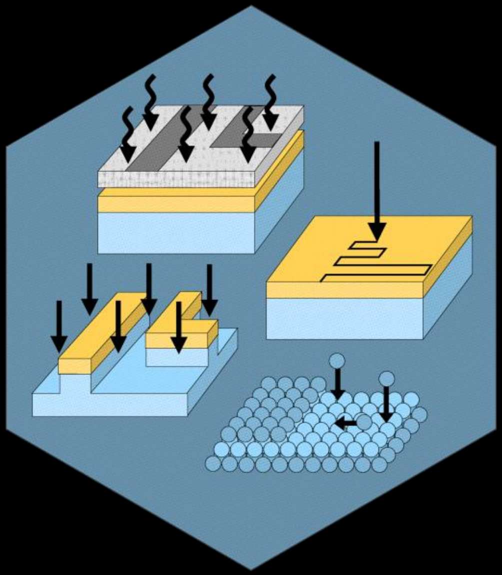
Scientific Facility

Nanostructuring Lab

https://www.fkf.mpg.de/NSL

From Brochure: FORSCHUNG LEBEN,
Uni Stuttgart (Photo: Max Kovalenko)



Scientific Facility

Nanostructuring Lab

@ Max Planck Institute for Solid State Research

Jürgen Weis

http://www.fkf.mpg.de/NSL

Few words on

Max Planck Institute
for Solid State Research

Max-Planck-Institut
für Festkörperforschung (MPI-FKF)

belongs to:

Max Planck Society

- Max Planck Institutes (about 84) carry out basic research in the life sciences, natural sciences and the social and human sciences.
- Harnack Principle:

  Identify and hire world's leading researchers as ‘Director’:

  They themselves define their research subjects and
  are given the best working conditions, as well as free reign in selecting their staff.

- Society is independent, self-organized by the Scientific Members (about 240 ‚Directors‘)
- Funded by tax payer (50% Bund, 50% 16 Bundesländer) (2 Mrd € per year)

Few examples:

- Max Planck Institute for Plasma Physics
- Max Planck Institute for Empirical Aesthetics
- Max Planck Institute for Biology of Ageing
- Max Planck Institute for Brain Research
- Max Planck Institute for the Study of Crime, Security and Law
- Max Planck Institute for Demographic Research
- Max Planck Institute for Evolutionary Anthropology
- Max Planck Institute of Quantum Optics
- Max Planck Institute for Software Systems

Campus Stuttgart-Büsnau

© Sky-Picture, Steffen Kreß

Campus Stuttgart-Büsnau:

before 03/2011:

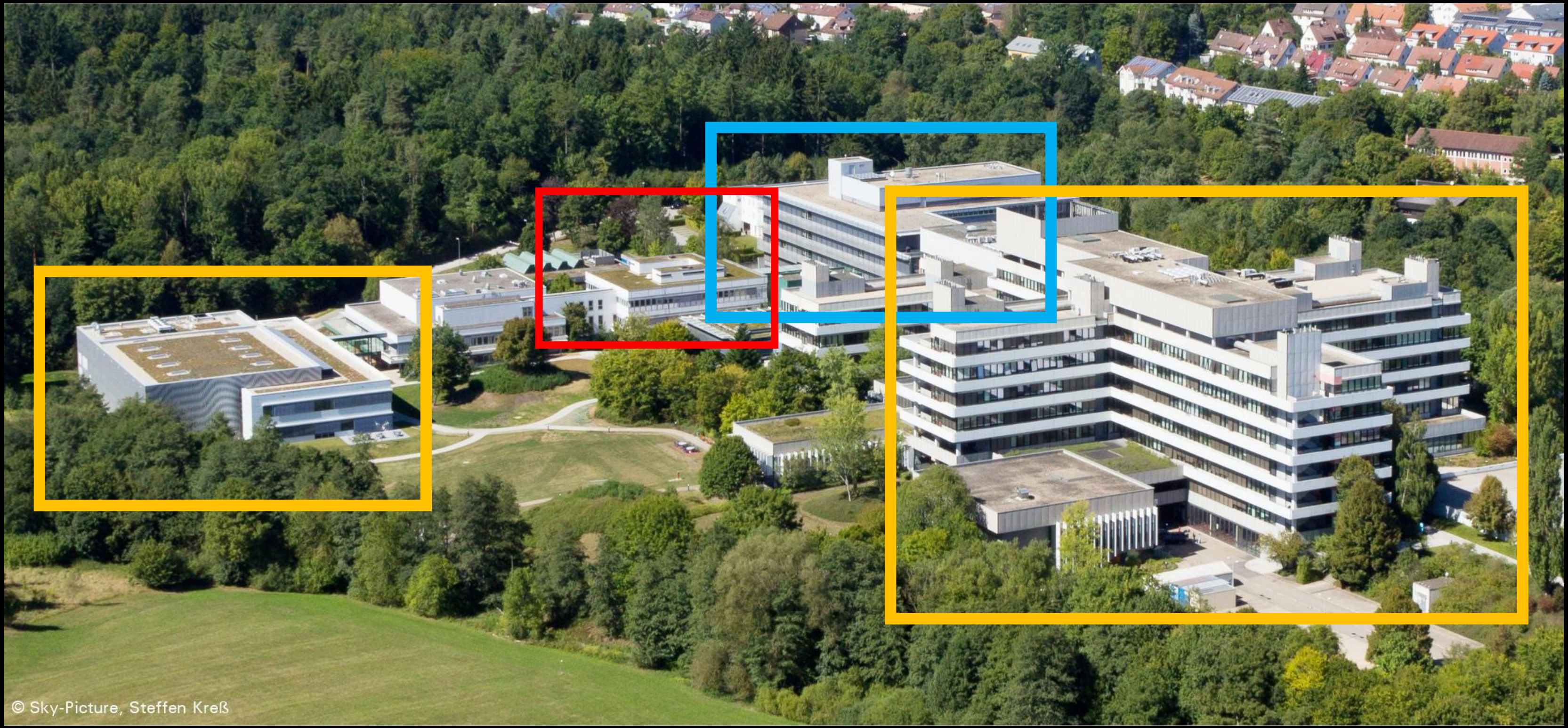
- Max Planck Institute for Metal Research (* 1921 as KWI)
- Max Planck Institute for Solid State Research (* 1969)
- Material Science of University Stuttgart

Campus Stuttgart-Büsnau:

after 03/2011:

- Max Planck Institute for Intelligent Systems (* 2011) (Stuttgart/Tübingen) (part of ‚Cyber Valley‘)
- Max Planck Institute for Solid State Research (* 1969)
- Material Science of University Stuttgart

Campus Stuttgart-Büsnau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Precision Lab

removed

MPI for Solid State Research

MPI for Intelligent Systems

Topic of the MPI for Solid State Research

Understanding and designing electronic/ionic properties of (crystaline) materials

(electron-, ion-, phonon transport,
superconductivity (@ RT ?), magnetism, spin textures ….)

Topic of the MPI for Solid State Research

Understanding and designing electronic/ionic properties of (crystaline) materials

(electron-, ion-, phonon transport,
superconductivity (@ RT ?), magnetism, spin textures ….)

- Pioneering various epitaxial growth techniques:
  Molecular Beam Epitaxy (MBE), Pulsed Laser Deposition (PLD),
  Thermal Laser Epitaxy (TLE), bulk crystal growth

Started in 1970s: MBE of III-V Compound Semiconductors

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  (neutron scattering spectrometer, probing ultrafast dynamics, scanning tunneling spectroscopy)

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- Design functionality at Interfaces / Surfaces

  Chemical Bonding, Mechanical Strain, Topology of Band Structure

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Chemical Bonding, Mechanical Strain, Topology of Band Structure

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- ➢ Confined to reduce spatial dimensions (quantum Hall effect, quantum dots)

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- Superpose another periodicity (‚superlattice‘)

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- Oxides of transition metals (d shell)

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- ➢ Superpose another periodicity (‚superlattice‘)
- ➢ Oxides of transition metals (d shell)
- ➢ Strong electron-electron correlations

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- Strong electron-electron correlations

‚New Quantum Materials’

Departments (Physics, Chemistry, Theory)

https://www.fkf.mpg.de

Electronic Structure Theory
Ali Alavi

Quantum Many-Body Theory
Walter Metzner

Solid State Spectroscopy
Bernhard Keimer

Nanoscale Science
Klaus Kern

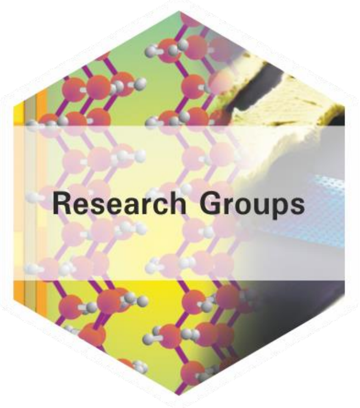
Solid State Quantum Electronics
Jochen Mannhart

Quantum Materials
Hidenori Takagi

Nanochemistry
Bettina V. Lotsch

Physical Chemistry of Solids

+



Research Groups

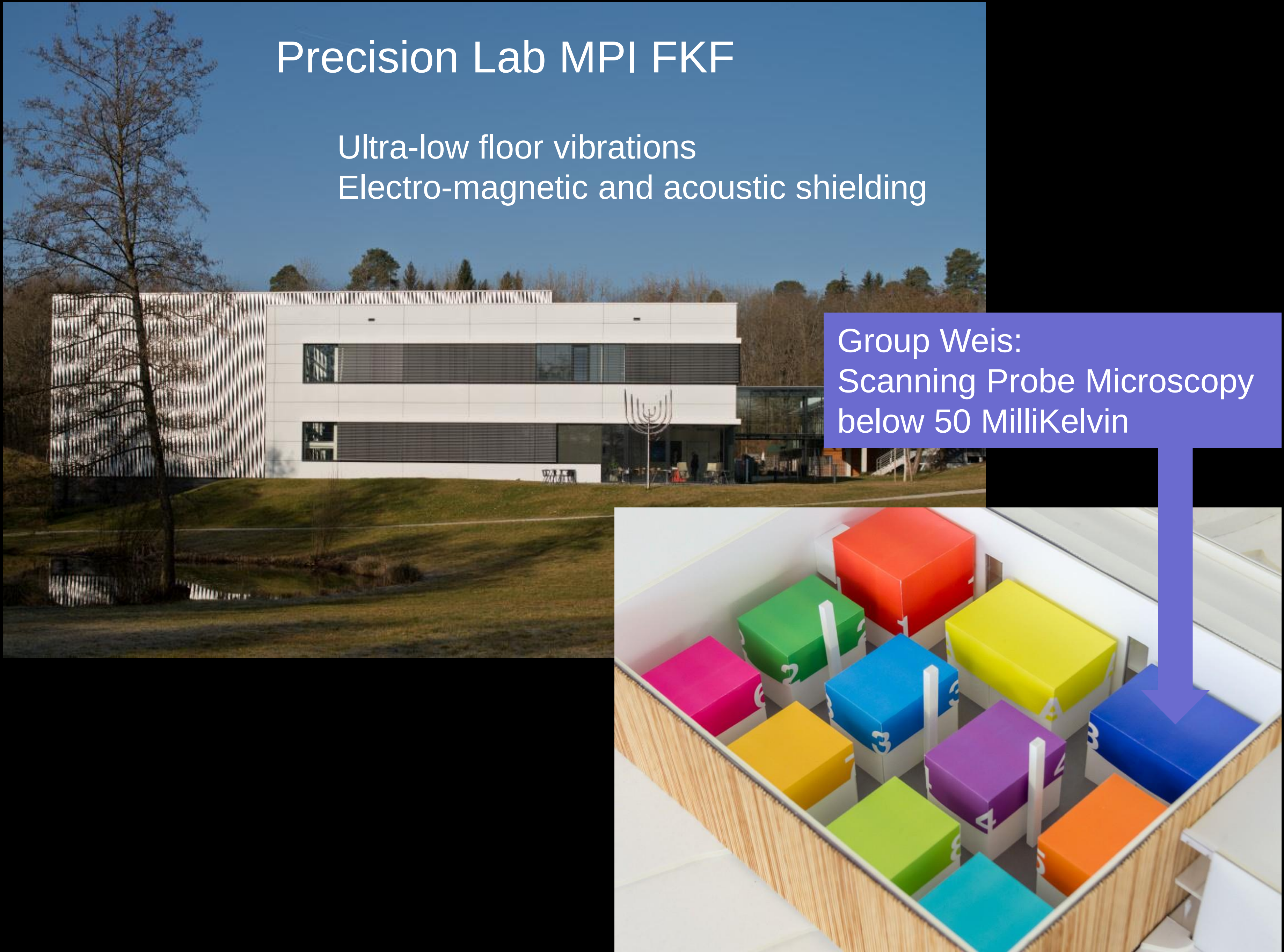
+

Scientific Facilities

480 persons (220 scientists including about 100 PhD students)

Institute offers Unique Infrastructure …

Precision Lab MPI FKF



Ultra-low floor vibrations
Electro-magnetic and acoustic shielding

Group Weis:
Scanning Probe Microscopy
below 50 MilliKelvin

Stuttgart Center for Electron Microscopy (StEM)

latest generation of

Transmission Electron Microscopes

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Nanostructuring Lab

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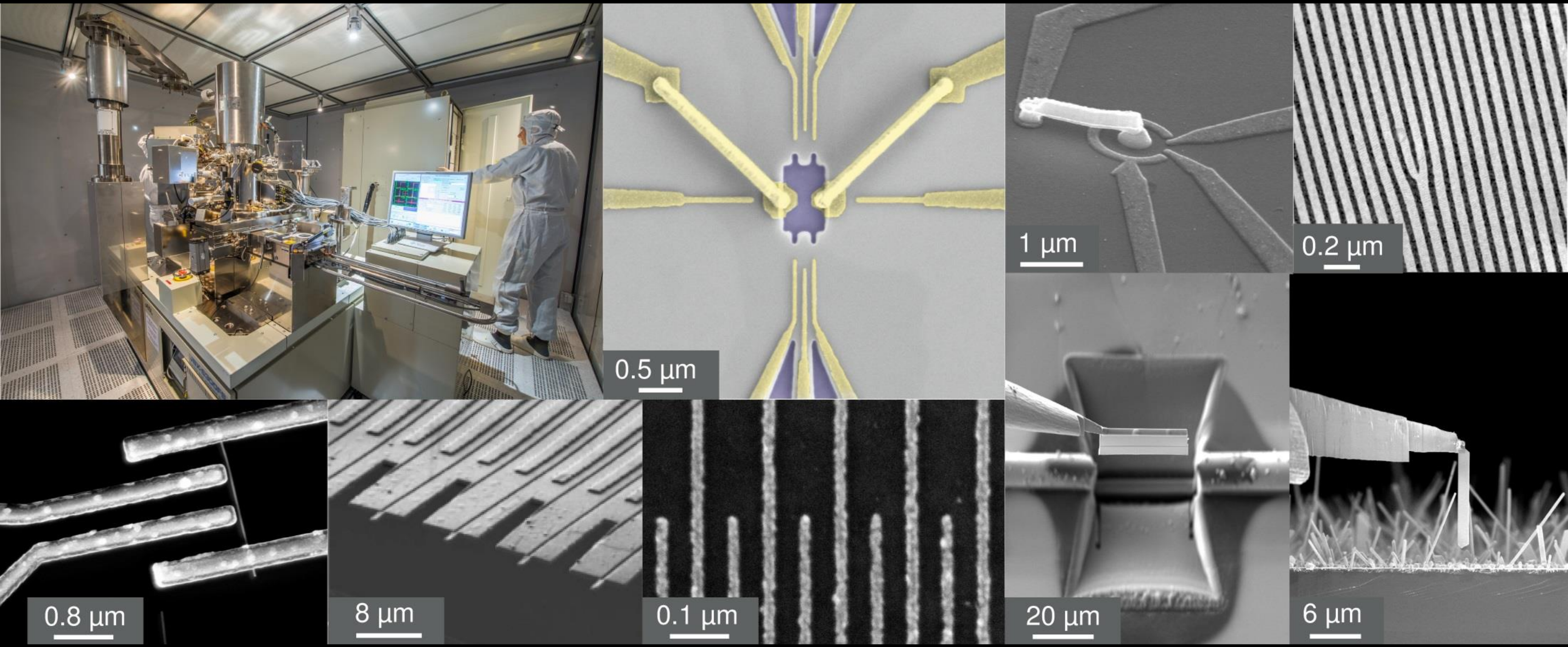
Scientific Facility

Nanostructuring Lab

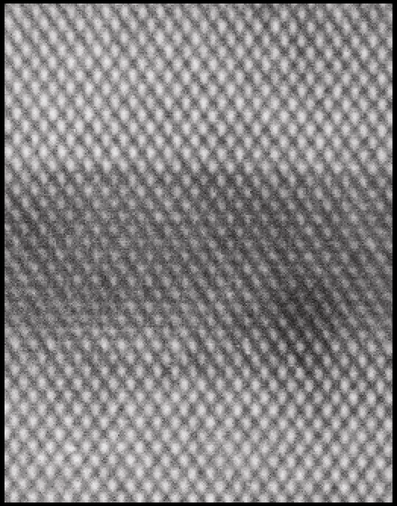


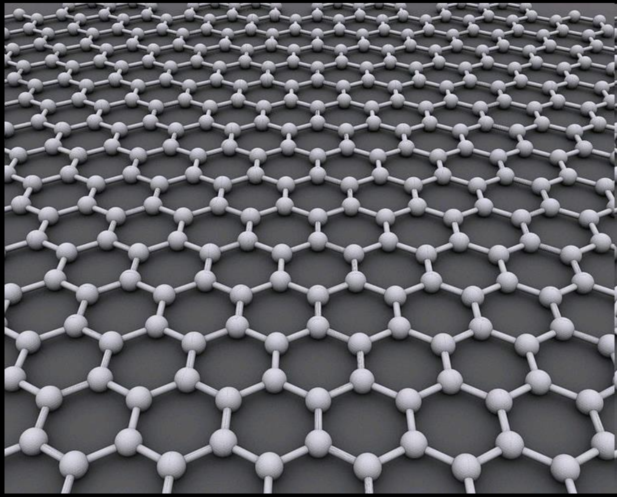
Mission:

To support Scientists of the Institute in their needs
on sample processing and characterization down to nm scale.

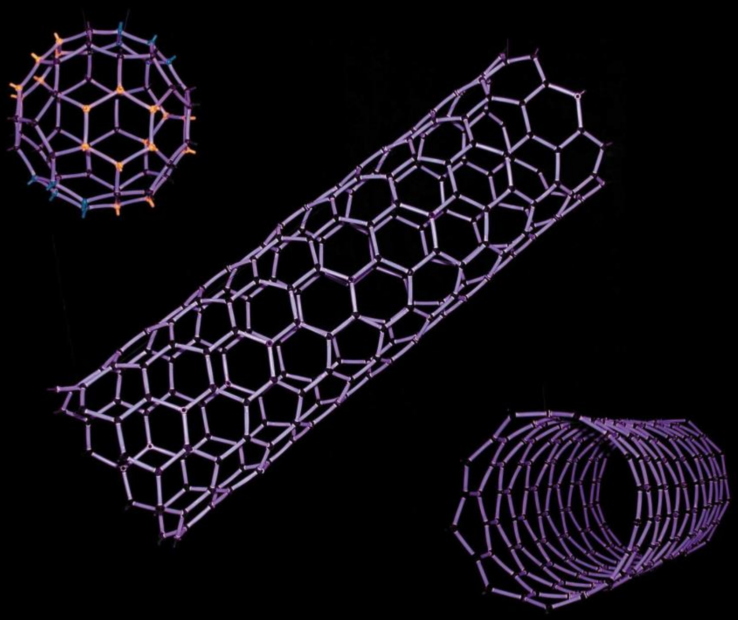
Materials which are processed:

- III-V Semiconductors
- Graphene, various 2D flakes
- Carbon nanotubes,
- Nanowires,
  - usually deposit
  - on glass or Si /SiO_2 substrate
- Organic films,
- Metal Oxide heterostructures
- Diamond
- Silicon
- SiC, BN
- Glass
- Li and Na based materials
- ….



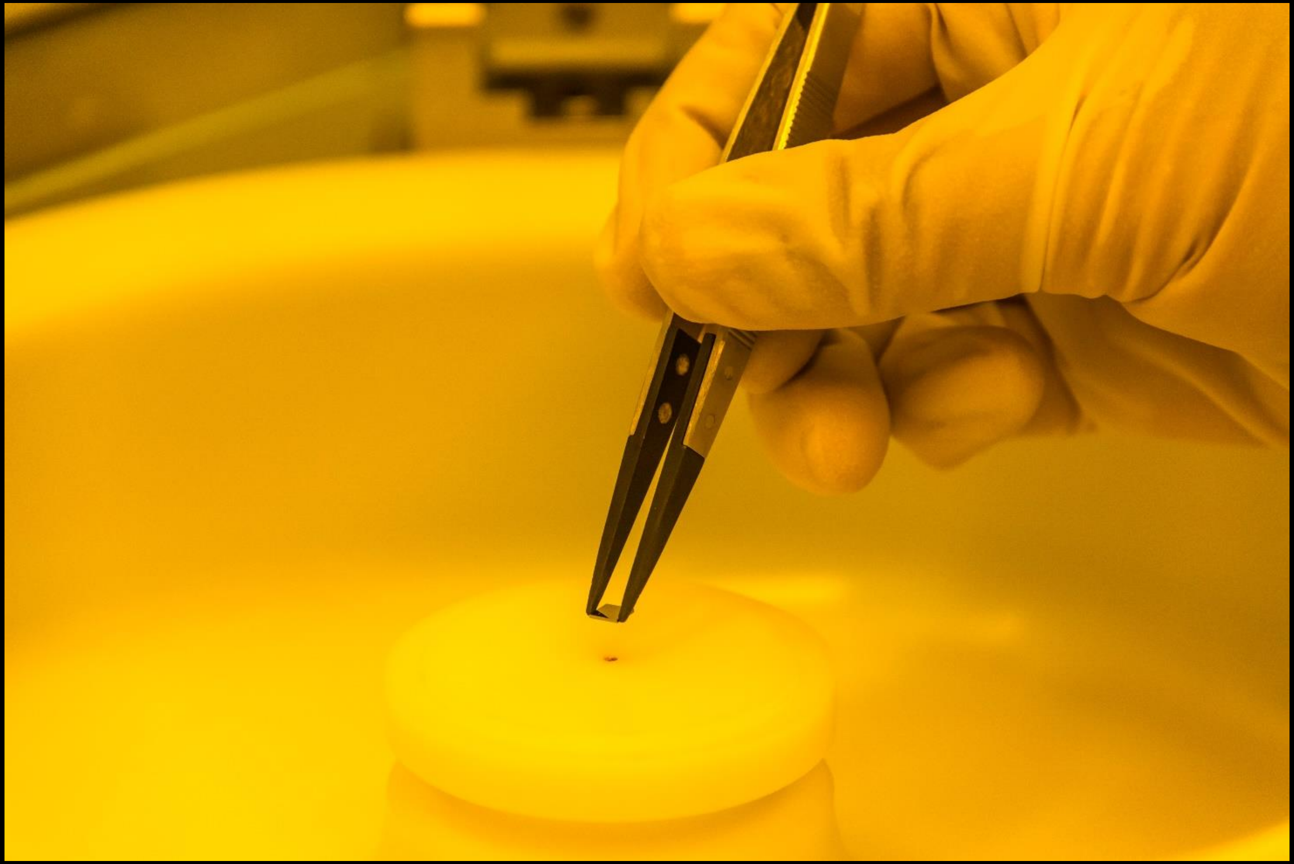


Source: Wikipedia



Source: Swiss Nanoscience Institute

Handling small pieces up to wafer



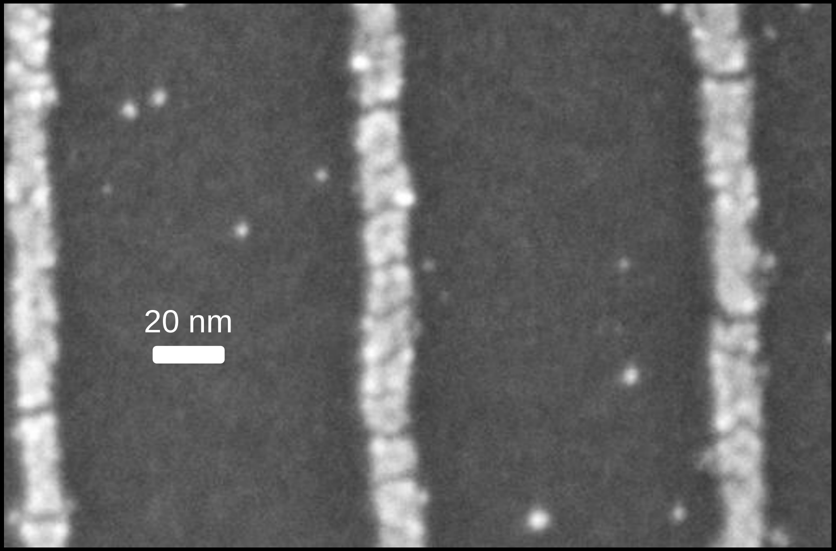
Tools / Techniques ?

Electron Beam Lithography

- JEOL JBX6300FS (100 kV)
- Raith eLine, Raith eLine plus (< 30 kV)

Electron Beam Lithography
- JEOL JBX6300FS
- Raith eLine, Raith eLine plus

Optical Lithography
(Mask aligner, Laser Direct Writer)



Electron Beam Lithography
  JEOL JBX6300FS
  Raith eLine, Raith eLine plus

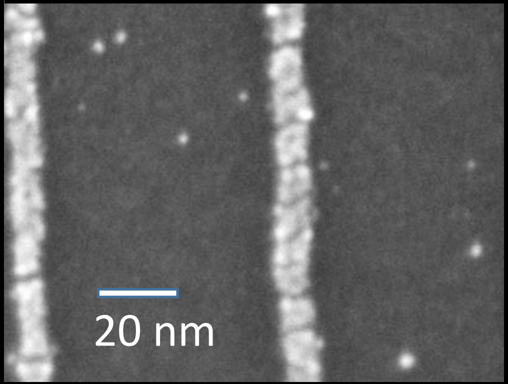
Optical Lithography

Scanning Electron Microscopy
  Zeiss Merlin, Zeiss SEM 500

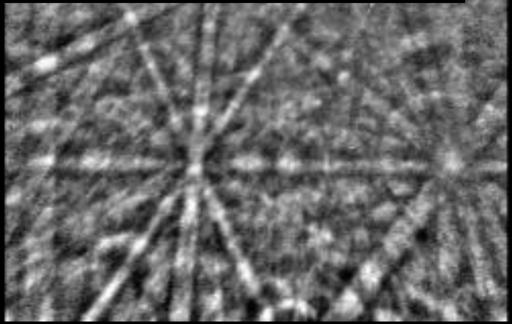
Scanning Electron Microscopy

Imaging + Analytics + In-situ Complementary Techniques

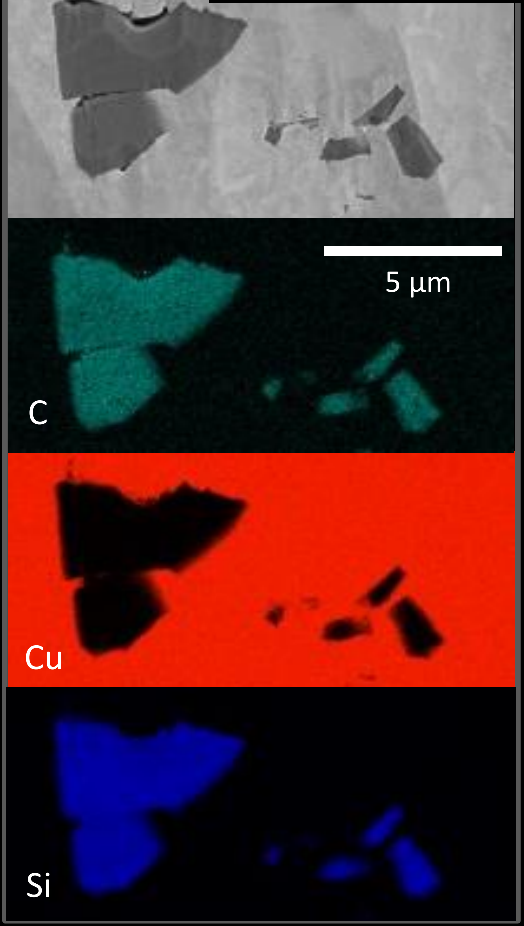
High-resolution SEM imaging



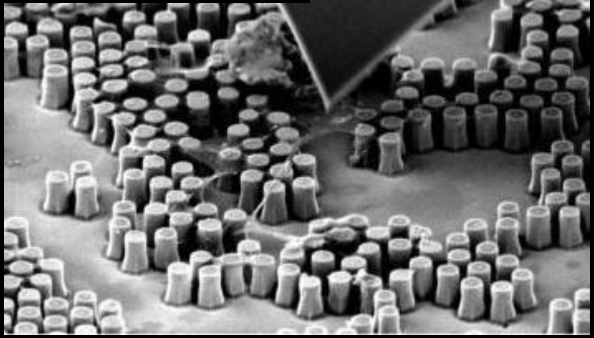
EBSD: Kikuchi pattern on thermally treated ALD-HfO_x



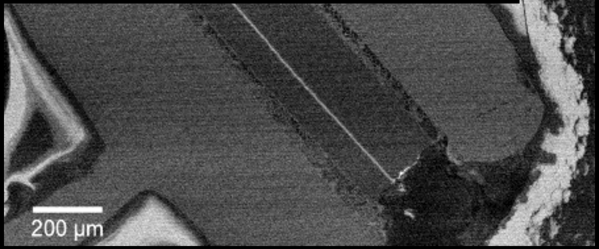
SEM/EDX (SiC on Cu)

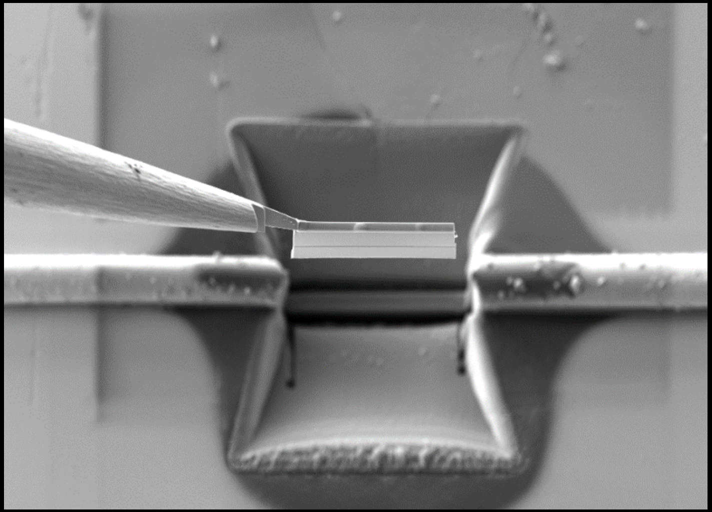


AFM/STM in SEM



Electron Beam Induced Current (EBIC) signal overlaid on SEM image of pn diode





Electron Beam Lithography
    JEOL JBX6300FS
    Raith eLine, Raith eLine plus

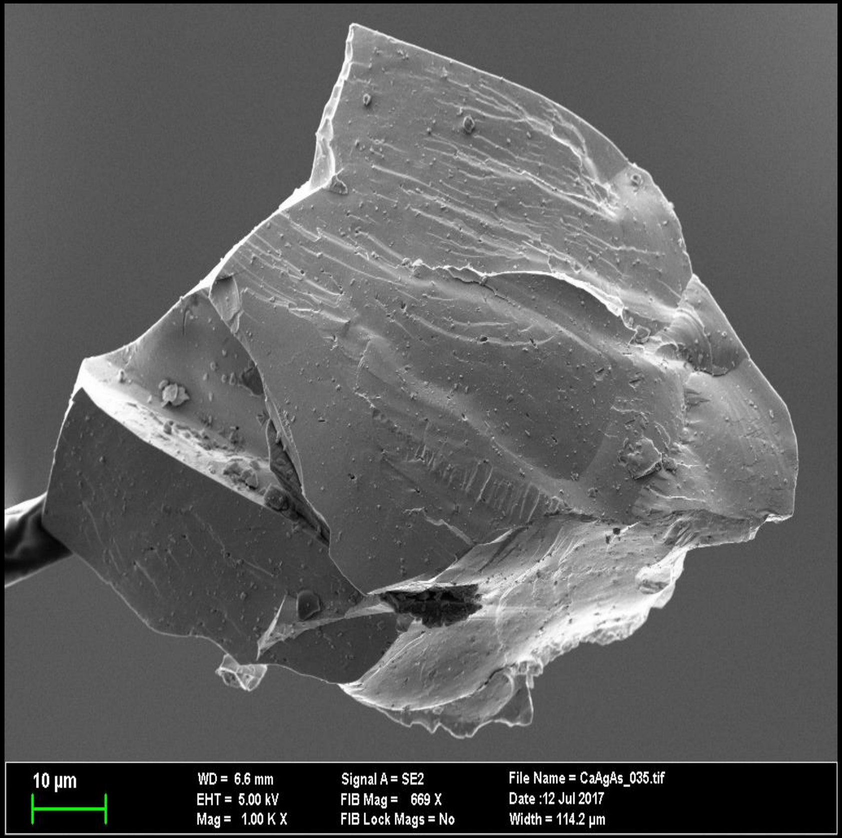
Optical Lithography

Scanning Electron Microscopy
    Zeiss Merlin, Zeiss SEM 500

‚Swiss Knife for the Nanoworld'
    Zeiss Crossbeam

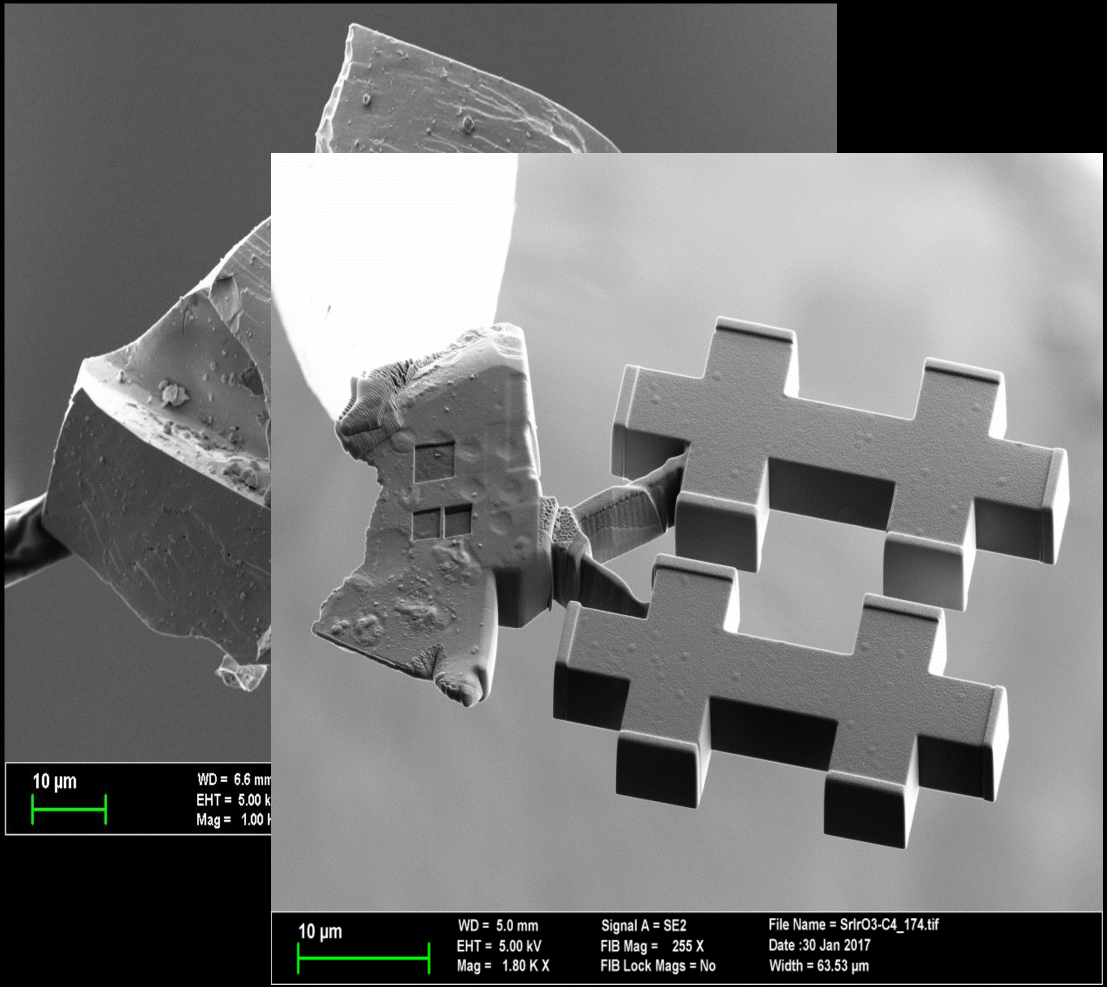
- Focused Ga Ion Beam
- Scanning Electron Microscope
- Gas Injection (‚Glue')
- Micromanipulators
- EDX
- …..

