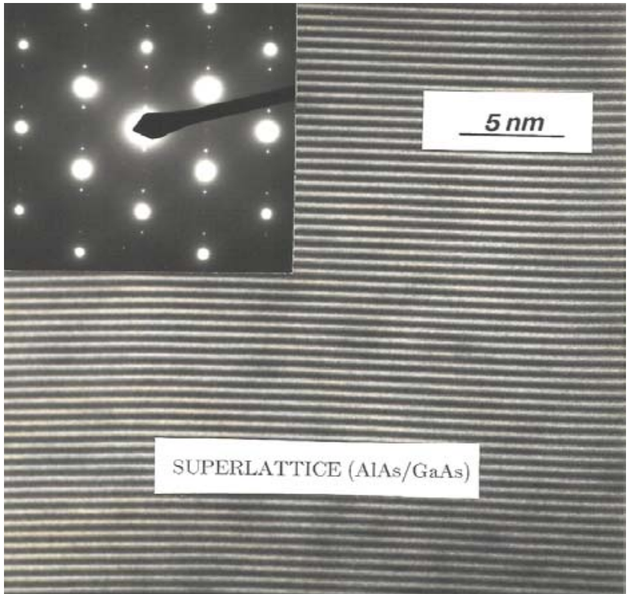
Advanced Characterization Needs in Epitaxial Semiconductor Nano-Structures

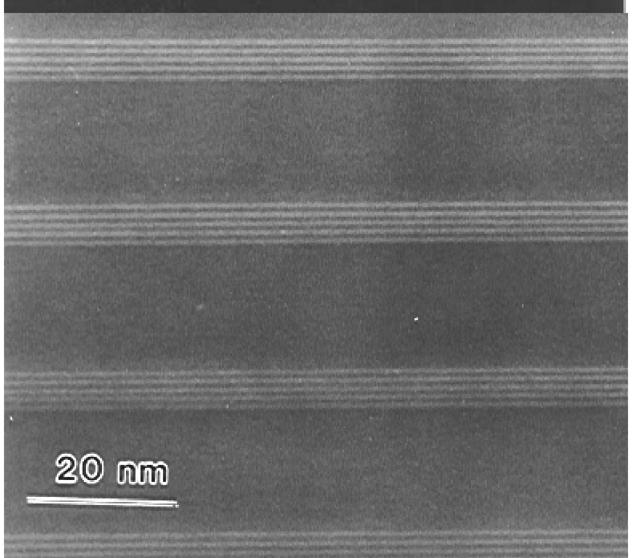
Robert Hull

Charles Henderson Professor of Engineering
University of Virginia
Department of Materials Science and Engineering

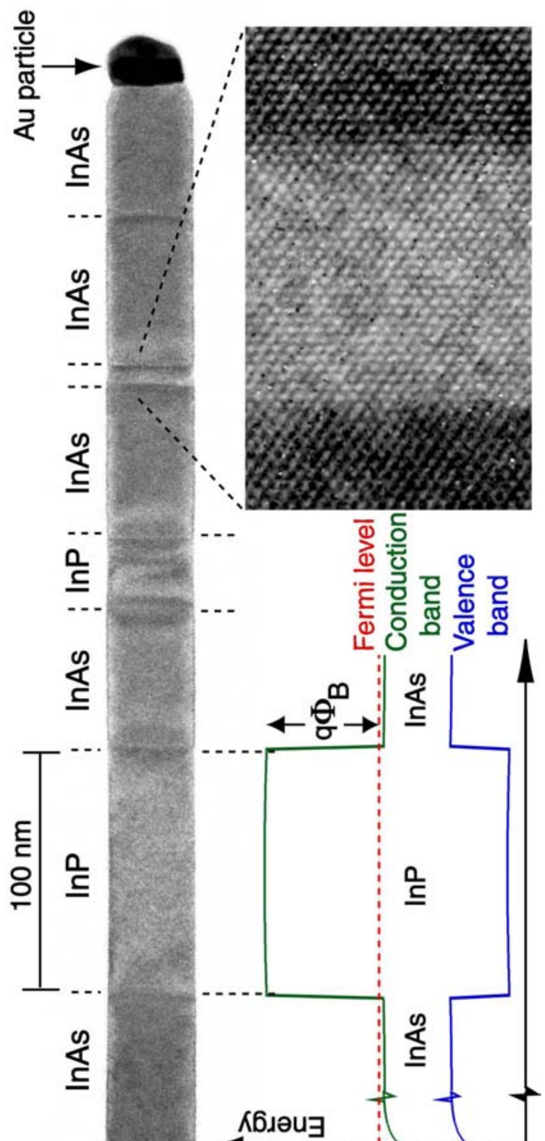
From 2D…….. To 1D……. To 0D……..



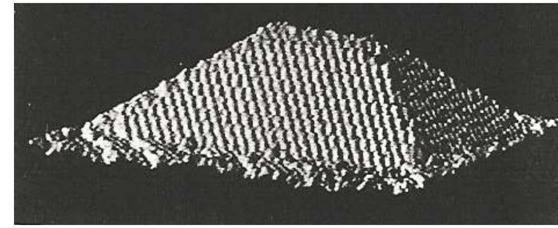
AlAs/GaAs; R. Hull, L.N. Pfeiffer



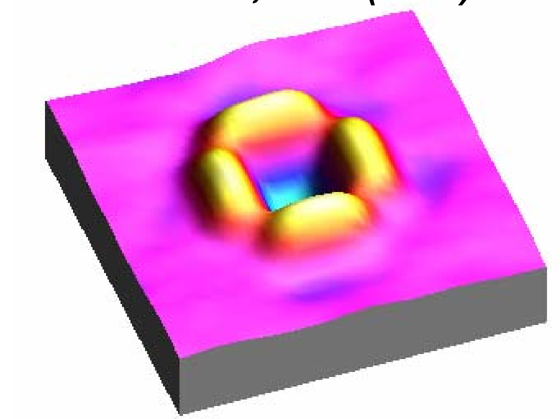
Ge/Si; R. Hull, J.C. Bean



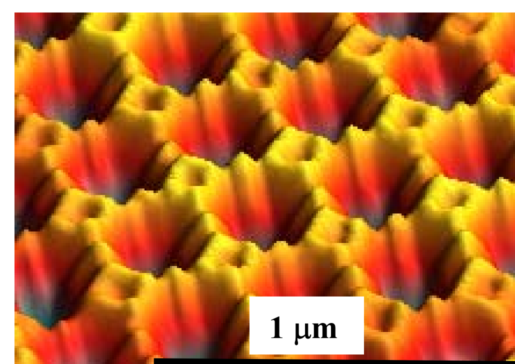
M.T. Björk et al, Nano Letters 2, 87 (2002)



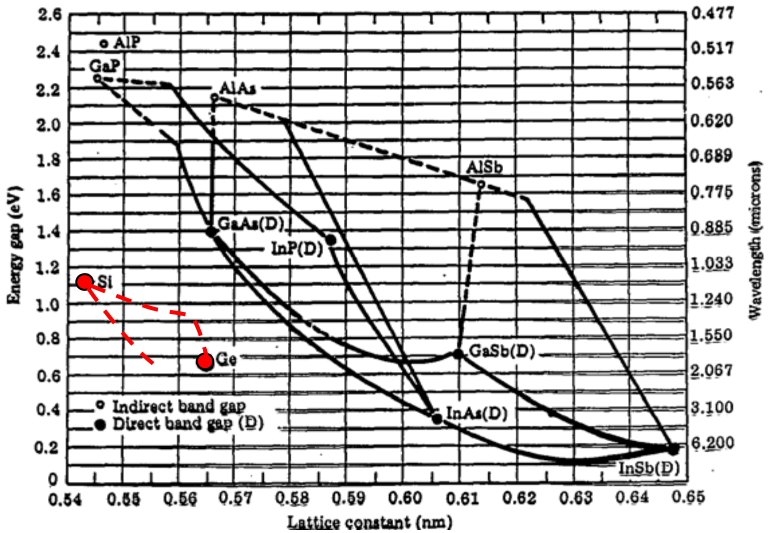
STM of Ge {105} hut clusters on (100) Si; Mo et al, Phys. Rev. Lett. 65, 1020 (1990)

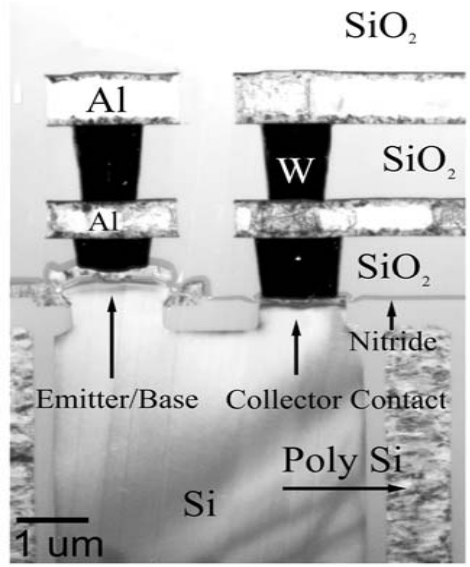


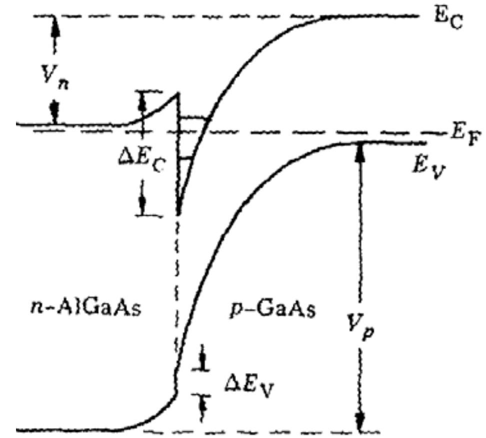
GeSi Quantum Dot Molecules on Si(100), Hull, Gray, Floro



Semiconductor Heteroepitaxy







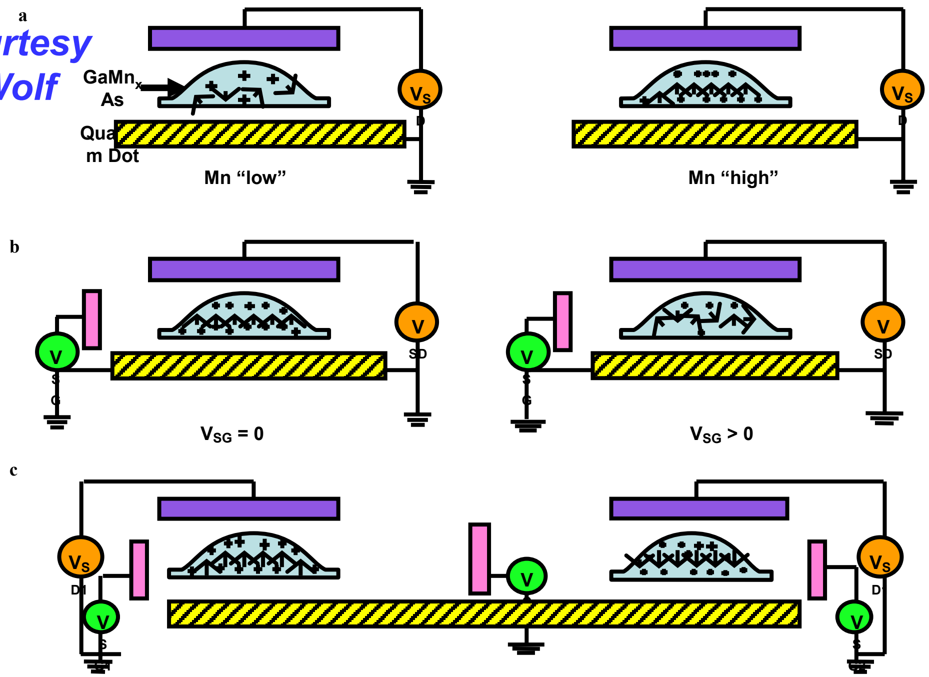
Model systems for studies of many fundamental materials phenomena:

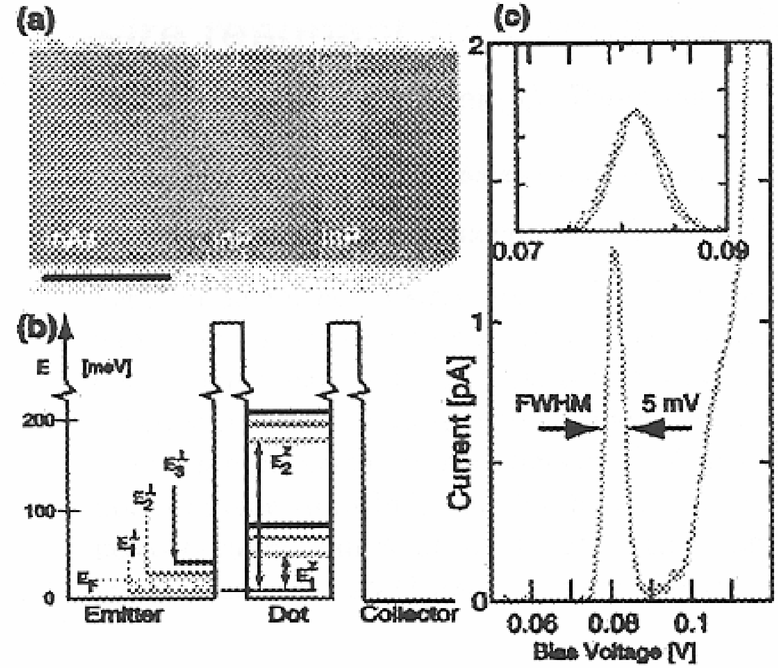
Surface Structure and Energetics
Nucleation and Growth
Self Organization
Strain-Induced Transformations
Dislocation Energetics and Kinetics
Alloy Ordering

