Conductive Atomic Force Microscopy of Quantum Dots

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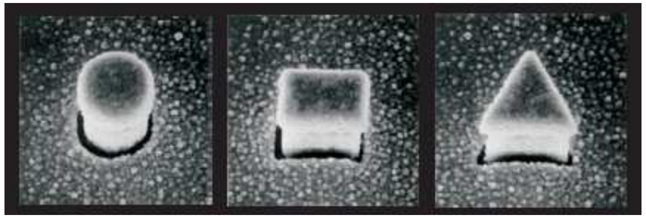
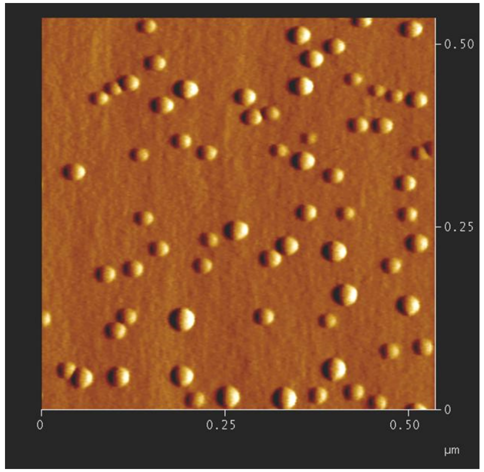
Outline

- Quantum dots
  - What are quantum dots?
  - QD fabrication
  - Self-assembled QDs
- Atomic force microscopy
  - AFM operation
  - Conductive AFM
- C-AFM studies of quantum dots
  - Surface band modulation of In-As QDs
  - Electron transport through Ge QDs
  - Lateral composition of Ge QDs
  - Conductivity of quantum rings
- Summary

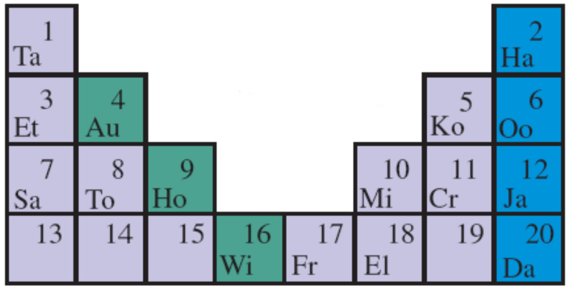
What are quantum dots?

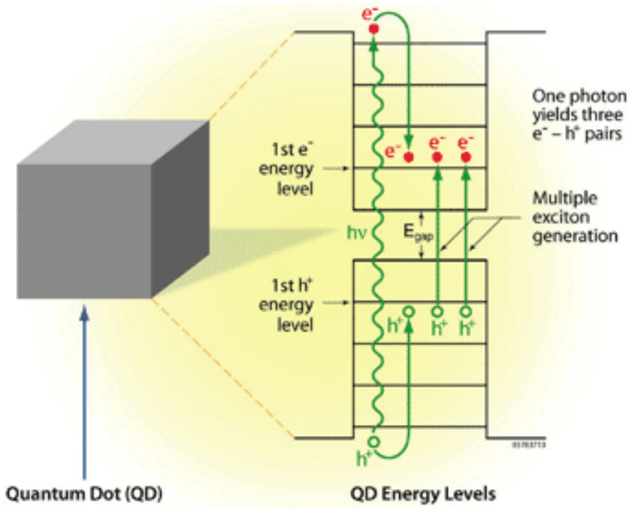
- QDs - small semiconductor structures (few nm)
- Electrons are confined due to small size





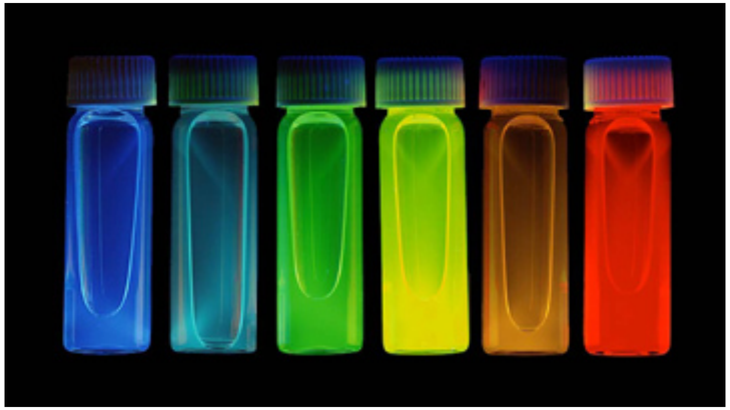
- Quantum confinement -> discrete energy states
- “Atom-like” properties

