Noisy dynamics in nanoelectronic systems

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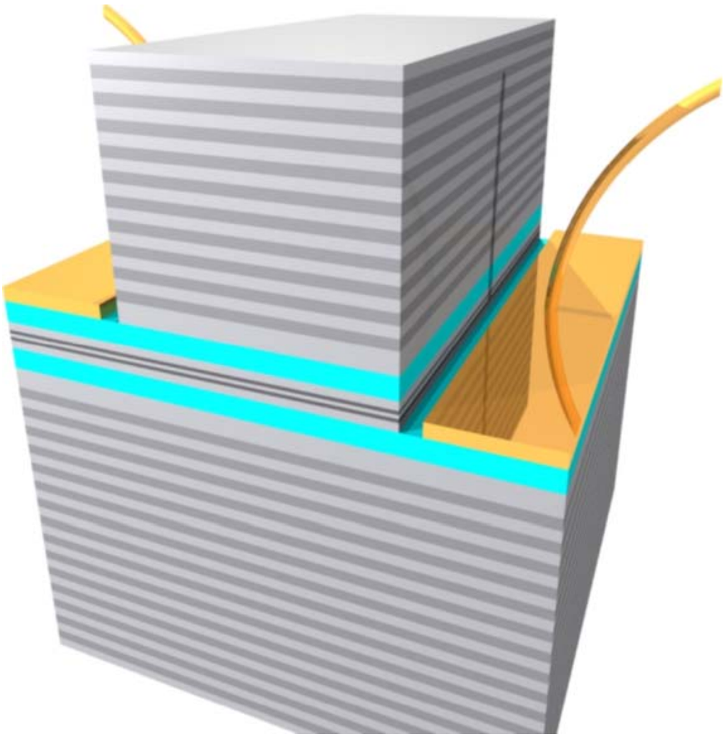

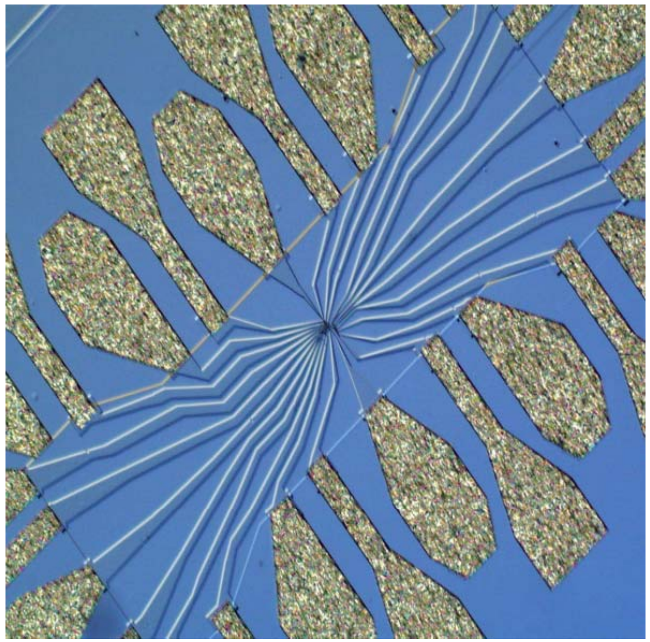

Team

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

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

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

SUBTLE
SUB KT LOW ENERGY TRANSISTORS AND SENSORS

NANO|POWER

LANDAUER
Operating ICT basic switches below the Landauer limit

Motivation: Stochastic resonance (SR), a noise enhanced information transfer process

- Stochastic resonance: Weak signals can be enhanced by fluctuations (for a review Ref.[1])
- Ingredients:
  - Noise
  - Sub-threshold signal
  - Non-linear system, e.g. bistable systems
- SR as model was introduced to explain the periodic recurrences of ice ages: Benzi, Parisi, Sutera, Vulpiani [2]
- SR has been found in various systems, e.g. in crayfish mechanoreceptors [3]

[1] L. Gammaitoni et al., “Stochastic resonance”, Reviews of Modern Physics, Vol. 70, No. 1, January 1998
[2] Benzi, R., G. Parisi, A. Sutera, and A. Vulpiani, 1982, Tellus 34, 10.
[3] Douglass, J. K., L. Wilkens, E. Pantazelou, and F. Moss, 1993, Nature (London) **365**, 337.

Outline

- Nanoelectronic semiconductor electronic devices
  - Technology
  - Mesoscopic devices
  - Nonlinear transport
    - BL Motors
    - Y-branch switch as half adder
    - Quantum dot as a memory
    - Resonant tunneling diode: Sensor, logic stochastic resonance
      - Best detection strategy

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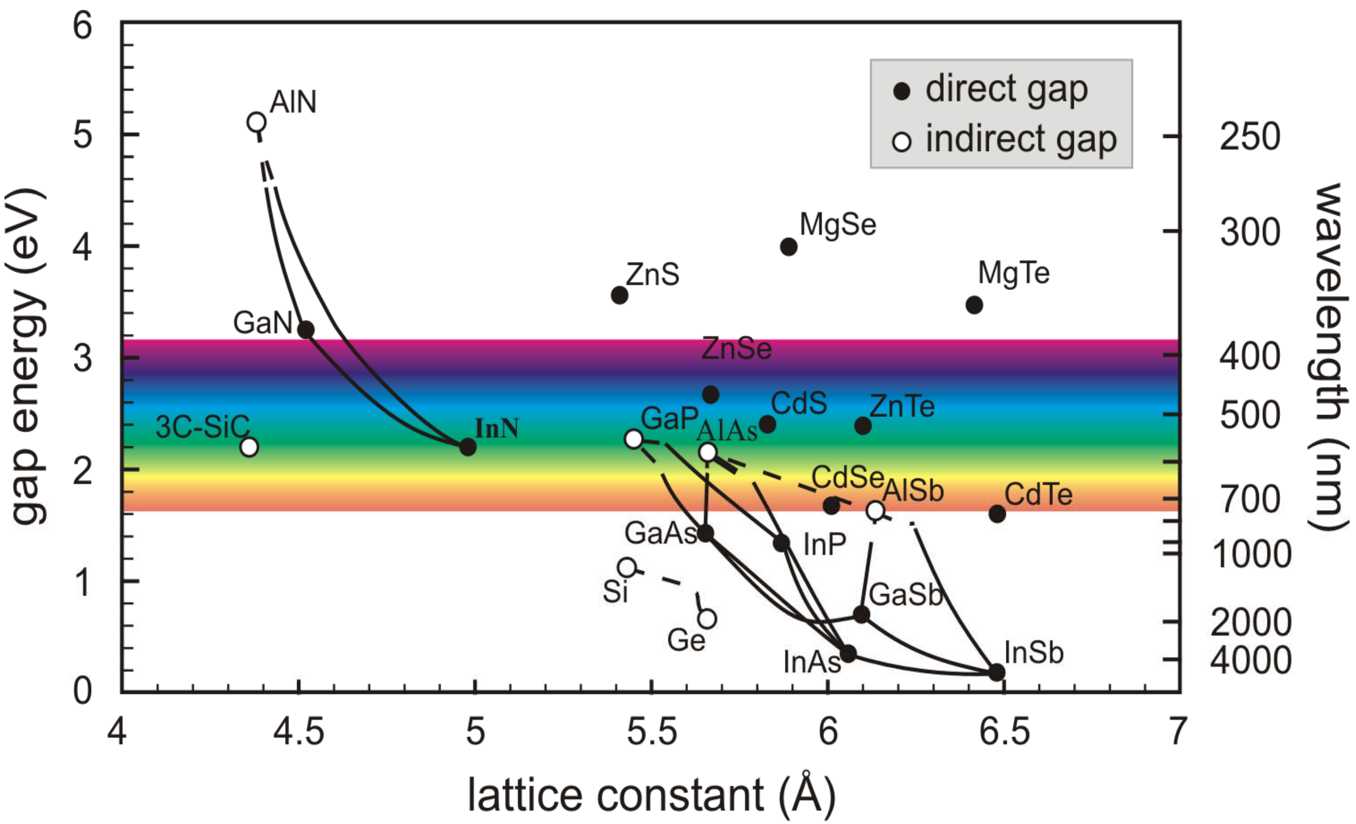
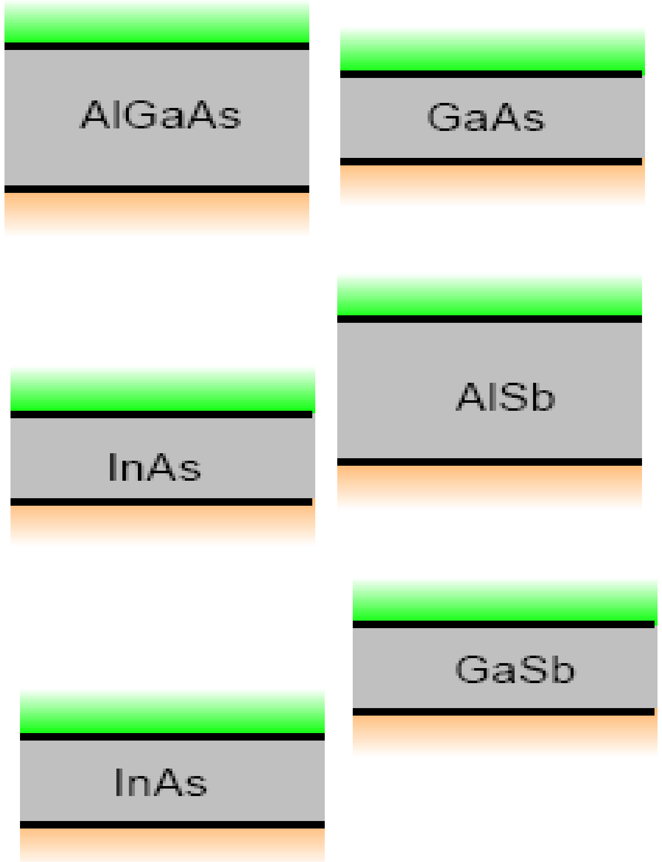
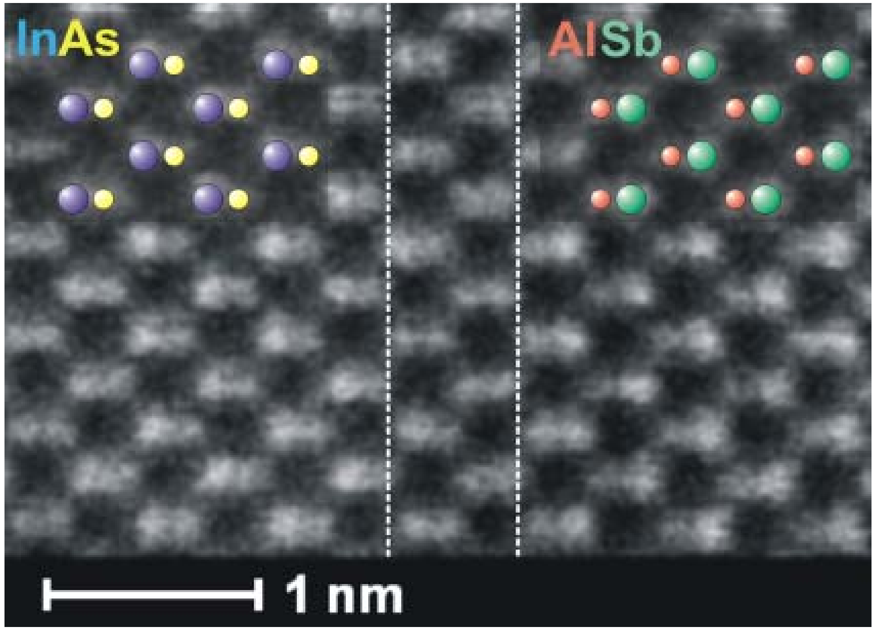
semiconductors



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

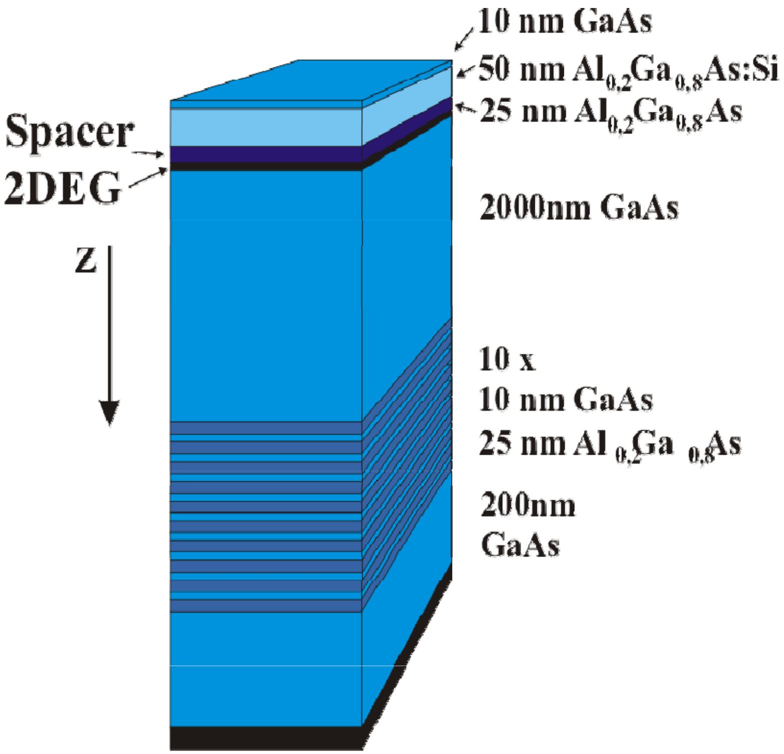
Heterostructures: Band gap engineering

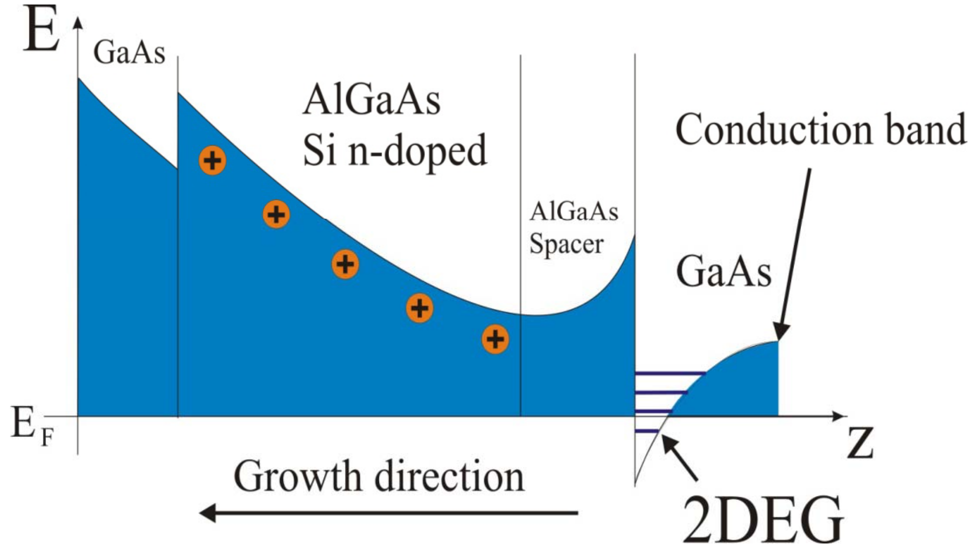




- ❒ Combination of different semiconductors with atomic precision
- ❒ Growth techniques: e.g. Molecular beam epitaxy (MBE)

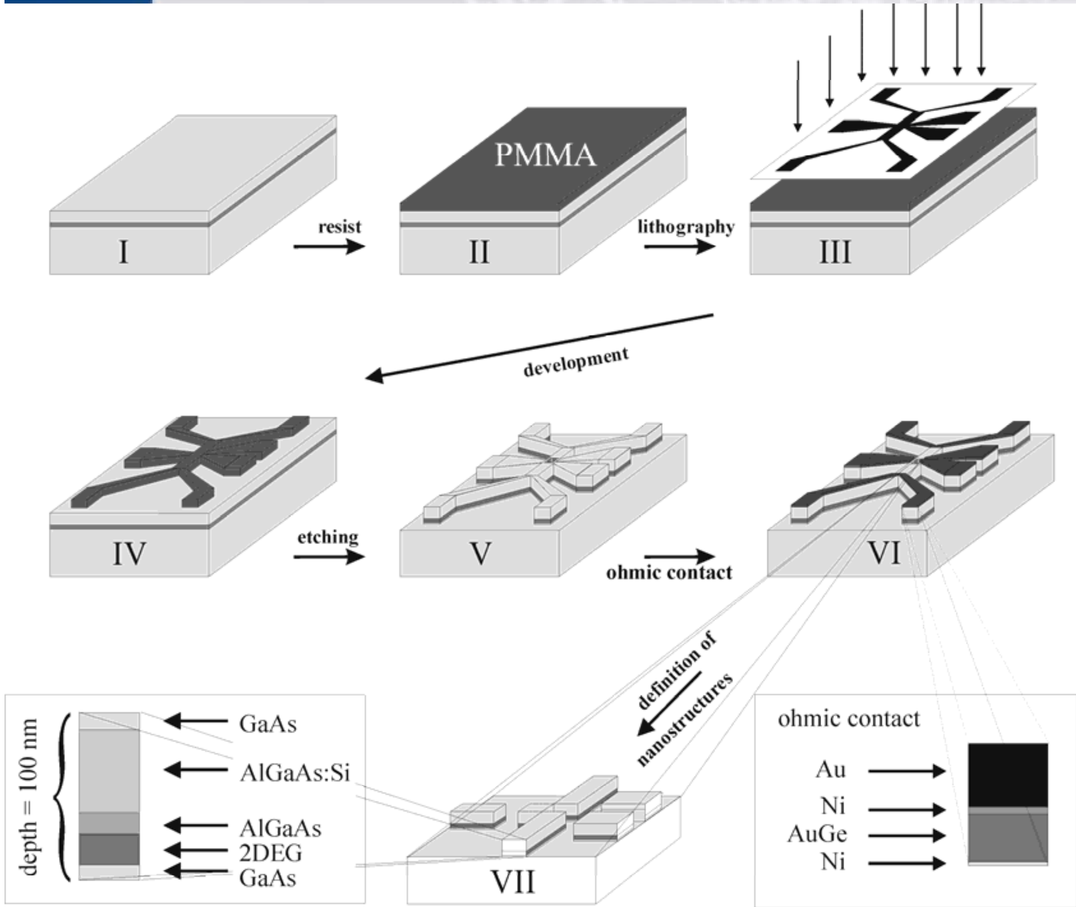
GaAs/AlGaAs HEMT

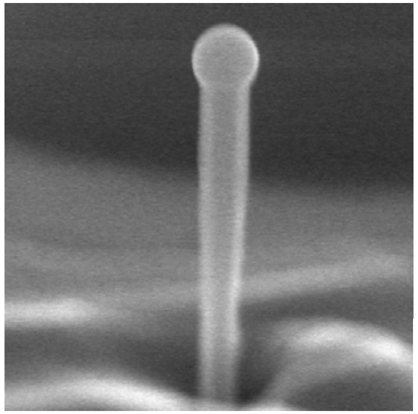


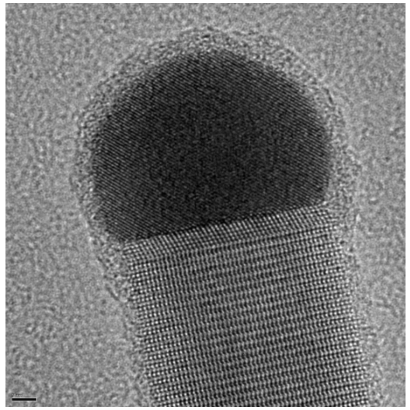


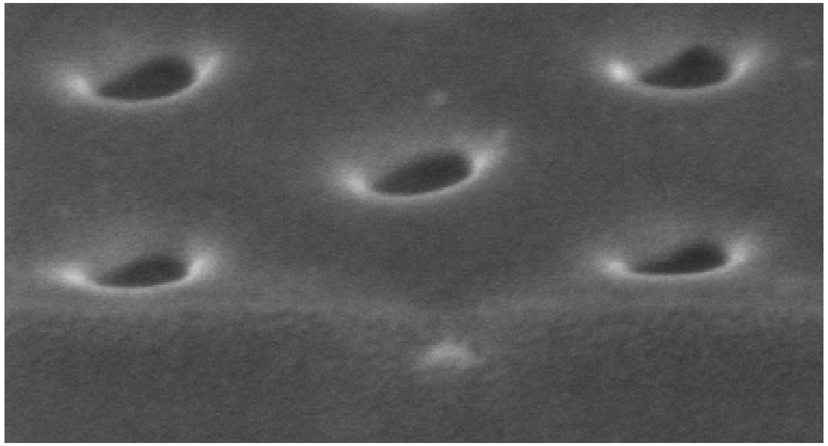
- ❒ Modulation-doped GaAs/AlGaAs heterostruktur (HEMT)
- ❒ Mean free path: ~10µms @ 4,2K / 50 – 200nm @ RT

