Noise induced and enhanced signal processing in nanoelectronics

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Motivation: From the macro-scale…

- **Stochastic resonance: Weak signals can be enhanced by fluctuations**
- **Ingredients:**
  - **Noise**
  - **Subthreshold 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**

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Abrupt Glacial Climate Changes due to Stochastic Resonance

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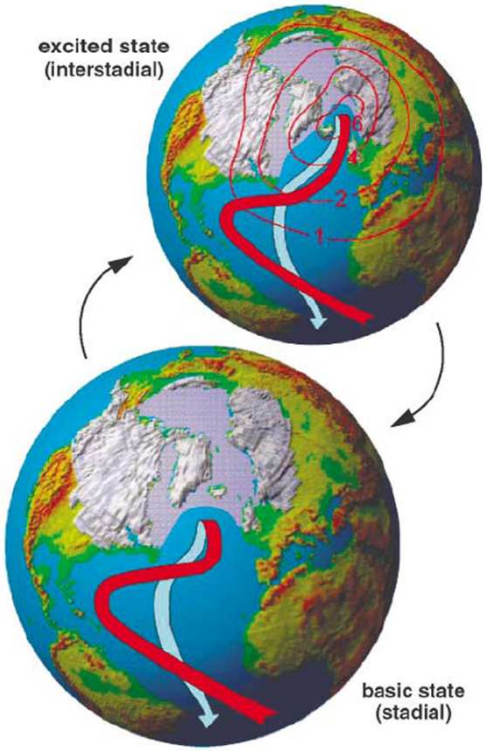
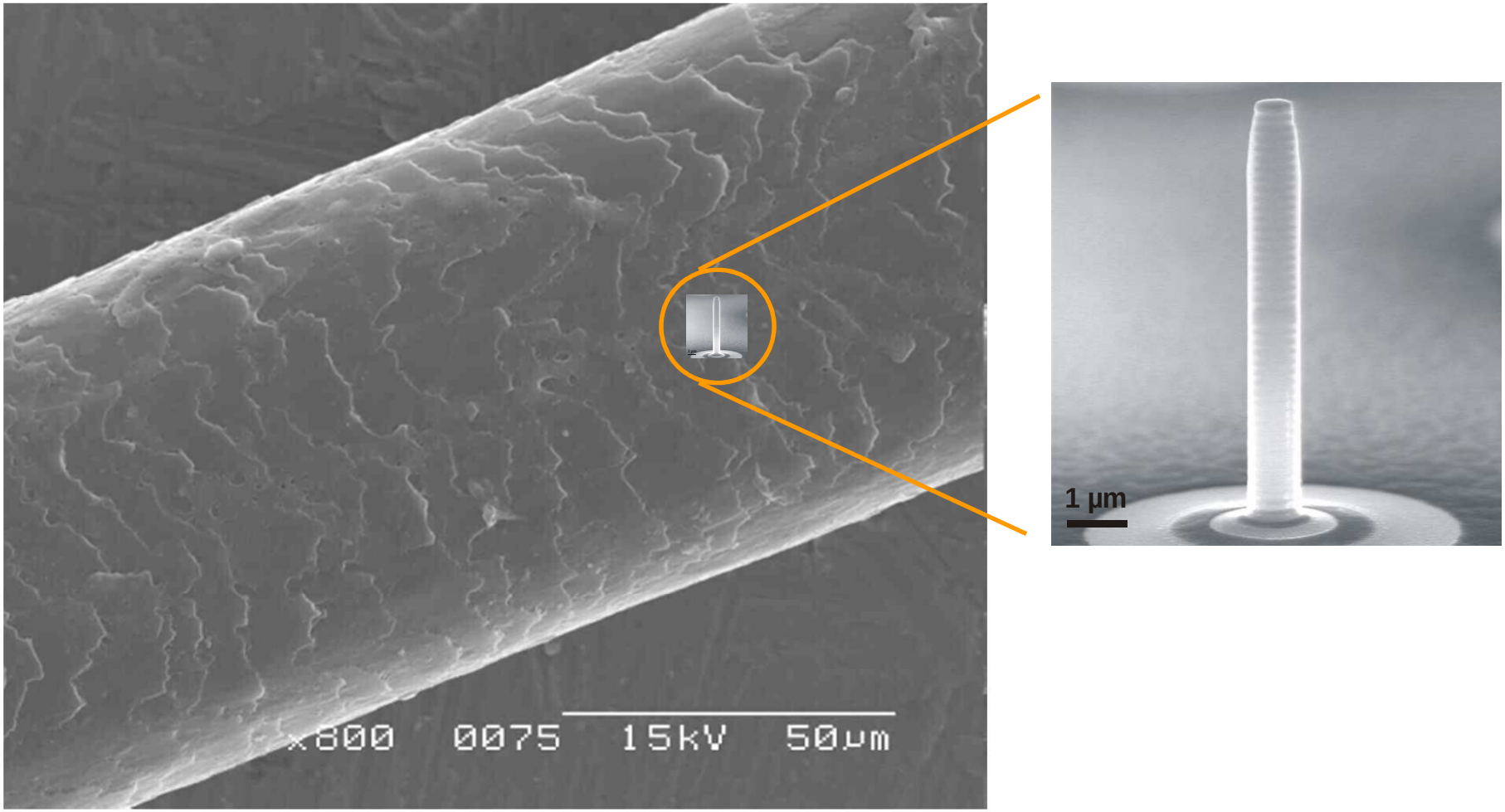