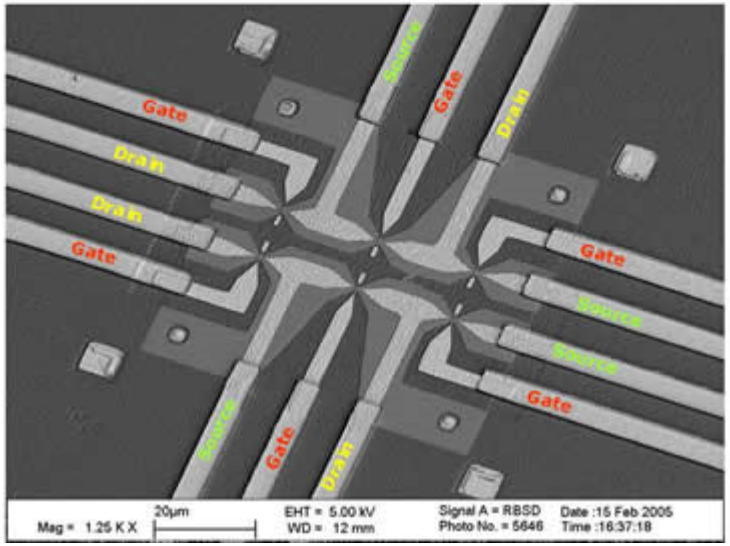




Quantum dot applications

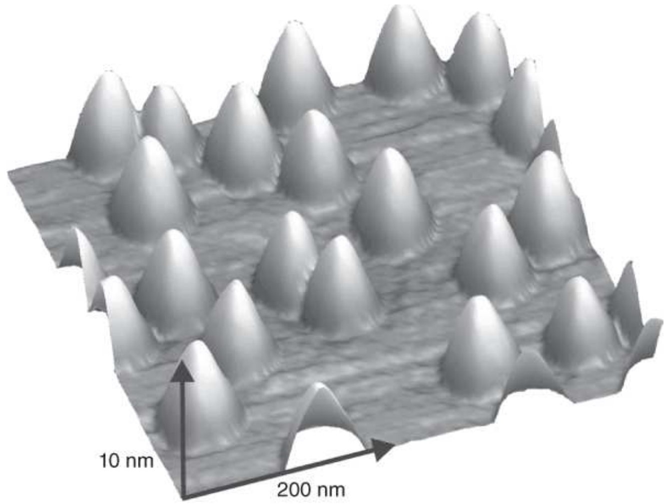
- Tunable size = tunable energy bandgap
- Diode lasers
- Photovoltaics
- QD displays
- Electronics – single electron transistors
- Quantum computing
- Flourescent dyes (high brightness)

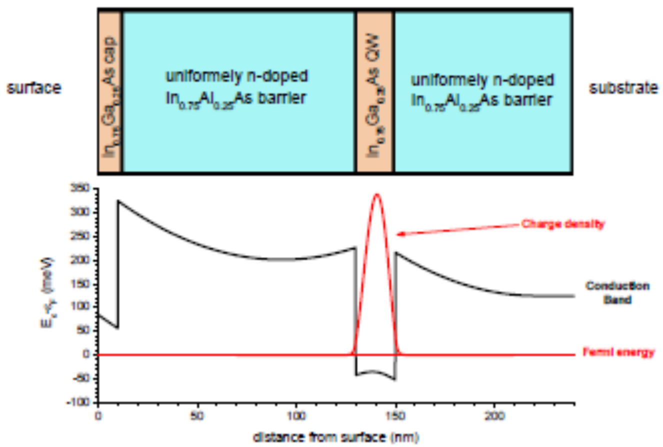


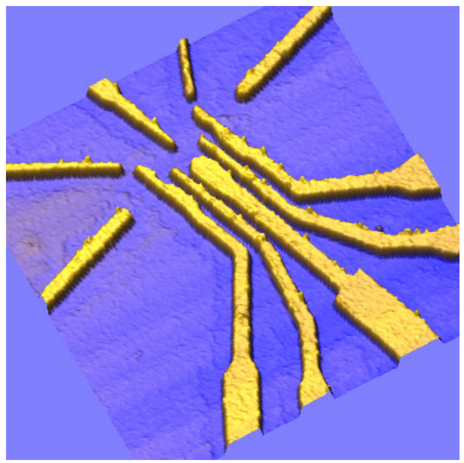


Quantum dot fabrication

- Colloidal synthesis (CdSe)
- Bottom-up approach (GaAs, InAs)
  - Self-assembled QDs
- Top-down approach (lithography)
  - Etching of semiconductor material
  - Metal gates -> electrostatically defined QD