Structuring









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

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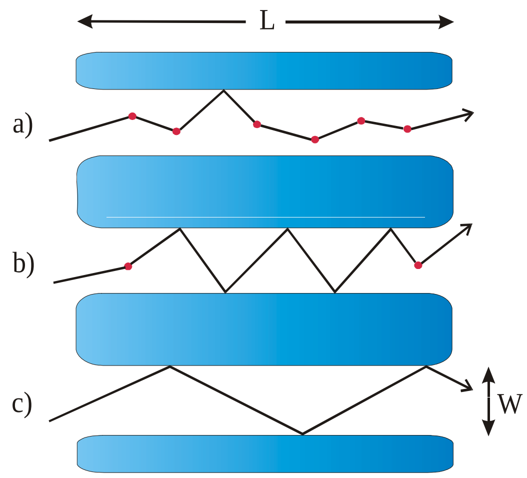
Characteristic lengths

- 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



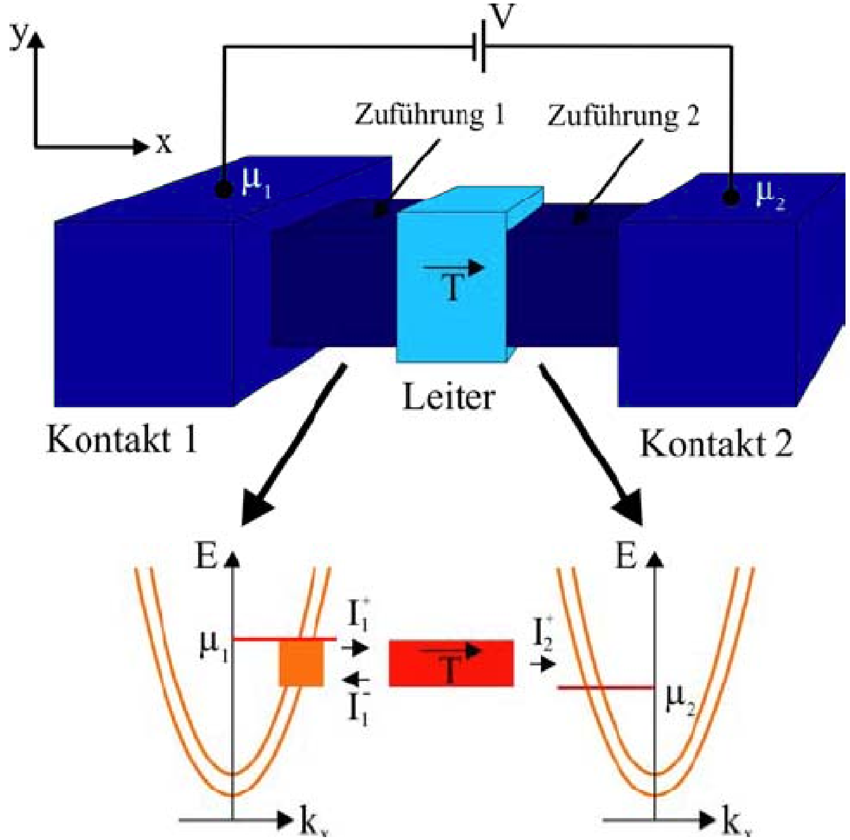
Linear mesoscopic transport

- Conductance quantization in 1D wires

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

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

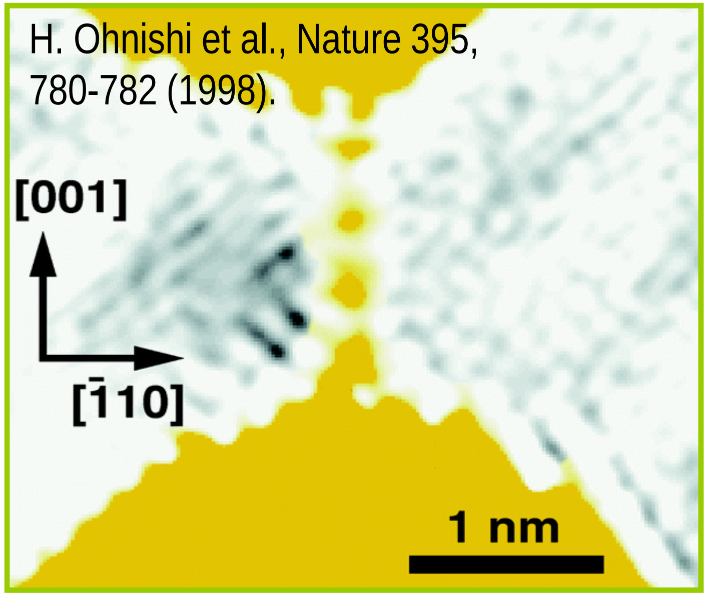
$$G = I/V = \frac{2e^2}{h}\sum_{\alpha} T_{\alpha}$$

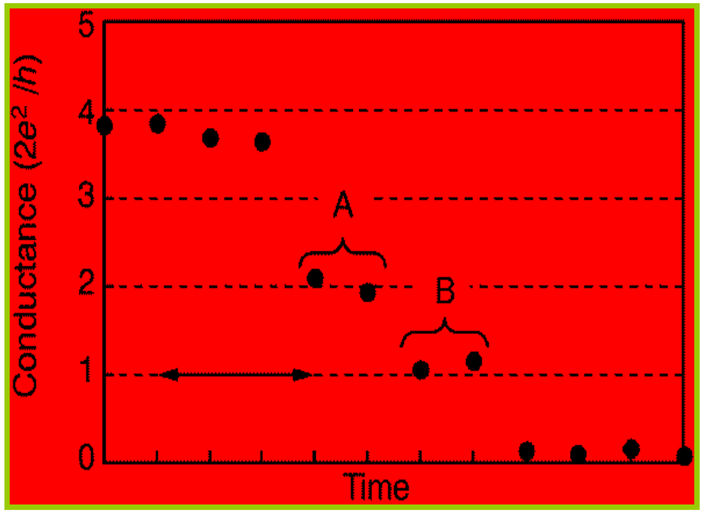


- Multi-terminal conductor: Landauer-Büttiker formula

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

What is nano? A comparison: metals vs semiconductor





Metal:
Gold film

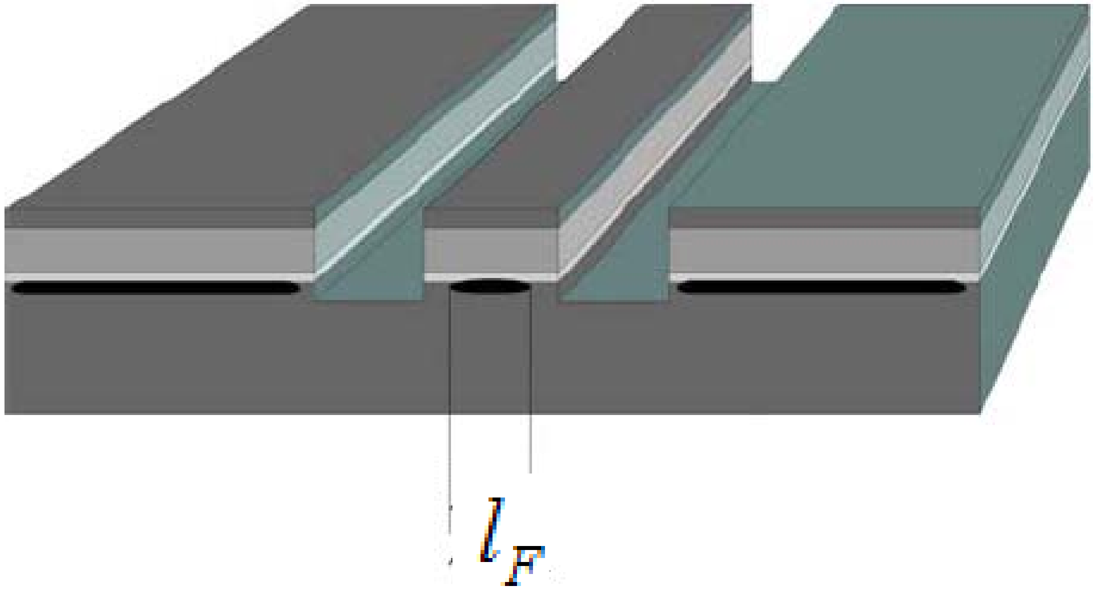
$n = 2.3 \times 10^{15}/cm^2$
$l_F = 0.52$ nm, $E_F = 5.5$ eV
$l_m \sim$ 1-10 nm
$l_\phi \sim$ 1-100 μm

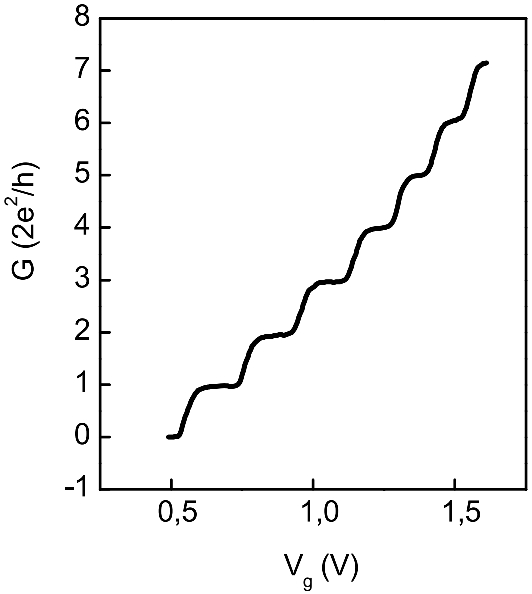
Semiconductor:
2 dimensional electron gas (2DEG)

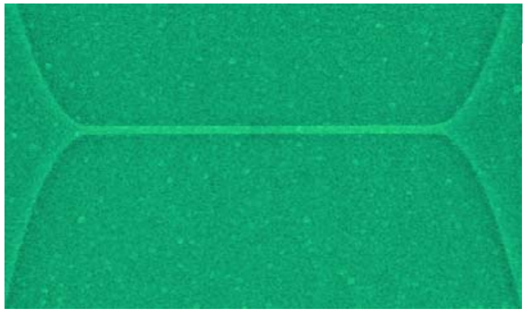
$n = 3.0 \times 10^{11}/cm^2$
$l_F = 46$ nm, $E_F = 11$ meV
$l_m \sim$ 1-100 μm $T < 4$ K
$l_\phi \sim$ 1-100 μm

Quantum wire

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

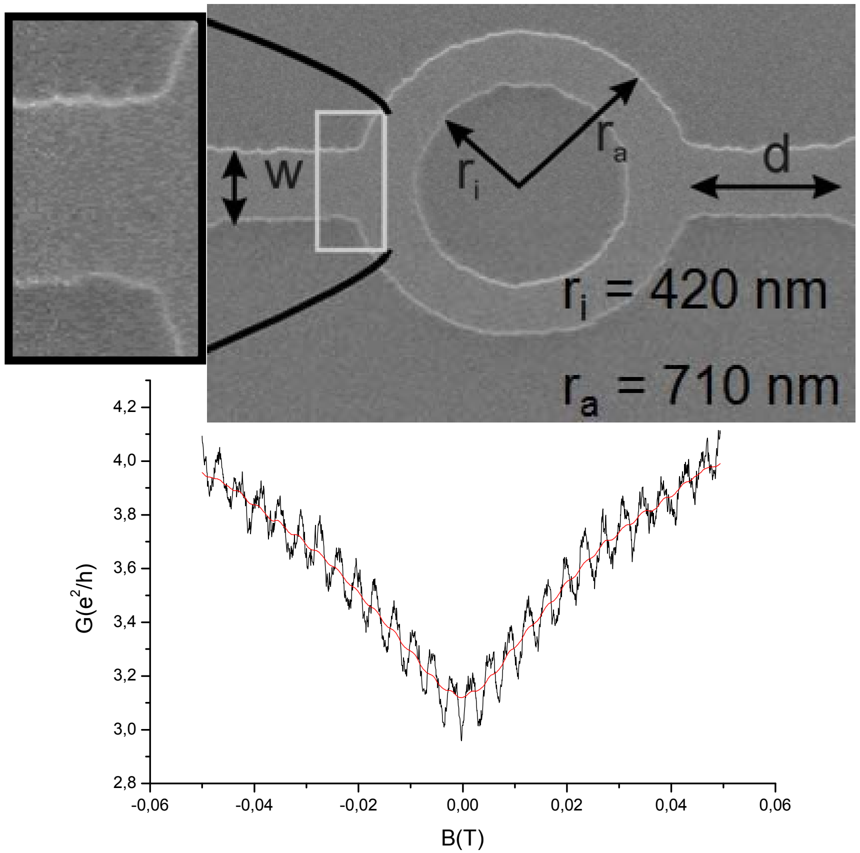


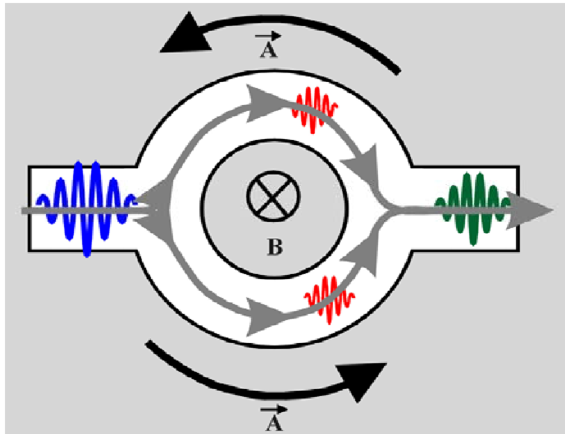




Quantum ring

- Quantum oscillations: Aharonov-Bohm effect
- Magnetic field symmetry in linear mesocopic transport G(B)=G(-B)





$$\Delta\phi \sim \int \vec{A}(\vec{r})\,d\vec{r}$$

$$\mathrm{r} = \sqrt{\frac{h\,\mathrm{f}}{e\pi}} = 59(0)\,nm$$

Conductor with 3 contacts

- Current conservation $S^{+} = S^{-1}$
- symmetry $s_{ij} = s_{ji}$ $\quad T_{ij} = \left|s_{ij}\right|^{2}$
- Transmission matrix

$$T = \begin{pmatrix} r^2 & G & 1-G-r^2 \\ G & \left[\frac{1-G-r}{1-r}\right]^2 & G\left[\frac{1-G-r^2}{(1-r)^2}\right] \\ 1-G-r^2 & G\left[\frac{1-G-r^2}{(1-r)^2}\right] & \left[\frac{G+r^2-r}{1-r}\right]^2 \end{pmatrix}$$

