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

F. Hartmann¹, D. Hartmann¹, P. Kowaltzki¹, T.Y. Kim¹, A.Dari², Forchel¹, L. Gammaitoni² and L. Worschech¹

¹Technische Physik, Physikalisches Institut, Universität Würzburg and Wilhelm Conrad Röntgen Research Center for Complex Material Systems
²NiPS Laboratory, Dipartimento di Fisica, Universita di Perugia
Würzburg is famous for:

- Wine (Wine producer of the year: Weingut Horst Sauer)
- And Dirk Nowitzki
Department of physics and astronomy

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

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

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

• 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.
• Modulation doped GaAs/AlGaAs heterostructure (HEMT).
• Grown by molecular beam epitaxy.
• High mobility $\mu = 1.1 \times 10^6$ cm$^2$/Vs and charge density $n = 3.7 \times 10^{11}$ 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 (HNO₃)

DONE!! (plus contacts)

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

1/R<sub>o</sub><sub>_0</sub><sub>_0</sub> < G<sub>RTD</sub> (DC-bistable)

1/R<sub>_o</sub><sub>_o</sub> > G<sub>RTD</sub> (DC-stable)

Simulation: d = 750 nm
- 100Ω
- 200Ω
- 500Ω
- 1000Ω

RTD diameter:
- 1 μm
- 750 nm
- 500 nm

I (µA)

V (V)

Simulation: 
- d = 750 nm
- 100Ω
- 200Ω
- 500Ω
- 1000Ω
• 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.
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
Switching voltages: $V_1 = V_2 = 0\text{mV}$
Reconfigurable logic universal gates: NOR and NAND configurations

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

![Image](image_url)

- $V_{ac} = 23$ mV
- $V_{ac} = 27$ mV
Switching voltages: \( V_1 = V_2 = 2 \text{ mV} \)
Reconfigurable logic universal gates: NOR and NAND configurations & truth tables

Switch from NOR to NAND for $\Delta V_{ac} < 1 \text{ mV}$ with a logic input voltage 2 mV.
Schmitt-Trigger simulation.

All Parameters from the experiment.

Excellent agreement !!
Reconfigurable logic universal gates: NOR/NAND high noise robustness

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

$V_{ac} = 24.6 \text{ mV}$

$V_{ac} = 26.6 \text{ mV}$
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.
For the logic NOR gate:

- The mean value difference is defined as
  \[<V>=V(I=0)−V(I=1)\]

- \(P_{\text{noise}} = 0.9 \text{ nW}\) the maximum corresponds to the logic NOR

For the logic NAND gate:

- The mean value difference is defined as
  \[<V>=V(I=1)−V(I=2)\]

- \(P_{\text{noise}} = 1.4 \text{ nW}\) the maximum corresponds to the logic NAND
• 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.
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

\[ r_K = \frac{1}{\pi \sqrt{2}} \exp\left(-\frac{\Delta V}{D}\right) \]

The time-scale matching condition for stochastic resonance:

\[ T_\omega = 2 T_K \]
• RTD is bistable with stable outputs $I_H = 800 \, \mu A$ and $I_L = 270 \, \mu A$.

• Works @ RT

• PVR $\sim 3$

• Noise induced switching between the two stable states appear.

• Time scale $T_k$ is given by the inverse of the Kramer's rate.
• For $P_{\text{noise}} < P_{\text{SR}}$ no spectral component at $f = 500$ Hz is found.

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

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

For $P_{\text{noise}} < P_{\text{SR}}$ the spectral component at $f = 500$ Hz is increasing.
- Maximum synchronization @ $P_{\text{SR}}$ => $\text{SR}$.
- For $P_{\text{noise}} > P_{\text{SR}}$ the spectral component is decreasing again.
Now:
- Change from ac modulation to a periodic light modulation.
- Energy of the light $E = 2.73 \text{ eV (448nm)}$ above the GaAs bandgap.
- Mechanically chopped light signal at $f = 500 \text{ Hz}$.

- For $P_{\text{noise}} < P_{\text{SR}}$ the spectral component at $f = 500 \text{ Hz}$ is increasing.
- Maximum synchronization @ $P_{\text{SR}}$ => $\text{SR}$.
- For $P_{\text{noise}} > P_{\text{SR}}$ the spectral component is decreasing again.
At $P_{\text{noise}} = 32$ nW the output follows almost perfectly the input signal!!