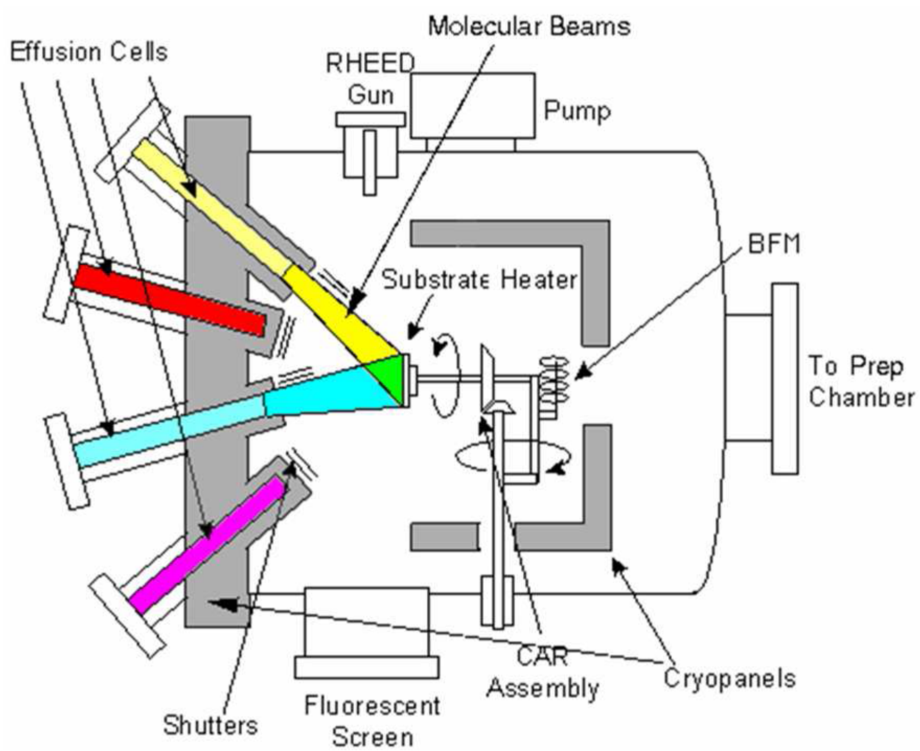






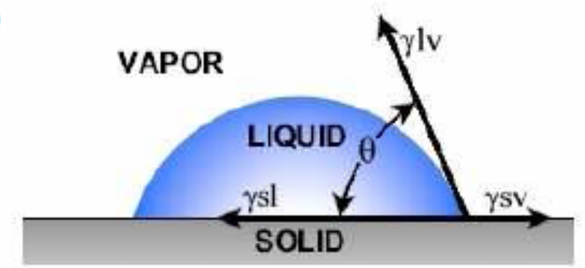
Self-assembled QDs

- Molecular beam epitaxy in ultra-high vacuum
  - High-purity materials in effusion cells
  - Ballistic transport to the substrate
  - High thickness control
  - Layer-by-layer growth

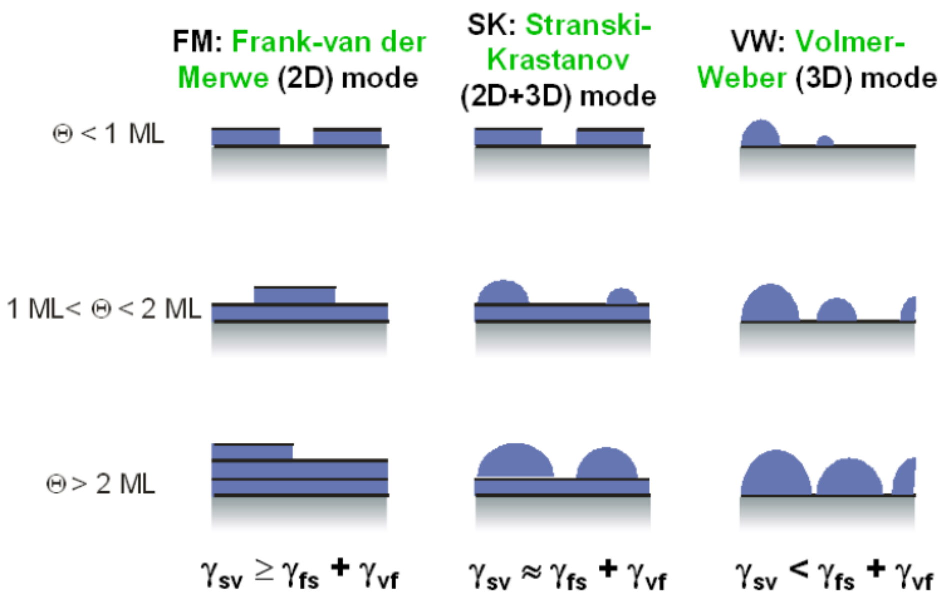


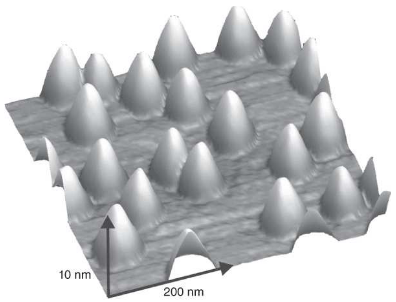
Self-assembled QDs

- Minimization of surface energy (lattice mismatched materials)
- Balance of forces: $\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos\Theta$



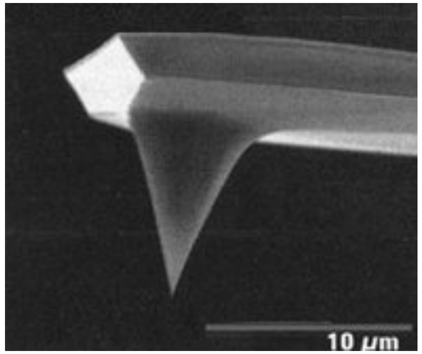
- Three types of growth:
  - Frank-van der Merve
    $\gamma_{SV} \geq \gamma_{SL} + \gamma_{LV}$
  - Stranski-Krastanov
    $\gamma_{SV} \approx \gamma_{SL} + \gamma_{LV}$
  - Volmer-Weber
    $\gamma_{SV} \leq \gamma_{SL} + \gamma_{LV}$