Example: Focussed Ion Beam Preparation
(for Dept. Takagi)



A. Bangura (Dept. Takagi), B. Fenk

Example: Focussed Ion Beam Preparation (for Dept. Takagi)



A. Bangura (Dept. Takagi), B. Fenk

Example: Focussed Ion Beam Preparation (for Dept. Takagi)

A. Bangura (Dept. Takagi), B. Fenk

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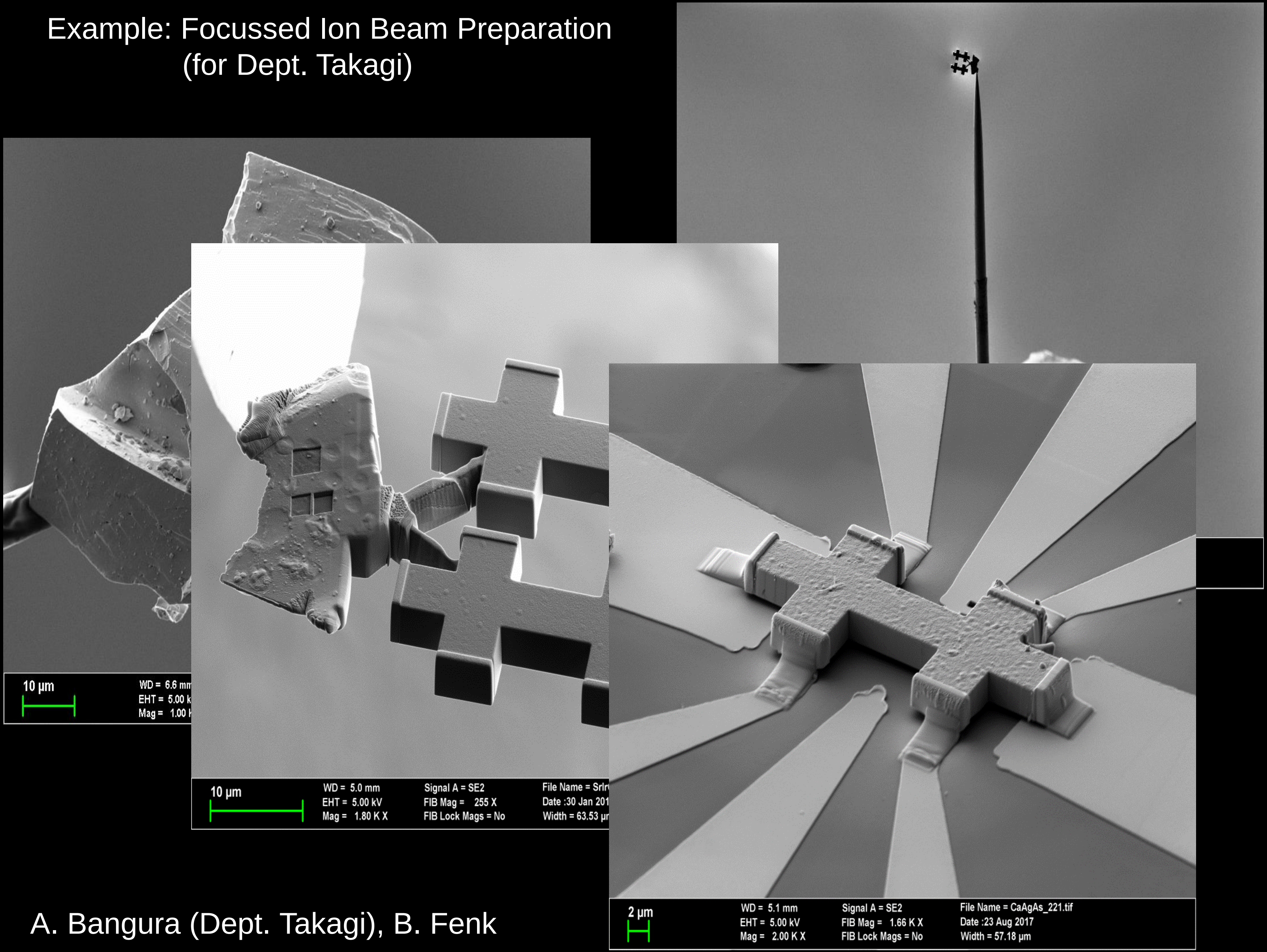
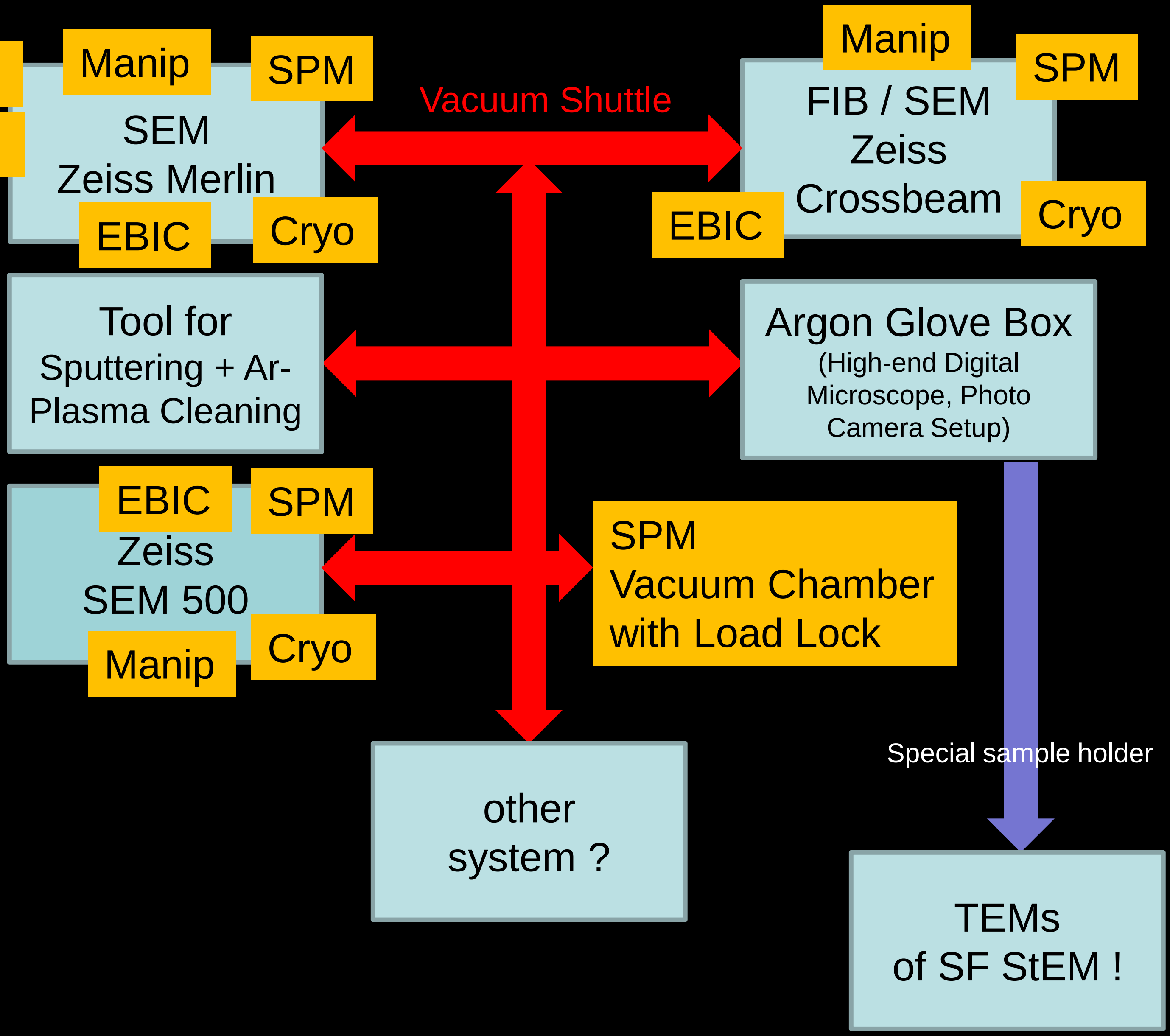


A. Bangura (Dept. Takagi), B. Fenk

Vacuum / Oxygen-free Shuttle between Systems



EDX

EBSD

Manip

SPM

SEM
Zeiss Merlin

EBIC

Cryo

Vacuum Shuttle

Manip

SPM

FIB / SEM
Zeiss
Crossbeam

EBIC

Cryo

Tool for
Sputtering + Ar-Plasma Cleaning

Argon Glove Box
(High-end Digital Microscope, Photo Camera Setup)

EBIC

SPM

Zeiss
SEM 500

Manip

Cryo

SPM
Vacuum Chamber
with Load Lock

Special sample holder

other
system ?

TEMs
of SF StEM !

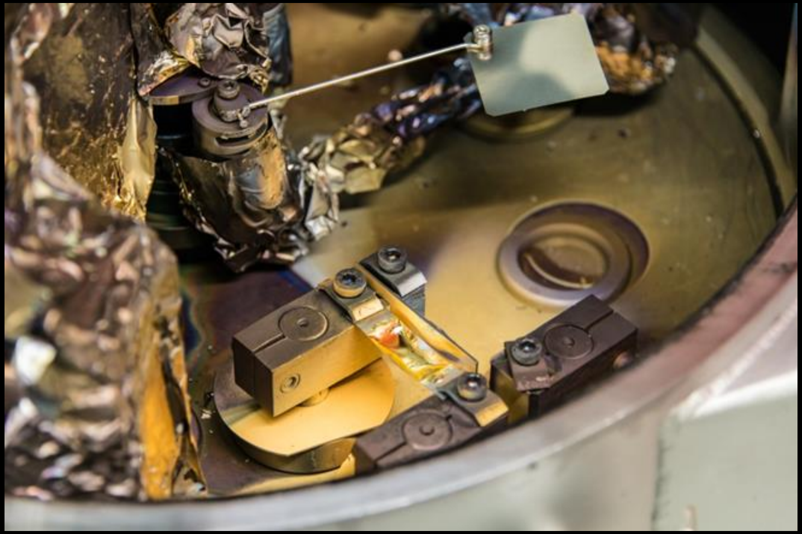
Electron Beam Lithography
    JEOL JBX6300FS
    Raith eLine, Raith eLine plus

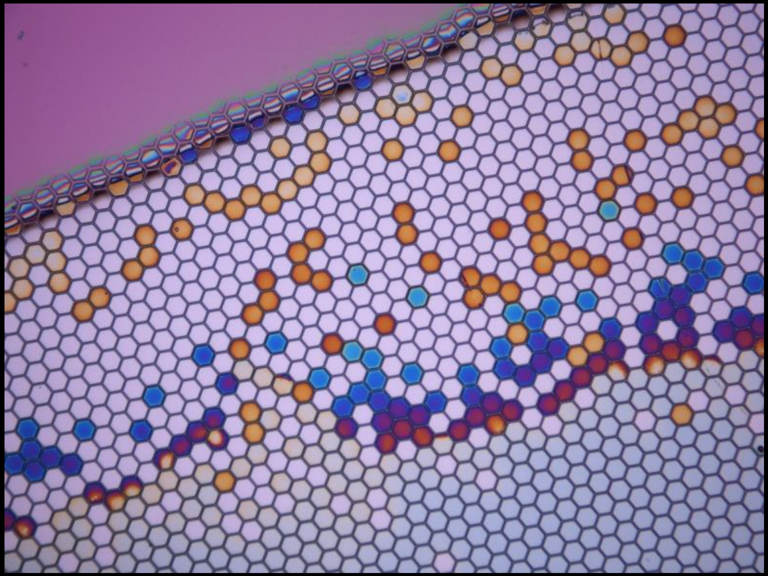
Optical Lithography

Scanning Electron Microscopy
    Zeiss Merlin, Zeiss SEM 500

‚Swiss Knife for the Nanoworld‘
    Zeiss Crossbeam

Material Deposition/Sputtering in Vacuum





Electron Beam Lithography
JEOL JBX6300FX
Raith eLine, Raith eLine plus

Optical Lithography

Scanning Electron Microscopy
Zeiss Merlin, Zeiss SEM 500

‚Swiss Knife for the Nanoworld'
Zeiss Crossbeam

Material Deposition/Sputtering in Vacuum

Wet and Dry Etching

Atomic Layer Deposition

Dry Etching / Reactive Ion Etching

Oxford Instruments Plasma Pro100 Cobra (ICP-RIE)

- installed 2016
- up to 16 process gases

  Ar, He, N_2
  O_2
  H_2, CH_4
  SF_6
  Cl_2, BCl_3, $SiCl_4$
  HBr
  C_4H_8, CHF_3, CF_4

- Sample Electrode -150 °C …. 300 °C
- ‚Bosch Process‘ for deep Si etching

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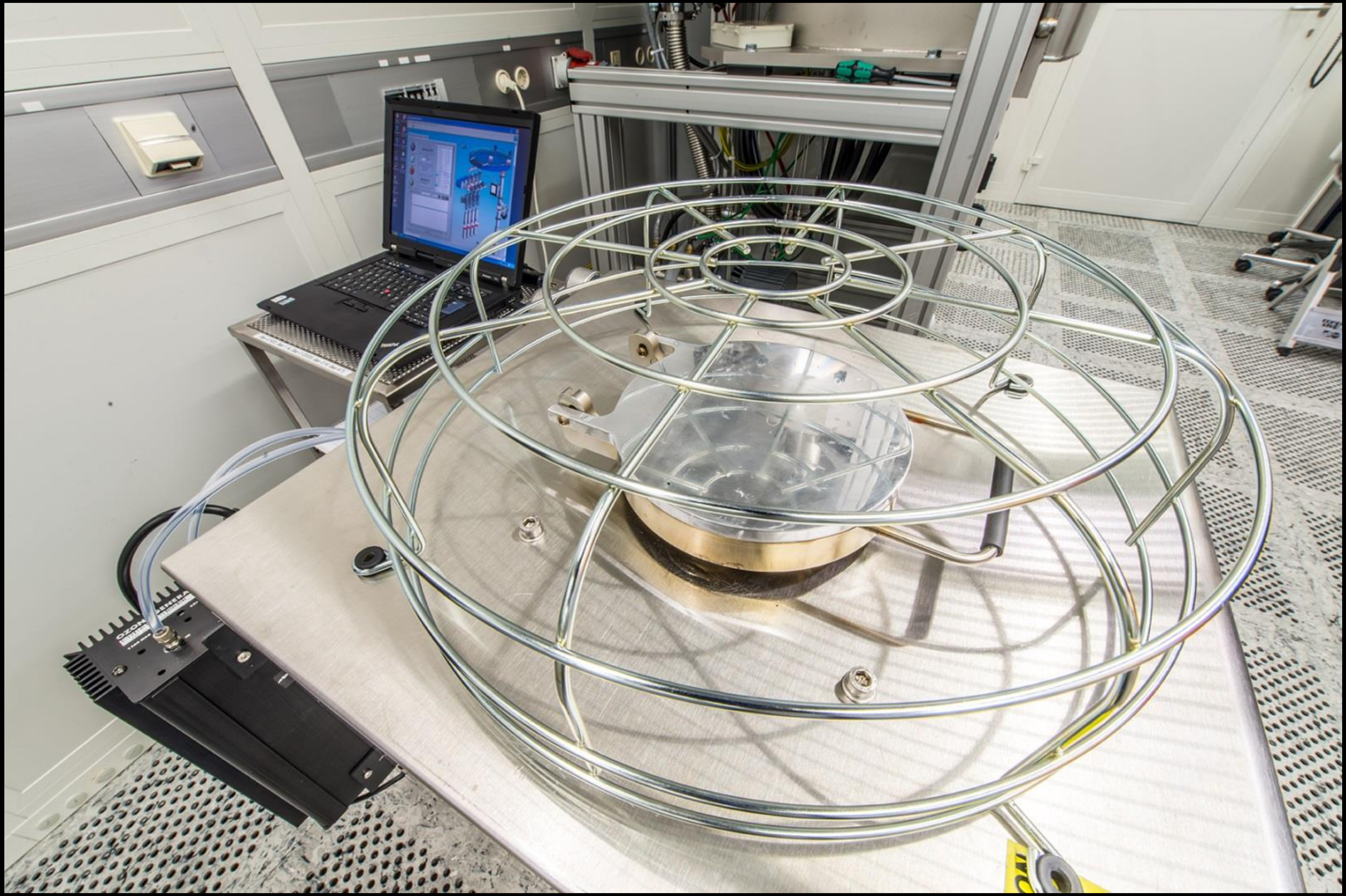
  HBr
  C_4H_8, CHF_3, CF_4

- Sample Electrode -150 °C …. 300 °C
- ‚Bosch Process‘ for deep Si etching

fluorine, chorine, bromine chemistry

Thermal Atomic Layer Deposition (ALD)

Cambridge Nanotechnolgy Shavanna 100

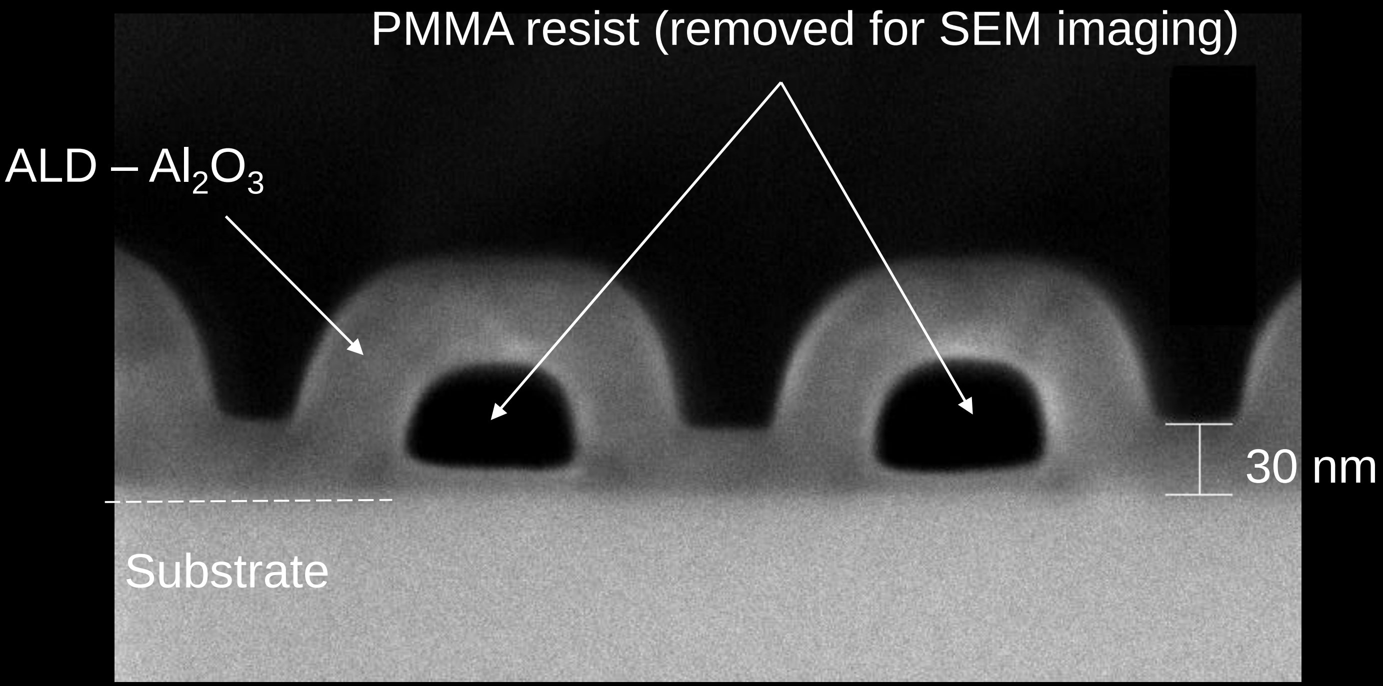


Materials deposited:

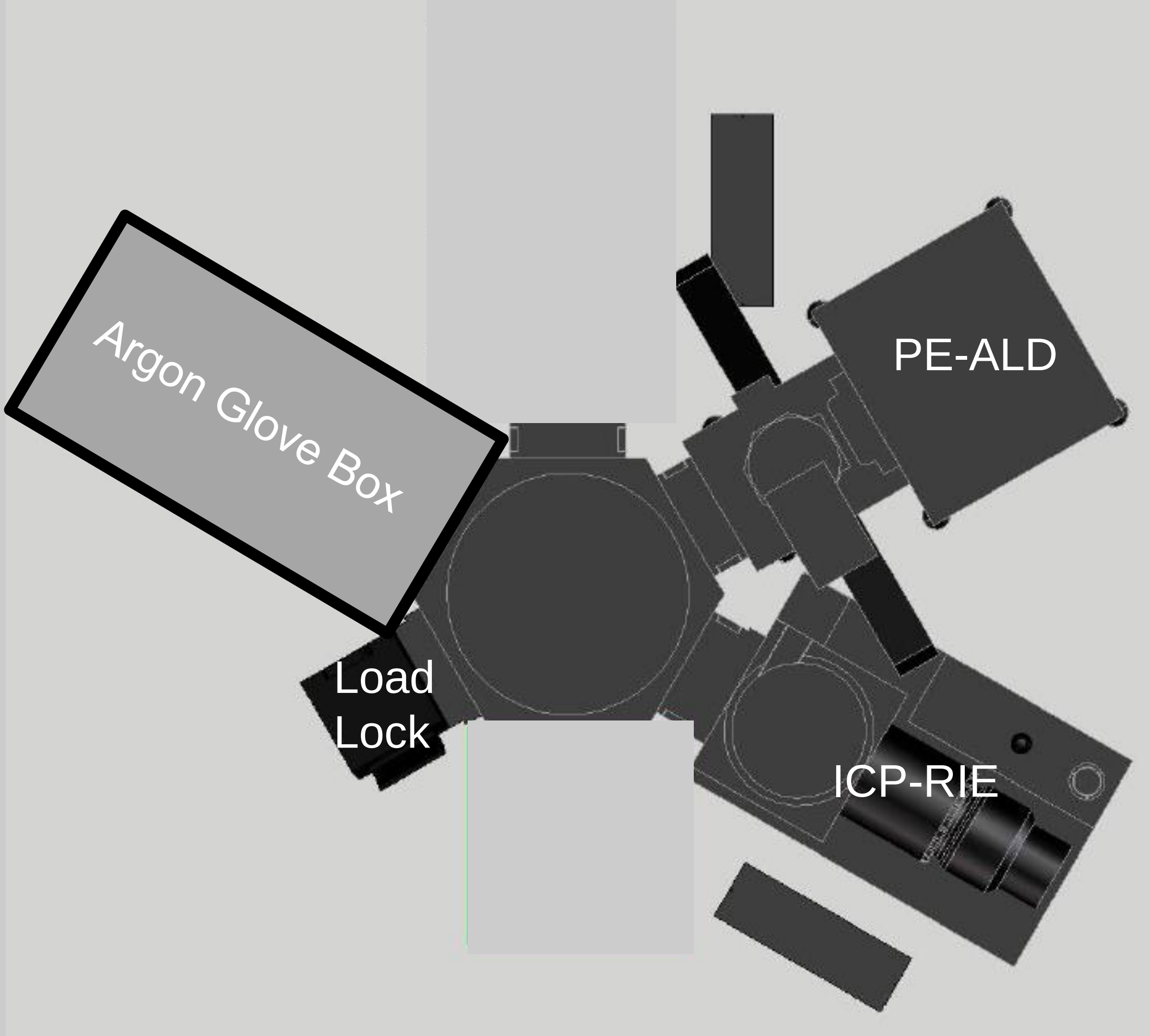
- Al_2O_3
- HfO_x
- TiO_2

Atomic Layer Deposition (ALD):

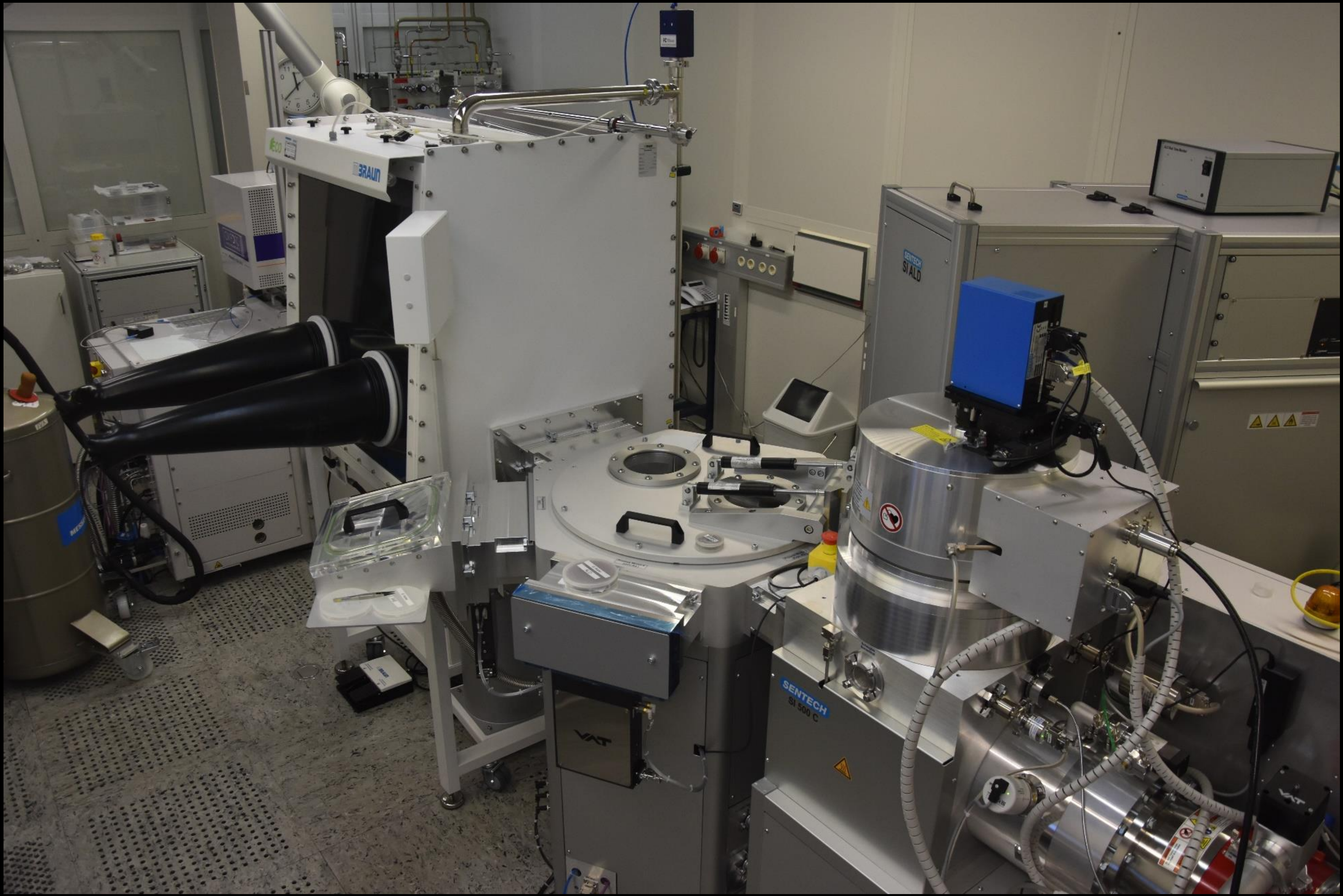
Resist Profiles (?)



Sentech-Cluster



Plasma Processing Cluster



Plasma Processing Cluster with

Induced Coupled Plasma Reactive Ion Etching (ICP RIE)
(fluorine, chorine, bromine chemistry)

Plasma Enhanced Atomic Layer Deposition (PEALD)
with in-situ Laser Ellipsometry
(oxides, nitrides, sulfides, metal)

→ Surface Treatment and Surface Sealing
without breaking vacuum

Broad Spectrum of Processing and Material Options

Electron Beam Lithography
JEOL JBX6300FX
Raith eLine, Raith eLine plus

Optical Lithography

Scanning Electron Microscopy
Zeiss Merlin, Zeiss SEM 500

‚Swiss Knife for the Nanoworld'
Zeiss Crossbeam

Material Deposition/Sputtering in Vacuum

Wet and Dry Etching

Atomic Layer Deposition

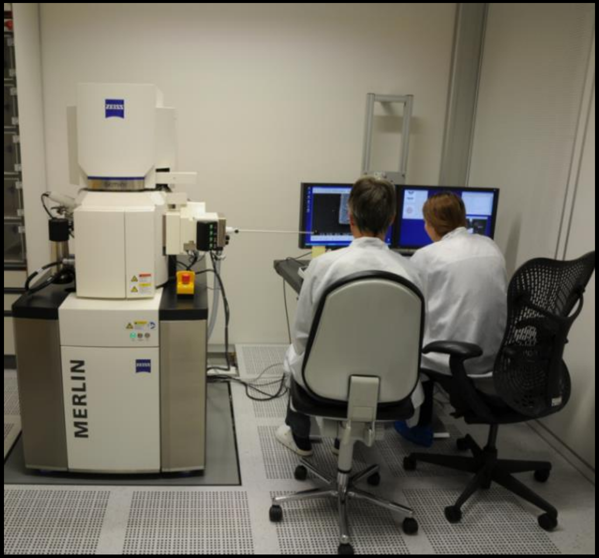
Wire Bonding

Clean Chemical Working Places
(‚Wet benches')

(including HF etching with safety infrastructure)

Service offered from the NSL Team

- You get trained / take ‚driver license‘ and use equipment on your own.
- We process samples / make SEM analysis / … for you.
- We take care of the equipment / infrastructure.
- We make a common process development.
- We push common research projects.
- We develop processing techniques
  and infrastructure further.
- We keep knowledge about processing techniques.
- We evaluate new tools for possible use in NSL.



NSL Customers are Scientists of

MPI-FKF, MPI-IS, University of Stuttgart

+ Collaborations (like PTB)

Electron-Beam Lithography

SEM-based
Electron Beam Lithography
Raith eLine

Established in Summer 2006

Meanwhile, more than 150 persons have been trained.

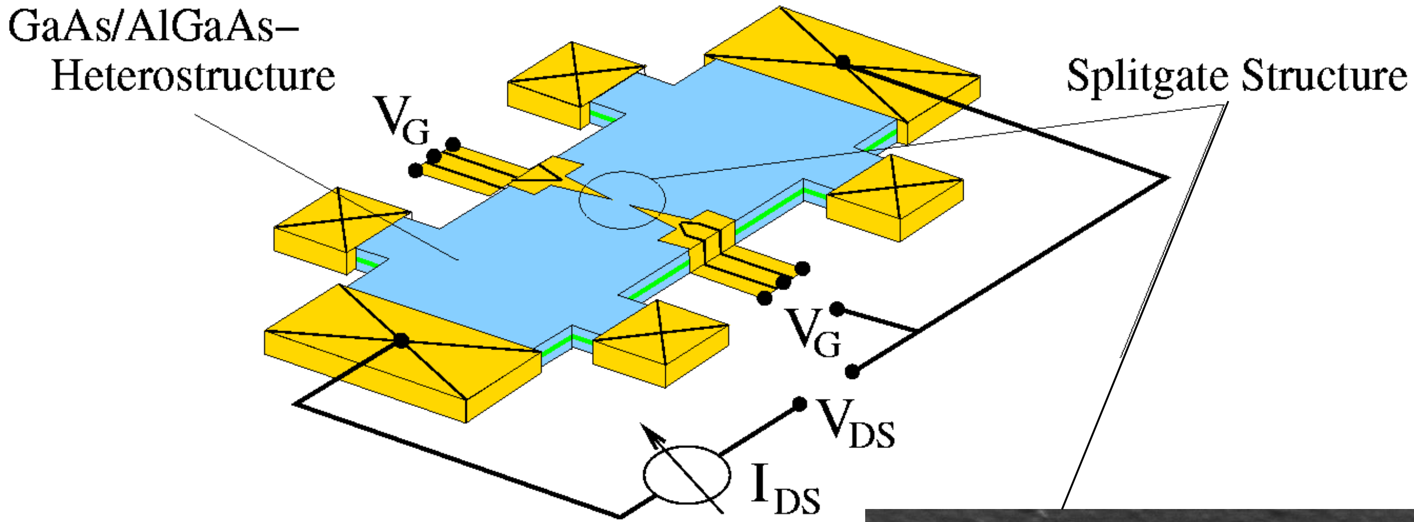
In the past, more than 40 persons had access in parallel.

Electron Beam Lithography

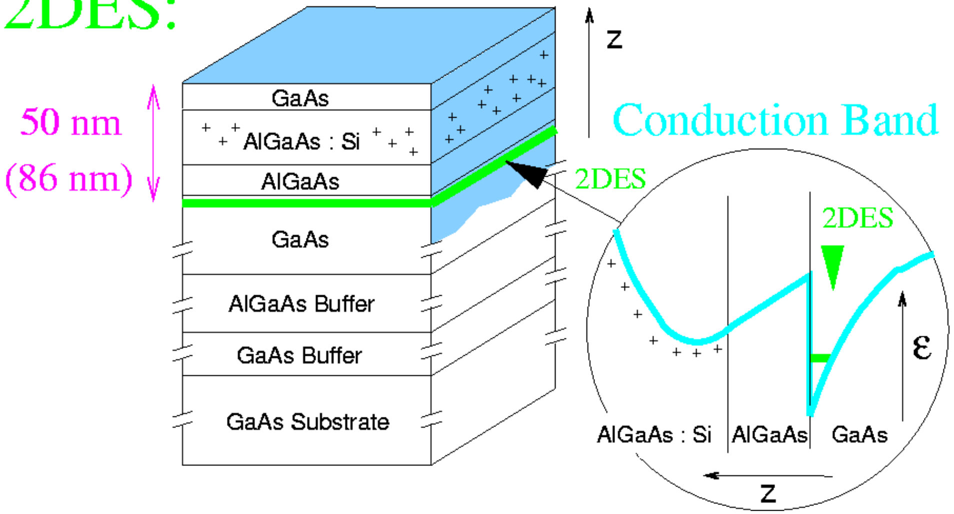
Raith eline plus (installed in 09/2021)

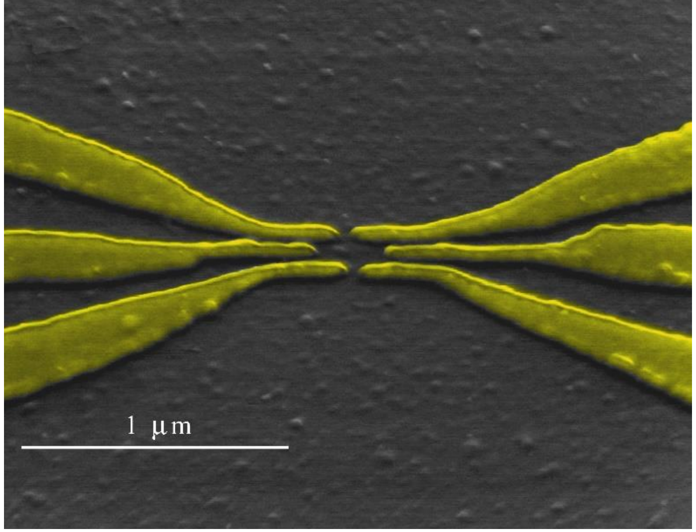
Examples for samples processed by users on the Raith eLine

Split–Gate Technique:



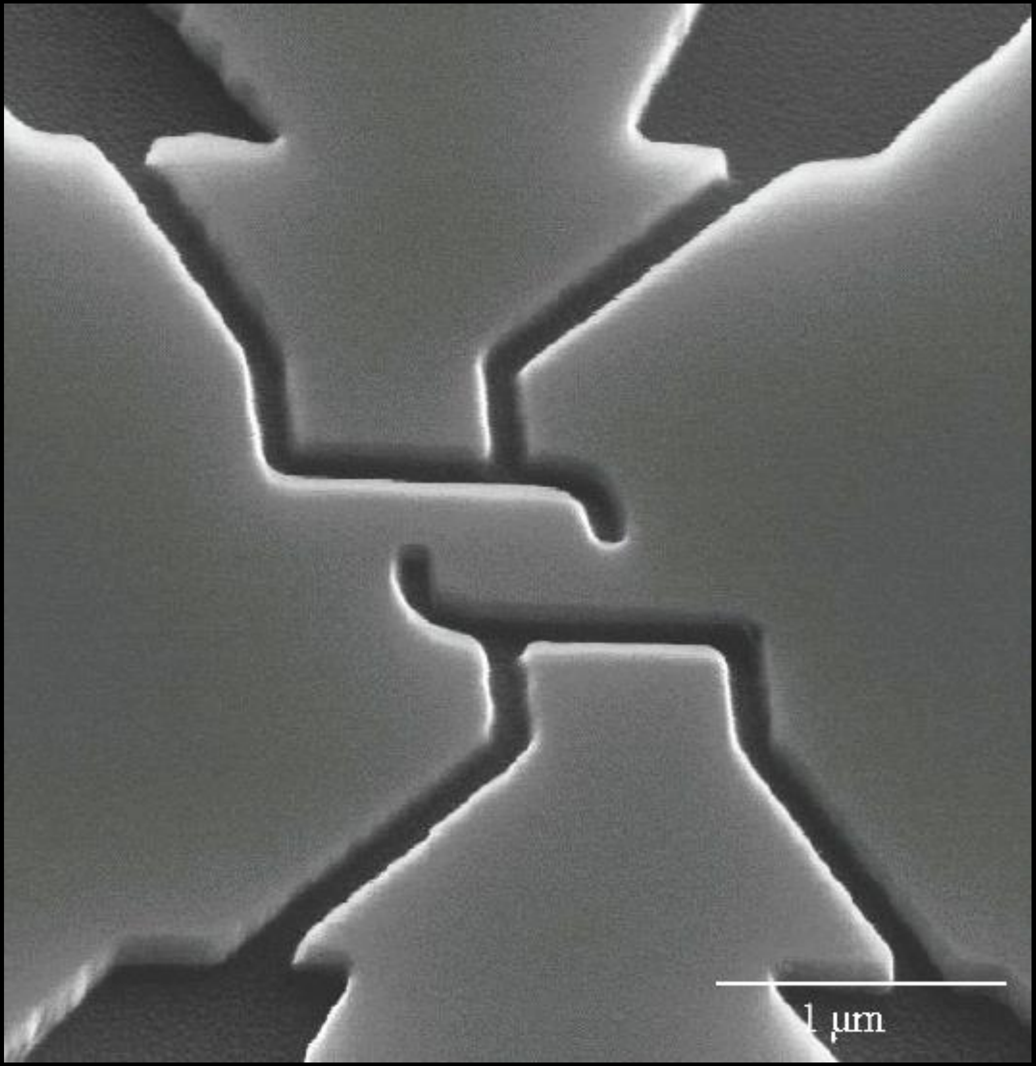
2DES:





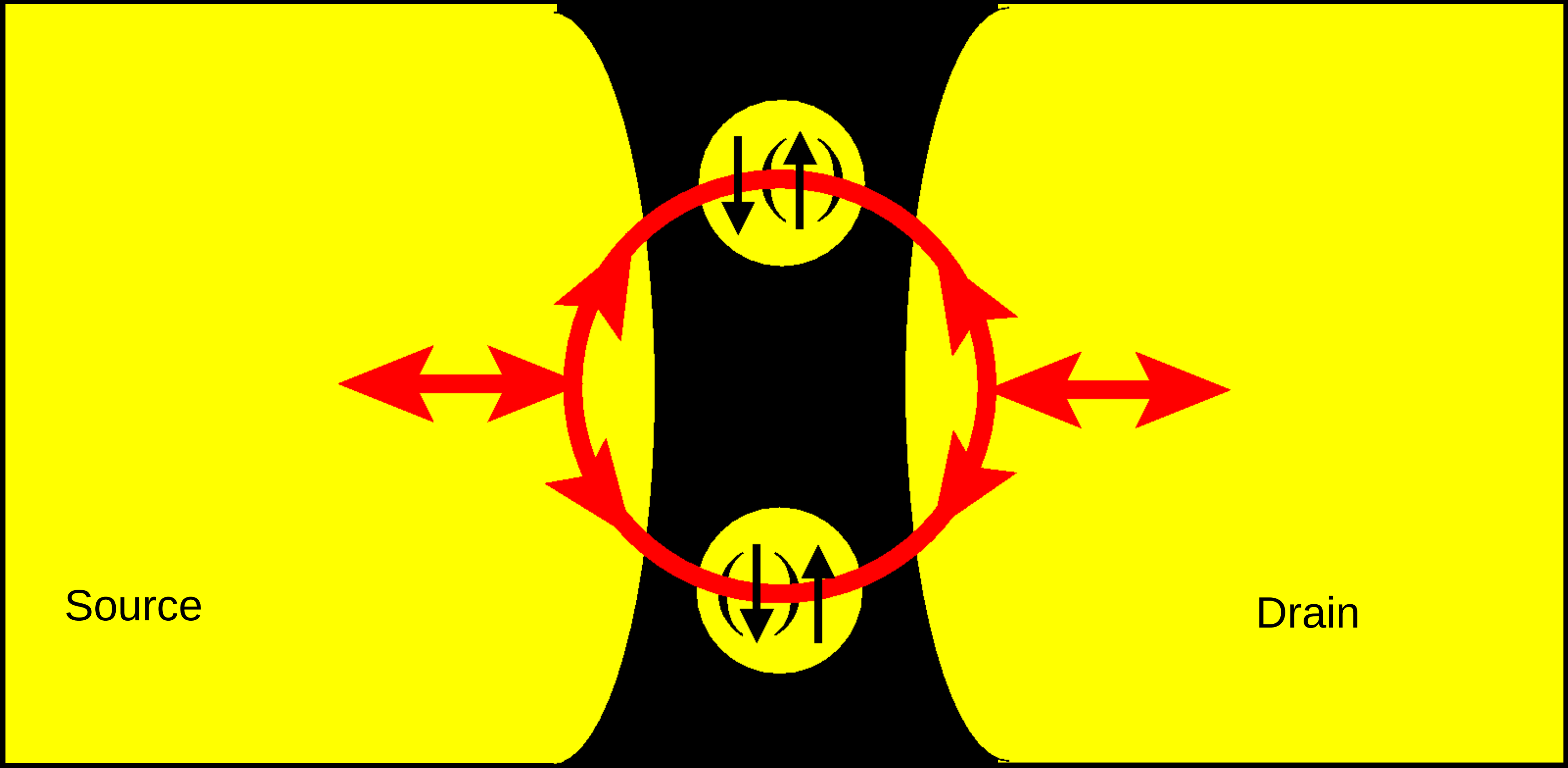
Started 1990s

Quantum Dot System by Etching Grooves

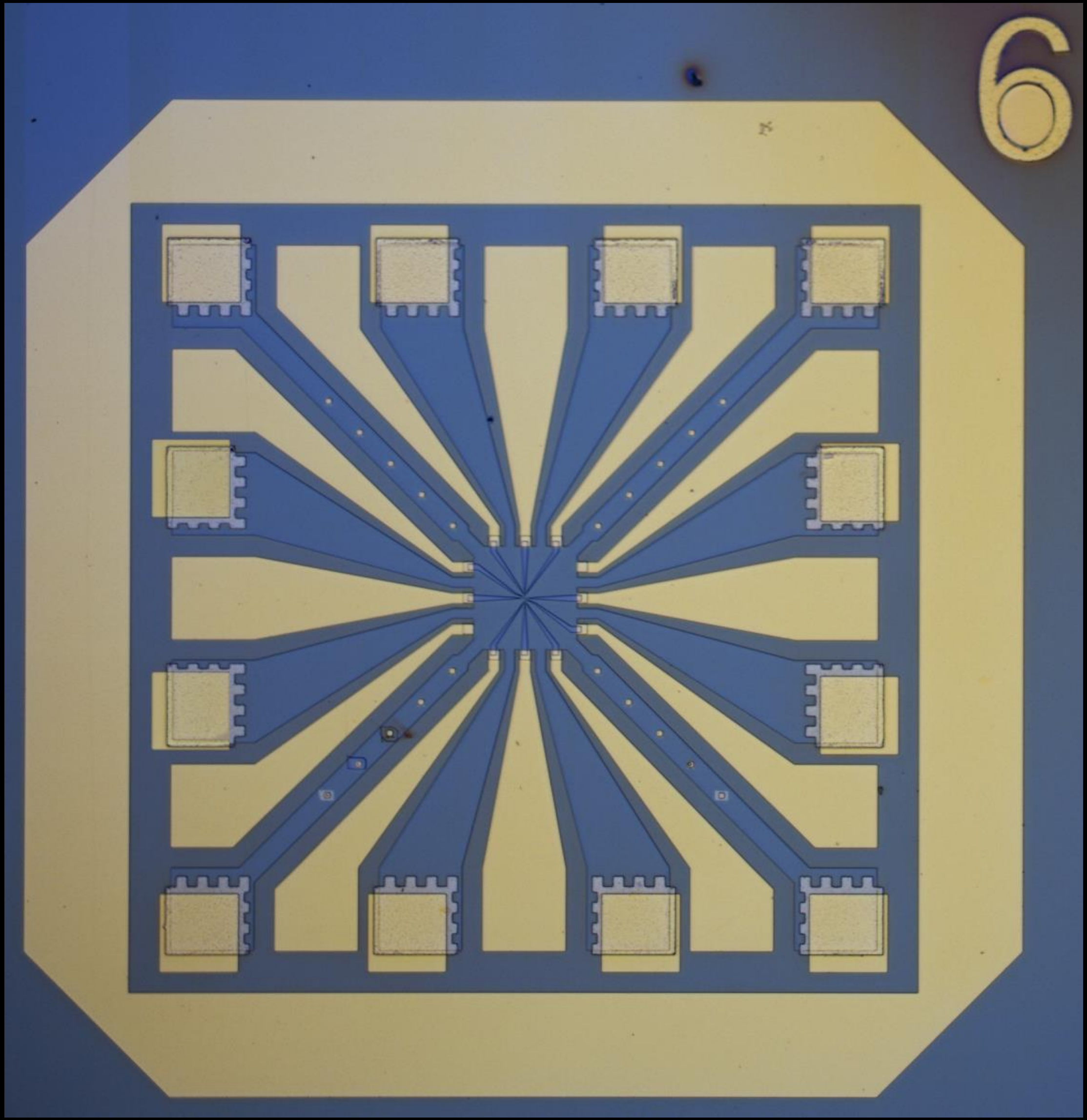


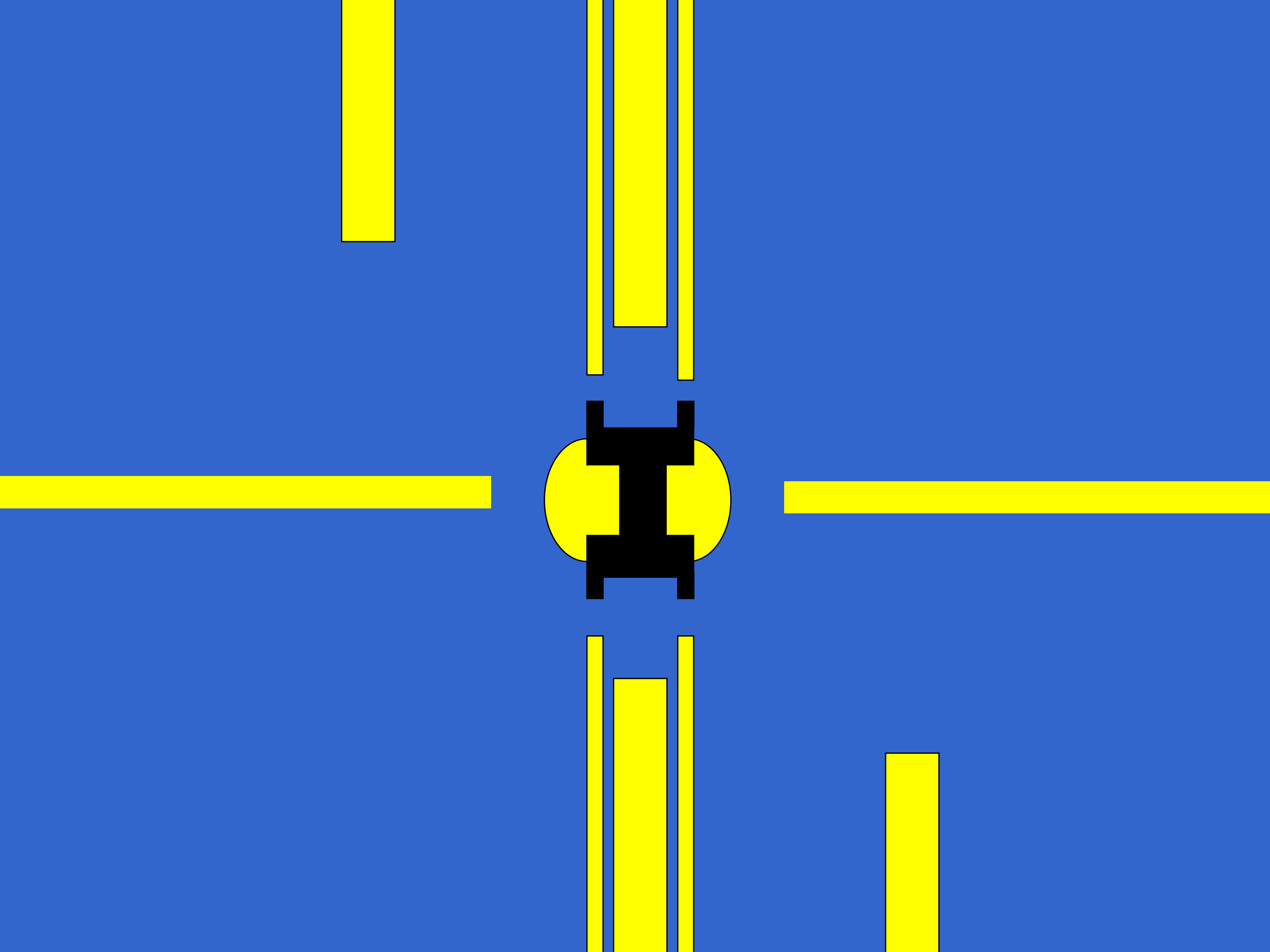
Armin Welker, MPI-FKF (2005)

