# Scanning probe lithography on semiconductor heterostructures: Technology and scientific applications

**Thomas Heinzel**

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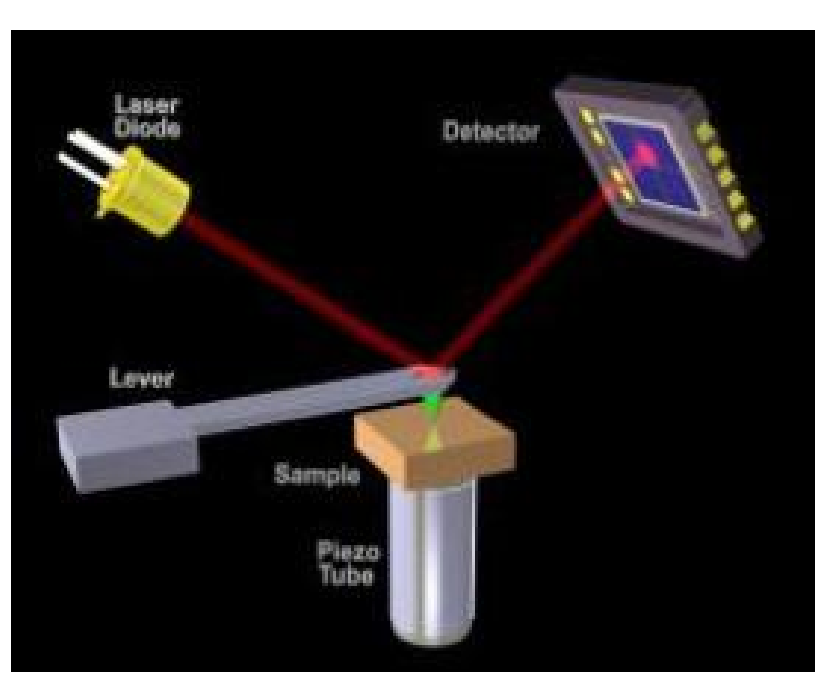
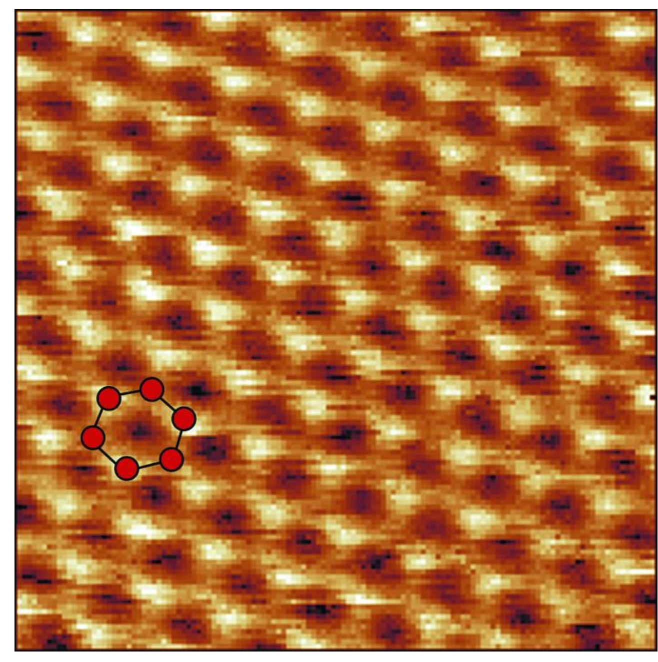
- Motivation and technology
- Options offered
- Some application examples

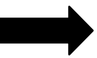
# Why patterning with an AFM?




AFM image
of a graphite surface

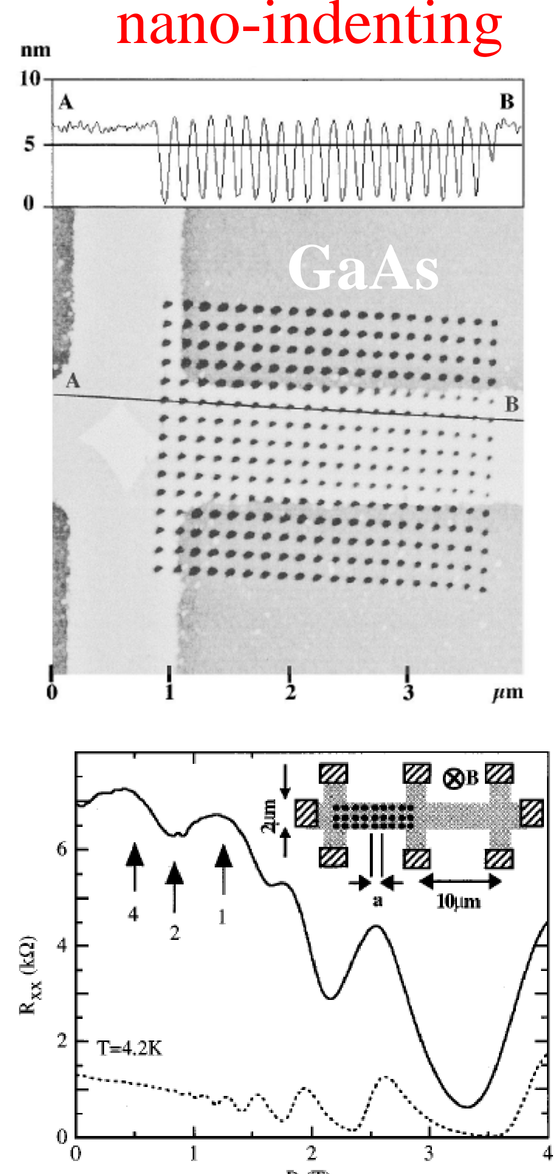


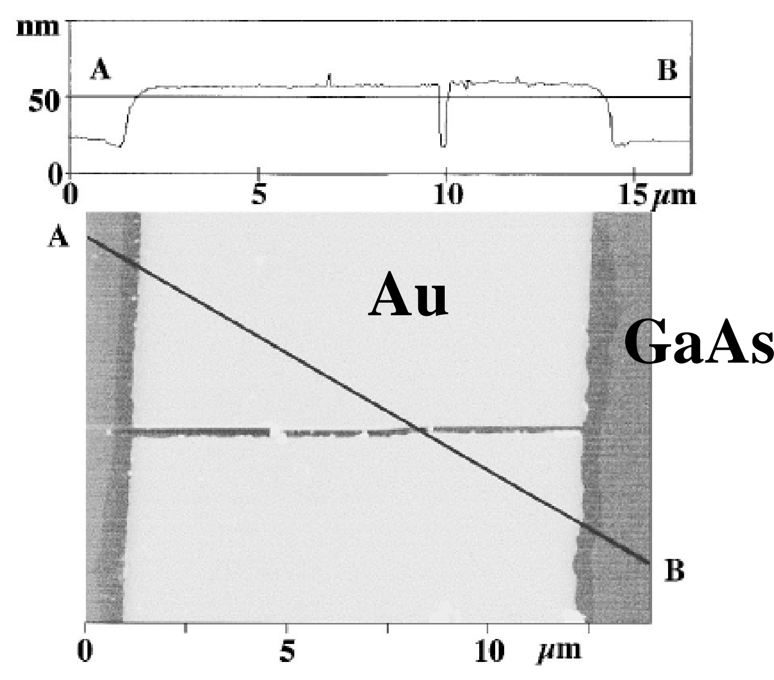
**Figures: courtesy of the Swiss Nanoscience Institute (SNI)**

 Functional modification of surfaces by AFMs?