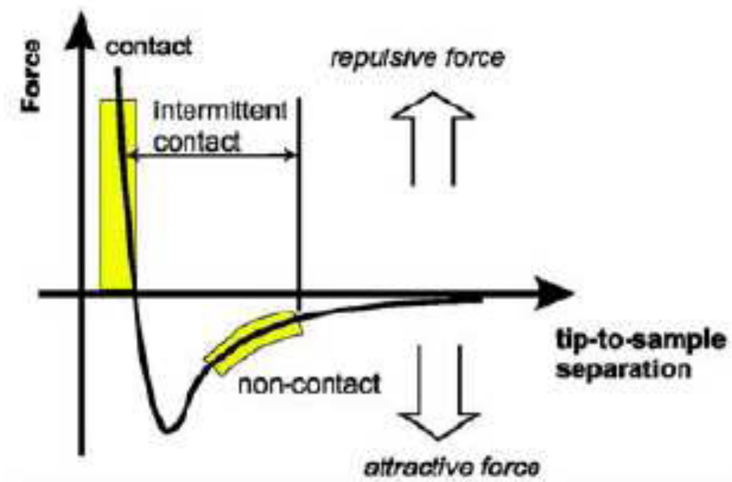




Atomic force microscopy

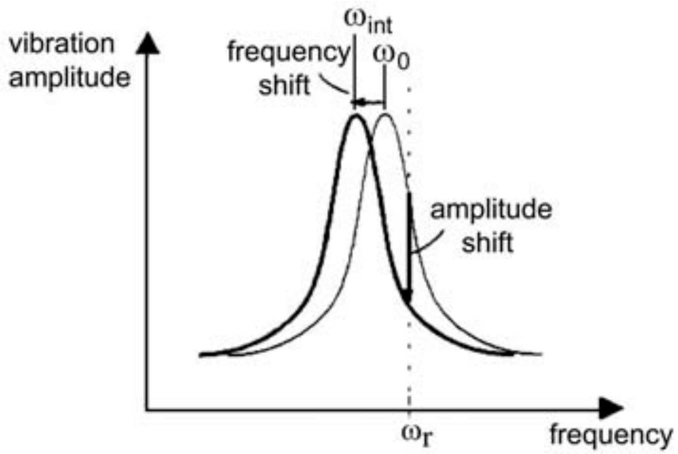
- Part of the scanning probe microscope family
- Raster scan of the surface topography
- Tip-sample forces
  - electrostatic interactions
  - van der Waals interactions
  - quantum-mechanical forces
  - capillary forces

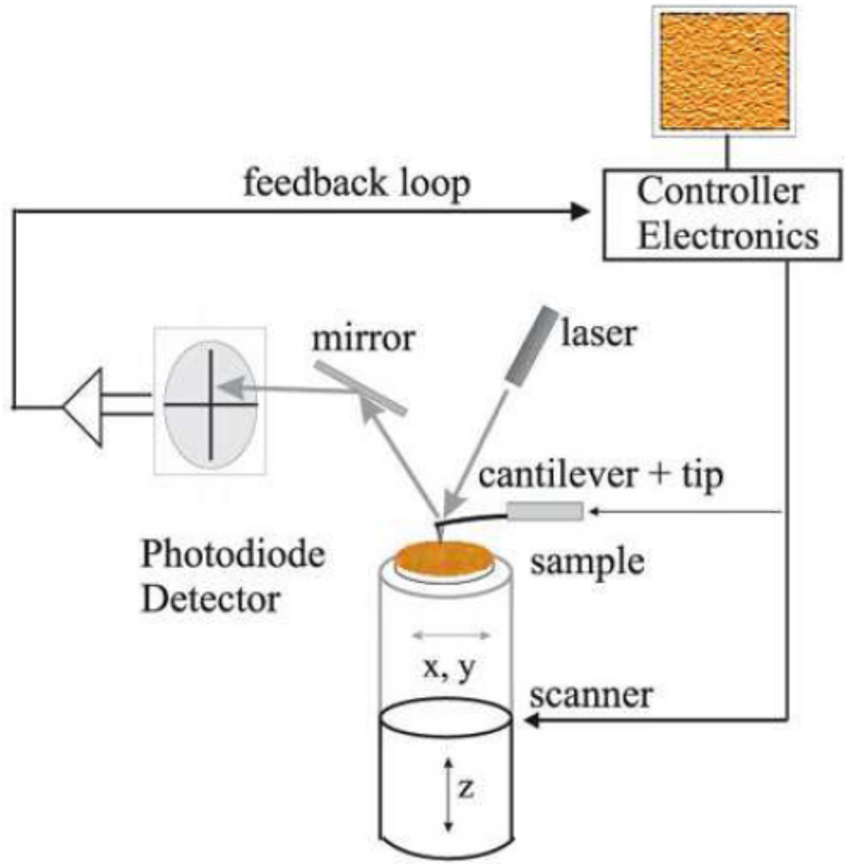




AFM operation

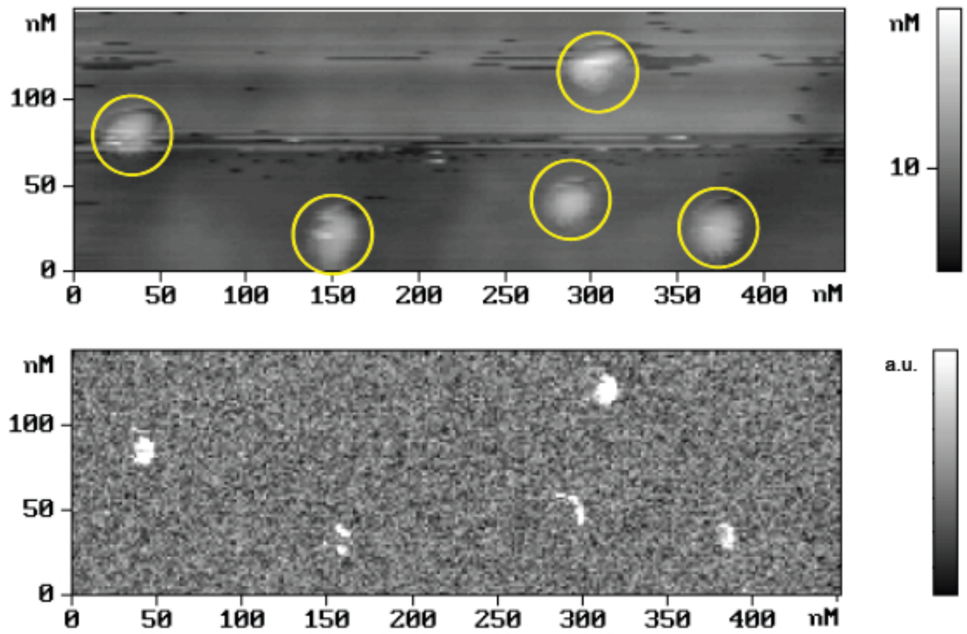
- Bending of the cantilever due to tip-sample interaction
- Laser beam detects the bending
- Feedback loop adjusts the height
- Modes of operation
  - Contact (repulsive force)
  - Intermittent mode
  - Non-contact (attractive force)
    - Vibration of the cantilever
    - Detection of frequency and phase changes