… down to the micro and nano-scale

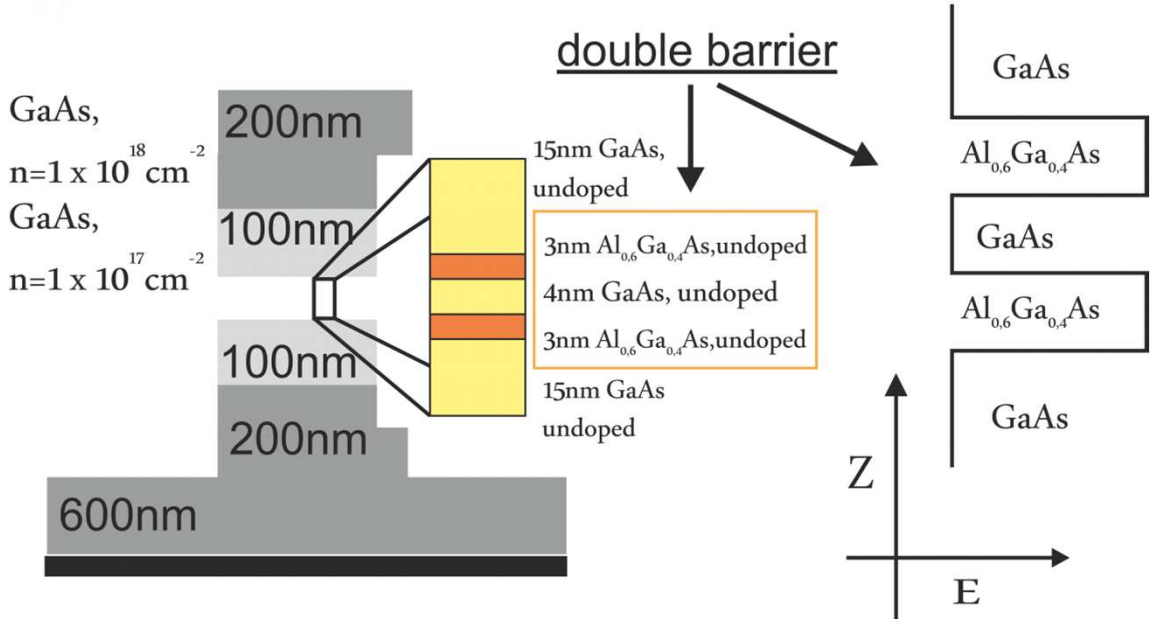
Electron microscope images of a human hair and micro-pillar fabricated @ our department



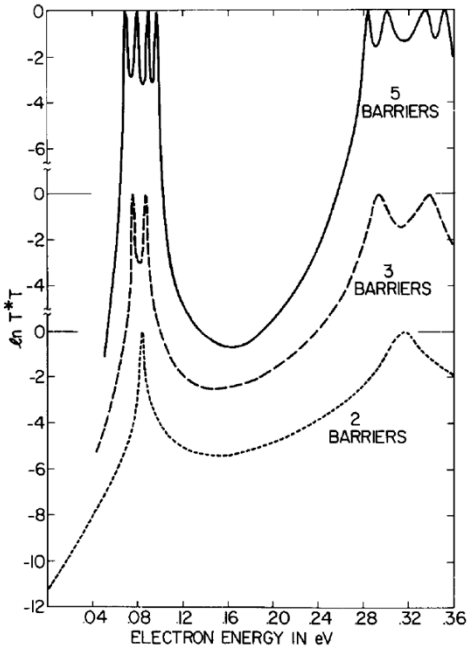
Outline

- Technology & working principle
  - Resonant tunneling diode
  - Negative differential conductance & bistability
  - Noise induced switching
- Stochastic Resonance
  - Starting: From AC modulation
  - To: Periodic light illumination
- Logic stochastic resonance (LSR)
  - NOR & NAND gates
  - Noise enhanced functioning

