Quantum devices for noise-induced switching, signal detection and energy harvesting

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Würzburg, a beautiful city in the middle of Germany

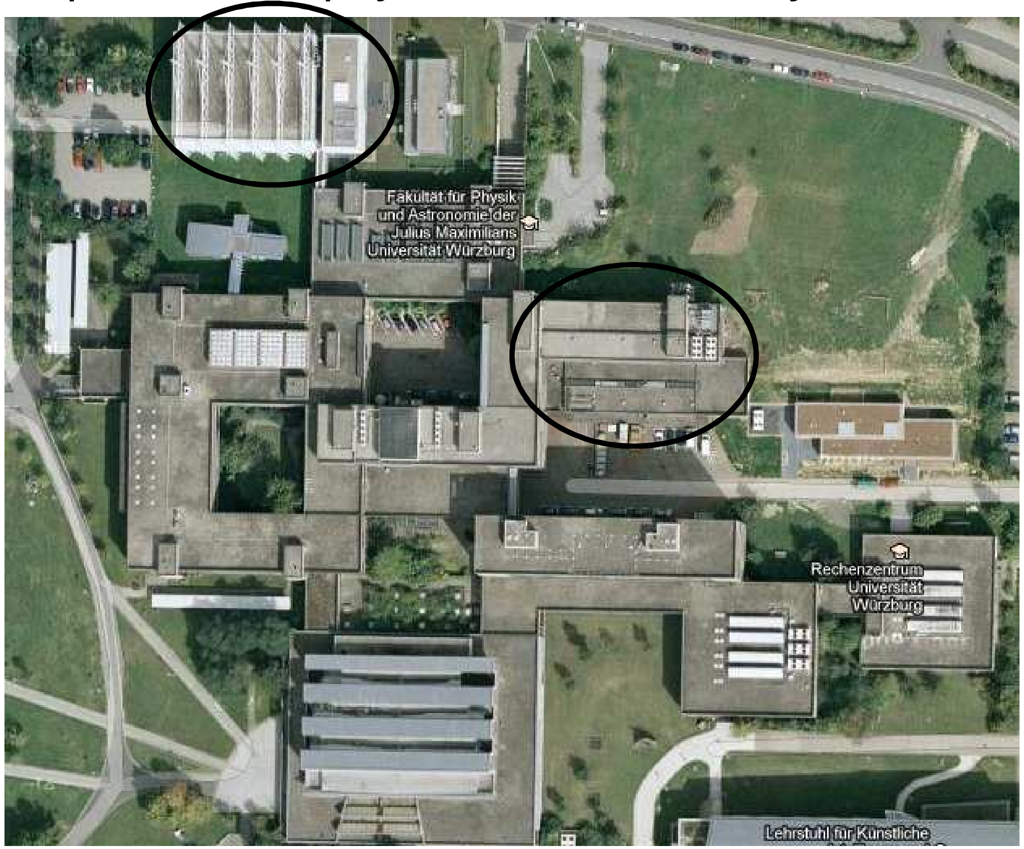
- Würzburg is located in the northern part of Bavaria.
- The region: **Franken**
- Population: 130,000
- Students: 24,300

<u>Würzburg is famous for:</u>

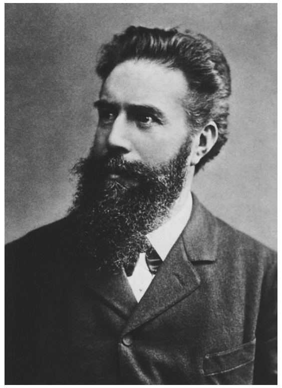
- Wine (Wine producer of the year:
  Weingut Horst Sauer)
- And Dirk Nowitzki

Department of physics and astronomy: An overview

Department of physics and astronomy



8 experimental physics chairs
5 theoretical physics chairs
+ several experimental and theoretical groups

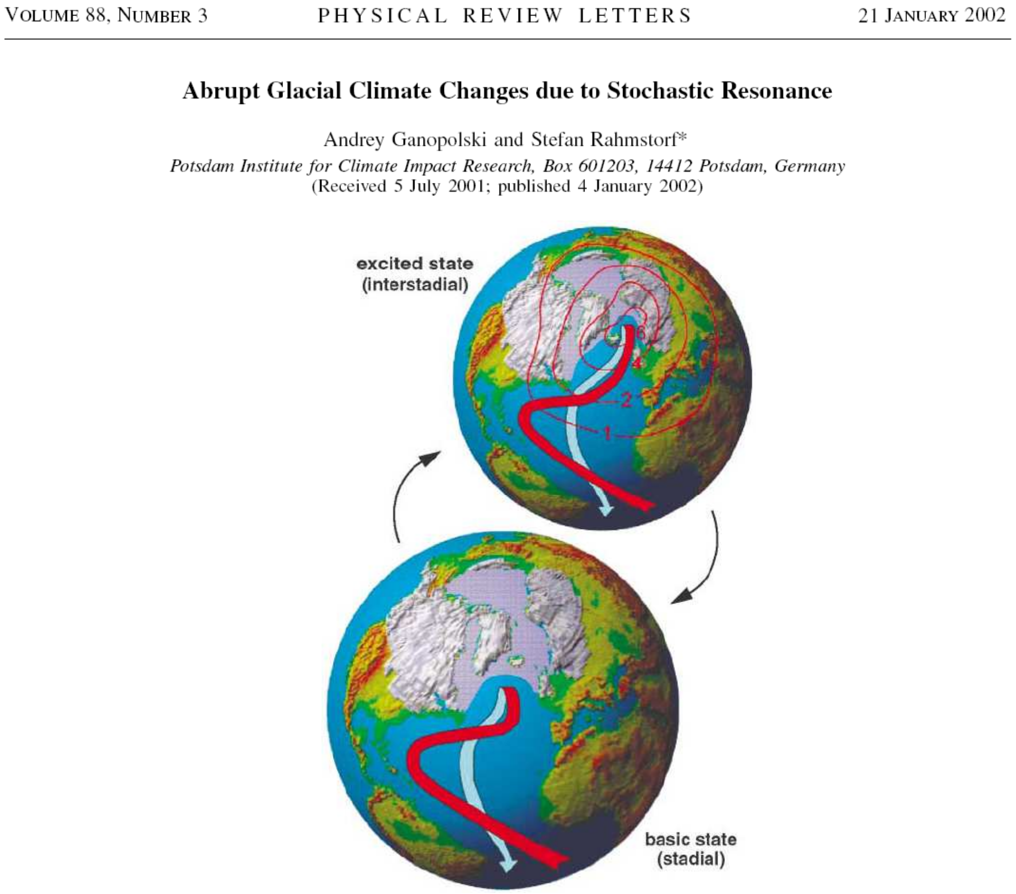


Wilhelm C. Röntgen
Nobel Prize 1901
(X-rays)

Klaus von Klitzing
Nobel Prize 1985
(Quantum Hall effect)

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]



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Abrupt Glacial Climate Changes due to Stochastic Resonance

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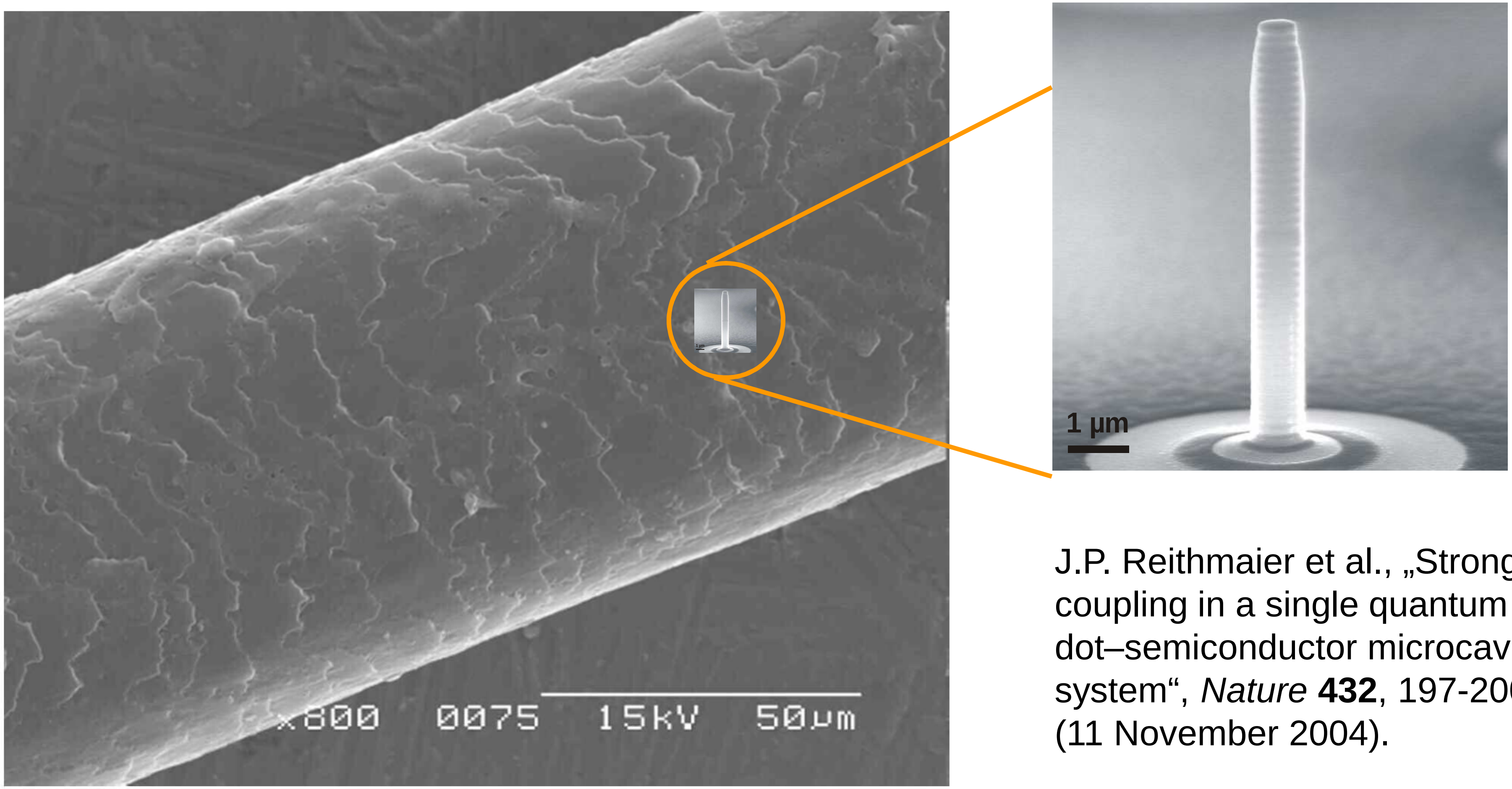
(Received 5 July 2001; published 4 January 2002)

[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.

Motivation: A human hair is still a macroscopic “device”

Electron microscope images of a human hair and a micro-pillar (fabricated @ our department)

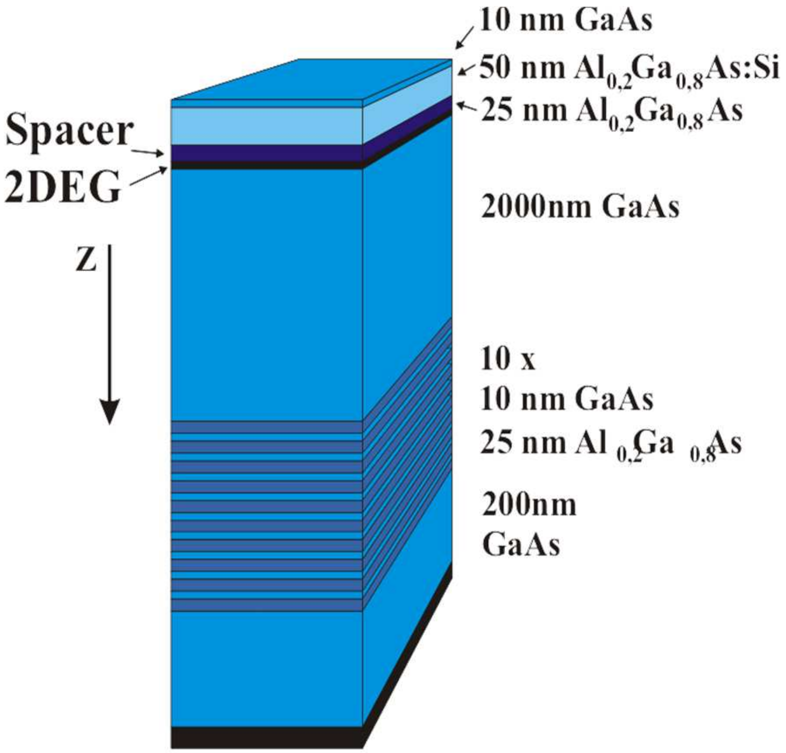


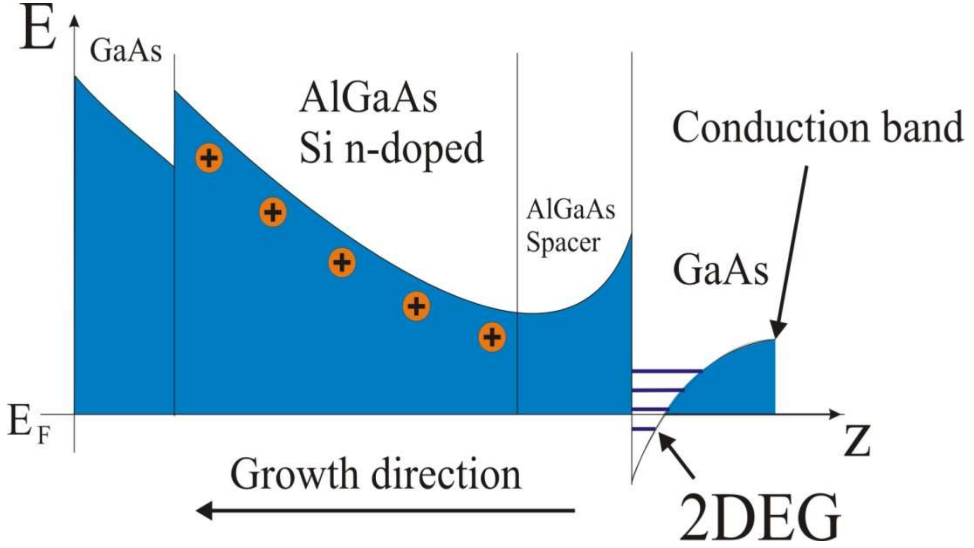
J.P. Reithmaier et al., „Strong coupling in a single quantum dot–semiconductor microcavity system“, *Nature* **432**, 197-200 (11 November 2004).