# The AFM as a mechanical tool:

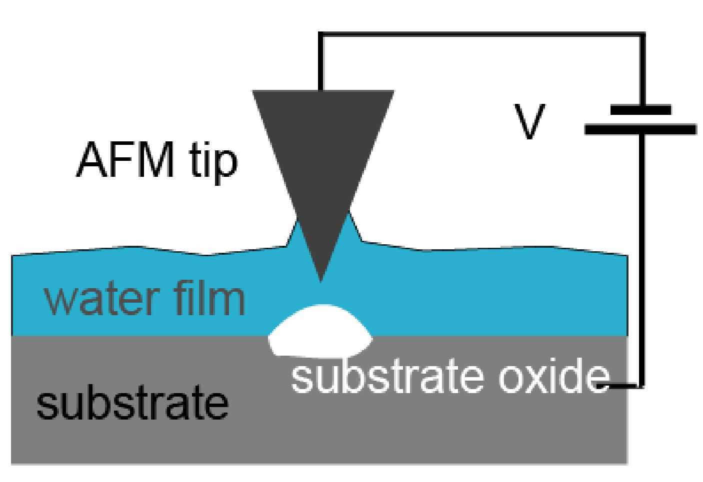
nano-indenting

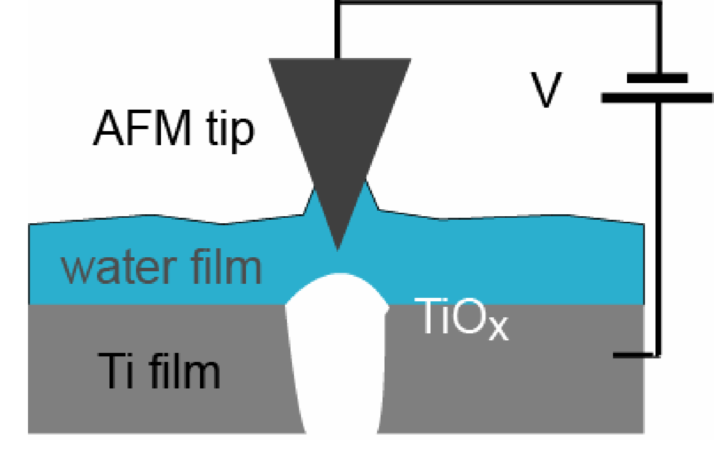



M. Wendel et al., Appl. Phys. Lett. **65**, 1775 (1994)

# The AFM as an electrochemical tool: Local Oxidation



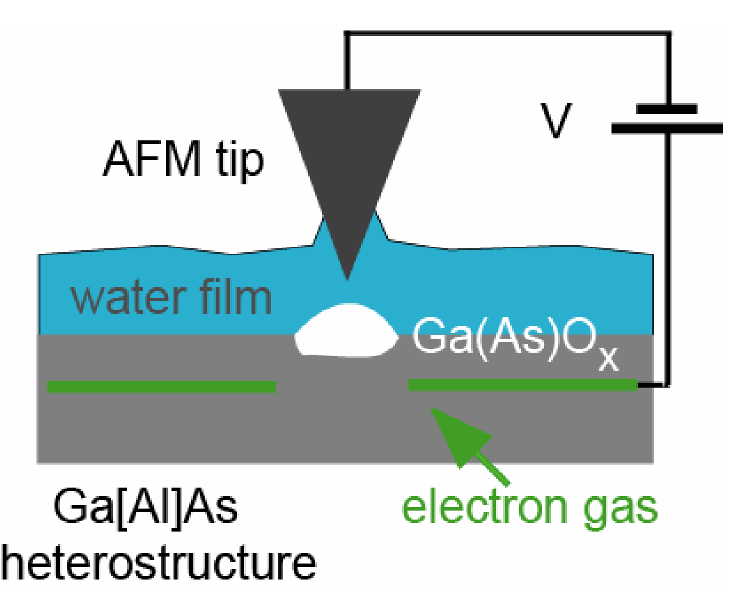

possible reaction:

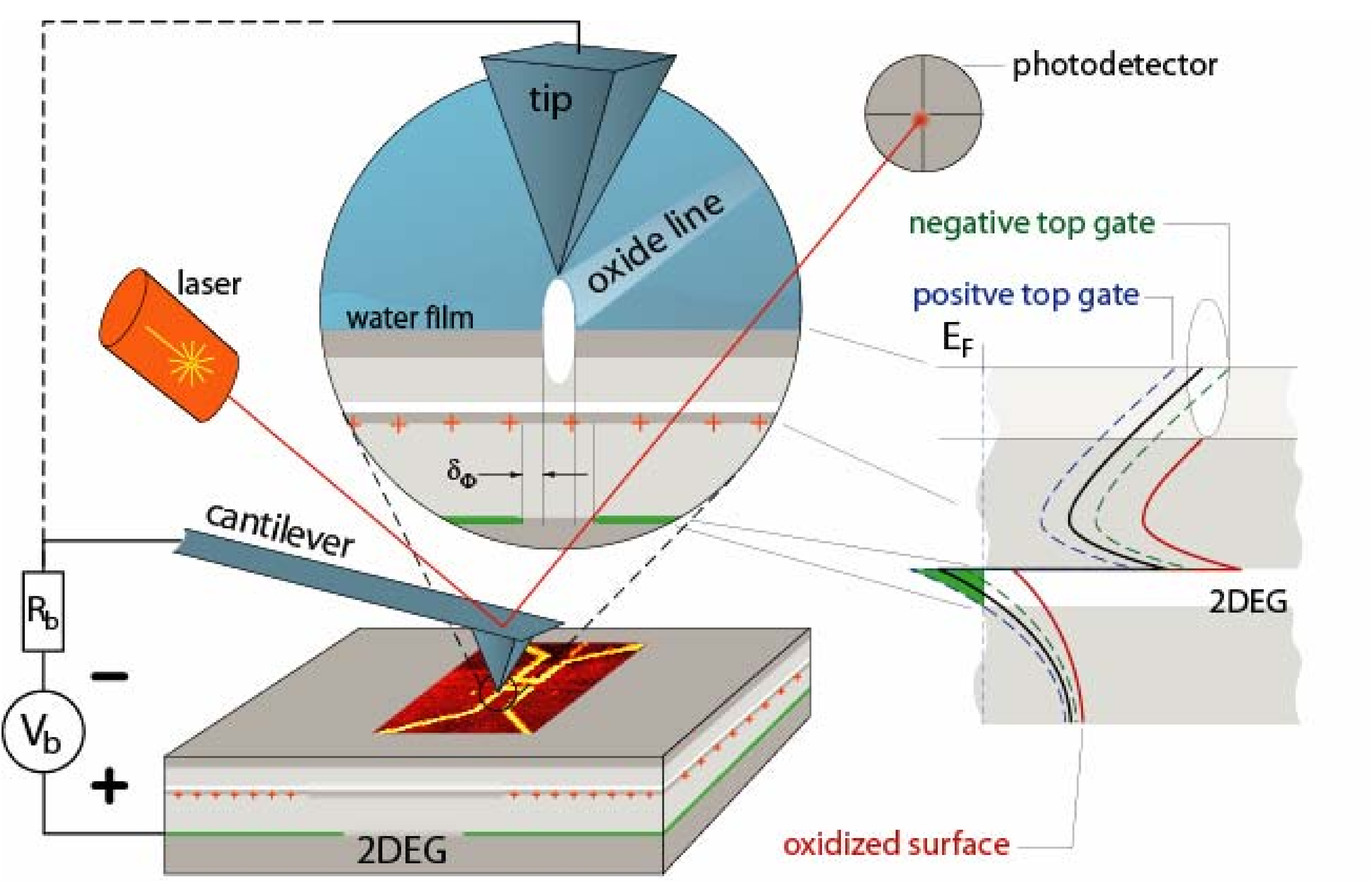
$$2GaAs + 6h^+ + 6OH^- \rightarrow Ga_2O_3 + As_2O_3 + 3H_2$$