RTD: Fabrication

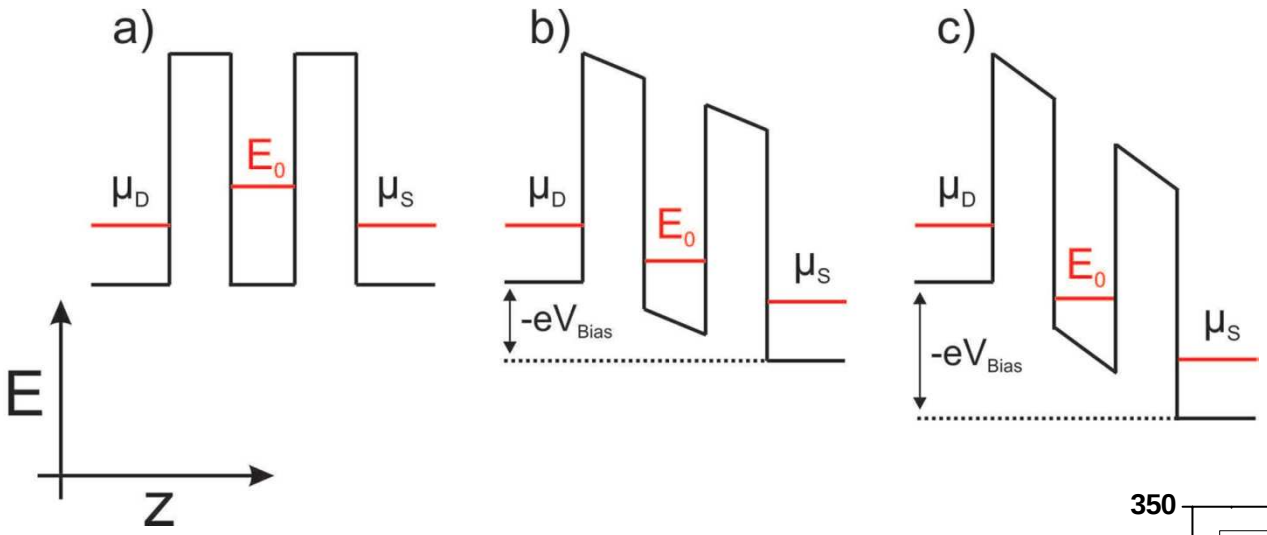


- RTDs AlGaAs/GaAs/AlGaAs DBS
- Dry chemical etching to define mesa from 1 µm down to 50 nm
- BCB (polymer) for mesa isolation
- Top Au/Ti/Ni contact

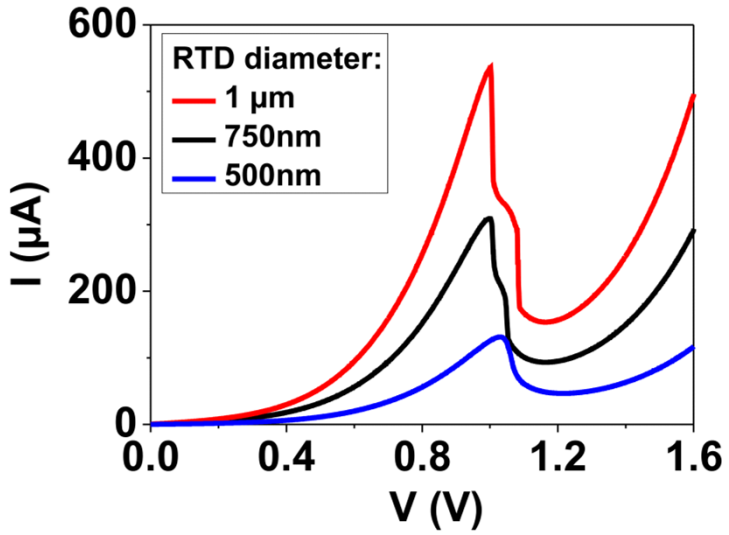


Esaki, L. and Tsu, R.: Tunneling in a Finite Supperlattice, Appl. Phys. Lett. Vol. 22 562 (1973).

RTD: Working principle

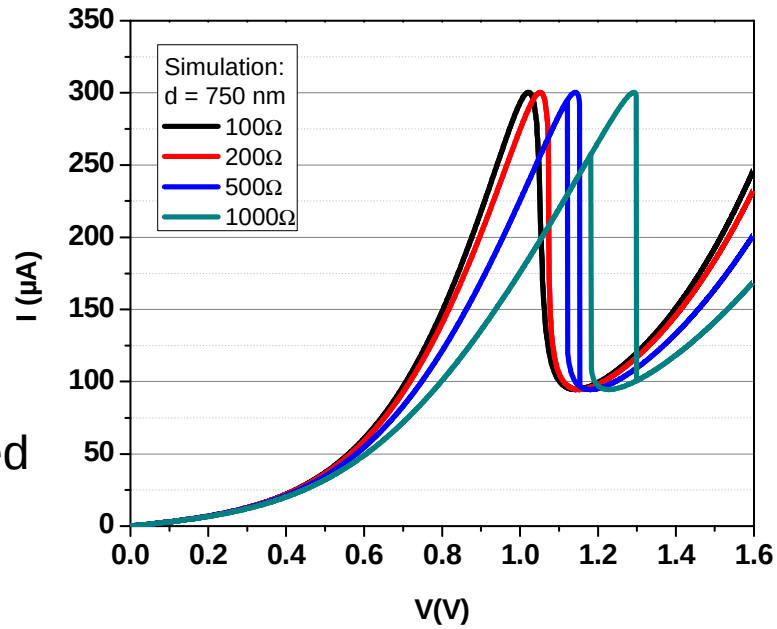


- Increasing bias from a) to c)
- No current in a)
- Resonance condition in b)
- Out of resonance in c)