Applications to many semiconductor devices, including:

Heterojunction Bipolar Transistors
MODFETs
Light Emitting Diodes
Lasers
Photodetectors / Solar Cells

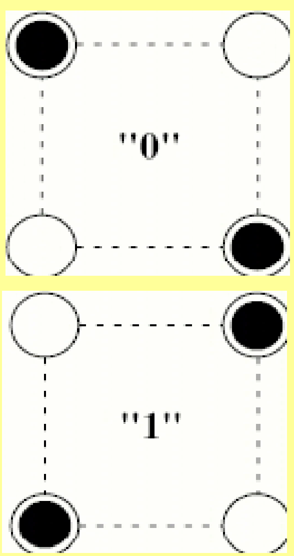
Courtesy S. Wolf



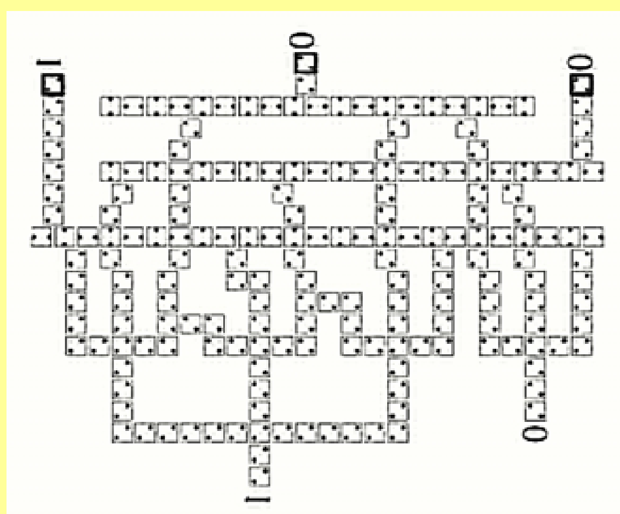


Bjork et al, Appl. Phys. Lett. 81, 4458

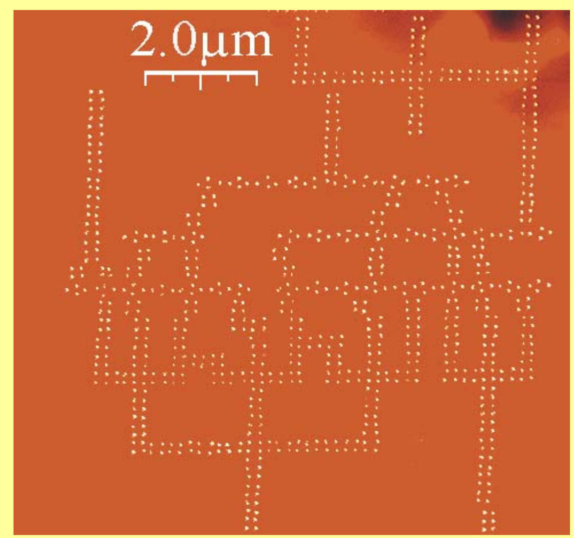
QCA Bistable Logic



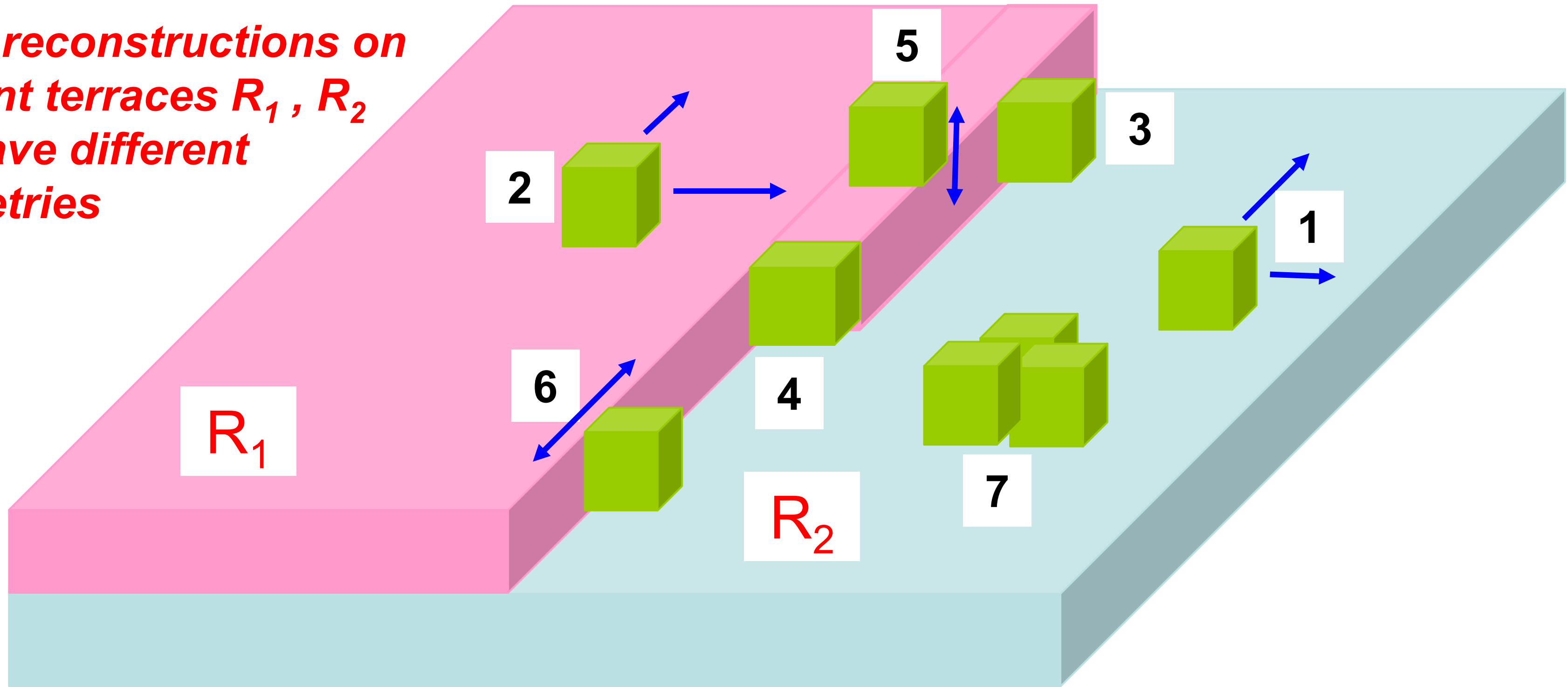
QCA Adder Circuit



FIB Nucleated Ge QDs



Note – reconstructions on different terraces R_1 , R_2 may have different symmetries



1,2. Adatom motion on terrace (may be anisotropic, and vary on diff terraces)

3. Attachment to steps (favorable)

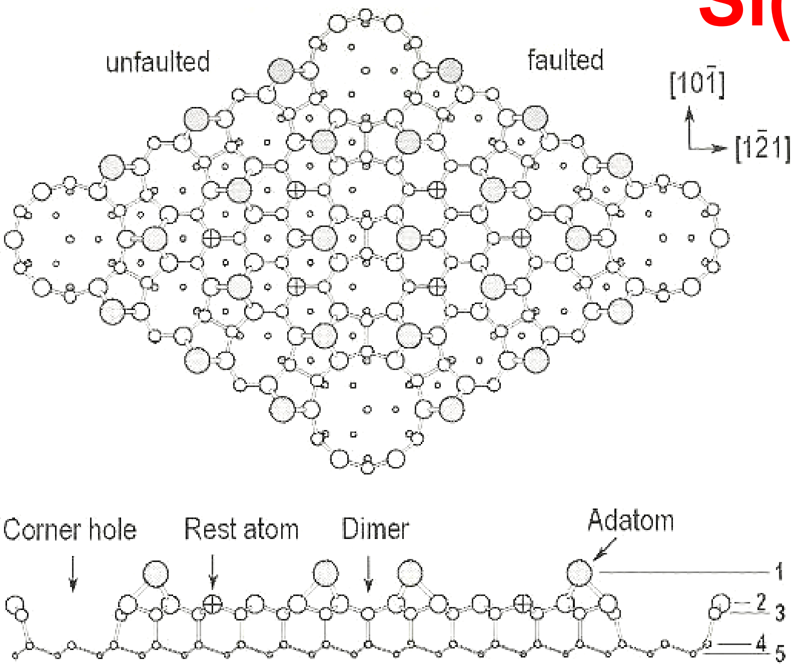
4. Attachment to kinks (more favorable still)

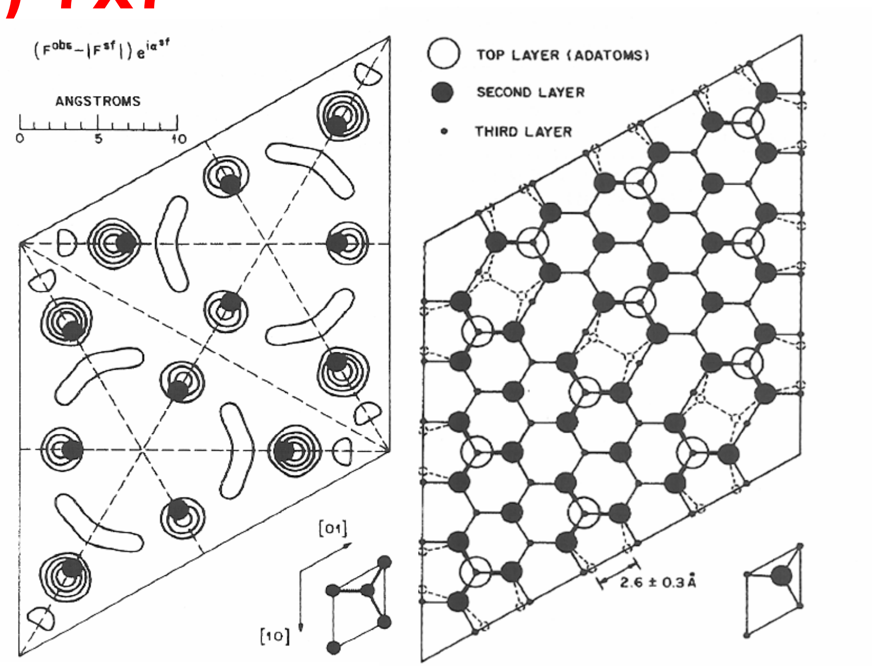
5. Motion up/down over step edge – Schwoebel-Ehrlich barrier E_{SE}

6. Motion parallel to step edge E_{PS}

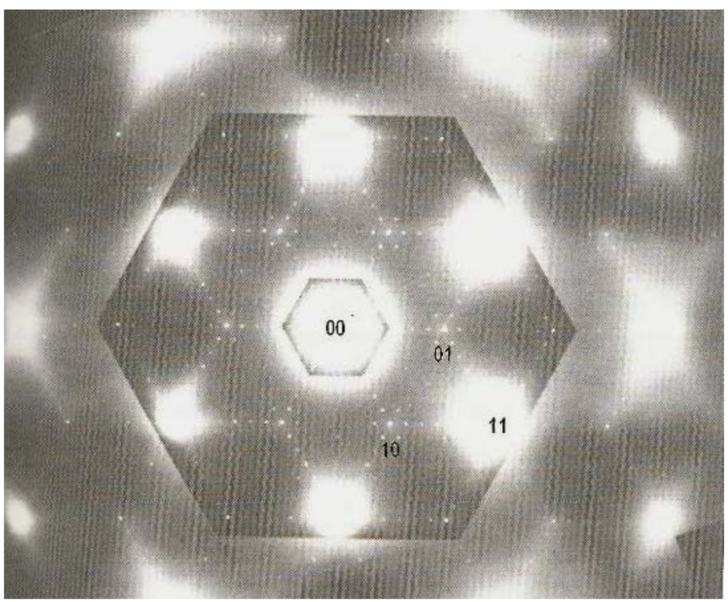
7. Critical nucleus forming on surface

Si(111)-7x7

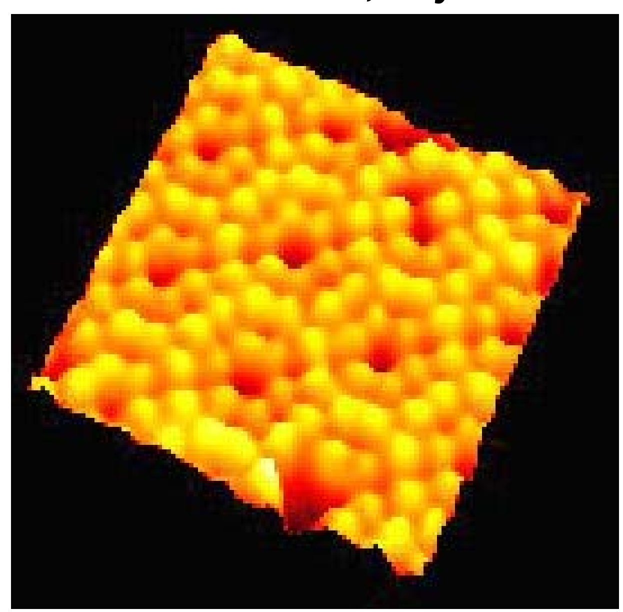




Robinson et al, Phys. Rev. B33, 7013 (1986)