- Switching parameter

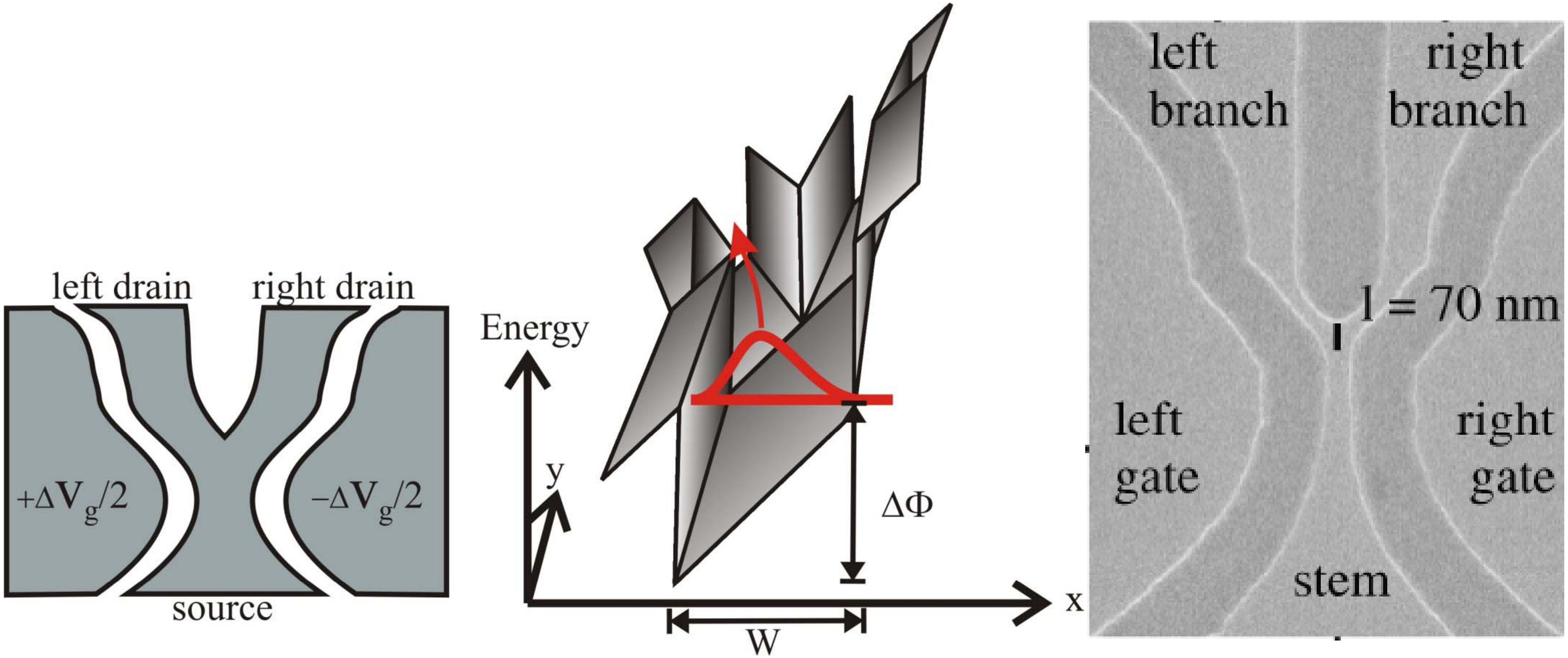
$$G = \frac{1-\gamma(V_g, V)}{2}$$

- I-V curve

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = \frac{2e^2}{h}(I-T)\begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix}$$

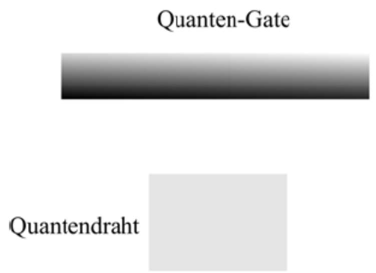
Y-branch switch

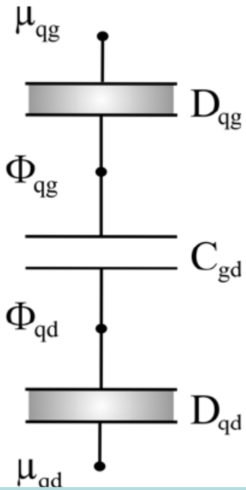
- Stem and 2 branches controlled by side gates



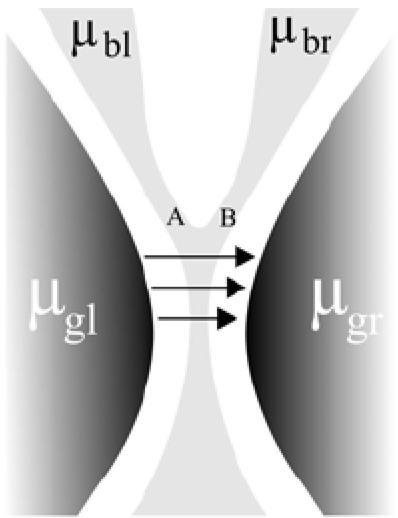
Non-linear transport via interaction

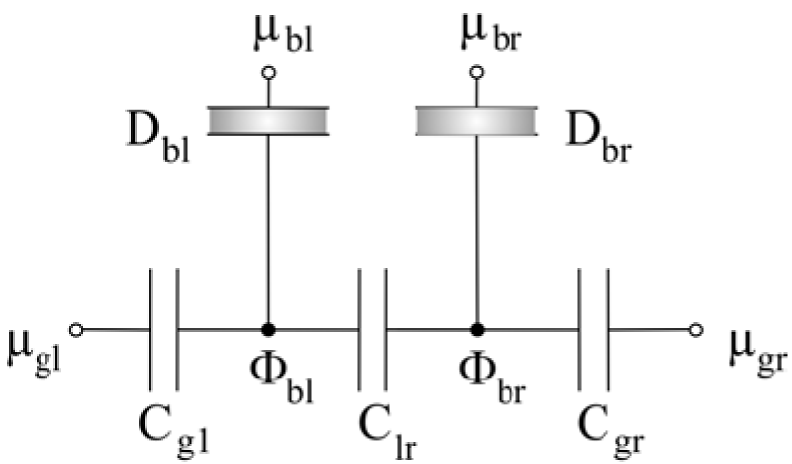
- Mesoscopic capacitance: Self-switching in a YBS





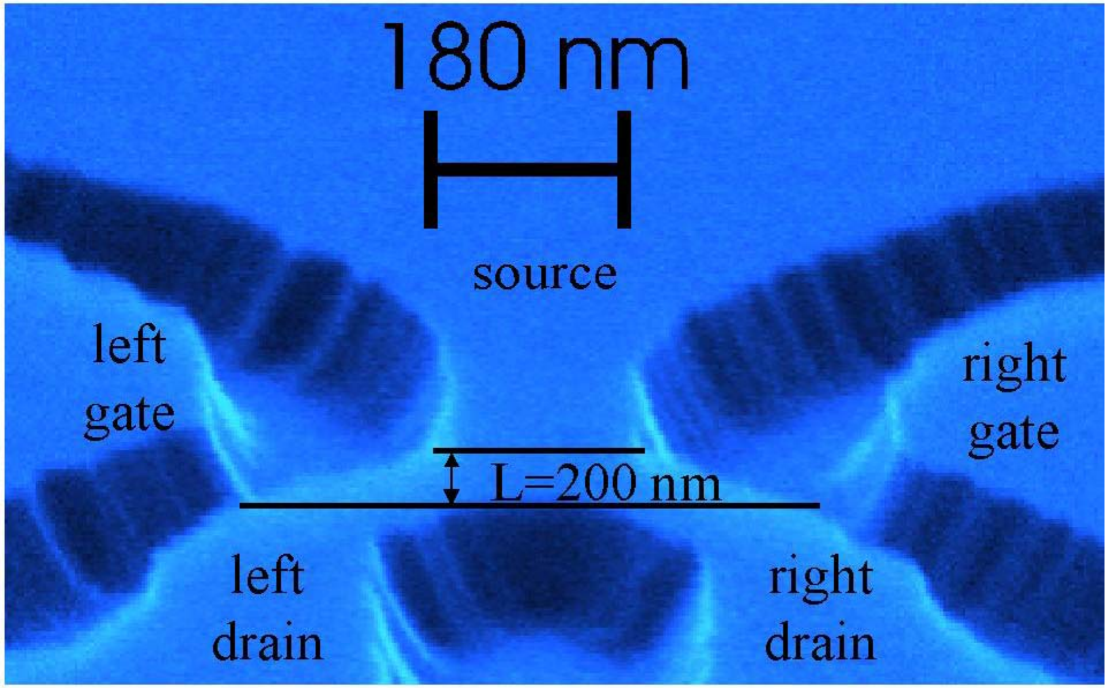
$$\Delta\Phi_{qd} = \frac{1}{1 + D_{qd}/C_{gd} + D_{qd}/D_{qg}} \Delta\mu_{qg}$$

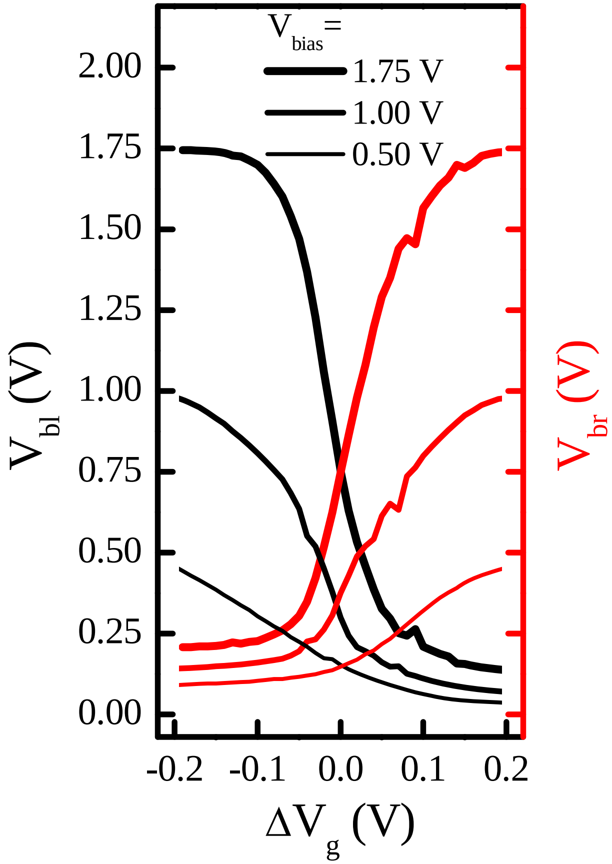




$$\Delta\Phi_b = \frac{C_g}{C_g + D_b + 2C_{lr}} \Delta\mu_g + \frac{D_b}{C_g + D_b + 2C_{lr}} \Delta\mu_b$$

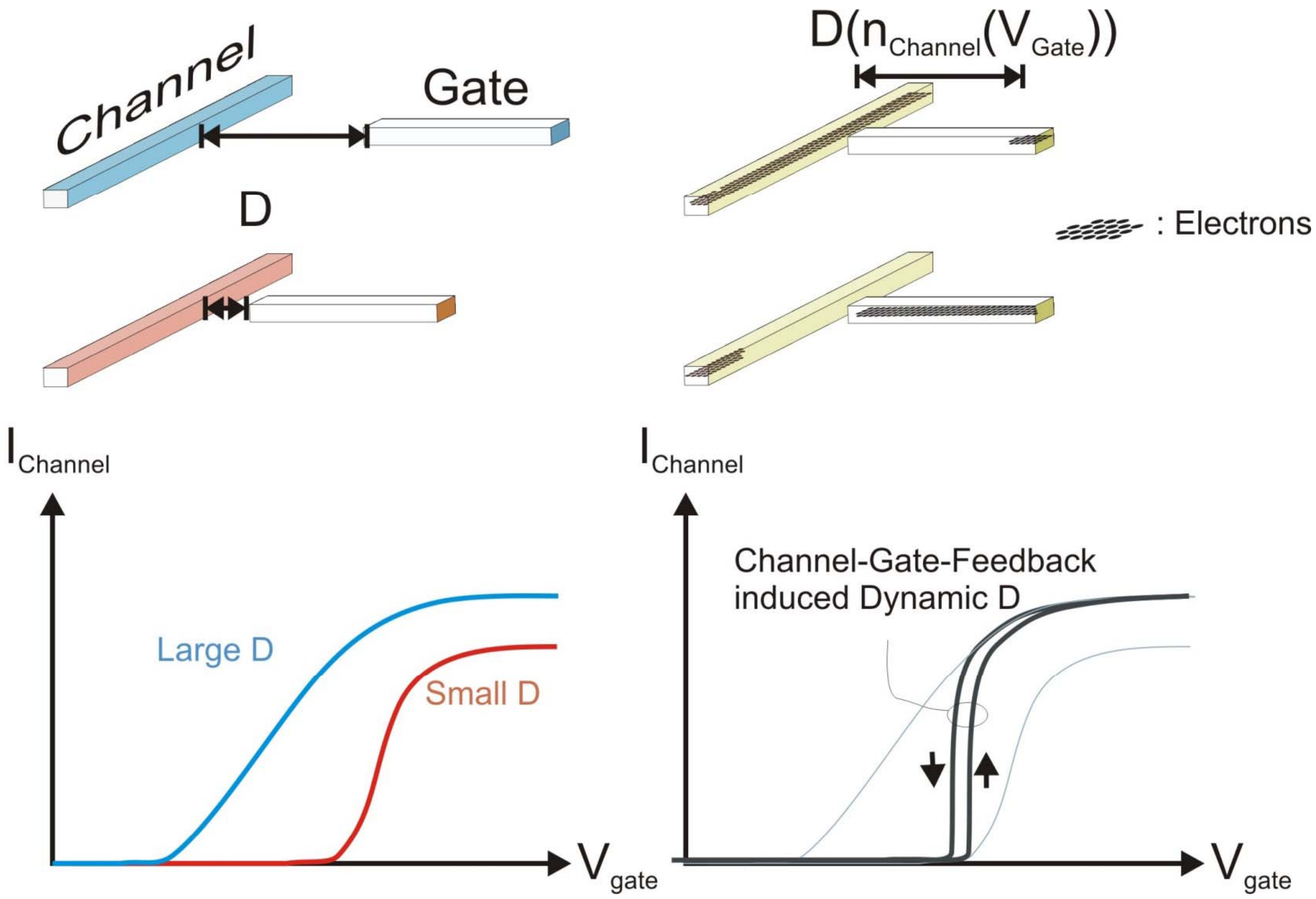
YBS





- Push-pull Mode:
  $V_{gl} + V_{gr} = const$ ($dV_{gl} = -dV_{gr}$)

Dynamical gate operation in a YBS



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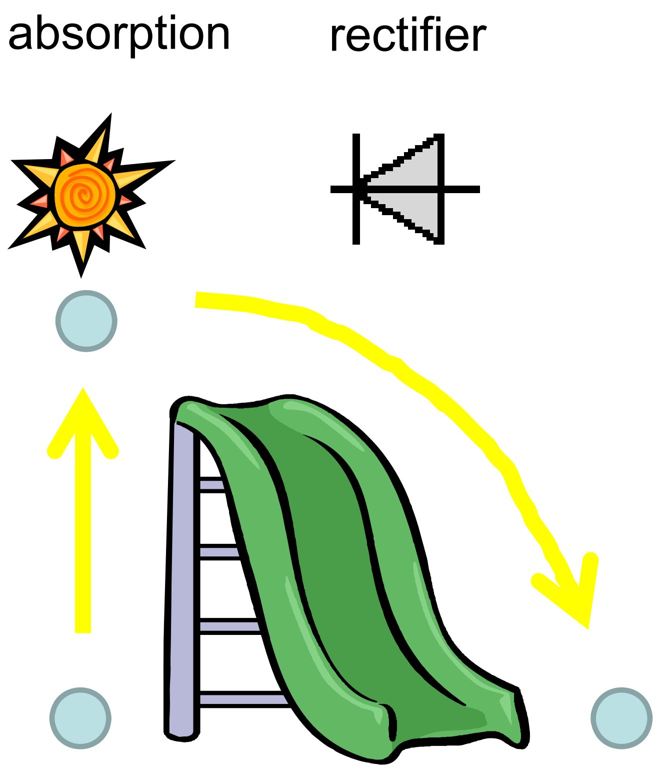
Solar cell

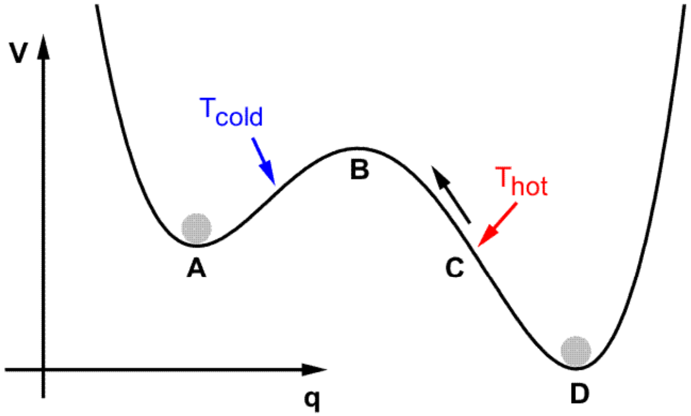


- Optical excitation of electron hole pair
- Separation by a p-n junction: asymmetry in the device structure
- Is it possible to generate a current in a symmetric structure?

Yes! If the nonlinear noise is asymmetric: Transport as a consequence of state-dependent diffusion

<u>Diffusion constants</u>:

$$D = \mu k T_H \,, \quad q \, in \, H$$
$$D = \mu k T_L \,, \quad q \, in \, L$$



- Double well potential with minima located at A and D.
- D is the energetic favorable point D with D < A.
- Consider two temperatures at the slopes T_{hot} and T_{cold} with $T_{hot} > T_{cold}$.

For systems subject to thermal noise, the Boltzmann factor is

$$\exp\left(\frac{-V}{kT}\right)$$

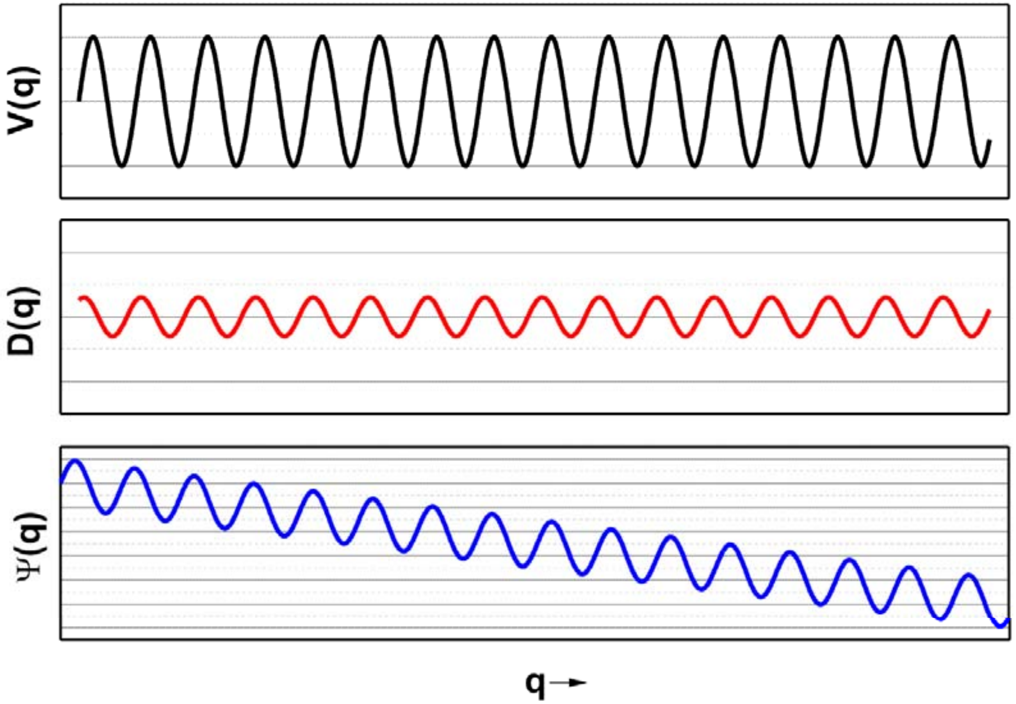
M. Büttiker, Z. Phys. B **68**, 161 (1987).
R. Landauer, J. Stat. Phys. **53**, 233 (1988).