$P_{\text{noise}} = 2$ nW

$P_{\text{noise}} = 32$ nW

$P_{\text{noise}} = 112$ nW
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:**

\[ V_g(t) = V_{g,0} + \delta V_g \cdot \sin(\omega t) \]

**Weak periodic signal:**

\[ \delta V_g = 1.3 mV \]
For the unmodulated system, e.g. \( f = 0 \text{ Hz} \), the residence time distribution decays exponentially.

The exponential decay is the inverse of the Kramer’s rate and given by \( T_K \):

\[
N_{L,H}(T) \propto \exp\left(-\frac{T}{T_K}\right)
\]

From fitting:

\[
T_K = (0.502 \pm 0.044) \text{ s}
\]

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 \( T_\omega \) occur:

\[
T_n = \frac{(2n-1)T_\omega}{2}
\]

At the optimum frequency \( f = 1 \text{ Hz} \) the residence time distribution is almost perfectly restricted to the first peak.
At \( f = 1 \) Hz the noise dynamics and the external (weak) periodic forcing are synchronized => Stochastic resonance.
• 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 $n=1,2,\ldots$

And $0<\alpha=0.2<0.25$
• 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.
The variable of interest is the residence time difference $\Delta T$ between the time spend in the two stable states $T_{H,L}$ with

$$\Delta T = T_H - T_L$$

The response of $\langle \Delta T \rangle$ for large noise intensity $\sigma_\xi$ is (expanded to first order in $\varepsilon$ (target signal):

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

• The detector is 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: $\Delta T = T_H - T_L$
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 $\Delta B$.
- 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]

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 $\Delta T$ is a linear function of the magnetic field around the symmetric point $\Delta T = 0$ s.

- Target signal (magnetic field) independent sensitivity.

\[ \Delta T(B) = T_0 - cB \]

\[ S(B) = \frac{\partial \Delta T}{\partial B} = c \]
• **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.
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 $T_{\text{hot}}$ and $T_{\text{cold}}$ with $T_{\text{hot}} > T_{\text{cold}}$.

For systems subject to thermal noise, the Boltzmann factor is

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

For systems with mobility $\mu$ 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

\[ V(q) = V(q + 2\pi) \]
\[ V(q) = V_0(1 - \cos(q)) \]
\[ D(q) = D(q + 2\pi) \]
\[ D^{-1}(q) = D_0^{-1}(1 - \alpha \cos(q - \phi)) \]
\[ D_0 = \mu kT \]
\[ \Psi(q) = -\int_0^q dp \frac{v(p)}{D(p)} \]
\[ \Psi(q) = \Psi(q + 2\pi) + 2\pi \Delta \]
\[ \Delta = \frac{\mu V_0}{D_0} \frac{\alpha}{2} \sin(\phi) \]


\[ I_{ov} = \frac{\pi^2 E_0^2 T_1}{\mathcal{L}^2 T_0^2} \exp\left(-\frac{E_0}{T_0}\right) \sin(\phi) \]
\[ I = \frac{\gamma T_1}{2mT_0} \exp\left(-\frac{E_0}{T_0}\right) \sin(\phi) \]

\[
\frac{I}{q} = \frac{J_g}{E_C}
\]

Every energy quantum of heat flow gets converted into a quantum of charge flow.
• **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 $P_{\text{noise}} \sim$ nW

• **Stochastic resonance in nanoelectronic devices**
  – SR @ $f= 1$Hz in electron waveguides: Tuning the periodic forcing
  – SR @ $f= 500$Hz in RTDs for ac and periodic optical modulation: $P_{\text{light}} = 160$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.
**Supervisors:** L. Worschech, M. Kamp and A. Forchel

**Growth:** F. Langer, D. Bisping and S. Höfling

**Fabrication:** M. Emmerling, S. Handel and M. Kamp

**Measurements:** A. Musterer and A. Pfenning

**Financial:**

- Supported by: EU IST-SUBTLE, EU FP7 Nanopower, State of Bavaria, BMBF via national project EIPHRIK
- www.nanopwr.eu

**Many thanks for your attention!**