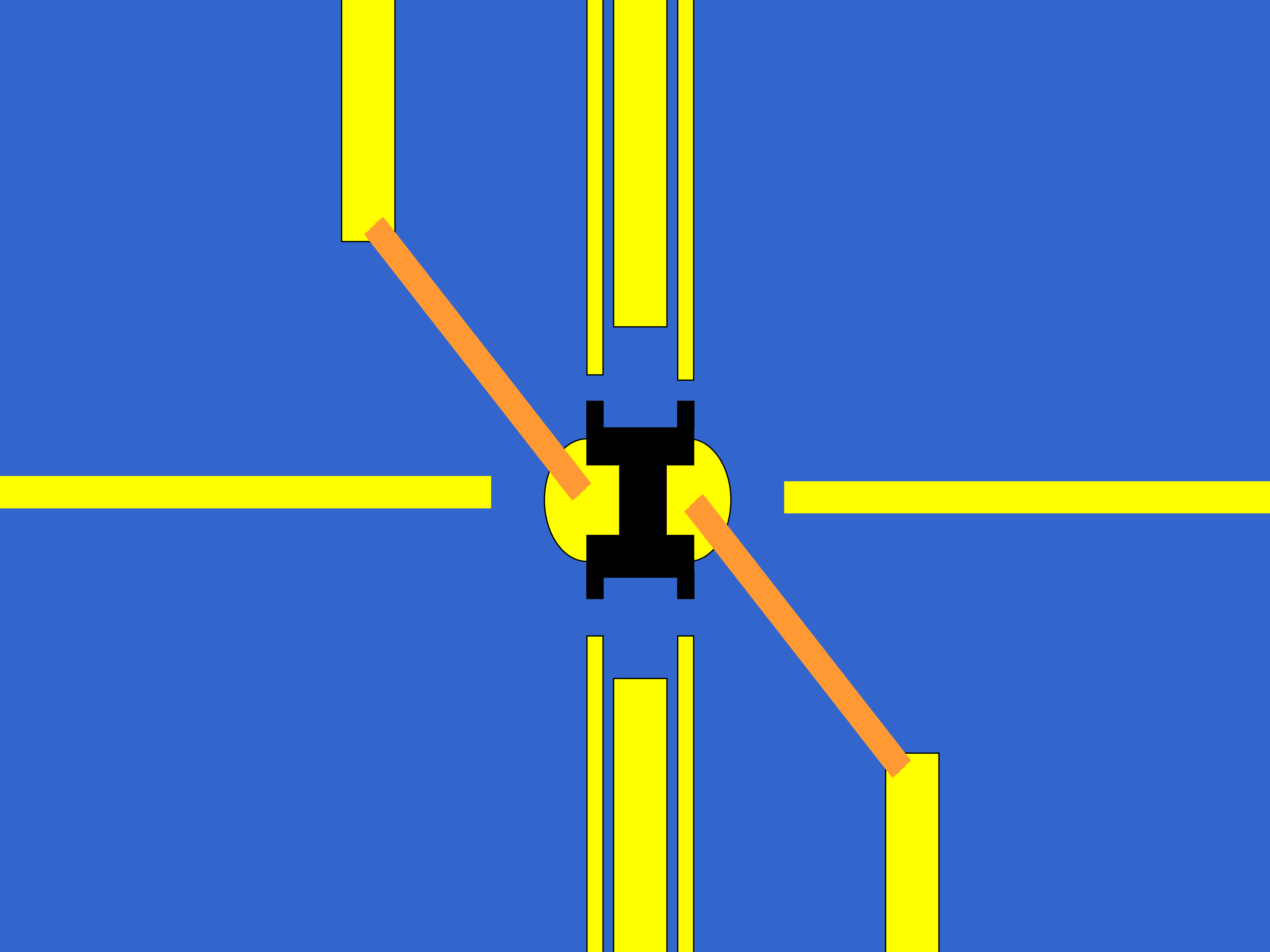
Electron Interference via Two Quantum Dots



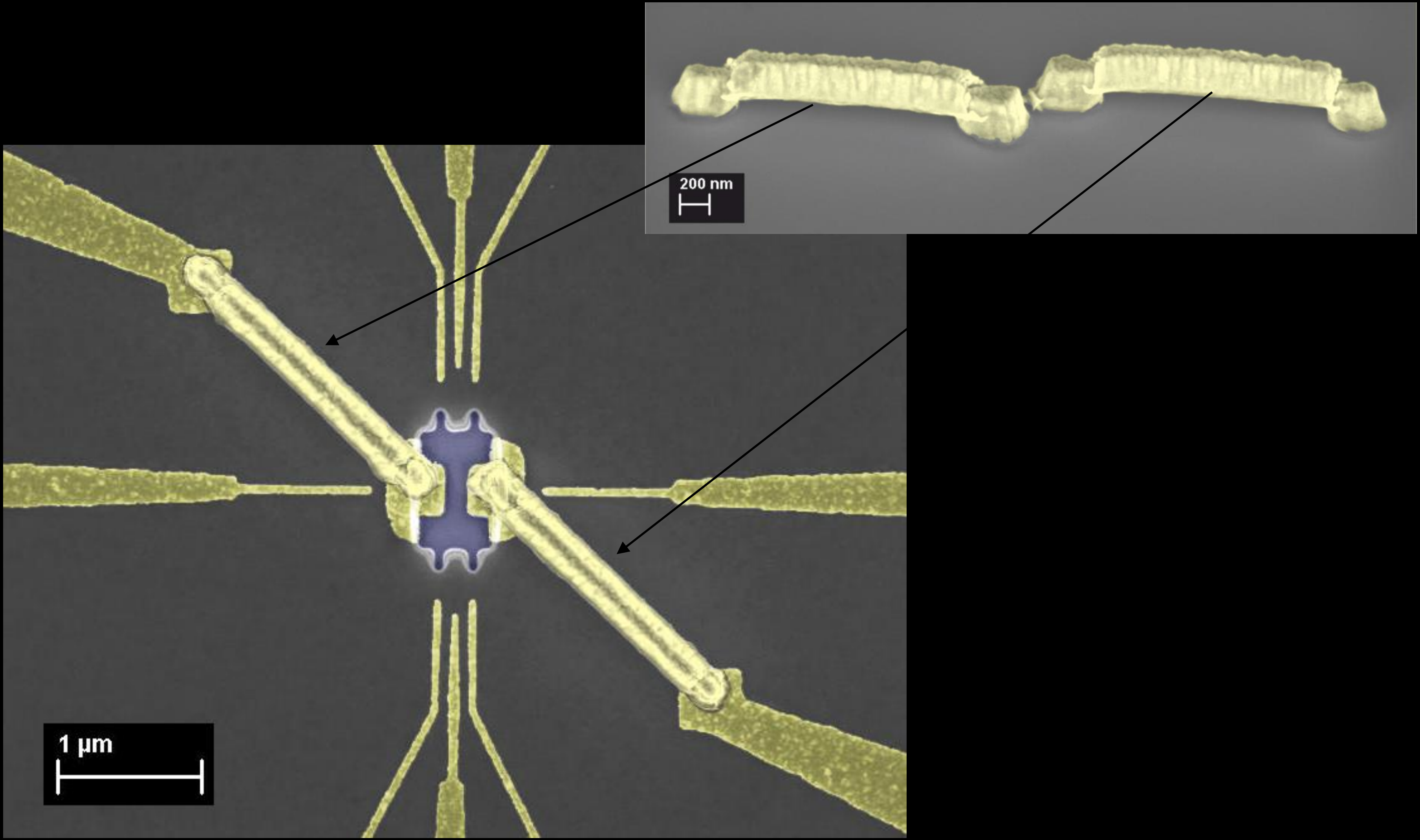
Pre-structured Substrate (Al,Ga)As Heterostructure with 2DES





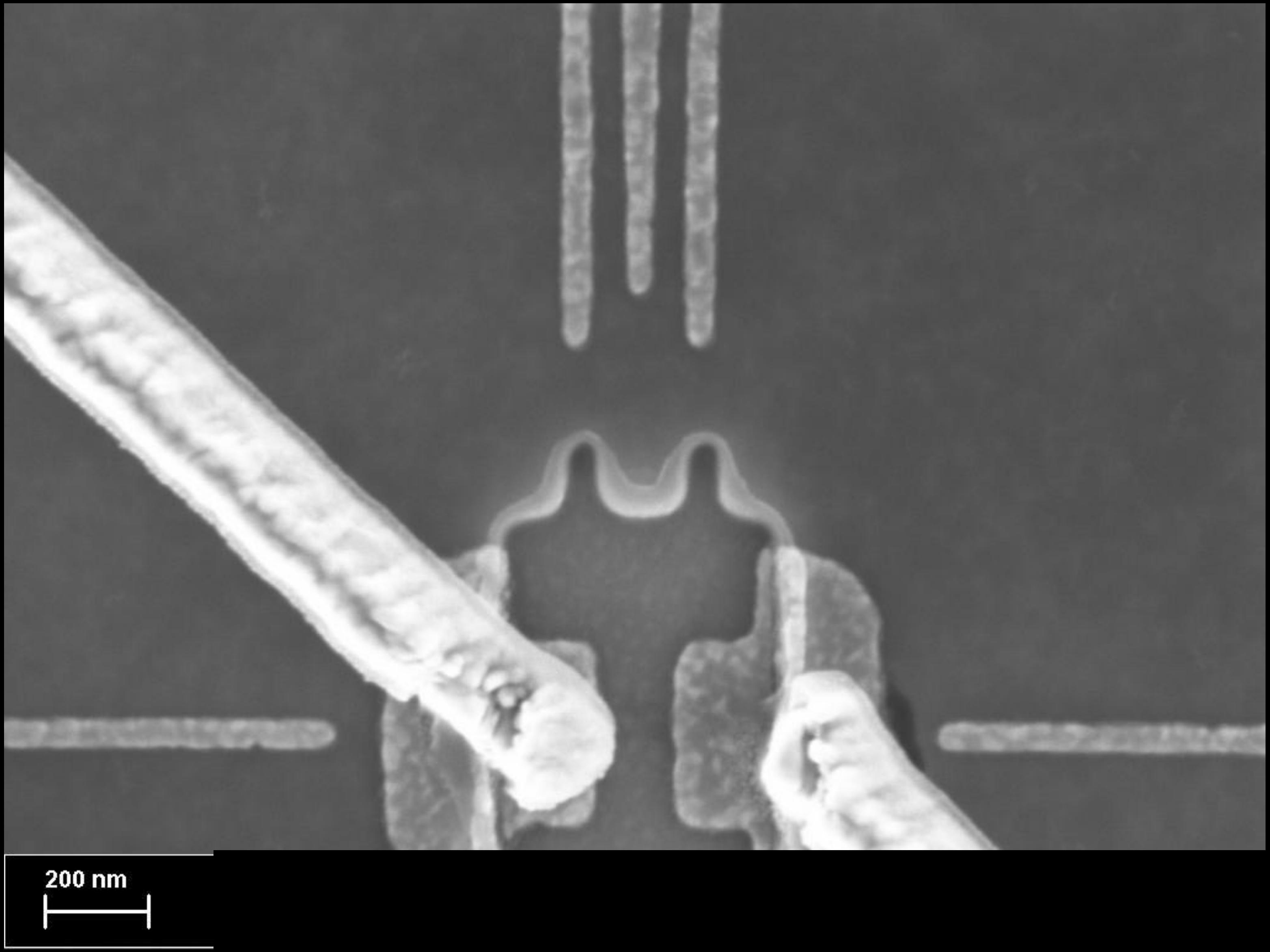


Two Quantum Dots in an Interferometric Arrangement



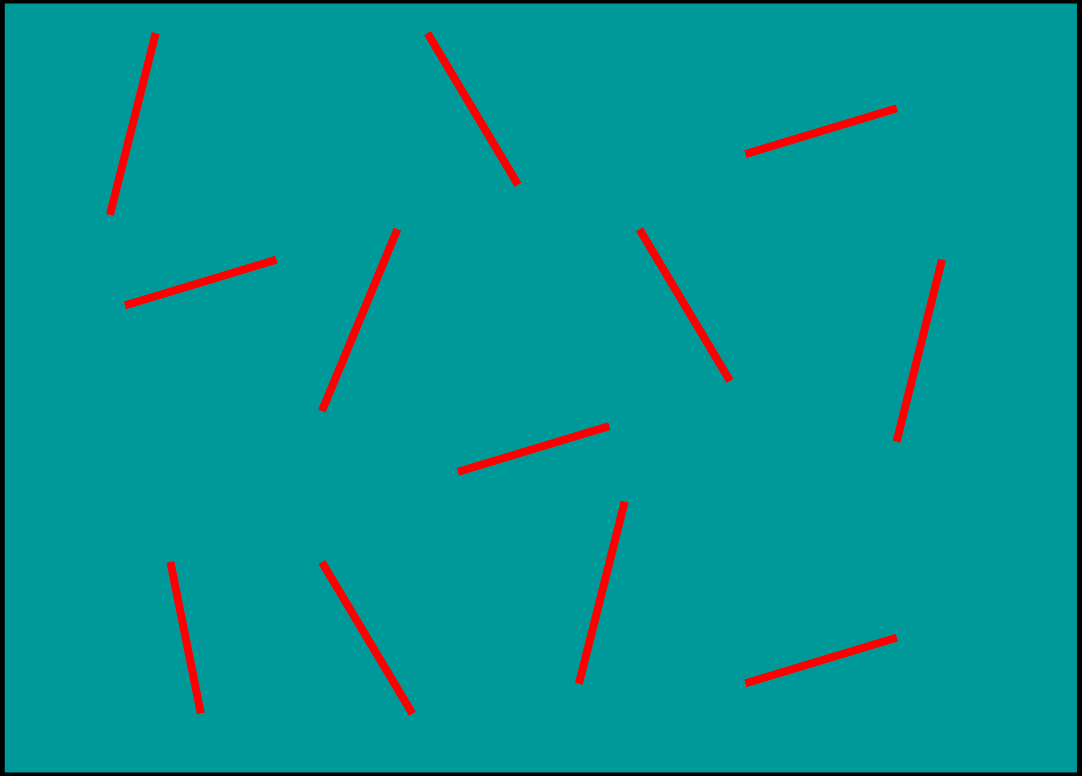
Leonhard Schulz, MPI-FKF (2008)

Aligment Accuracy of Three E-beam Steps



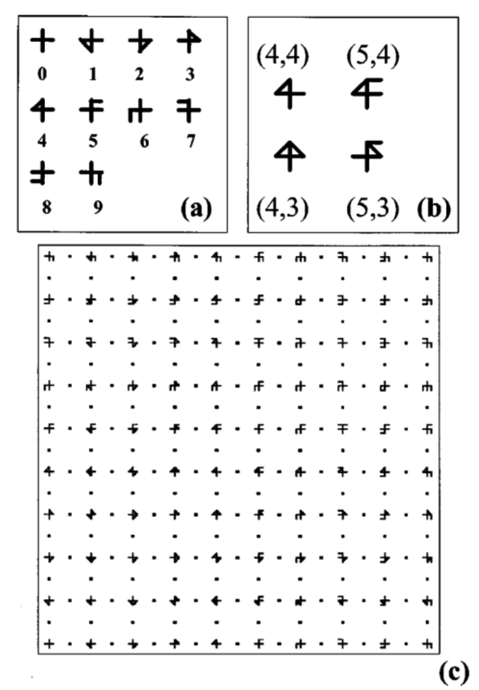
Leonhard Schulz, MPI-FKF (2008)

Examples for Contacting Randomly Distributed Nanowires / Flakes

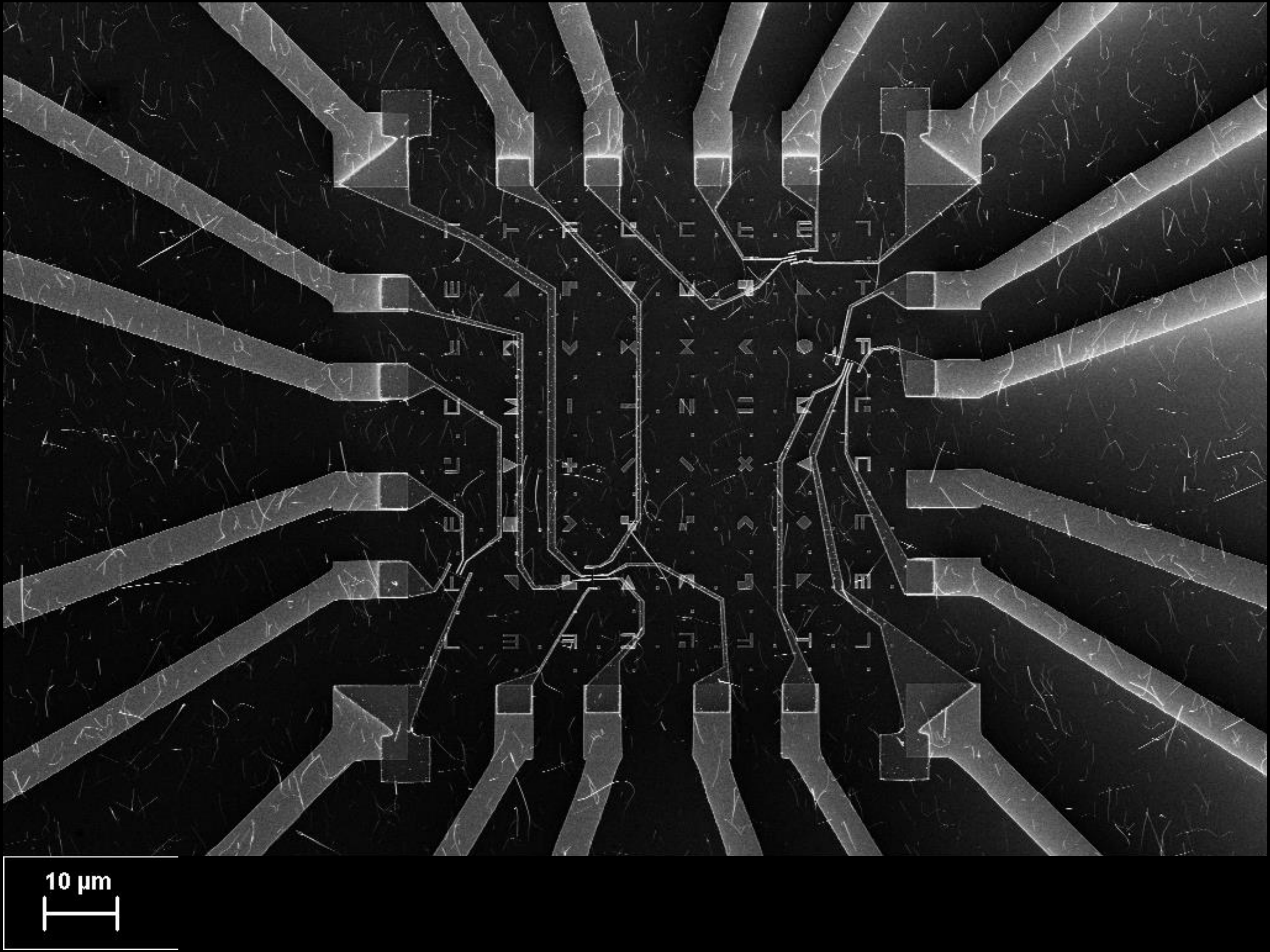


Examples for Contacting
Randomly Distributed Nanowires / Flakes

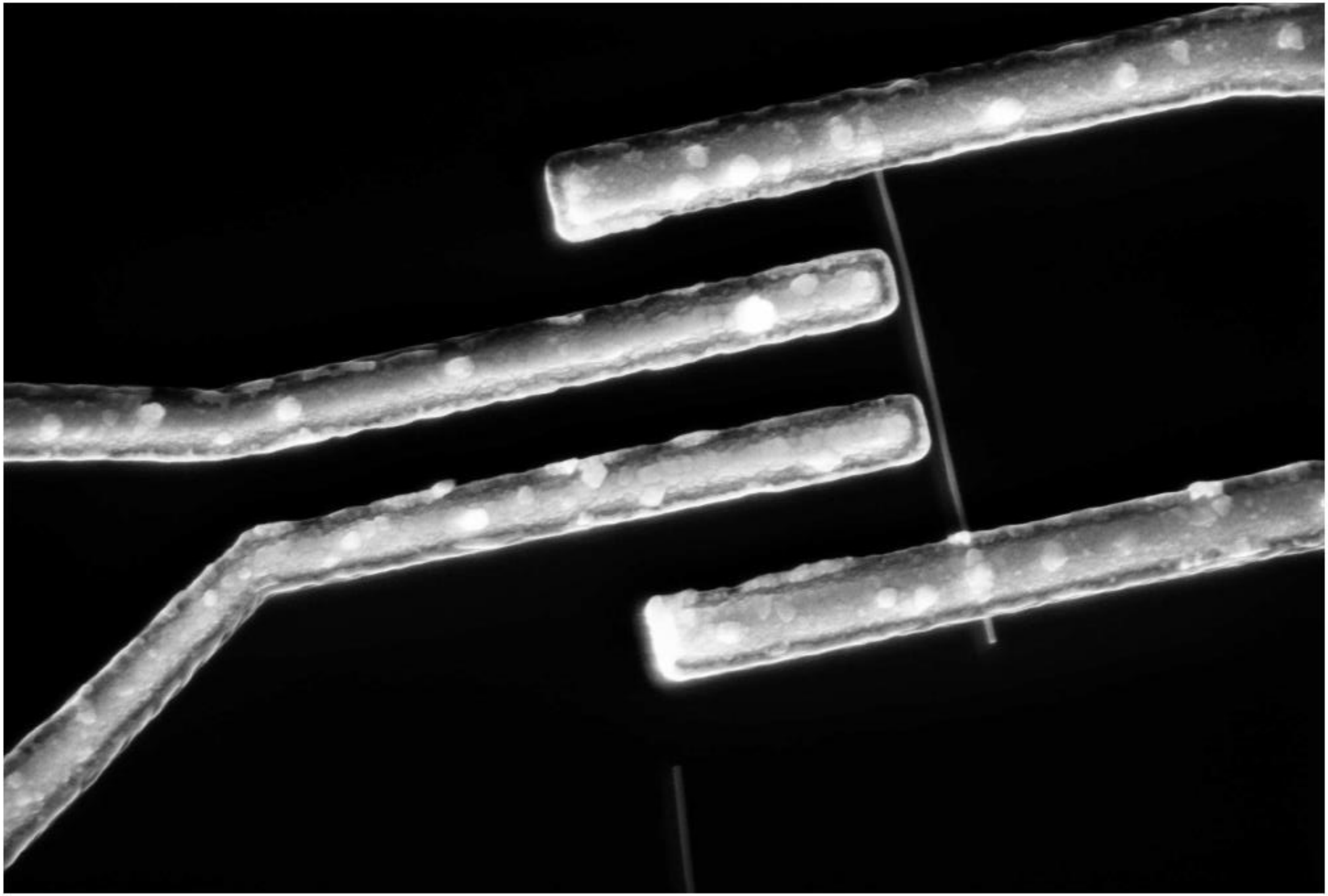
Before : define a coordinate system on the substrate by e-beam lithography



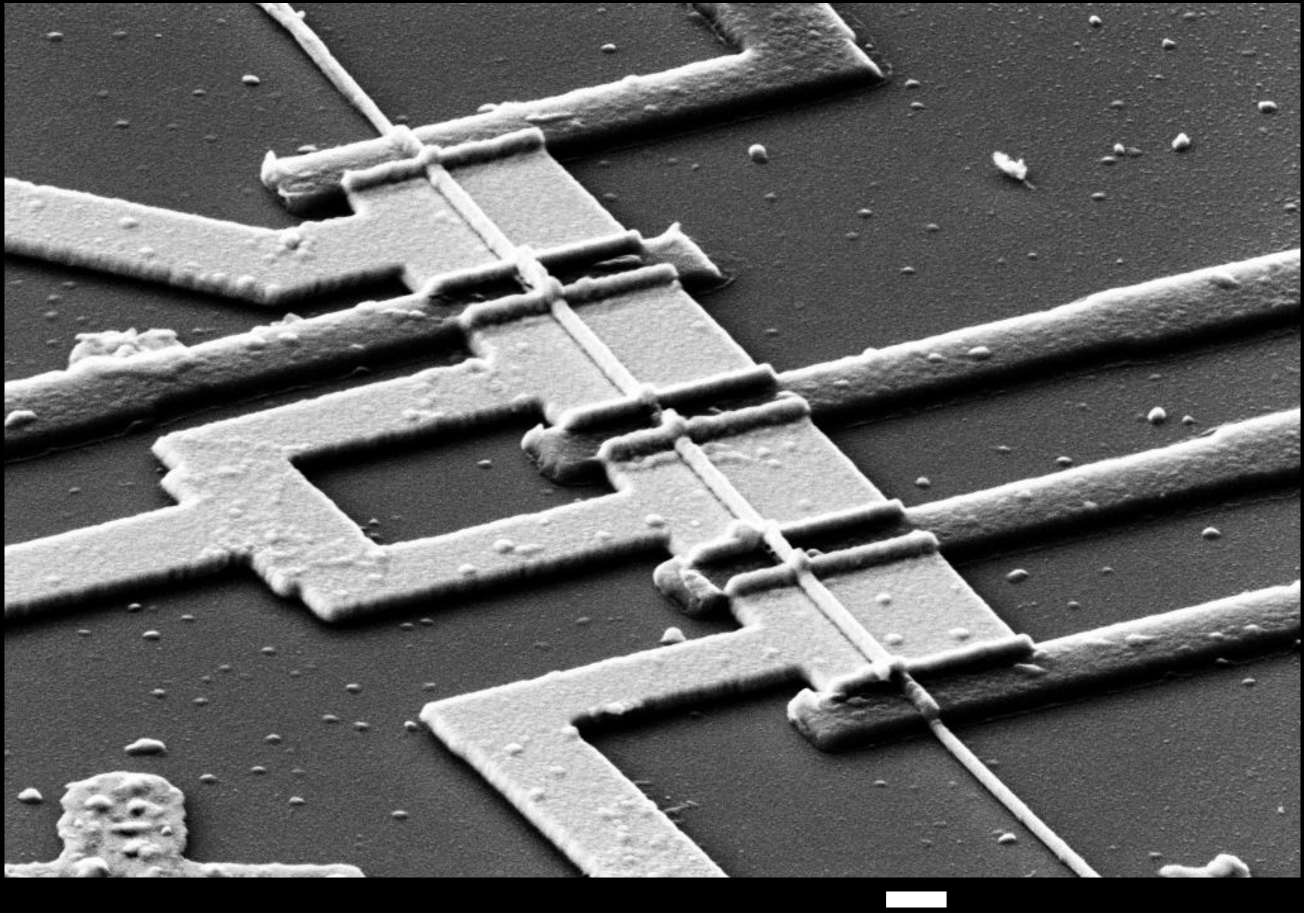
‘Simple efficient coordinate markers for investigating synthetic nanofibers’
Gyu-Tae Kim, Ulrike Waizmann, Siegmar Roth
Appl. Phys. Lett. 79, 3497–3499 (2001)

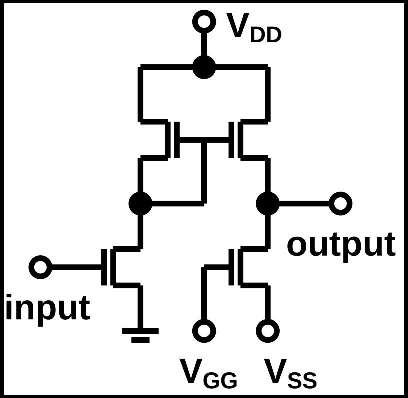


Eleonora Storace, MPI-FKF (2007)



InAs wire contacted by metal
Eleonora Storace (2007)

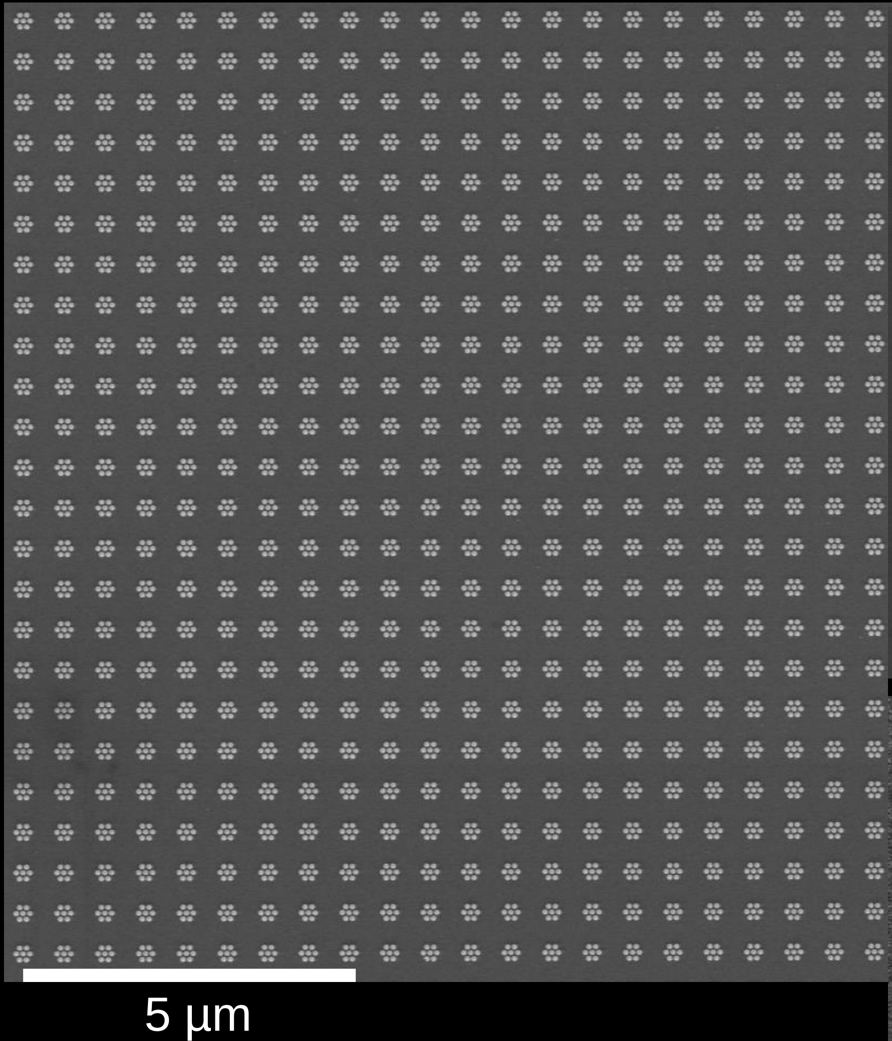


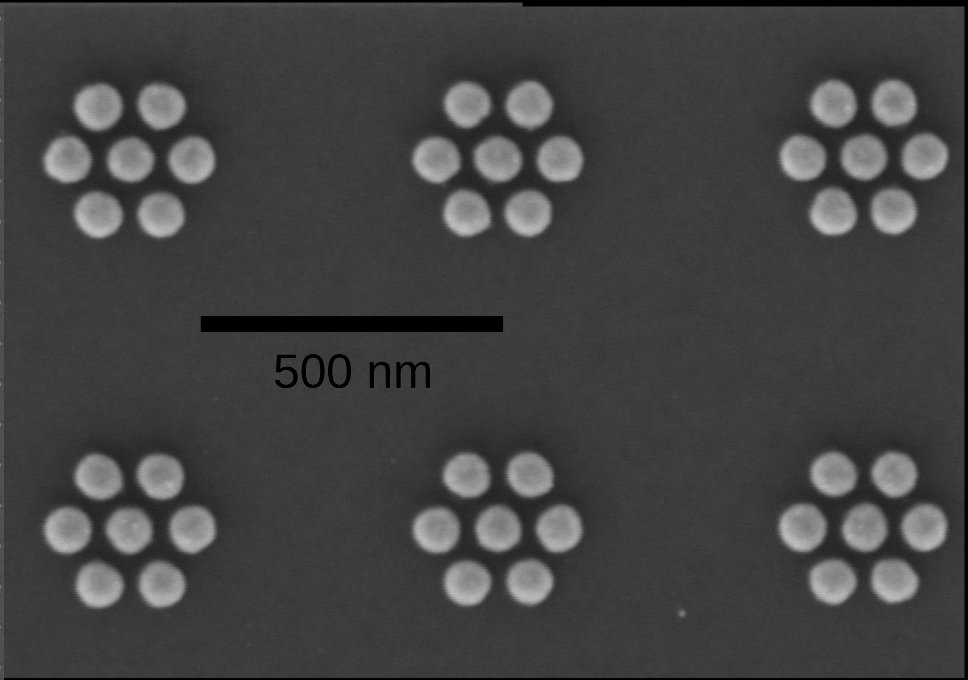


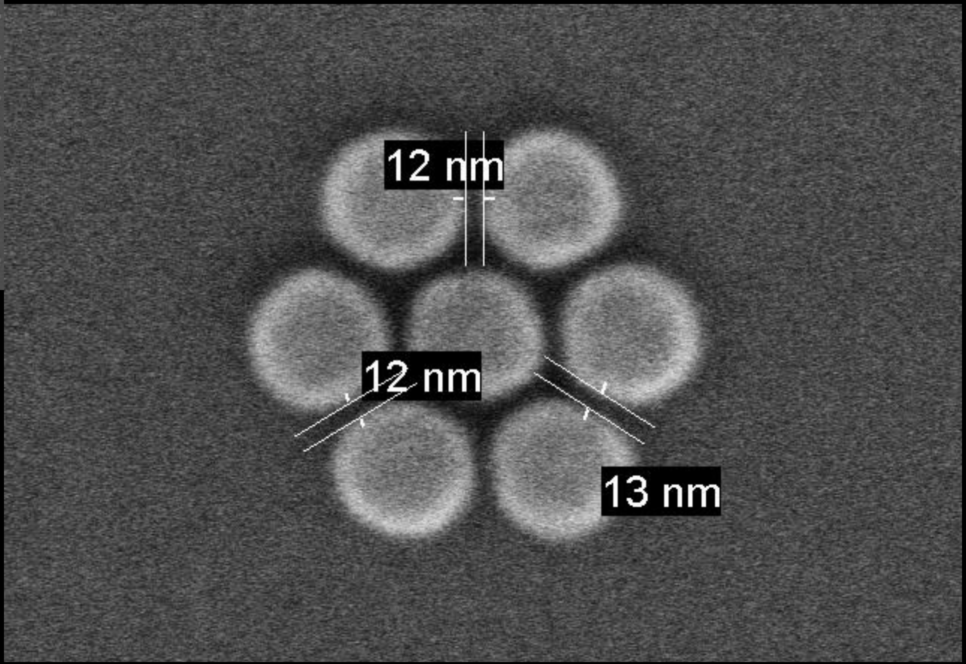
NMOS inverter with level-shift stage realized on a single ZnO nanowire

Daniel Kälblein (2009)

Examples for Plasmonic Structures
(Optical Meta Materials)