For systems with mobility μ subject to drift and state dependent diffusion the Boltzmann factor is

$$\exp(-\Psi(q))$$

with $\Psi(q) = -\int_0^q dp \, \frac{v(p)}{D(p)}$

Transport as a consequence of state-dependent diffusion



$$V(q) = V(q+2\pi)$$

$$V(q) = V_0(1 - \cos(q))$$

$$D(q) = D(q+2\pi)$$

$$D^{-1}(q) = D_0^{-1}(1 - \alpha\cos(q-\phi))$$

$$D_0 = \mu kT$$

$$\Psi(q) = -\int_0^q dp\,\frac{v(p)}{D(p)}$$

$$\Psi(q) = \Psi(q+2\pi) + 2\pi\Delta$$

With: $\Delta = \frac{\mu V_0}{D_0}\frac{\alpha}{2}\sin(\phi)$

M. Büttiker, Z. Phys. B **68**, 161 (1987).
Ya. M. Blanter and M. Büttiker, Phys. Rev. Lett. **81**, 4040-4044 (1998).

$$I_{ov} = \frac{\pi^2 E_0^2 T_1}{\gamma L^2 T_0^{\,2}} \exp\left(-\frac{E_0}{T_0}\right)\sin(\varphi)$$

$$I = \frac{\gamma T_1}{2mT_0}\exp\left(-\frac{E_0}{T_0}\right)\sin(\varphi)$$

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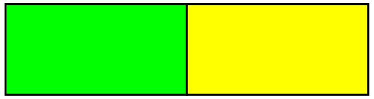
Y-branch as ballistic rectification

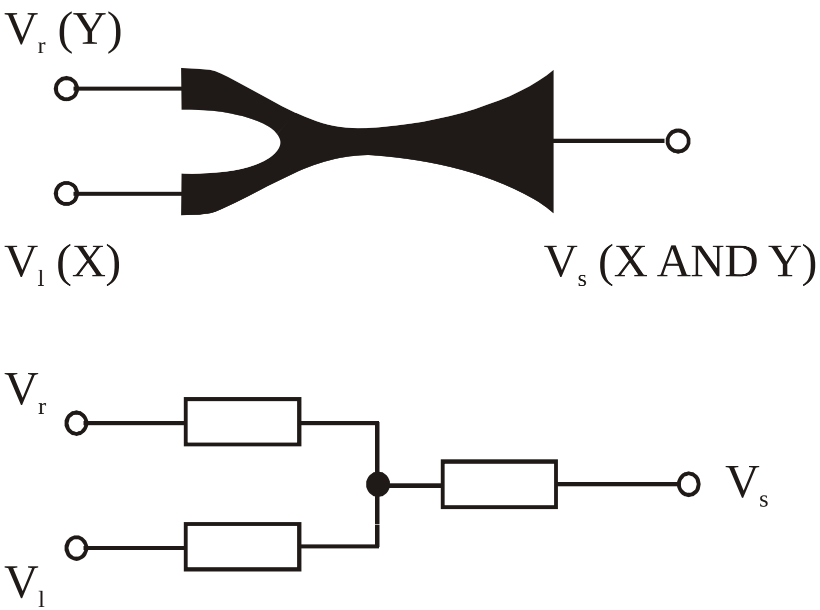
Rectification due to junctions:

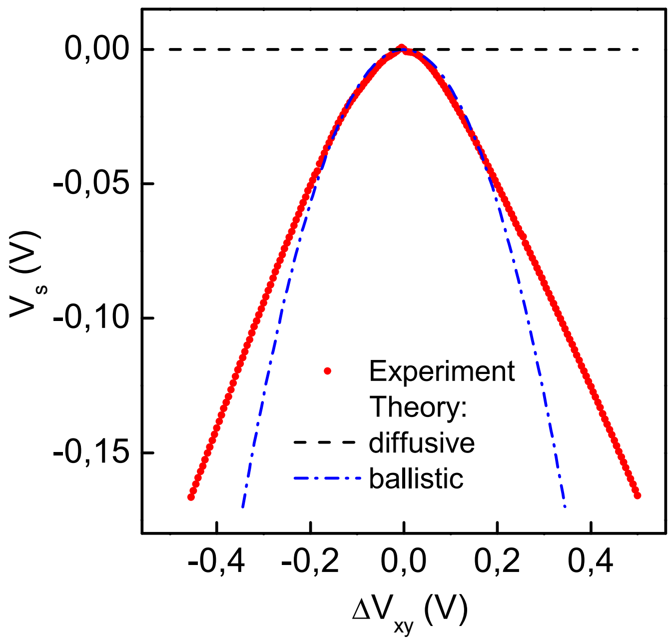
- pn-junction



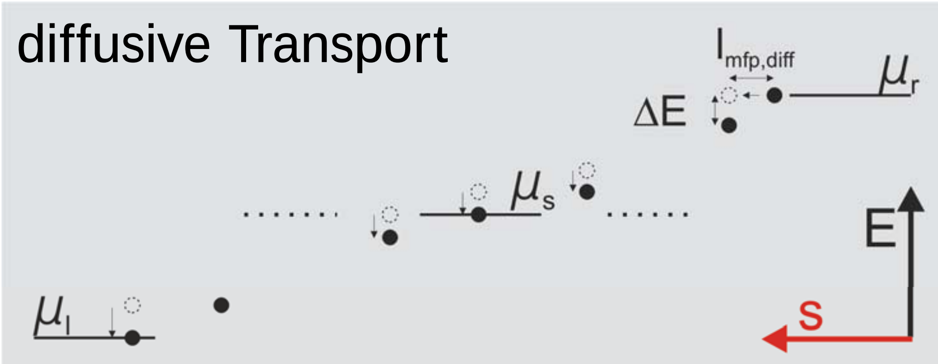
- Metal-semiconductor junction

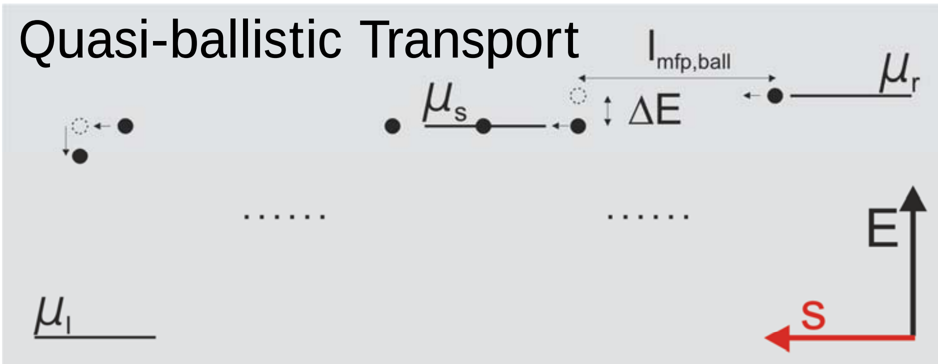
Y-branch junction: no geometrical asymmetry!

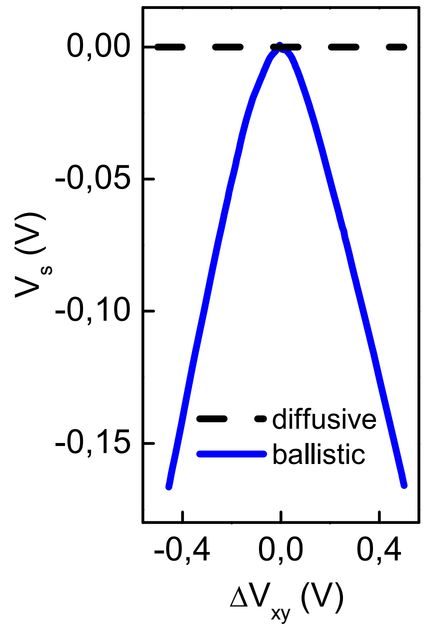




Y-branch as ballistic rectification







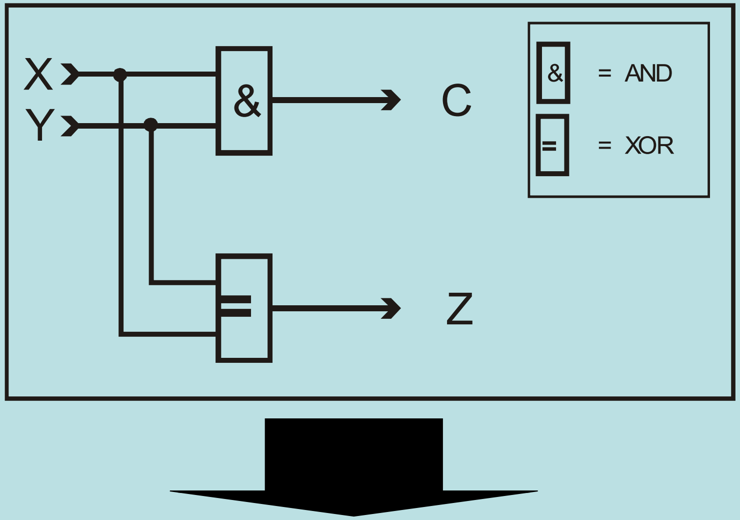
YBS nonlinearity used for a compact adder

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

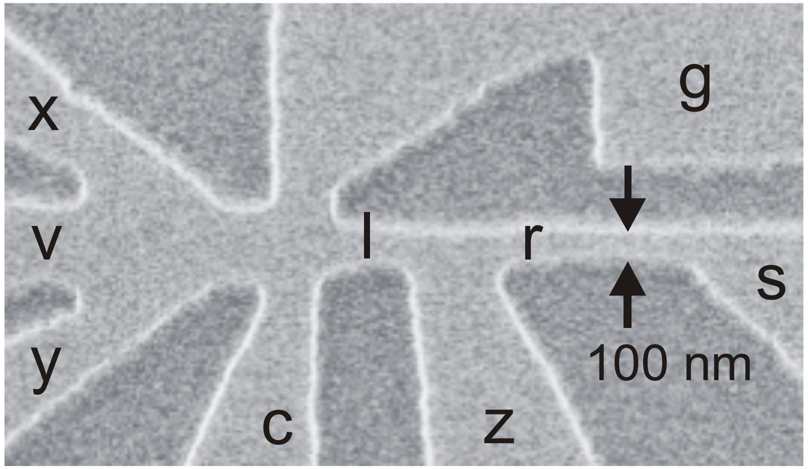
Scheme



> 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

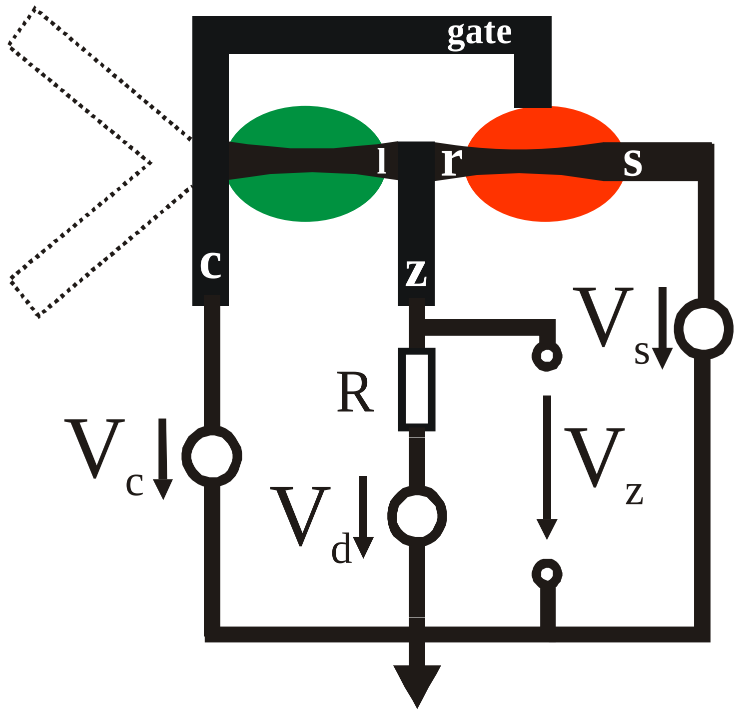
control of V_z via V_c:

a) Injection of electrons

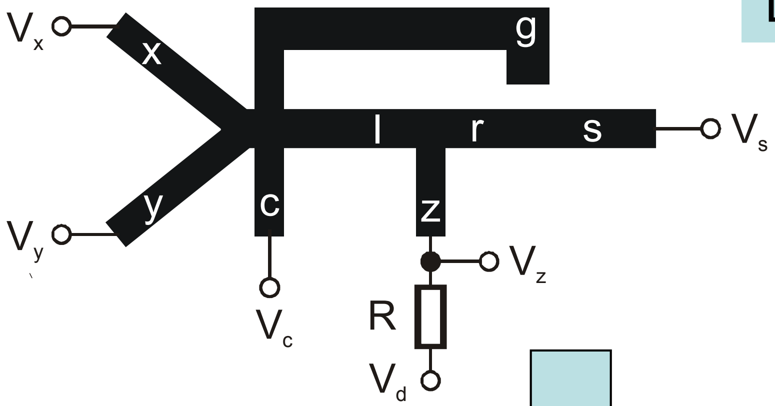
b) Gating

No external gate!

