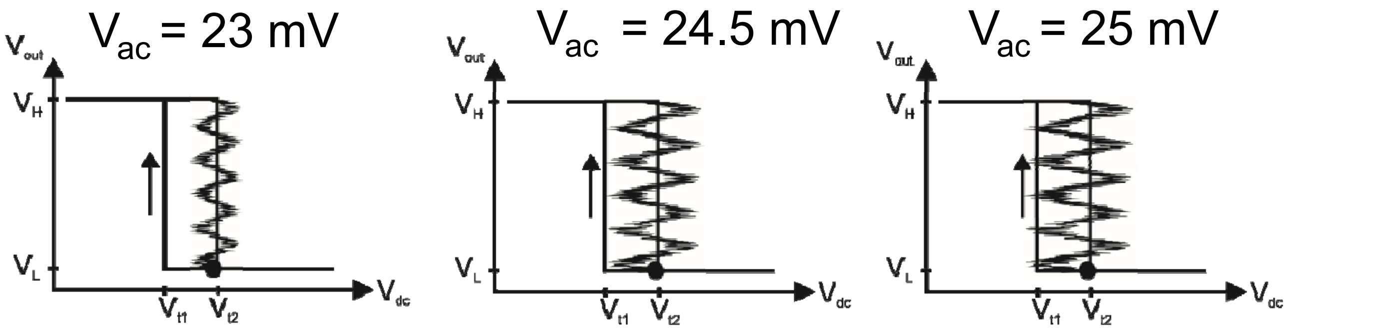




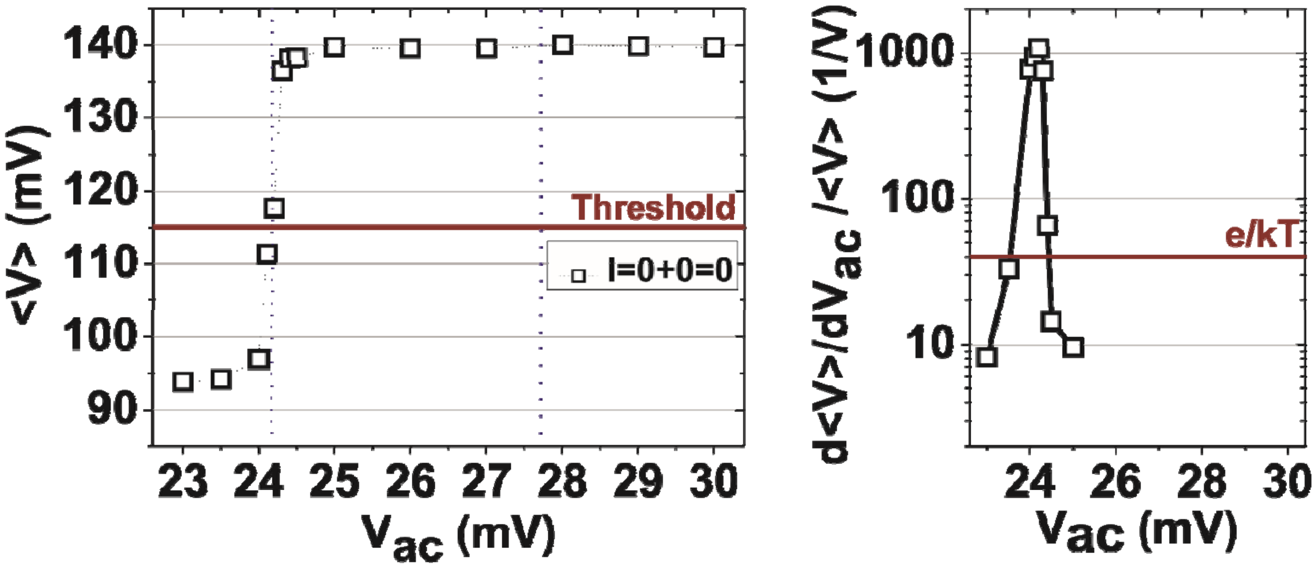
No thermal transconductance limit ➔ ultra small switching voltages