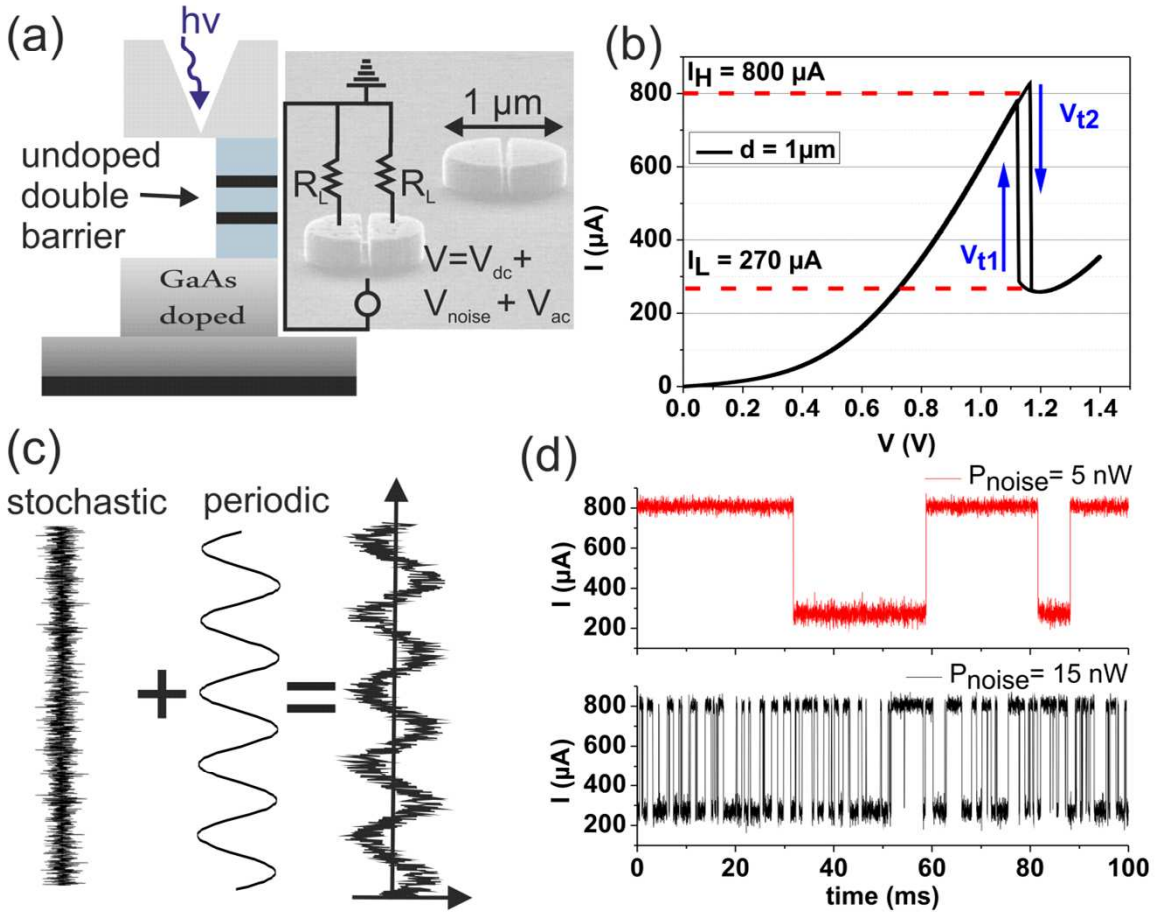


Simulations

Load induced bistability

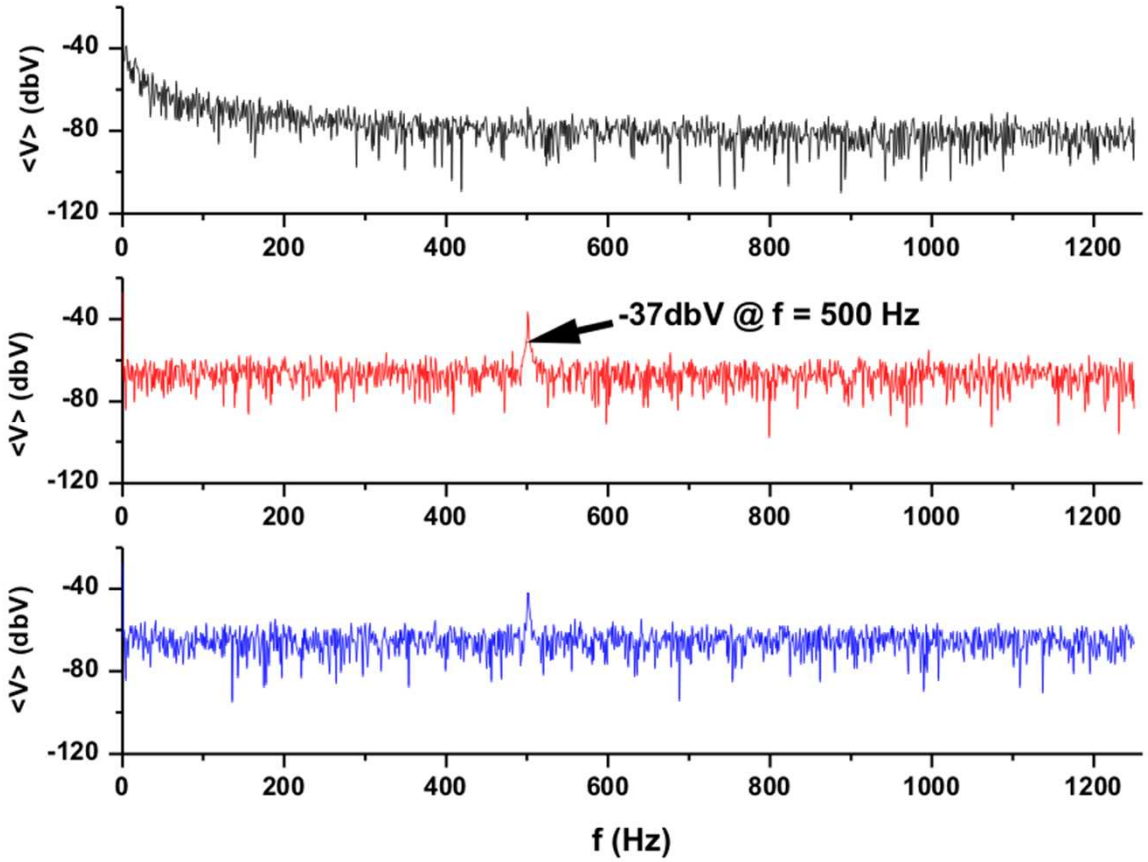


SR in Resonant Tunneling diodes



- RTD is bistable with stable outputs I_H = 800 µA and I_L = 270 µA
- Works @ RT
- PVR ~ 3
- Noise induced switches from one stable state appear
- Time scale is given by the inverse of the Kramer‘s rate