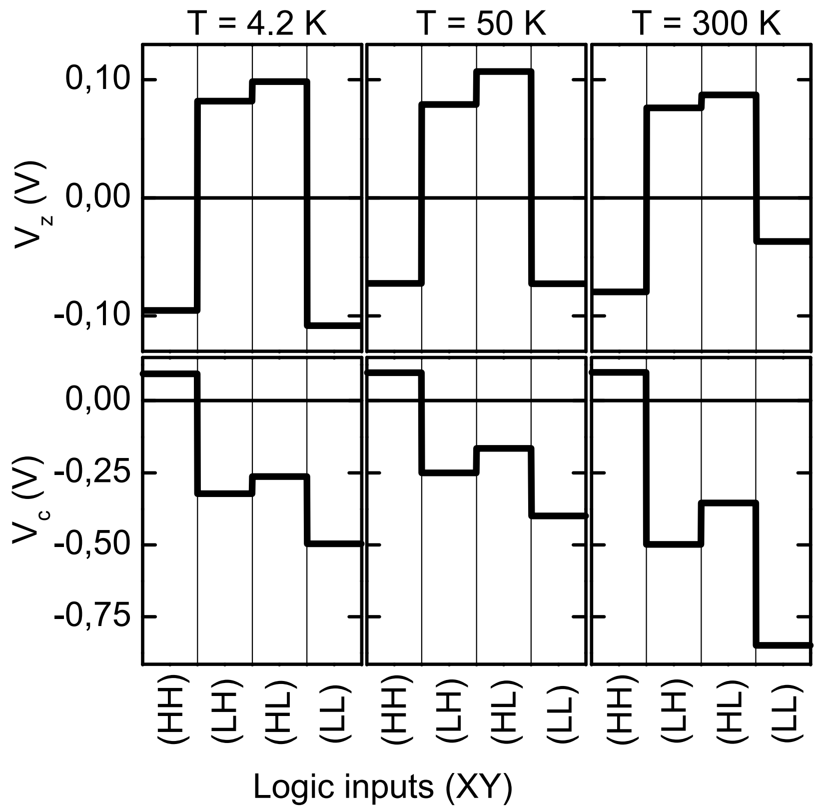
⇒ Self induced switching



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



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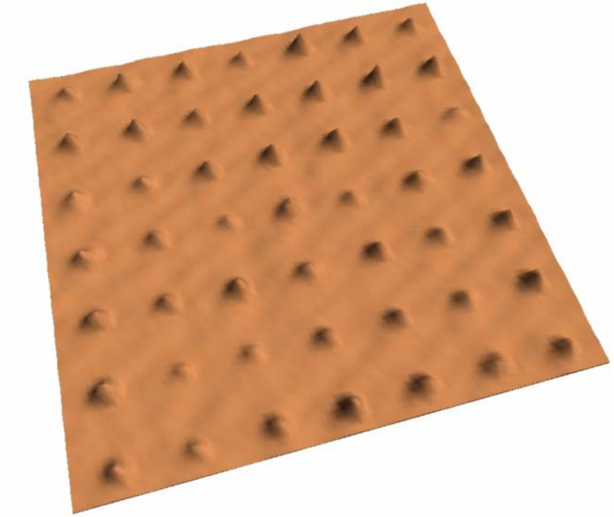
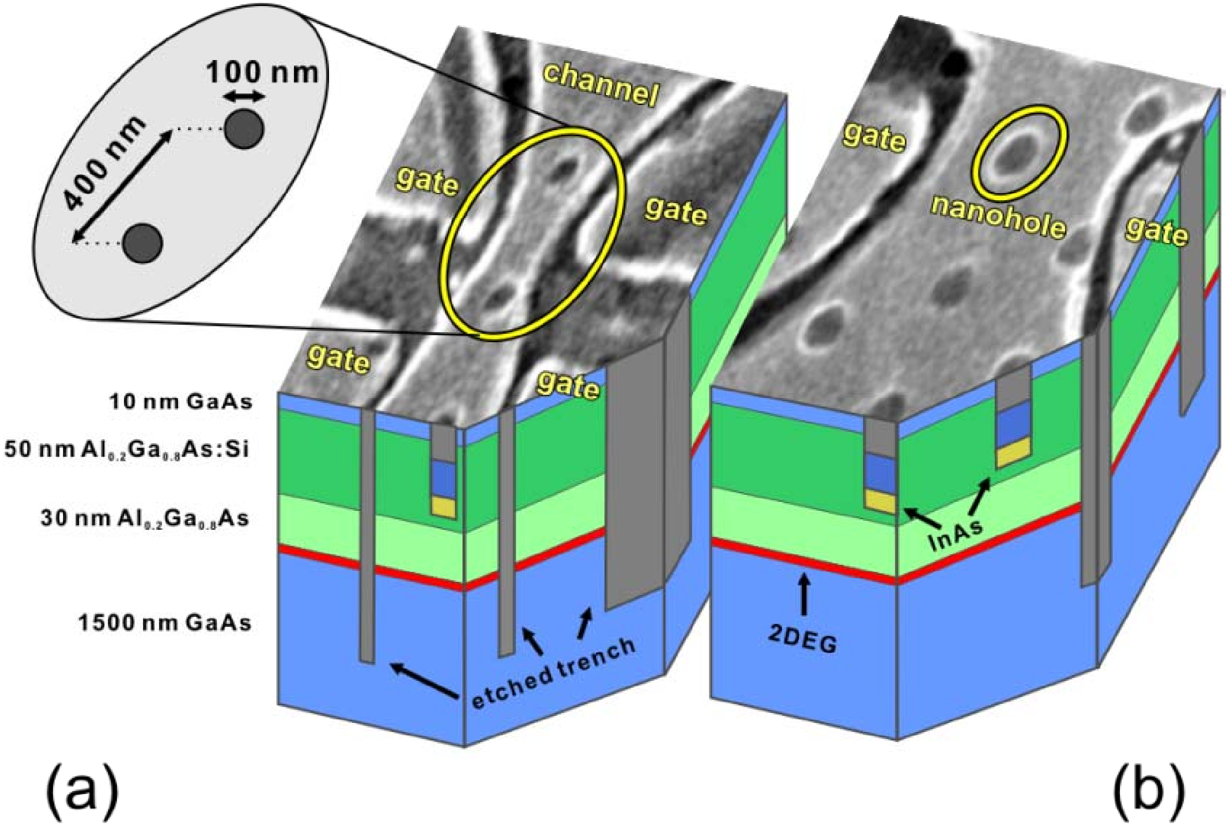
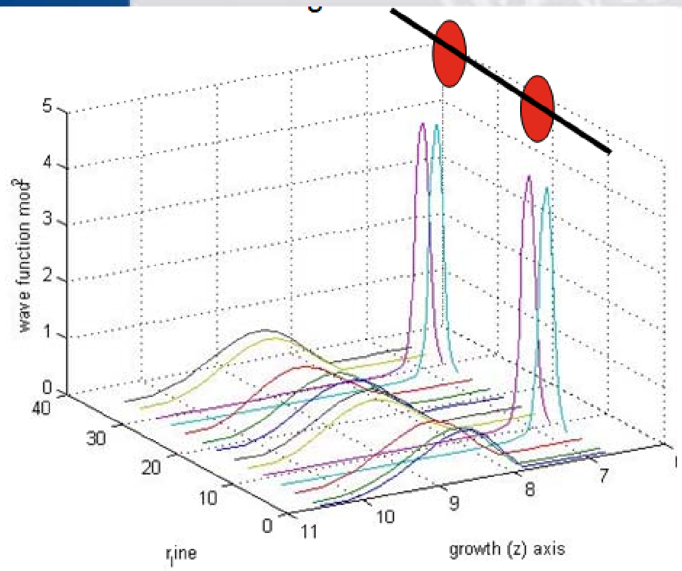
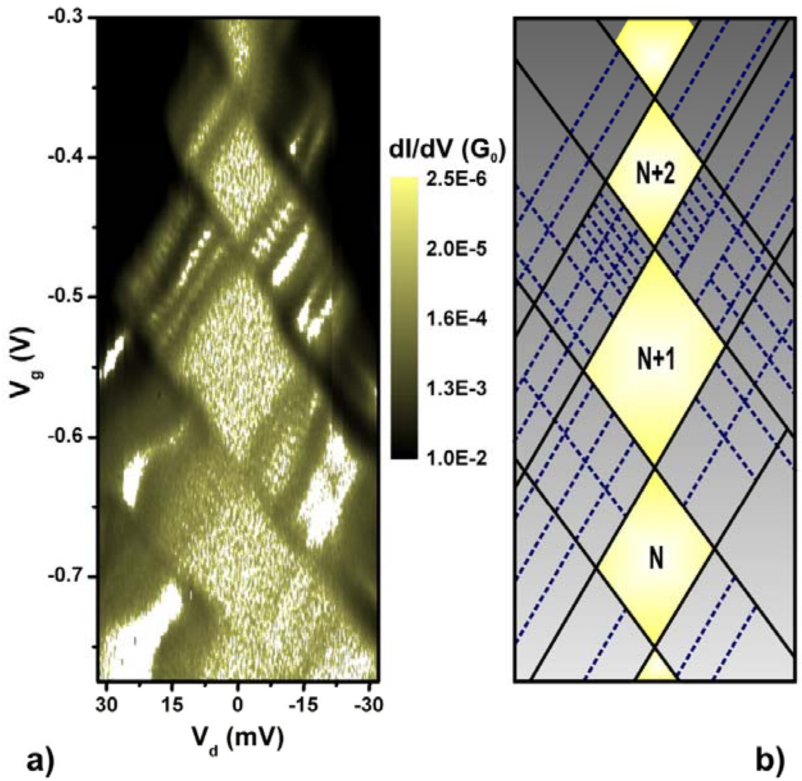
Positioned QDs

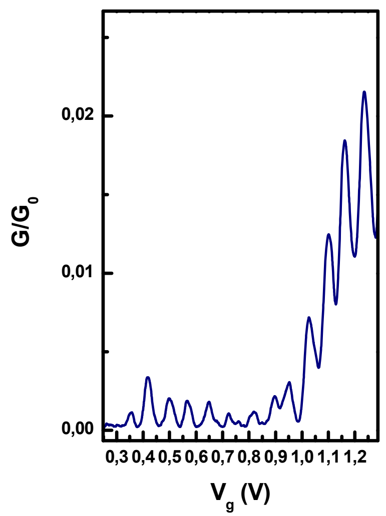




SET by positioning of 2QDs in a wire

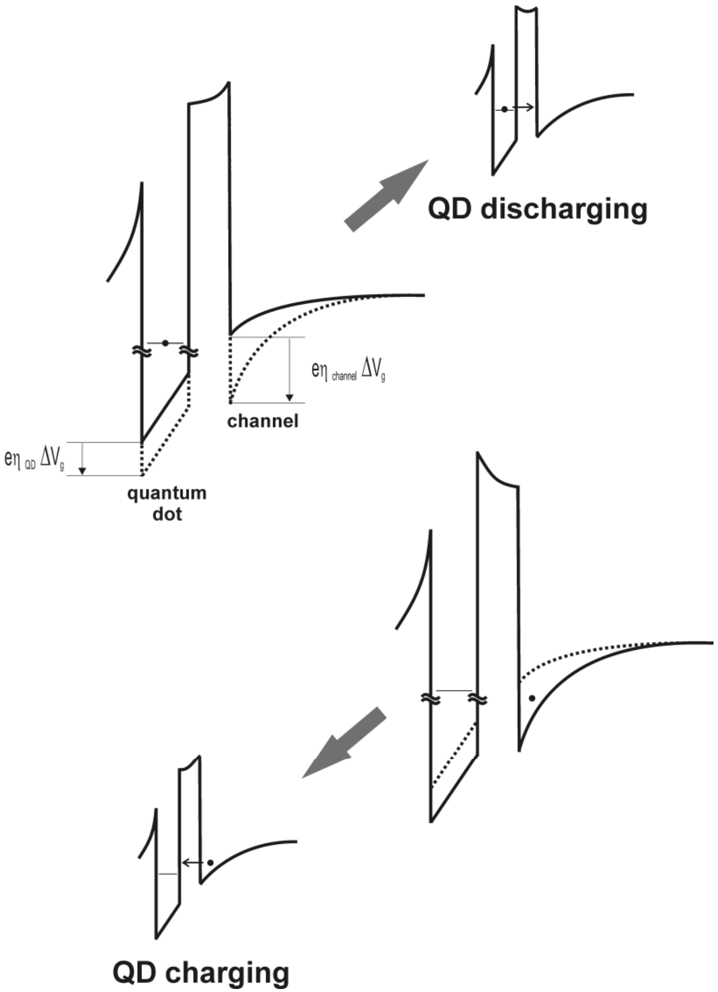


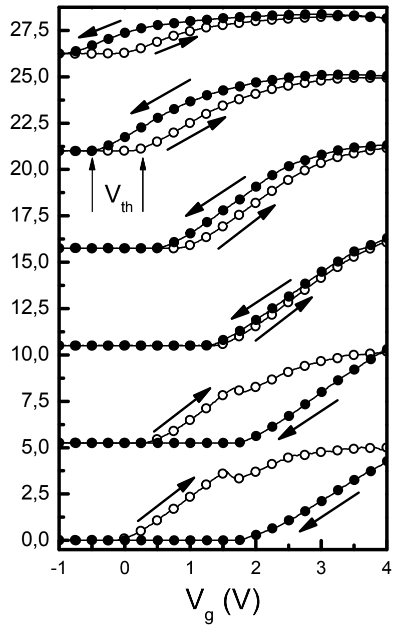


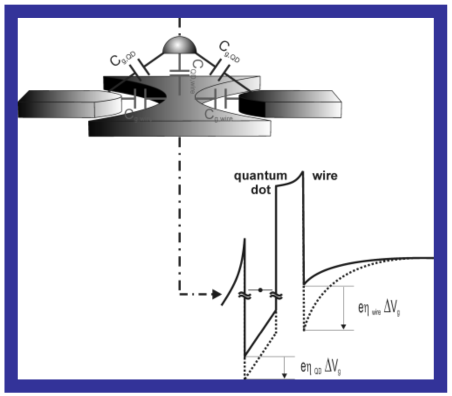


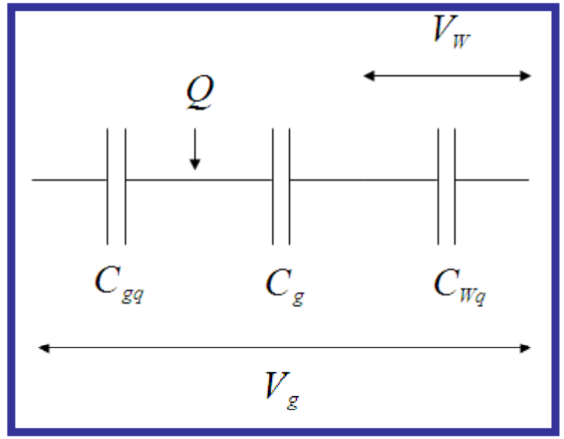
- **Coulomb oscillations due to charging of island with single electrons**
- **Coulomb-Diamond used to extract capacitances, charging energy > 10 meV**

Memory: threshold shift of read-out transistor









- Schaltspannung

$$V_W = \frac{V_g - \frac{Q}{C_{gq}}}{1 + \frac{C_{Wq}}{C_g} + \frac{C_{Wq}}{C_{gq}}}$$

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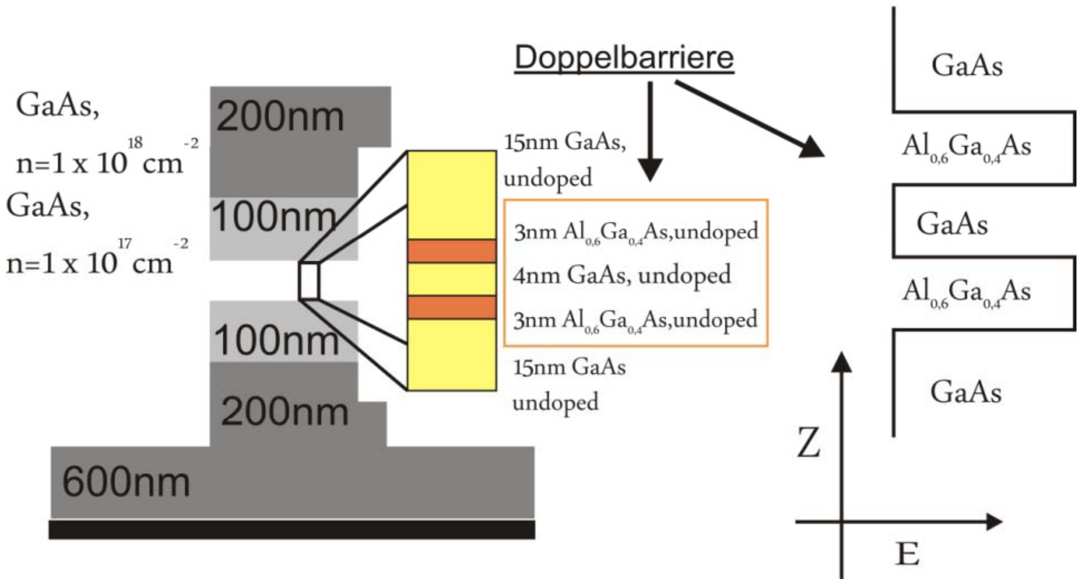
Outline

Technische Physik Universität Würzburg

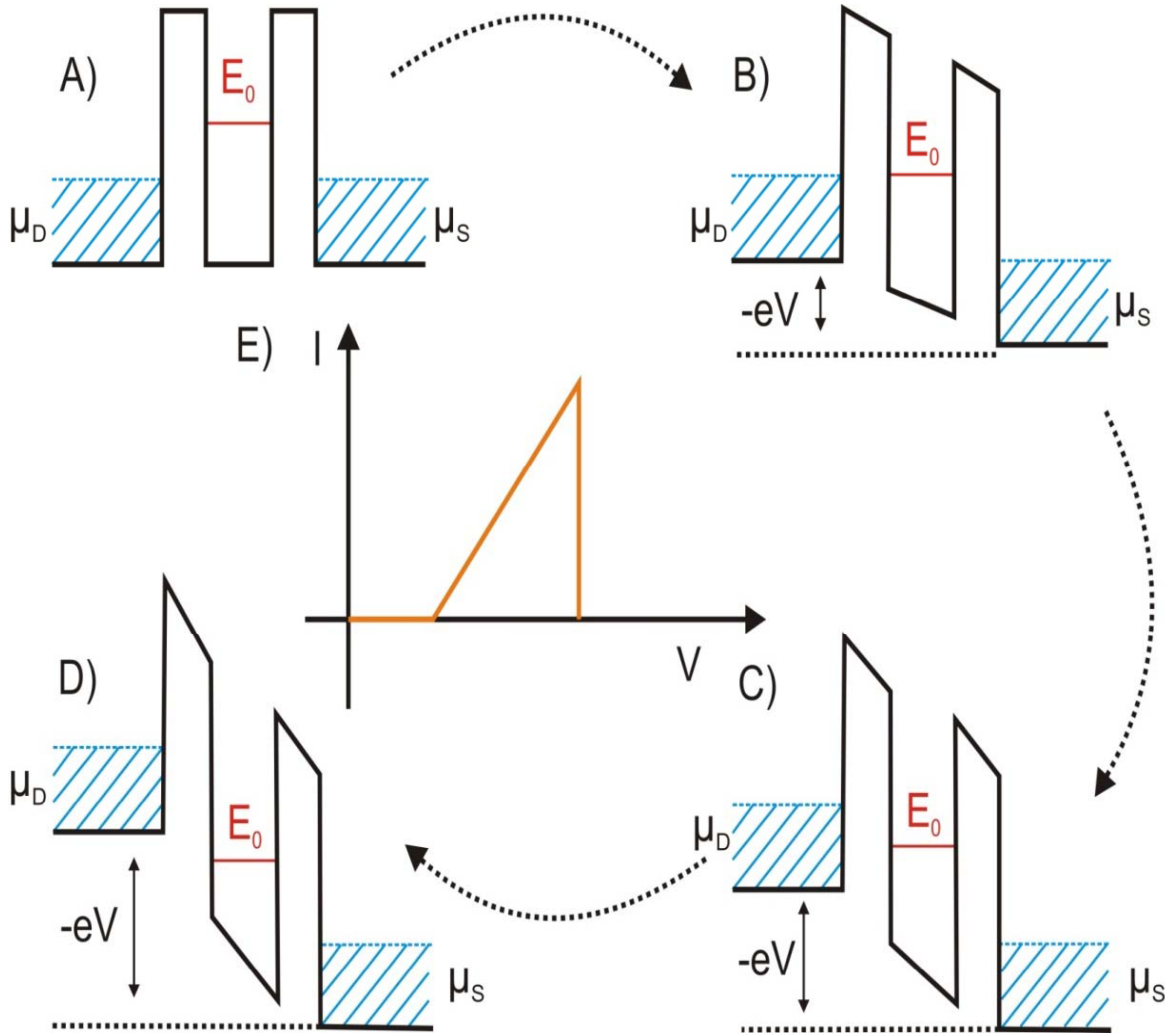
- Nanoelectronic semiconductor electronic devices
  - Technology
  - Mesoscopic devices
  - Nonlinear transport
    - BL Motors
    - Y-branch switch as half adder
    - Quantum dot as a memory
    - Resonant tunneling diode: Sensor, logic stochastic resonance
      - Best detection strategy

Resonant-tunneling diode

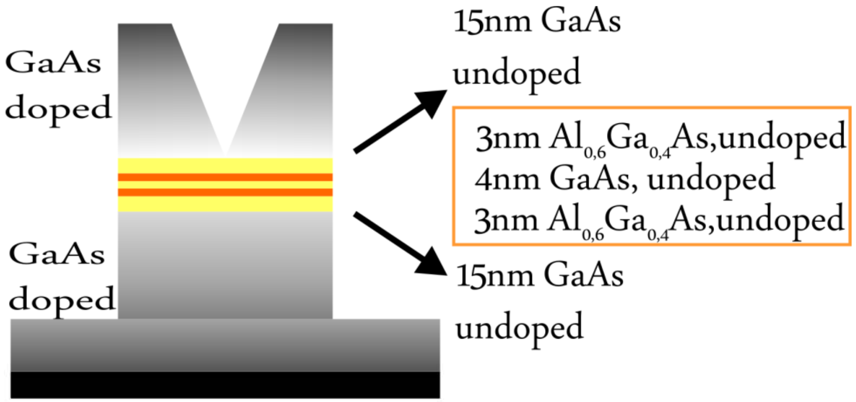


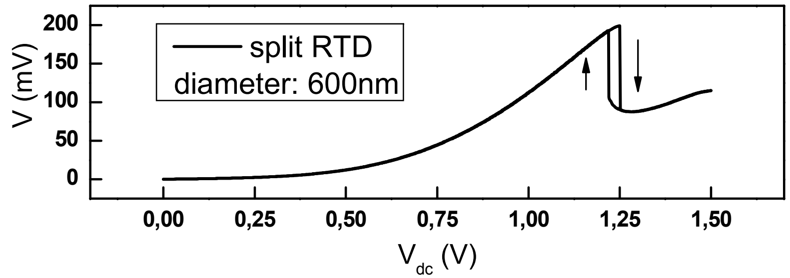
- fast operation ~THz
- negative differential resistance
- ballistic operation at room temperature

