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Department of physics and astronomy: An overview

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

Klaus von Klitzing
Nobel Prize 1985
(Quantum Hall effect)

Other nobel laureates with a Würzburg history:
- Wilhelm Wien, Johannes Stark, Svante Arrhenius, Ferdinand Braun, Max von Laue, “Werner Heisenberg”

Source: google.de/maps
8 experimental physics chairs
5 theoretical physics chairs
+ several experimental and theoretical work groups

Fabian Hartmann, 17 July 2014
NiPS Summer School 2014
Quantum electrodynamics


Polariton laser

"An electrically pumped polariton laser"

Mars Exploration Rover Mission

0) The intro part: Growth, fabrication and transport properties of nanoelectronic devices

1) The logic gate part: Stochastic universal logic gates

2) The memory part: Quantum dot floating gate transistor

3) The sensor part: Cavity enhanced light detection by resonant tunneling

4) The energy harvester part: Voltage fluctuation to current conversion

*Picture borrowed from V. Zhirnov’s talk
Modulation doped GaAs/AlGaAs heterostructure.

Grown by molecular beam epitaxy.

High mobility $\mu = 1.1 \times 10^6 \text{ cm}^2/\text{Vs}$ and charge density $n = 3.7 \times 10^{11} \text{ cm}^{-2}$. 

Fabian Hartmann, 17 July 2014
Fabrication of electron waveguides and other nanoelectronic devices – Top down

Electron beam or optical lithography.

Wet or dry chemical etching (e.g. ECR-RIE).
Fabrication and working principle of resonant tunneling diodes

GaAs based RTDs with AlGaAs barriers.

Trench etched RTD

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Applications of electron waveguide devices and resonant tunneling diodes

Oscillator


Photosensor


Noise correlation


Noise activated nonlinear dynamical sensor


Half and full adder


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1) The logic gate part: Stochastic universal logic gates
Universal logic gates – NOR and NAND gate

NOR gate:

Truth table:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
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<tbody>
<tr>
<td>0</td>
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XOR gate (binary sum):

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NAND gate:

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Universal logic gate:

- Any logic gate can be made from a combination of NAND or NOR gates.
Reconfigurable logic universal gates: Noise induced firing rates in RTDs

- Electron microscopy images of a trench etched RTD with diameter $d = 600 \text{ nm}$
- 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: $V_1 = V_2 = 0\text{mV}$

$V_{ac} = 23\text{ mV}$

$V_{ac} = 25\text{ mV}$
Switching voltages: $V_1 = 0, 2$ mV $V_2 = 2, 0$ mV
Reconfigurable logic universal gates: NOR and NAND configurations

Switching voltages: $V_1 = V_2 = 2 \text{ mV}$
Switch from NOR to NAND for $\Delta V_{ac} < 1$ mV with a logic input voltage 2 mV
Previous:
• Universal logic gate switching controlled the amplitude of the periodic forcing.

Now:
• Universal logic gate switching solely controlled by the noise floor.

• Two universal logic gates: NOR/NAND.

• Switching between the gates only as a function of noise power.
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
2) The memory part: Quantum dot floating gate transistor
Floating gate transistor: Short introduction

Floating gate transistor:

- Non-volatile memory having a retention time of more than 10 years.
- A floating gate in a metal-oxide semiconductor field effect transistor (MOSFET) acts as the storage unit.
- SiO$_2$ barriers with an energetic height of 3.2 eV.

Threshold voltage shift:

$$\Delta V_{th} = \frac{\Delta Q}{C_{eff}}$$
QD floating gate transistor: a quantum dot-based memory device

Demonstration of working principle of a ‘silicon single-electron memory transistor‘.

L. Guo et al., Science 275, 649 (1997)

**Discrete** shift of threshold voltage in dependence on the number of stored electrons on the dot with

\[ V_{th,up} = \frac{ne}{C_{dg}} \]
Advantages compared to Si/SiO$_2$ system:

- The height of the barrier can be designed.
- Defect-free interfaces.
- Writing or erasing the device does not damage the structure.
- Hole-based charge storage can be used.

QD floating gate transistor: a quantum dot-based memory device

QD-Flash memory with self-assembled QDs:

- Self-assembled QDs are randomly distributed.
- Charging of several QDs contribute to the threshold voltage shift.
- Ensembles of QDs are typically not practical for the study of single electron properties.

→ Control the number and position of the QDs.

QD-Flash memory with positioned site-controlled QDs:

bottom-up

top-down
Fabrication of QD memories with positioned and site-controlled quantum dots

Level 1-Growth:
Growth of high mobility 2DEGs on the basis of AlGaAs/GaAs.

Level 2-Mesa definition:
Optical lithography and wet chemical etching of mesas with a depth of 500 nm – 1000 nm. -> 4 blocks with 63 possible structures
Fabrication of QD memories with positioned and site-controlled quantum dots

Level 3 – Nanoholes:
1) 100 nm PMMA. 2) E-beam lithography (periods from 200 to 400 nm). 3) Develop the resists. 4) Dry chemical etching.