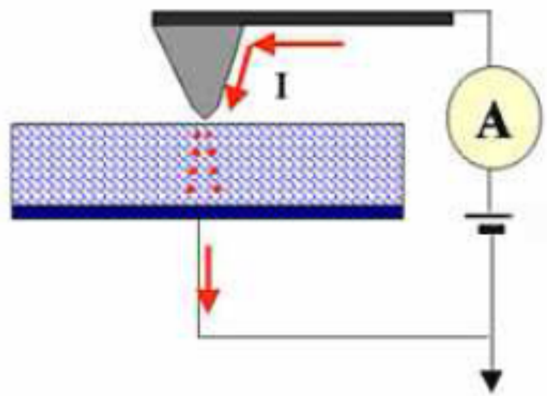




Conductive AFM

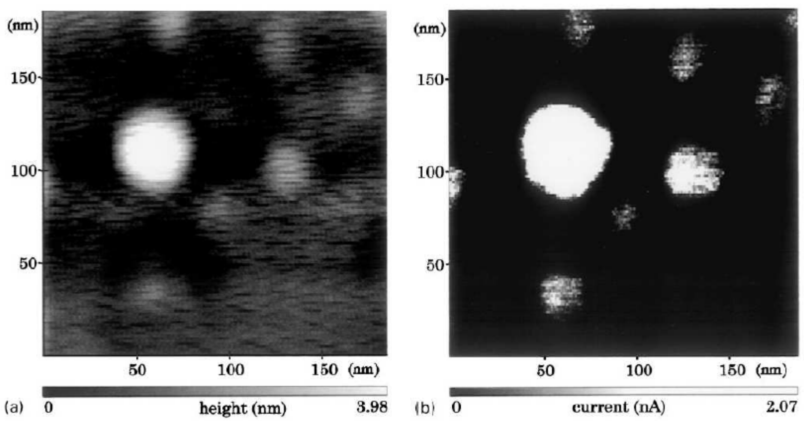
- Voltage applied to the AFM tip
- Simultaneous topography and conductivity measurements (fA – nA ranges)
- Local conductivity - I-V curves

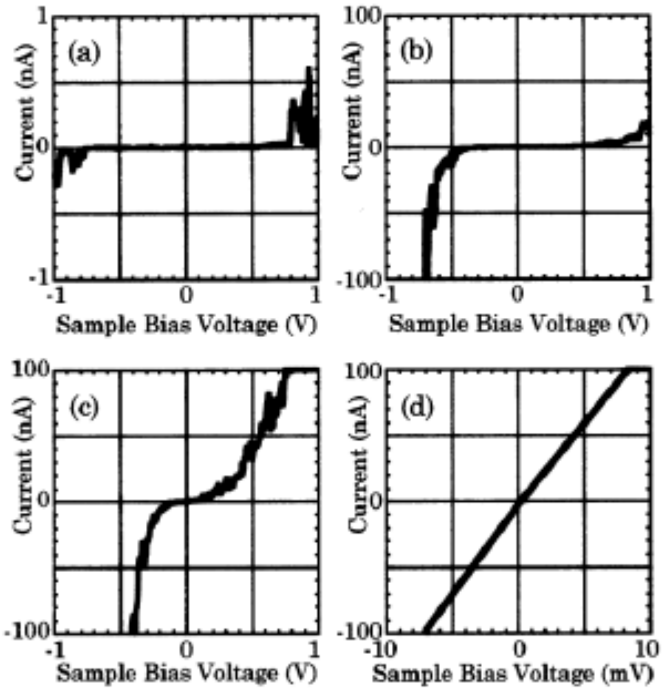




Surface band modulation of InAs QDs

- Self-assembled InAs QDs
- Grown on n-doped ($2x10^{18}cm^{-3}$) GaAs substrate
- 2.3 monolayers of InAs deposited on GaAs buffer layer
- C-AFM scans of the surface
  - Larger QDs more conductive
  - Wetting layer not conductive

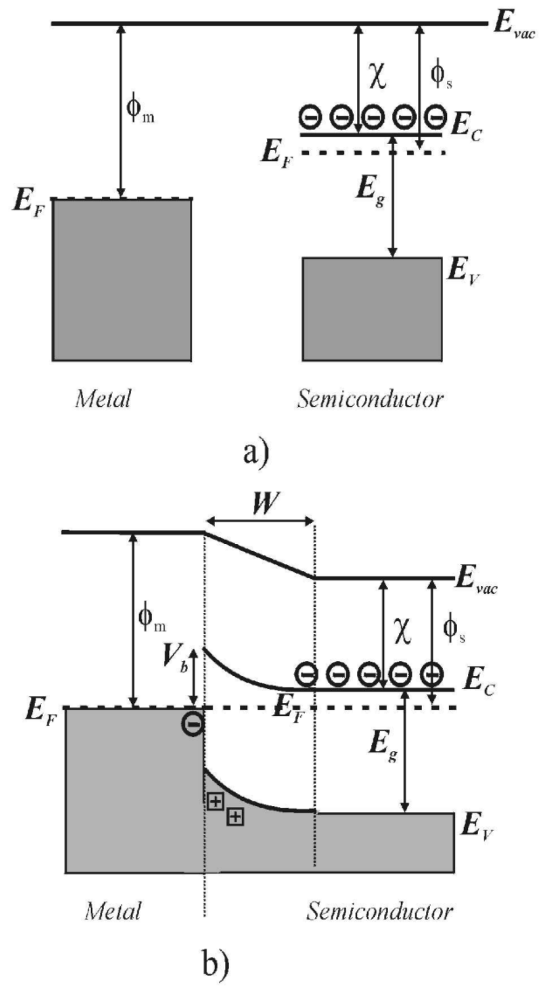




Tanaka et al, J. Cryst. Growth **201/202** (1999)