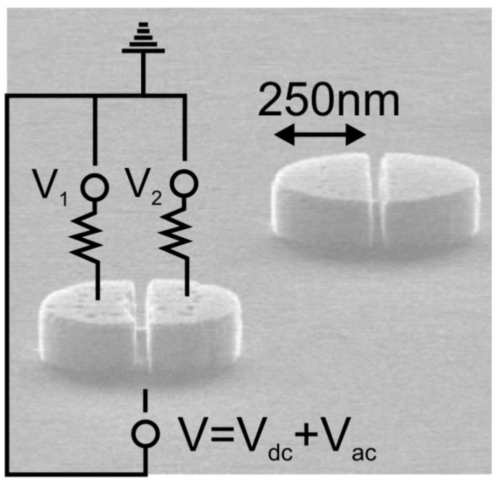
RTD operation

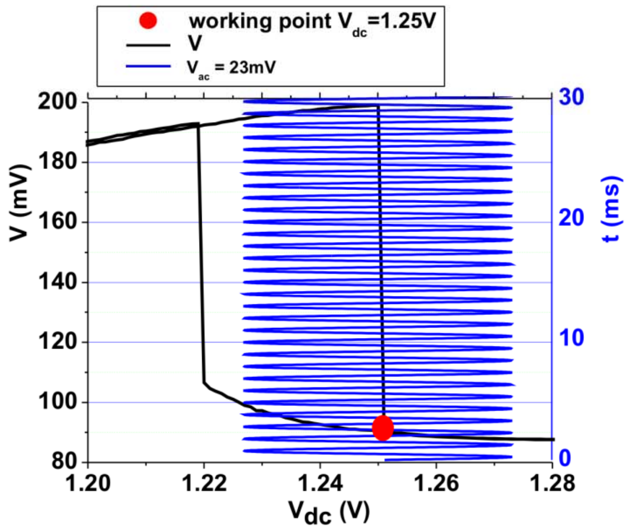


Logic operation with RTD mesas

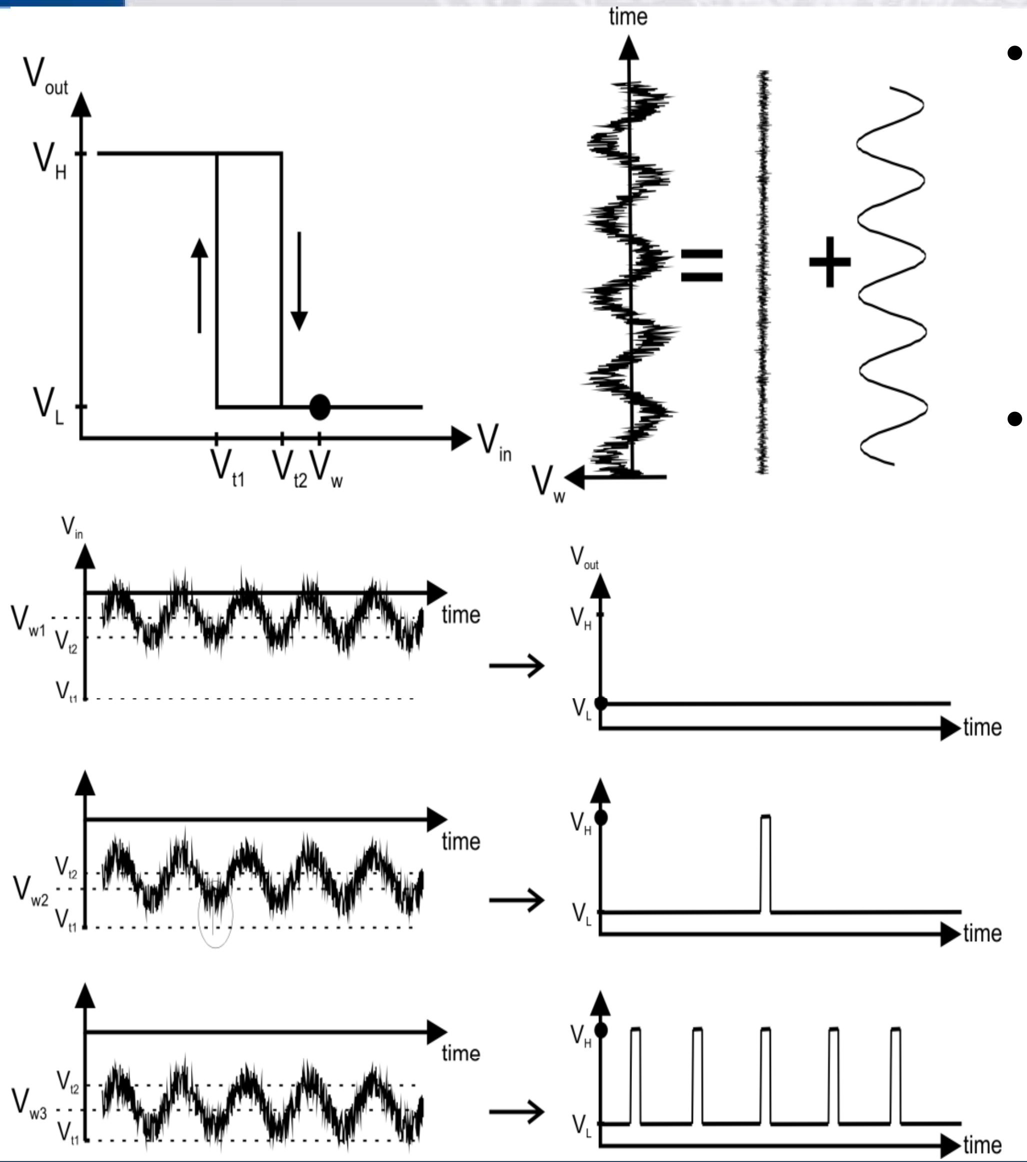




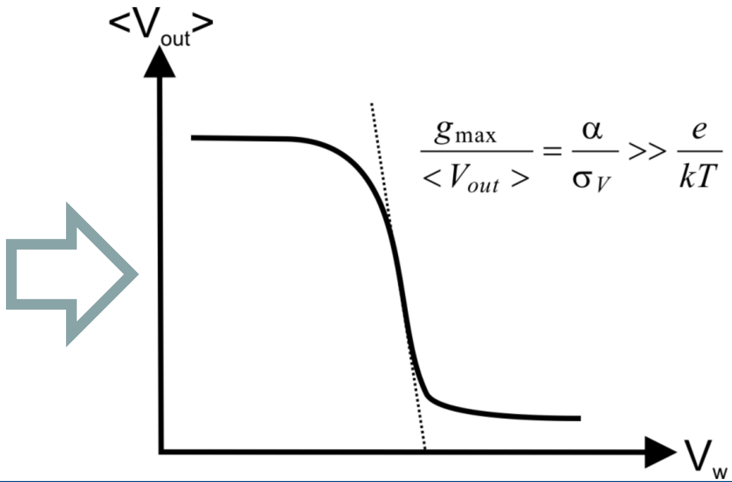


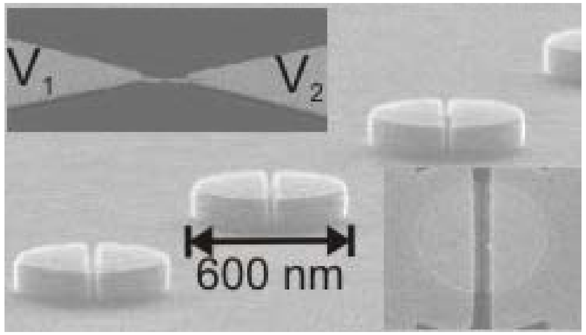


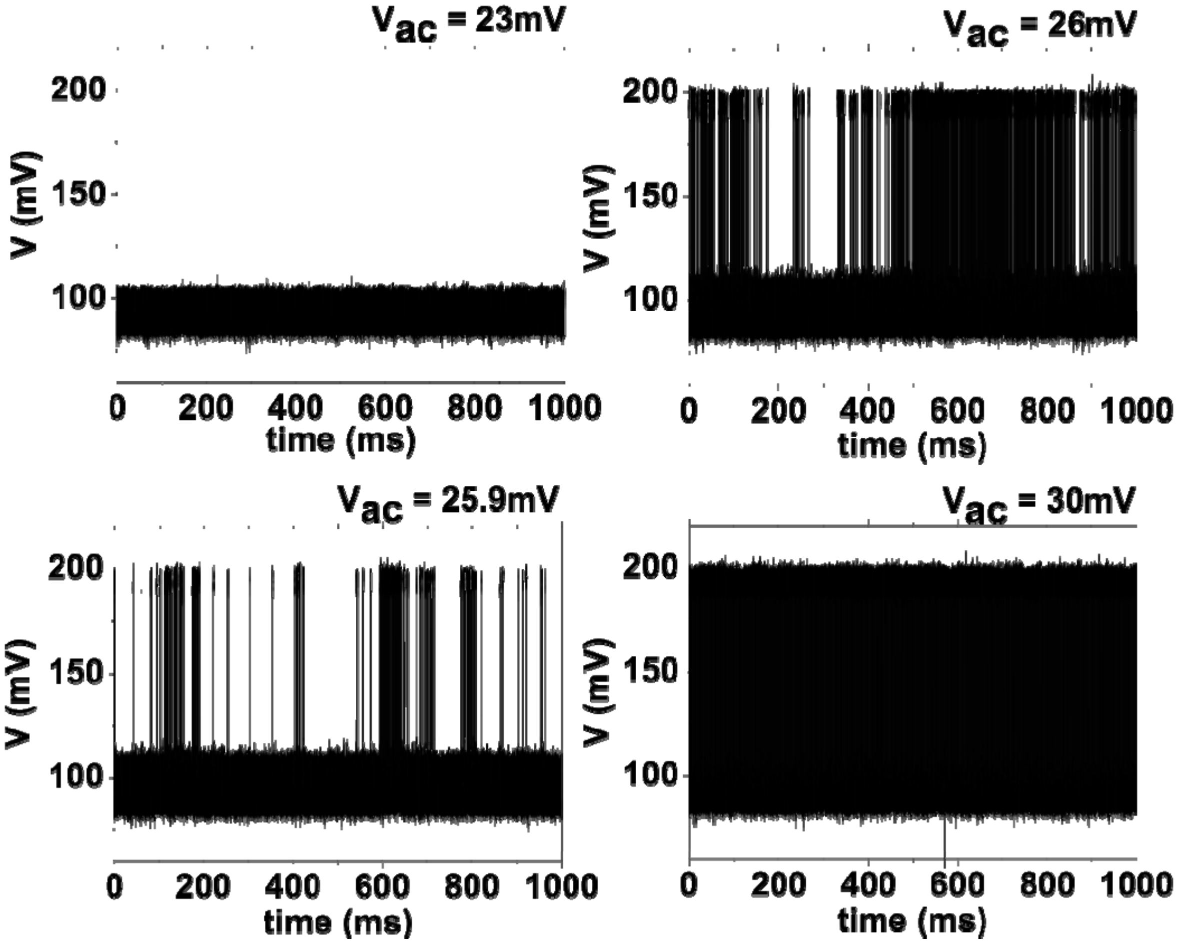
Noise-activated switching



- Ultra-miniaturized circuits: Small signal-to-noise ratios (SNR) & feedback between different devices are unavoidable
- Subtle strategy: exploit ambient noise and feedback action for electronic applications

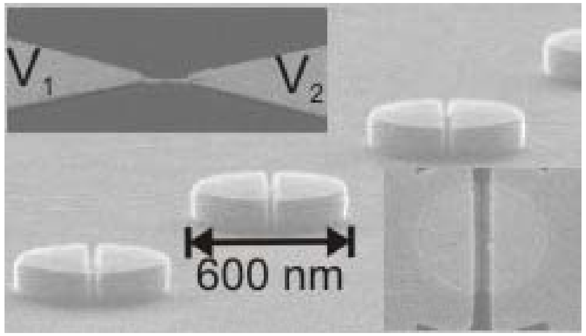


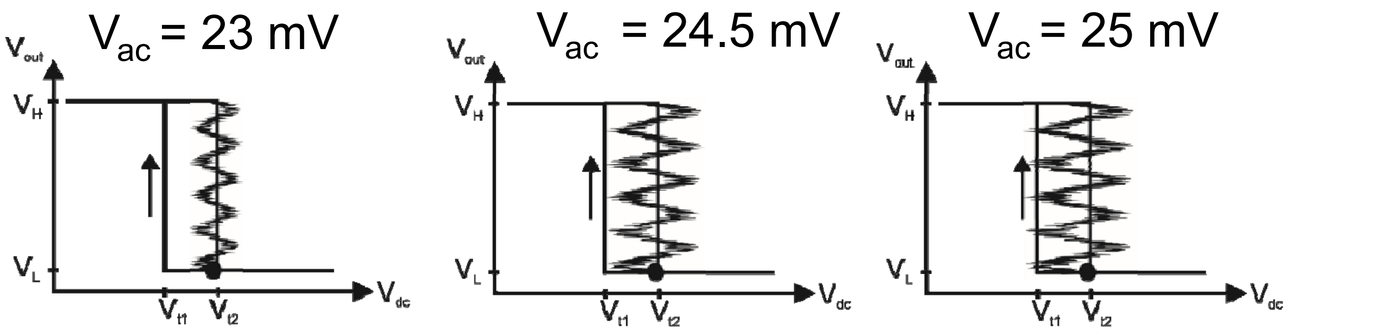




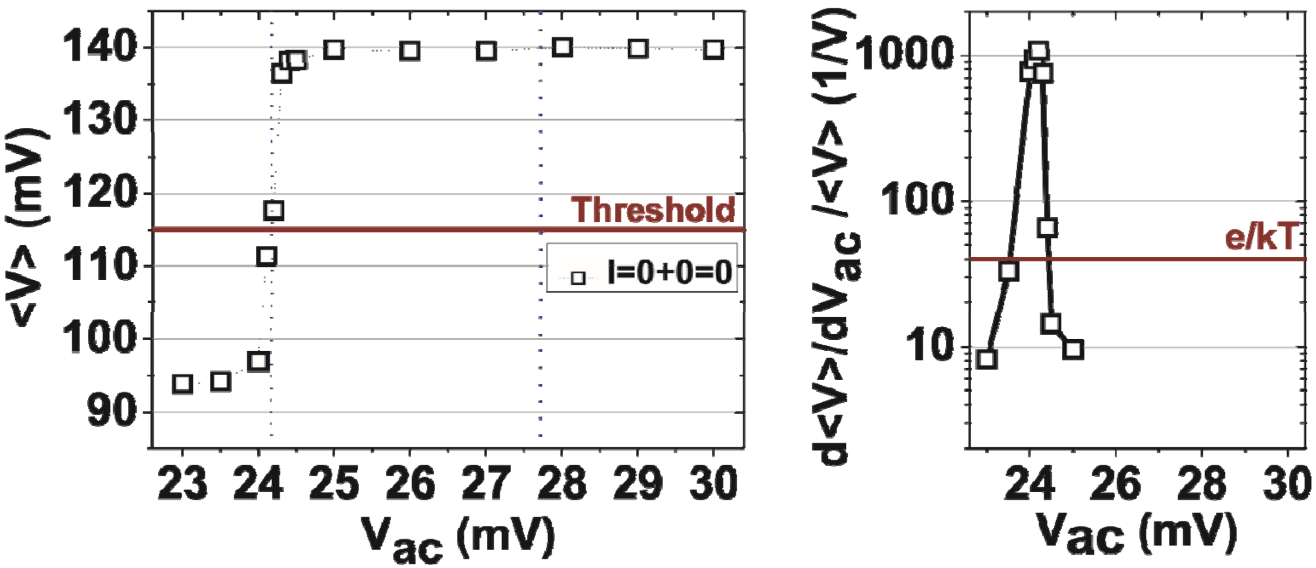
No thermal transconductance limit ➔ ultra small switching voltages

Logic RTD gates

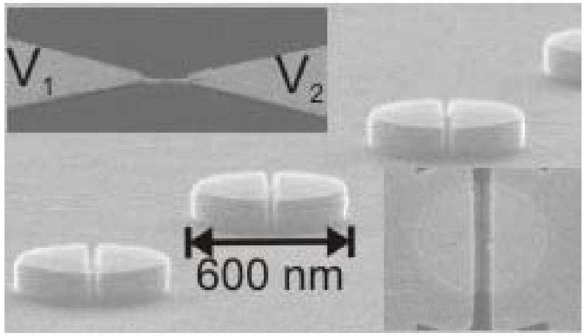


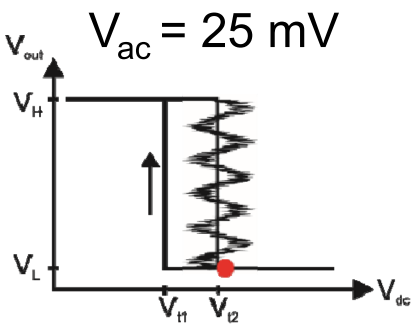


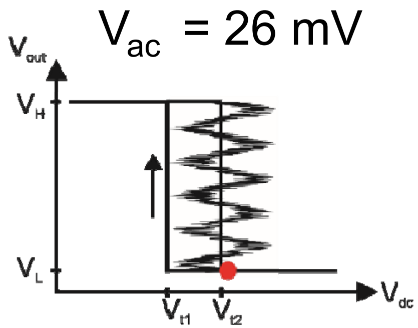
$V_1 = V_2 = 0$ mV == Log. input I = $I_1+I_2=0+0=0$