Outline

- **Growth, fabrication and transport properties of nanoelectronic devices**
  - Growth of 2DEGs and fabrication of electron waveguides.
  - Growth and fabrication of resonant tunneling diodes (RTD).
- **Universal logic gate switching in resonant tunneling diodes (RTDs)**
  - Universal logic gate switching => NOR to NAND
  - Logic stochastic resonance (LSR)
- **Stochastic resonance in nanoelectronic devices**
  - SR in electron waveguides
  - SR in RTDs for ac and periodic optical modulation
- **Noise activated nonlinear dynamic sensors**
  - Magnetic field sensor based on (bistable) electron waveguides
- **Energy harvesting: The quantum harvester class**
  - Transport as a consequence of state dependent diffusion.
  - Optimal energy to quanta conversion: A coupled QD system.

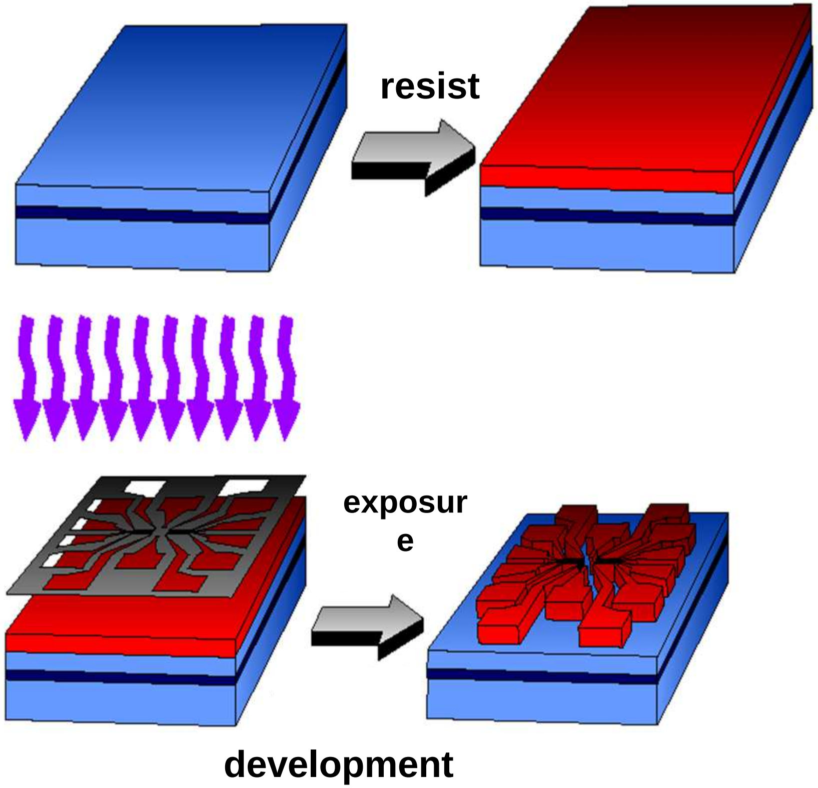
Growth of high mobility two dimensional electron gases based on AlGaAs/GaAs

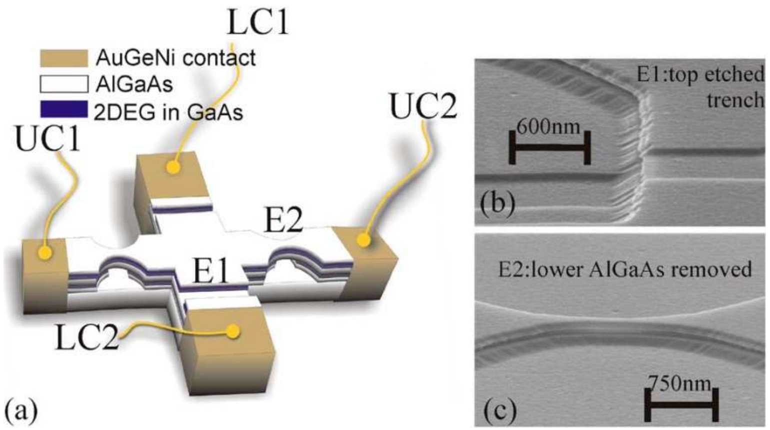


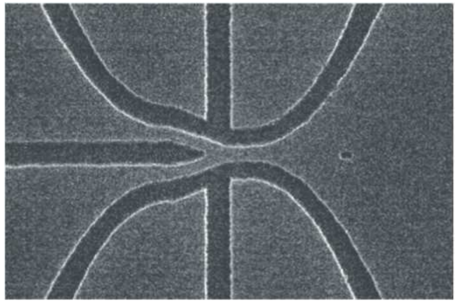


- Modulation doped GaAs/AlGaAs heterostructure (HEMT).
- Grown by molecular beam epitaxy.
- High mobility μ = $1.1 \cdot 10^6$ cm^2/Vs and charge density n = $3.7 \cdot 10^{11} cm^{-2}$

Fabrication of electron waveguides and other nanoelectronic devices







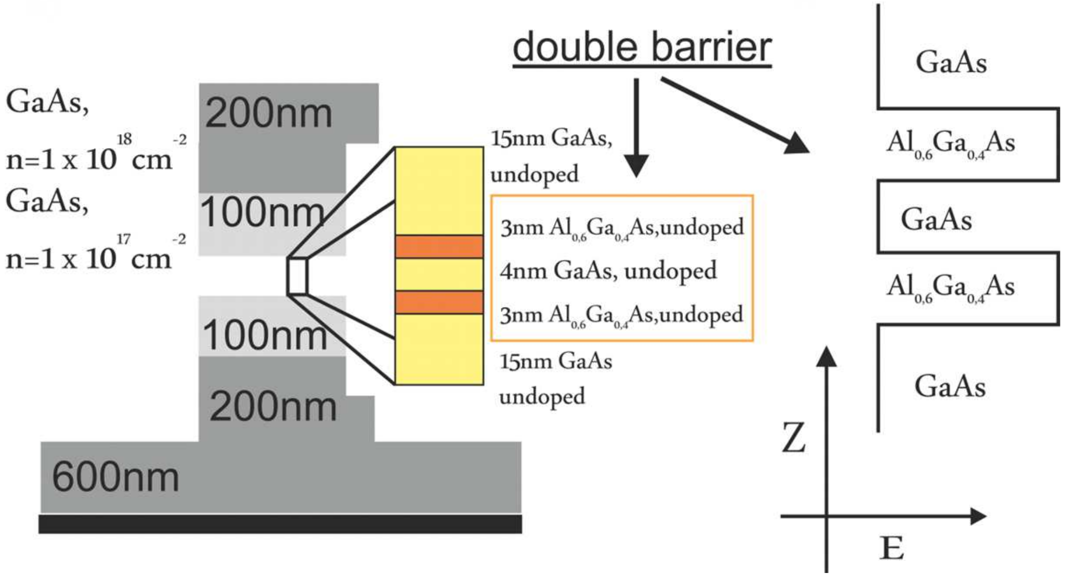
- Samples are grown by molecular beam epitaxy.
- Electron beam or optical lithography.
- Evaporating the etching mask (e.g. Cr) & Lift-off.
- Remove the etching mask (HNO_3)

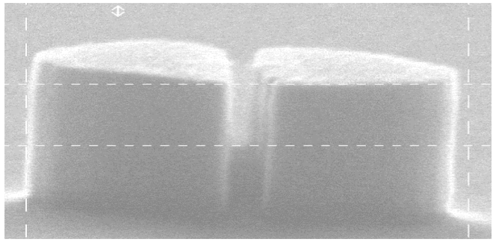
- Resist (e.g. positive PMMA).
- Development of the resist.
- Wet or dry chemical etching (e.g. ECR-RIE)

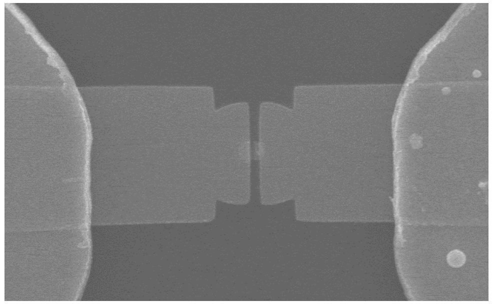
DONE!! (plus contacts)

Growth and fabrication of trench etched and three terminal resonant tunneling diodes (RTDs)

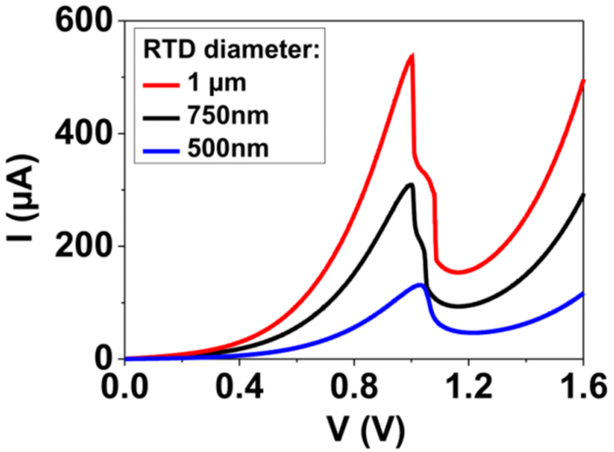
- RTDs based on the GaAs material system with AlGaAs/GaAs/AlGaAs double barriers.



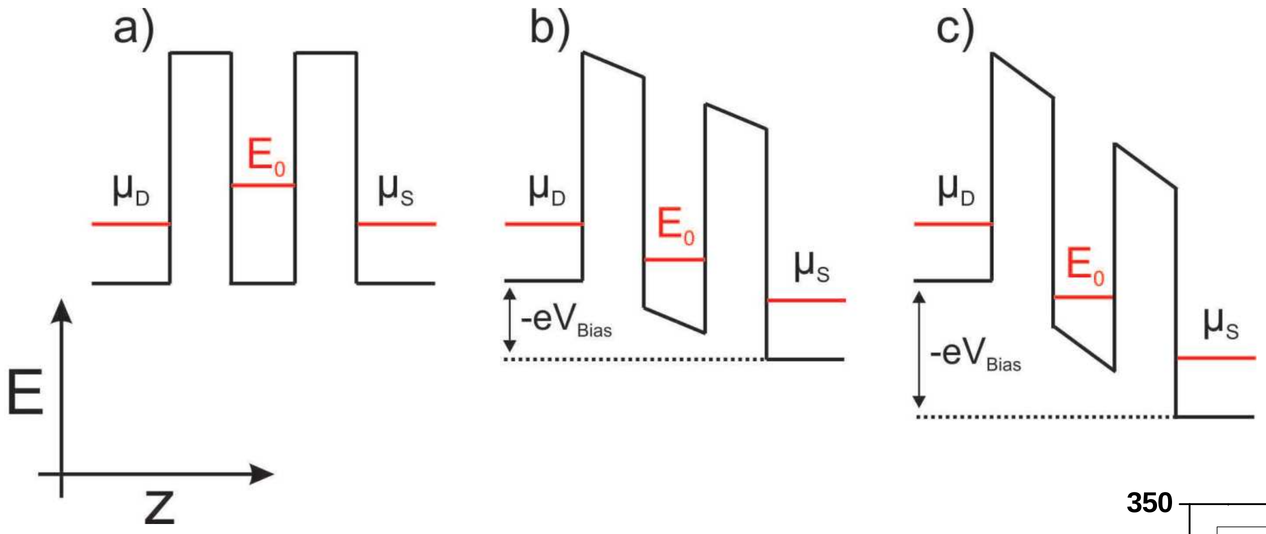


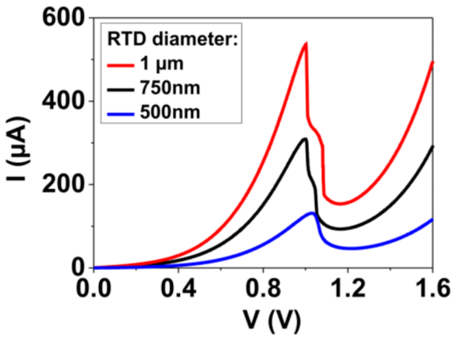


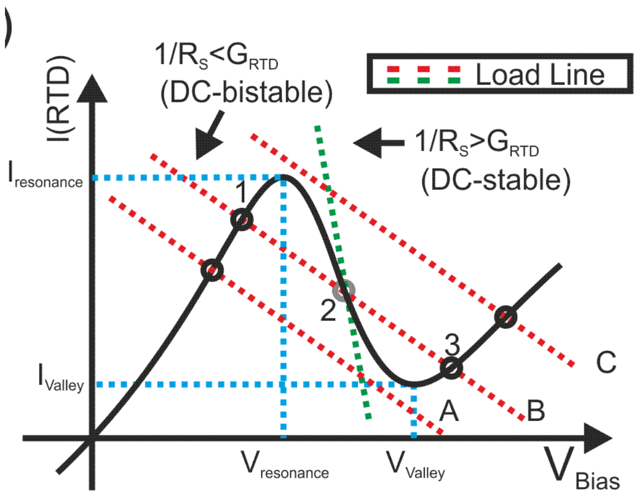
- Dry chemical etching is used to define RTD mesas from 12 µm down to 50 nm.
- BCB (polymer) for mesa isolation.
- Top Au/Ti/Ni contact.