Logic RTD gates

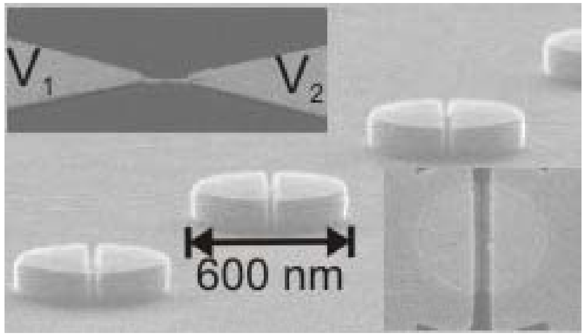


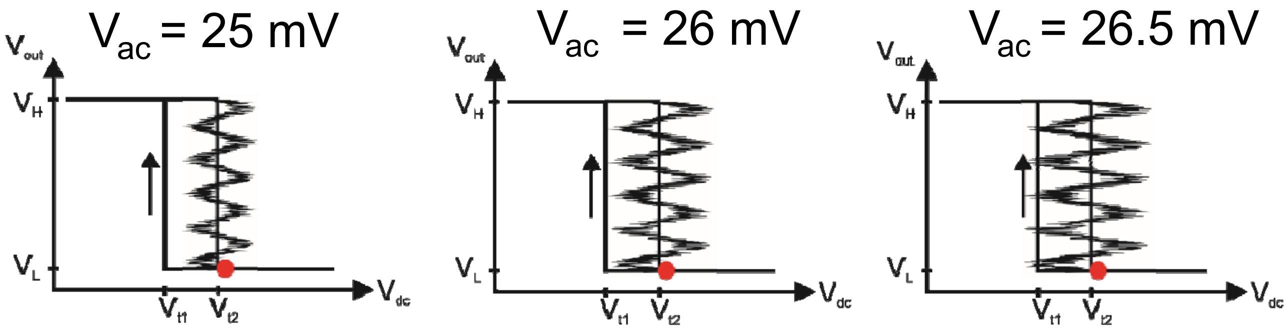


$V_1 = V_2 = 0$ mV == Log. input $I = I_1+I_2=0+0=0$

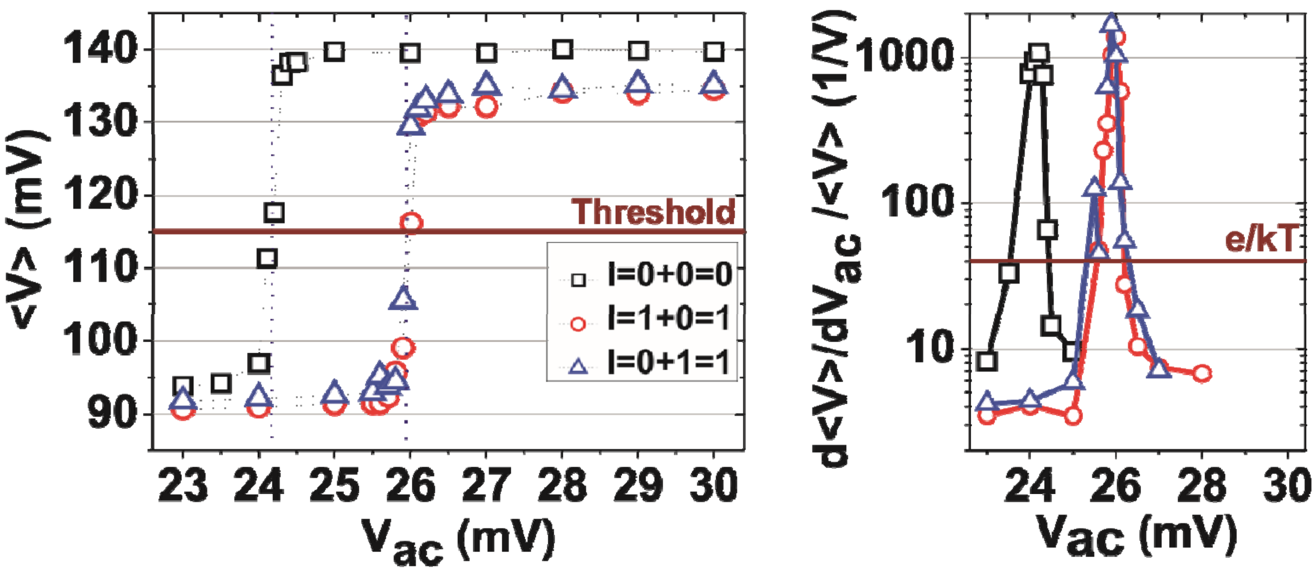


Logic RTD gates

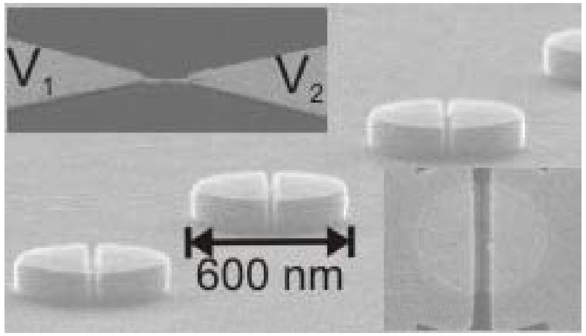


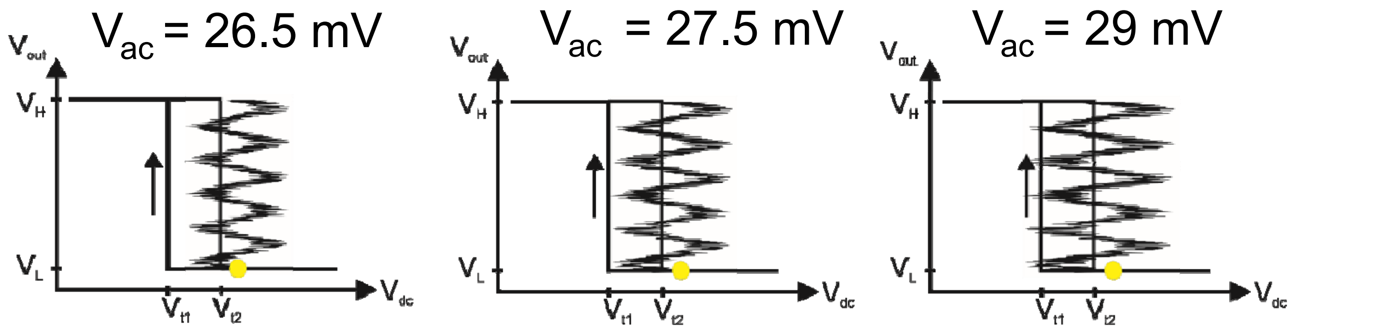


$V_1 = 0{,}2\ V_2 = 2{,}0$ mV == Log. input $I = I_1+I_2=1+0=0+1=1$