Surface band modulation of InAs QDs

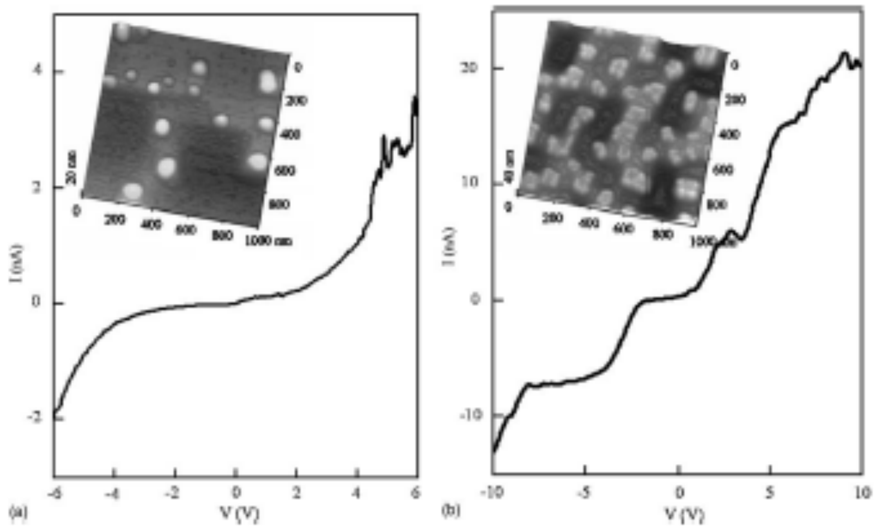
- Conductance related to local Schottky barrier
- The wetting layer is oxidized in air, leading to mid-gap Fermi level pinning by negatively charged surface states
- Bias voltage band lowering is strongly blocked by Fermi level pinning of states surrounding the contact
- In contrast, charge accumulation layers form at the surface of InAs (large QDs), which lowers the Schottky barrier



Tanaka et al, J. Cryst. Growth **201/202** (1999)

Electron transport through Ge QDs

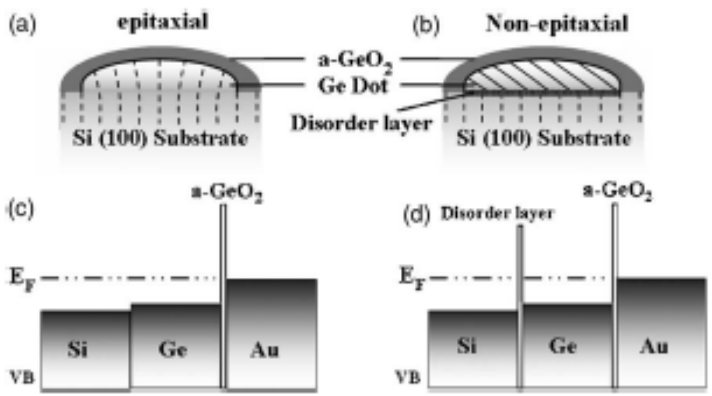
- Ge QDs fabricated by UHV ion beam sputtering
- Two types of samples
  - Coherent (lattice matched growth)
  - Incoherent (randomly orientated islands with interfacial defects)
- C-AFM and I-V curves
  - Linear to non-linear & symmetric (coherent)
  - Staircase (incoherent)

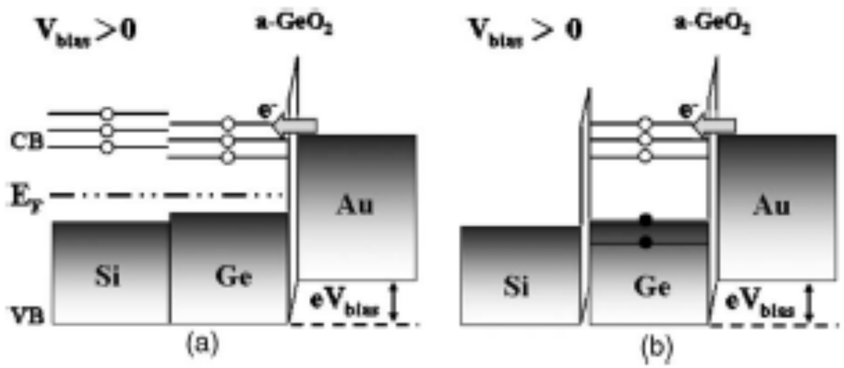


Chung et al, Appl. Phys. Lett. **89** (2006)

Electron transport through Ge QDs

- Difference due to QD microstructure
- Non-epitaxial growth (incoherent case) forms a disorder region which acts as a potential barrier
- Confinemet of electrons leads to discrete energy states
- Increasing the bias increases the number of open channels which results in sharp jumps in current