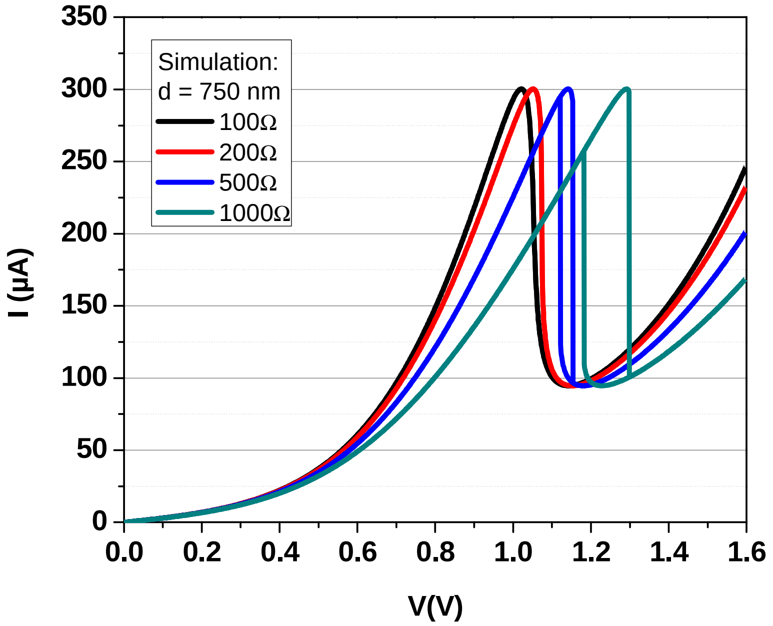


Resonant tunneling diodes (RTDs): Tunable bistability via the load line effect









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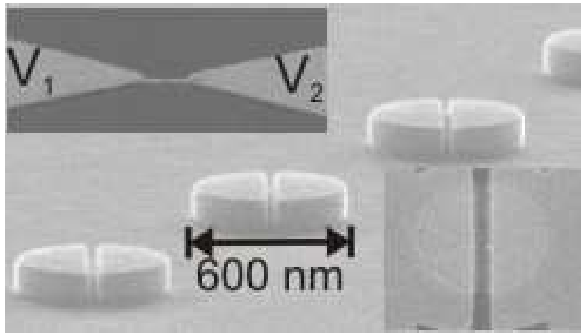
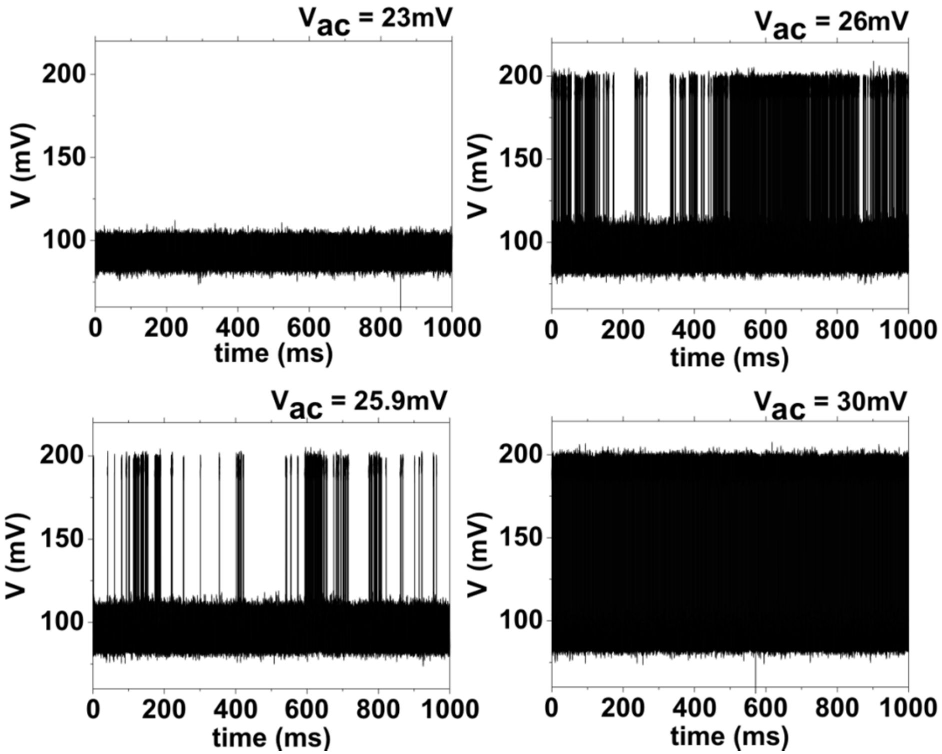
Reconfigurable logic universal gates: Noise induced firing rates in RTDs

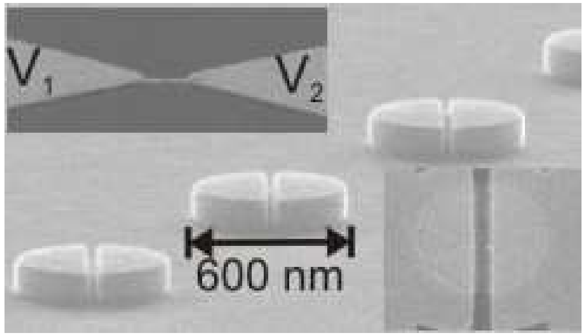


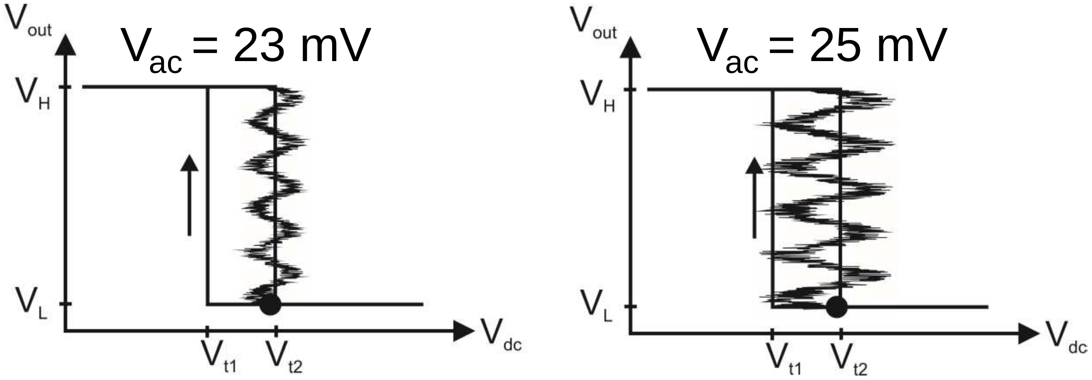
- ❒ Electron microscopy images of a trench etched RTD with diameter d = 600 nm
- ❒ Branches serve as logical inputs



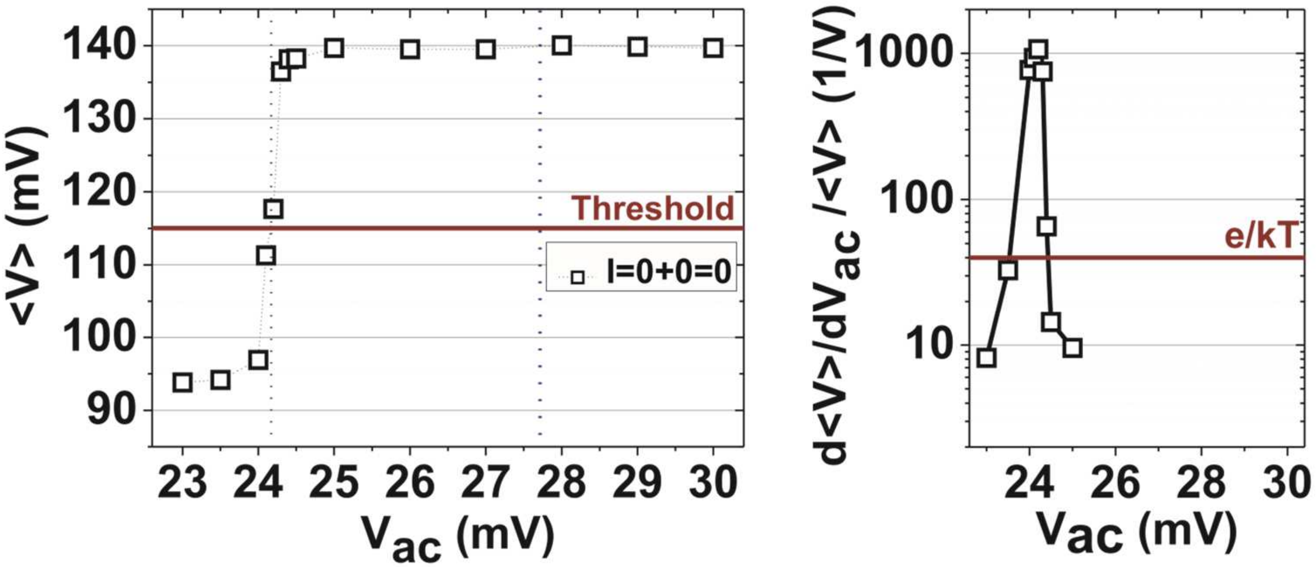
- ❒ Noise induced signal trains
- ❒ Mean value is efficiently controlled by input signals
- ❒ Can be integrated to arrays
- ❒ No classical kT limit of transconductance

Reconfigurable logic universal gates: NOR and NAND configurations

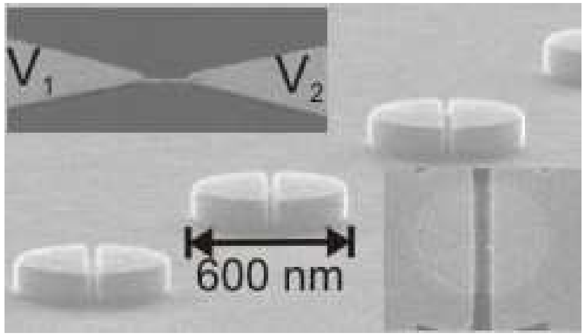


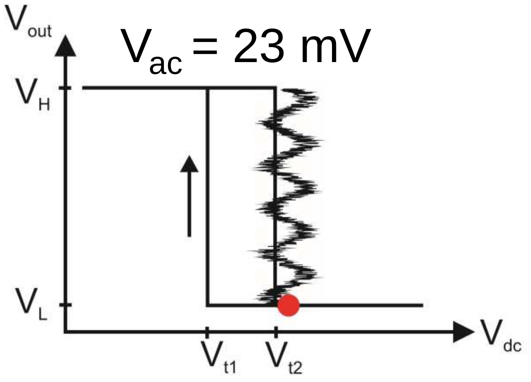


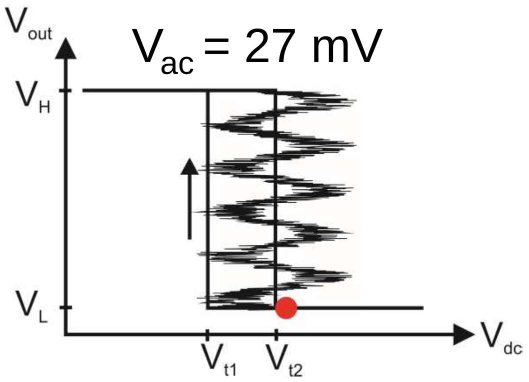
Switching voltages: $V_1 = V_2 = 0$mV



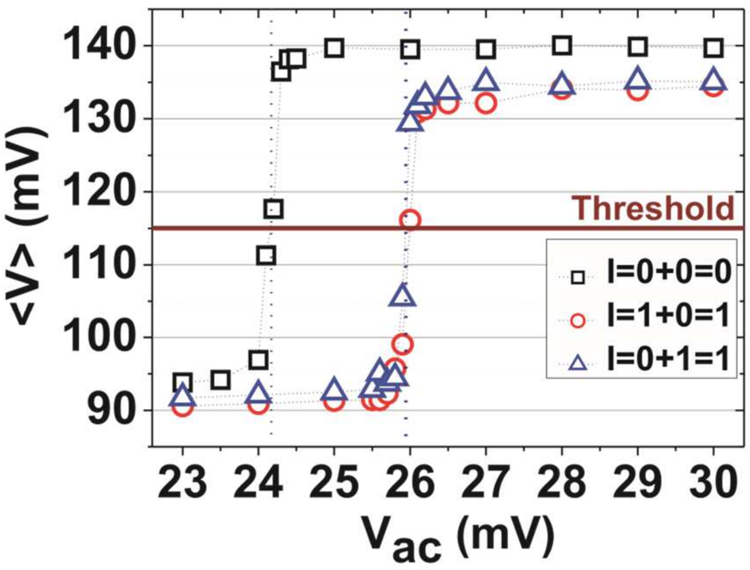
Reconfigurable logic universal gates: NOR and NAND configurations

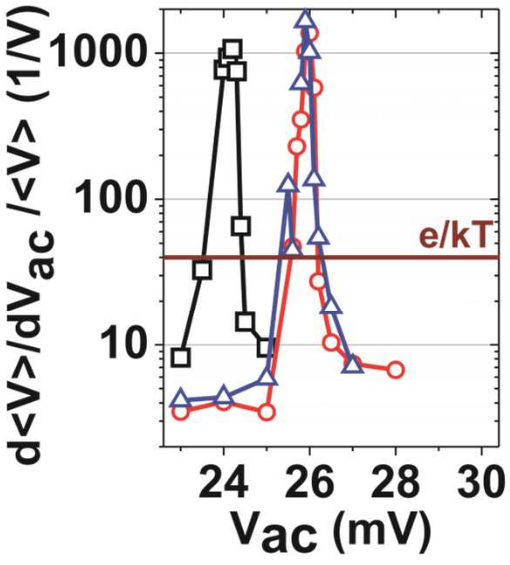




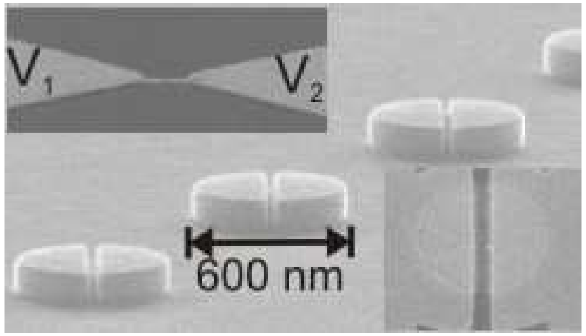


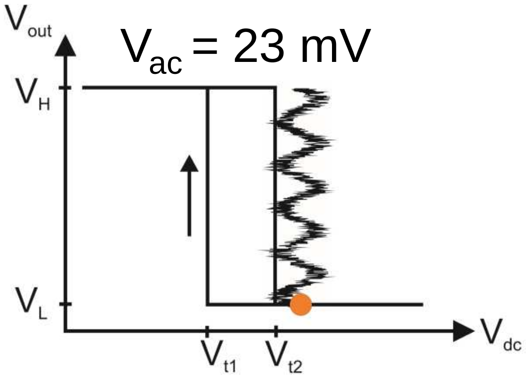
Switching voltages: V_1 = 0, 2 mV V_2 = 2, 0 mV