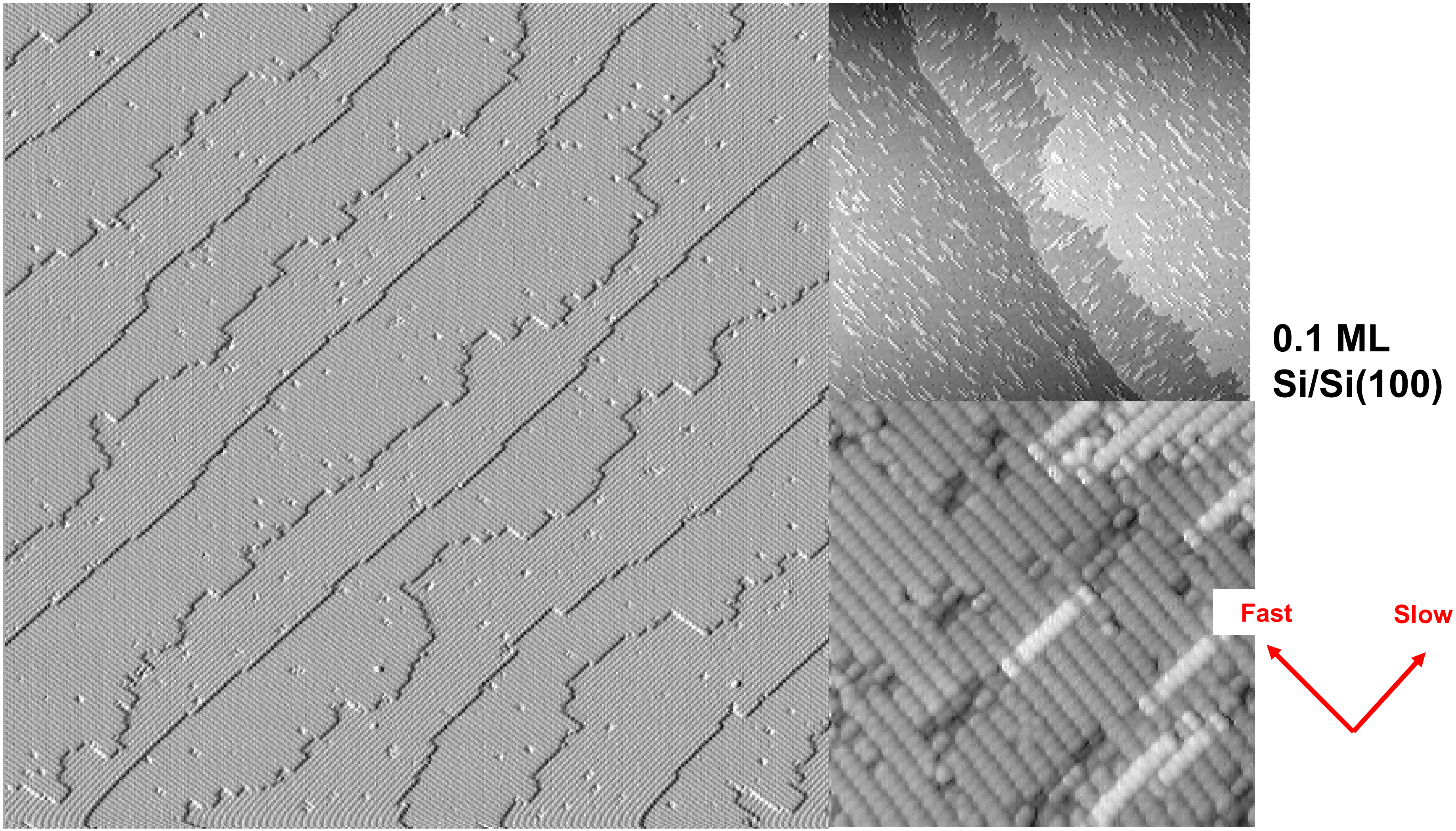


(Takayanagi et al, JVST 3, 1502, 1983)



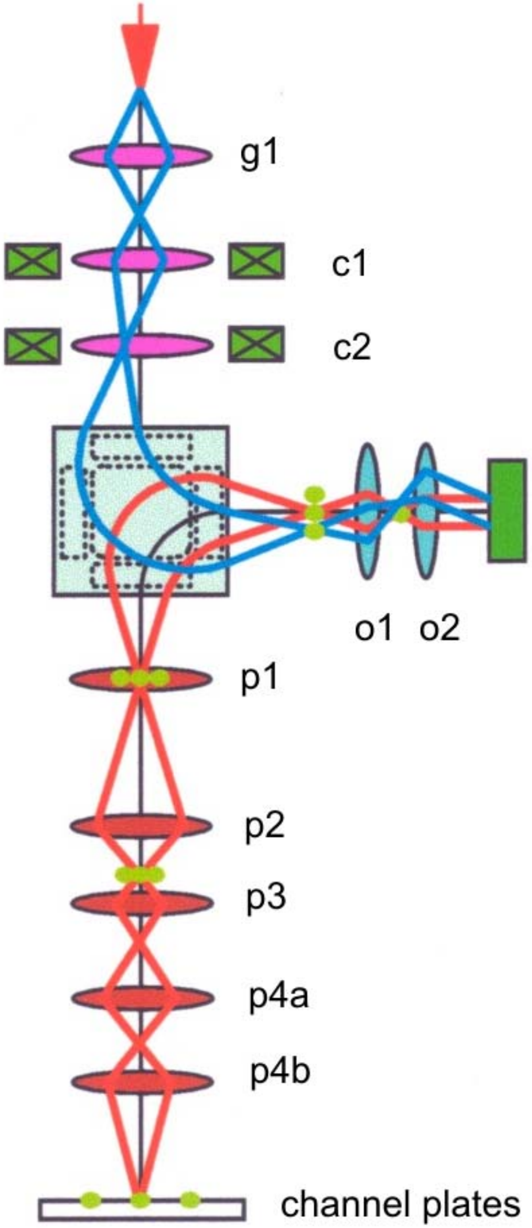
Erlandsson et al, Phys. Rev. B 54, R8309 (1996)

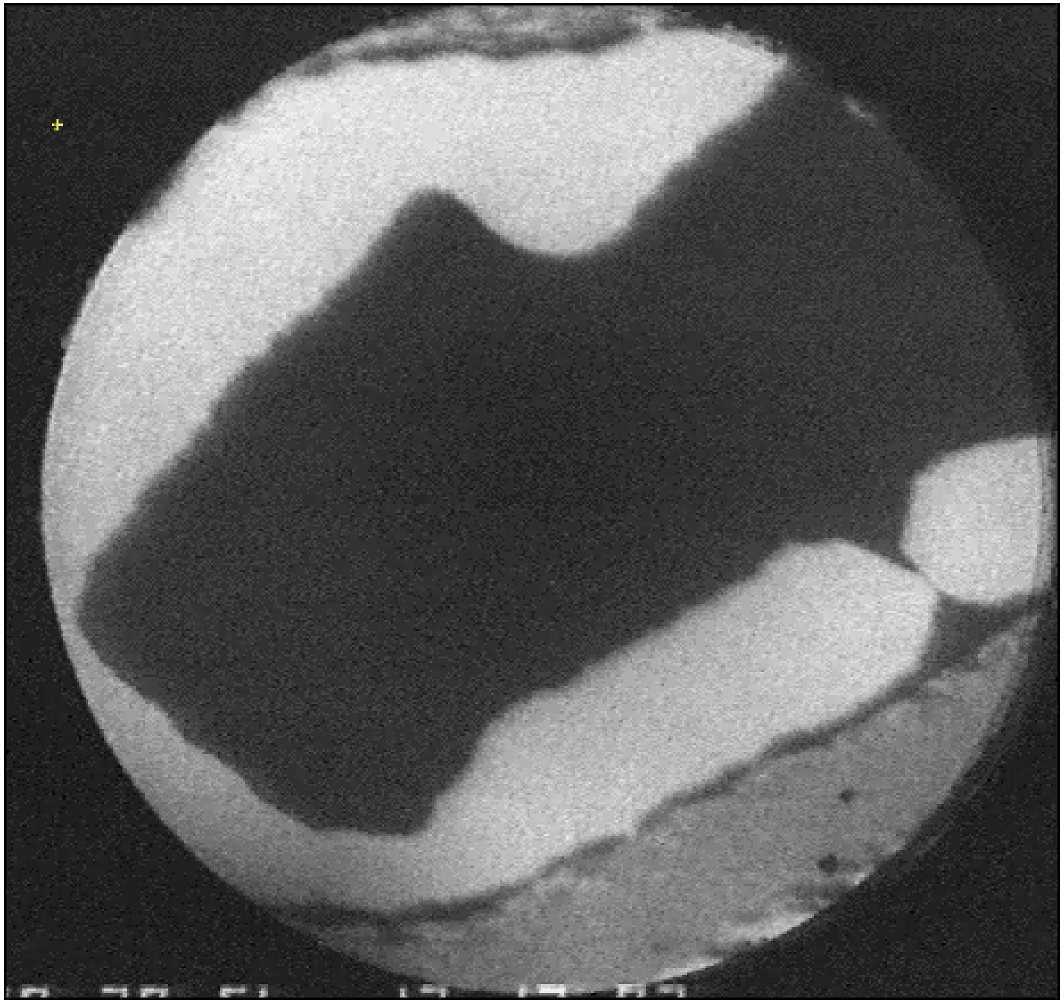
STM Images of Si(100) Surface



Lagally Group, U. Wisconsin

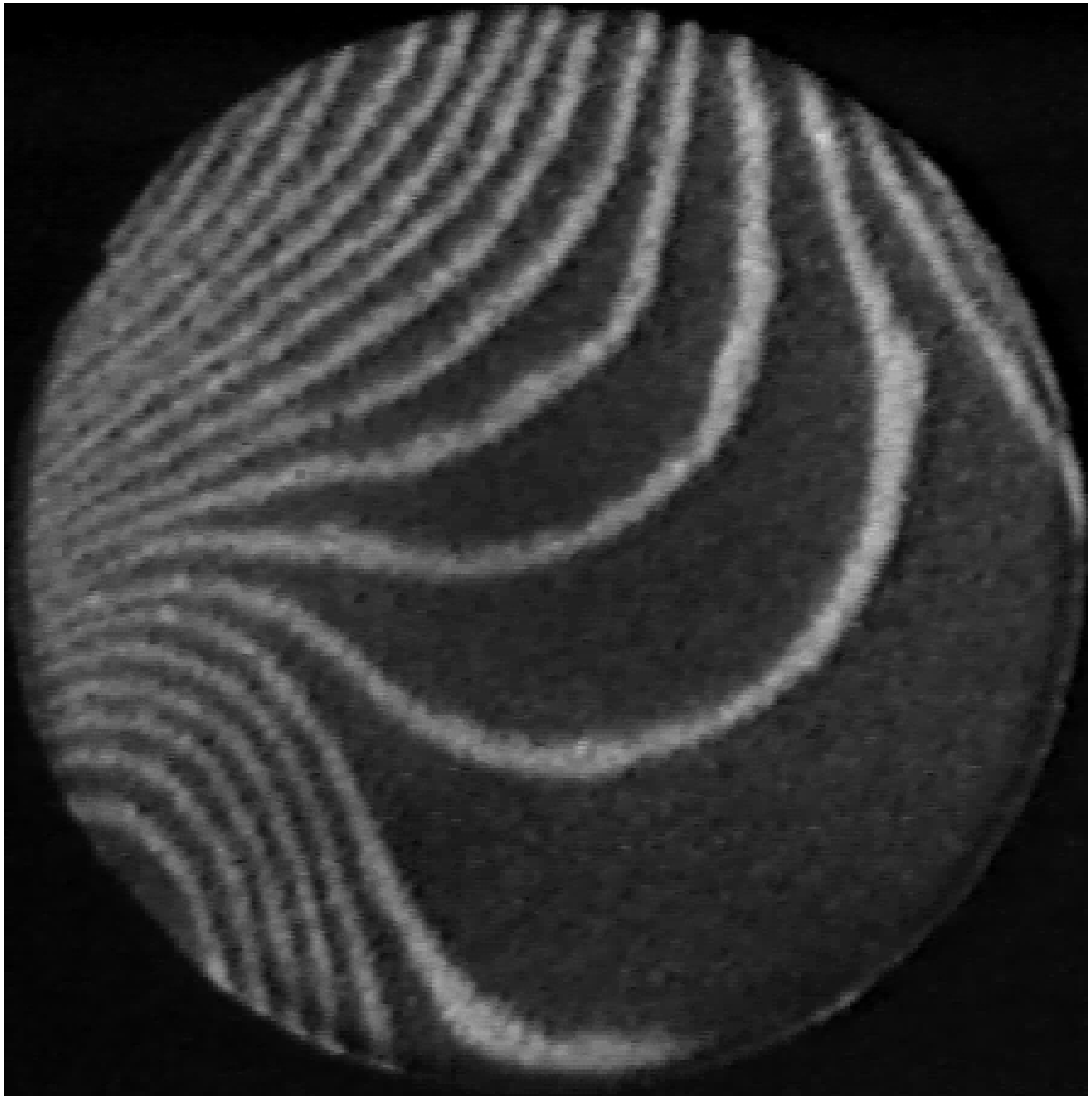
Low Energy Electron Microscopy (LEEM)





Real-time video of the dark-field (1/2,0) from the FE LEEM P90 of O2 etching Si(100) at 800° C.