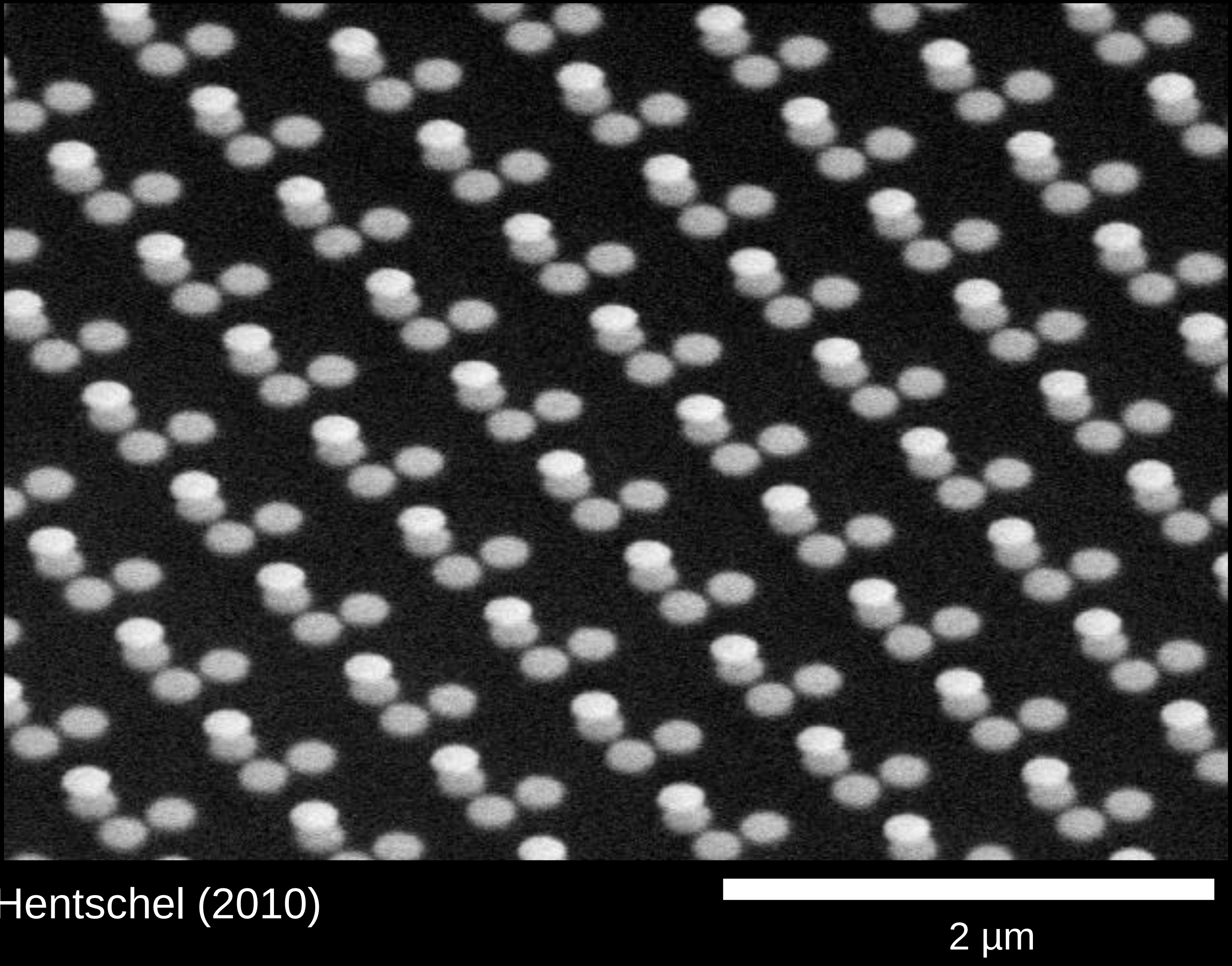


Plasmonic molecule

Septamere

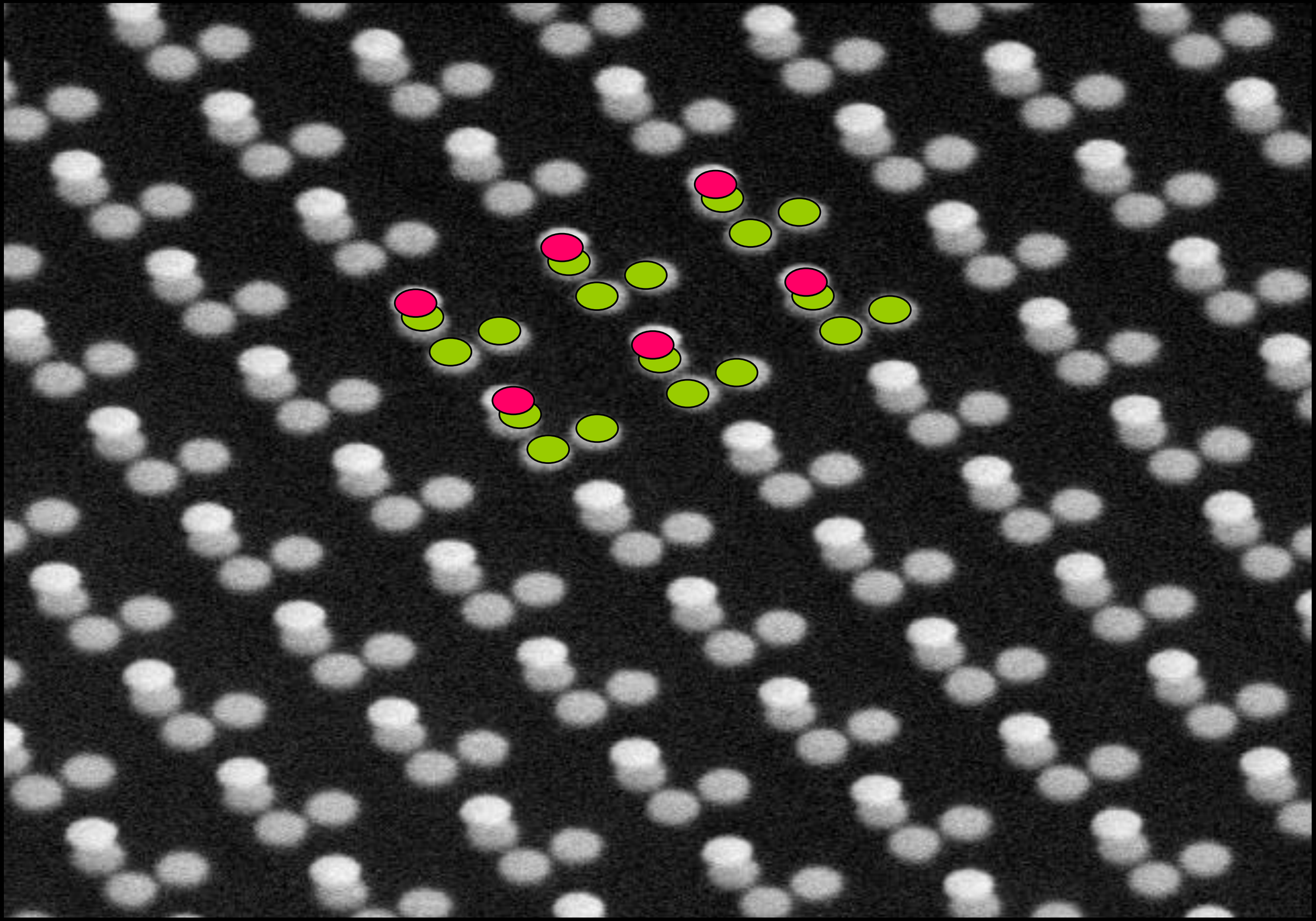
Mario Hentschel (2009)

Two layers of plasmonic structures



Mario Hentschel (2010)

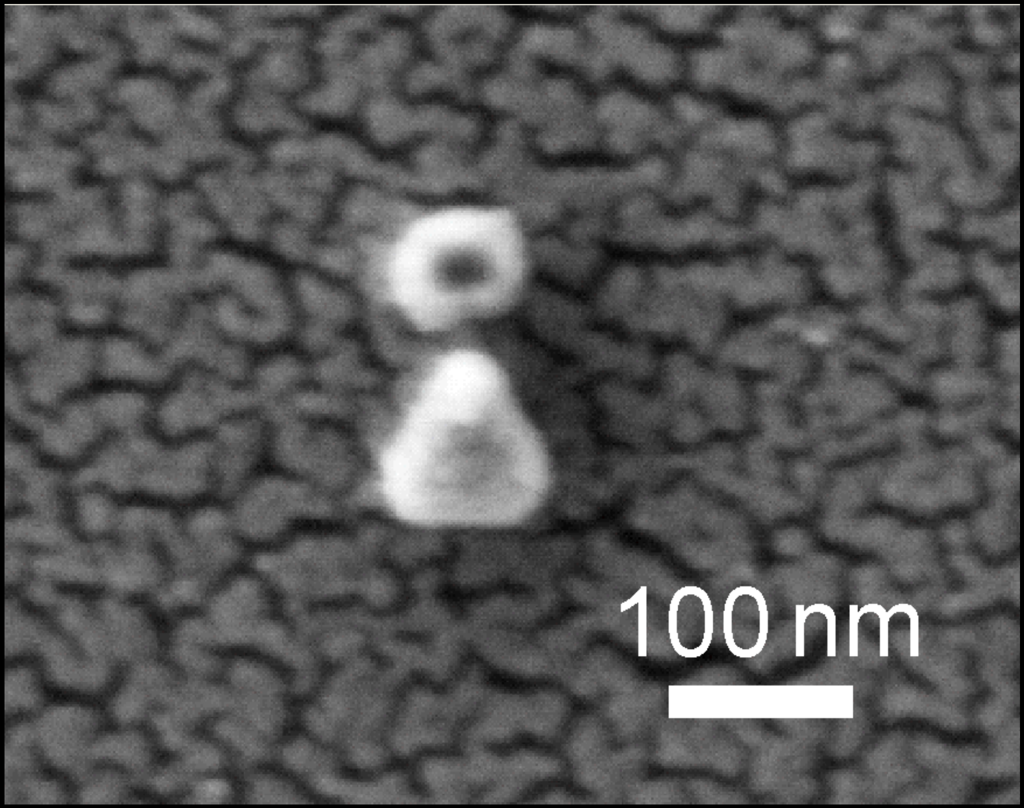
Two layers of plasmonic structures



Mario Hentschel (2010)

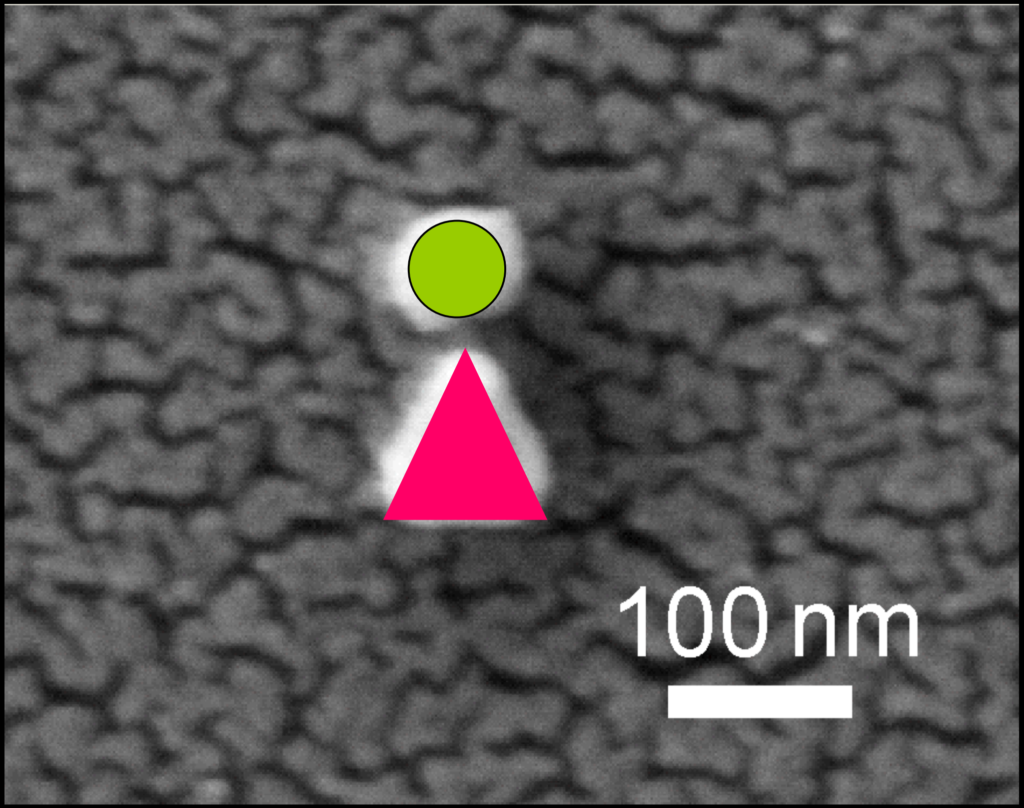
2 µm

Gold (Triangle) – Palladium (Dot)



Mario Hentschel (2010)

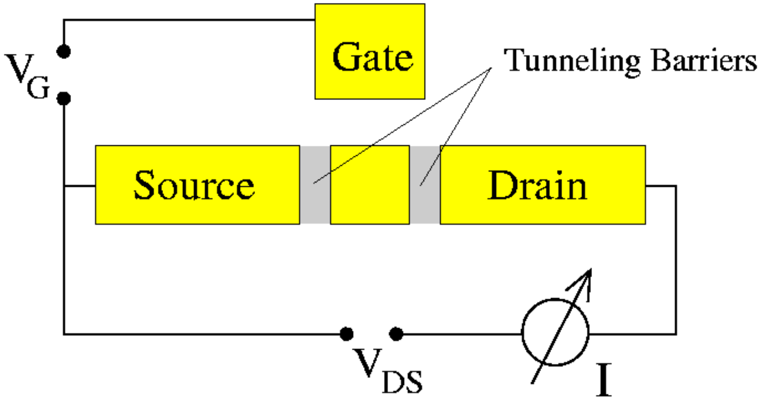
Gold (Triangle) – Palladium (Dot)

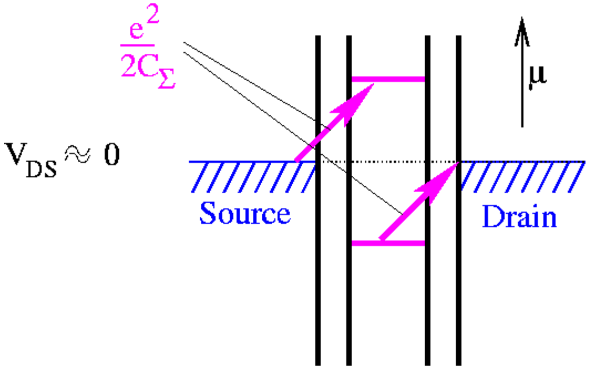


Mario Hentschel (2010)

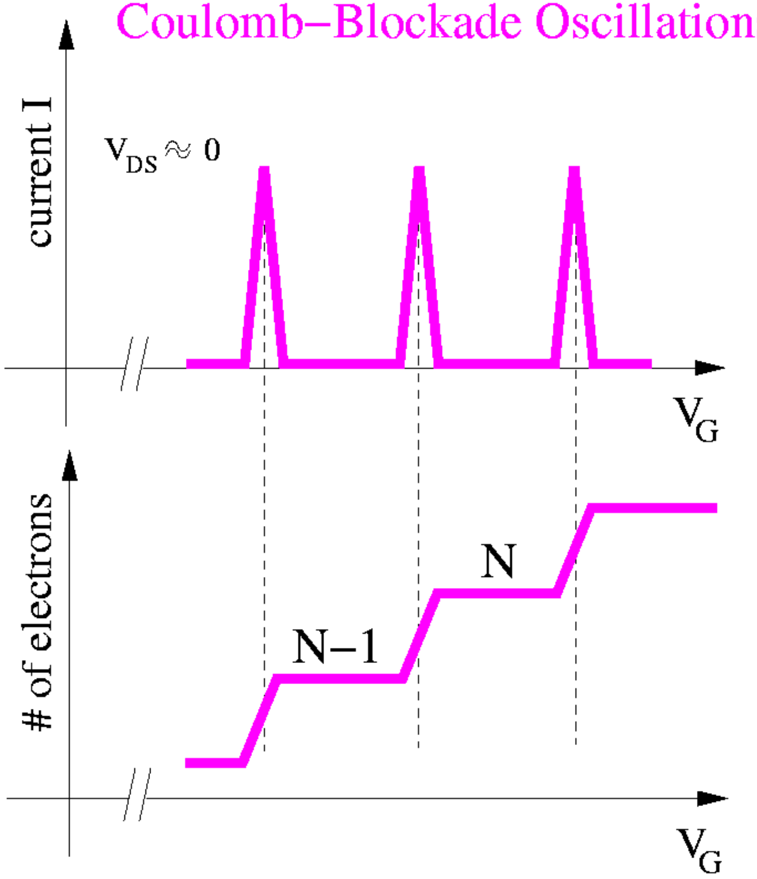
Example for Double-layer Resist with large Undercut for Shadow Evaporation

Single–Electron–Transistor (SET)





Coulomb–Blockade Oscillations



Proposed: D. Averin, K.K. Likharev, IEEE Trans. Magn. 23, 1142 (1987)

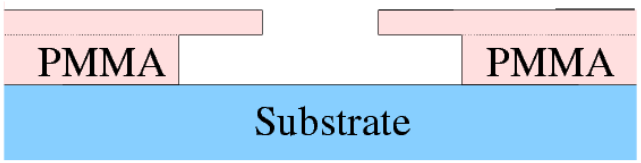
First Realisation: T.A. Fulton and G.J. Dolan, Phys. Rev. Lett. 59,109 (1987)

Single–Electron Transistor Made of Aluminum

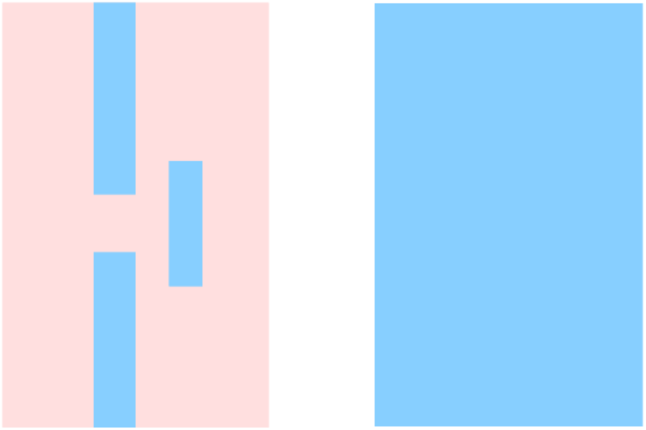
Two–Angle Shadow Evaporation Process:

after Dolan 1987

Cross Section:



Top View: PMMA Mask

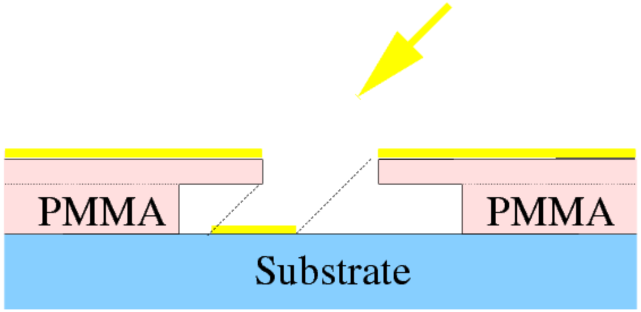


Single–Electron Transistor Made of Aluminum

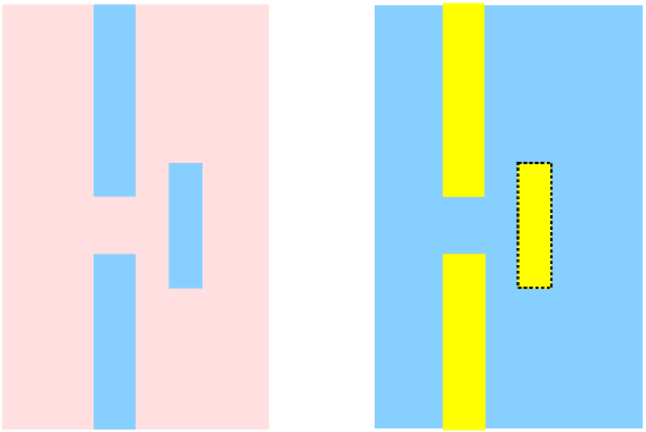
Two–Angle Shadow Evaporation Process:

after Dolan 1987

Cross Section:



Top View:



PMMA Mask

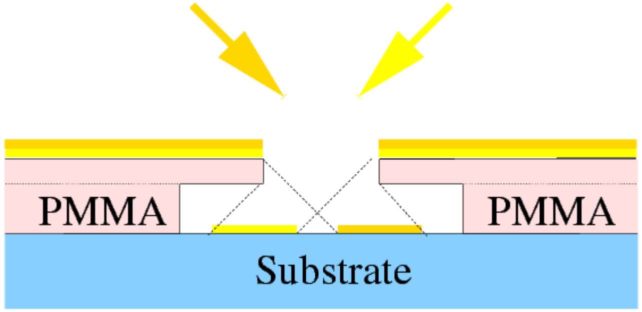
Metal Structure

Single–Electron Transistor Made of Aluminum

Two–Angle Shadow Evaporation Process:

after Dolan 1987

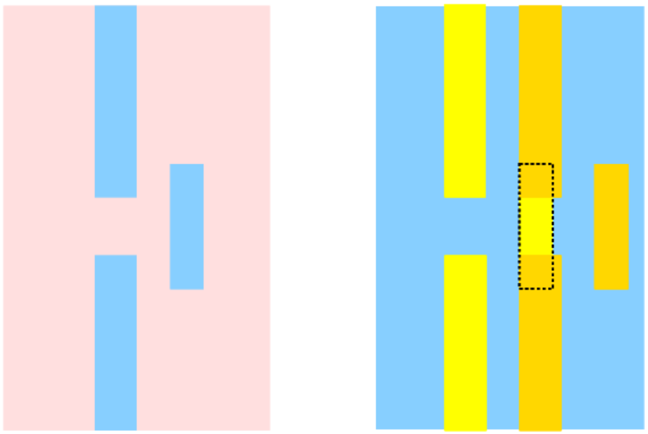
Cross Section:



Top View:

PMMA Mask

Metal Structure

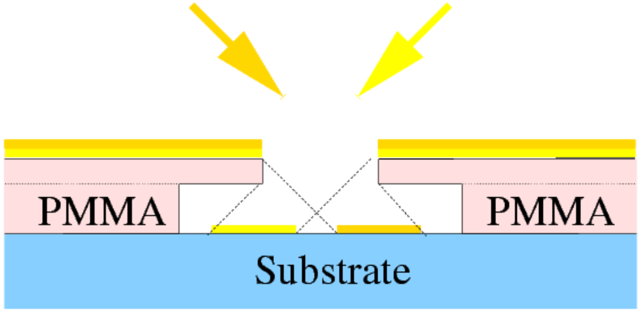


Single–Electron Transistor Made of Aluminum

Two–Angle Shadow Evaporation Process:

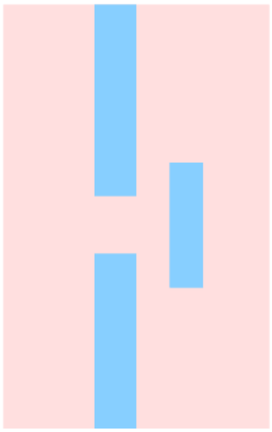
after Dolan 1987

Cross Section:

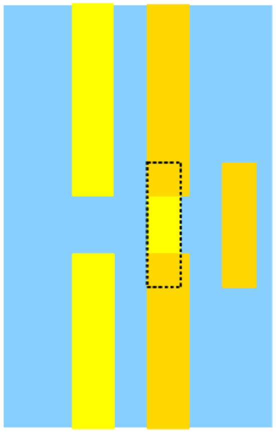


Top View:

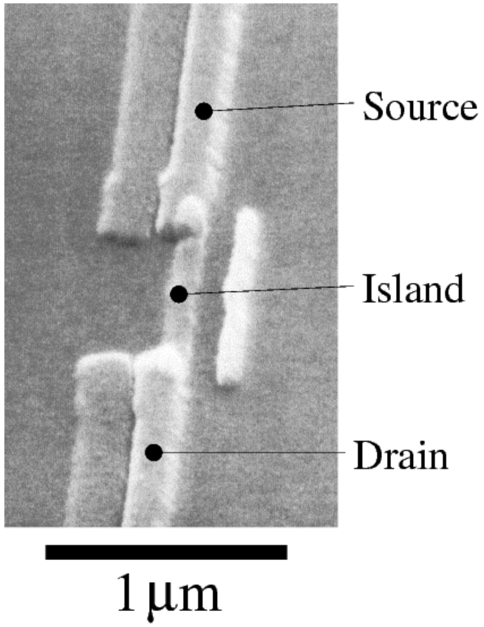
PMMA Mask

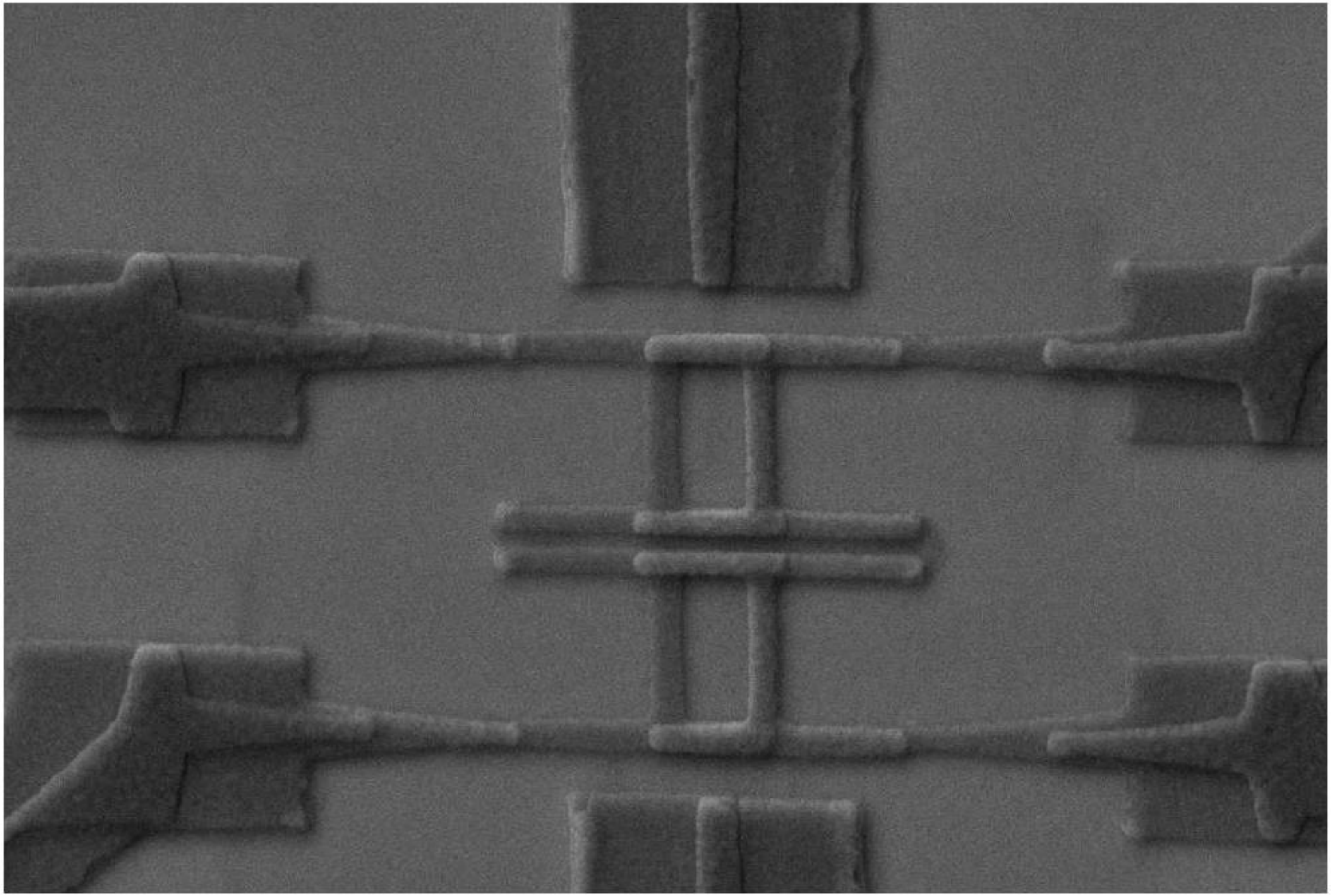


Metal Structure



SEM Image





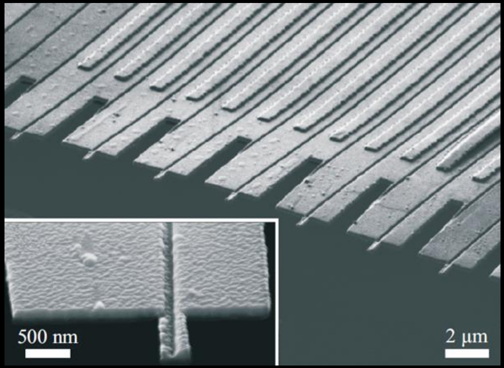
Two electrostatically coupled metal single−electron transistors

Ingmar Bruder / Jochen Weber (2007)

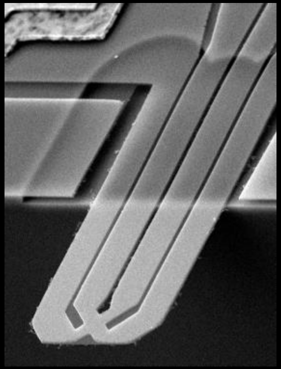
Scanning-Probe Experiments on Quantum Hall Samples at 50 mK

Several PhD projects:
Jochen Weber, Kostas Panos,
Marcel Mausser, Andreas Gauss,
Maximilian Kühn, Lukas Freund

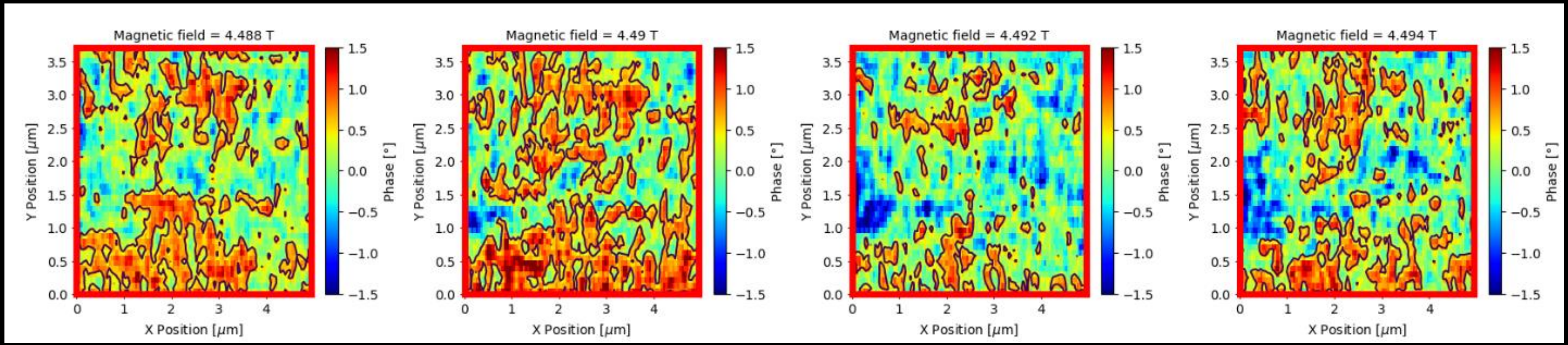
Array of metal single-electron transistors



Hall sensor



Evolution of compressible/incompressible landscape versus magnetic field within the 2DES bulk



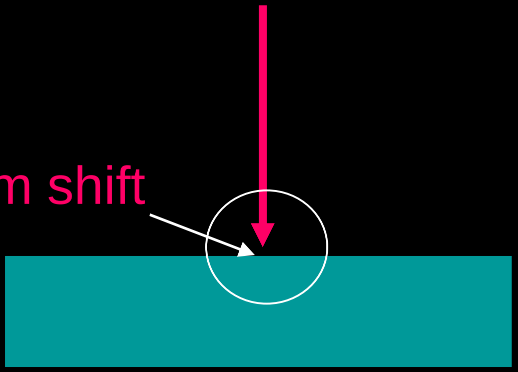
100 kV Electron Beam Lithography System
Jeol JBX 6300 FS (installed 2009)

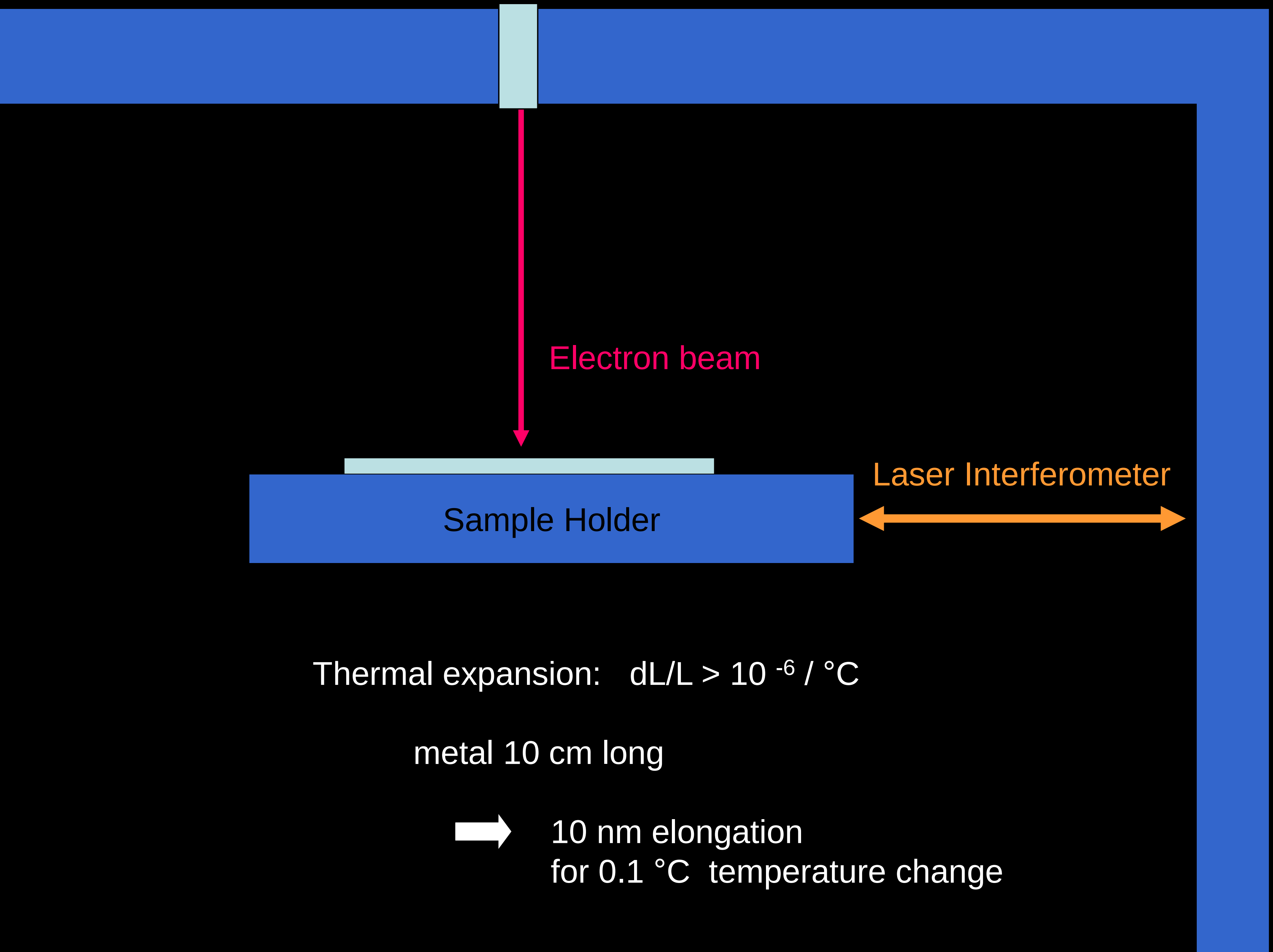
with special environmental conditions

Enviromental Requirements for Dedicated Electron Beam Lithography System

- Temperature Stability: < 0.1 °C
- Magnetic Field Stability: < 0.1 µT peak-to-peak during writing time
- Low Floor Vibrations
- Cleanroom Class 100

Not fulfilling? This means about 10 nm shift





Electron beam

Sample Holder

Laser Interferometer

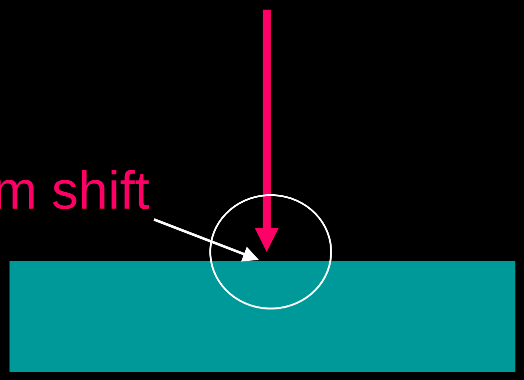
Thermal expansion: $dL/L > 10^{-6} / °C$

metal 10 cm long

➡ 10 nm elongation
for 0.1 °C temperature change

Enviromental Requirements for Dedicated Electron Beam Lithography System

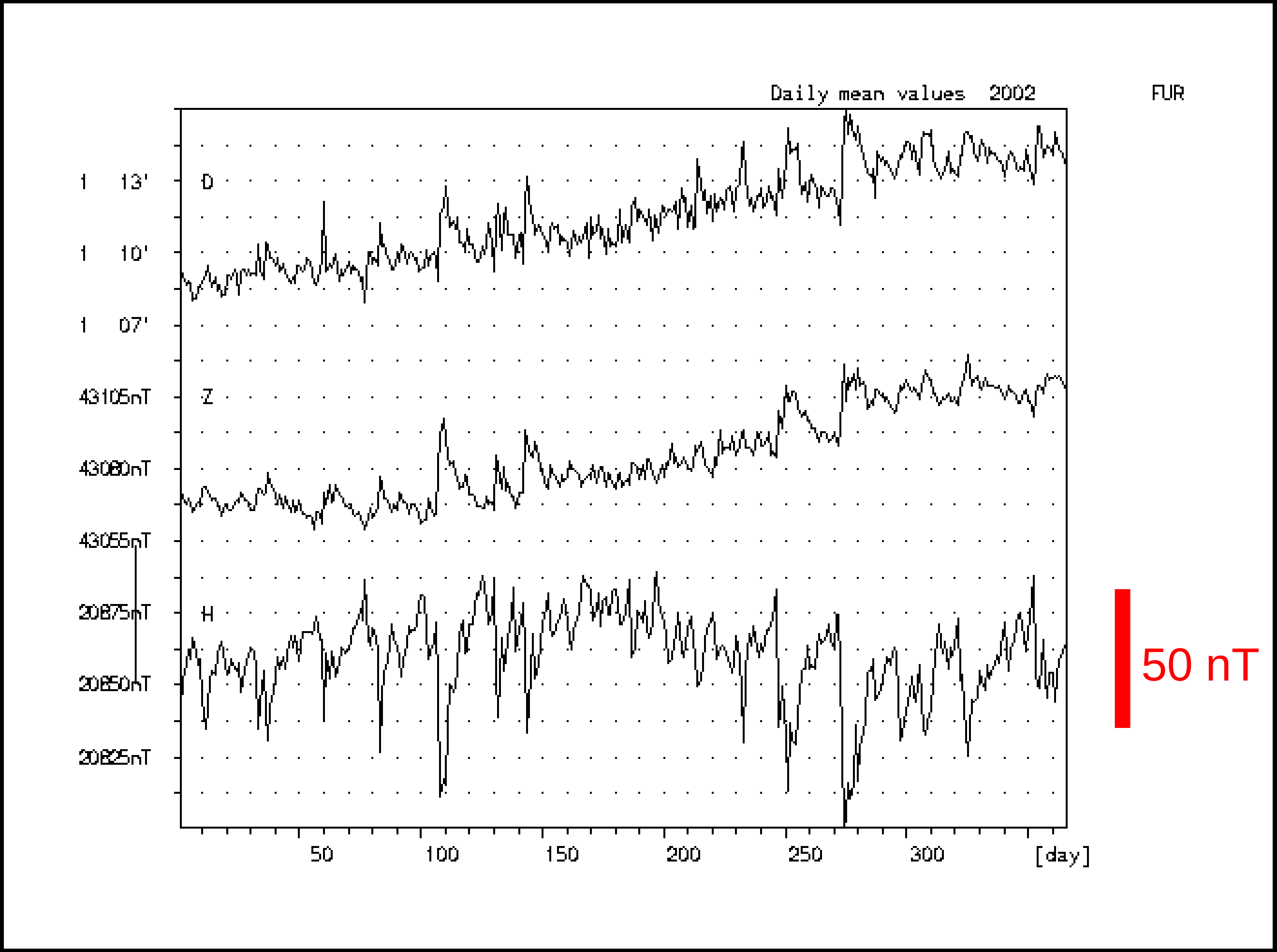
- Temperature Stability: < 0.1 °C
- Magnetic Field Stability: < 0.1 µT peak-to-peak during writing time
- Low Floor Vibrations
- Cleanroom Class 100



Not fulfilling? This means about 10 nm shift

Stability of the earth magnetic field over a year

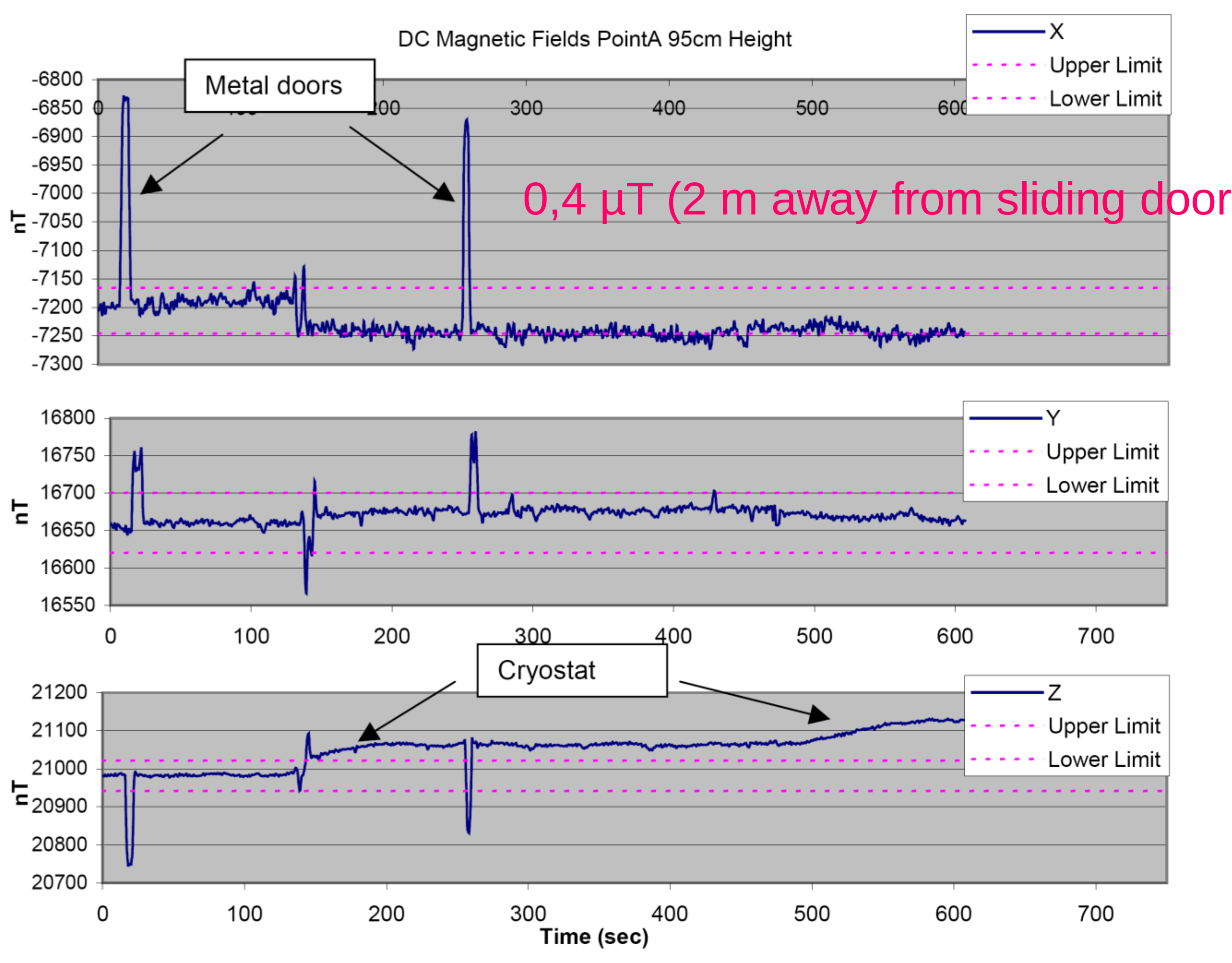
(close to Munich in 2002)



Strong magnetic fields everywhere !