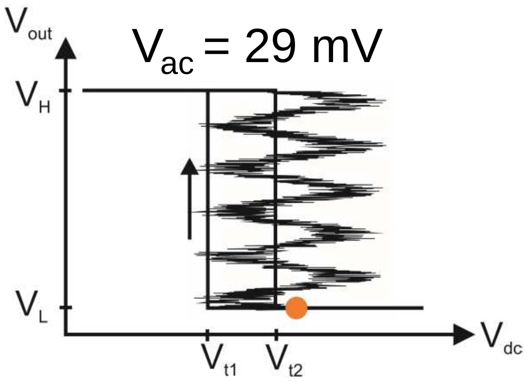




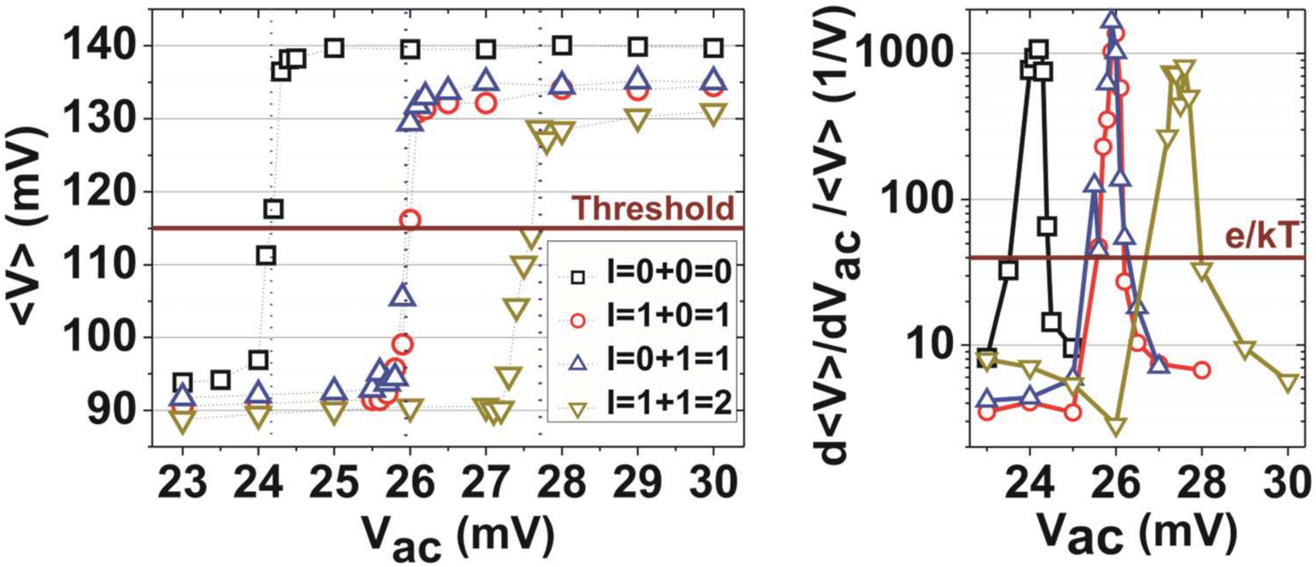
Reconfigurable logic universal gates: NOR and NAND configurations



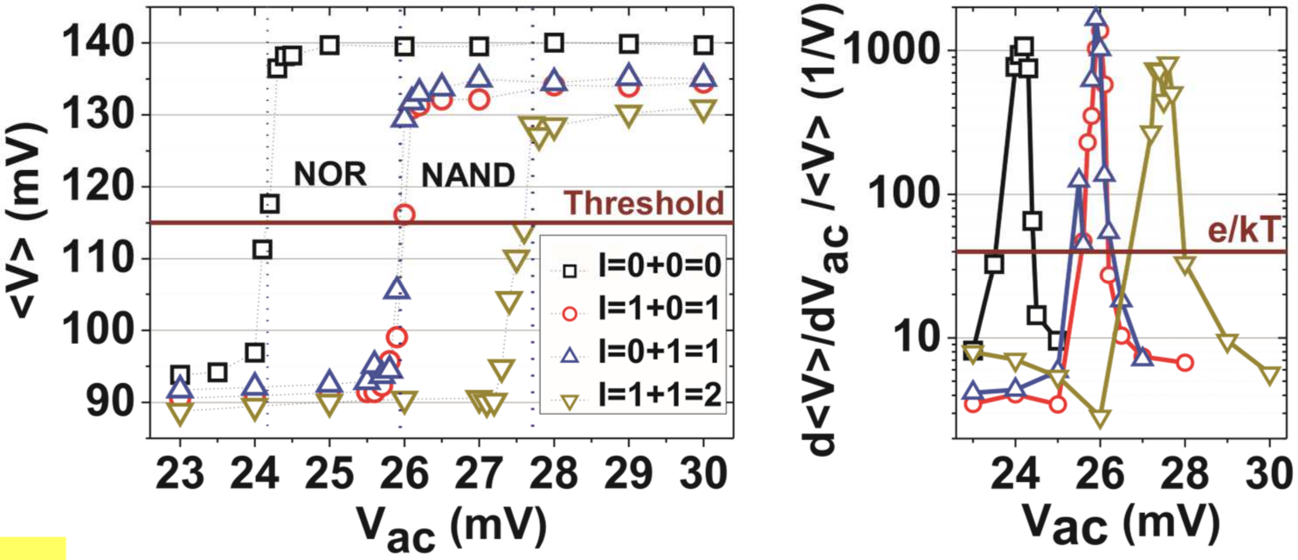




Switching voltages: $V_1 = V_2 = 2$ mV



Reconfigurable logic universal gates: NOR and NAND configurations & truth tables



NOR

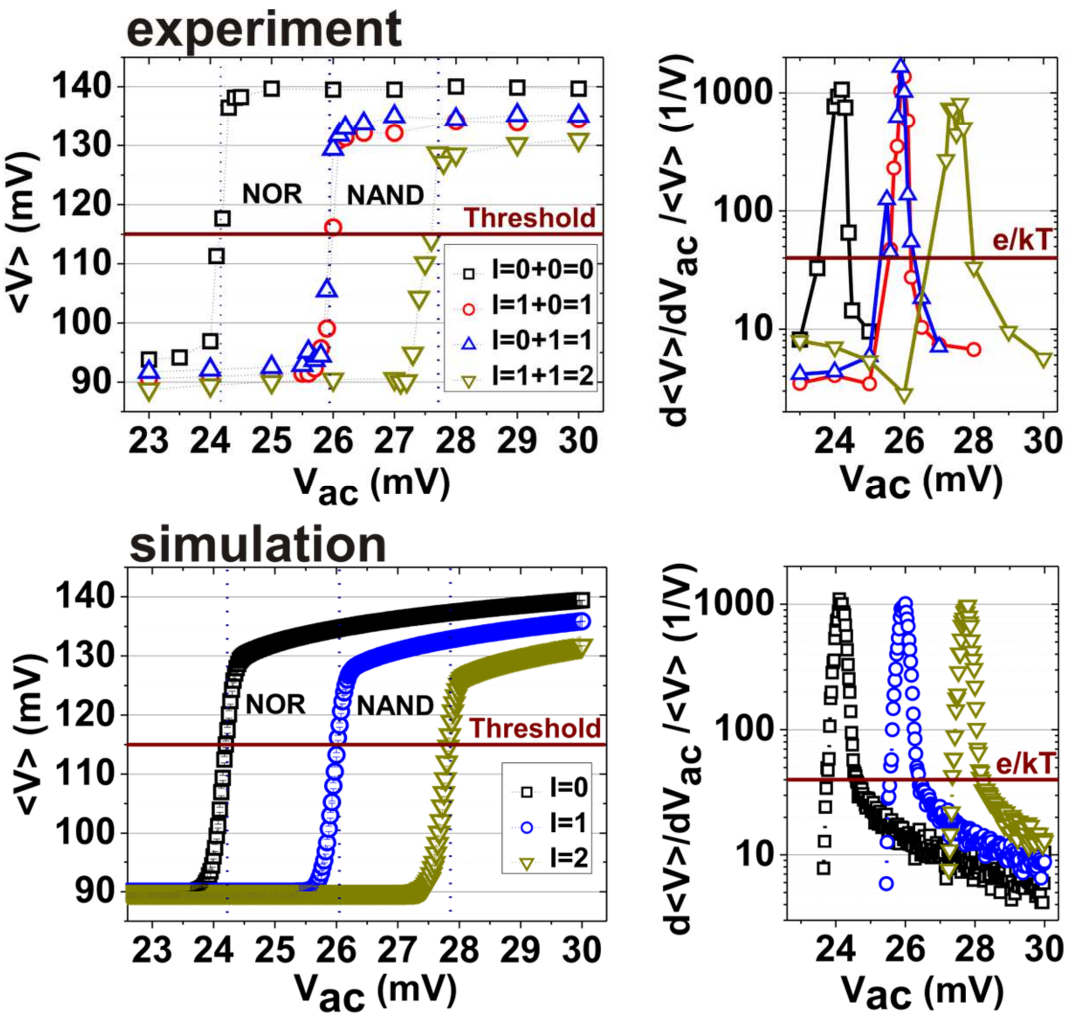
0	0	1
1	0	0
0	1	0
1	1	0

NAND

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

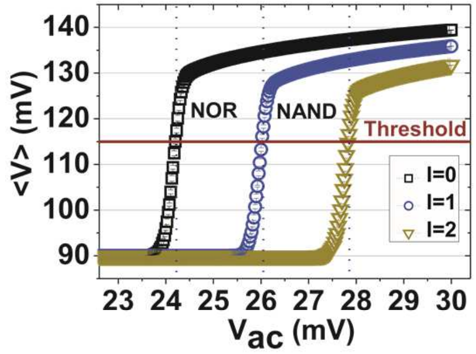
- Switch from NOR to NAND for ΔV_{ac} < 1 mV with a logic input voltage 2 mV.

Reconfigurable logic universal gates: NOR and NAND configurations & ST simulations

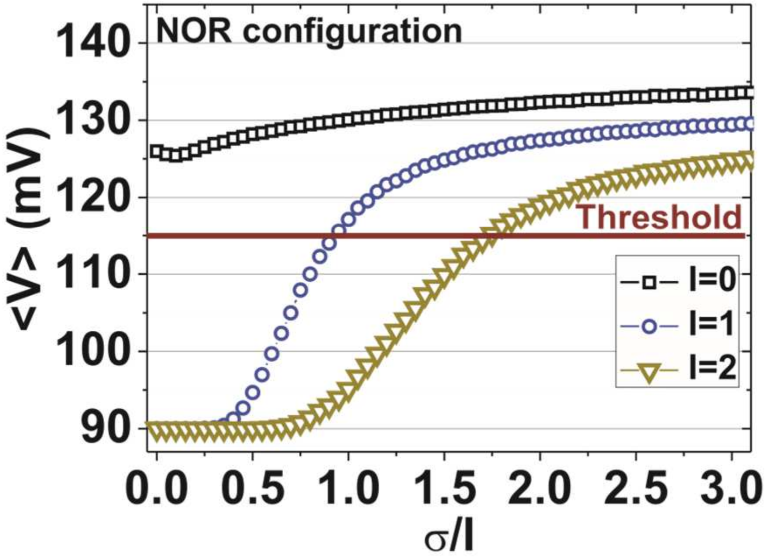


- Schmitt-Trigger simulation.
- All Parameters from the experiment.
- Excellent agreement !!

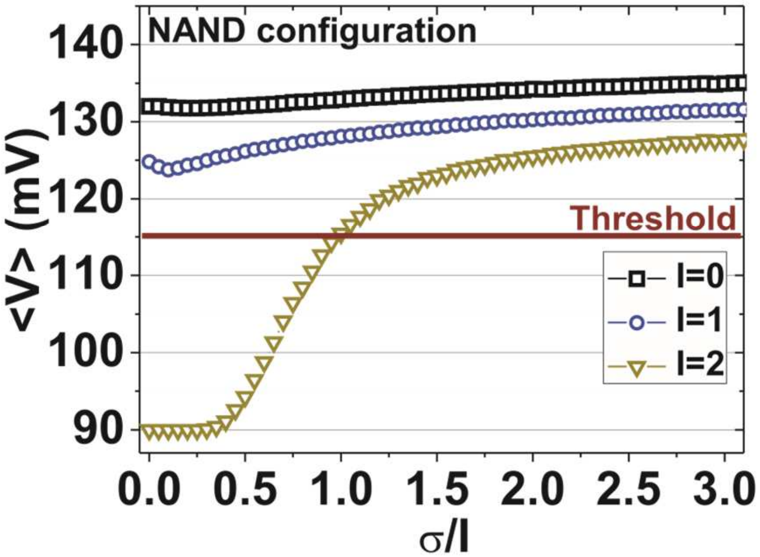
Reconfigurable logic universal gates: NOR/NAND high noise robustness



V_{ac} = 24.6 mV

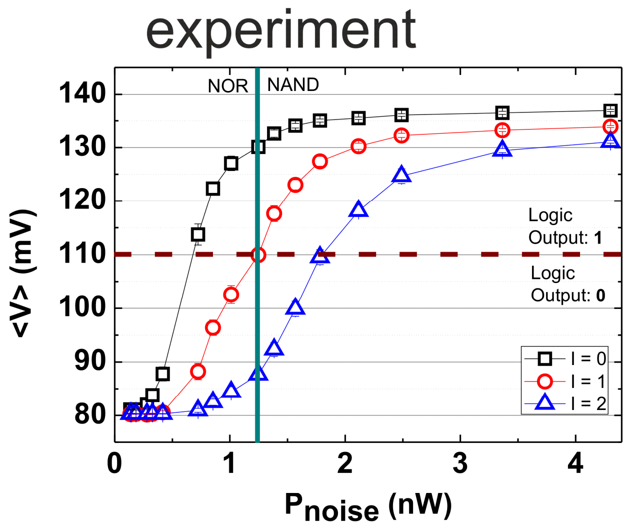


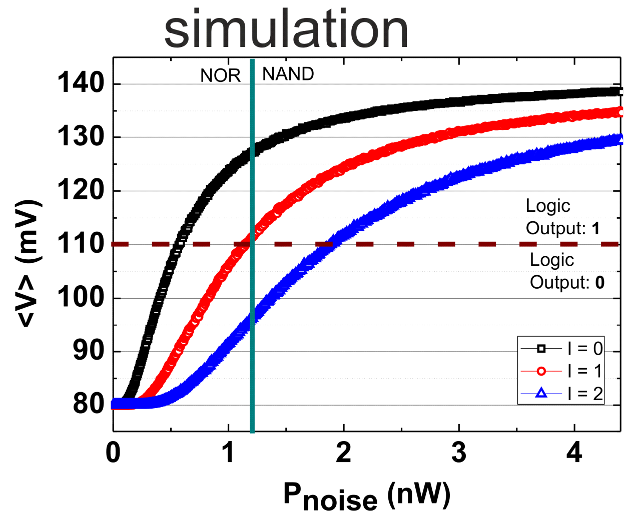
V_{ac} = 26.6 mV



- Robust response to the noise floor up to **100%** of logic input

Reconfigurable logic universal gates: Logic stochastic resonance





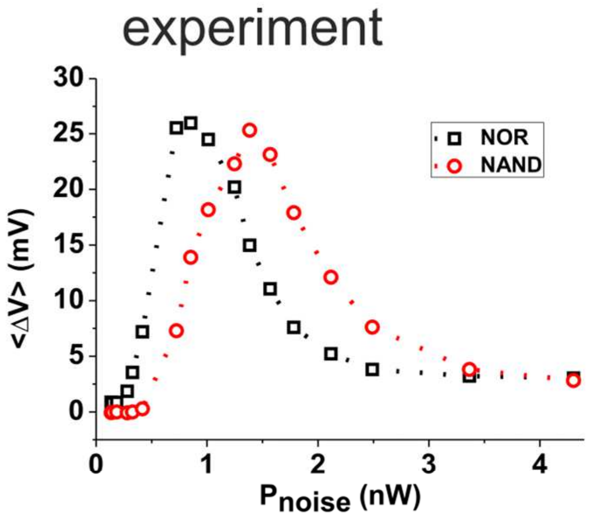
Previous:

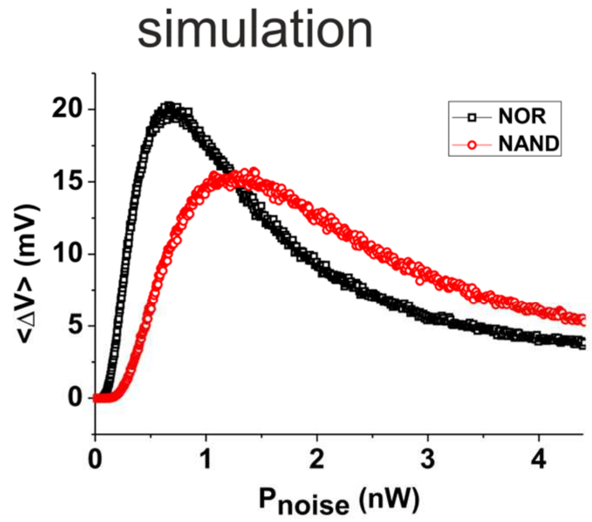
- Universal logic gate switching controlled by the amplitude of the periodic forcing V_{ac}.

Now:

- Universal logic gate switching solely controlled by the noise floor.
- Two universal logic gates: NOR/NAND.

Reconfigurable logic universal gates: Benefit from noise in logic operations


experiment


simulation

For the logic NOR gate:

- The mean value difference is defined as

<V>=V(I=0)−V(I=1)

P_{noise}=0.9 nW the maximum corresponds to the logic NOR

For the logic NAND gate:

- The mean value difference is defined as

<V>=V(I=1)−V(I=2)

P_{noise} = 1.4 nW the maximum corresponds to the logic NAND

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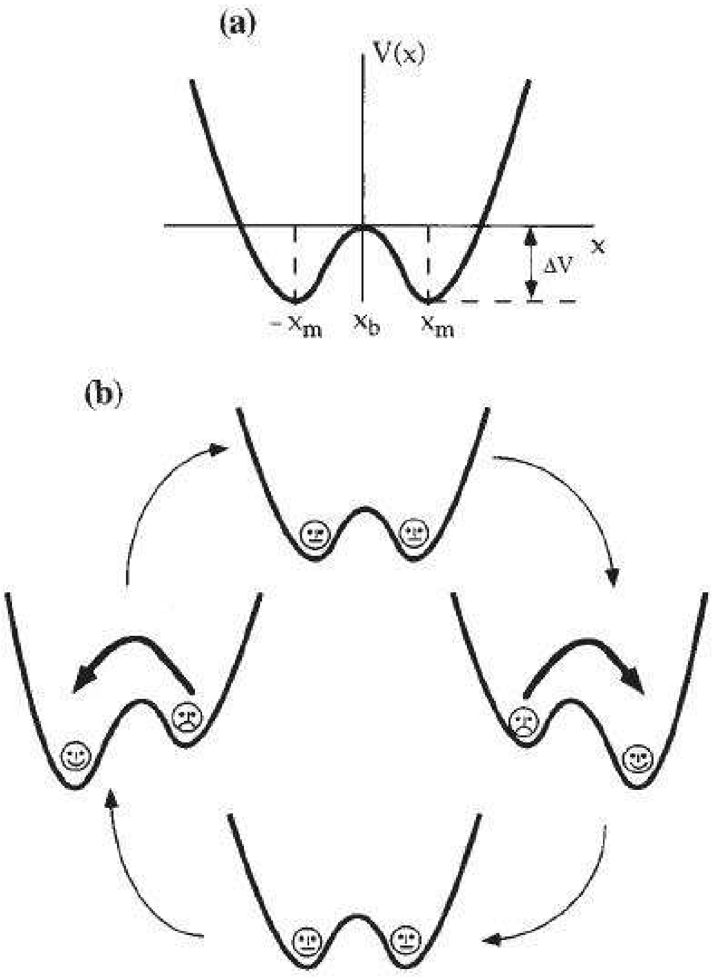
Stochastic resonance : A short introduction



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

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

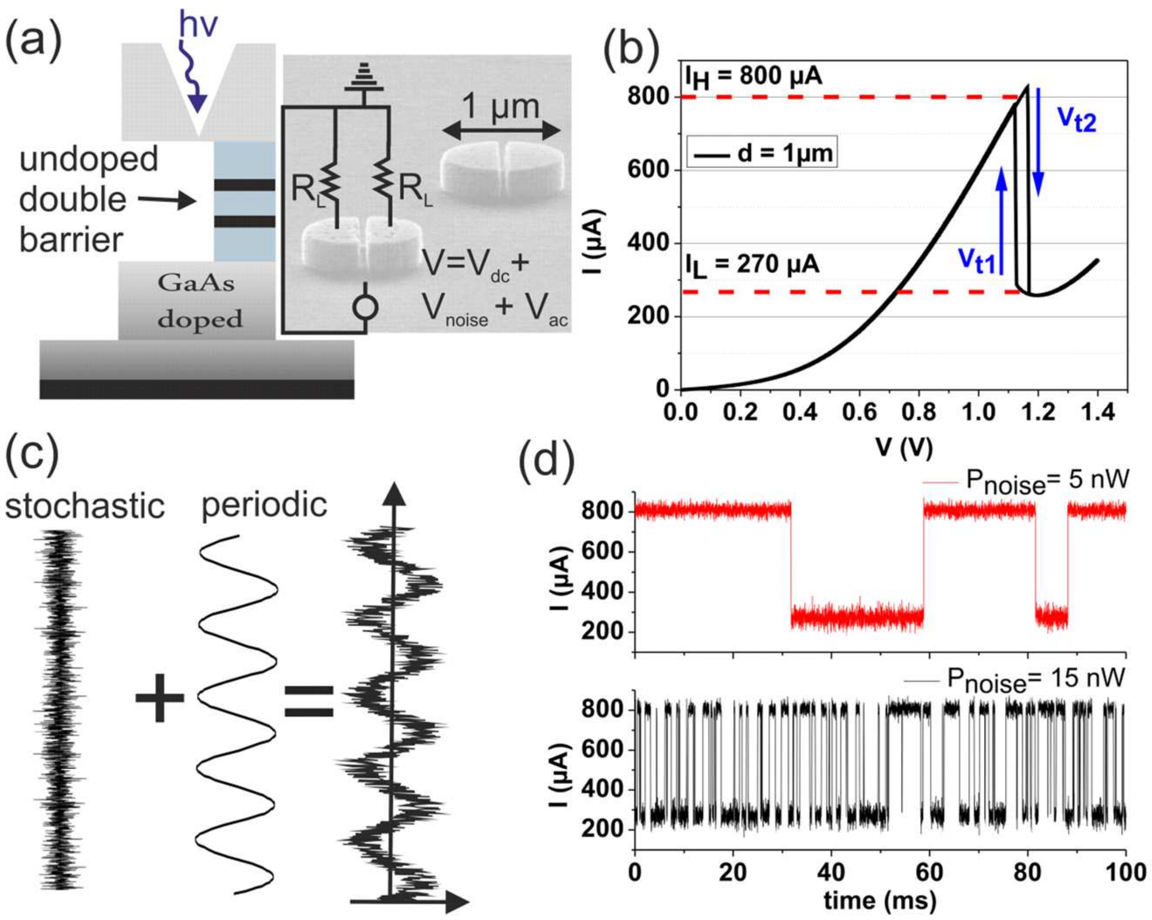
Noise-induced hopping between the local equilibrium states with the Kramers rate

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

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

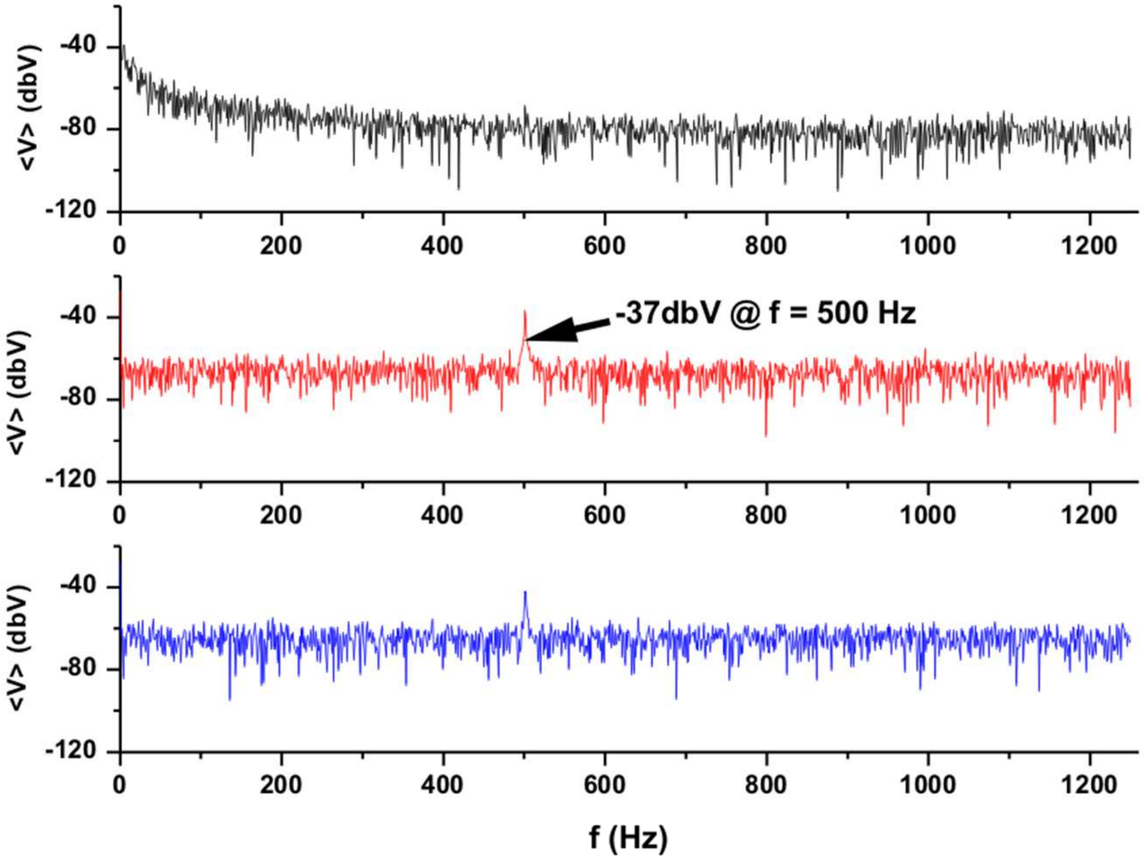
$$T_\omega = 2T_K$$

Stochastic resonance in resonant tunneling diodes: Exploiting noise & nonlinearity



- 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

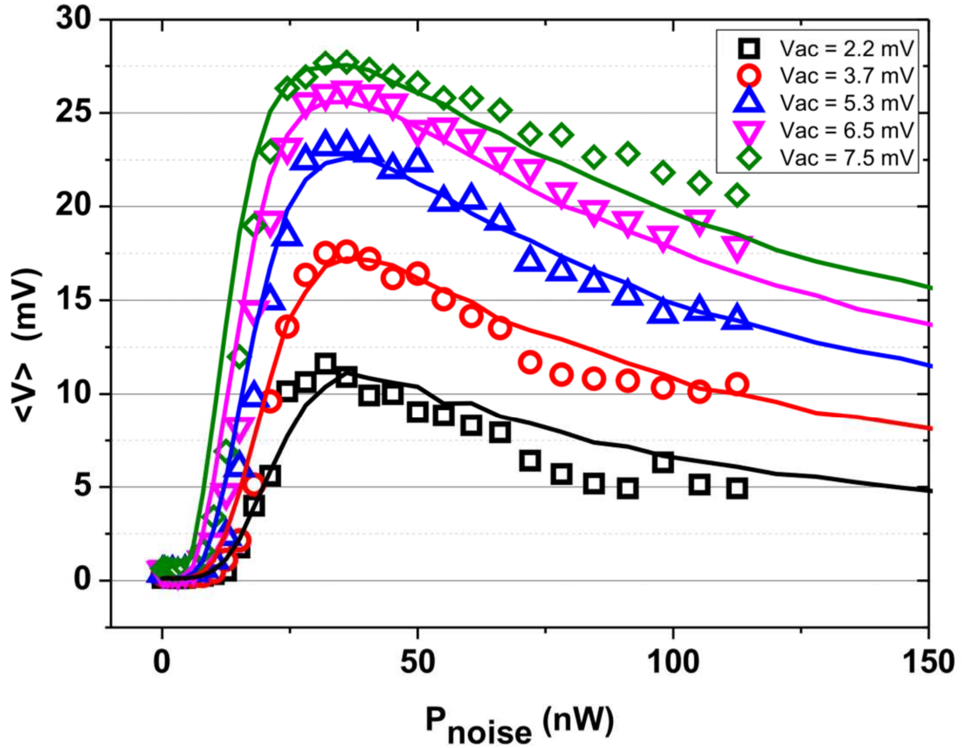


- For $P_{noise} < P_{SR}$ no spectral component at f = 500 Hz is found.

- 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: Ac modulation with a frequency f = 500Hz



- For $P_{noise} < P_{SR}$ the spectral component at f = 500 Hz is increasing.
- Maximum synchronization @ P_{SR} => **SR**.
- For $P_{noise} > P_{SR}$ the spectral component is decreasing again.