The partial pressure of O2 is ˜ 1 x10^{-7} Torr and the field of view is 5.6 μm. *R. Tromp, IBM*

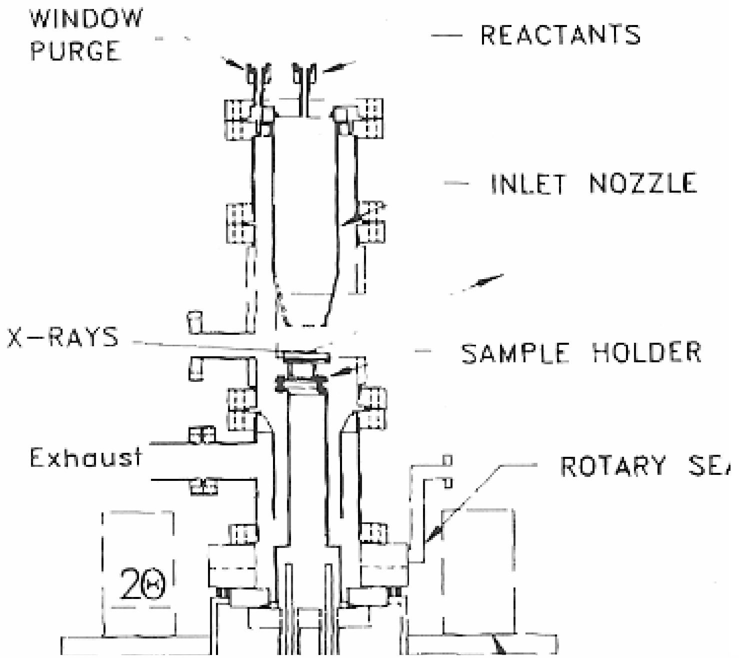


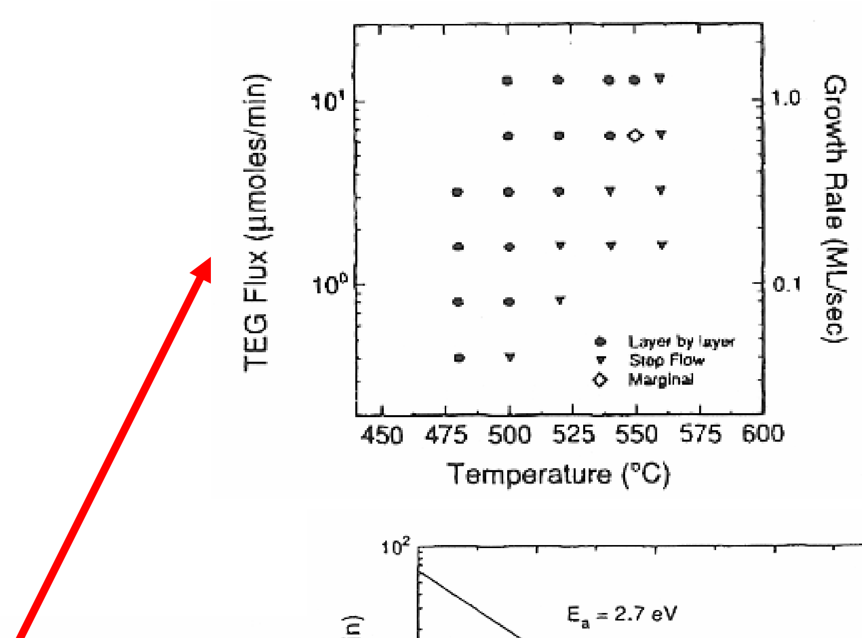
Step faceting and stripe formation on the (001) surface of heavily boron-doped silicon. FOV 9 microns.

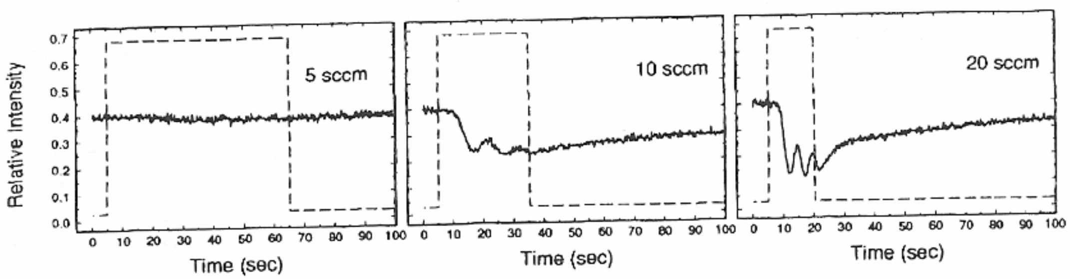
http://www.sandia.gov/surface_science/glk/leem_images_movies.html

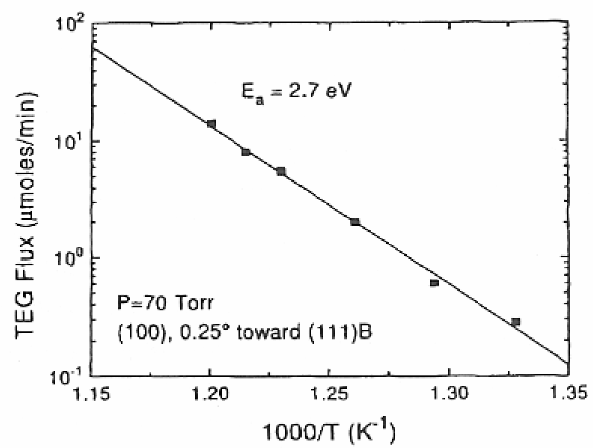
(Gary Kellogg, Sandia)

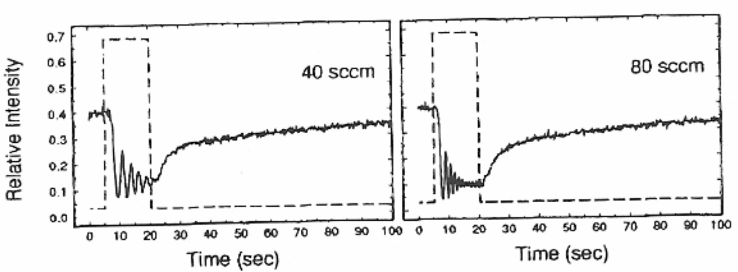
Real-Time Studies of III-V Surface Evolution / MOCVD Growth









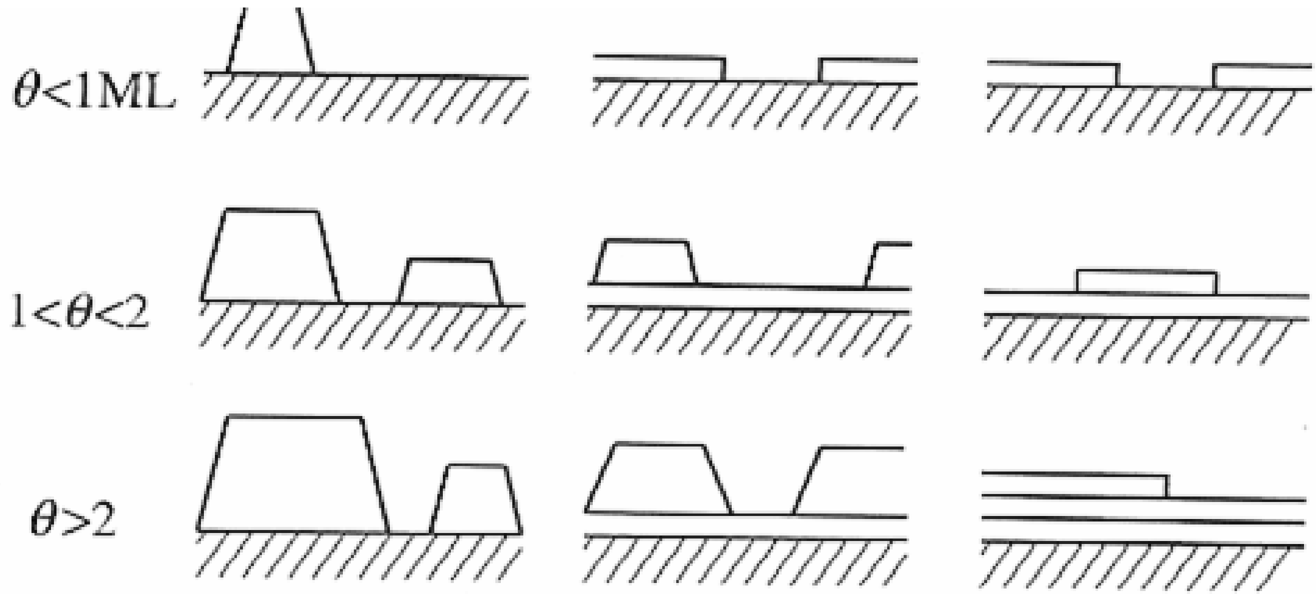


Brennan et al, Nucl. Inst. Meth A291, 86 (1990)

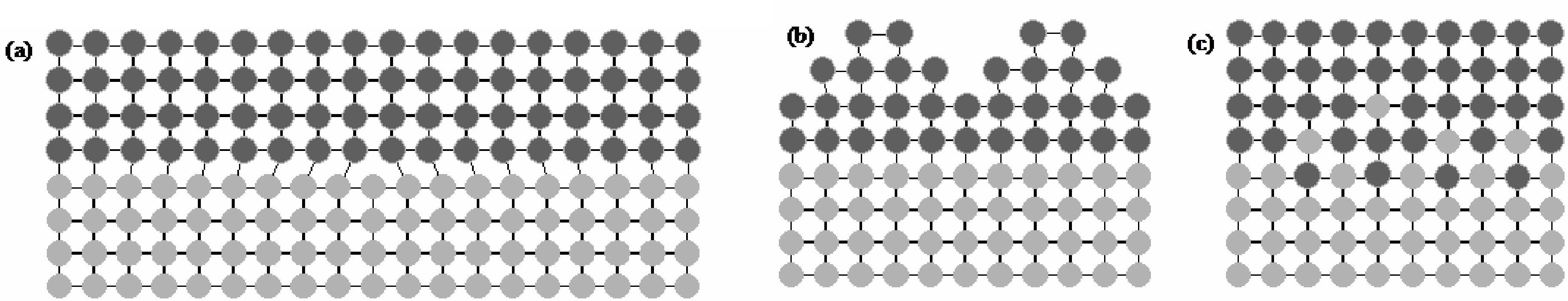
Kisker et al, J. Cryst. Growth 163, 54 (1996)

Lamelas et al, Phys. Rev. B49, 1957 (1994)

Growth Modes / Strain Relief Mechanisms



From J.A. Venables "Introduction to Surface and Thin Film Processes"