SR recording: Spectral amplitude

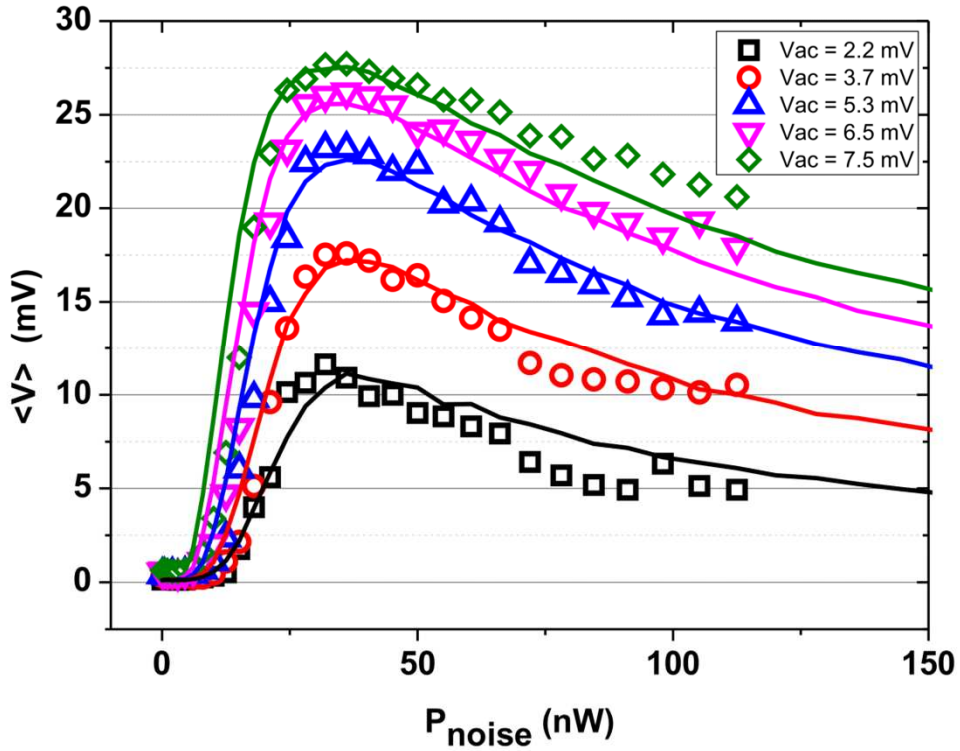


- For $P_{noise} < P_{SR}$ no spectral component at f = 500 Hz is found.

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

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

SR: Under ac drive



- 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.

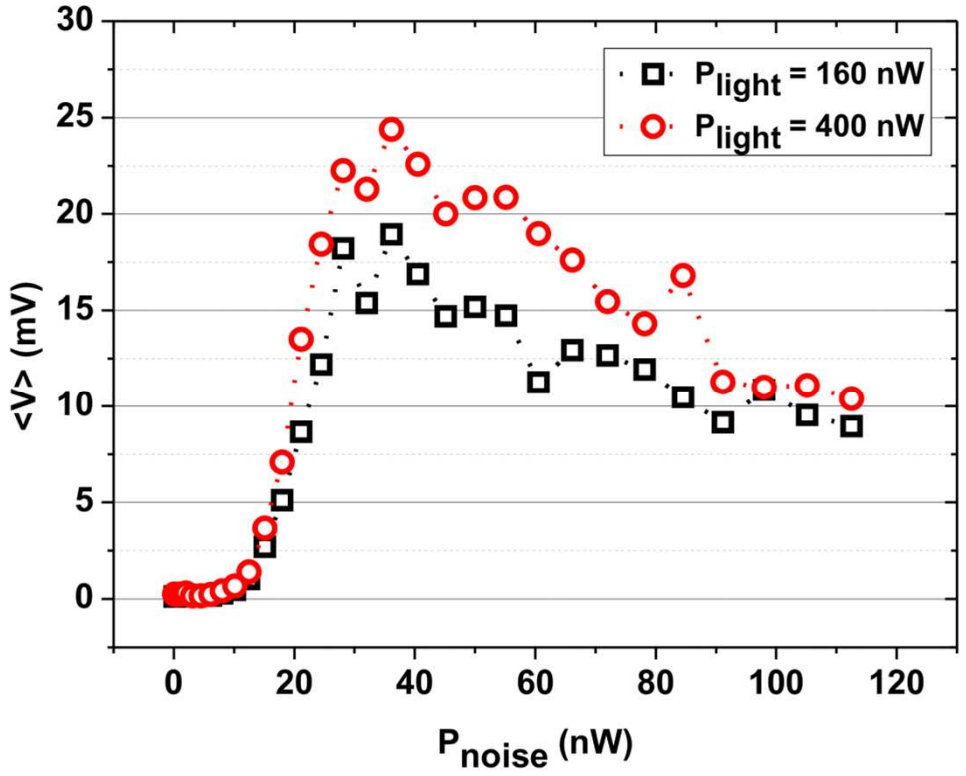
Simulations (solid):