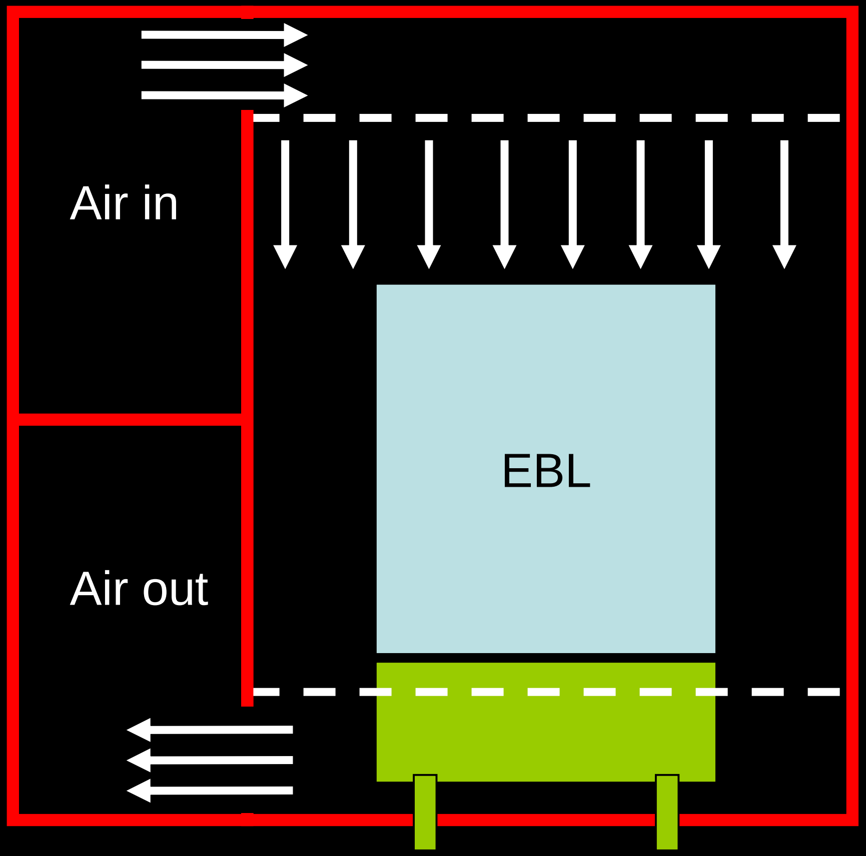
Cryostat with
superconducting magnet

Magnetic field variations by moving parts



0,4 µT (2 m away from sliding door)

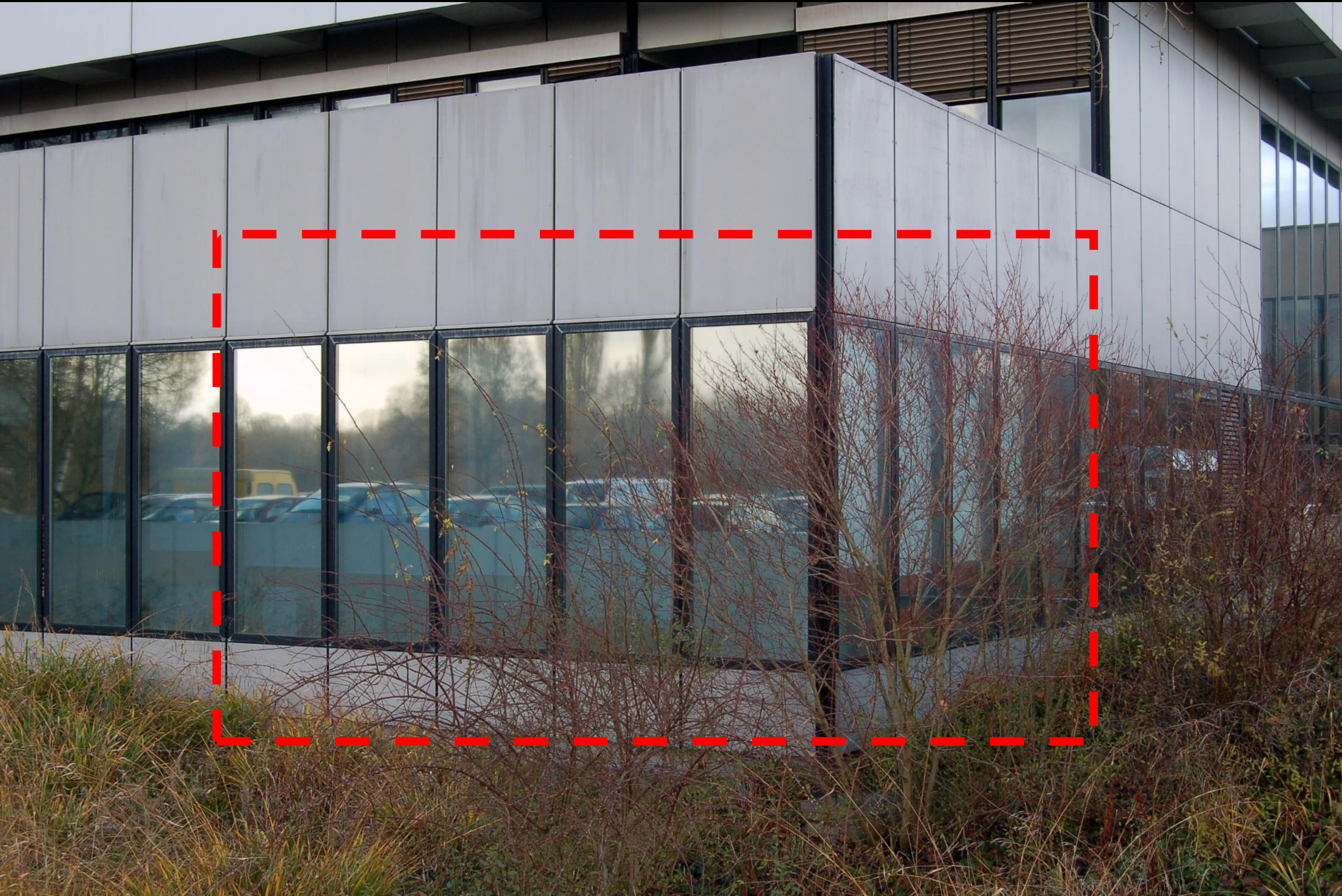
Concept:



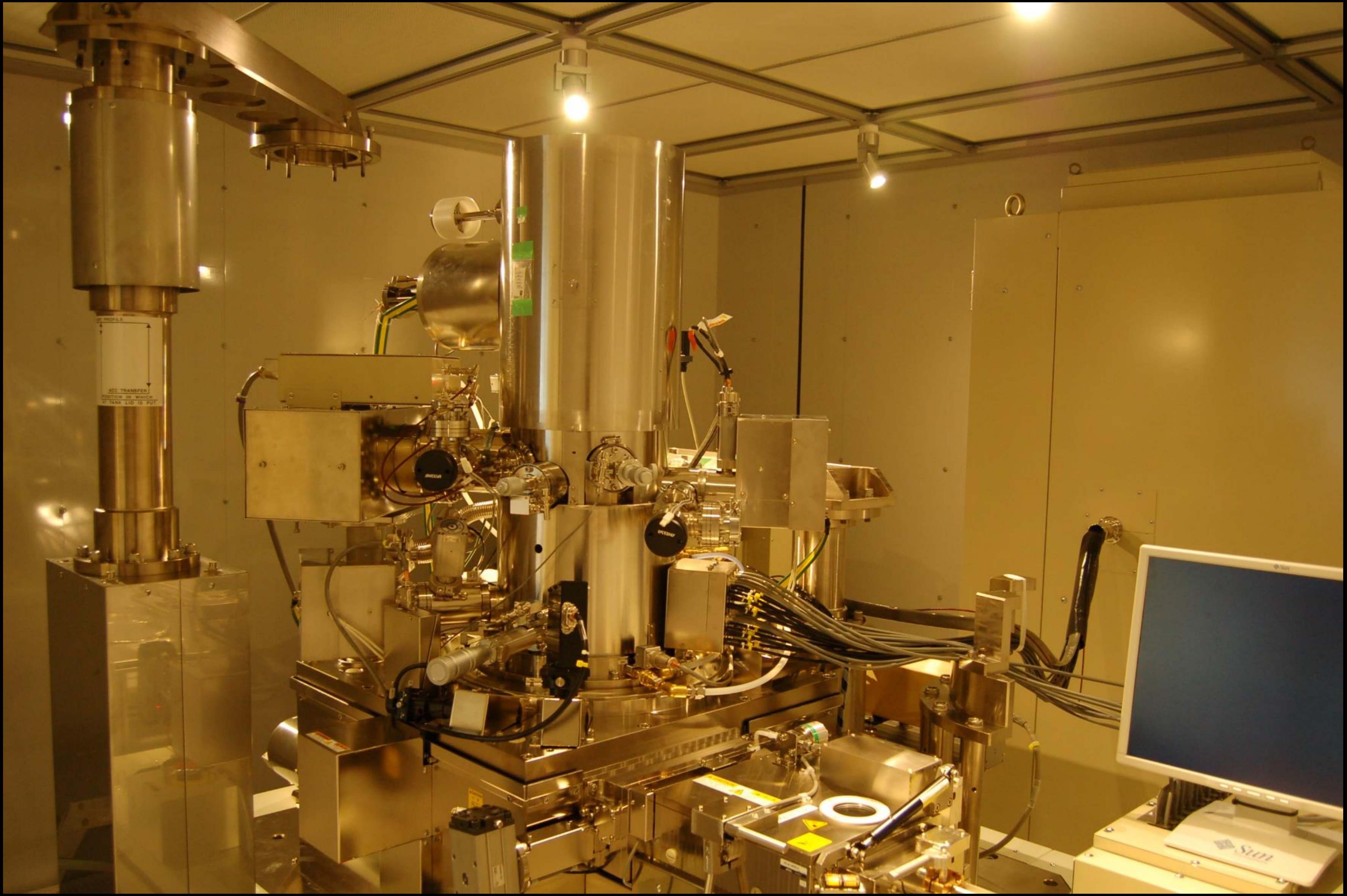
Laminar air flow to obtain constant temperature and cleanroom conditions

Passive magnetic field shielding and active compensation (Helmholtz coils)

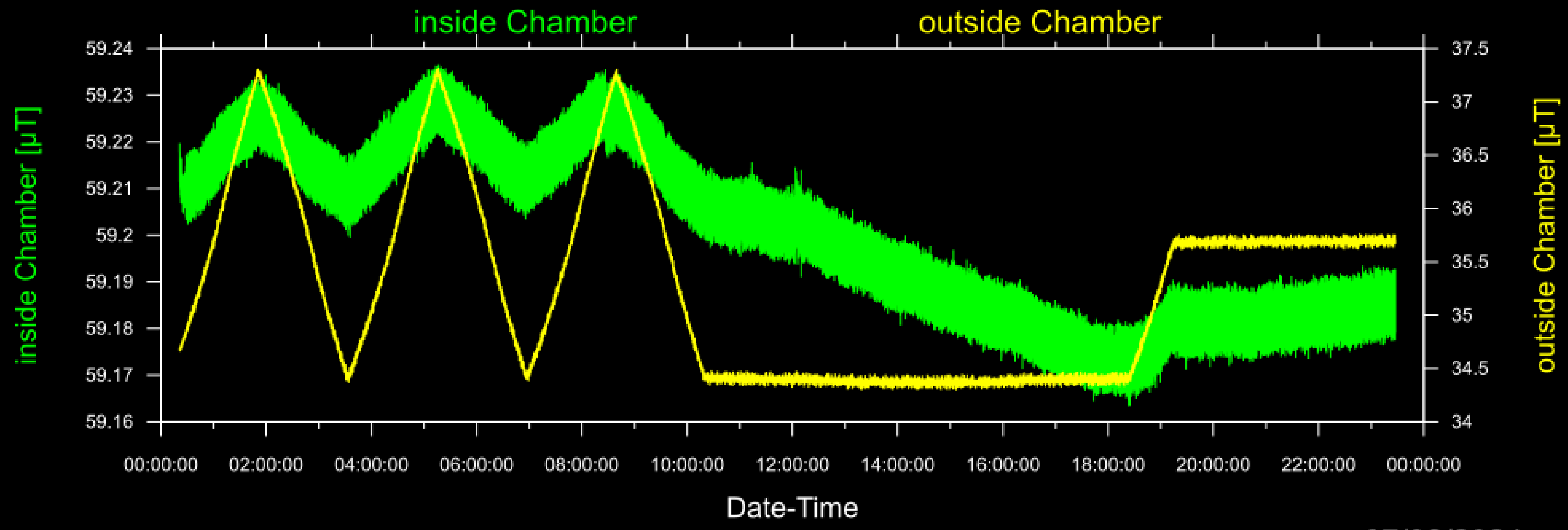
Active floor vibration isolation



Jeol JBX6300FS in Shielded Cleanroom in 2B24



Absolute Magnetic Field in Room 2B24 (JEOL JBX6300FS)

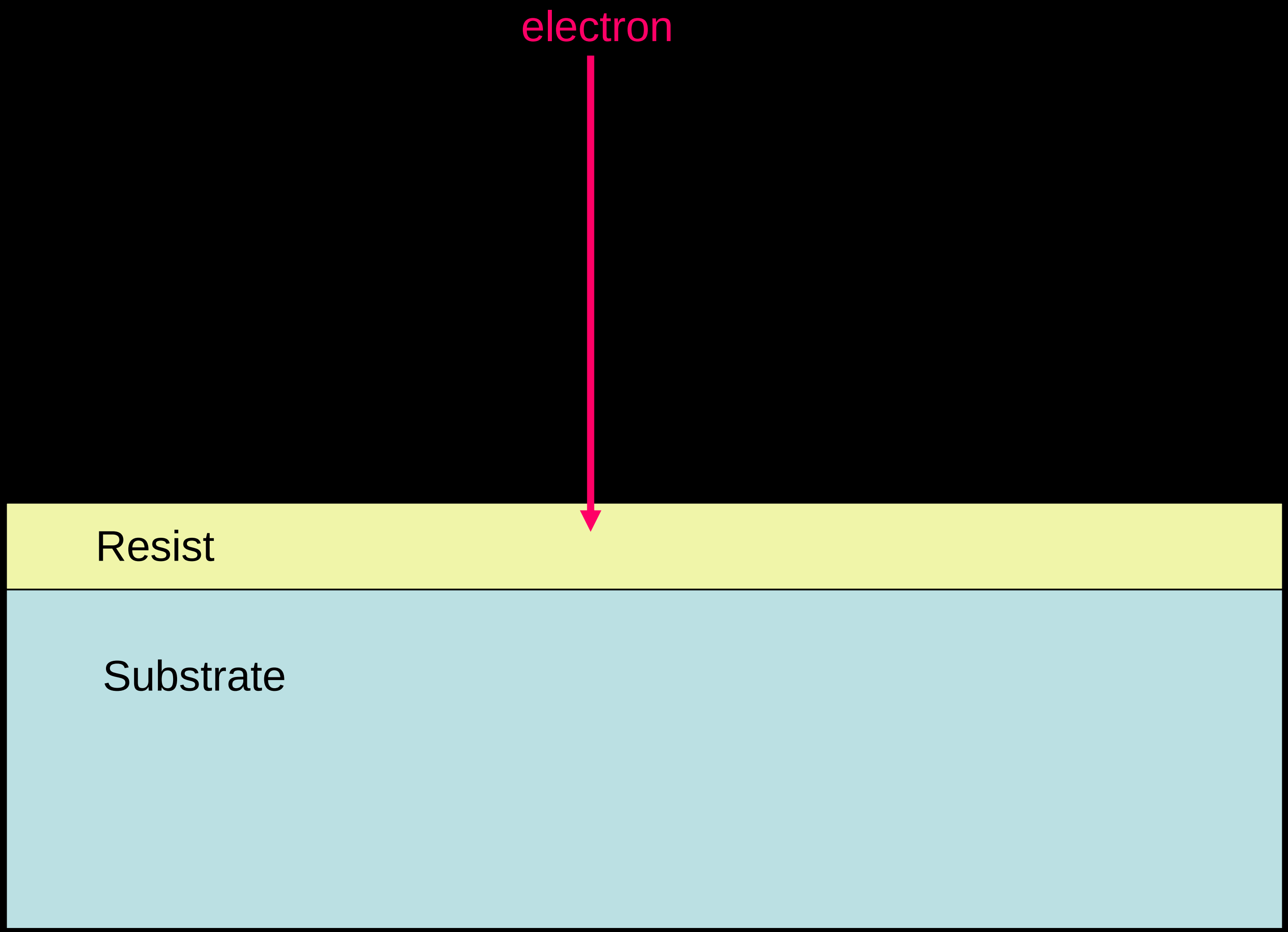


07/02/2024

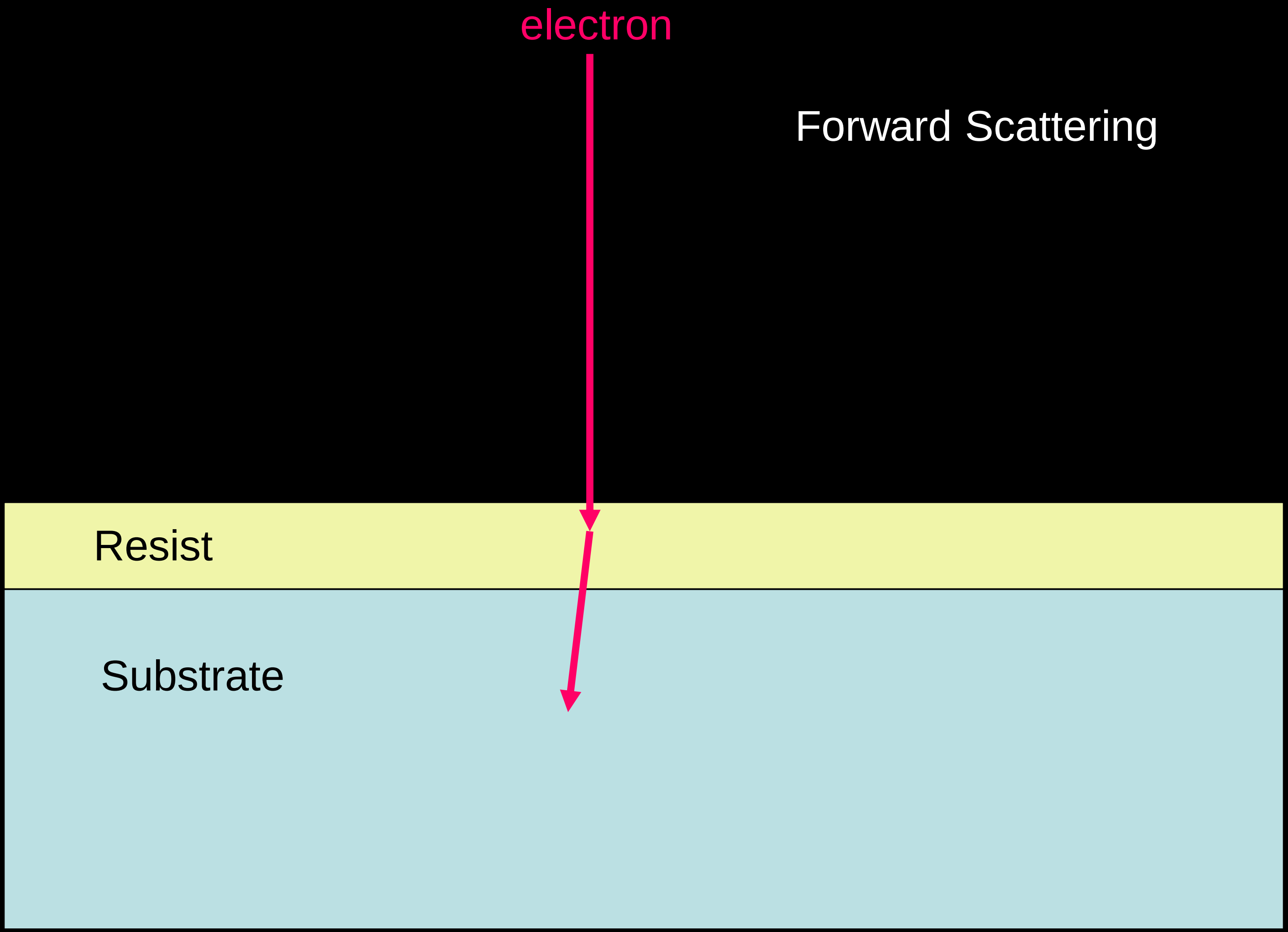
Dedicated 100 kV Electron Beam Lithography System ?

- Acceleration Voltage: Interaction with resist/substrate
  (Proximity Effect, Damage)

Interaction of Electron Beam with Sample



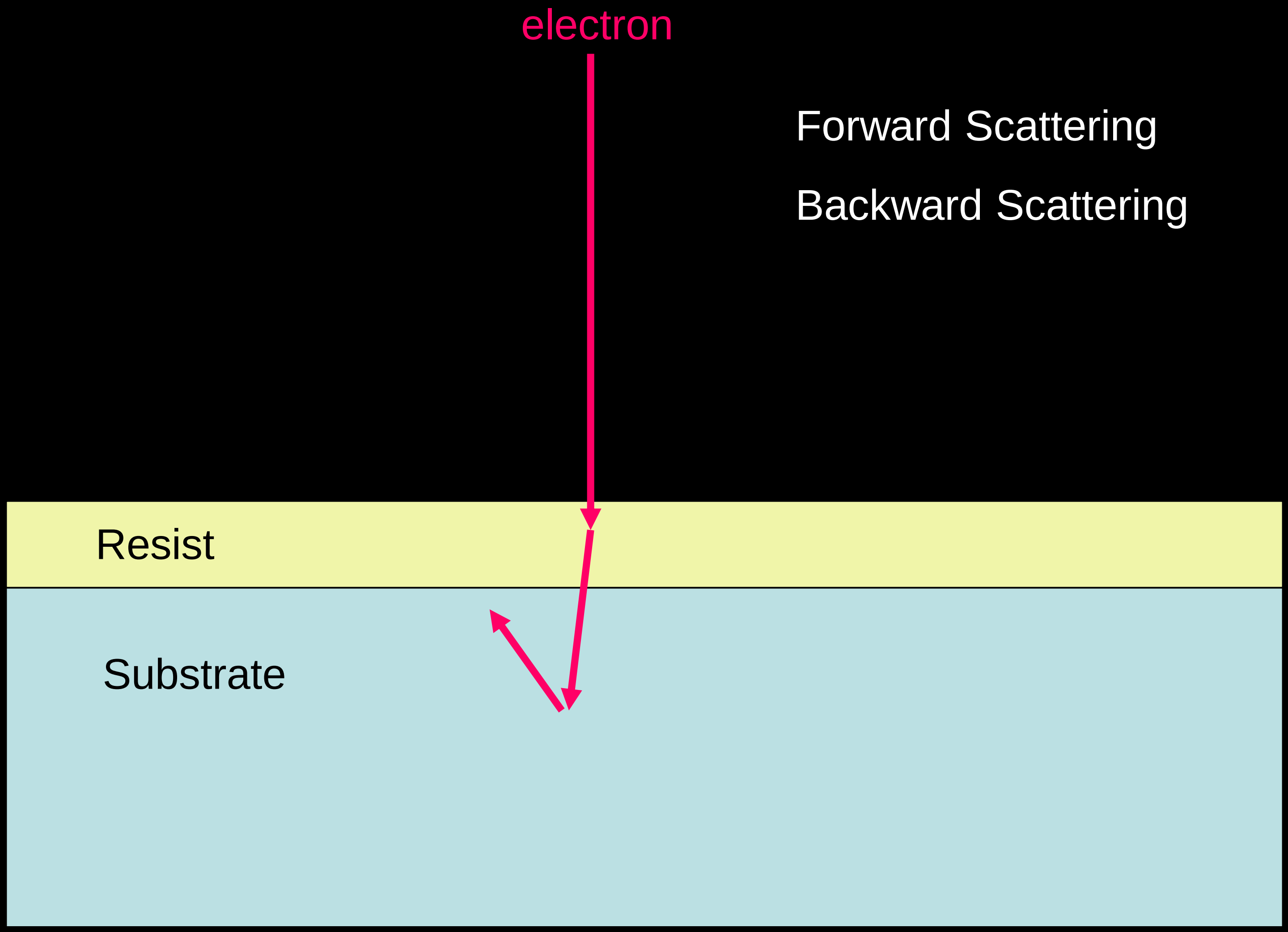
Interaction of Electron Beam with Sample



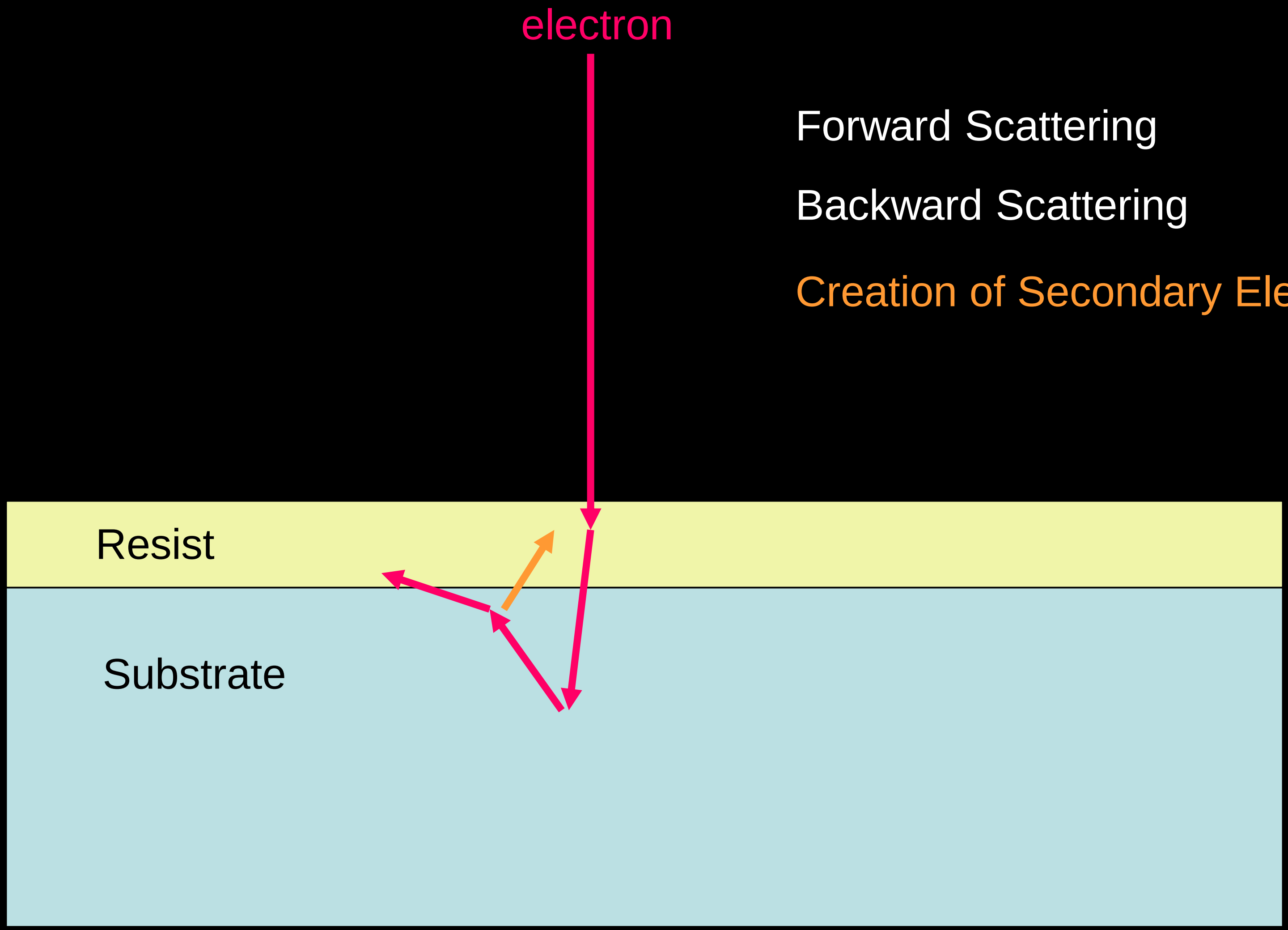
Interaction of Electron Beam with Sample

Forward Scattering

Backward Scattering



Interaction of Electron Beam with Sample

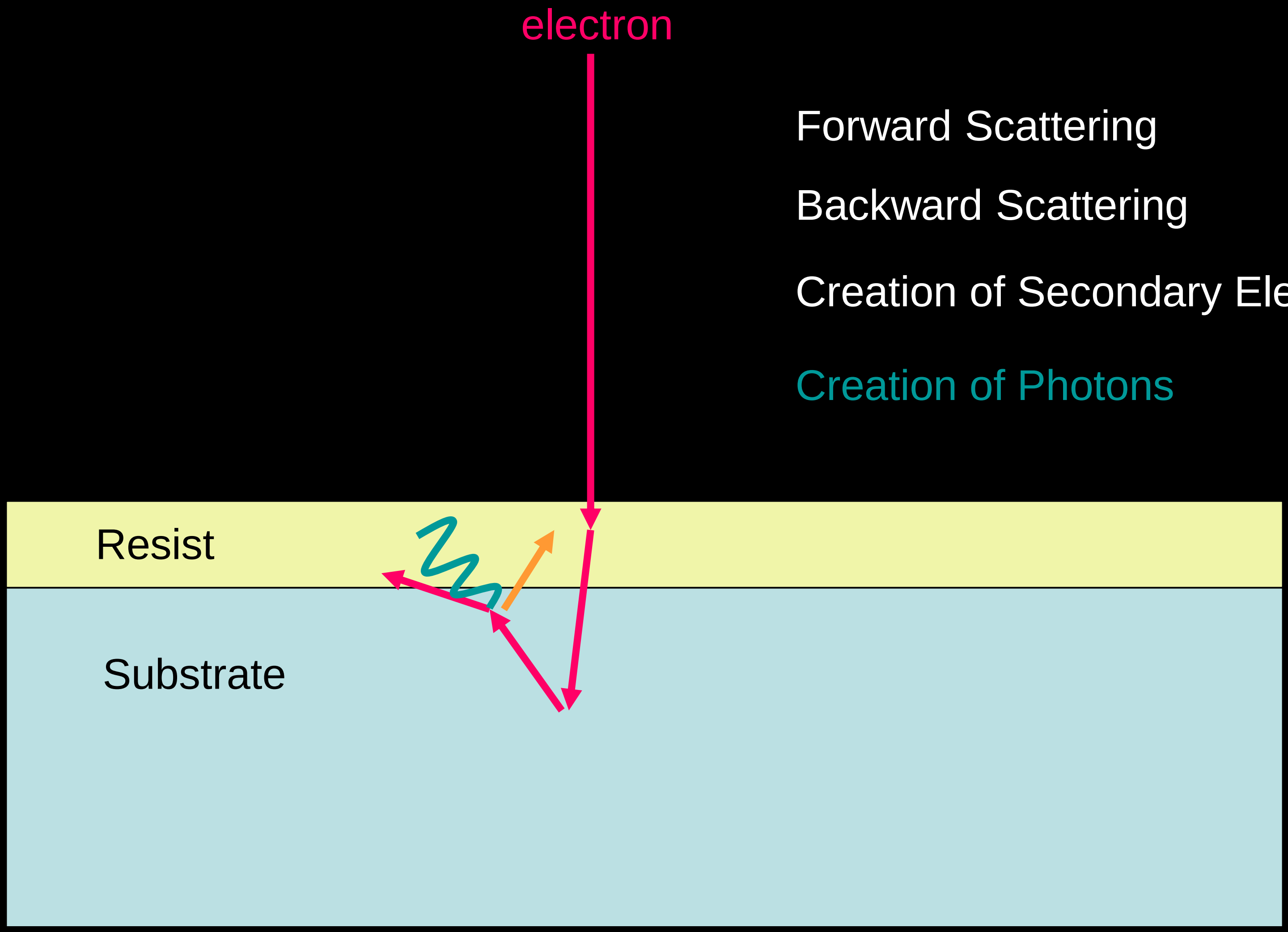


Forward Scattering

Backward Scattering

Creation of Secondary Electrons

Interaction of Electron Beam with Sample



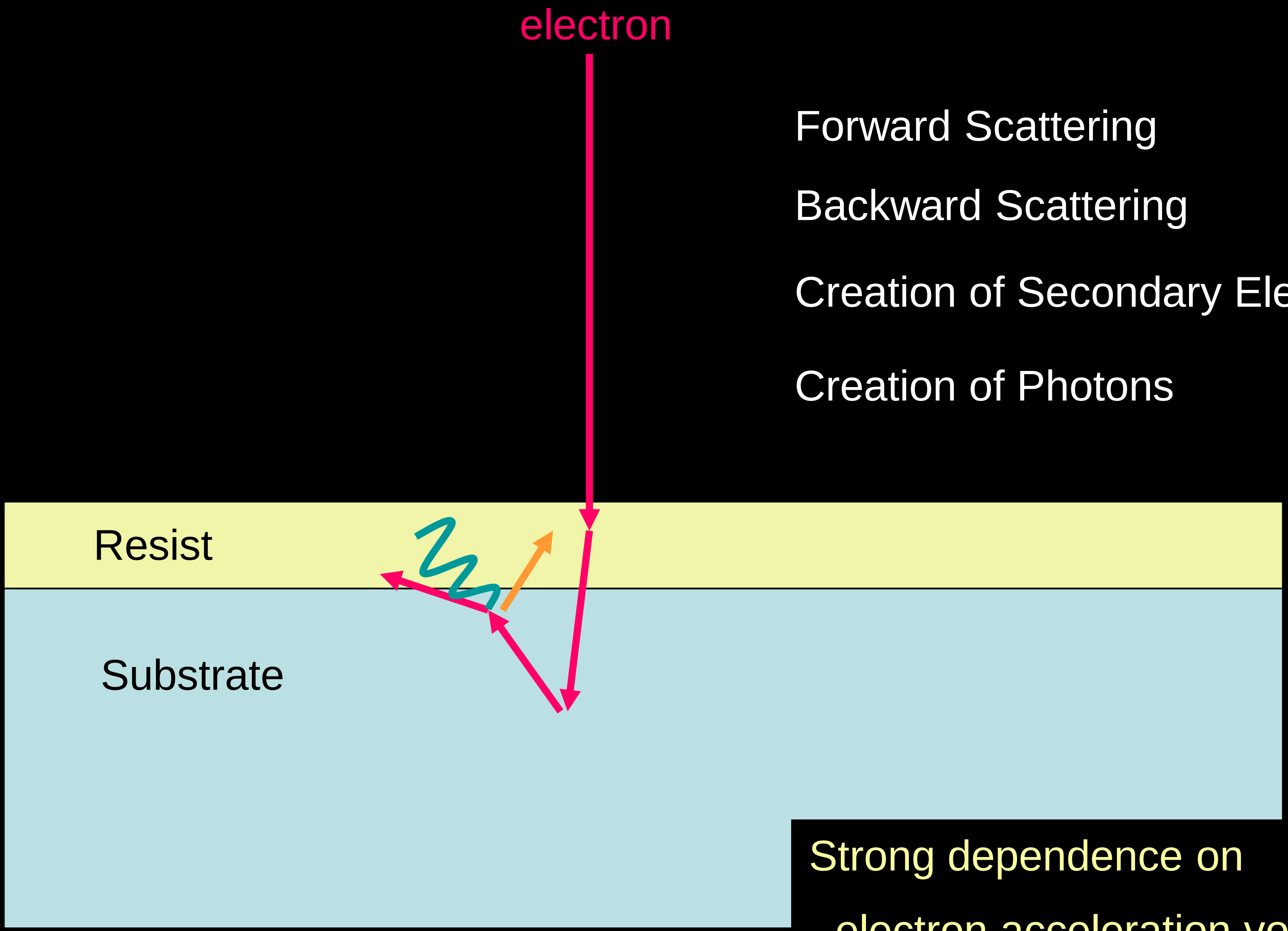
Forward Scattering

Backward Scattering

Creation of Secondary Electrons

Creation of Photons

Interaction of Electron Beam with Sample



Forward Scattering

Backward Scattering

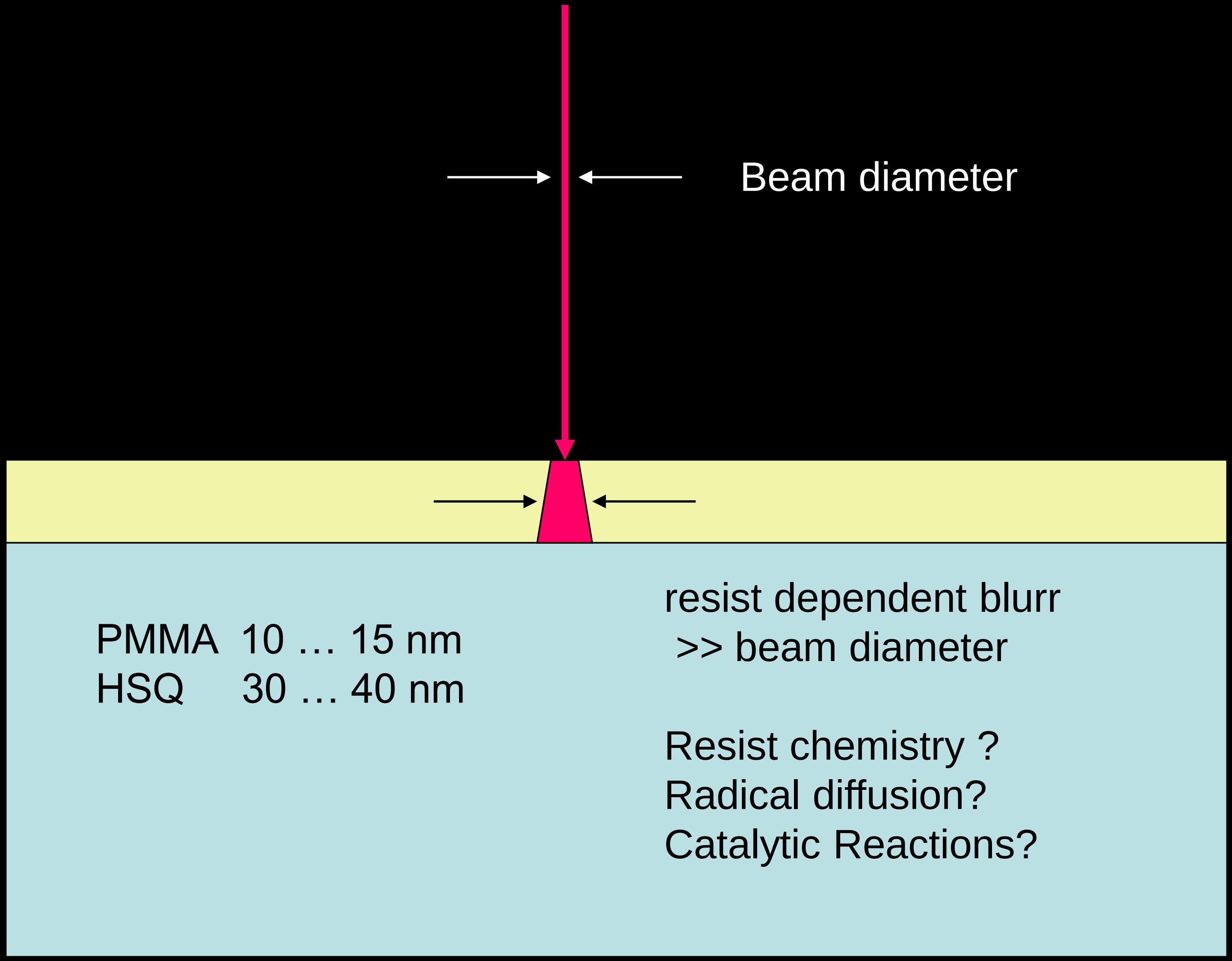
Creation of Secondary Electrons

Creation of Photons

Strong dependence on

- electron acceleration voltage
- substrate composition / density

Interaction of Electron Beam with Sample



Beam diameter

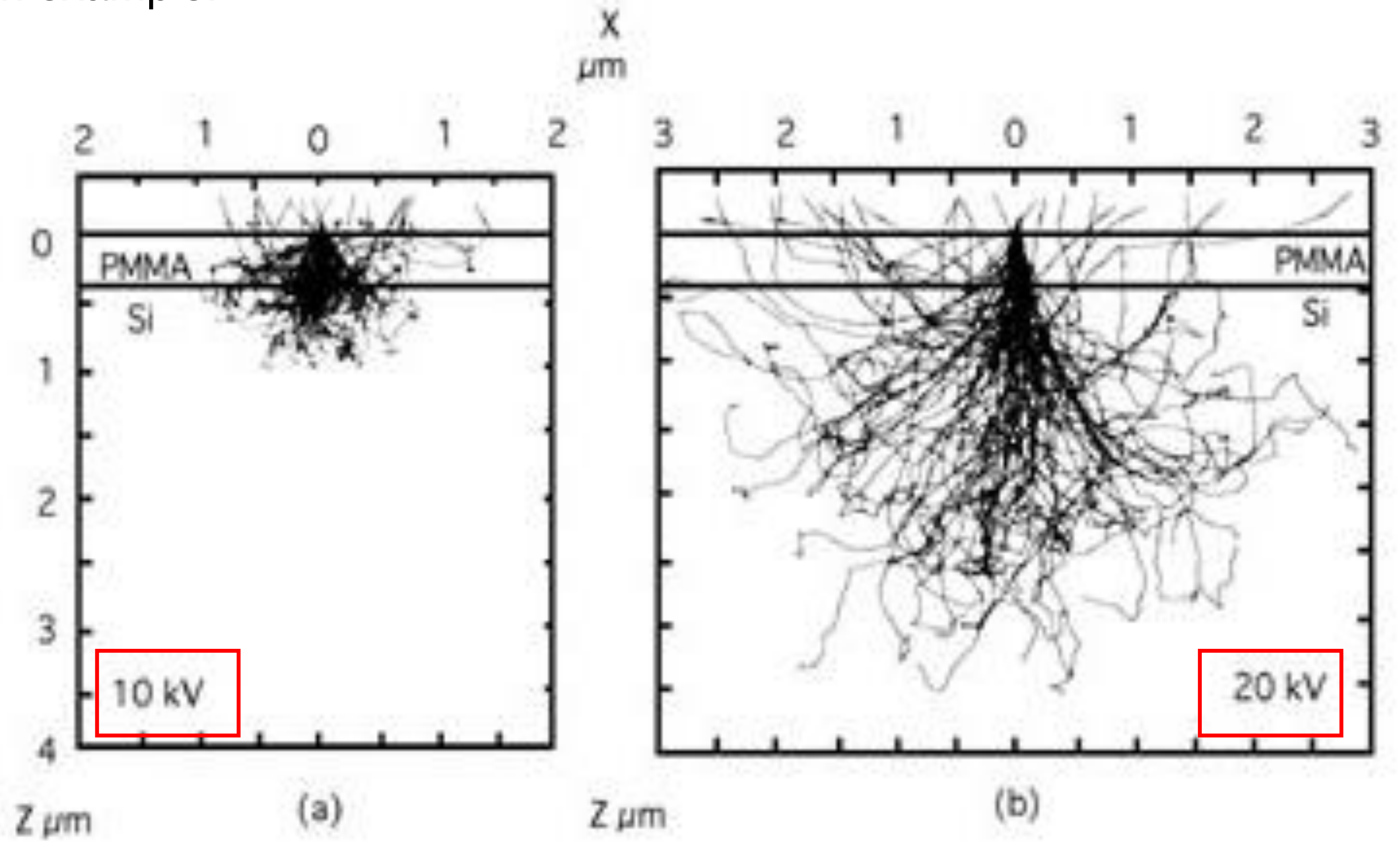
PMMA	10 … 15 nm
HSQ	30 … 40 nm

resist dependent blurr
>> beam diameter

Resist chemistry ?
Radical diffusion?
Catalytic Reactions?