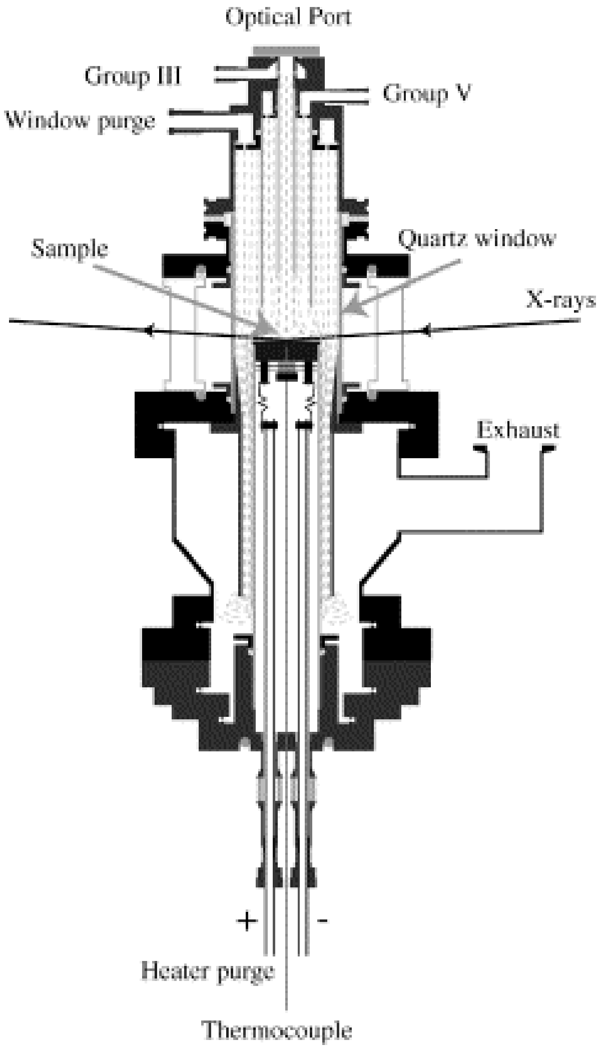


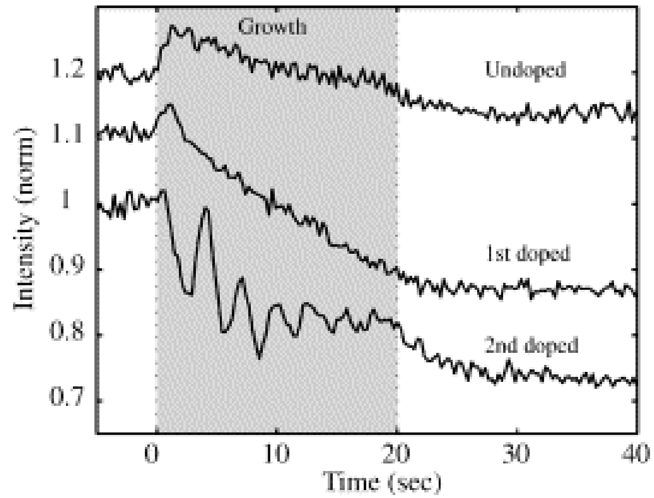
Misfit Dislocations

Roughening / Islanding

Interdiffusion

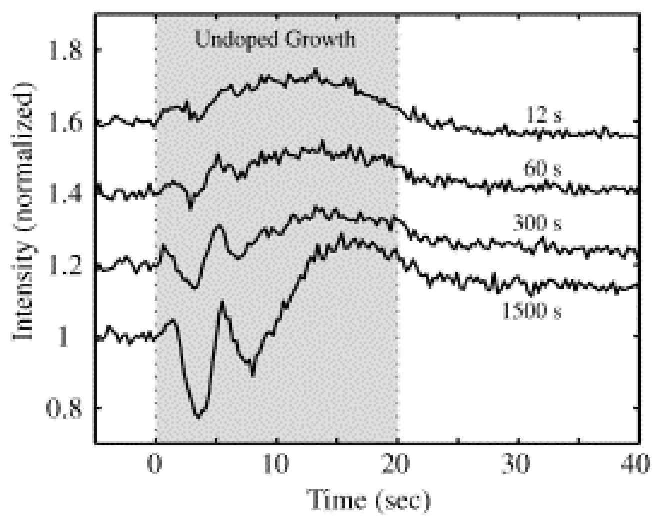
In-Situ X-Ray Diffraction Studies of Epitaxial Growth





11-2 Intensity doped / undoped growth

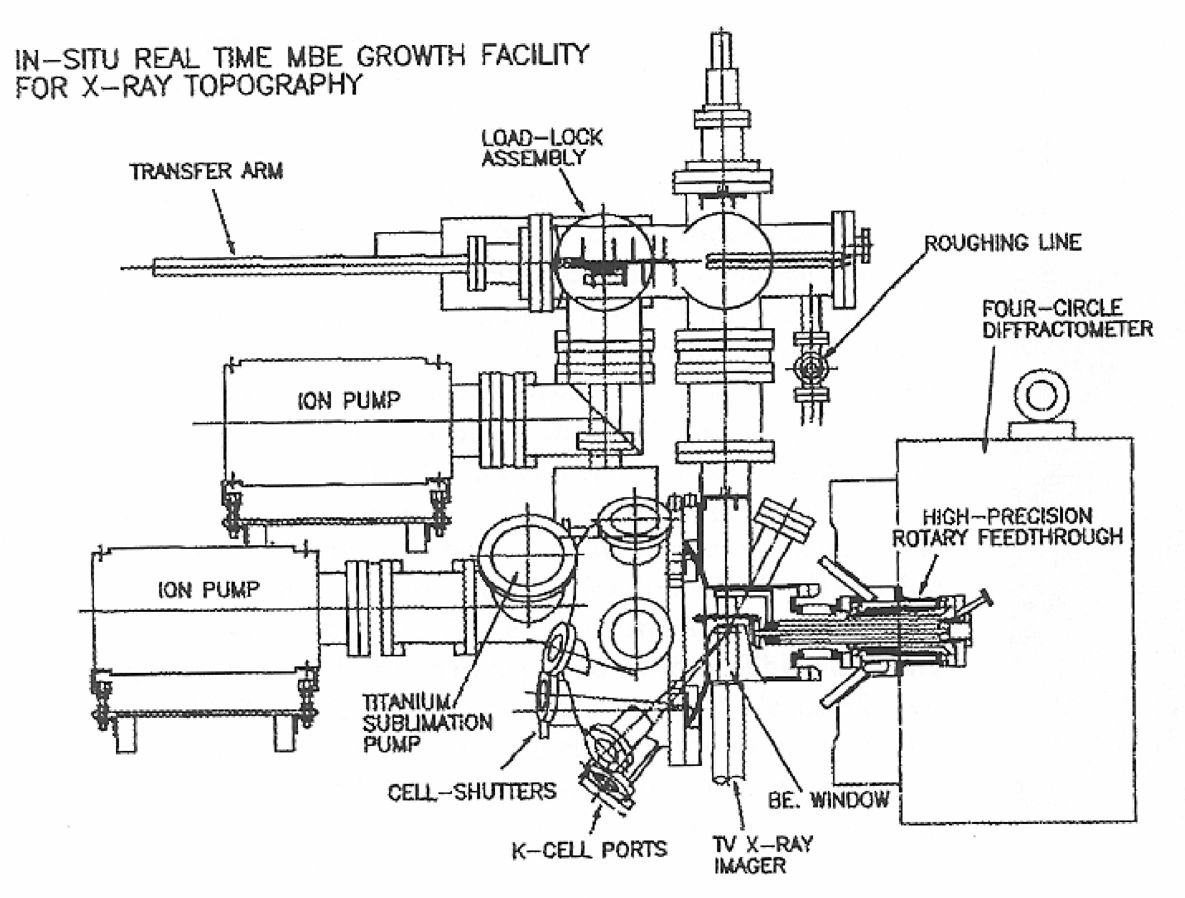
Growth mode changes from step flow to layer-by-layer

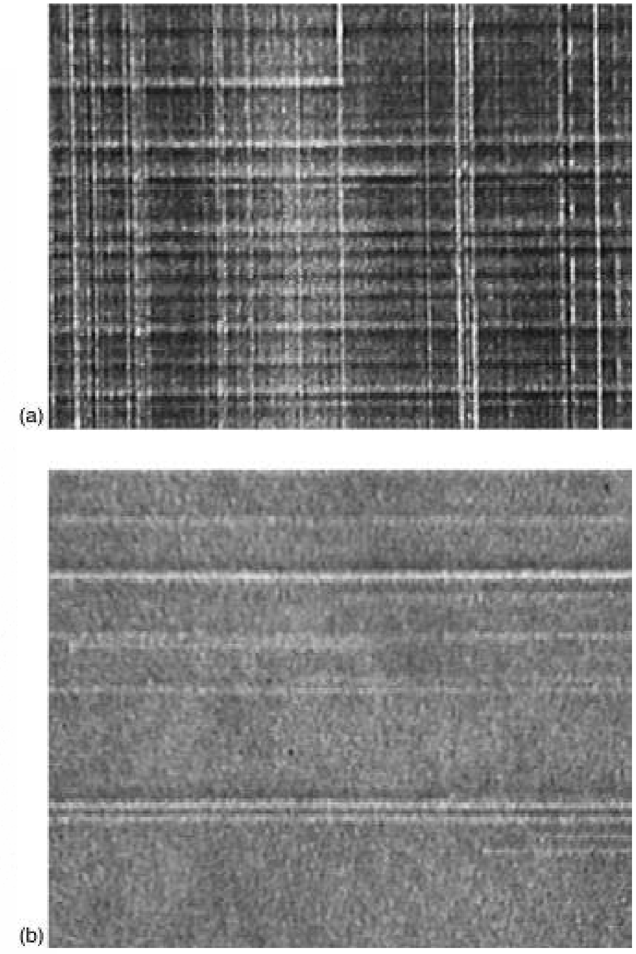


11-2 Intensity following 4 ML 6e20 Si

A. Munkholm et al, "In-situ studies of the effect of Si on GaN growth modes", J. Crtsyal Growth 21, 98 (2000)

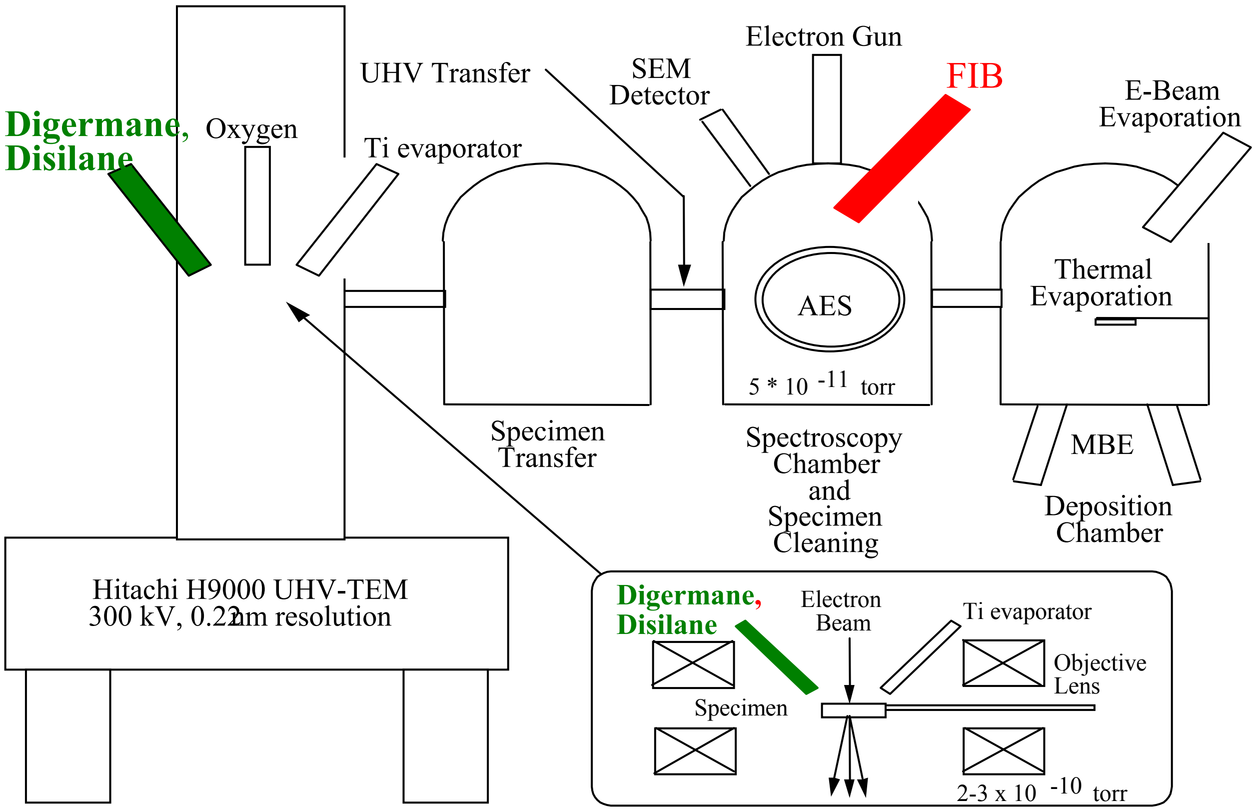
In-Situ X-Ray Topography Studies of Misfit Dislocation Kinetics in InGaAs/GaAs

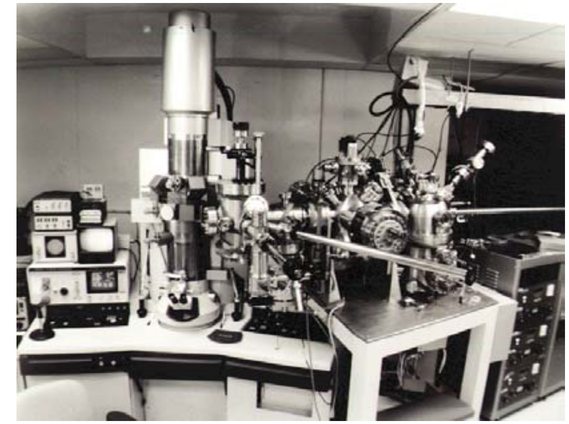


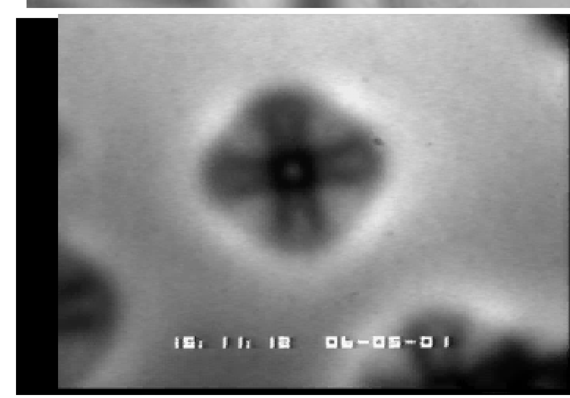


C.R. Whitehouse et al, Rev., Sci. Inst. 63, 634 (1992)