Level 4 - Overgrowth process:
Overgrowth process with InAs and GaAs

Electron microscopy images
Fabrication of QD memories with positioned and site-controlled quantum dots

Level 5 – Hallbars:
Optical lithography and wet chemical etching.

Level 6 – Contacts:
Evaporate the contacts (AuGe/Ni/Au)
Fabrication of QD memories with positioned and site-controlled quantum dots

**Level 7 - Y-branch:**
E-beam lithography and dry chemical etching
Electron image:

- $I(V_g)$-characteristics for two charging voltages.
- Trace during down-sweep remains unaltered.
- $V_{tu}$ shifts towards larger values when decreasing $V_{gm}$.

\[ V_{hy} = V_{tu} - V_{td} \]

QD discharged
$\Rightarrow Q = 0$

QD charged
$\Rightarrow \Delta V_{tu} = \frac{\Delta Q}{C_{eff}}$

$V_{gm}$:
-3.5 V
-3.9 V
3) The sensor part: Cavity enhanced light detection by resonant tunneling
Photocurrent:
\[ \Delta I = \eta \cdot SE \cdot M \cdot P \]
\[ SE = \frac{e\lambda}{hc} \]

Sensitivity:
\[ S = \frac{\partial \Delta I(V, \lambda)}{\partial P} \]
\[ \text{InGaAs: APD} \sim 10 \text{ A/W} \]
\[ \text{Gain} = 10 \]

But, noise:
\[ i_{APD} \propto M, I_{dark} \]

\[ P = \text{light power; } M = \text{gain} \]
\[ SE = \text{spectral response} \]
\[ \eta = \text{Quantum efficiency} \]
Light detection in RTDs with embedded quantum dots:

- GaAs or InGaAs based RTDs with InAs quantum dots.
- Single-photon detection for light in the visible and IR wavelength region at ~ 4K.

Pros:
- It works!!
- Single photon resolution even for IR.

Cons:
- InP wafer for 1.3 µm -> expensive.
- Cryogenic temperatures.

Light sensing with RTDs at telecommunication wavelengths: 1.31 and 1.55 µm.
GaInNAs absorption layer

Light active at 1.3 µm
Lattice matched growth to GaAs

High amplification of photo generated charge carriers

Enhancement of quantum efficiency

AlGaAs/GaAs double barrier RTD

AlAs/GaAs DBR-cavity

Light detection in RTDs: Our approach
The quaternary GaInNAs: Band gap engineering and lattice matched growth to GaAs

- Band gap energy of GaInNAs depends on the In and N contents.
- For lattice matched growth on GaAs: $\text{In[\%]}/\text{N[\%]} \sim 3$
- For 1.3 µm: $\text{Ga}_{0.91}\text{In}_{0.09}\text{N}_{0.03}\text{As}_{0.97}$

Dashed lines correspond to the ternary materials e.g. InGaAs

Blue shaded: Realizable area of GaInNAs

Cavity enhanced light detection by resonant tunneling at telecommunication wavelengths

Sample Design:
- Cavity consists of 5/7 GaAs/AlAs DBR mirror pairs, with width of $2\lambda$.

DBR-Properties:
- Resonance $\lambda = 1.29 \, \mu m$
- Quality factor $Q = 50$

Electrical-Properties:
- Peak-to-Valley Ratio $PVR = 1.3$
- $I(V)$-shift under illumination
- No hole accumulation for reverse bias

CW-Measurements:

- Small signal linear fit:
  - $S(1.29 \mu m) = 31.2 \text{ kA W}^{-1}$
  - $S(1.26 \mu m) = 2.90 \text{ kA W}^{-1}$
  - $S(1.32 \mu m) = 5.89 \text{ kA W}^{-1}$
- Enhancement of a factor 11 and 5!

Pulsed Excitation:

- For a single photon:
  - $I_{ph} = (779 \pm 15) \text{ fA photon}^{-1}$
- Single Photon Detection possible!
4) The energy source part: Voltage fluctuation to current conversion
Energy harvesting in nanoelectronic devices: Optimal energy quanta to current conversion

Theory developed by:


Sánchez et al.

**Coulomb blockade regime:**

Quanta relation:

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

Efficiency:

\[
\eta(V_0) = \eta_c
\]

Sothmann et al.

**Chaotic cavity regime:**

Maximum power:

\[
P_{\text{max}} = \frac{A^2}{4G_1^2} (k_B(\Theta_1 - \Theta_2))^2
\]

Efficiency:

\[
\eta_{\text{max}} @ P_{\text{max}}
\]

Fabian Hartmann, 17 July 2014
Summary and take home message…

Coupled QD system = Efficient heat engine

Universal and reconfigurable logic gates

Cavity enhanced light detection by resonant tunneling

QD flash memory

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