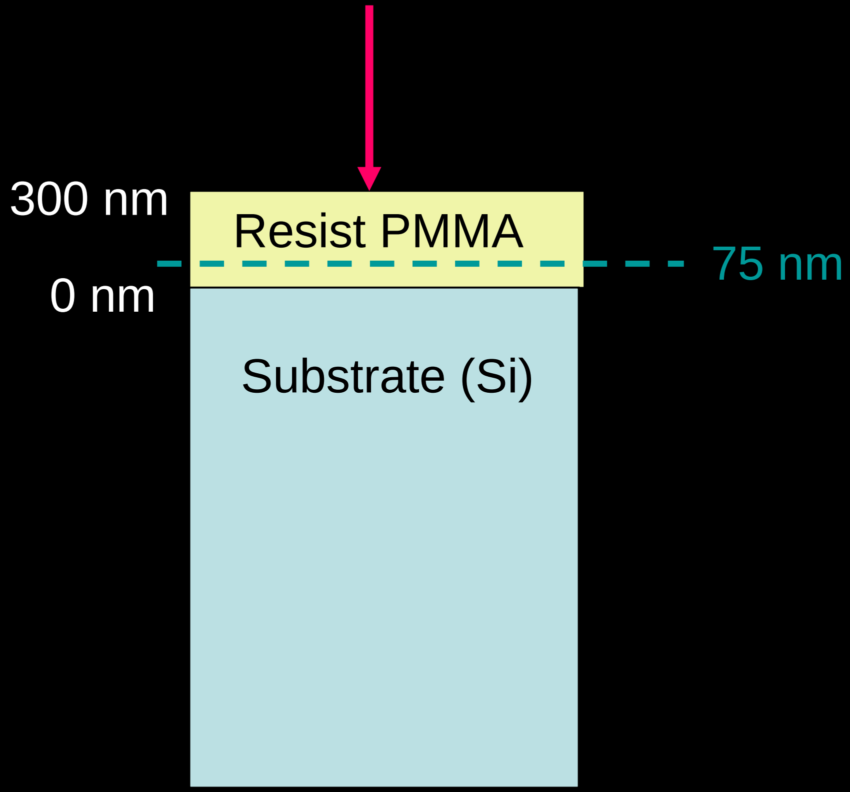
Electron Scattering: Monte-Carlo-Simulation

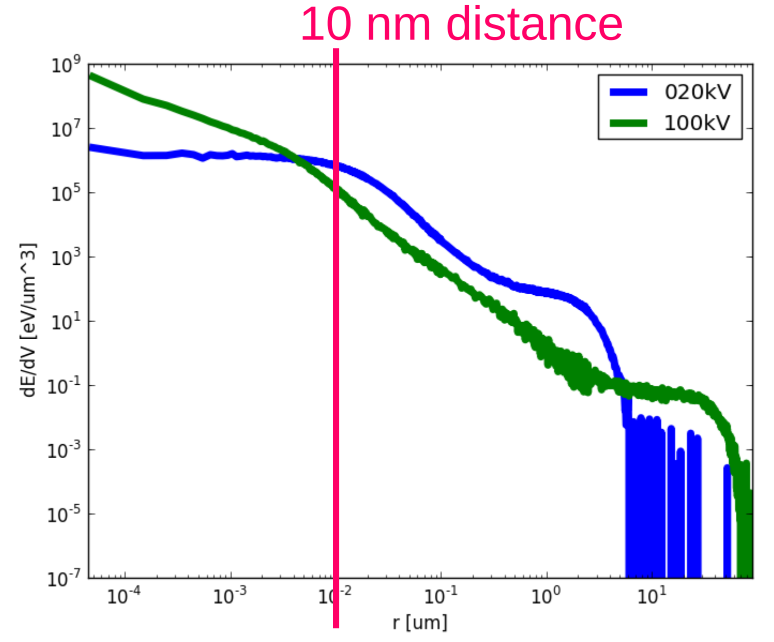
An example:



From Kyser and Viswanathan (1975)

Point Spread Function:
(Energy density deposited radially vs. Distance)

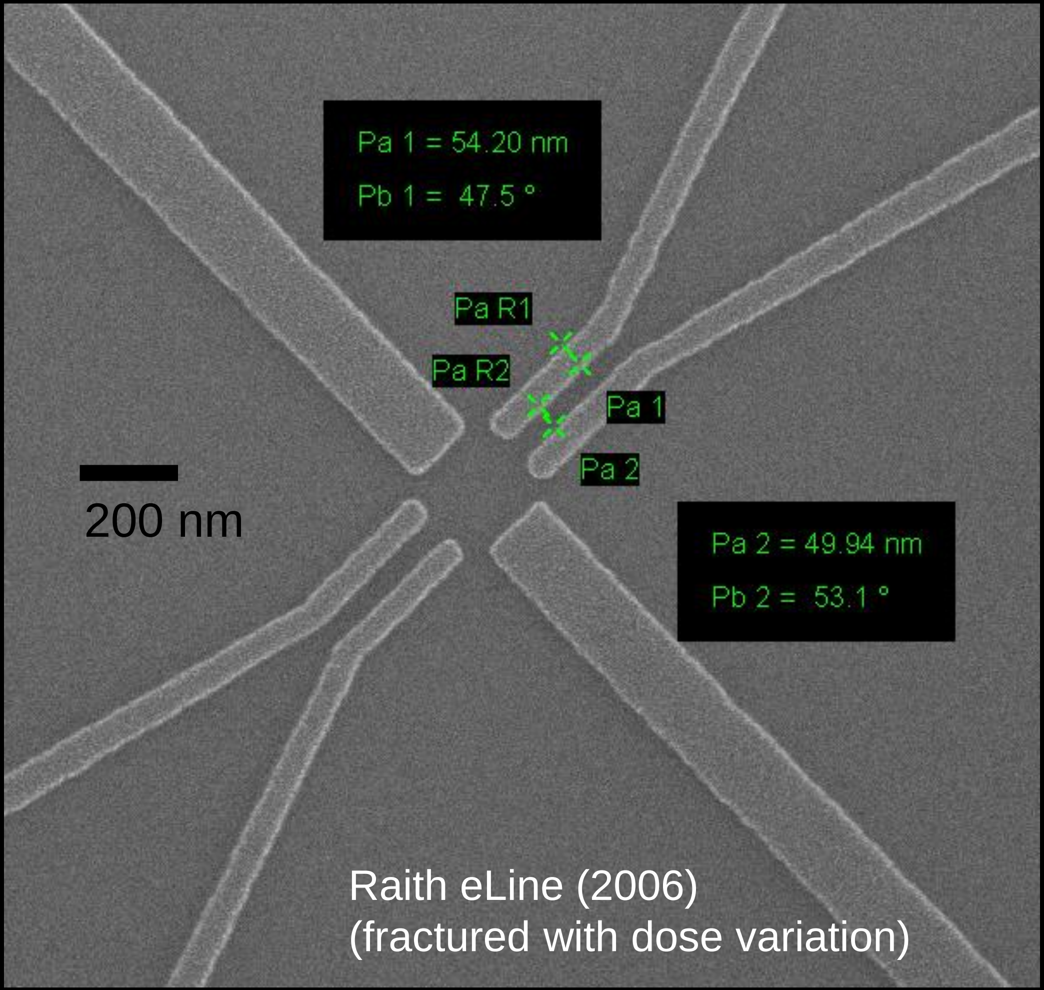



10 nm distance

log/log scale !!

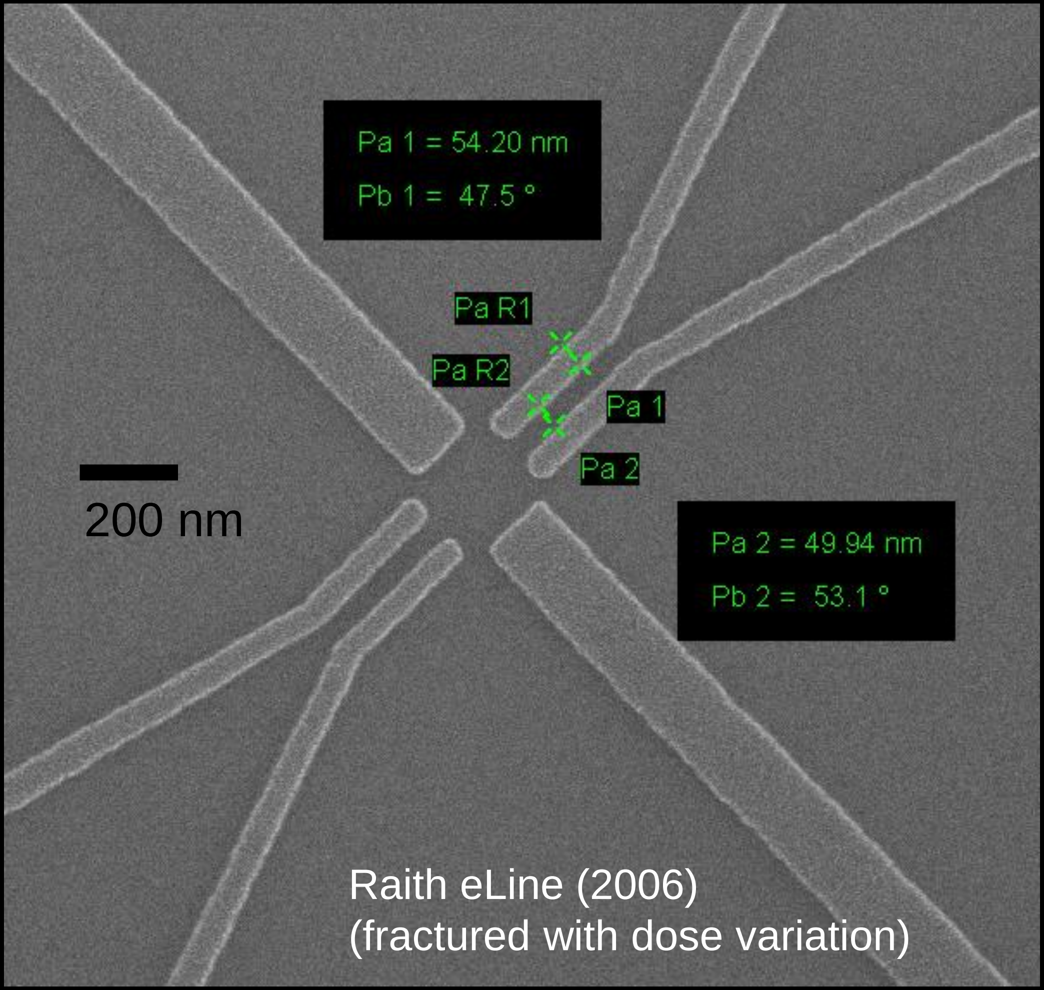
Marcus Rommel
Monte-Carlo-Code ‚Penelope‘

Split-gate structure:

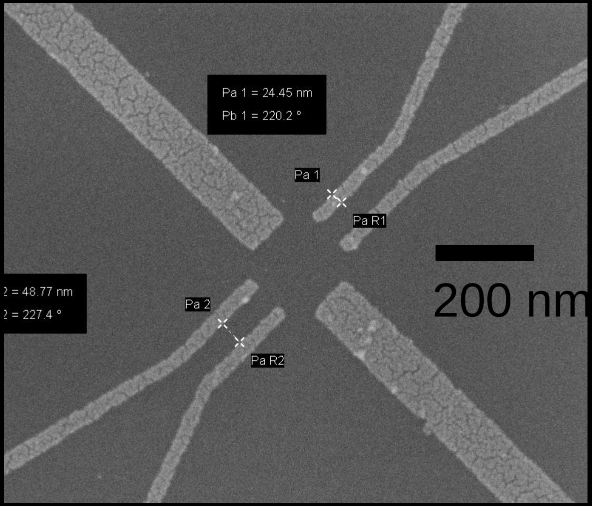


Raith eLine (2006)
(fractured with dose variation)

Split-gate structure:

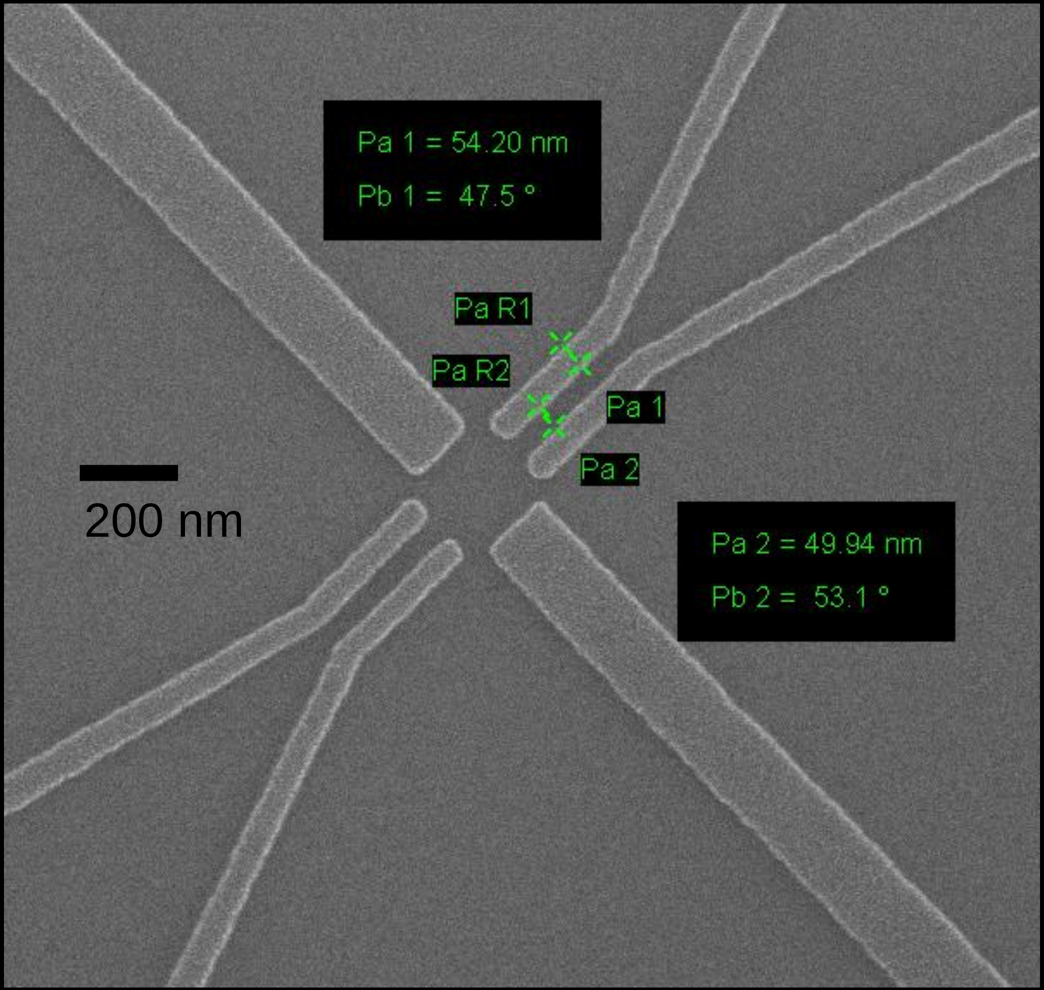


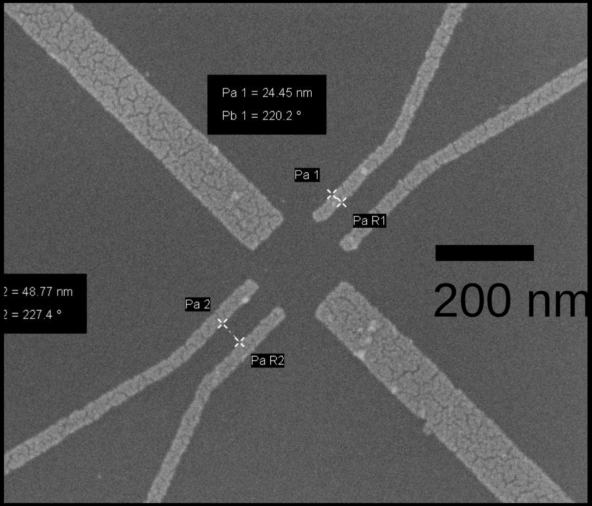
Raith eLine (2006)
(fractured with dose variation)



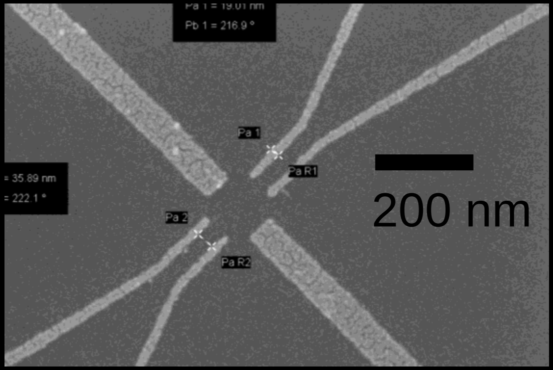
Jeol JBX6300FS (2009)
(no fracturing and dose variation)

Split-gate structure:

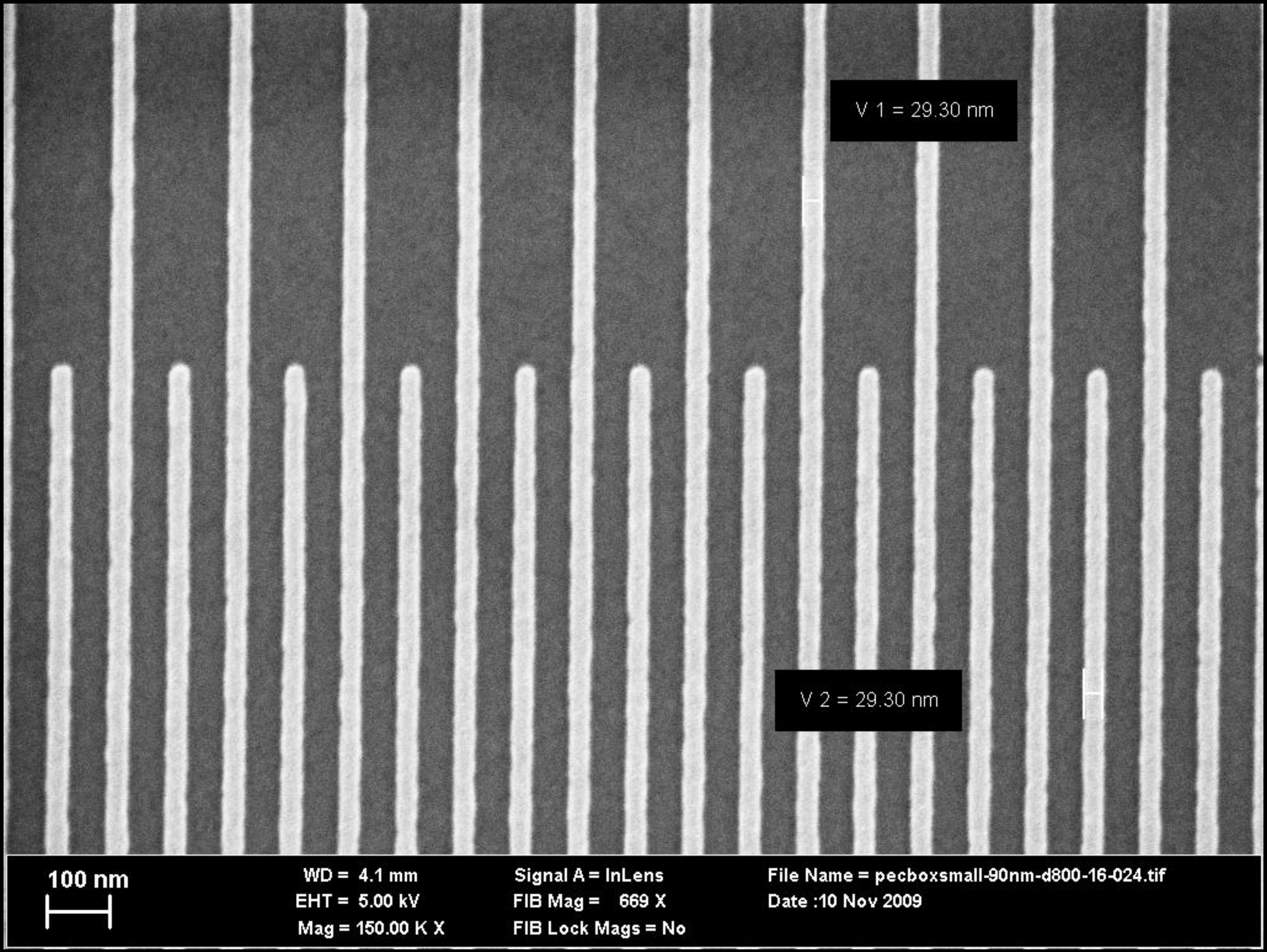




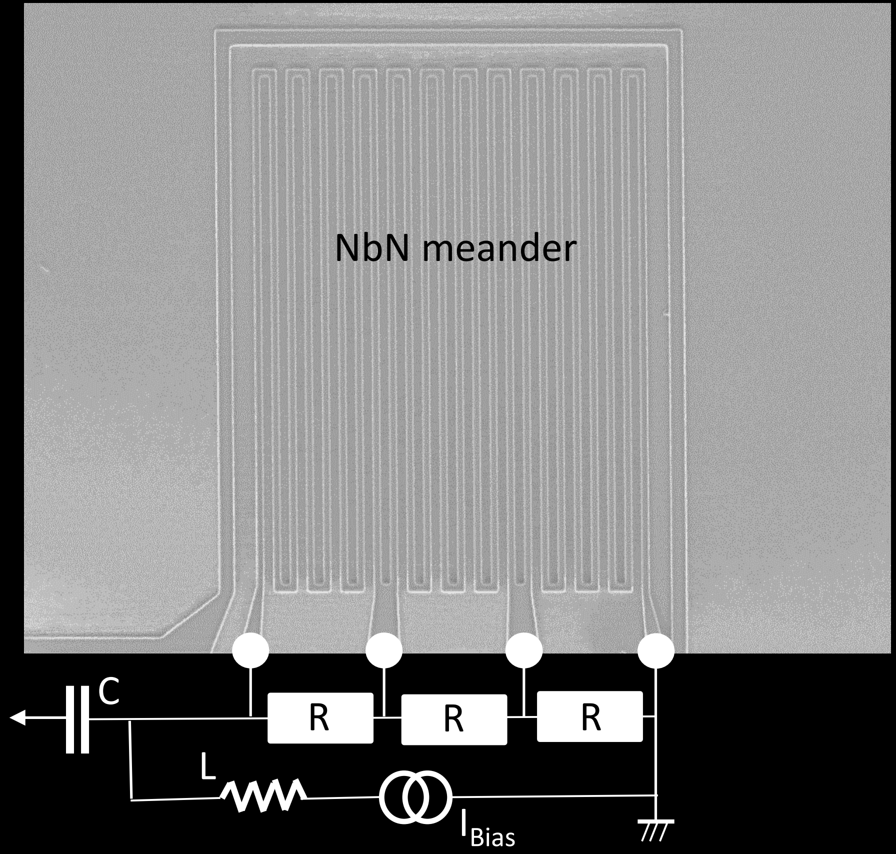
Even smaller:

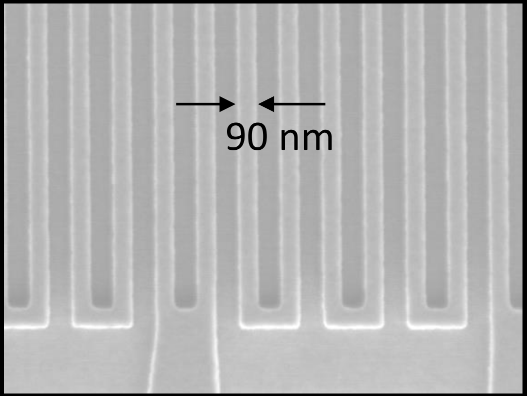


Interdigital Metal Structure for generating Surface-Acoustic Waves



Single-Photon Detector Based on NbN Superconductor

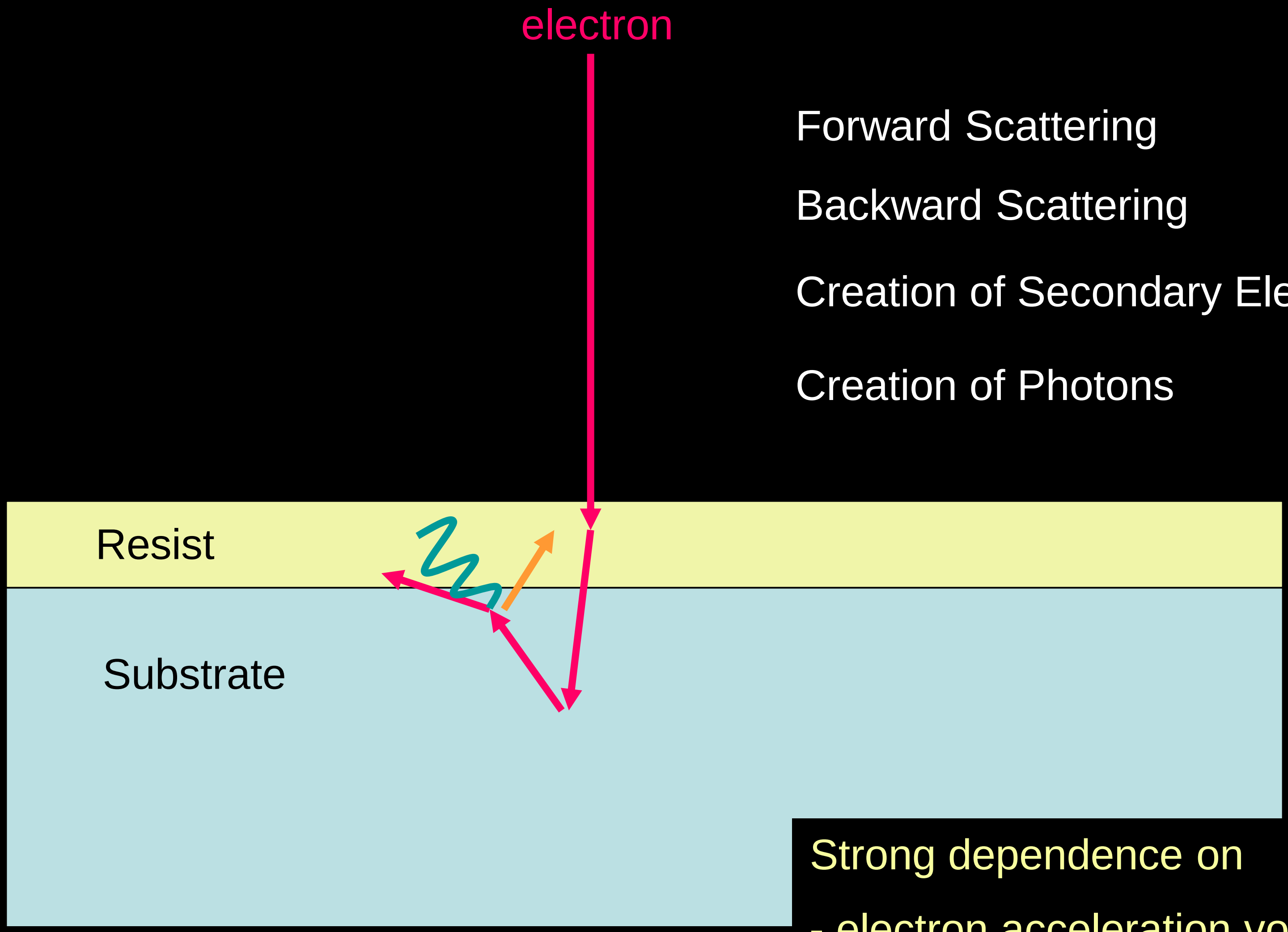




Eric Reutter, MPI-FKF (2022)

following Nature Photonics 2, 302 (2008)

Interaction of Electron Beam with Sample



Forward Scattering

Backward Scattering

Creation of Secondary Electrons

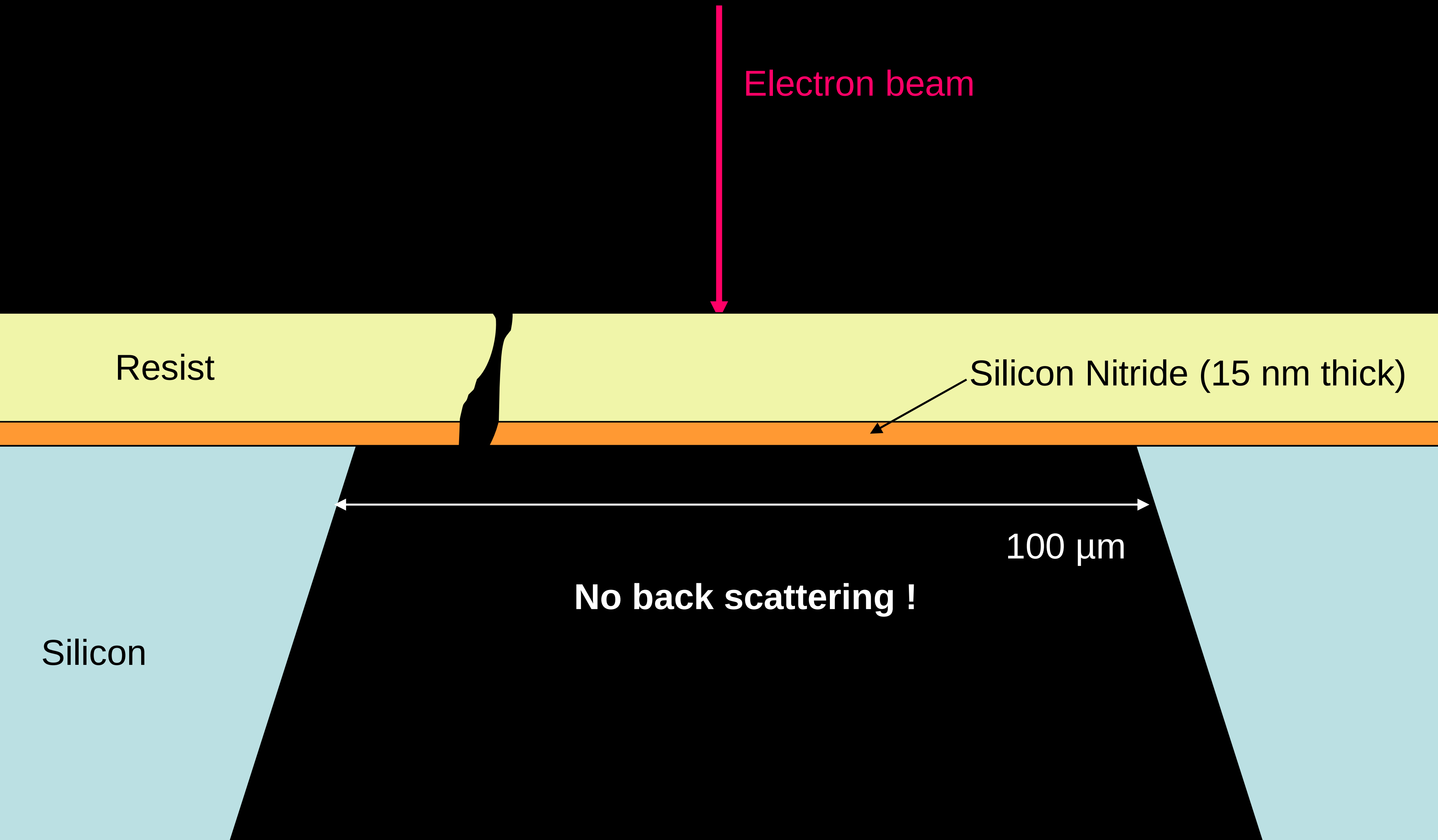
Creation of Photons

Strong dependence on

- electron acceleration voltage

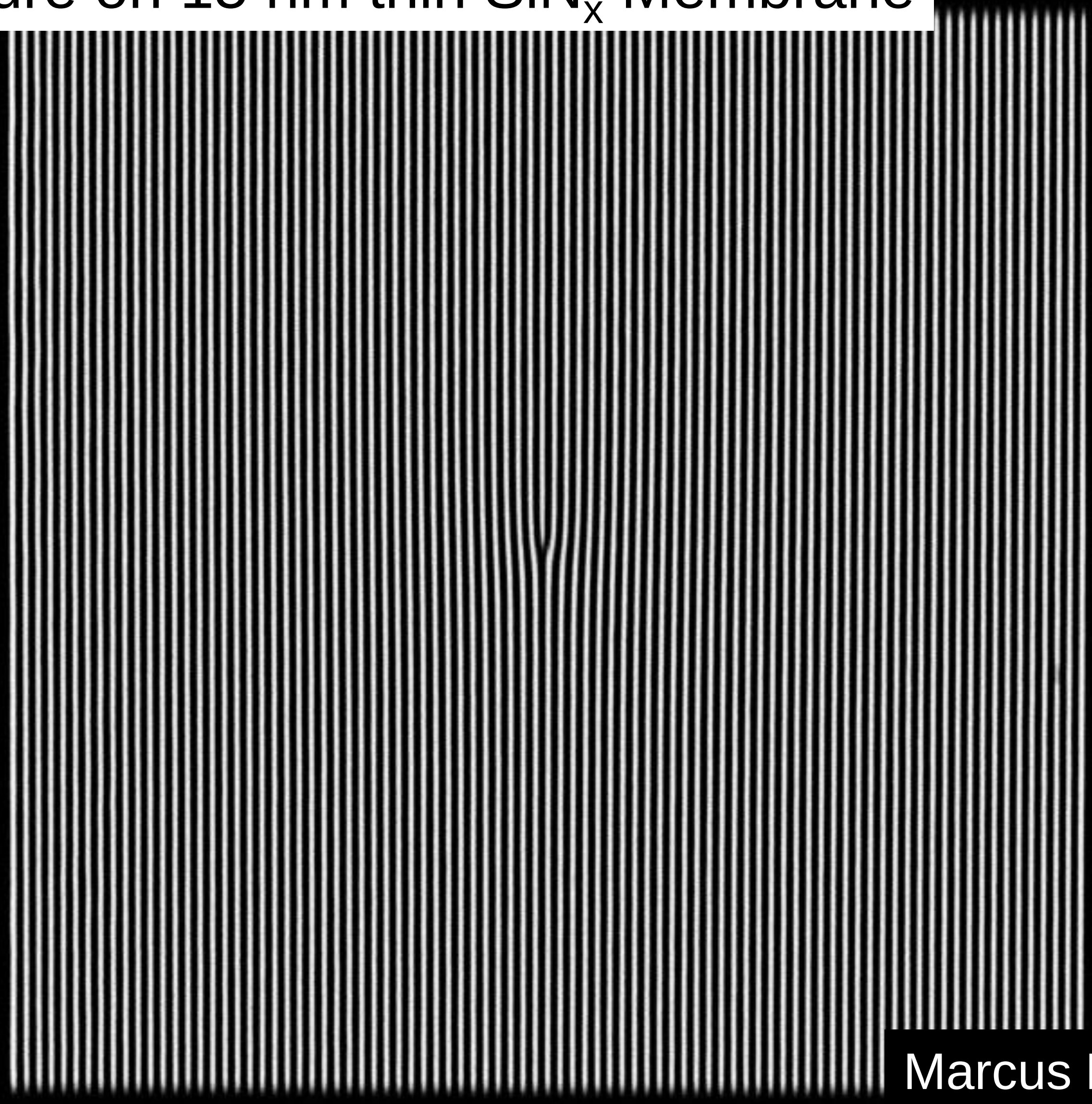
- substrate composition / density

Electron Beam Lithography on a Thin Membrane



No back scattering !