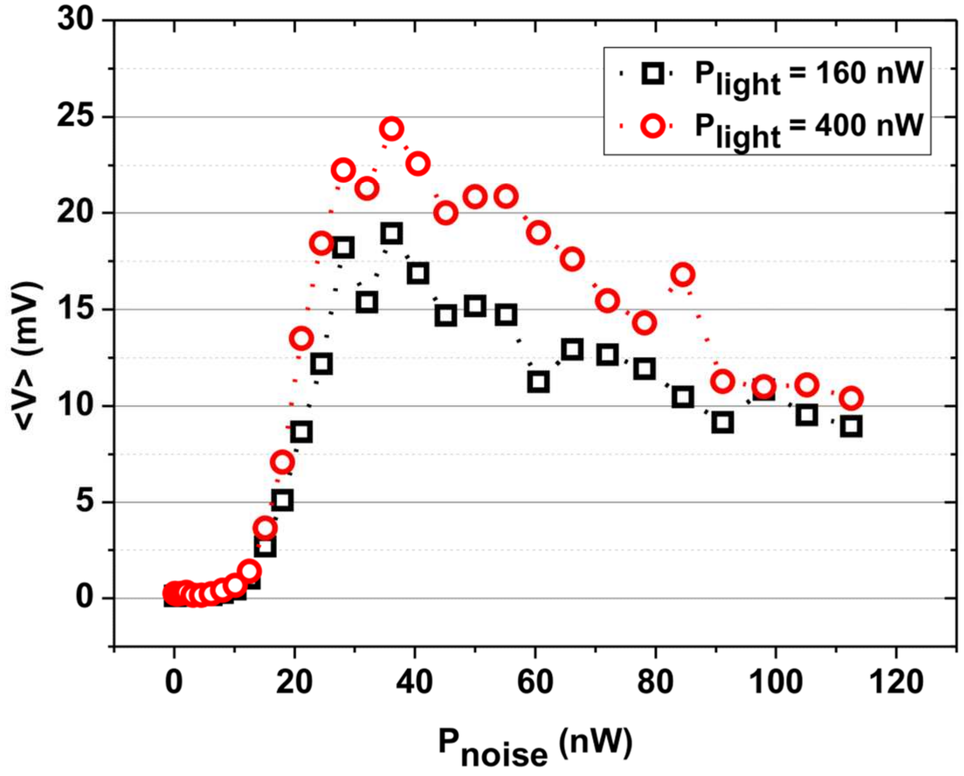
Simulations (solid):

- Ideal two state model (Schmitt Trigger) with parameters from the experiment.
- e.g. the barrier height was set to 16 mV as the hysteresis width of the device was 32 mV.

Stochastic resonance: Periodic optical modulation with a frequency f = 500Hz

Now:

- Change from ac modulation to a periodic light modulation.
- Energy of the light E = 2.73 eV (448nm) above the GaAs bandgap.
- Mechanically chopped light signal at f = 500 Hz.

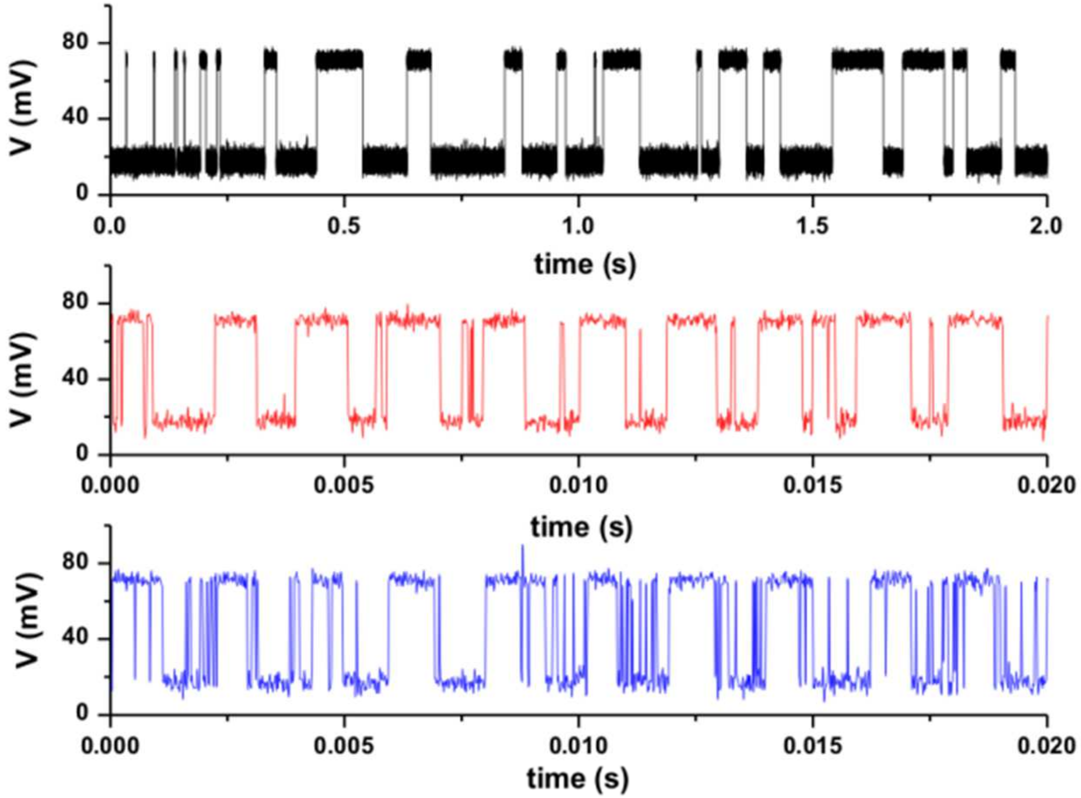


- For $P_{noise} < P_{SR}$ the spectral component at f = 500 Hz is increasing.

- Maximum synchronization @ P_{SR} => **SR**.

- For $P_{noise} > P_{SR}$ the spectral component is decreasing again.

Stochastic resonance: Time trace signals



P_{noise} = 2 nW

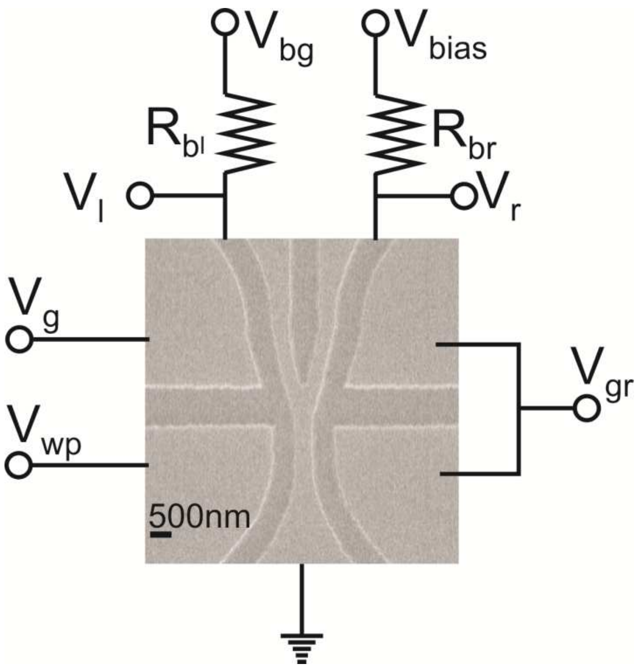
P_{noise} = 32 nW

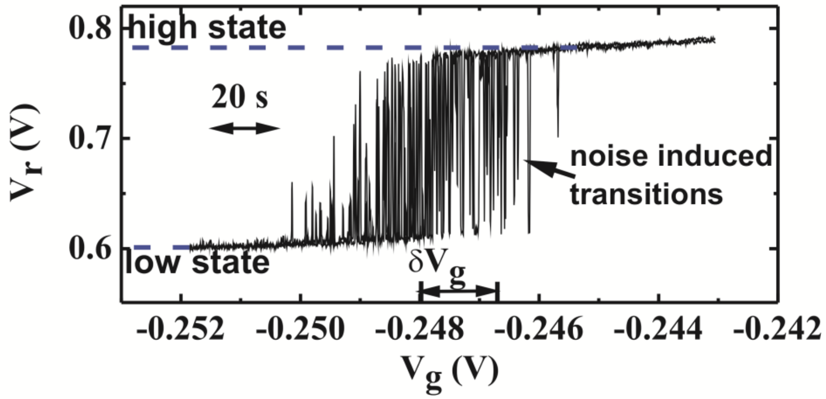
P_{noise} = 112 nW

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

Stochastic resonance in three terminal electron waveguides: Noise activated switching

- 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:

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

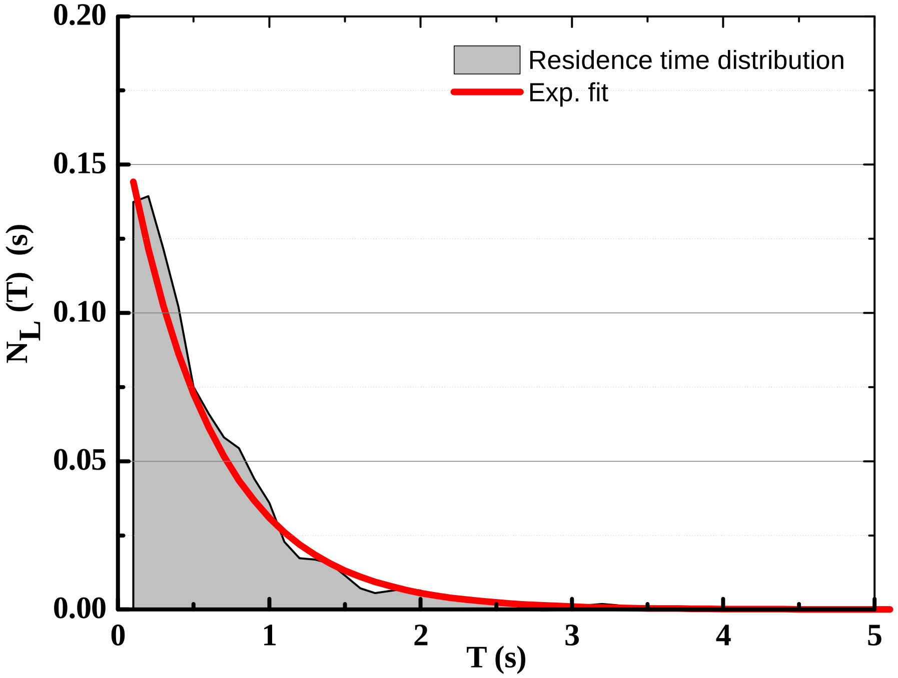
Weak periodic signal:

$$\delta V_g = 1.3mV$$

Stochastic resonance in three terminal electron waveguides: Intrinsic (noise) timescale

- For the unmodulated system, e.g. f = 0 Hz, the residence time distribution decays exponentially.
- The exponential decay is the inverse of the Kramer‘s rate and given by $T_{k:}$

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

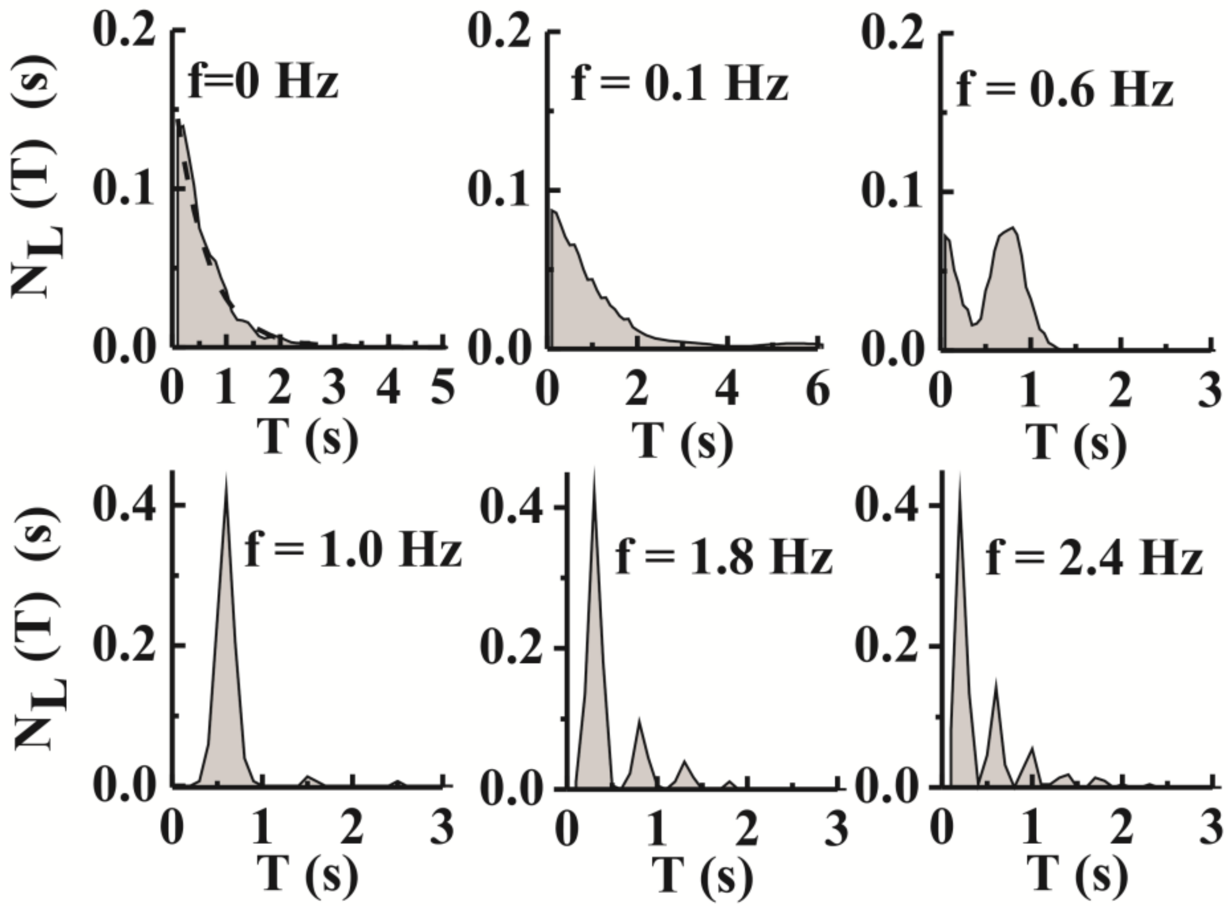


From fitting:

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

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

Stochastic resonance in three terminal electron waveguides: Residence time distributions