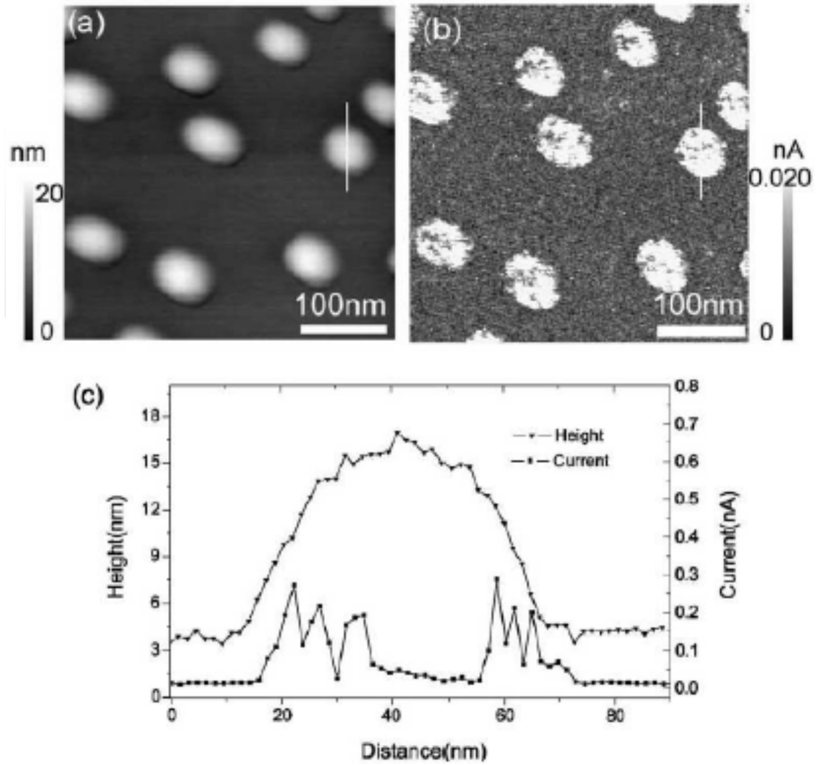




Chung et al, Appl. Phys. Lett. **89** (2006)

Lateral composition of Ge QDs

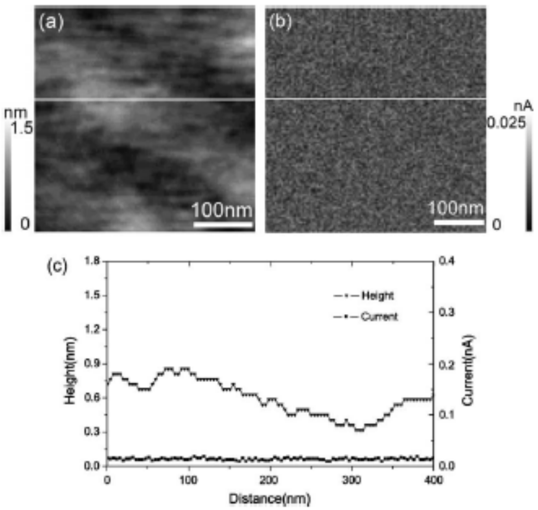
- Self-assembled Ge QDs on Si substrates
  - Sample A: 1.7nm of Ge at 550°C
  - Sample B: 0.85nm of Ge at 640°C
- Sample A
  - Center more conductive than periphery
  - Difference attributed to modifications of the Schottky barrier
- Sample B
  - Periphery more conductive
  - Shape and size is similar -> the difference can not be attributed to different local lowering of the Schottky barrier
  - Hypothesis: different diffusion levels of Si into the Ge QDs

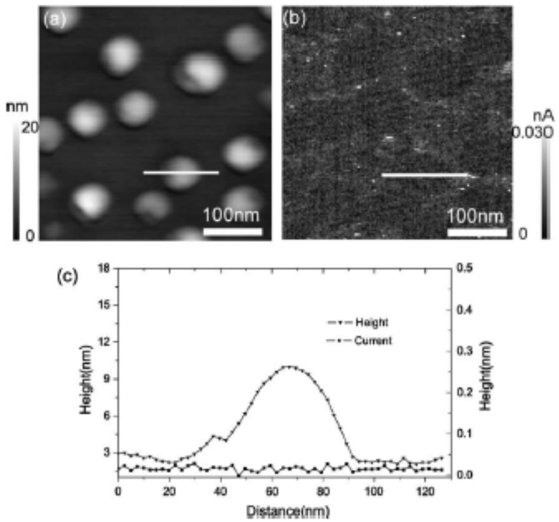


Xue et al, Surf. Sci. **592** (2005)

Lateral composition of Ge QDs

- Intermixing of Si with Ge at T > 550°C
- Conductivity of Ge higher than that of Si
- If Si is alloyed into Ge, edges have lower resistance ($R_D > R_C$)
- Selective etching of samples A and B
  - 30% H_2O_2 etches away GeSi where Ge > 65%

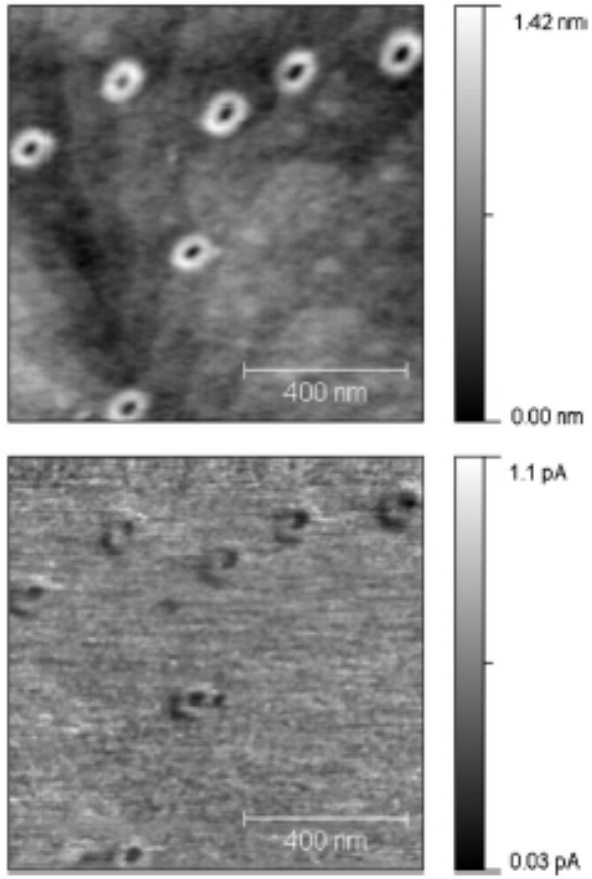




Xue et al, Surf. Sci. **592** (2005)