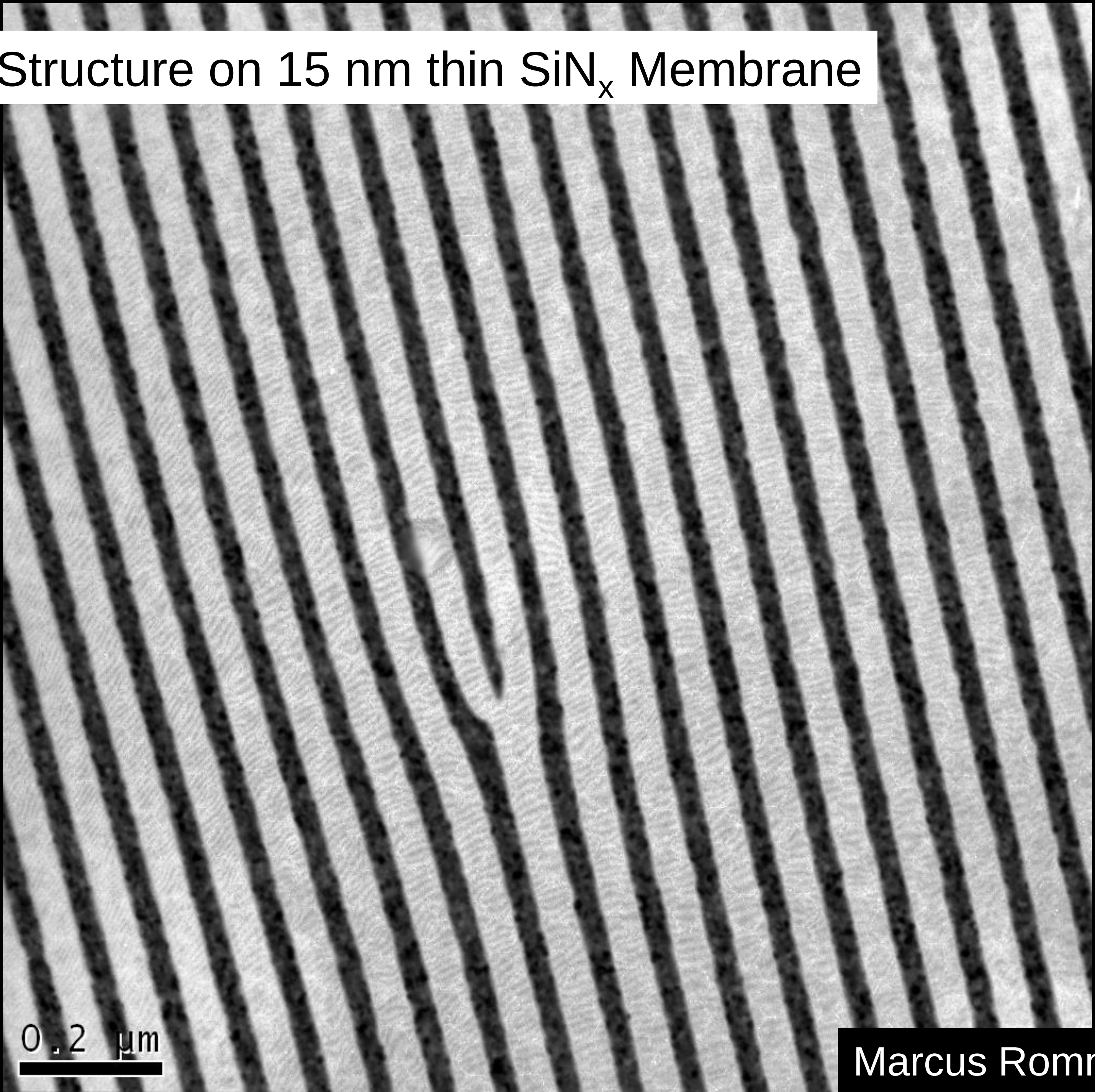
Gold Structure on 15 nm thin SiN_x Membrane



Marcus Rommel (2011)

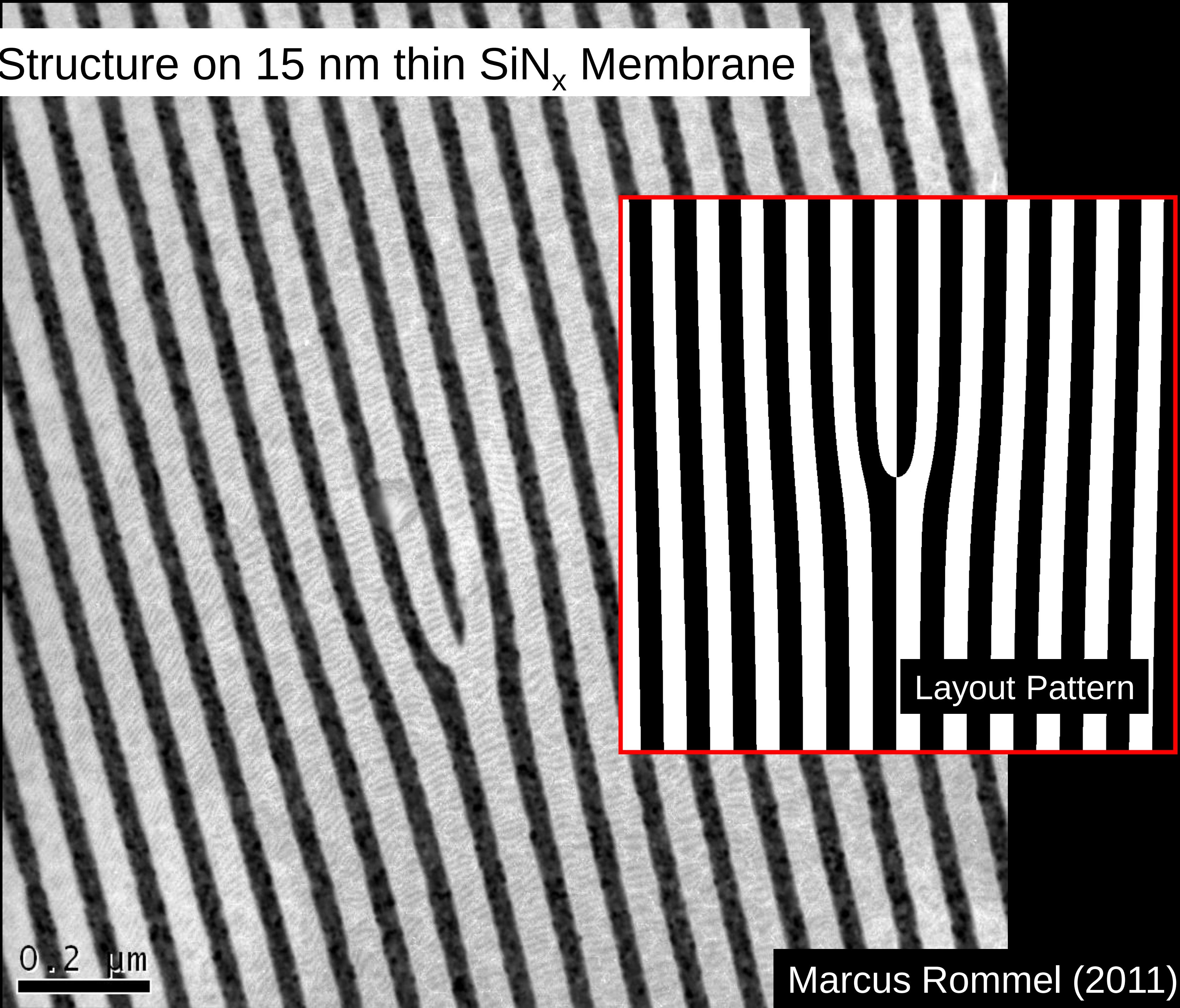
Diffraction pattern for use in a TEM (Koch, van Aken, MPI IS)

Gold Structure on 15 nm thin SiN_x Membrane



Marcus Rommel (2011)

Gold Structure on 15 nm thin SiN$_x$ Membrane



Marcus Rommel (2011)

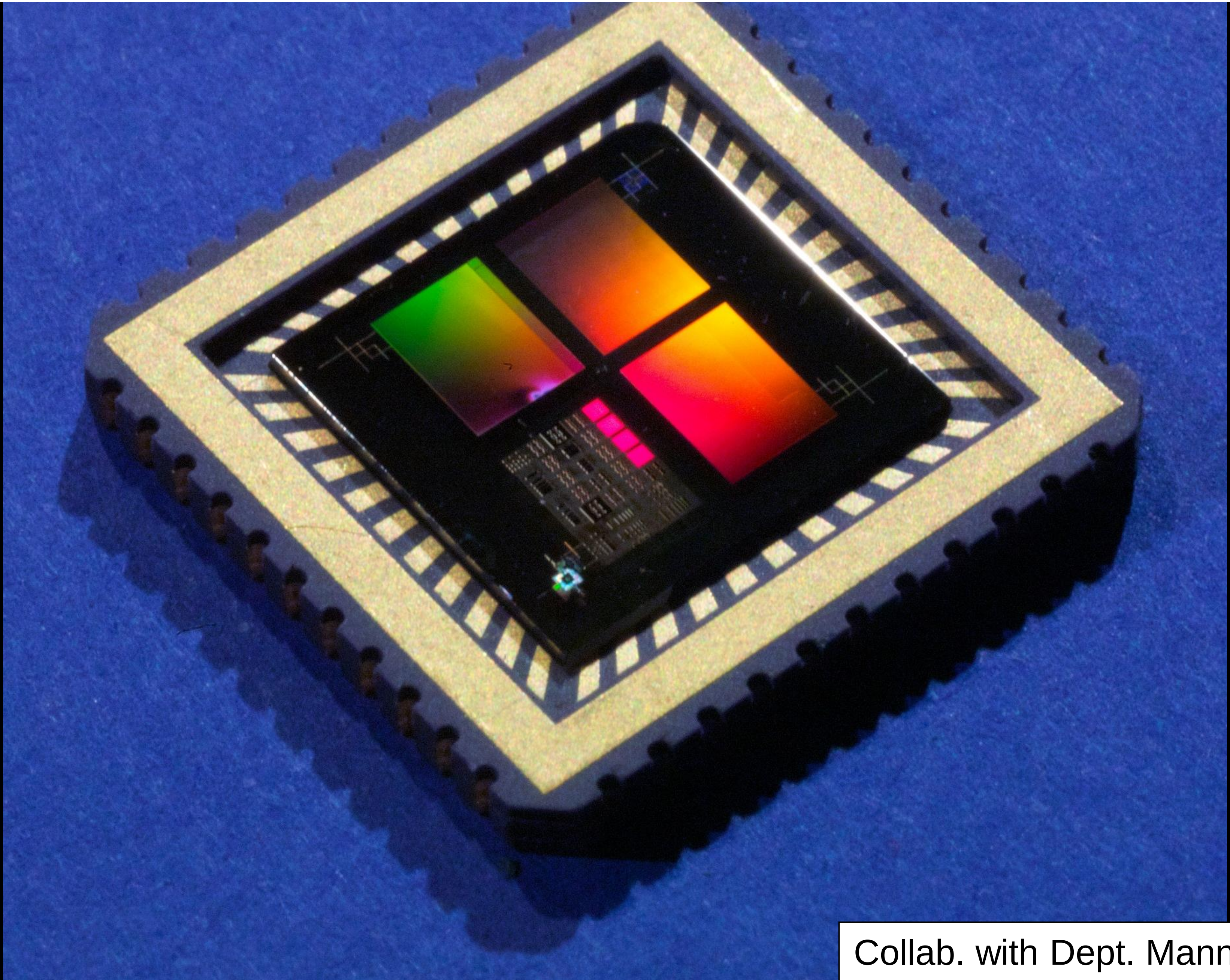
Dedicated 100 kV Electron Beam Lithography System ?

- Acceleration Voltage: Interaction with substrate
  (Proximity Effect, Damage)

- Writing speed:

  typically 1 nA (Jeol) versus 5 pA (Raith eline)

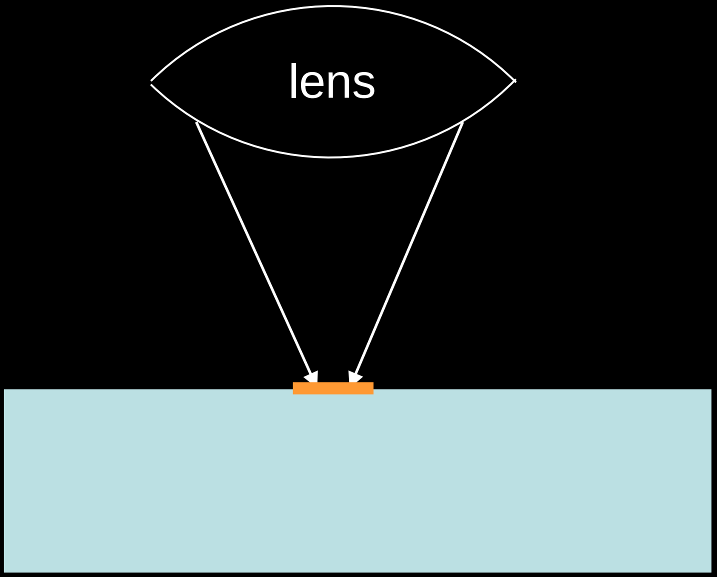
Millions of Transistor Structures based on Oxide Heterostructures



Collab. with Dept. Mannhart

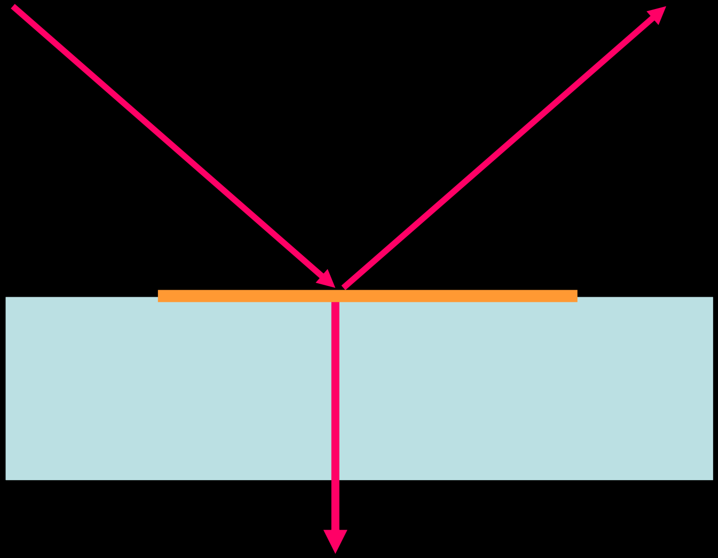
Why Large Area ? An Example:
Optics / Metamaterials

Small area sample



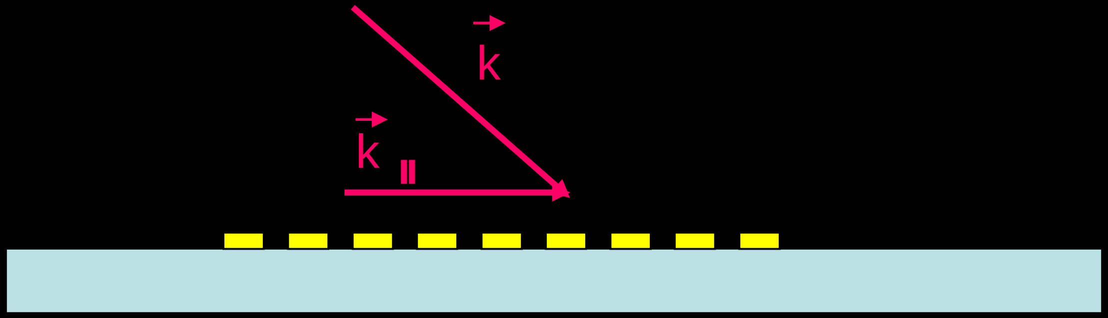
No well defined $\vec{k}$ for light

Large area sample

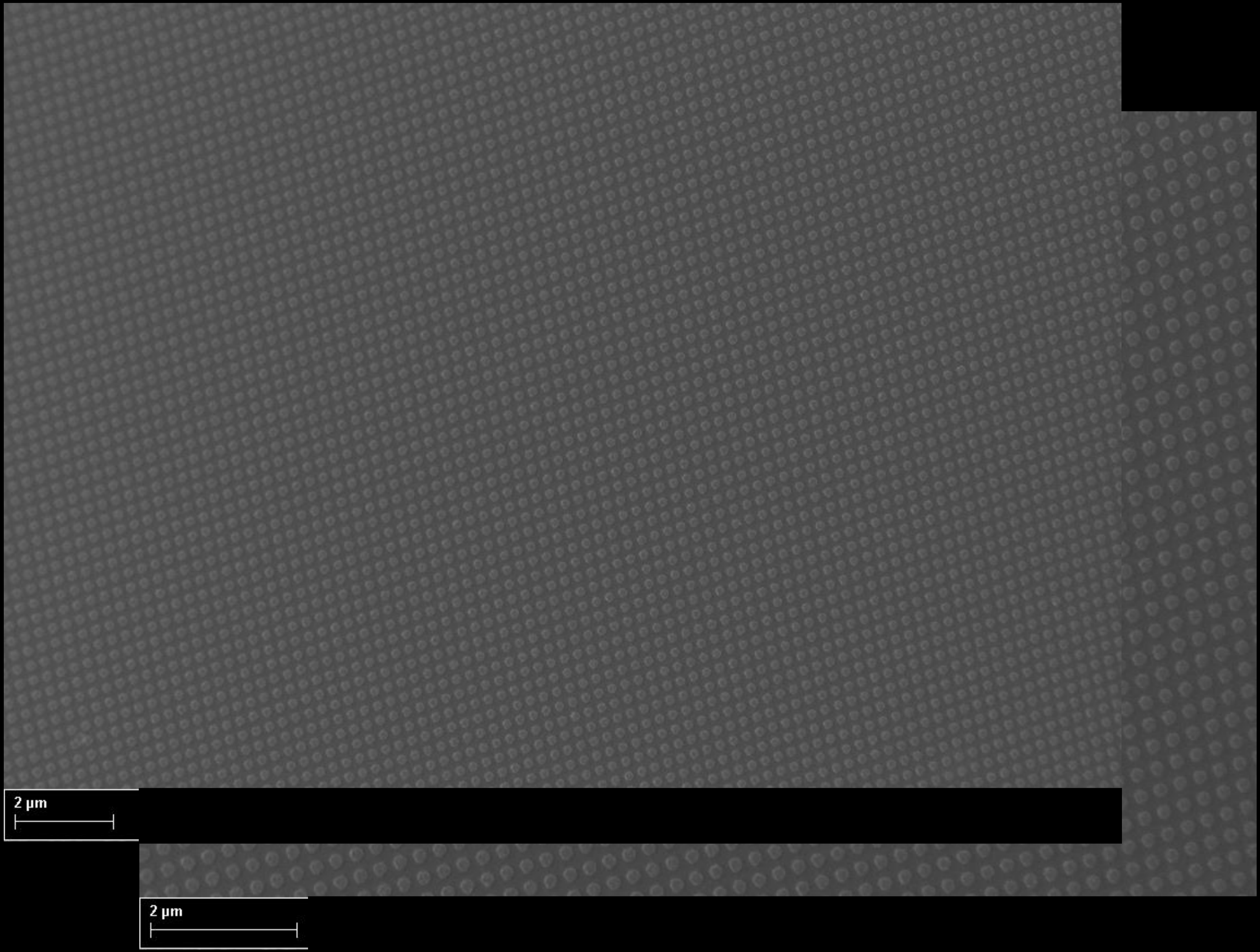


Allows angle dependent reflection / transmission measurements FIR to Visible

$r(\omega,k)$ $t(\omega,k)$

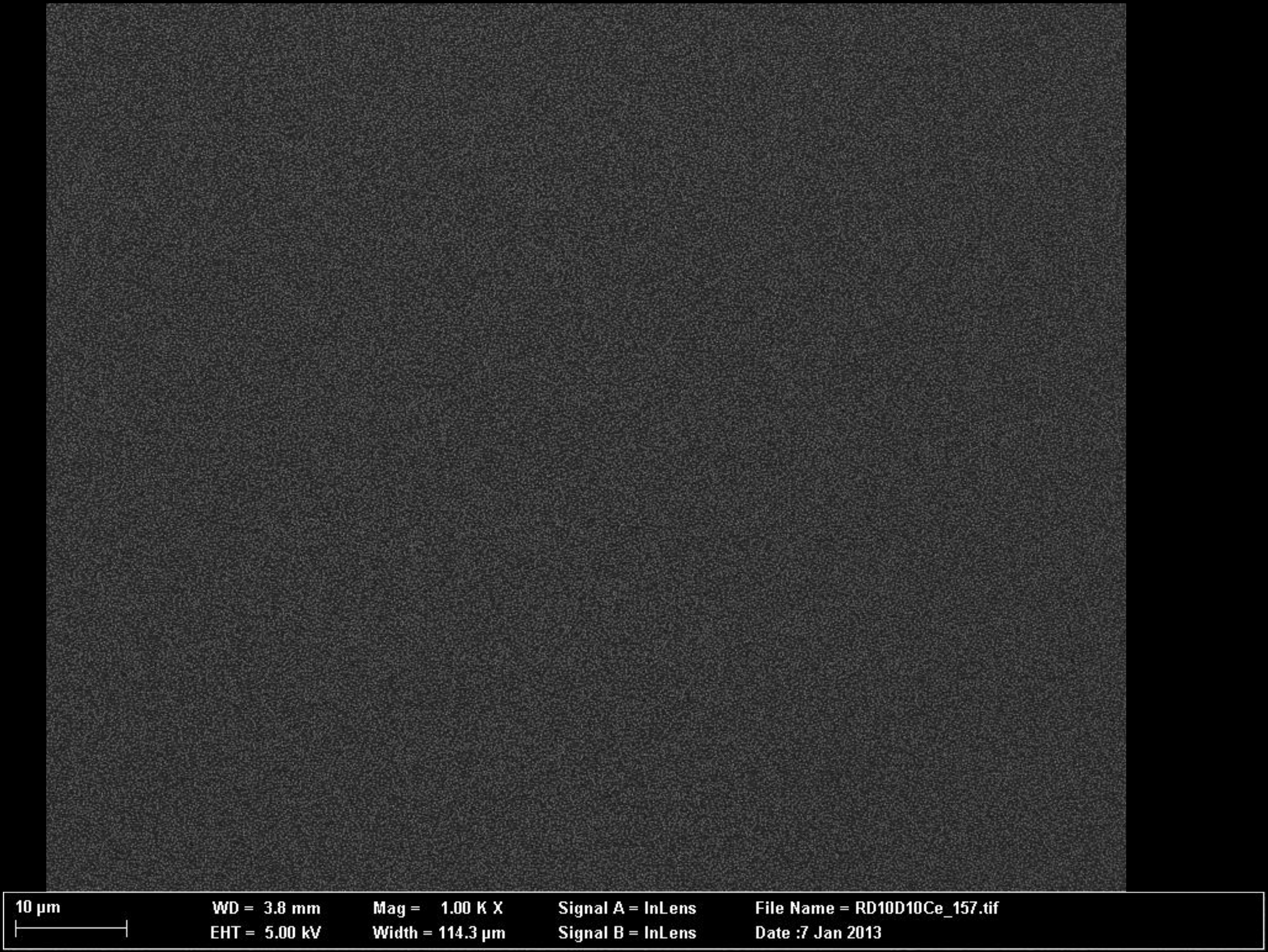

$\vec{k}$
$\vec{k}_{\parallel}$

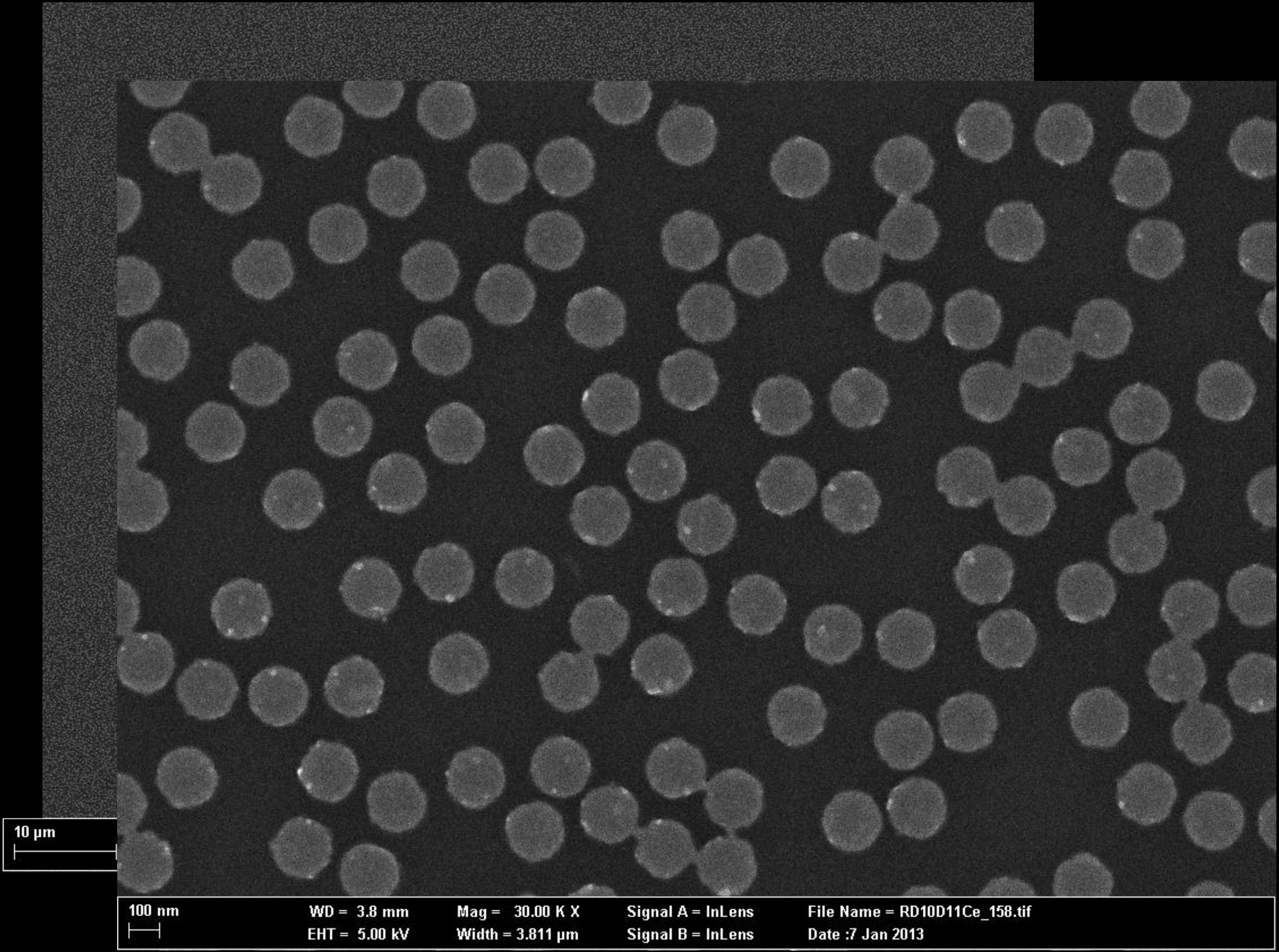

2 µm


2 µm
2 µm

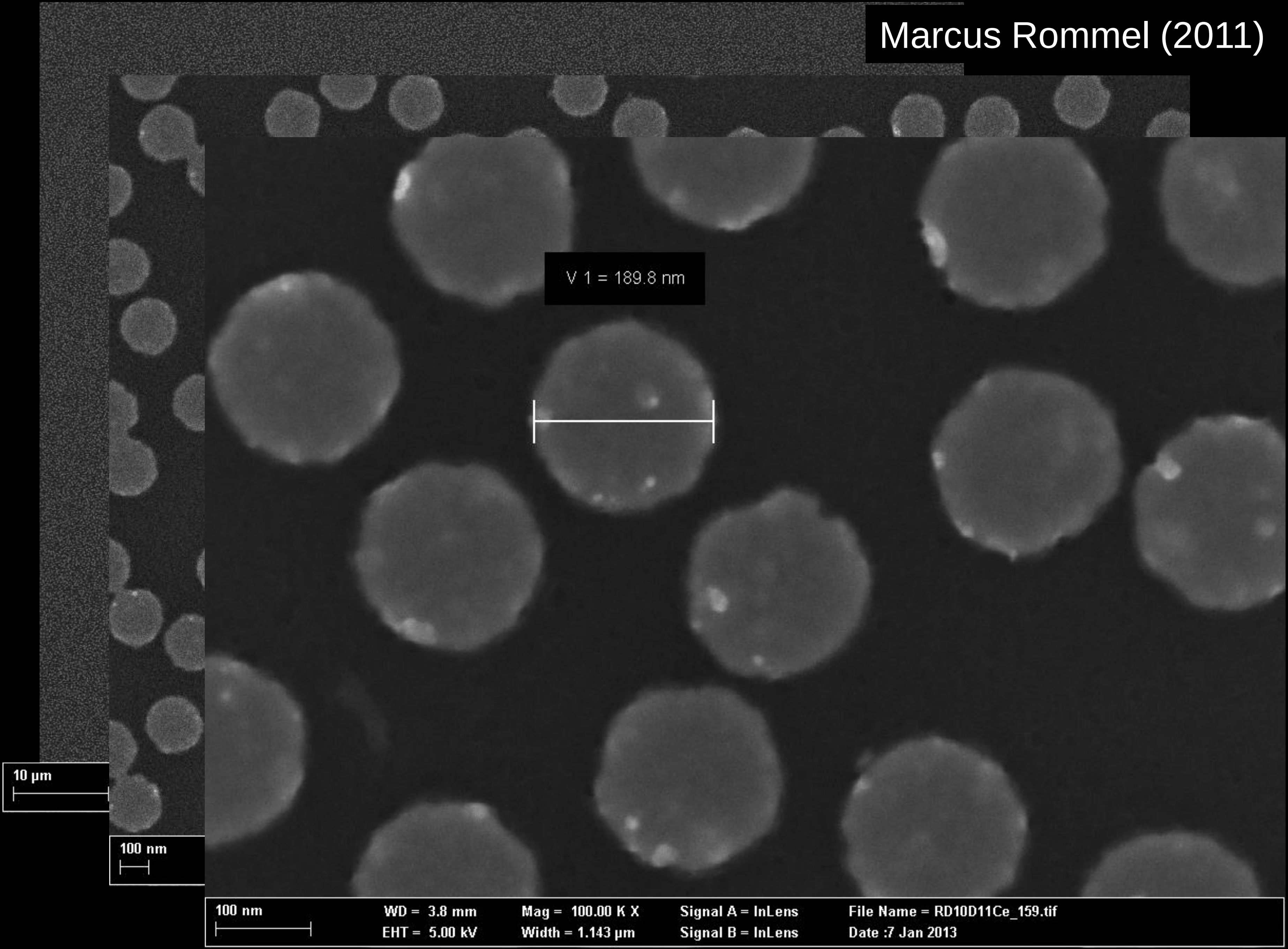

2 µm
2 µm
2 µm

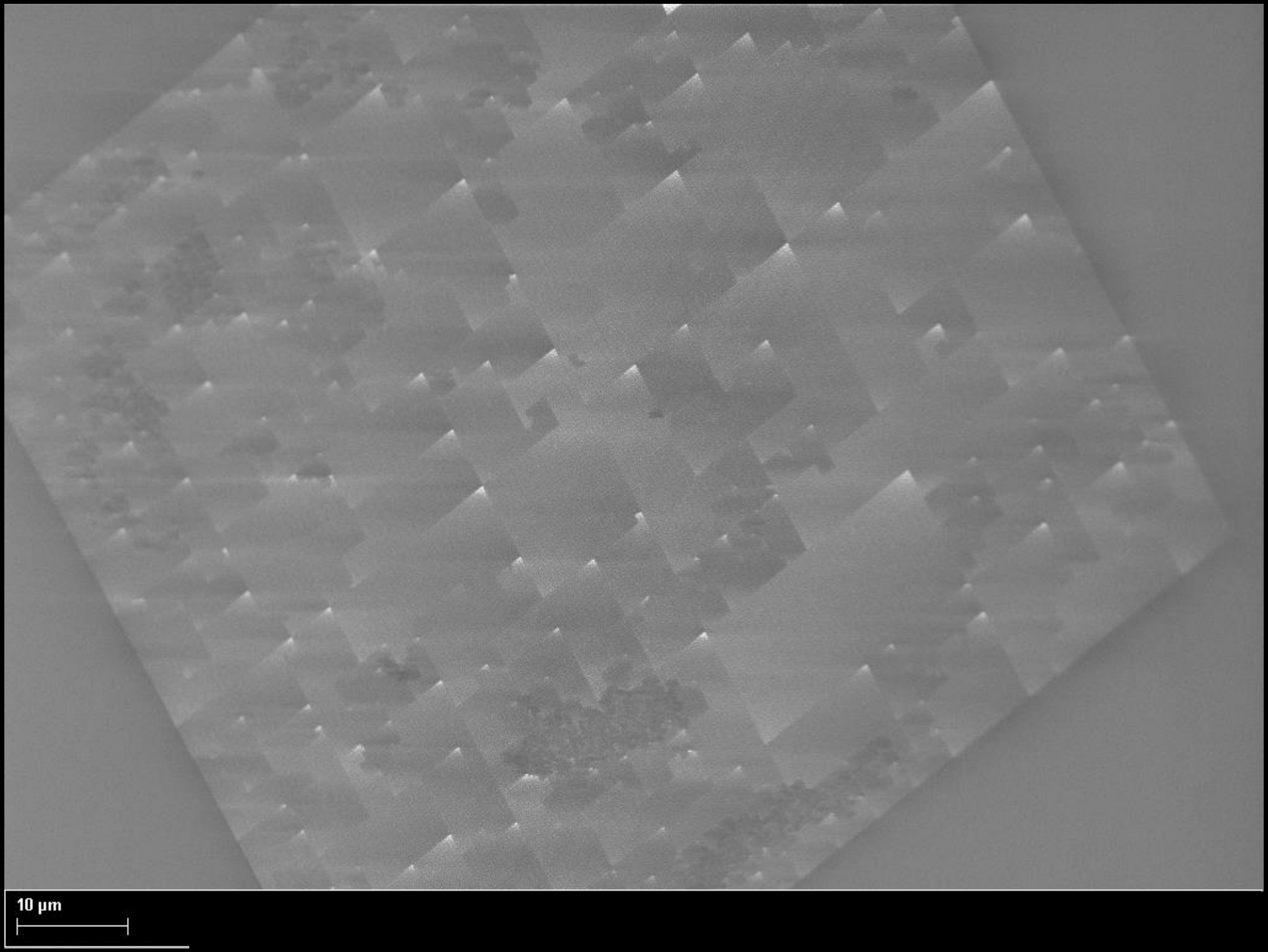
Marcus Rommel (2011)


10 µm
WD = 3.8 mm
EHT = 5.00 kV
Mag = 1.00 K X
Width = 114.3 µm
Signal A = InLens
Signal B = InLens
File Name = RD10D10Ce_157.tif
Date :7 Jan 2013

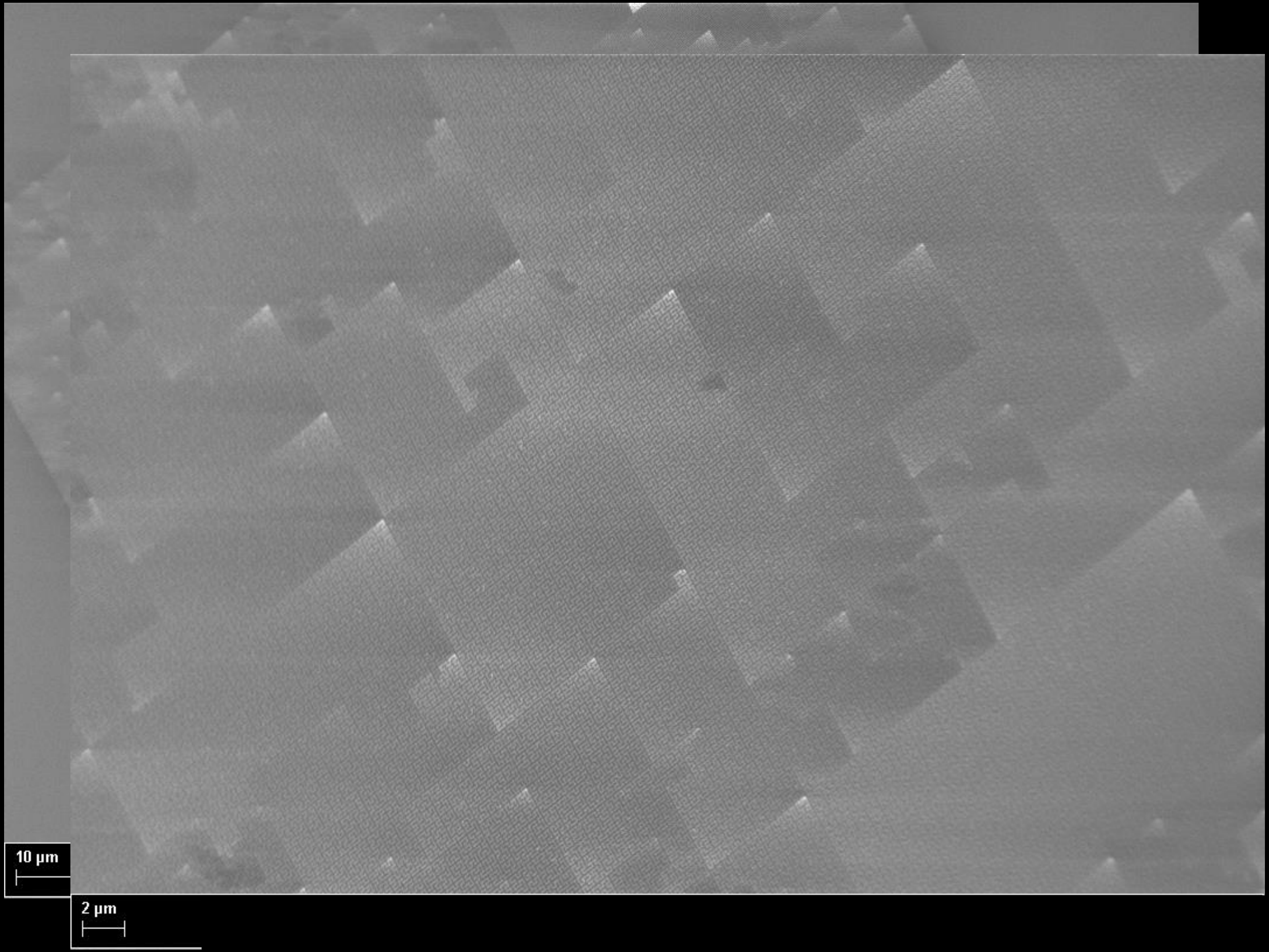

10 µm
100 nm
WD = 3.8 mm
EHT = 5.00 kV
Mag = 30.00 K X
Width = 3.811 µm
Signal A = InLens
Signal B = InLens
File Name = RD10D11Ce_158.tif
Date :7 Jan 2013

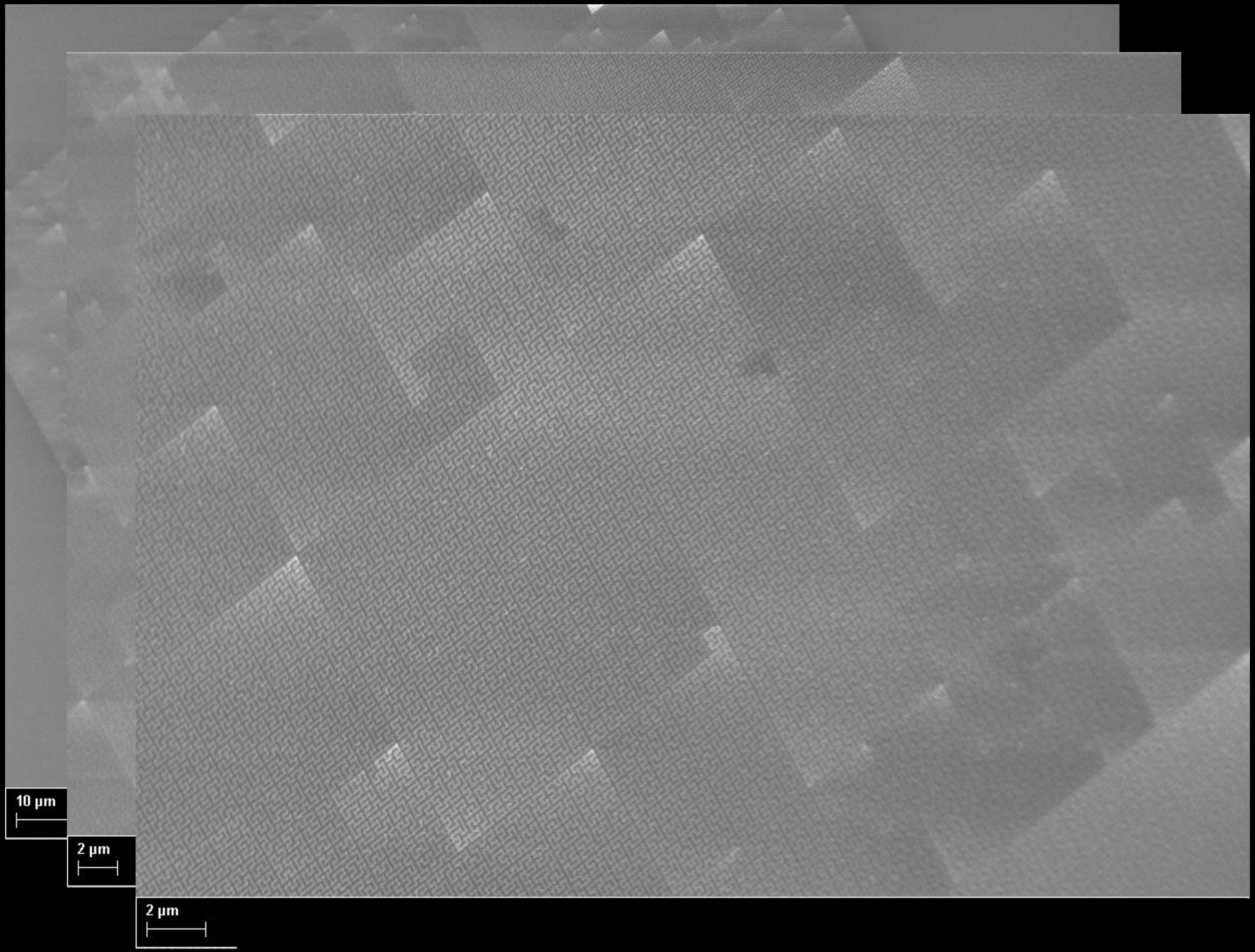
Marcus Rommel (2011)