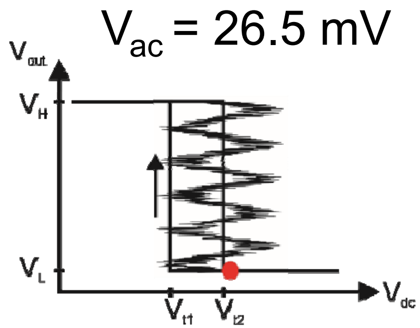


Logic RTD gates

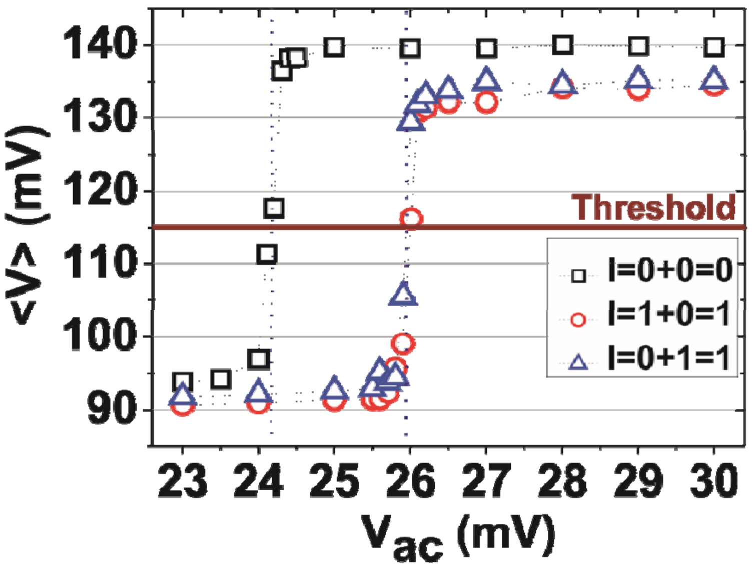


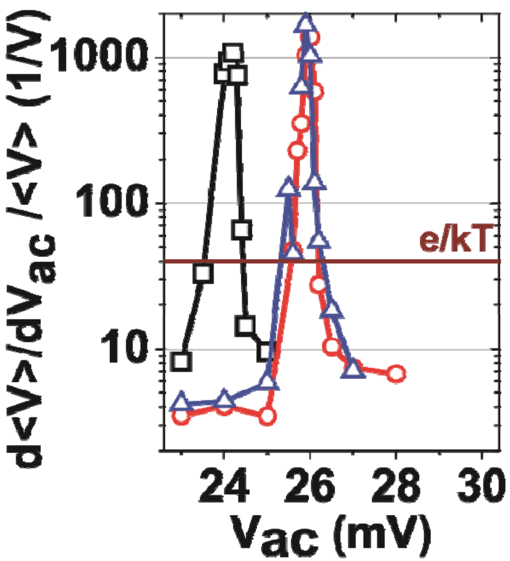




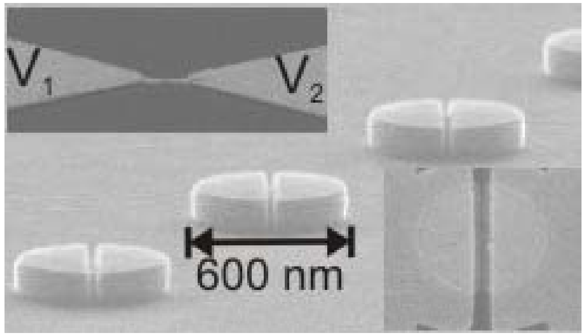


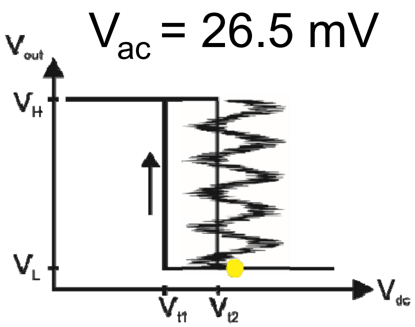
$V_1 = 0{,}2\ V_2 = 2{,}0$ mV == Log. input $I = I_1+I_2=1+0=0+1=1$

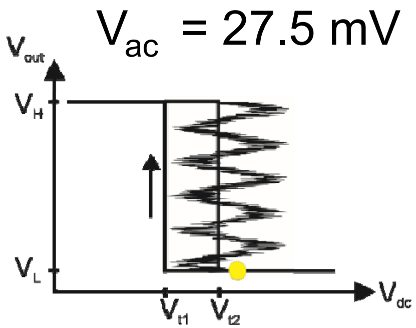


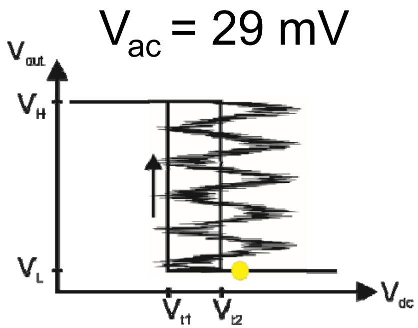


Logic RTD gates

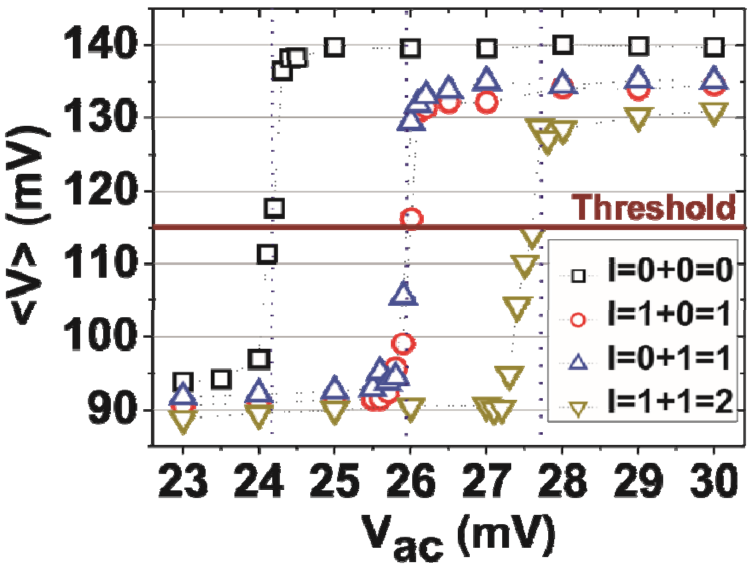


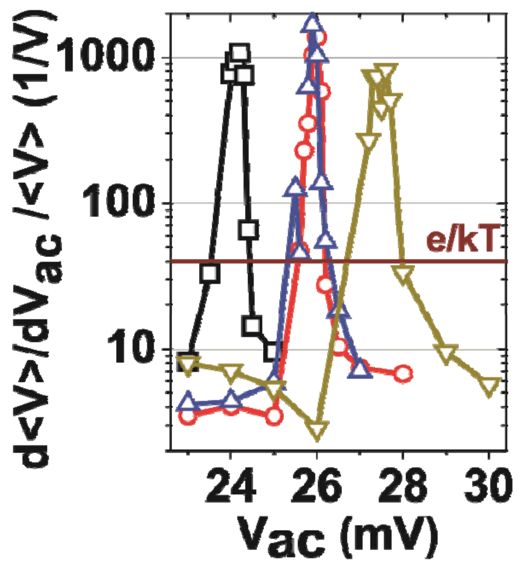




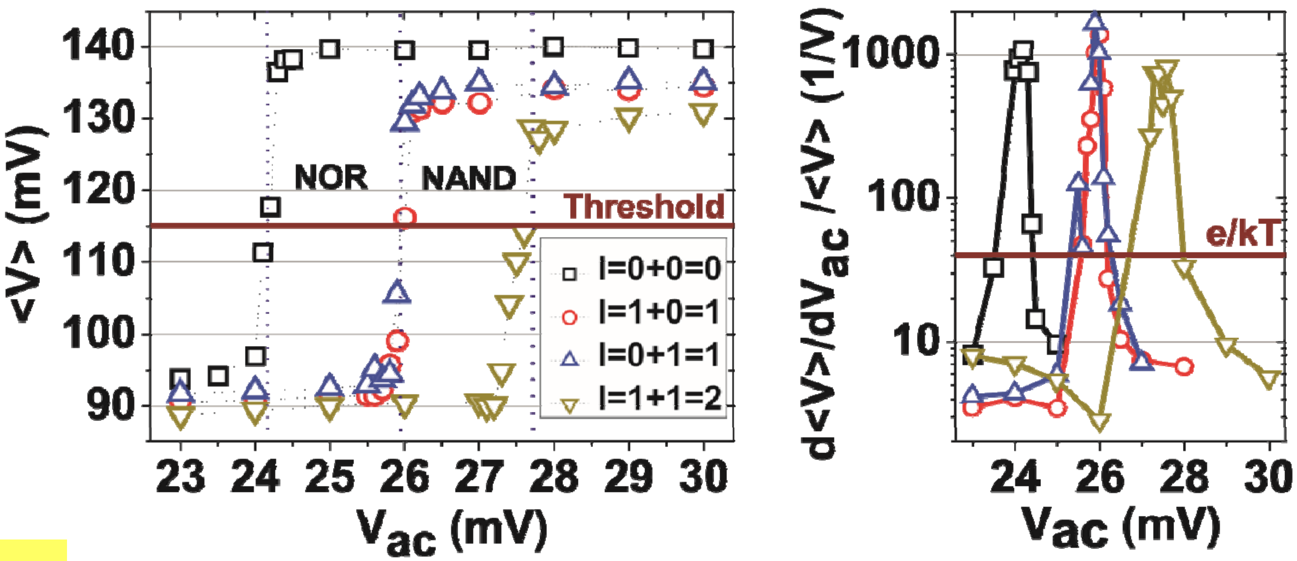


$V_1 = V_2 = 2$ mV == Log. input $I = I_1 + I_2 = 1+1=2$





Logic RTD gates



NOR

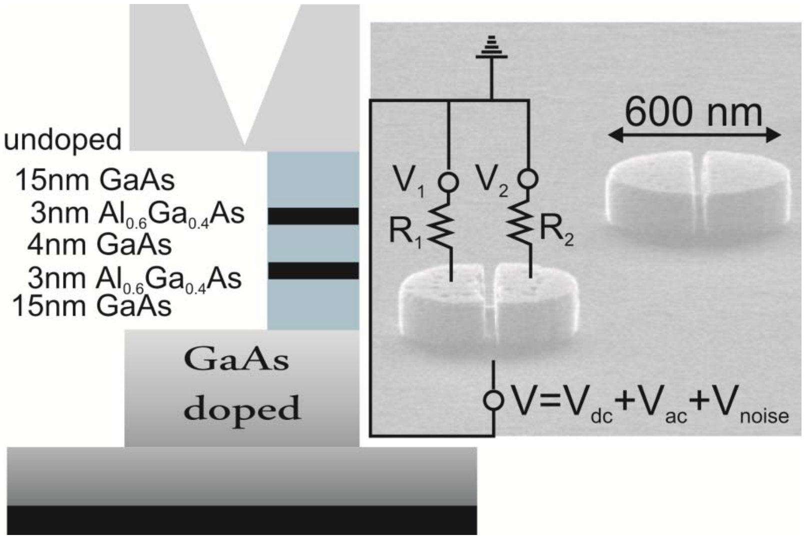
0 0	1
1 0	0
0 1	0
1 1	0

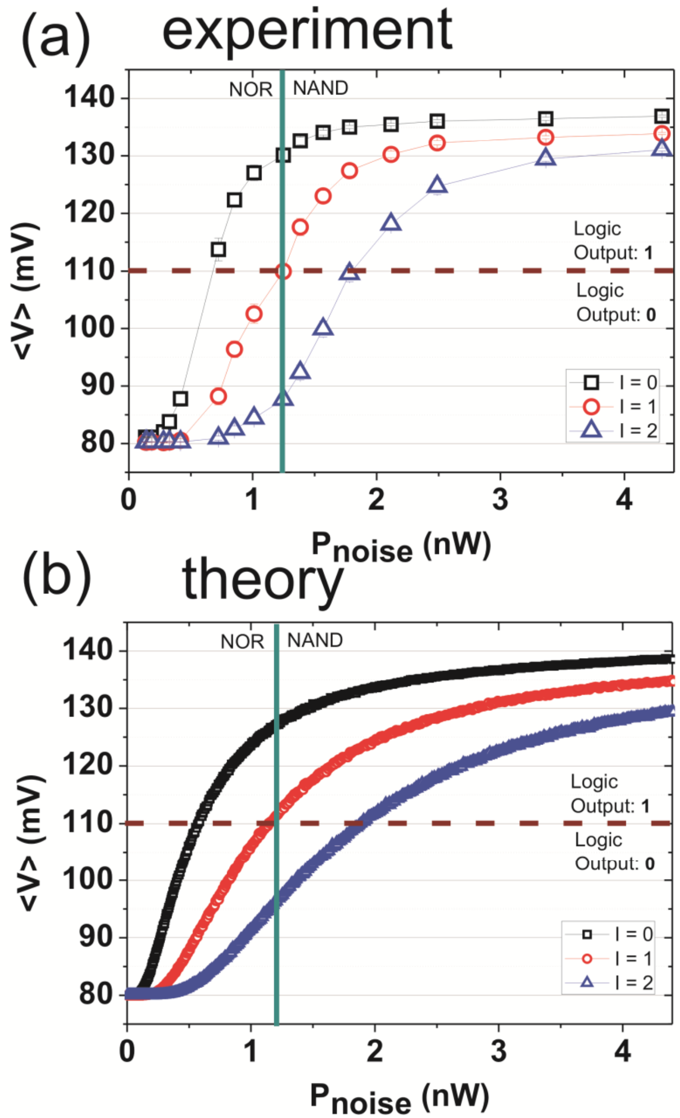
NAND

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



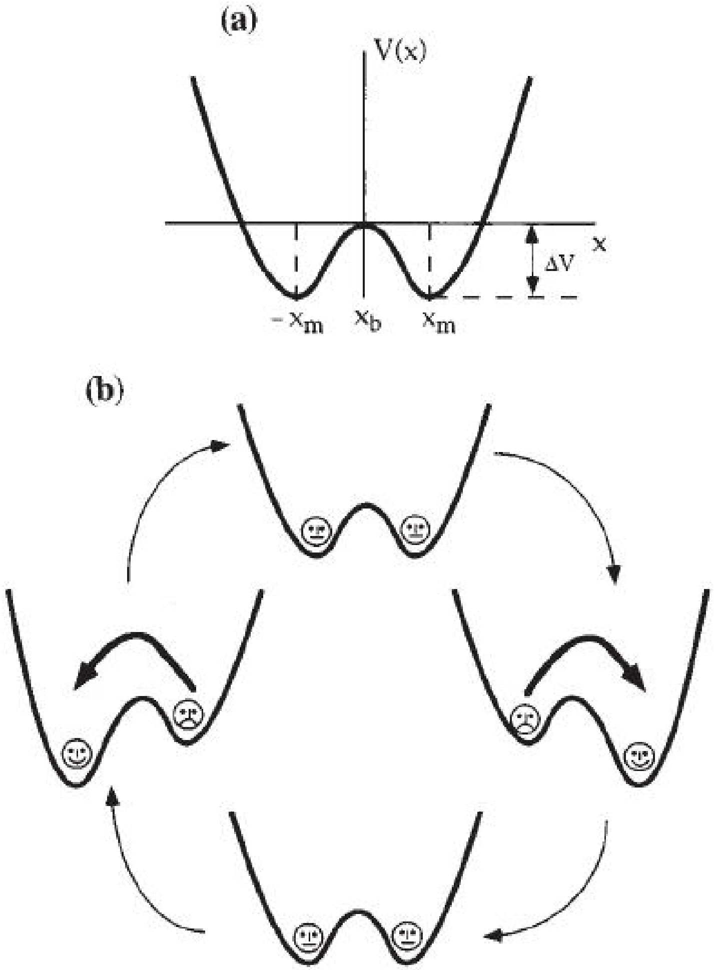


Murali, K. , Sinha, S. , Ditto, W. , Bulsara, A. Phys. Rev. Lett. **102**, 104101 (2009).

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

Stochastic resonance : A short introduction



L. Gammaitoni et al., “Stochastic resonance”, Reviews of Modern Physics, Vol. 70, No. 1, January 1998

Overdamped motion of a Brownian particle in a bistable potential in the presence of noise and periodic forcing

$$\dot{x} = -V`(x) + A_0 \cos(\omega t + \varphi) + \xi(t)$$

with

$$V(x) = -\frac{1}{2}x^2 + \frac{1}{4}x^4$$

Noise-induced hopping between the local equilibrium states with the Kramers rate

$$r_K = \frac{1}{\pi\sqrt{2}} \exp(-\frac{\Delta V}{D})$$

The *time-scale matching condition* for stochastic resonance:

$$T_\omega = 2T_K$$

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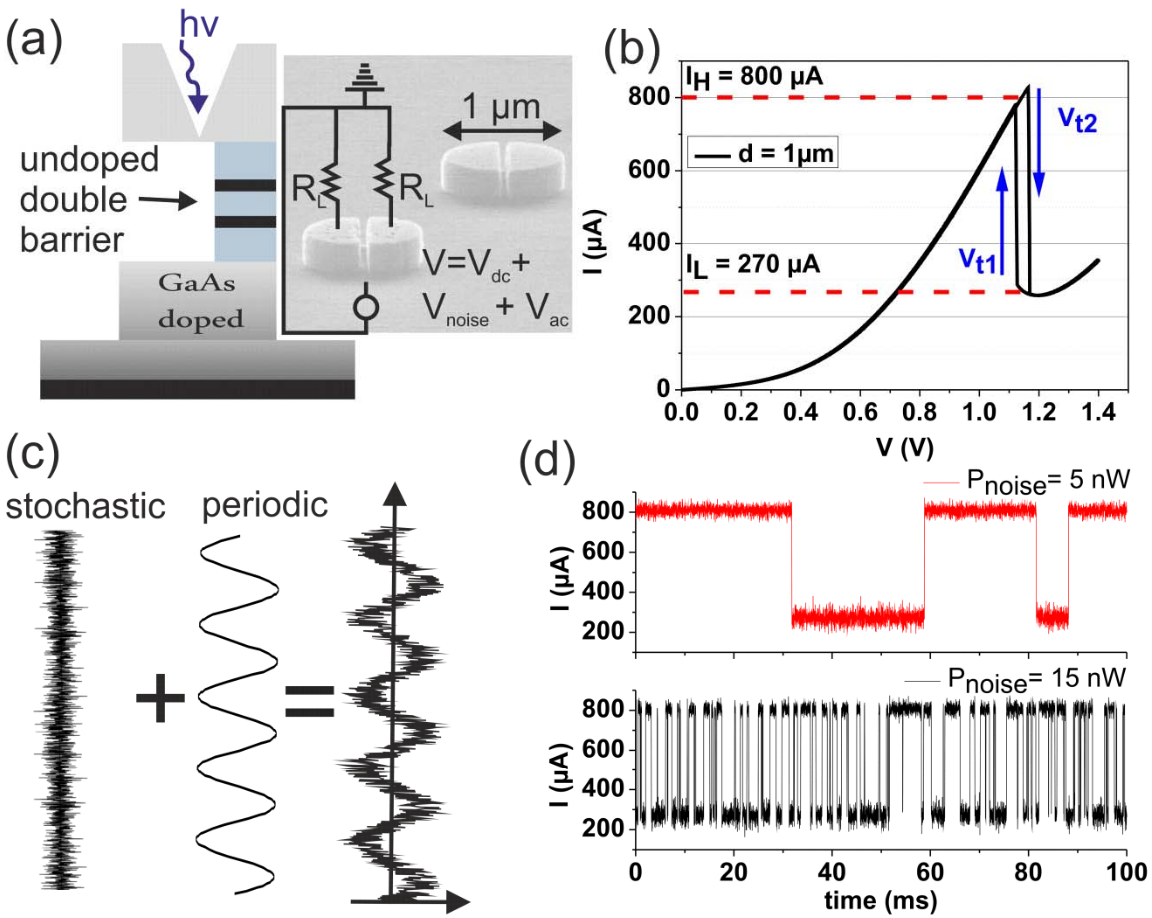
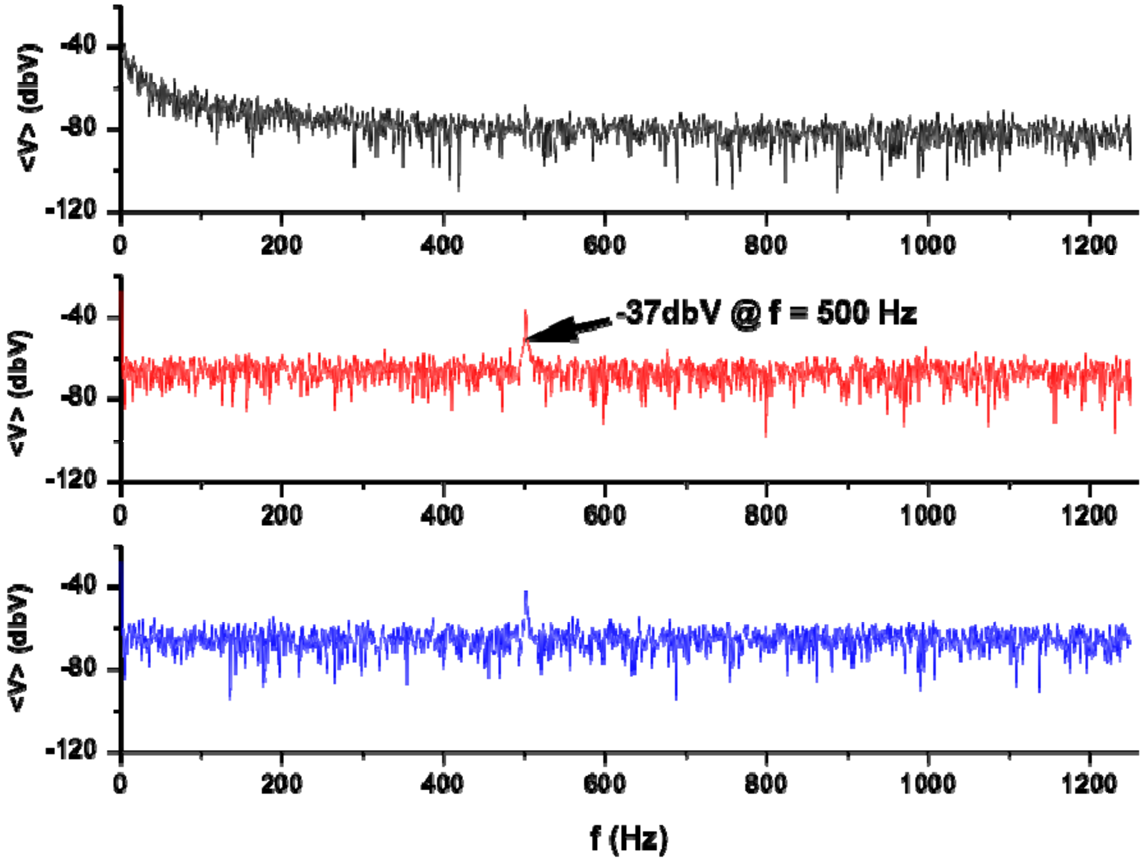
Stochastic resonance in resonant tunneling diodes: Exploiting noise & nonlinearity

TEP Technische Physik Universität Würzburg



- RTD is bistable with stable outputs I_H = 800 µA and I_L = 270 µA.
- Works @ RT
- PVR ~ 3
- Noise induced switching between the two stable states appear.
- Time scale T_k is given by the inverse of the Kramer‘s rate.

Recording of SR: Spectral response <V> versus the noise power added to the device

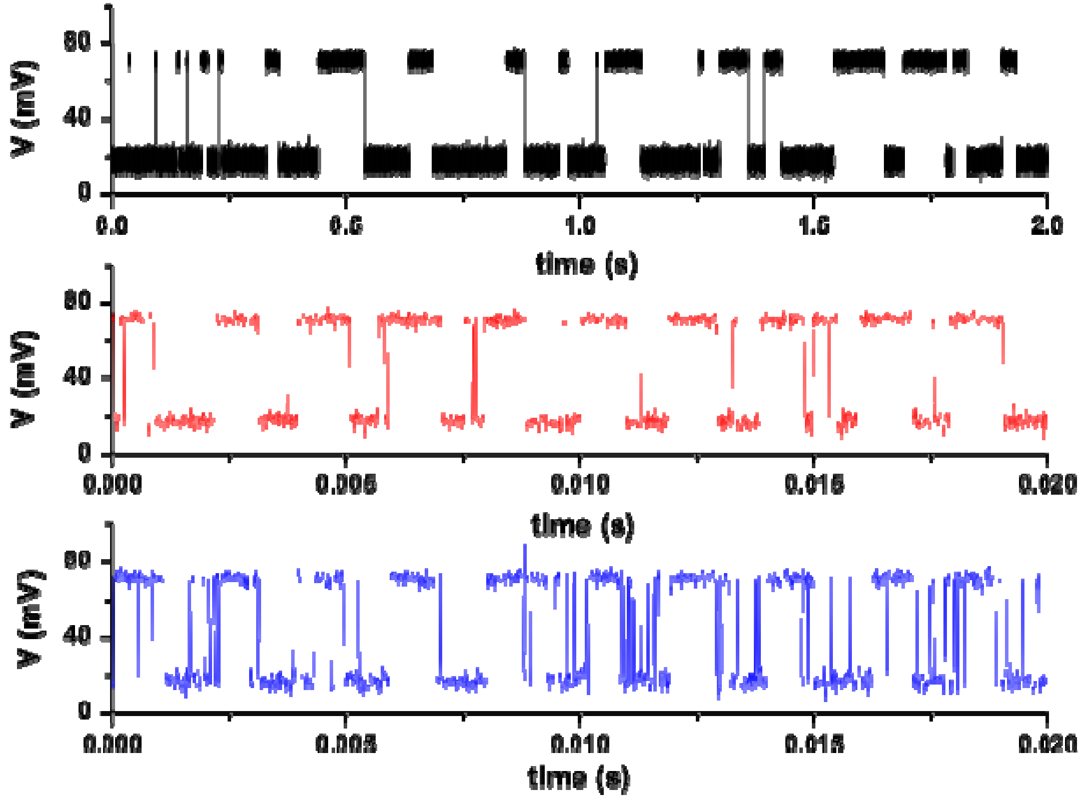


- For $P_{noise} < P_{SR}$ no spectral component at f = 500 Hz is found.

- For $P_{noise} > P_{SR}$ the spectral component at f = 500 Hz is still apparent.

- At the optimum noise level P_{SR}, the spectral amplitude reaches a maximum value and is decreasing apart from P_{SR}.

Stochastic resonance: Time trace signals



P_{noise} = 2 nW

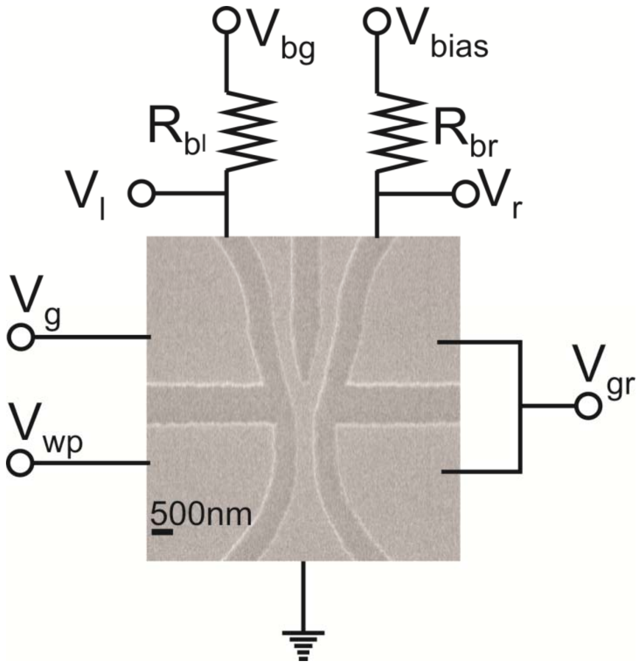
P_{noise} = 32 nW

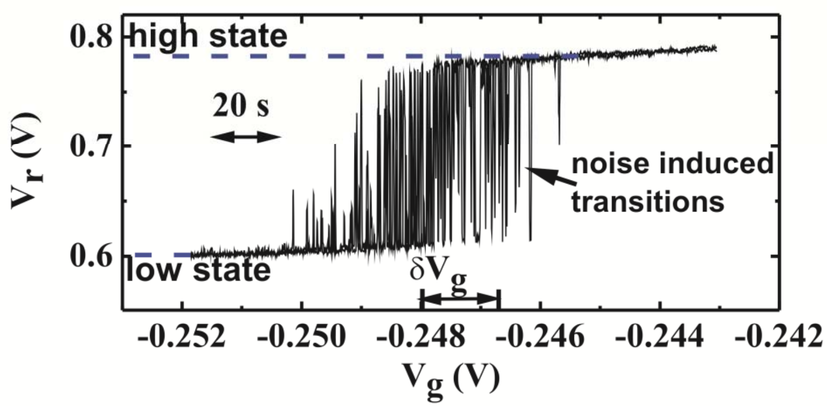
P_{noise} = 112 nW

At P_{noise} = 32 nW the output follows almost perfectly the input signal !!

YBS: Residence time magnetic field detector

- The input and the working point voltages set the condition of the Y-branch switch.
- Self-gating leads to a bistable transfer characteristic.
- Noise induced oscillations occur
- All measurements @ 20K.





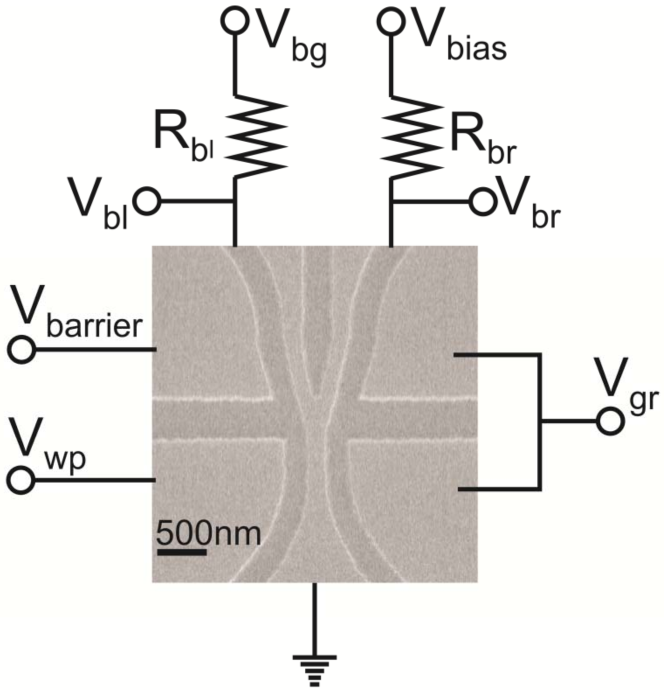
Input signal:

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

Weak periodic signal:

$$\delta V_g = 1.3mV$$

Magnetic field sensors based on the residence time difference in electron waveguides



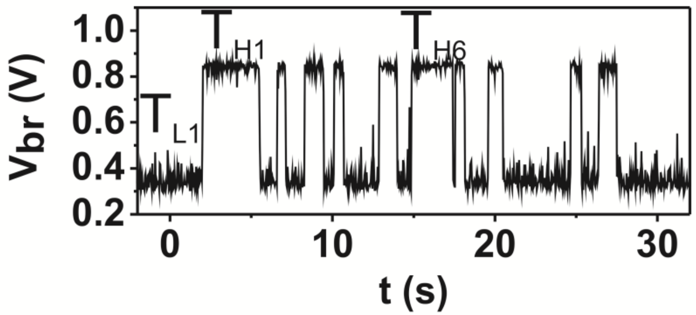
- The detector in biased in the strongly noise activated regime.

- Switching between V_H and V_L solely controlled by the internal noise.

- Magnetic field is applied perpendicular to the motion of electrons.

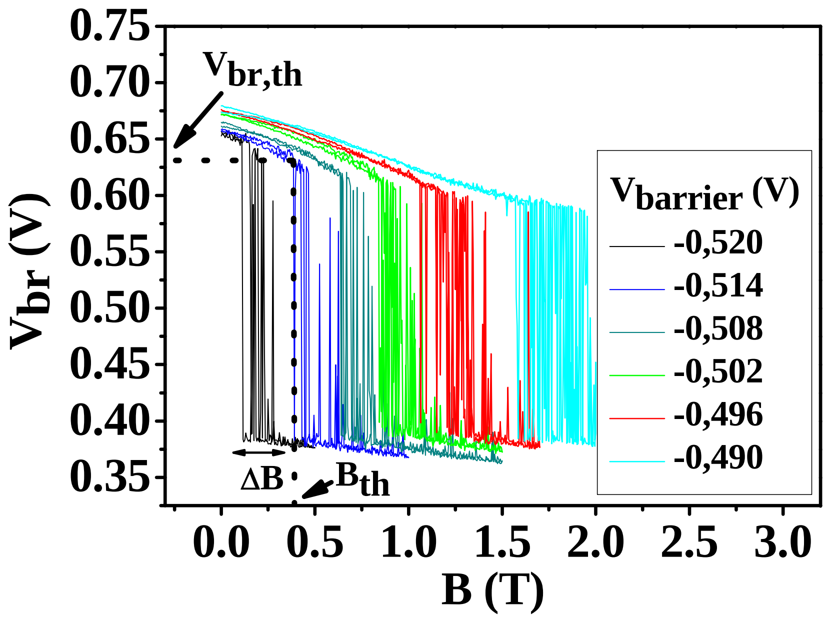
- Measure the time spent in each of the two stable states:

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



- Output of the detector is the residence time difference: $\Delta T = T_H - T_L$

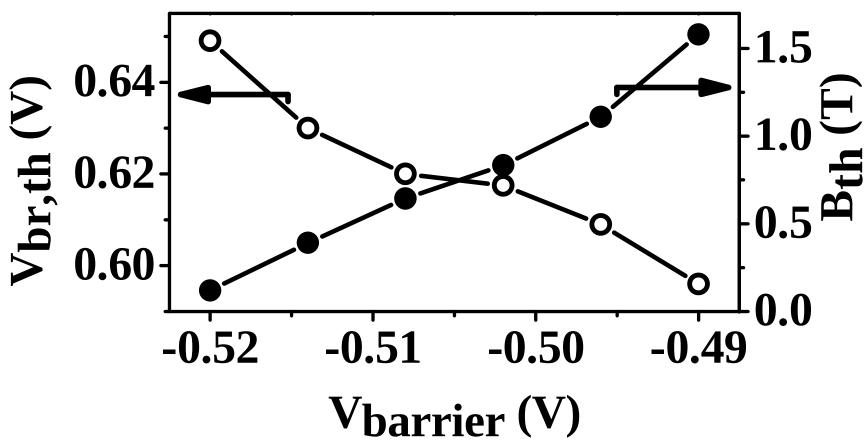
Magnetic field sensors based on the residence time difference in electron waveguides



Increasing magnetic field:

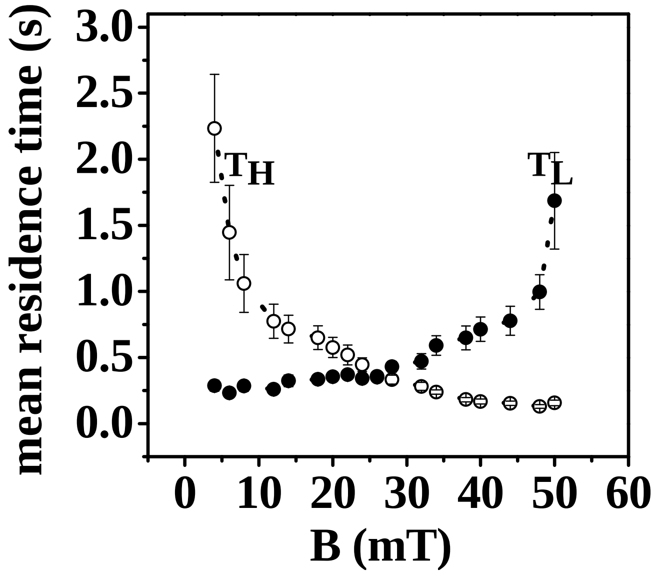
- The output V_{br} decreases linearly down to a magnetic field threshold B_{th}.
- Transitions between the two stable states occur within a magnetic field range ΔB.
- The output V_{br} changed its stable state from $V_{br} = V_H$ to $V_{br} = V_L$.

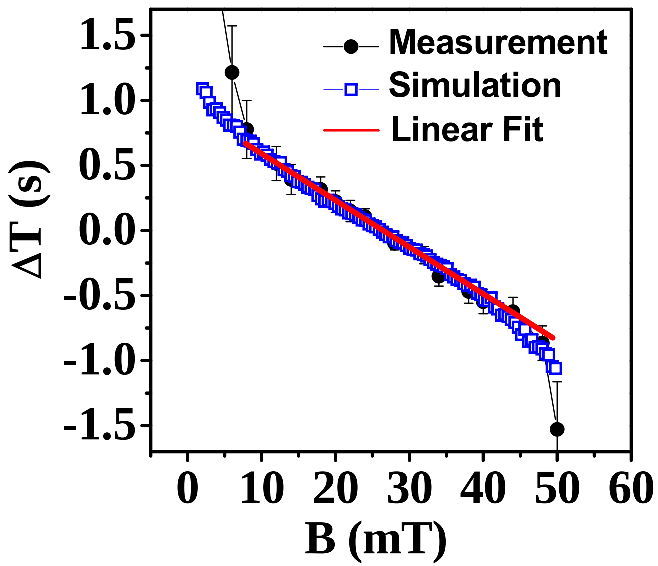
- The magnetic-field induced switching (between V_H and V_L) is associated with an interplay between a scattering asymmetry at the boundaries. [1]



[1] D. Hartmann *et al.*, PHYSICAL REVIEW B **78**, 113306 (2008).

Magnetic field sensors based on the residence time difference in electron waveguides





- The residence time T_H (high state) is decreasing and T_L (low state) is increasing with increasing B.

- Output ΔT is a linear function of the magnetic field around the symmetric point **ΔT = 0 s**.

- Target signal (magnetic field) independent sensitivity.

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

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