B.K. Tanner et al, Appl. Phys. Lett. 77, 2156 (2000)







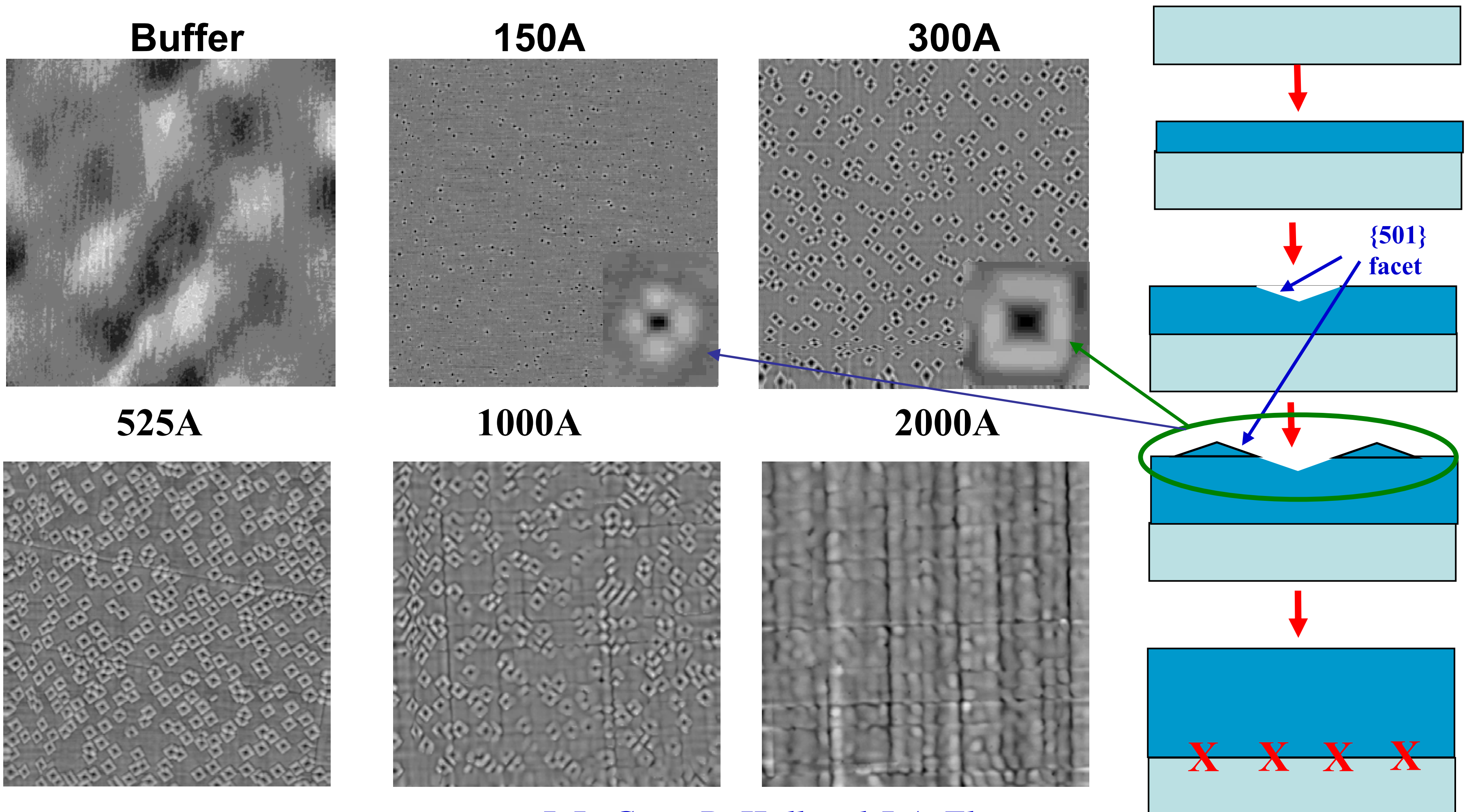
UHV-CVD-TEM-FIB (!)

F. Ross, R. Tromp, IBM;

M. Kammler, A. Portavoce, R. Hull, UVA

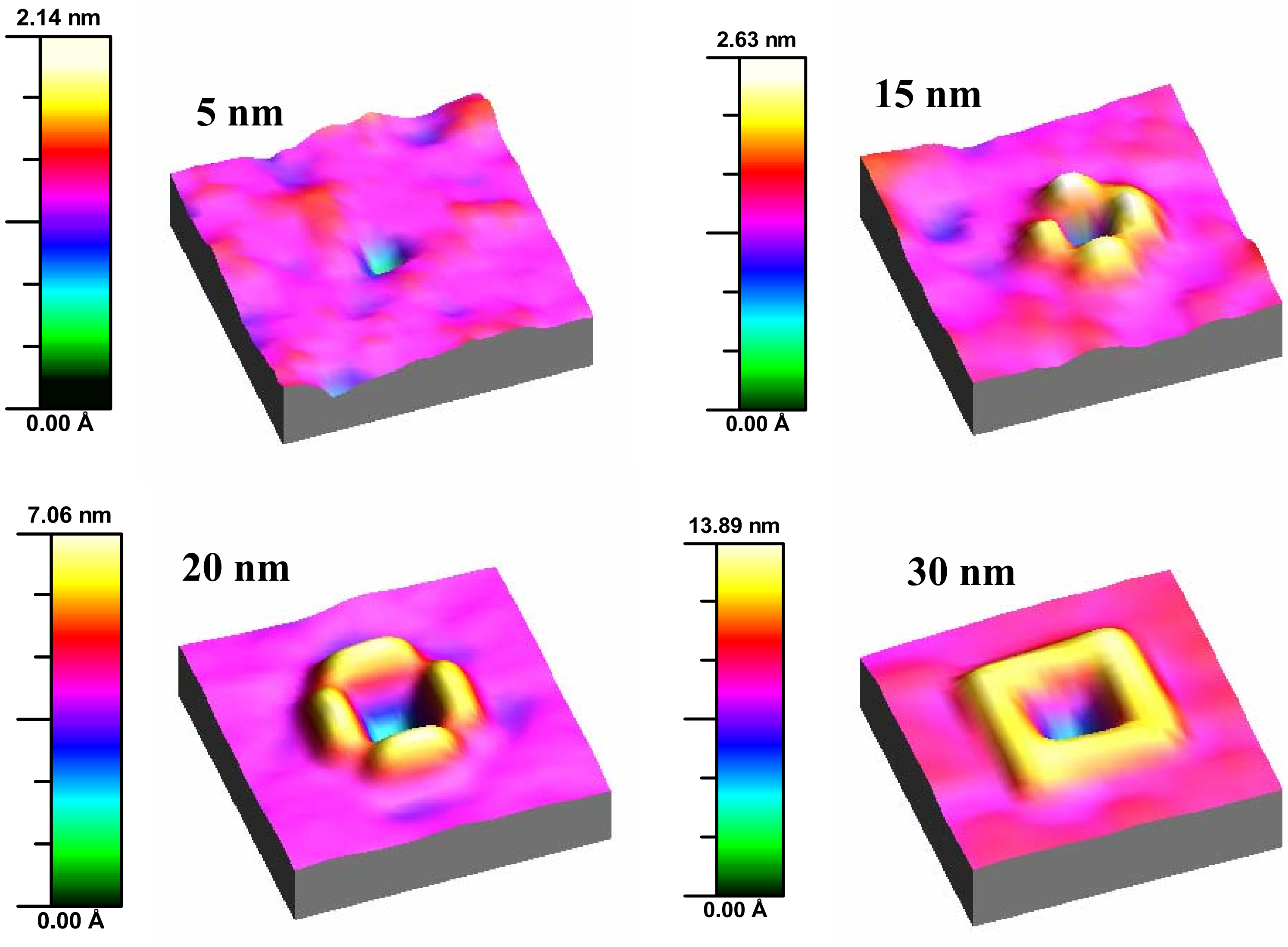
SELF-ASSEMBLY OF QUANTUM DOT MOLECULES

$Ge_{0.3}Si_{0.7}$ / Si(100), 550°C, 0.9 A/s



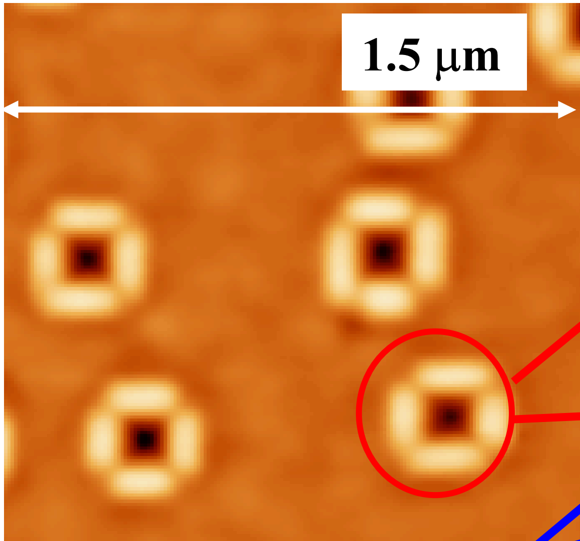
5 x 5 μm AFM scans

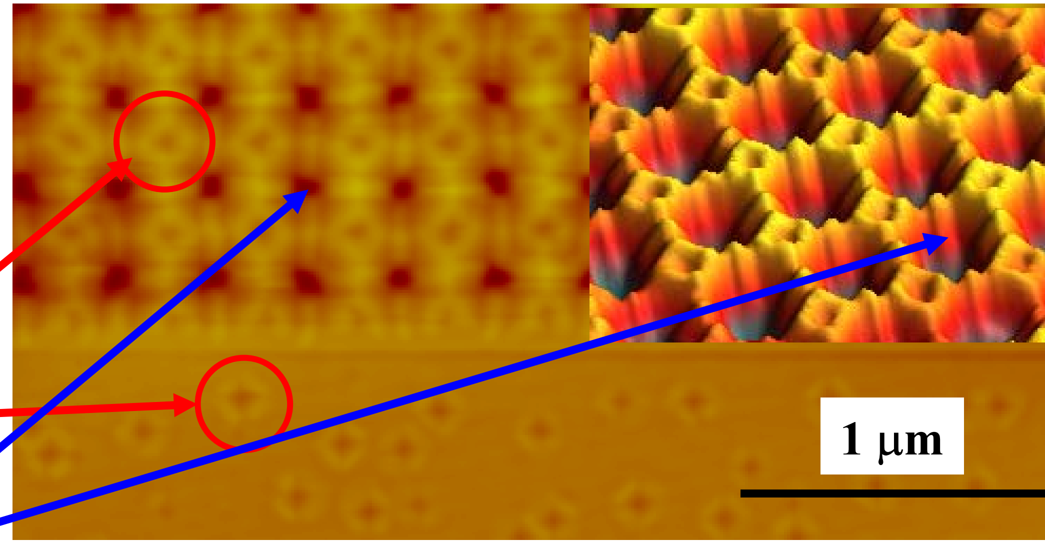
J. L. Gray, R. Hull and J.A. Floro, Appl. Phys. Lett. 81, 2445 (2002)



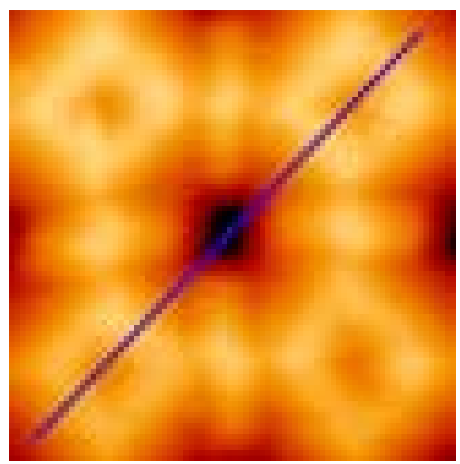
h nm $Ge_{0.3}Si_{0.7}$/Si(100), 550^o C, 0.09 nm/s

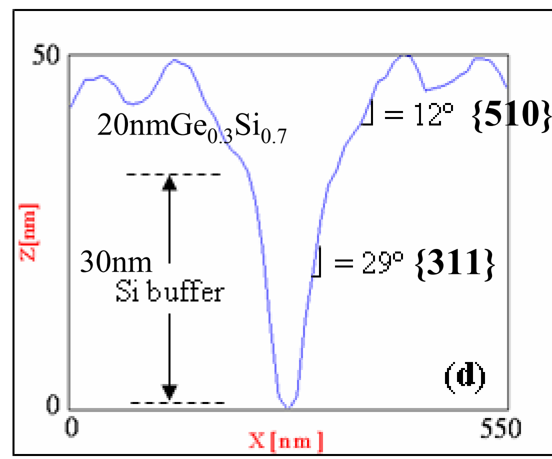
Hierarchical Assembly of Semiconductor Nanostrutures