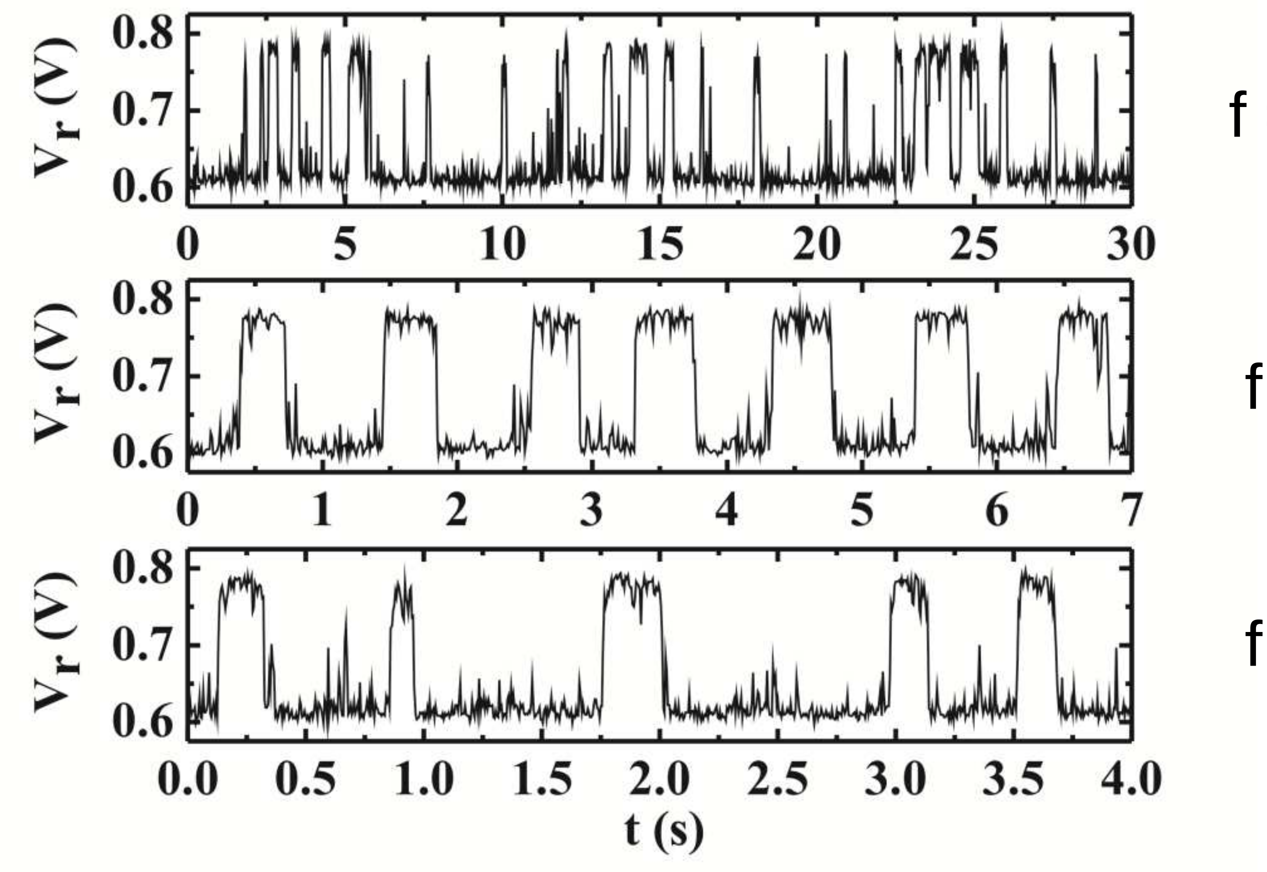
- For f < f_{SR} the residence time distribution is strongly controlled by the noise

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

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

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

Stochastic resonance in three terminal electron waveguides: Time traces



f = 0.1 Hz

f = 1 Hz

f = 1.8 Hz

At f = 1 Hz the noise dynamics and the external (weak) periodic forcing are synchronized => Stochastic resonance.

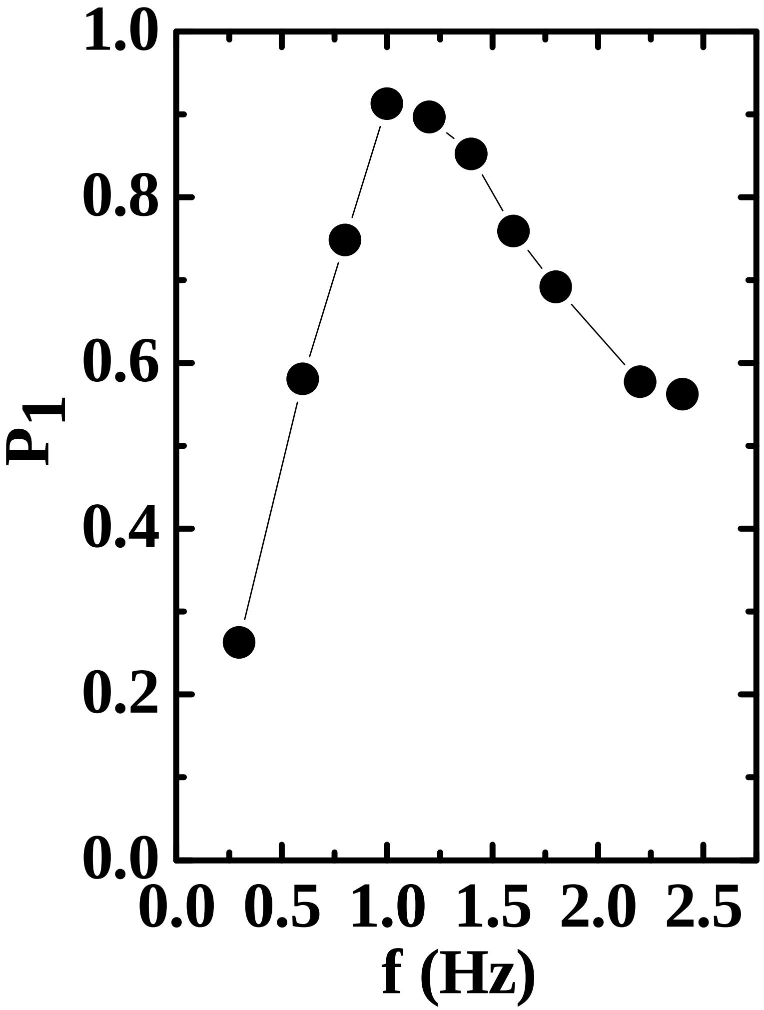
Stochastic resonance in three terminal electron waveguides: Area under the first peak

- The strength P_1 of the first peak at $T_\omega/2$ (the area under the peak) is a measure of the synchronization between the periodic forcing and the switching between the wells.

- P_1 is defined as

$$P_1 = \int_{T_1-\alpha T_\omega}^{T_1+\alpha T_\omega} N_L(T)\,dT$$

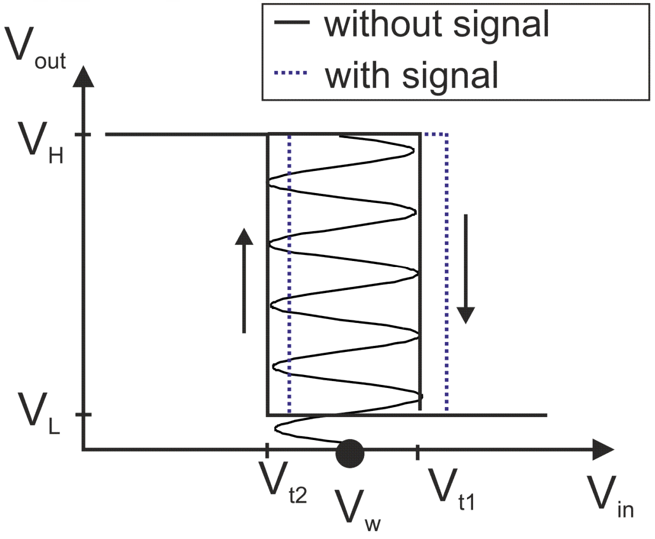
With n=1,2,…
And $0<\alpha=0.2<0.25$

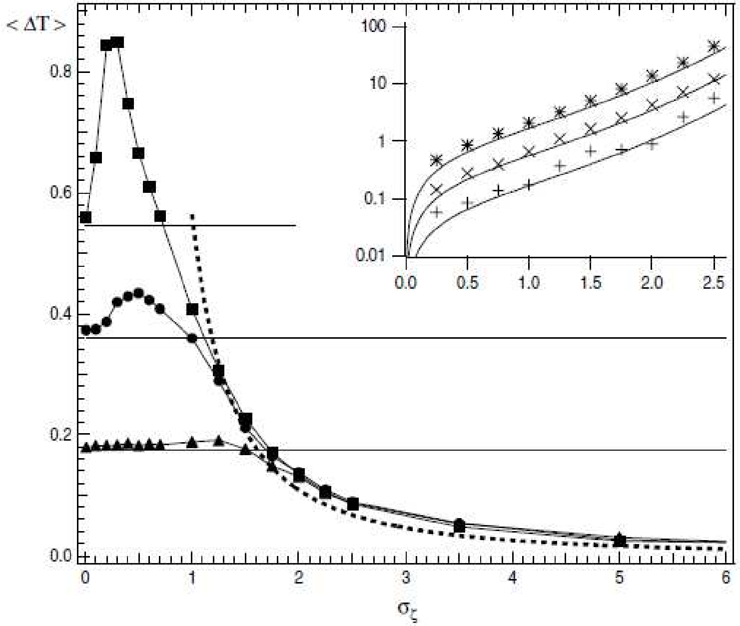


Outline

- **Growth, fabrication and transport properties of nanoelectronic devices**
  - Growth of 2DEGs and fabrication of electron waveguides.
  - Growth and fabrication of resonant tunneling diodes (RTD).
- **Universal logic gate switching in resonant tunneling diodes (RTDs)**
  - Universal logic gate switching => NOR to NAND
  - Logic stochastic resonance (LSR)
- **Stochastic resonance in nanoelectronic devices**
  - SR in electron waveguides
  - SR in RTDs for ac and periodic optical modulation
- **Noise activated nonlinear dynamic sensors**
  - Magnetic field sensor based on (bistable) electron waveguides
- **Energy harvesting: The quantum harvester class**
  - Transport as a consequence of state dependent diffusion.
  - Optimal energy to quanta conversion: A coupled QD system.

Noise Activated Nonlinear Dynamic Sensors (NANDs): A short introduction





The variable of interest is the residence time difference ΔT between the time spend in the two stable states $T_{H,L}$ with

$$\mathbf{\Delta T = T_H - T_L}$$

From: L. Gammaitoni and A.D. Bulsara, „Noise Activated Nonlinear Dynamic Sensors “, PRL **88**, 230601-1 (2002).

The response of $<\Delta T>$ for large noise intensity σ_ξ is (expanded to first order in ε (target signal):

$$\langle \Delta T\rangle = 4\epsilon\sqrt{\pi\tau/\sigma^2}\exp[b^2/2\sigma_\zeta^2]\mathrm{erf}\left(\frac{b}{\sqrt{2\sigma_\zeta^2}}\right) + O(\epsilon^2)$$

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

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

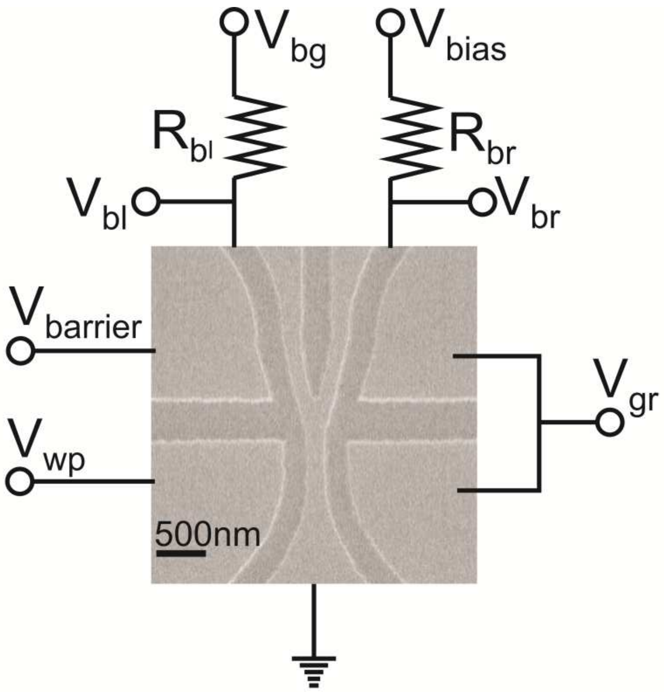
- Switching between V_H and V_L solely controlled by the internal noise.

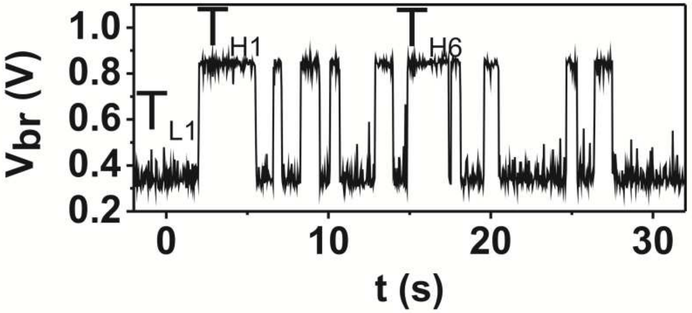
- Magnetic field is applied perpendicular to the motion of electrons.