## Requirements:

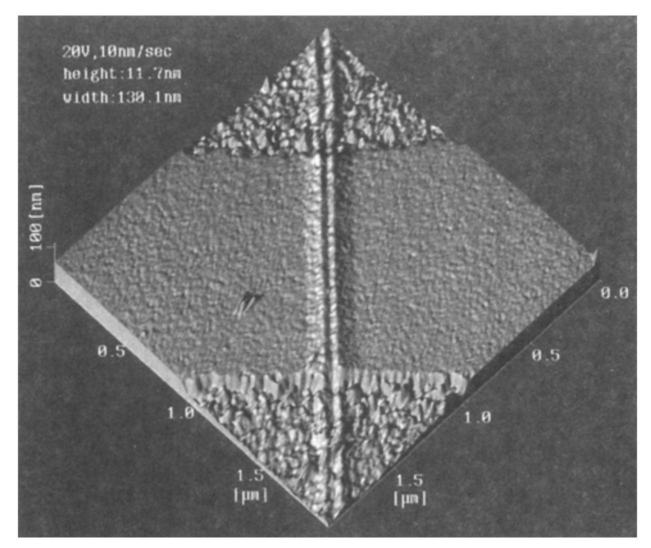
**Controlled humidity 40% - 60%**

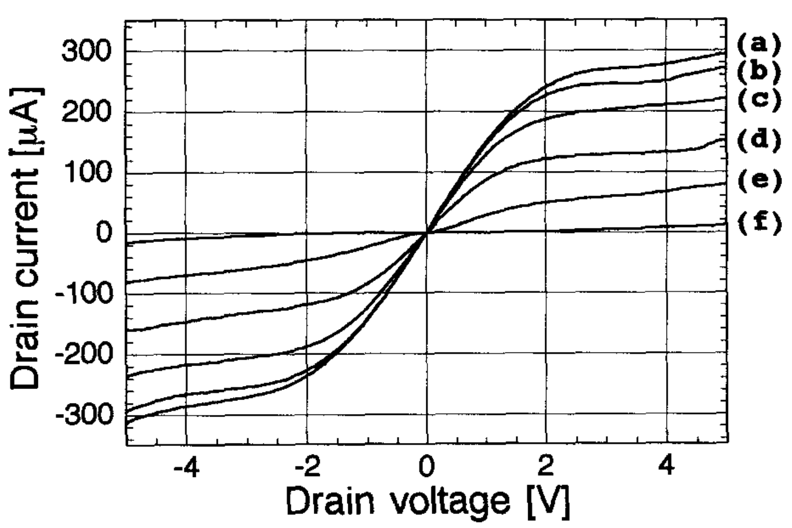
**Voltage < -12 V  to conductive AFM tip**
(we use diamond-coated, doped  Si tips)




tip
photodetector
oxide line
laser
water film
negative top gate
positve top gate
$E_F$
$\delta_\Phi$
cantilever
2DEG
$R_b$
–
$V_b$
+
2DEG
oxidized surface

# Local Oxidation of Ga[Al]As:



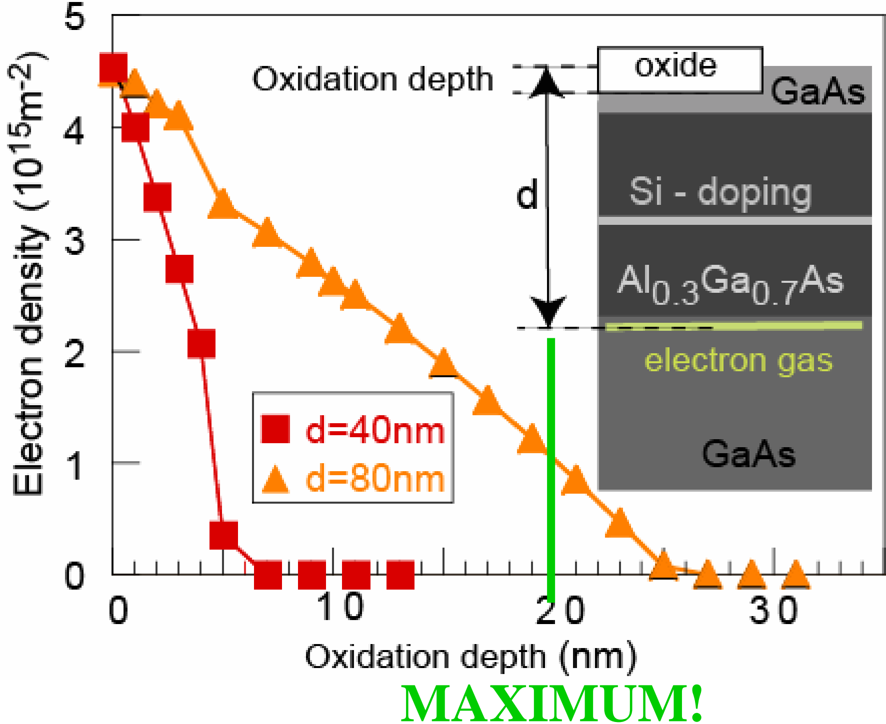




Resistance across line of length L:
RL ~ 250kΩ x µm at 4 K

M. Ishii and K. Matsumoto, Jpn. J. Appl. Phys. **34**, 1329 (1995)

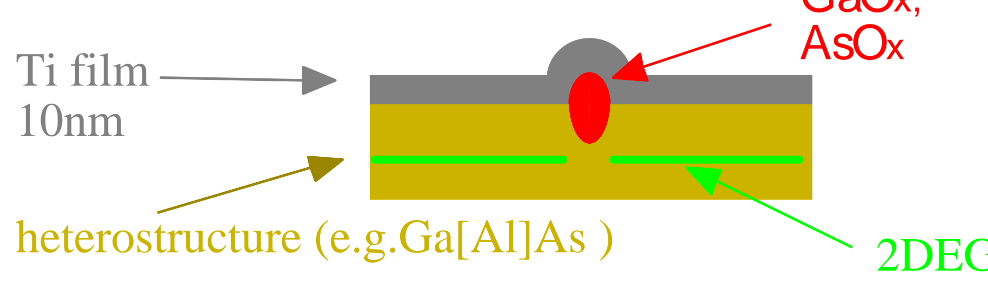
# Depletion of the 2DEG in Ga[Al]As:

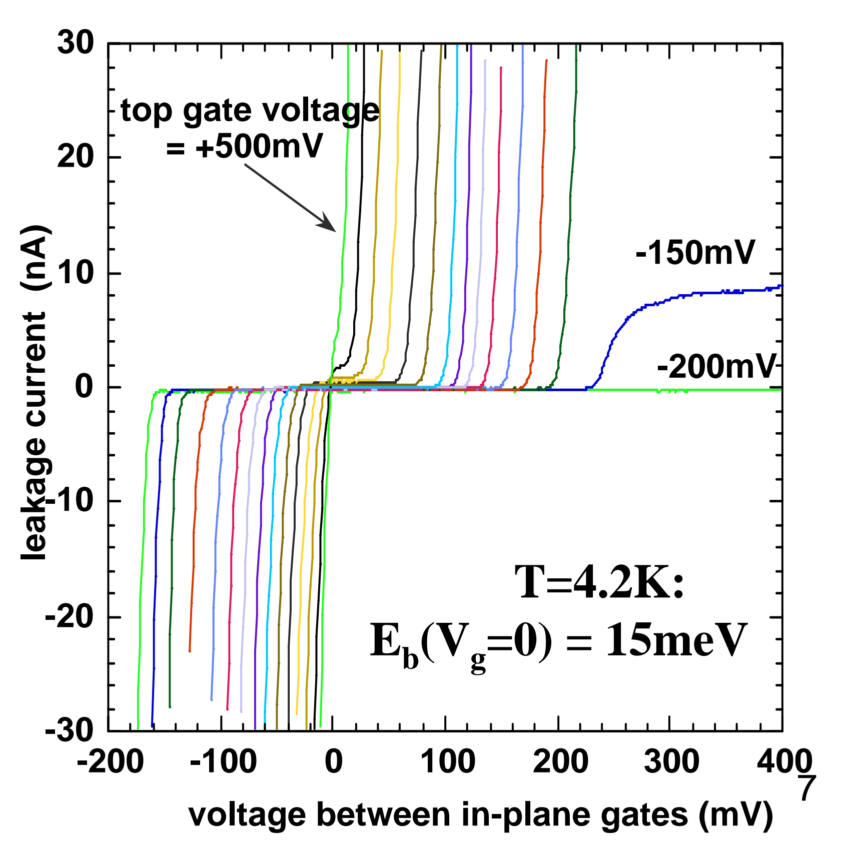
Simulation:



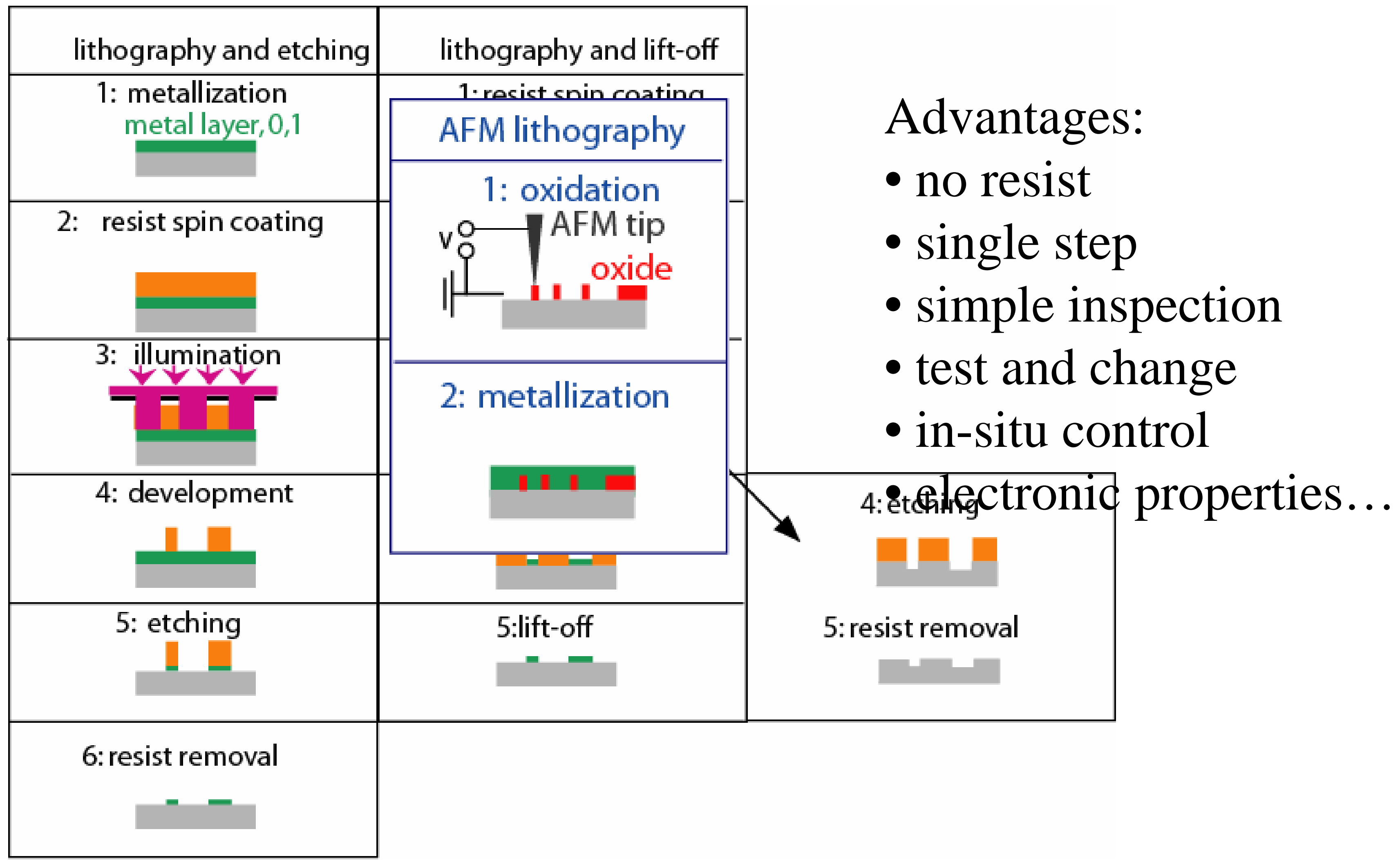

MAXIMUM!