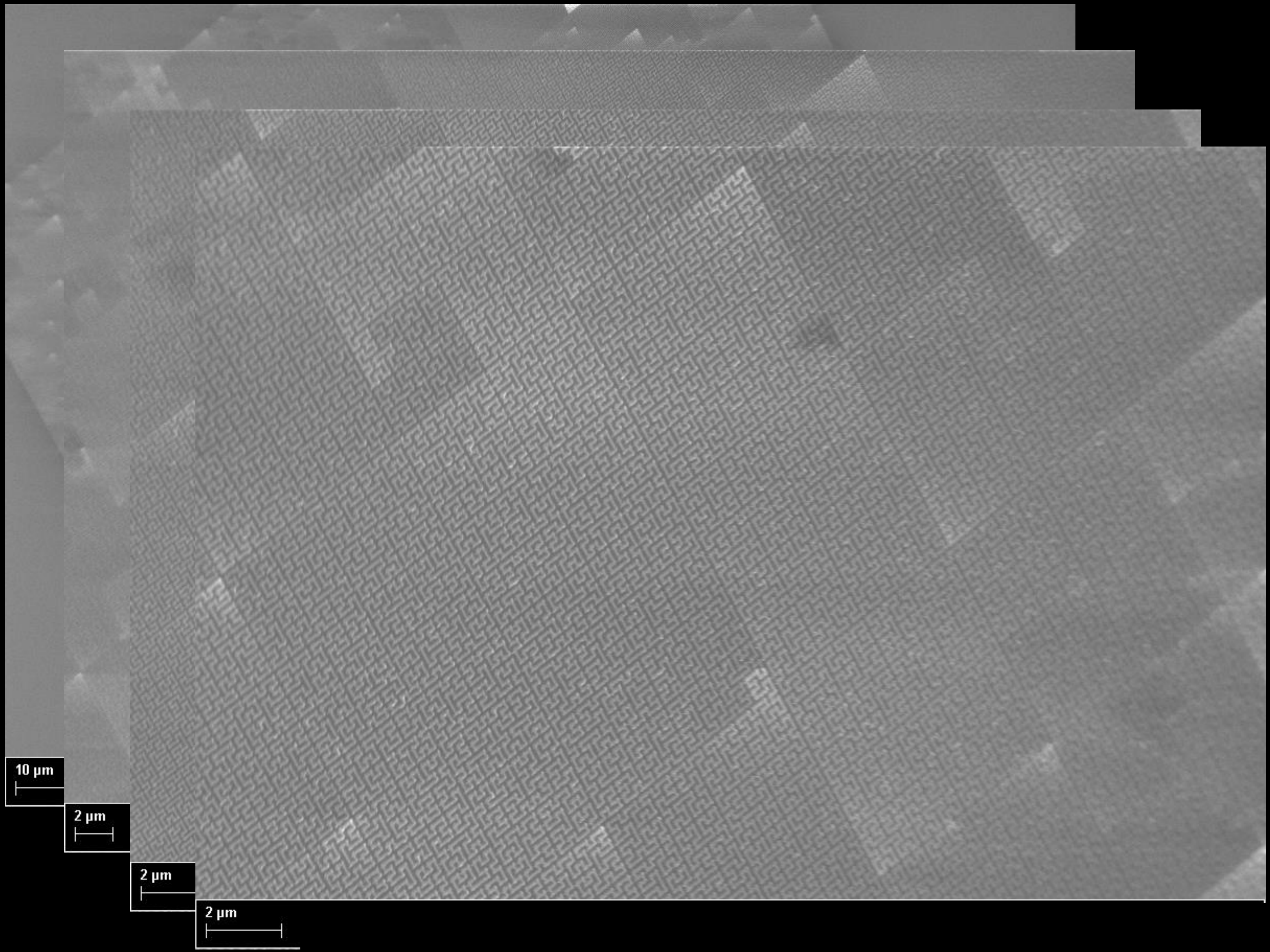




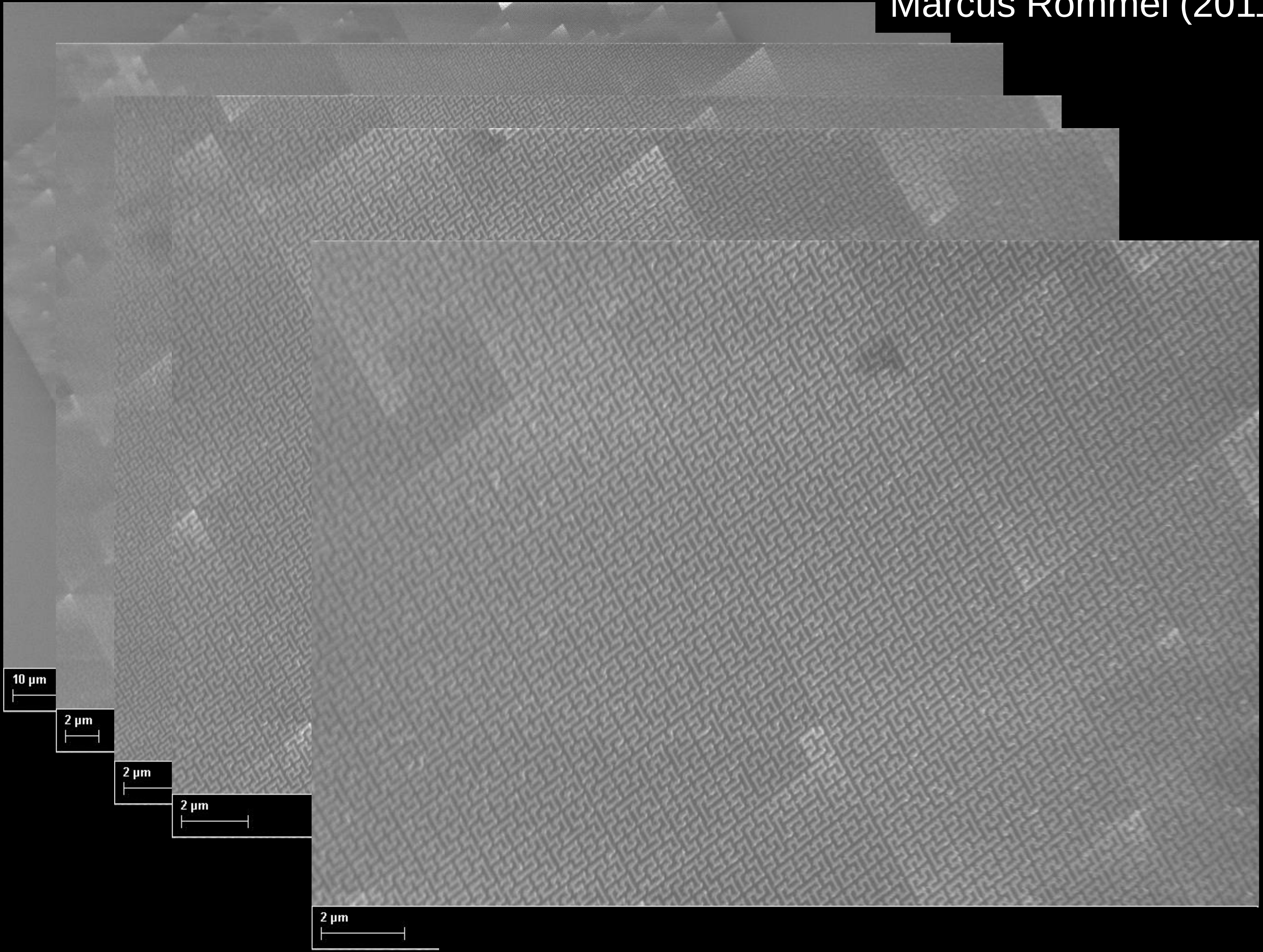
10 µm


10 µm
2 µm


10 µm
2 µm
2 µm

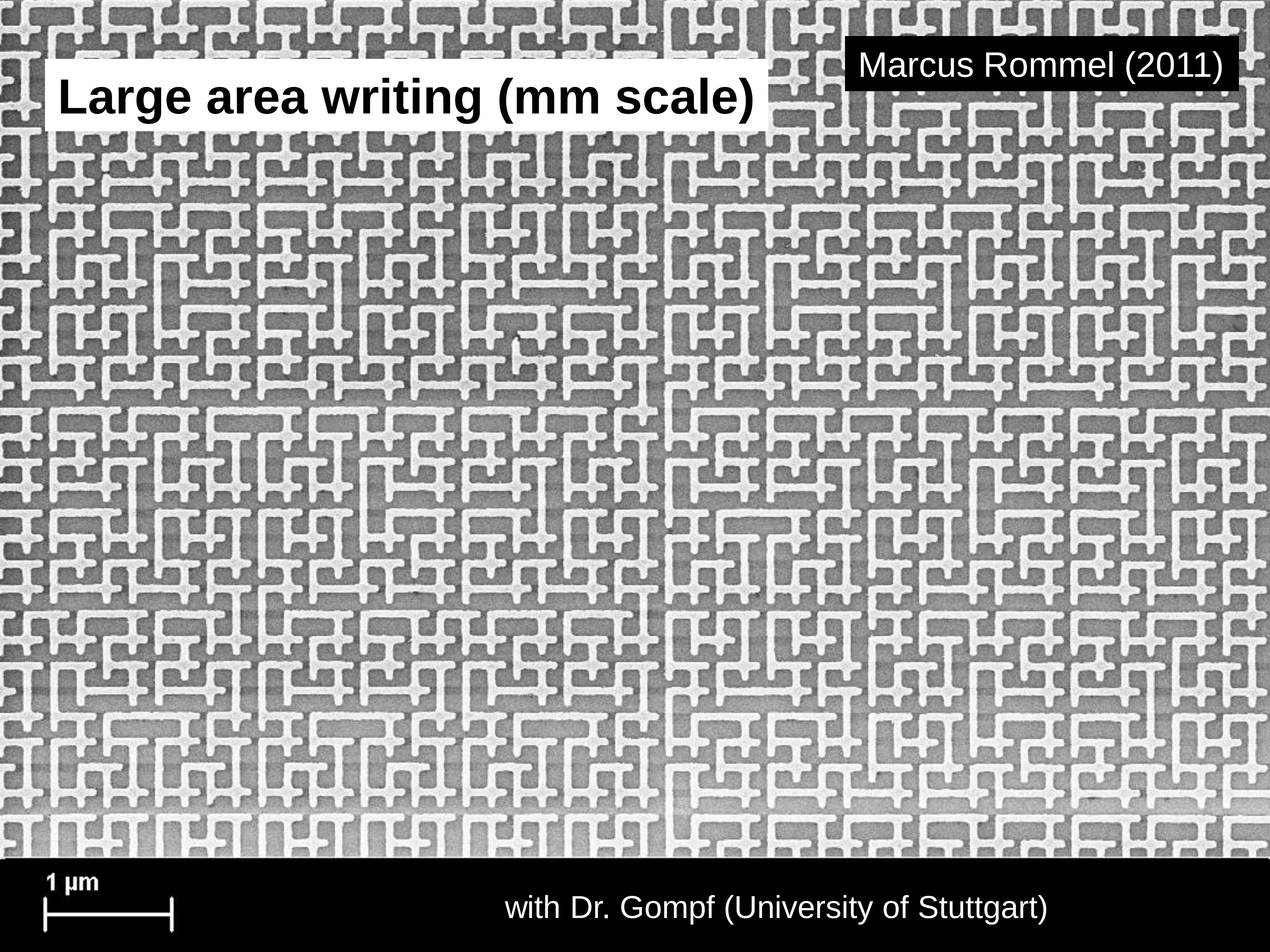

10 µm
2 µm
2 µm
2 µm

Marcus Rommel (2011)



Large area writing (mm scale)

Marcus Rommel (2011)



with Dr. Gompf (University of Stuttgart)

Dedicated 100 kV Electron Beam Lithography System ?

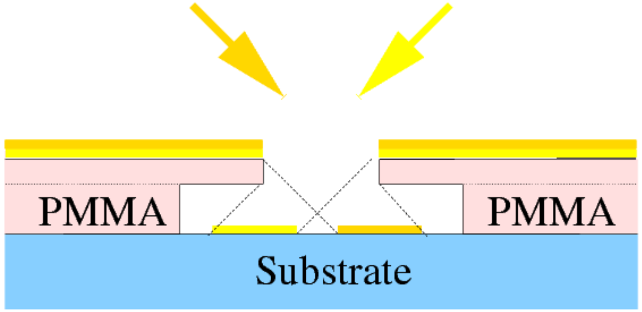
- Acceleration Voltage: Interaction with substrate
  (Proximity Effect, Damage)
- Writing speed:
  typically 1 nA (Jeol) versus 5 pA (Raith eline)
- Enables patterning thick resists
- Allows defined large undercut in double-layer resists

Single–Electron Transistor Made of Aluminum

Two–Angle Shadow Evaporation Process:

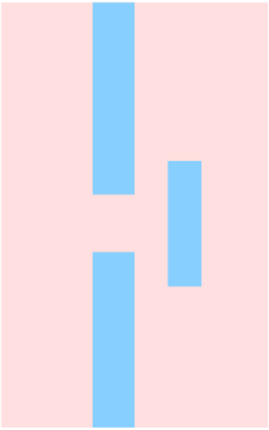
after Dolan 1987

Cross Section:

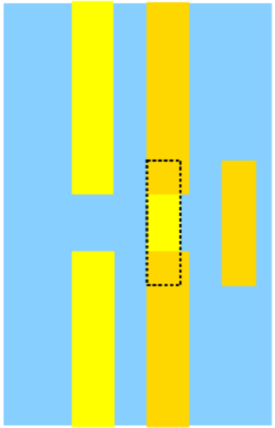


Top View:

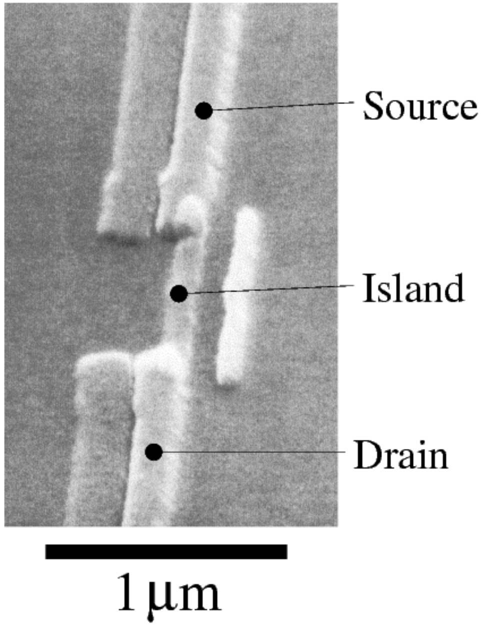
PMMA Mask



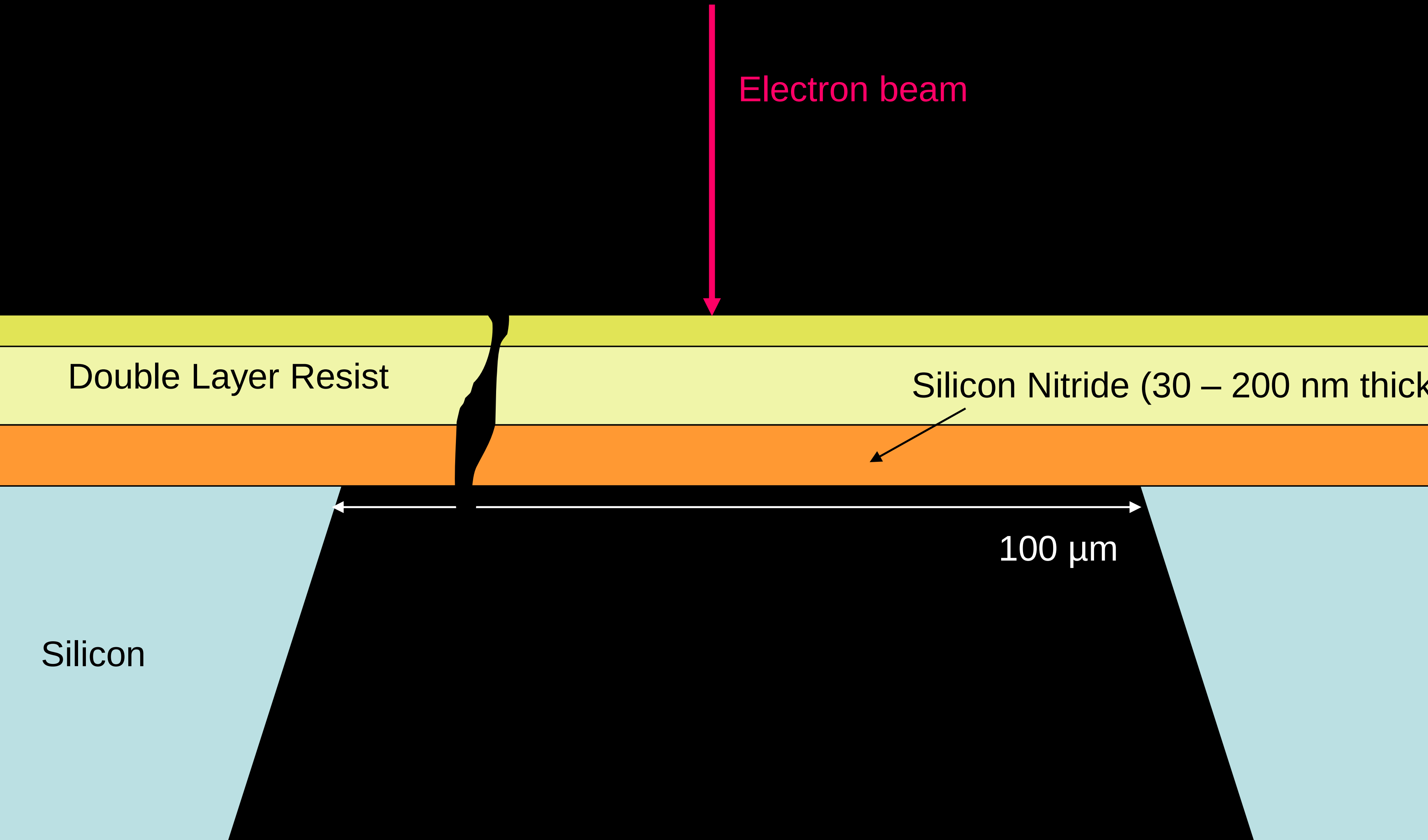
Metal Structure



SEM Image



Electron Beam Lithography on a Thin Membrane



Electron beam

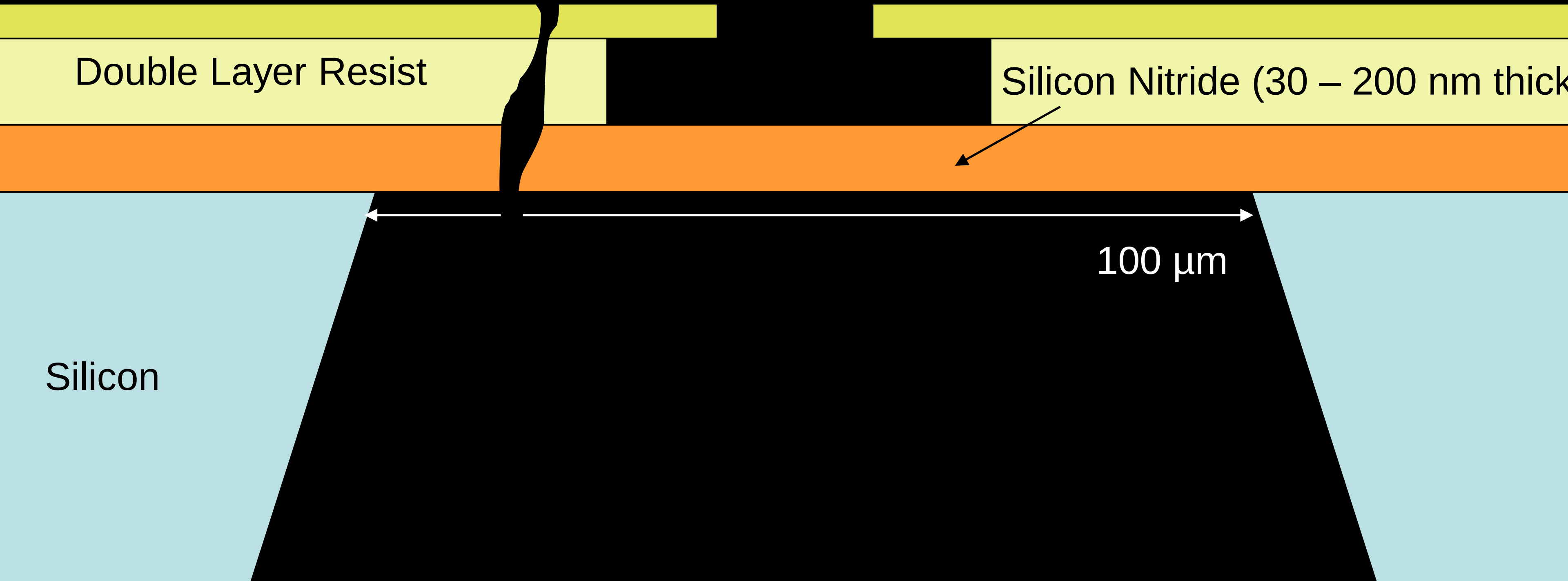
Double Layer Resist

Silicon Nitride (30 – 200 nm thick

100 µm

Silicon

Electron Beam Lithography on a Thin Membrane



Double Layer Resist

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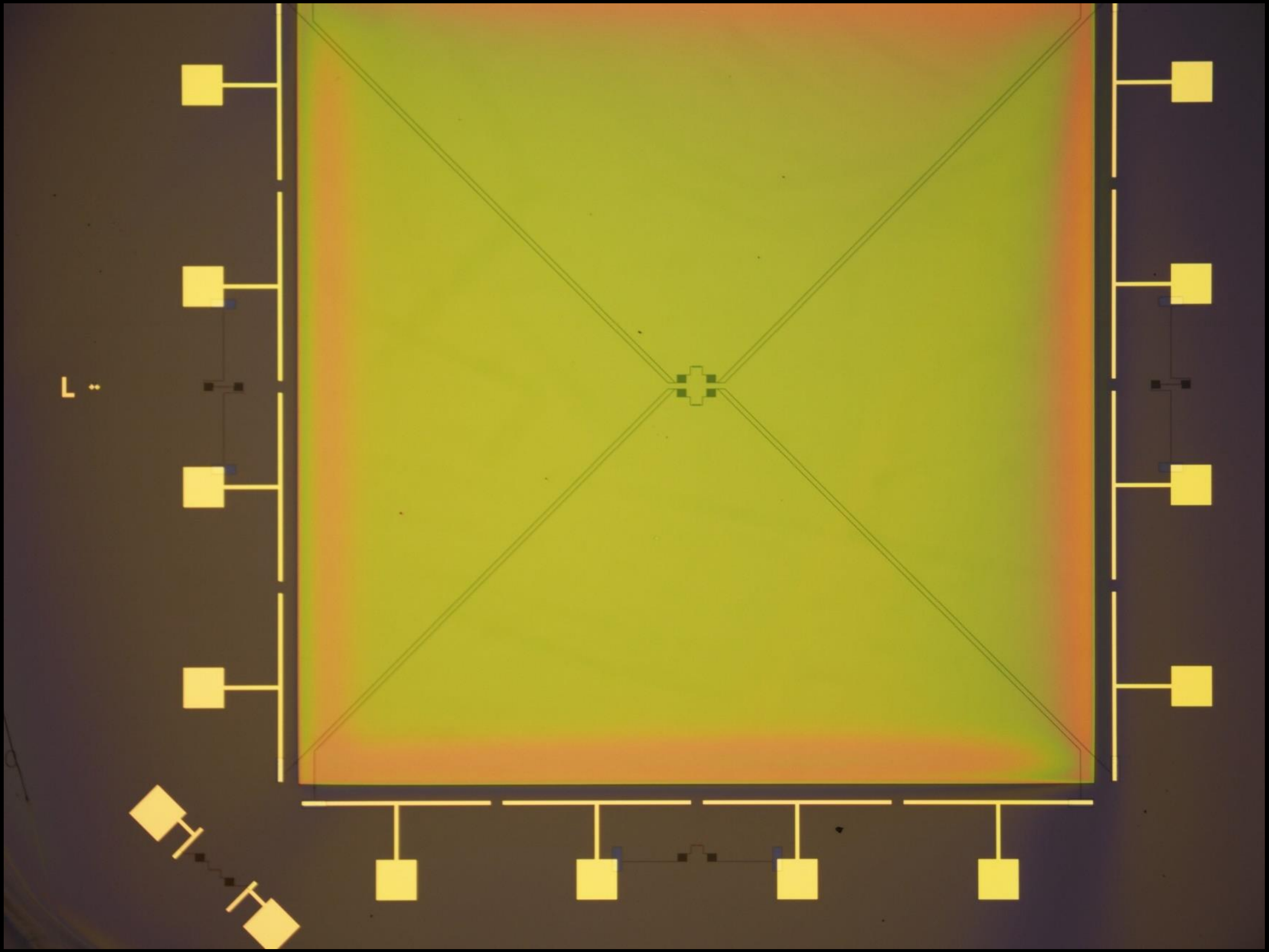
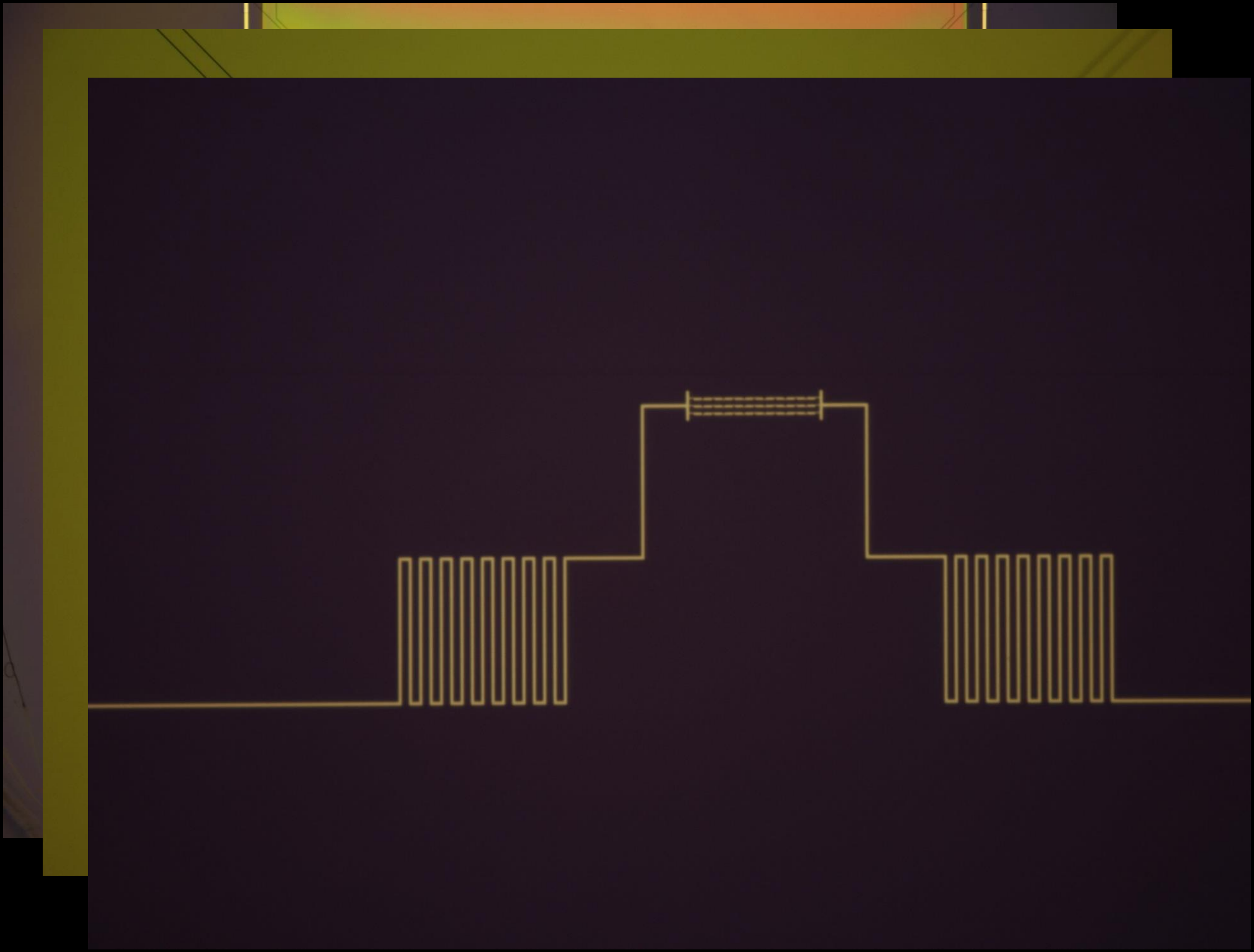


T. Reindl, MPI FKF

T. Reindl, MPI FKF



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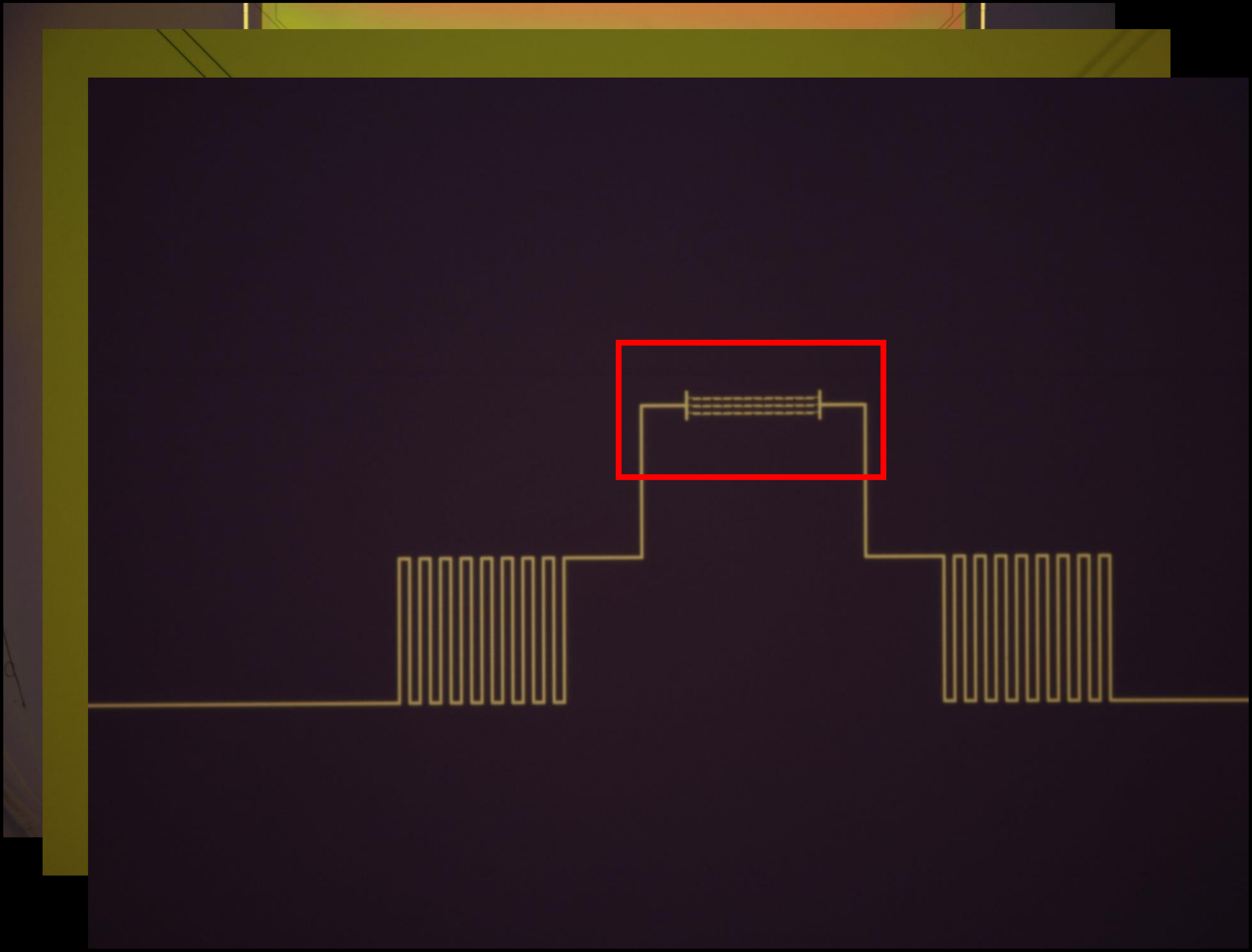

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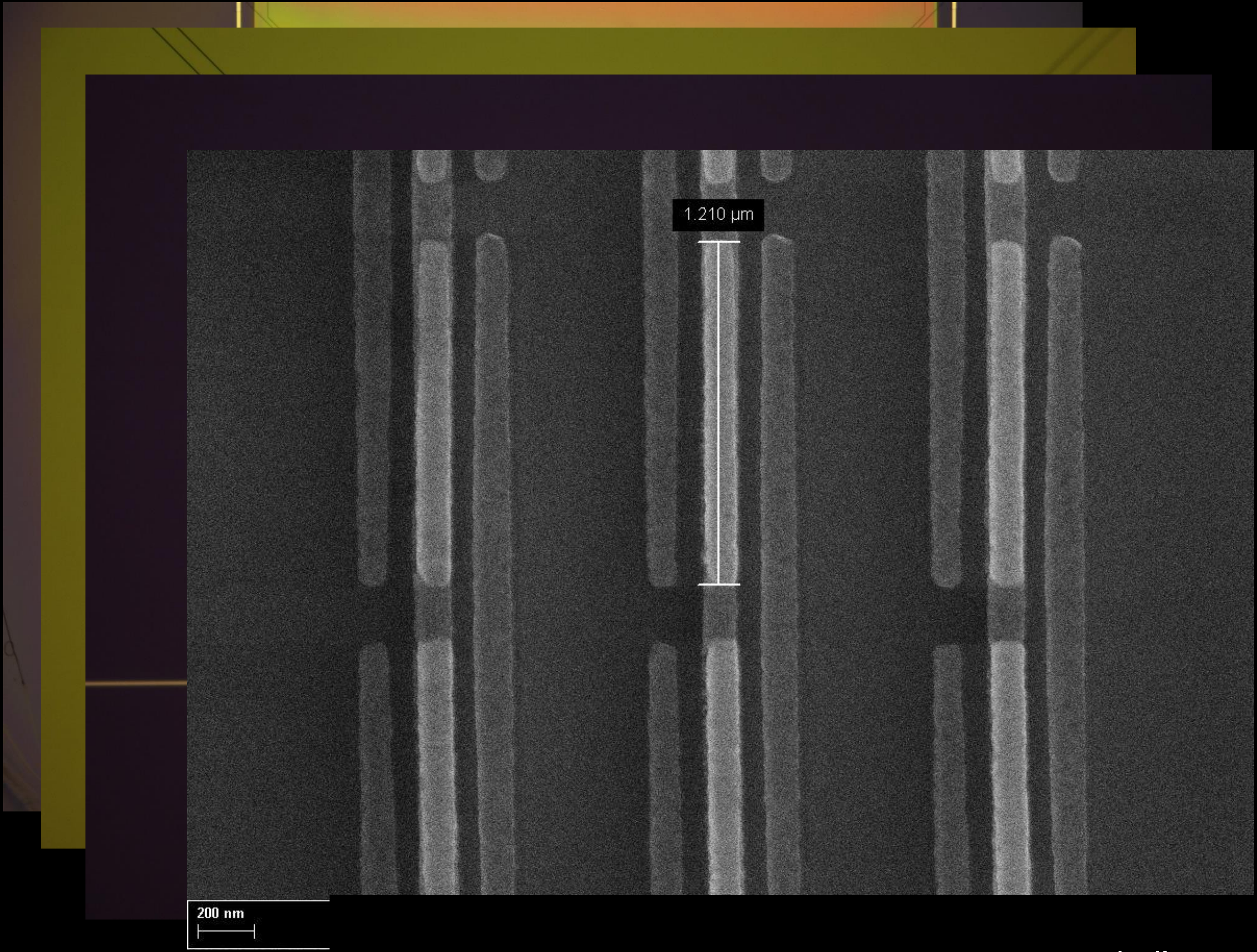
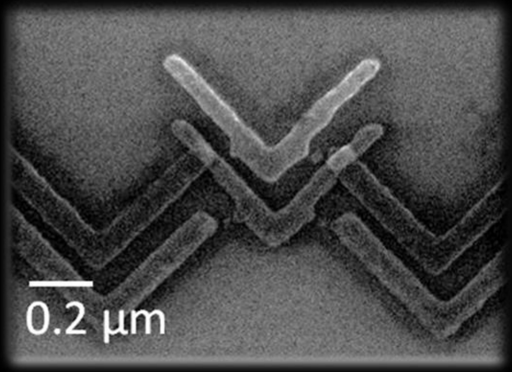


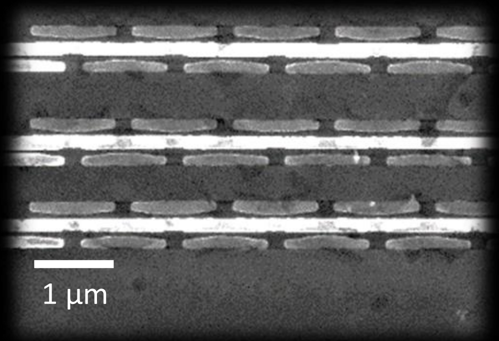
T. Reindl, MPI FKF

Array of Metal Single-Electron Transistors as Primary Thermometer on 30 nm thin Membrane for Heat Capacity Measurements

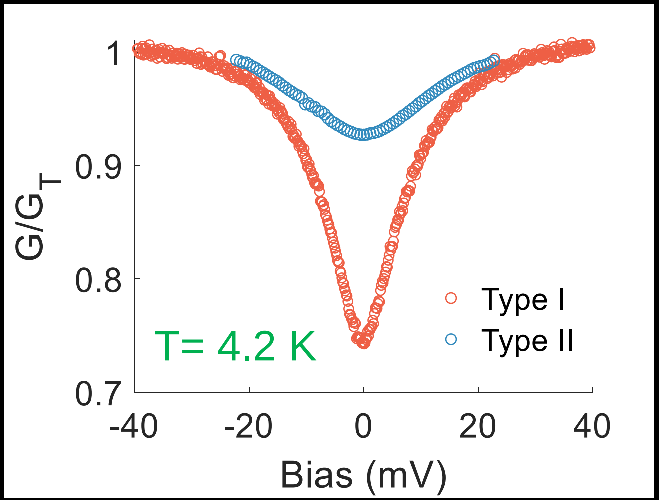
T. Reindl et al. with Andreas Rost (St. Andrews, Schottland)



Type I
0.004 µm^2 area
1 K < T < 100 K



Type II
0.04 µm^2 area
0.1 K < T < 10 K



$$\frac{G}{G_T} = 1 - \left(\frac{E_C}{k_B T}\right) g\left(\frac{eV}{N k_B T}\right)$$

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- Reproducibility, Stability, Precision

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Facilitating and Enabling certain Lithography !

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- Reproducibility, Stability, Precision
- Alignment requires good metal marks
- High investment / high running costs
- Flexible ? (sample size, alignment)
  requires well developed work flow

Dedicated 100 kV EBL system

versus SEM-based Raith eLine ?

They are partly complementary.

We need both.

Thank you for your attention !

https://www.fkf.mpg.de/NSL