C-AFM of quantum rings

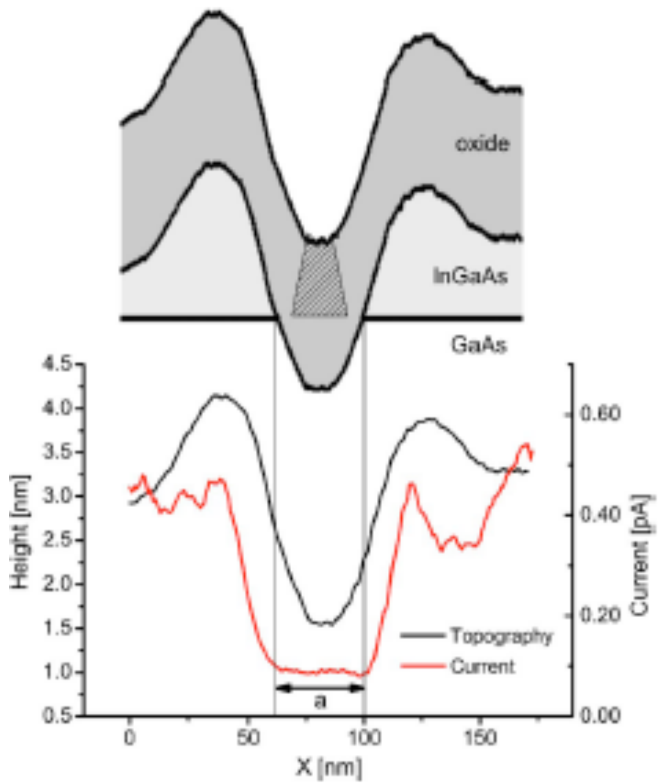
- Quantum ring fabrication
  - Capping InAs QDs with 2nm GaAs at 490°C + 30s annealing
- C-AFM of current and topography
  - Lower conductivity of central QR hole
  - XPEEM, XSTM show In rich core
  - In rich regions should be more conducting
  - Surface oxide needs to be considered



Mlakar et al, Appl. Phys. Lett. **92** (2008)

C-AFM of quantum rings

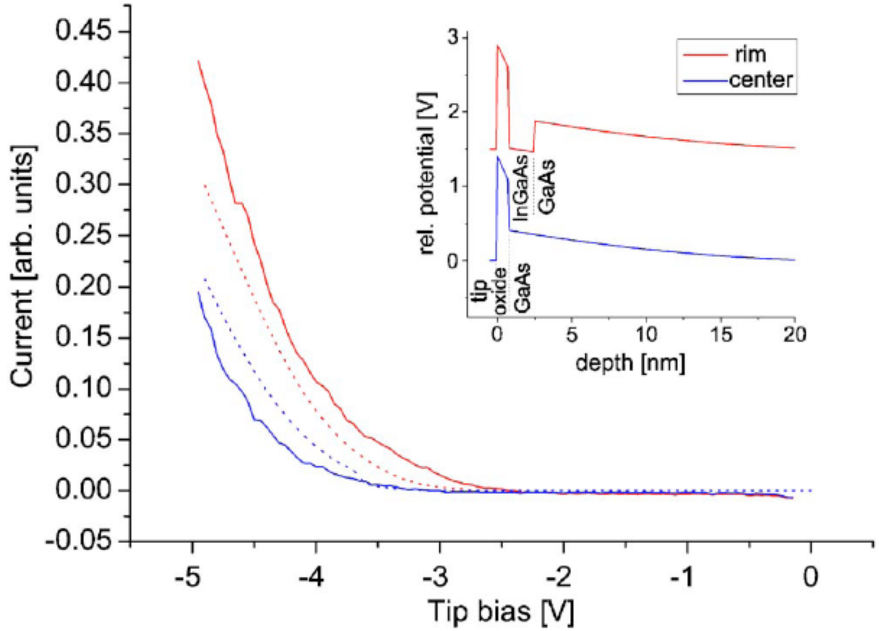
- Regions of lowest conductivity are assumed to be completely oxidized
- Geometrical analysis yields an oxide thickness of about 1nm
- Samples were further investigated by measuring I-V curves on QR rim and central hole
- Results were compared to a theoretical model



Mlakar et al, Appl. Phys. Lett. **92** (2008)

C-AFM of quantum rings

- Modelling the I-V curves
  - Energy band diagram (Poisson-Schroedinger solver)
  - TMM for calculating the transmission coefficient
  - 1D approximation of current density (Tsu-Esaki formalism)
- When taking surface oxide is taken into account, we find good qualitative agreement between theory and measurements



Mlakar et al, Appl. Phys. Lett. **92** (2008)

Summary

- C-AFM studies of basic QD properties (size, shape, composition, energy levels, transport ...)
- Performance of QD based transport and optoelectronic devices is determined by shape, size and microstructure
- C-AFM characterization of QDs provides input for the optimization of QD fabrication -> optimization of key properties