R. Held et al.,
Appl. Phys. Lett. **73**, 262 (1998),
ibid. **75**, 1134 (1999).

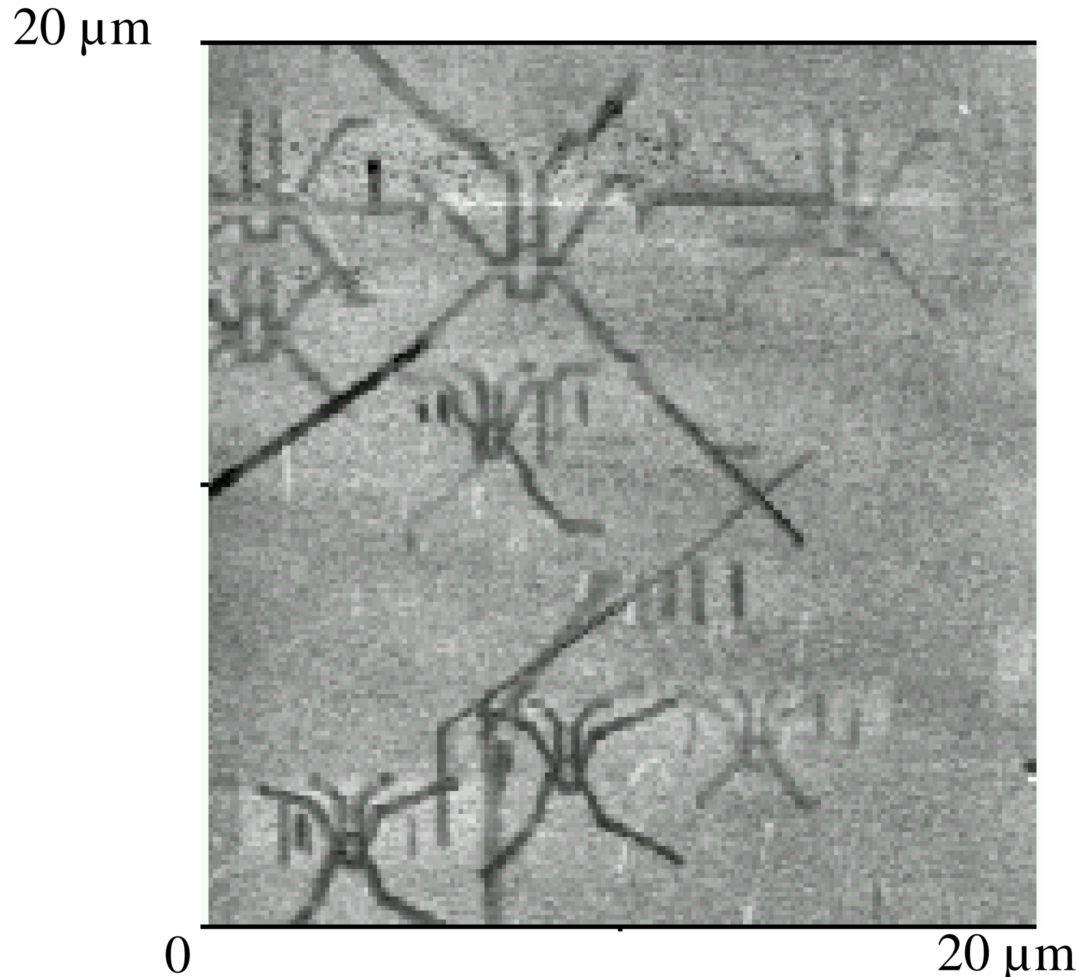


# Some features of lithography by local oxidation :



## On-chip trial and error:






(T.H. et al.,unpublished)

STEP 5: see STEP 3

STEP 6: see STEP 2

STEP 3:
narrow down
point contacts

STEP 4: see STEP 2

STEP 2:
Magnetotransport at 100mK

STEP 1:
write the dot

1.3μm

R(k Ω)

15
10
5

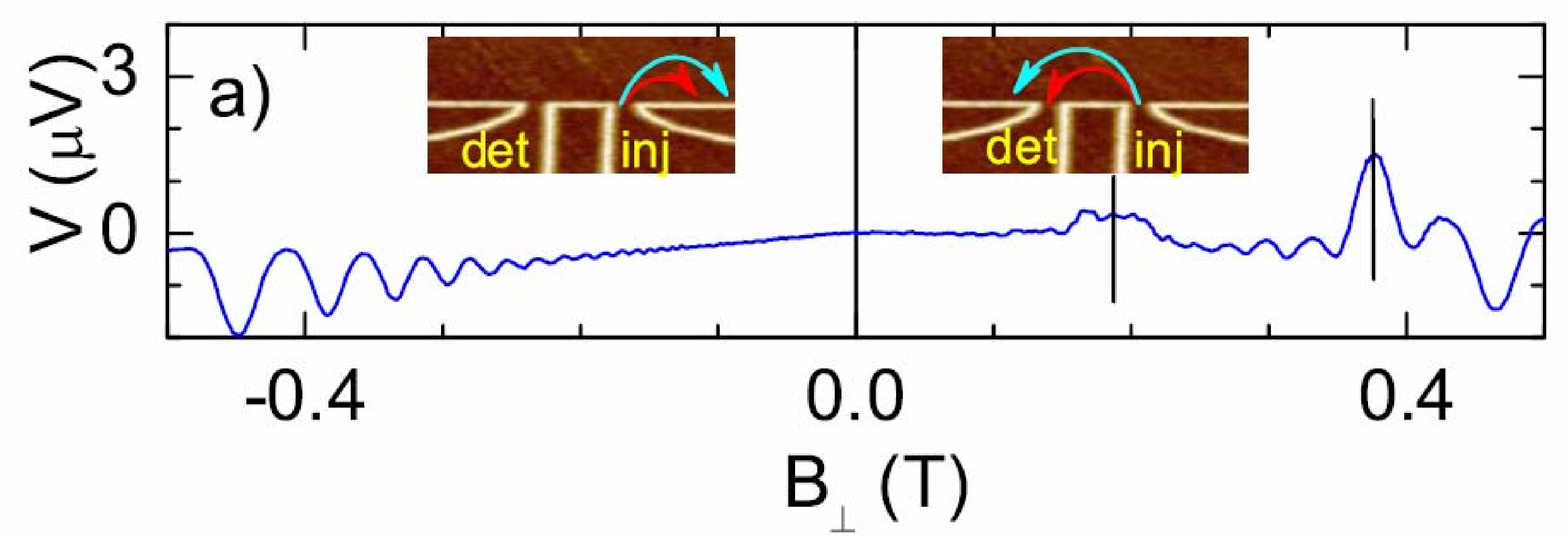
0 0.2 0.4 0.6 0.8 1

B (T)



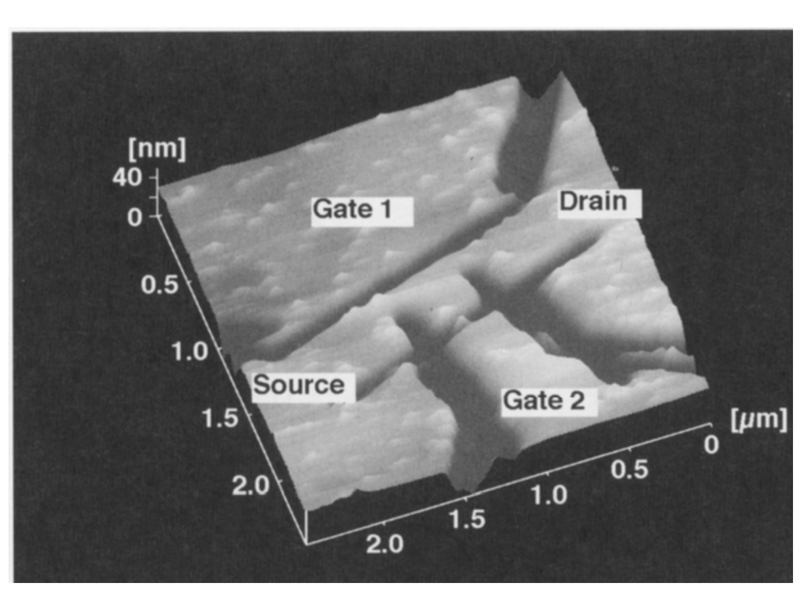
(T.H. et al.,unpublished)