Focused Ion Beam – Created Pits





Length Scales:

10^{-9}- 10^{-8} m QDM components

10^{-8} - 10^{-7} m QDM

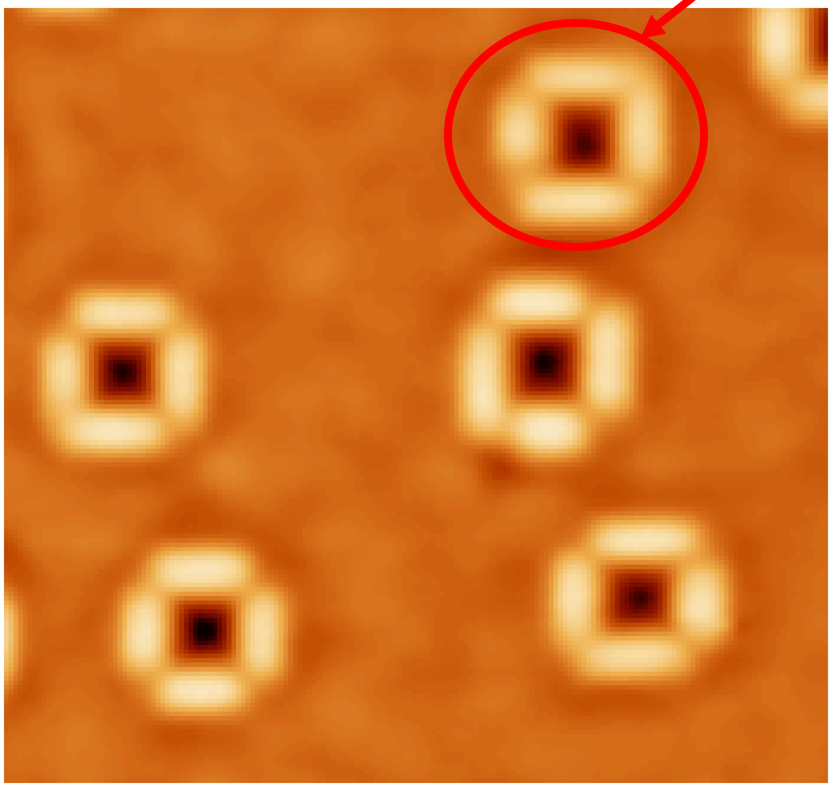
10^{-5} ↑ m Topographic Array

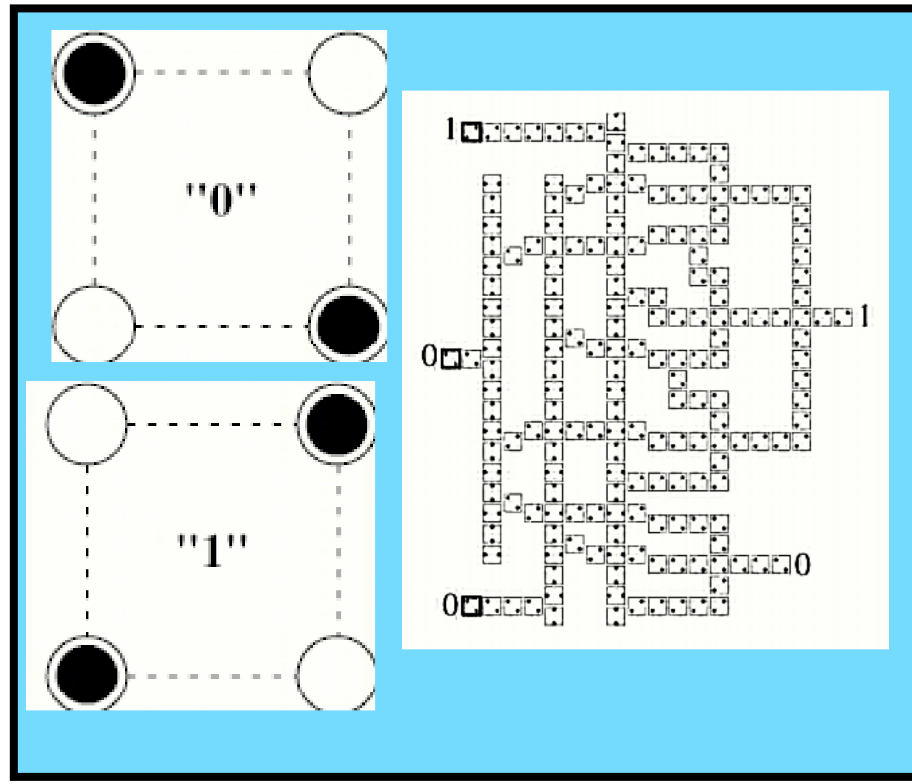
J.L. Gray, S. Atha, R. Hull and J.A. Floro, Nanoletters 4, 2447-40 (2004)

Carrier Confinement Requires Ge Segregation and/or Doping

How to measure?

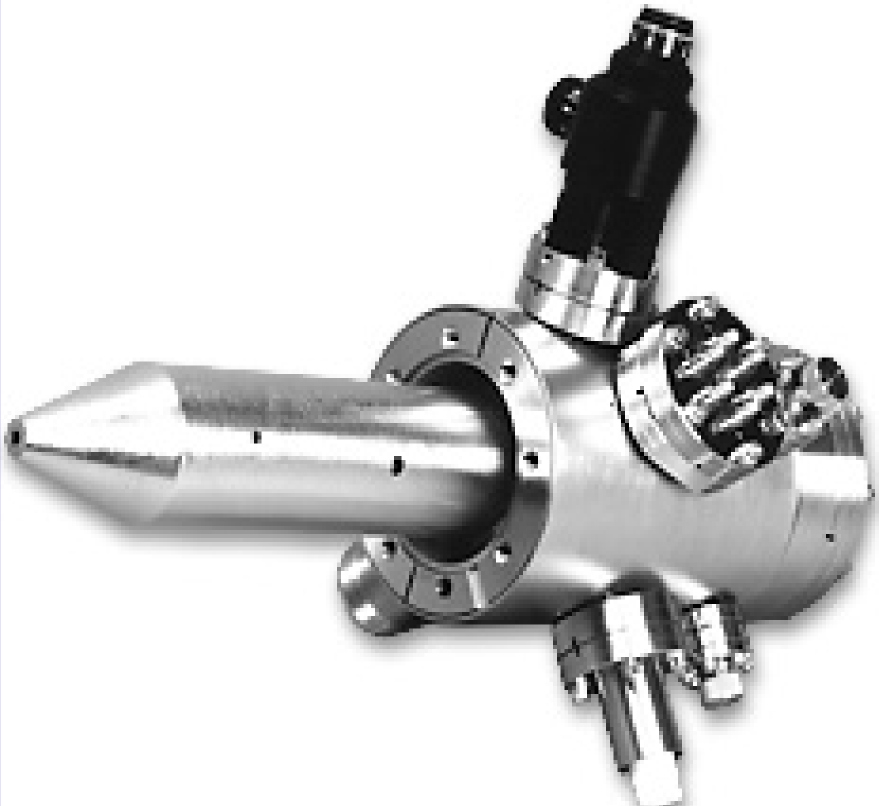
FOV 1 x 1 μm





x = 0.3, 550 C, 0.9 A/s

Focused Ion Beam Nanoscale Doping



Arriving Dec 2004 (Orsay Physics, Marseilles)

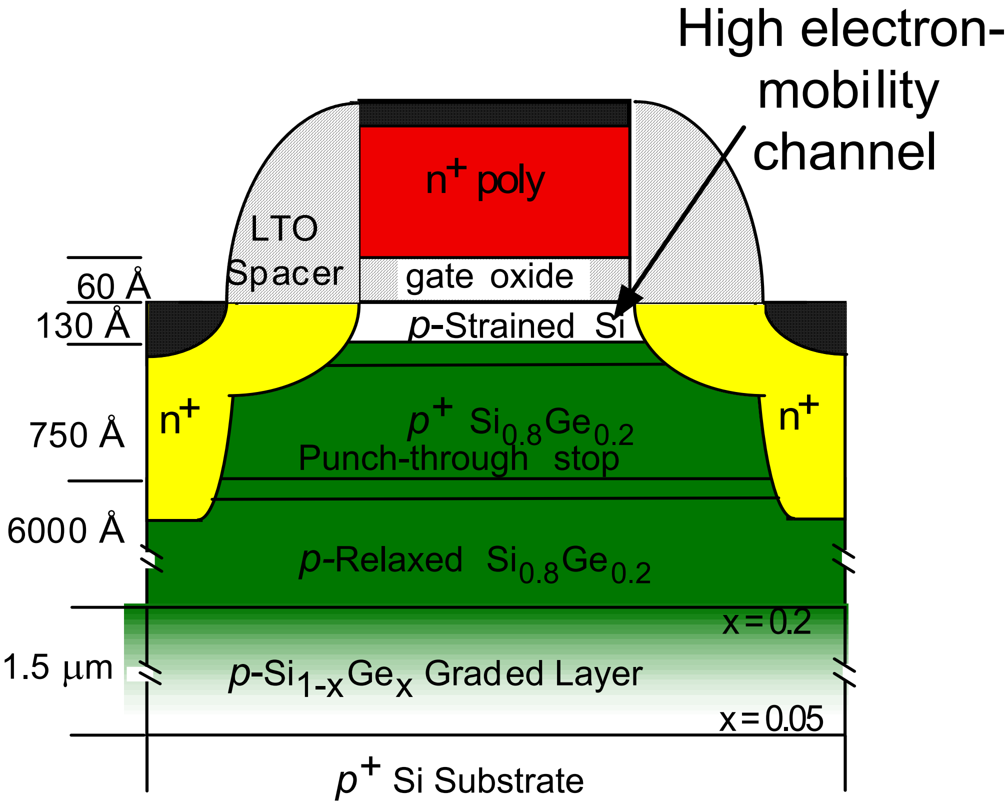
5nm FIB Column

ExB Filter for Alloy Source Selection (AuSi, PdAsB….)

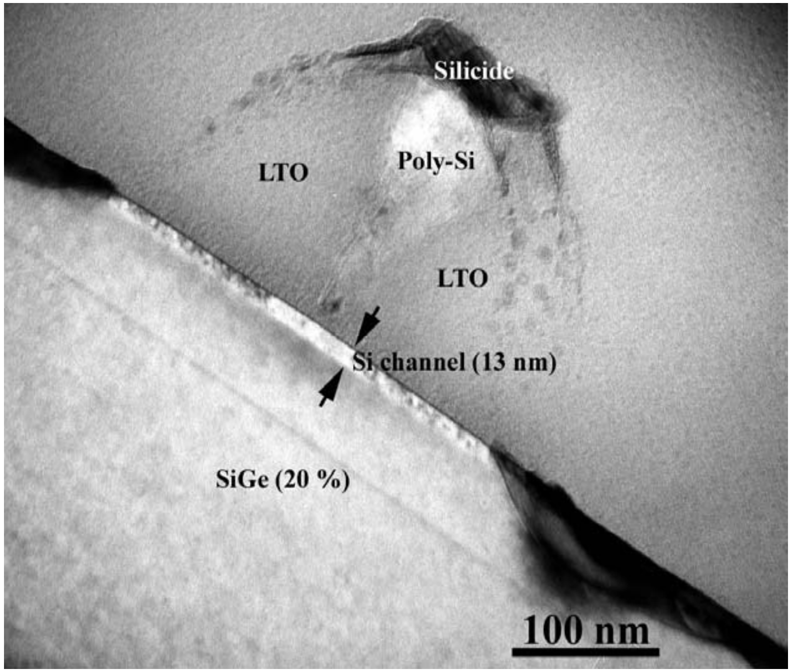
Candidates for Mn Ion identified (MnGa, MnSn…)

Few ion delivery (1 pA, 0.1 - 1μS ~ 1- 10 ions)