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

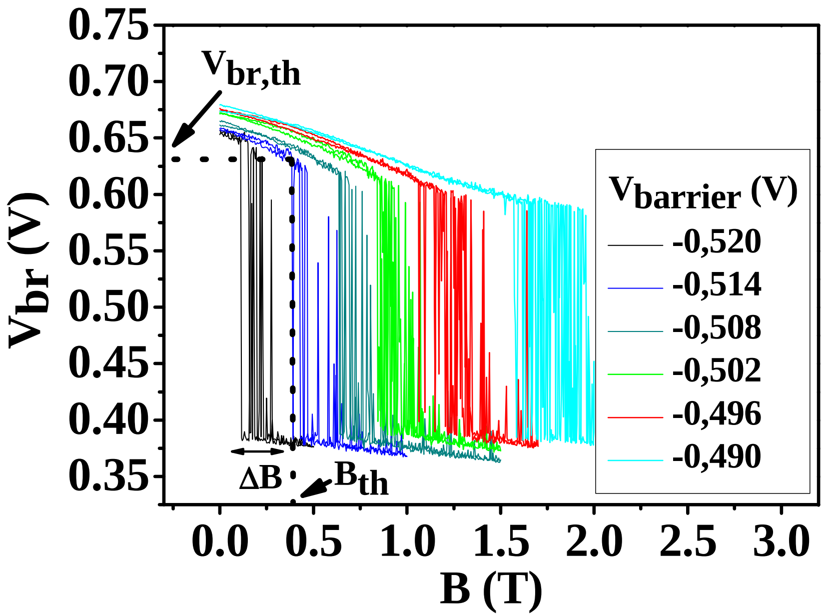
$$T_{H,L} = \frac{1}{n_{H,L}} \sum_{i=1}^{n_{H,L}} T_{H_i,L_i}$$

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





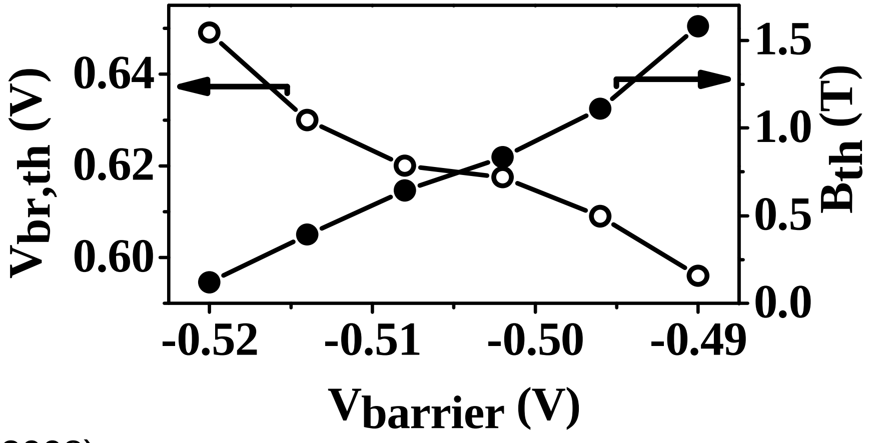
Magnetic field sensors based on the residence time difference in electron waveguides



Increasing magnetic field:

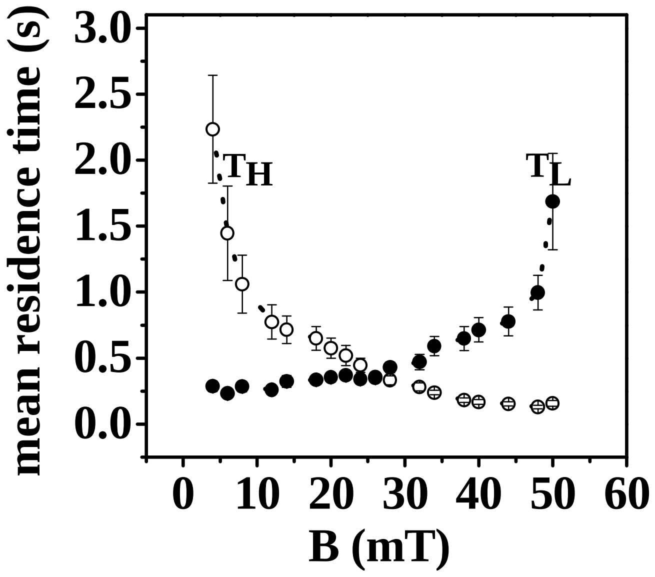
- The output V_{br} decreases linearly down to a magnetic field threshold B_{th}.
- Transitions between the two stable states occur within a magnetic field range ΔB.
- The output V_{br} changed its stable state from $V_{br} = V_H$ to $V_{br} = V_L$.

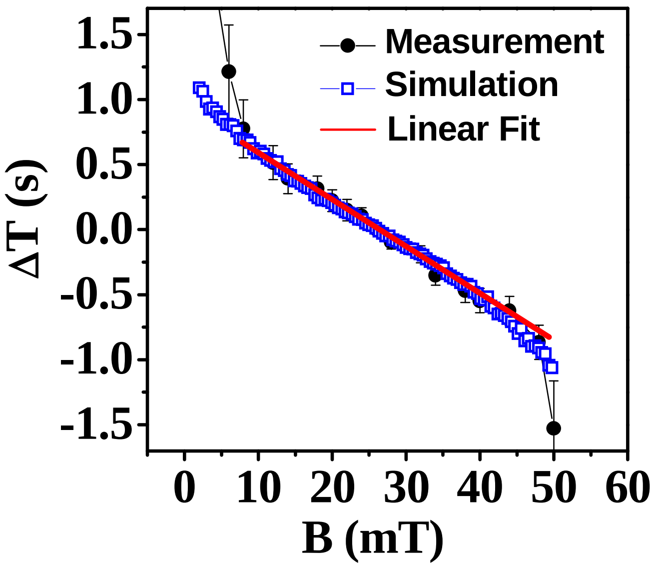
- The magnetic-field induced switching (between V_H and V_L) is associated with an interplay between a scattering asymmetry at the boundaries. [1]



[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.

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

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

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

- Target signal (magnetic field) independent sensitivity.

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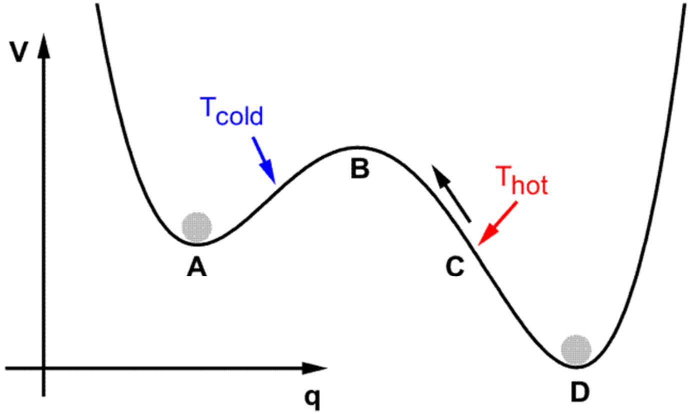
Transport as a consequence of state-dependent diffusion

Diffusion constants:

$$D = \mu\, kT_H\,,\quad q\, in\, H$$

$$D = \mu\, kT_L\,,\quad q\, in\, L$$



- 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

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

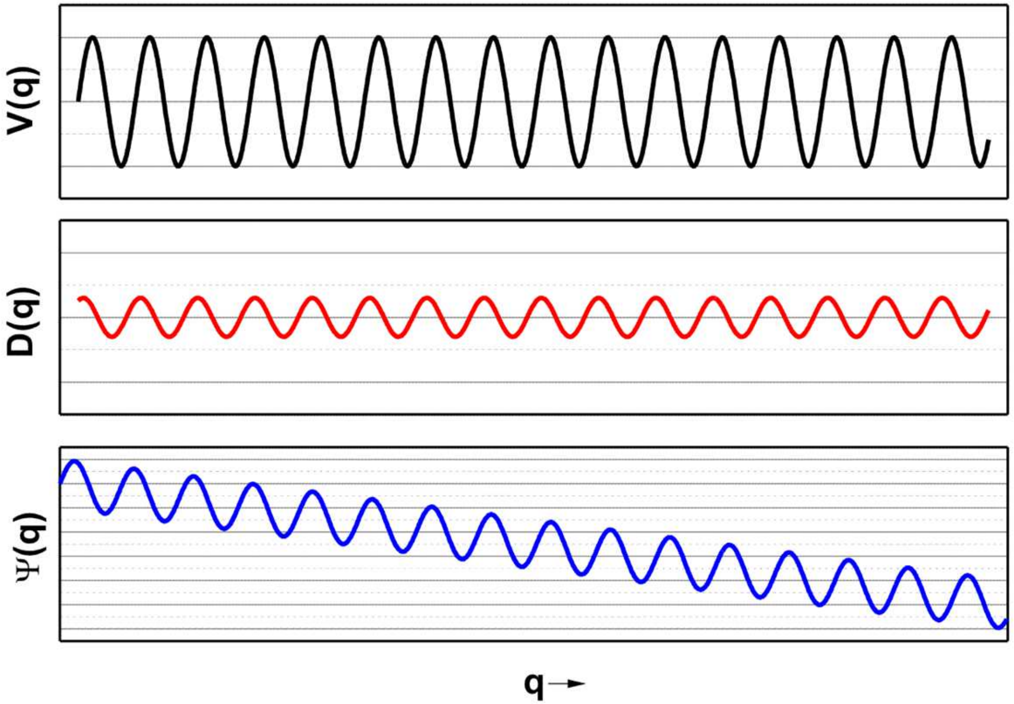
M. Büttiker, Z. Phys. B **68**, 161 (1987).
R. Landauer, J. Stat. Phys. **53**, 233 (1988).

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



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

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

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

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

$$D_0 = \mu kT$$

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

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

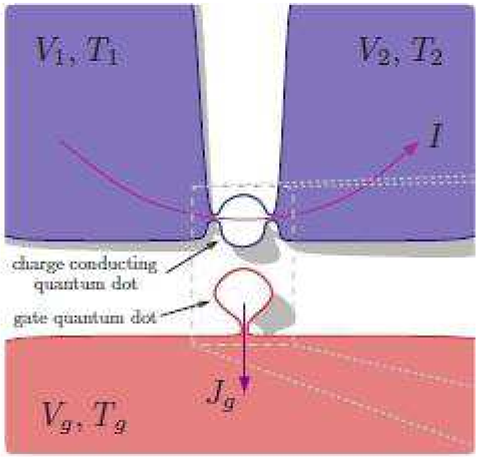
With: $\Delta = \frac{\mu V_0}{D_0}\frac{\alpha}{2}\sin(\phi)$

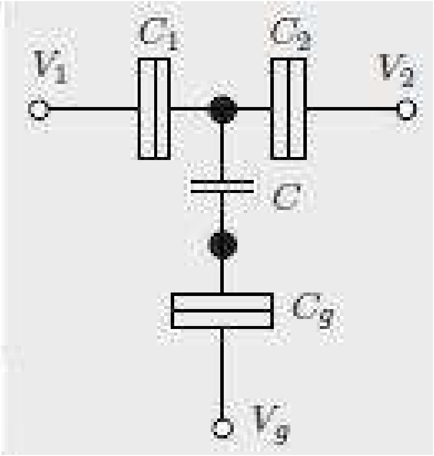
M. Büttiker, Z. Phys. B **68**, 161 (1987).
Ya. M. Blanter and M. Büttiker, Phys. Rev. Lett. **81**, 4040-4044 (1998).

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

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

Energy harvesting in nanoelectronic devices: Optimal energy quanta to current conversion

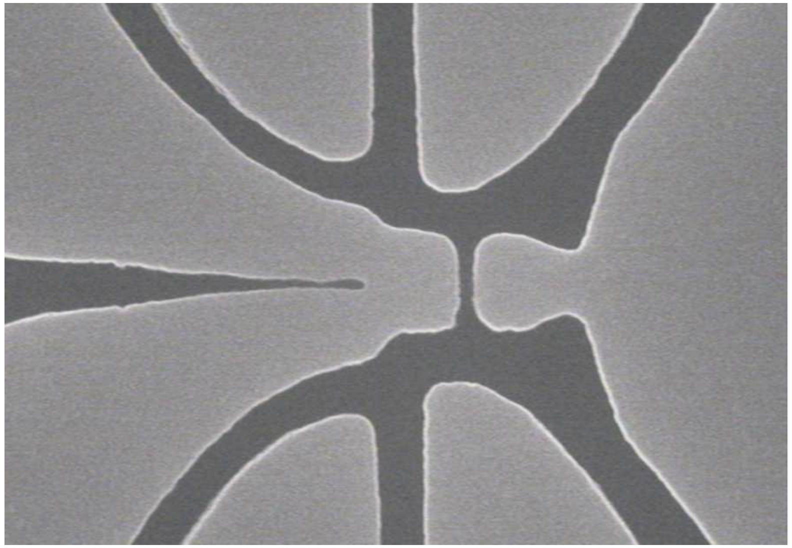


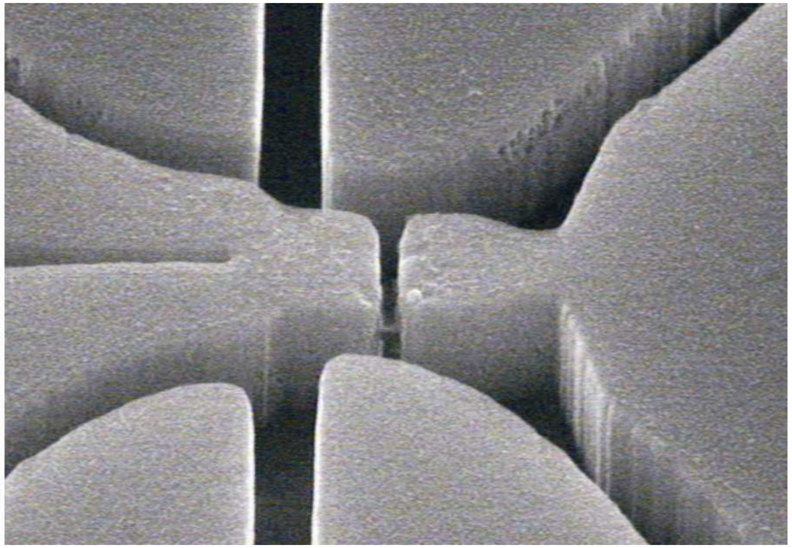


Proposed by R. Sanchez and M. Büttiker, PRB **83**, 085428 (2011).

$$\frac{I}{q} = \frac{J_g}{E_C}$$

Every energy quantum of heat flow gets converted into a quantum of charge flow





Summary

- **Growth, fabrication and transport properties of nanoelectronic devices**
  - Samples are based on GaAs/AlAs and grown by molecular beam epitaxy
  - Dry and wet chemical etching is used to define the structures
- **Universal logic gate switching in resonant tunneling diodes (RTDs)**
  - Two universal logic gates => NOR to NAND for $\Delta V_{ac} \sim 0.1$ mV
  - Logic stochastic resonance (LSR) with P_{noise} ~nW
- **Stochastic resonance in nanoelectronic devices**
  - SR @ f= 1Hz in electron waveguides: Tuning the periodic forcing
  - SR @ f = 500Hz in RTDs for ac and periodic optical modulation: $P_{light} = 160$nW
- **Noise activated nonlinear dynamic sensors**
  - Magnetic field sensor based on (bistable) electron waveguides
- **Energy harvesting: The quantum harvester class**
  - Transport as a consequence of state dependent diffusion.
  - Optimal energy to quanta conversion: A coupled QD system.

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- www.nanopwr.eu

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Many thanks for your attention!