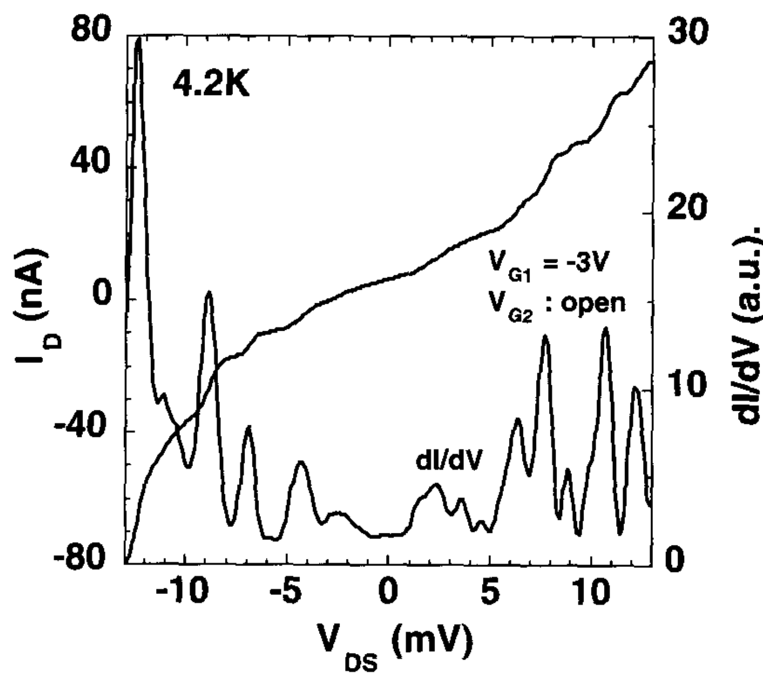
# Ungateable materials: Hole focusing in p-Ga[Al]As




L. Rokhinson et al., Phys. Rev. Lett. **96**, 156602 (2006)

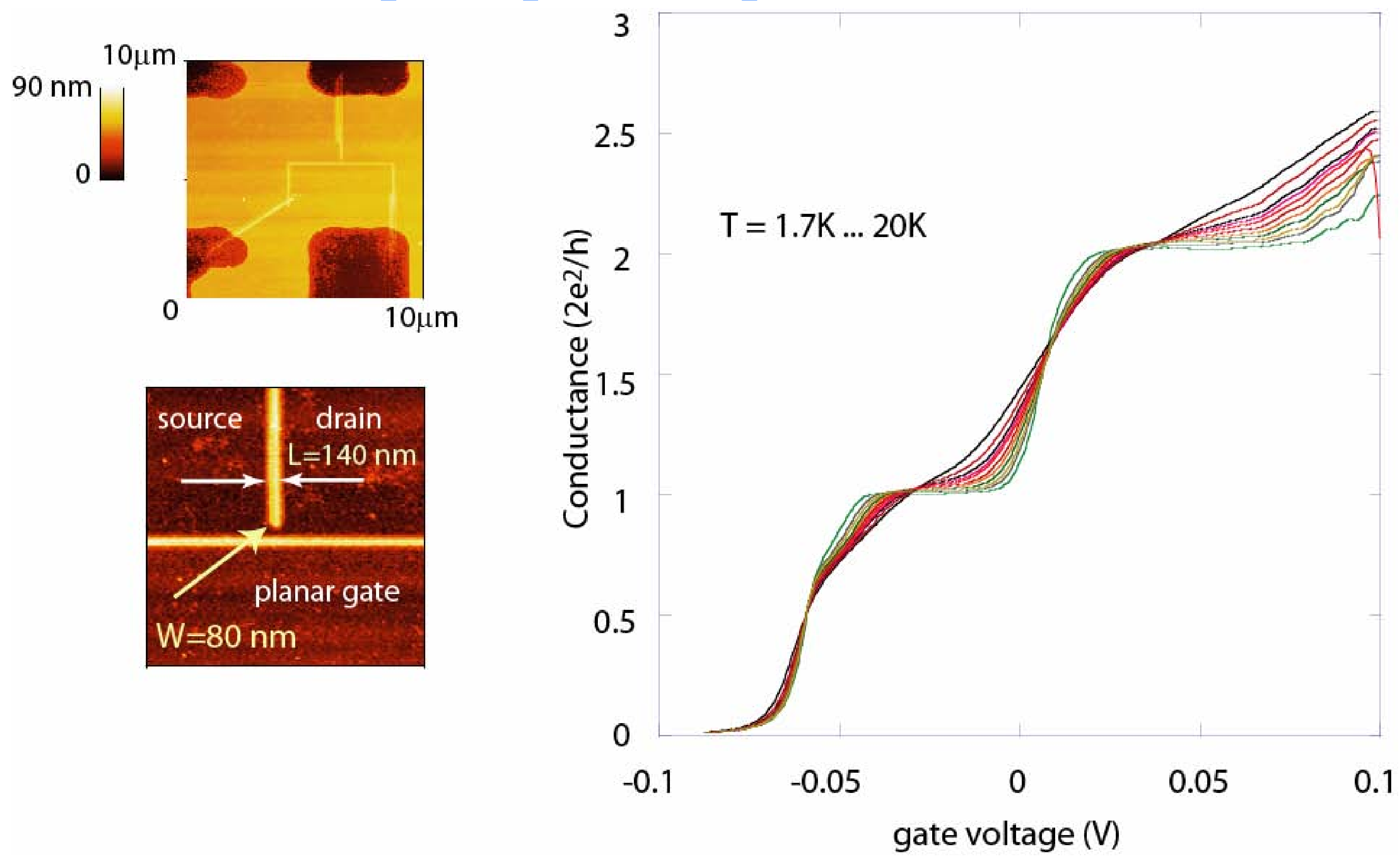
# Other heterostructure systems: Coulomb blockade in an InAs/AlGaSb quantum well structure:




S. Sasa et al., Jpn. J. Appl. Phys. **38**, 480 (1998)

# Electronic properties:
# For example a quantum point contact:



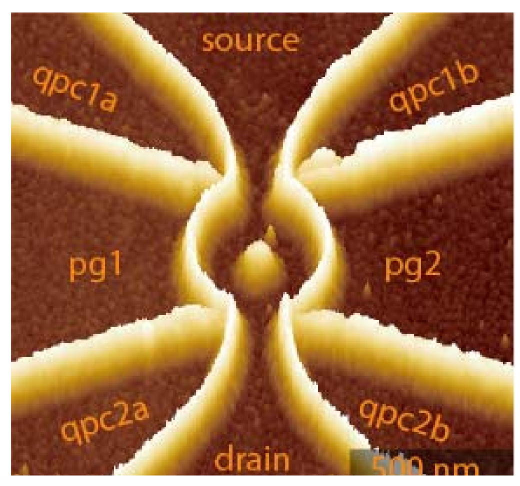

Lateral depletion length $l_{dep}$ = 15 nm << $l_{dep}$ by FIB or etching

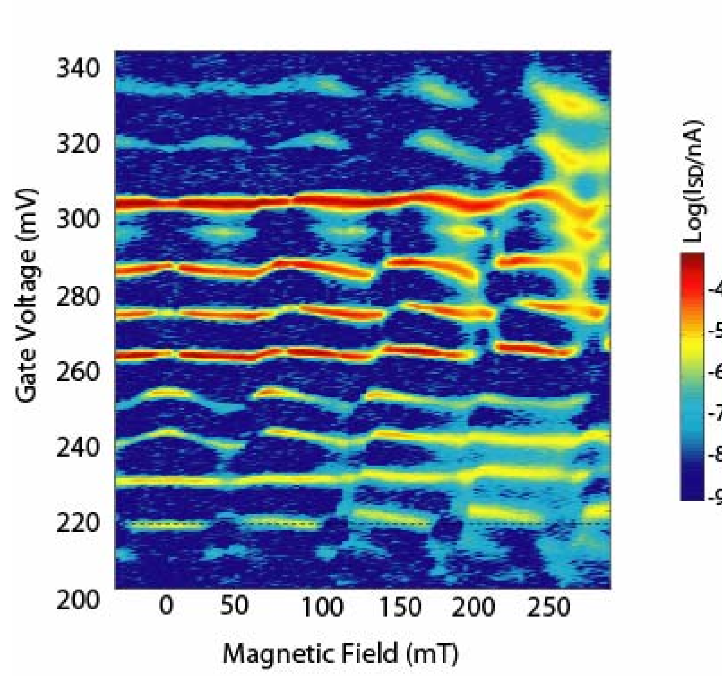
Steep walls; nonparabolic confinement possible



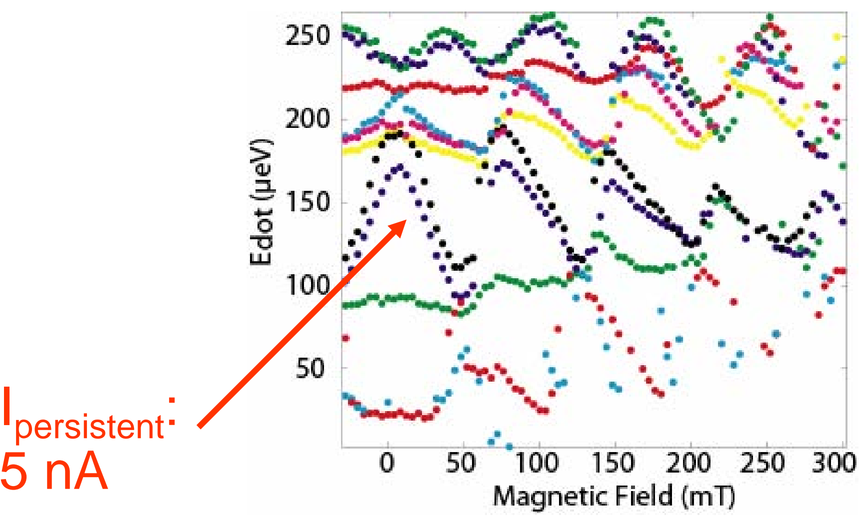
(T.H. et al.,unpublished)

# Definition of multiply connected nanostructure geometries without etching / air bridges: Coulomb blockade of a quantum ring