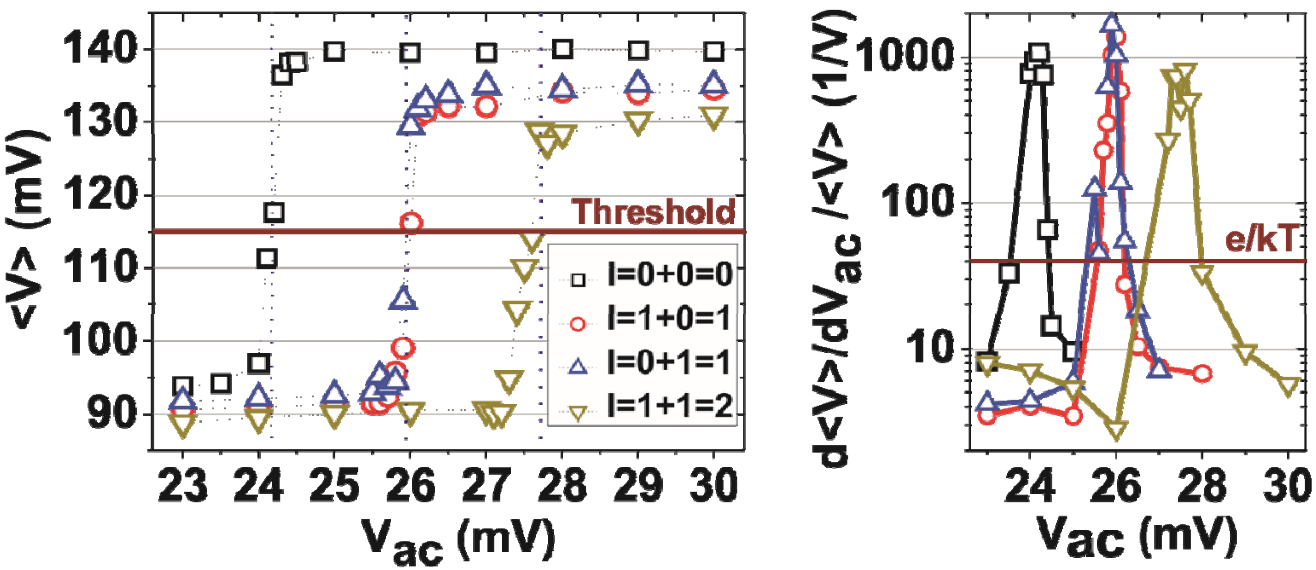


Logic RTD gates

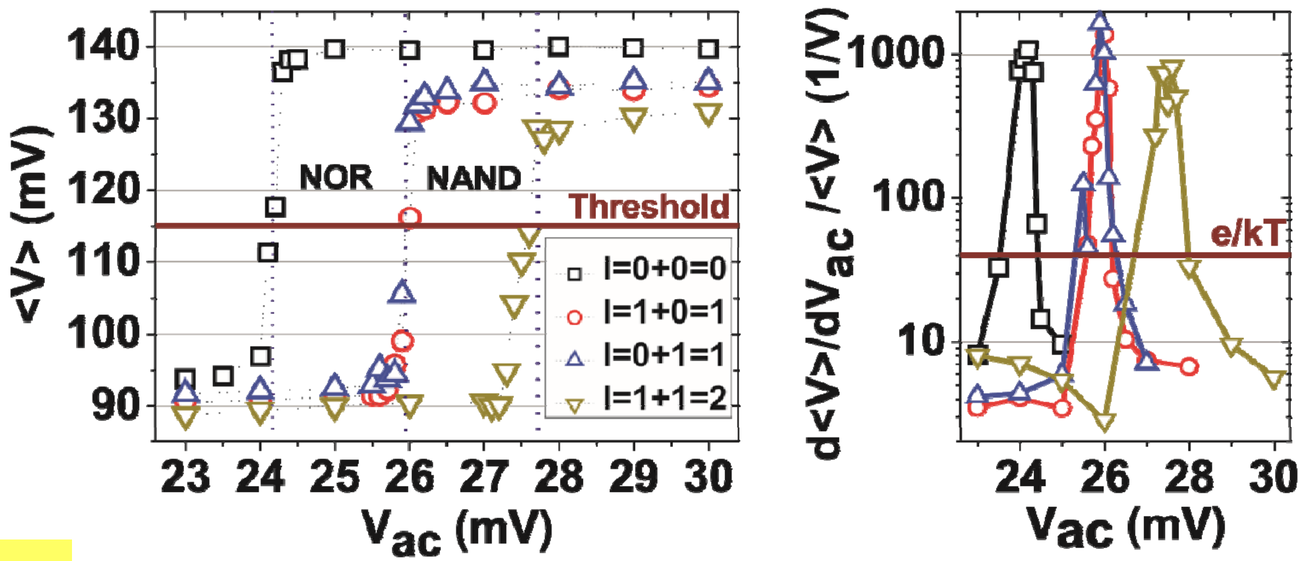




$V_1 = V_2 = 2$ mV == Log. input $I = I_1 + I_2 = 1+1=2$



Logic RTD gates



NOR

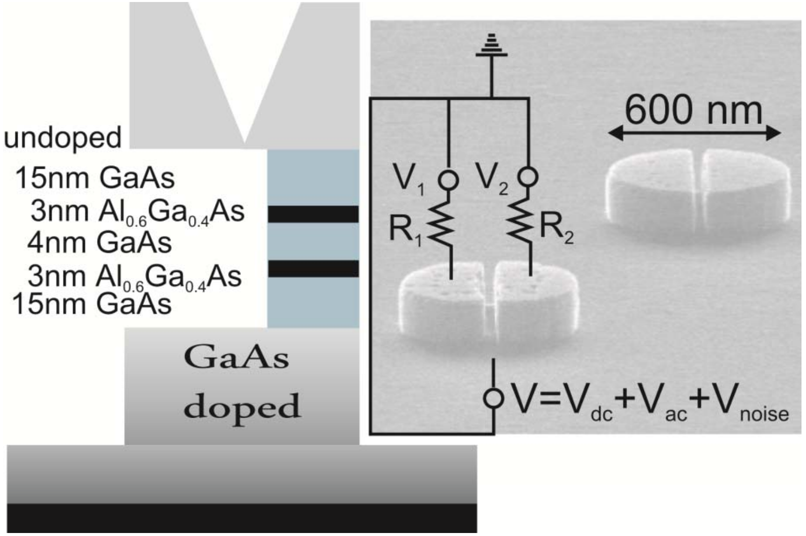
0 0 | 1
1 0 | 0
0 1 | 0
1 1 | 0

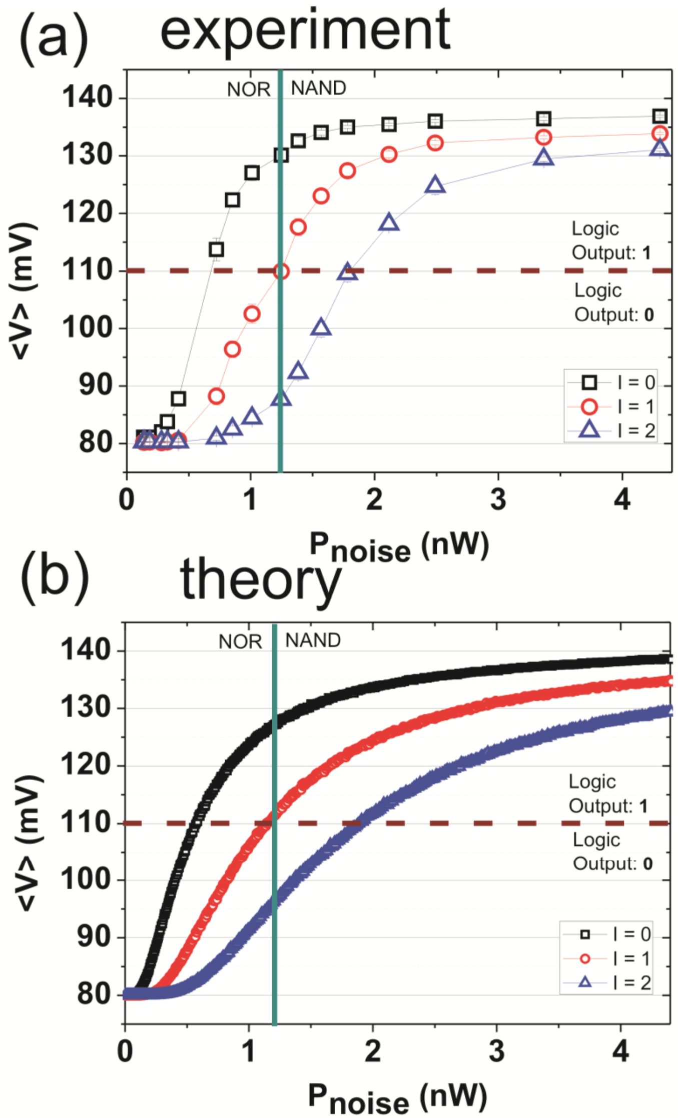
NAND

0 0 | 1
1 0 | 1
0 1 | 1
1 1 | 0

- transition from NOR to NAND opertation for amplitude changes smaller than 1 mV