- Ideal two state modell (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

SR: Under periodic light modulation

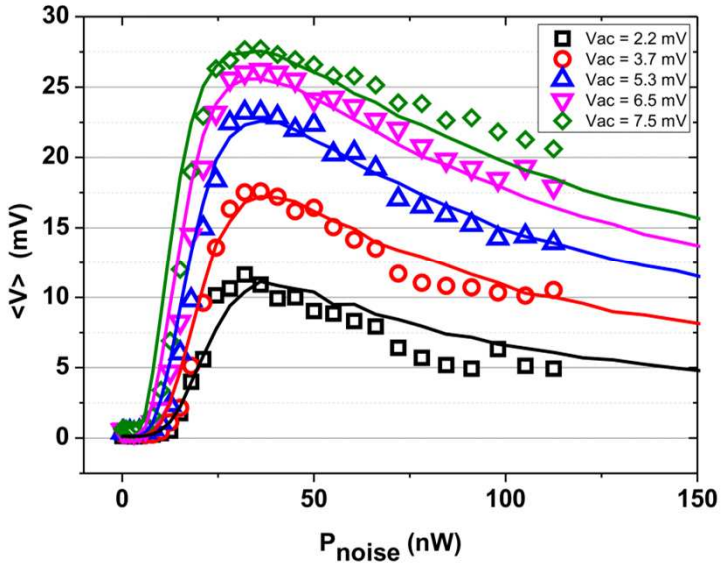
Now:

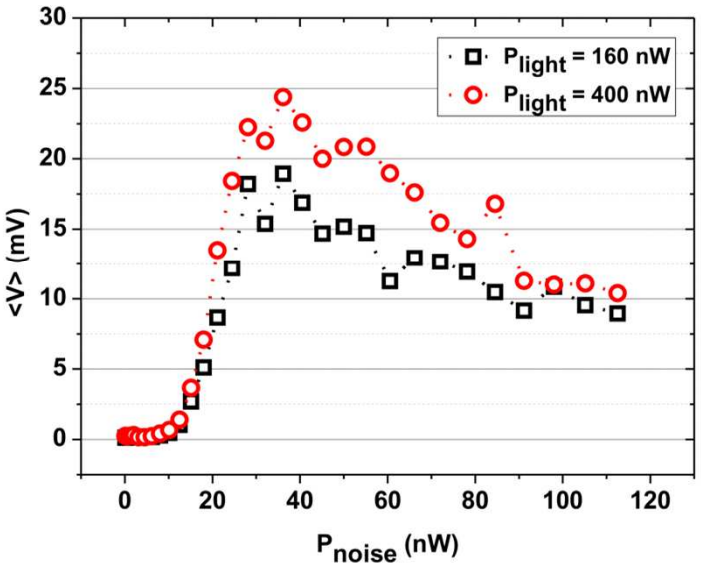
- Change from ac modulation to a periodic light modulation
- Energy of the light E = 2.73 eV (448nm) above the GaAs bandgap
- Mechanically chopped at 500 Hz



- 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.

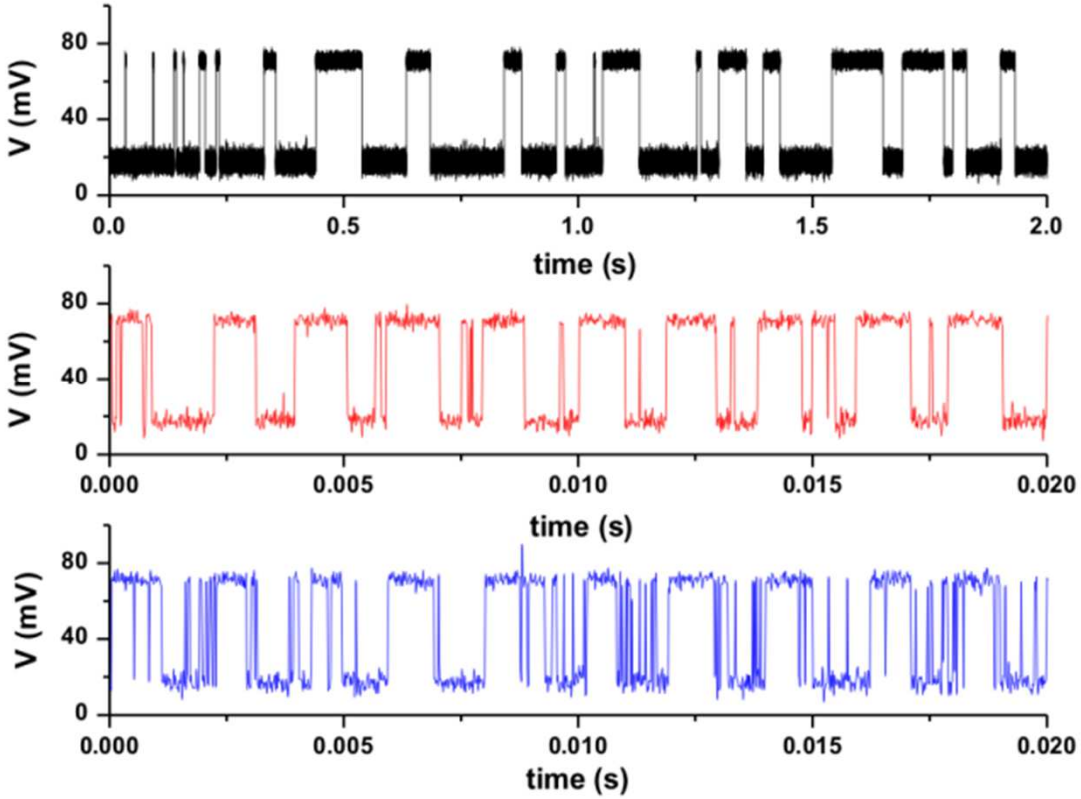
SR: Comparsion ac versus light modulation