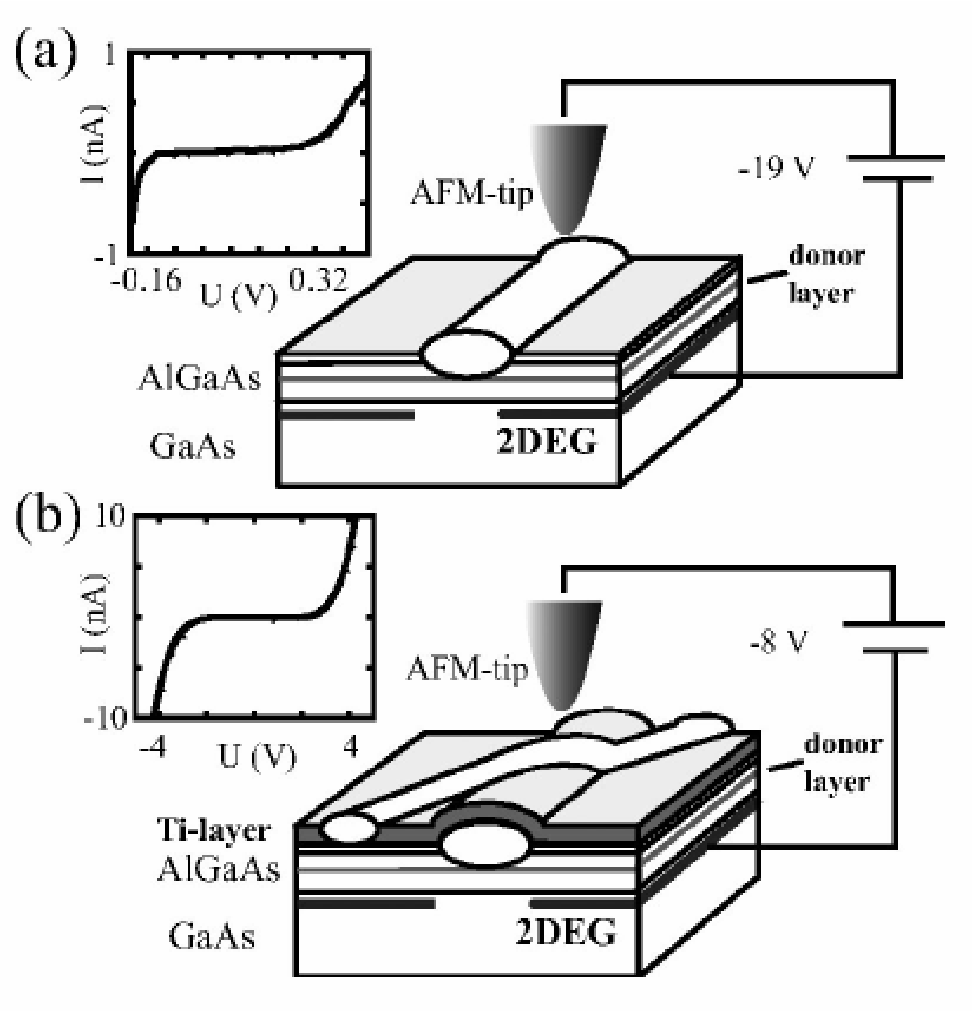

$I_{persistent}$: 5 nA






A. Fuhrer et al., Nature **413**, 822 (2001)

# Double layers of nanostructured electrodes:



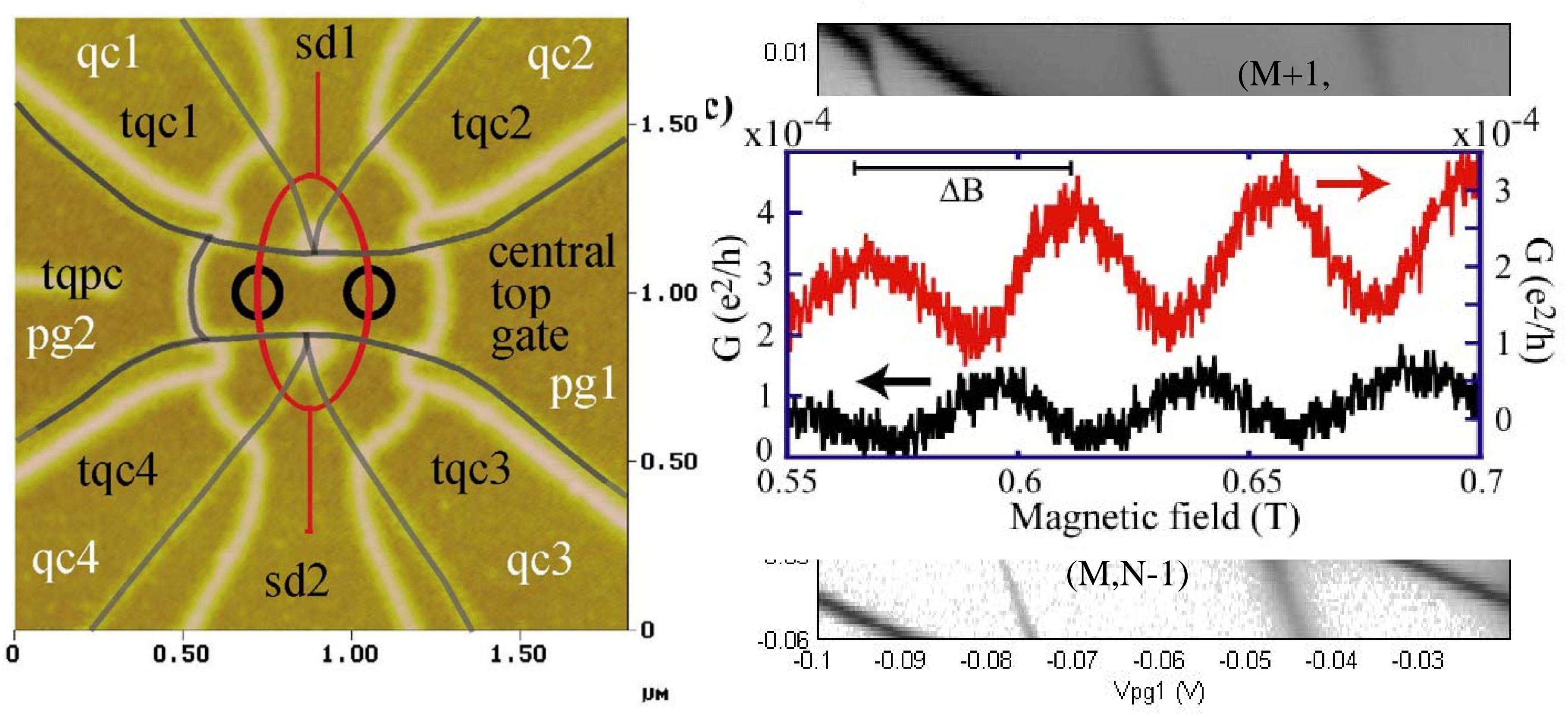

1. Local oxidation of the Ga[Al]As
2. Ti film deposition (<10nm)
3. Local oxidation of the Ti layer, aligned.



M. Sigrist et al., Appl. Phys. Lett. **85**, 3558 (2004)

# Example: coupled quantum dots embedded in a ring: Investigation of coherence in inelastic cotunneling

8 top gates, self aligned, 7 in plane electrodes




Figures: courtesy of T. Ihn, ETH Zurich

Each dot: Charging energy ~ 0.7 meV

Single-particle level spacing ~ 0.1 meV

Electron number ~ 30



M. Sigrist et al., Phys. Rev. Lett. **96**, 036804 (2006)

## Summary and Conclusions:

Scanning probe lithography is a powerful complementary technique

**Advantages:**

simple: direct writing, single step, see immediately what you get
in-situ control possible;
VERY small lateral depletion length, steep walls;
patterning ungateable samples (InAs, p-GaAs,…);
simple patterning of multiply connected geometries;
aligned double layers of nanostructures.

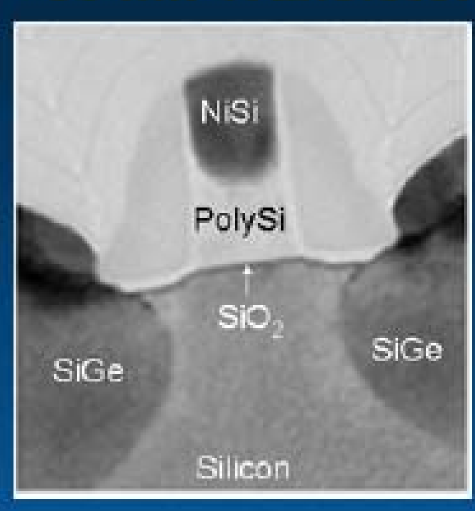
**Disadvantages:**

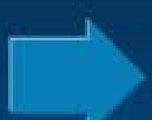
works only for shallow 2D systems;
serial process, slow;
(probably) no significant size reduction

# High-k + Metal Gate Transistors

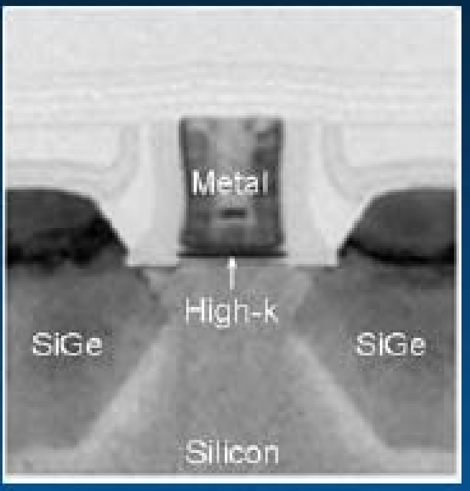
| | |
|---|---|
| Improved Transistor Density | ~2x |
| Improved Transistor Switching Speed | >20% |
| Reduced Transistor Switching Power | ~30% |

**65 nm Transistor**

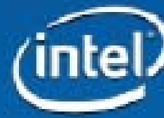


**45 nm HK + MG**




Enables New Features, Higher Performance, Greater Energy Efficiency



## Own results presented have been obtained in collaboration with:

Ryan Held
Andreas Fuhrer
Silvia Lüscher
Thomas Ihn
Klaus Ensslin — ETH Zürich

Mihai Cerchez
Stefan Hugger — HHU Düsseldorf

Thank you for your attention!