Logic stochastic resonance



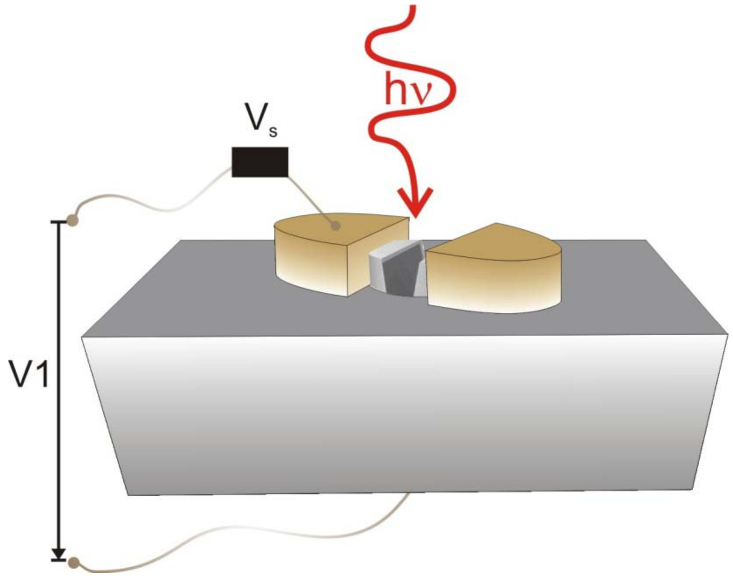


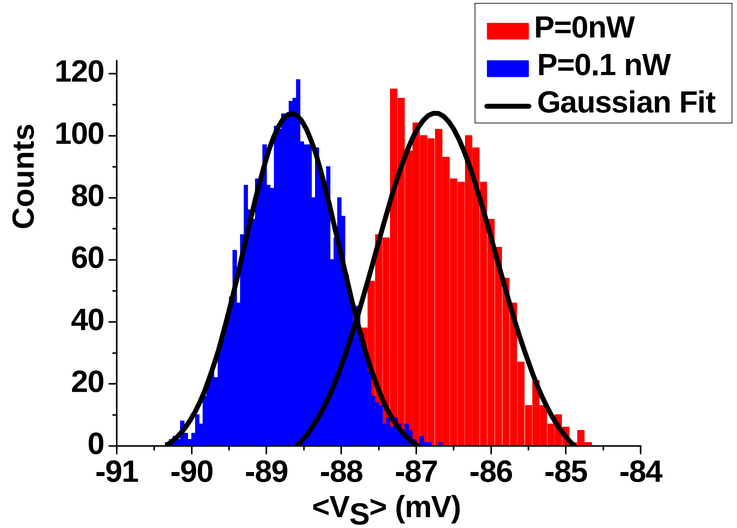
Murali, K. , Sinha, S. , Ditto, W. , Bulsara, A. Phys. Rev. Lett. **102**, 104101 (2009).

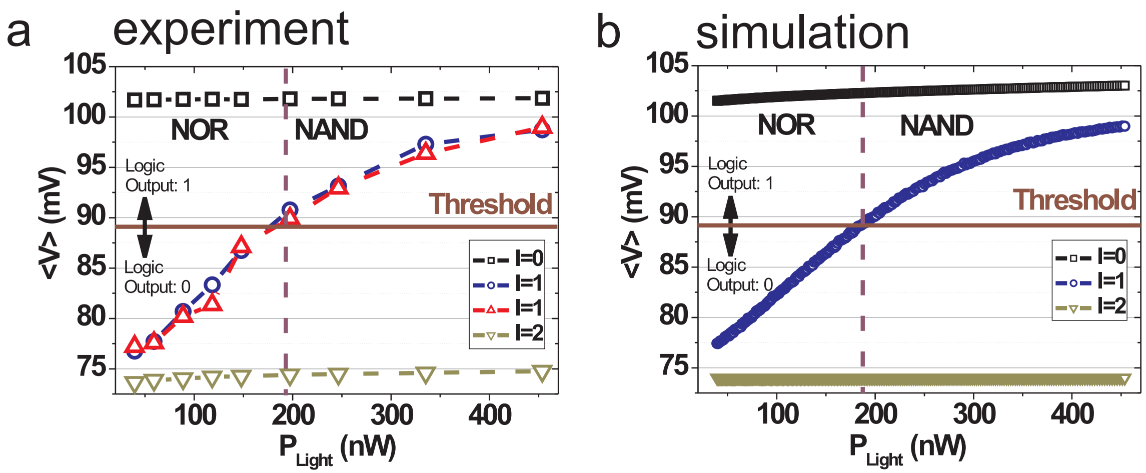
Murali, K., Rajamohamed, I. , Sinha, S. , Ditto, W. , and Bulsara, A. , Appl. Phys. Lett. 95, 194102 (2009).

L. W., F. Hartmann,T. Y. Kim,S. Höfling,M. Kamp,A. Forchel,J. Ahopelto,2I. Neri,A. Dari, L. Gammaitoni, APL 2010

RTD as light sensor and light-programmable LSR







Summary

- Introduction into different nanoelectronic devices
- Nonlinear transport: rectification, bistable switching
- Noise-induced switching, logic stochastic resonance
- Routes for energy harvesting in nanoelectronics

For important contributions many thanks to

Transport:
F. Hartmann, S. Kremling, S. Göpfert, A. Dari, L. Gammaitoni

Technology:
M. Emmerling, S. Kuhn, T. Steinl, G. Heller, M. Kamp

III-V samples:
C. Schneider, S. Höfling, A. Forchel

NANO POWER

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SUBTLE

SUB KT LOW ENERGY TRANSISTORS AND SENSORS

NANOPOWER

- **Many thanks for your attention!**