- At P_{noise} = 32 nW the output follows almost perfectly the input signal !!
- SR for either peridoic ac modulation or periodic light modulation

SR: Time traces



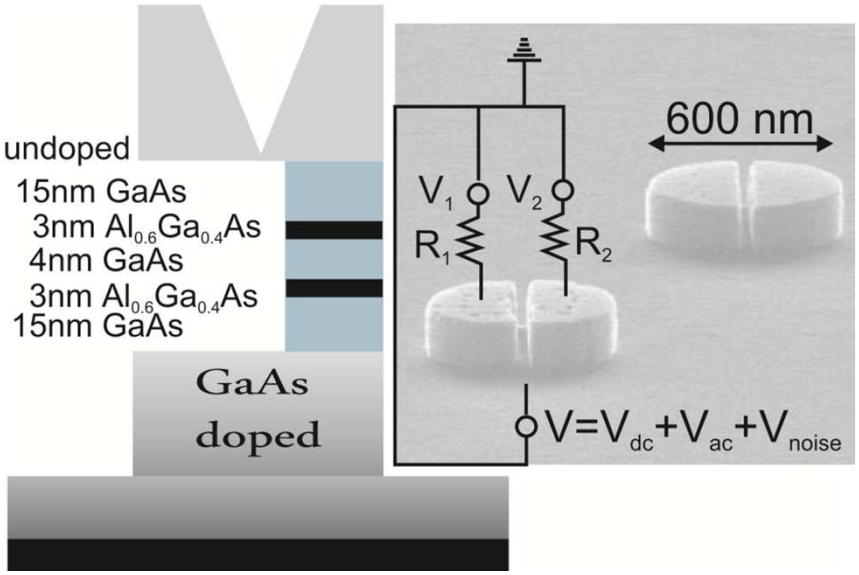
P_{noise} = 2 nW

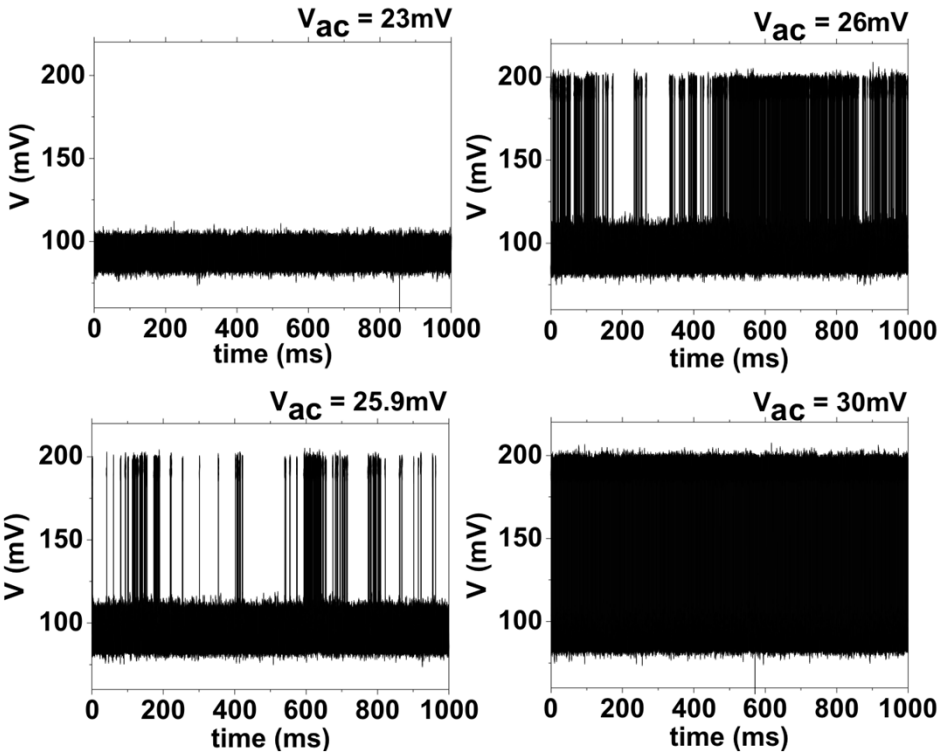
P_{noise} = 32 nW

P_{noise} = 112 nW

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

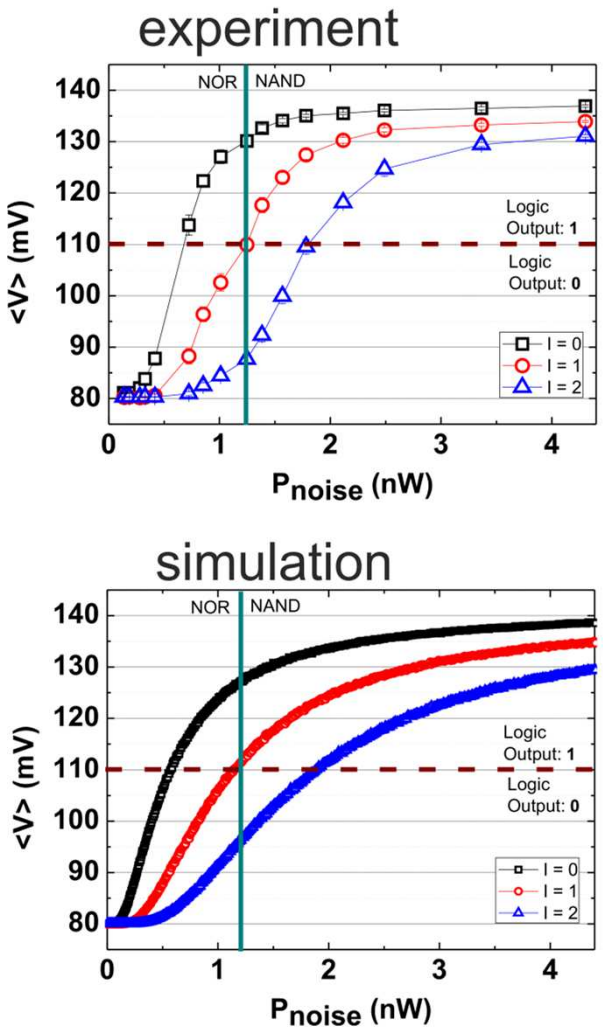
Logic Stochastic Resonance (LSR)





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

Logic Stochastic Resonance



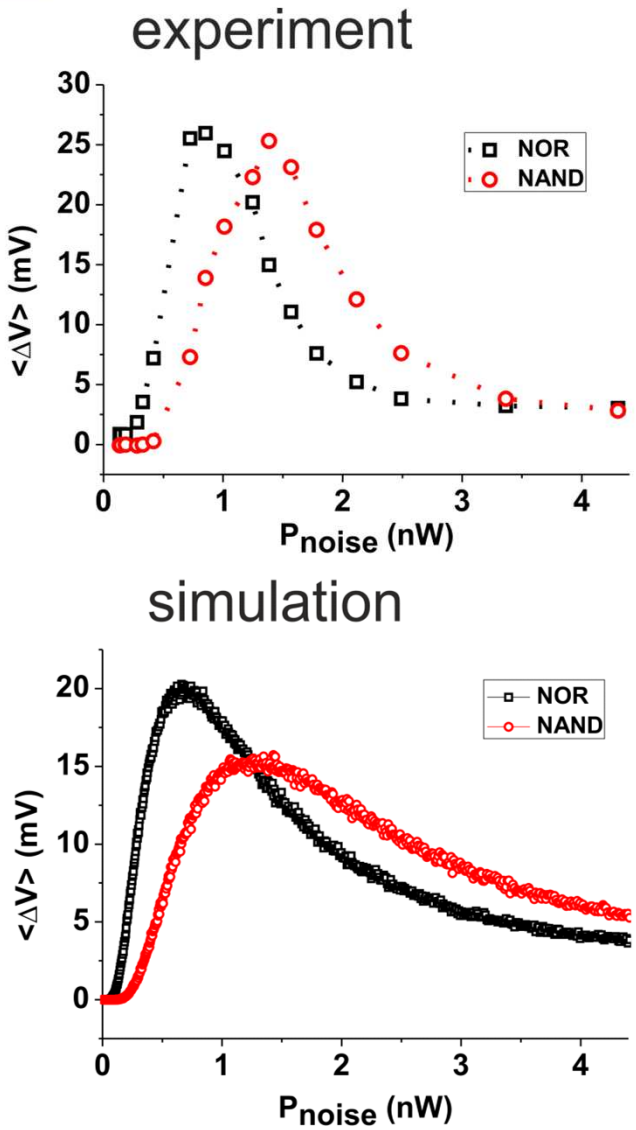
Parameters:

- Logic inputs: $V_{1,2}$ = 0 (2) mV
- $I = I_1 + I_2 = 0 + 0 = 0$
- $I = 0 + 1 = 1 + 0 = 1$
- $I = 1 + 1 = 2$
- Vac was set to 76.8 mV with a frequency of 1 kHz.

Two universal logic gates:

- NOR/NAND
- Noise induced logic gate switching
- Simulations agree with experiment

Logic Stochastic Resonance



- It is useful to describe the probability to obtain for the logic gates by the differences

NOR:

$\langle \Delta V \rangle = \langle V(I=0) \rangle - \langle V(I=1) \rangle$

NAND:

$\langle \Delta V \rangle = \langle V(I=1) \rangle - \langle V(I=2) \rangle$

- Two maxima occur:

For the NOR gate operation:

P_{noise}=0.9 nW

And for the NAND gate operation:

P_{noise} =1.4 nW

Summary

- **Stochastic resonance in RTDs**
  - RTDs are bistable devices even @ RT
  - SR for weak ac forcing with f = 500 Hz @ Pnoise = 32 nW
  - SR for weak periodic illumination with f = 500 Hz @ Pnoise = 32 nW
- **Logic stochastic resonance**
  - Logic NOR & NAND gate with switching voltages $V_{1,2}$ = 0(2)mV
  - LSR for both gates @ noise powers ~nW

Acknowledgment

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- www.nanopwr.eu

NANOPOWER

Many thanks for your attention!