J. Graham, R. Hull, Orsay Physics



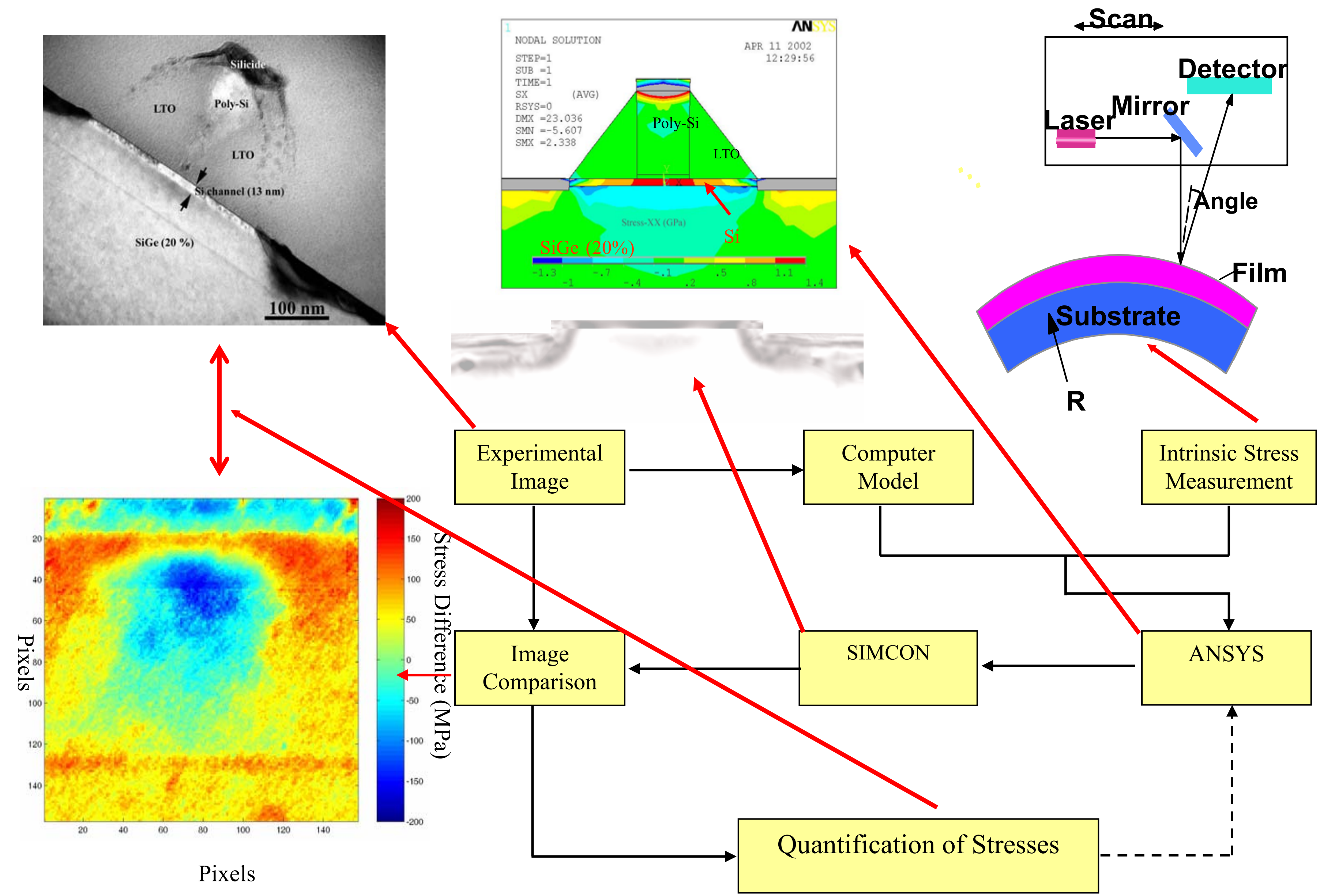
Strained Si-Channel MOSFET (J. Hoyt, MIT)



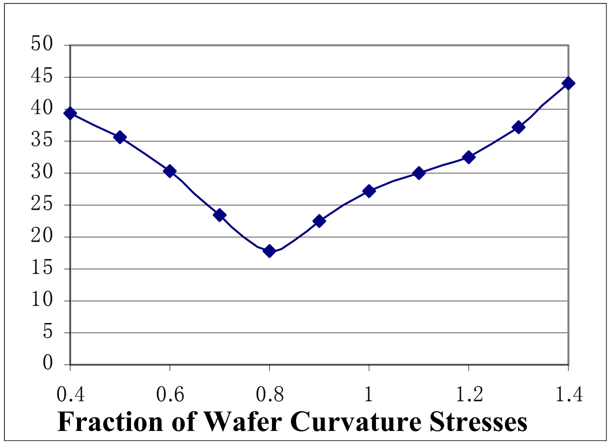
XTEM–(400)BF image Gate length=100nm

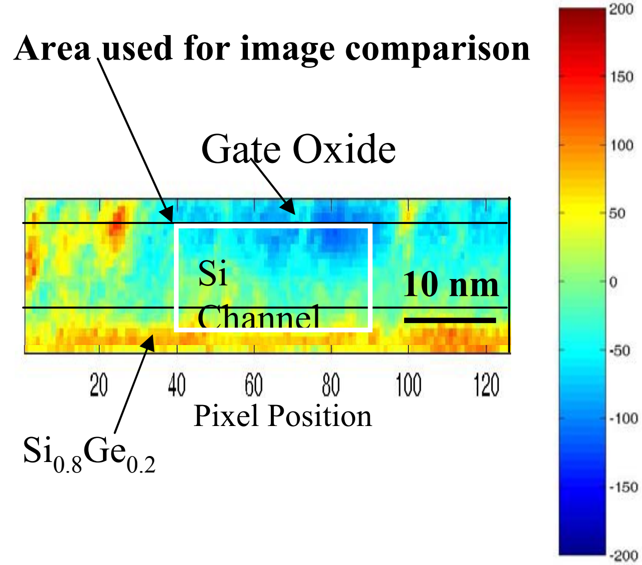
Nanoscale Stress/Strain Mapping Techniques

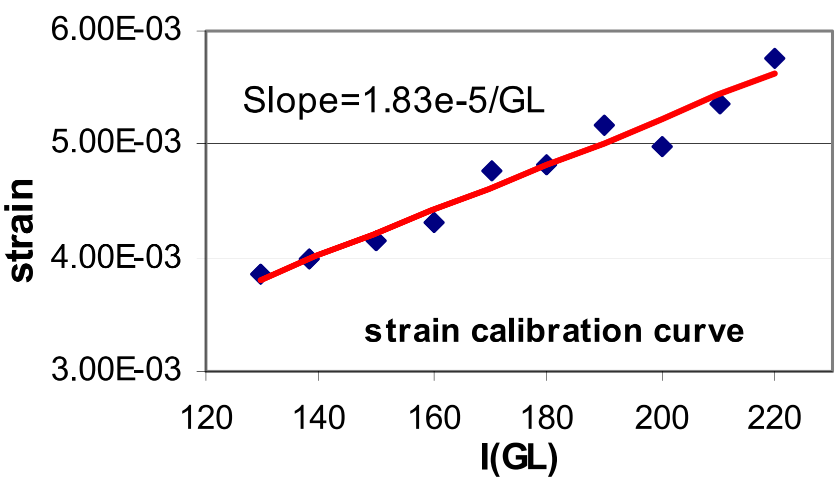
Technique	Spatial Resolution	Strain Sensitivity	Thin Foil Required?
X-ray diffraction	0.5~1 μm	10^{-5}	No
μ-Raman	0.2~1 μm	10^{-3}	No
Photoelastic	> 1 μm	10^{-5}	No
CBED/LACBED	2~10 nm	10^{-4}	Yes
EDC Quantification	10 nm	10^{-4}	Yes

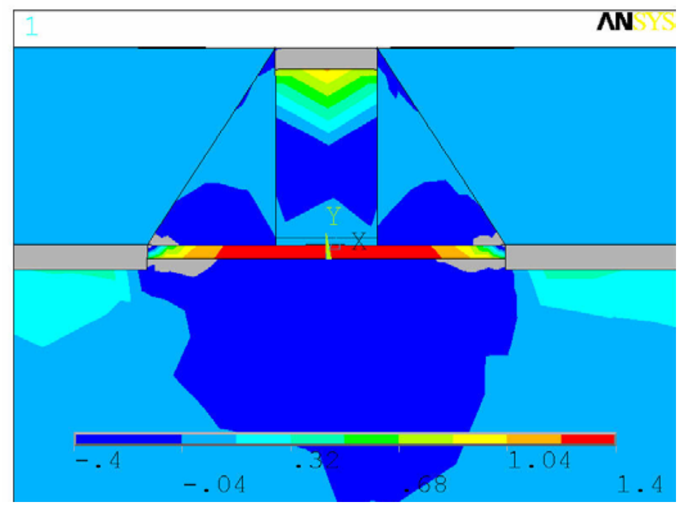


Jian Li, UVa Physics





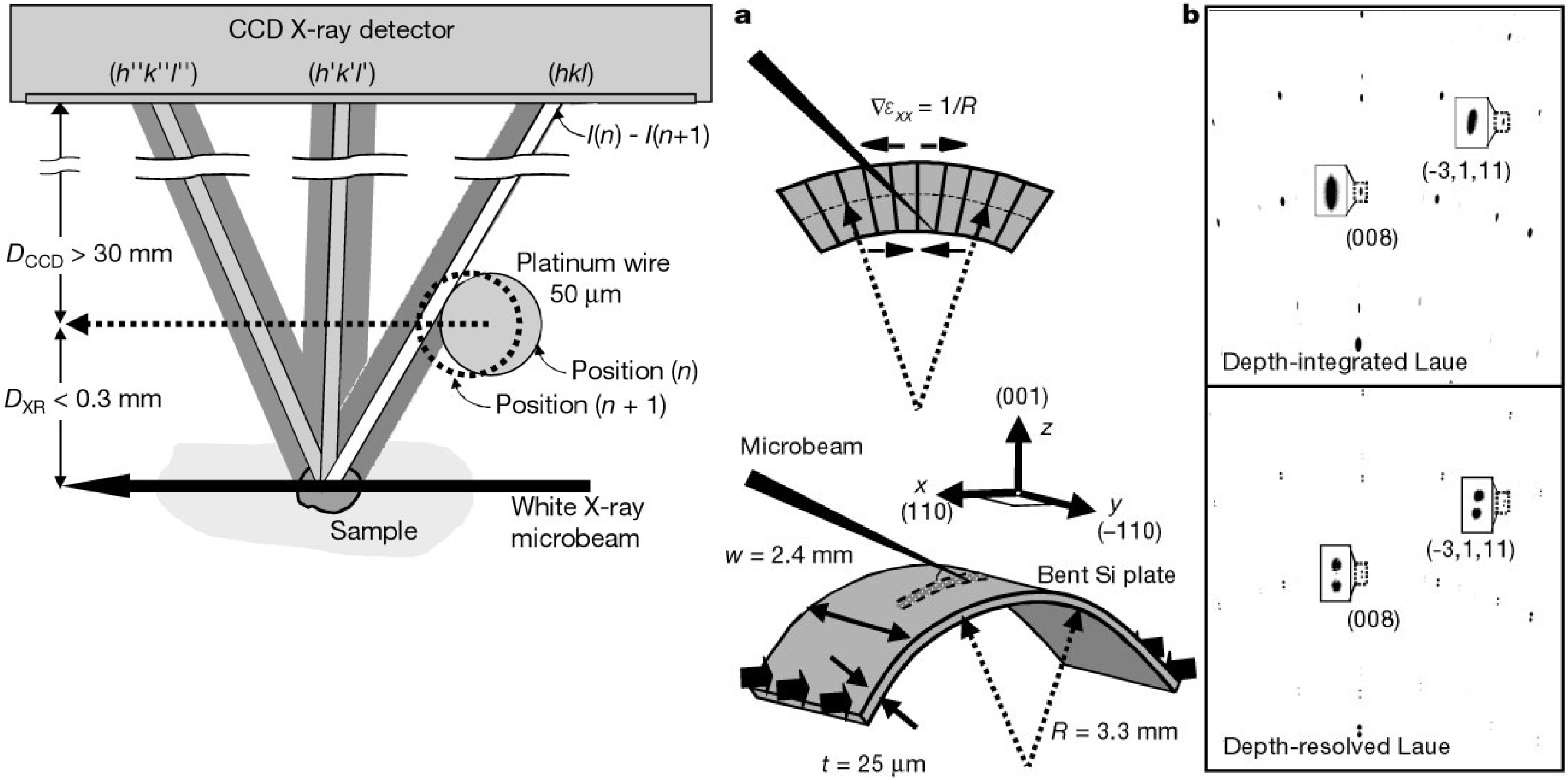




Spatial Resolution < 10 nm

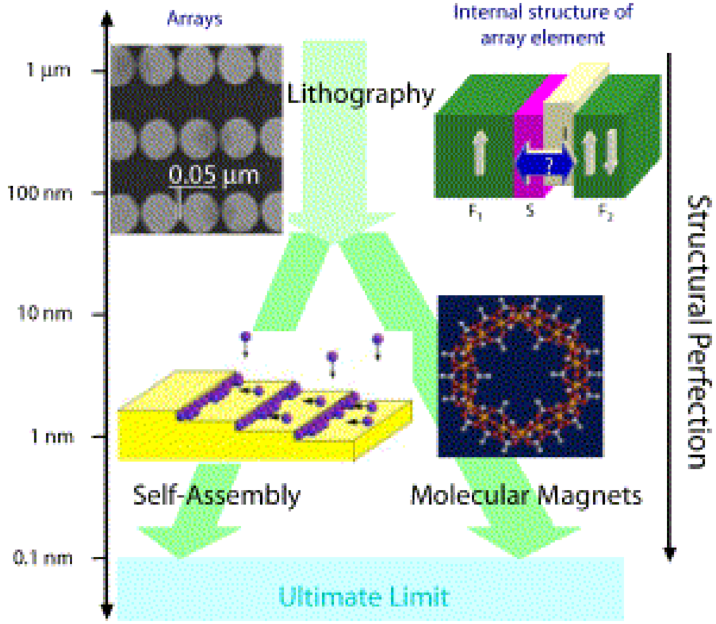
Stress Sensitivity c. 30 MPa (Multi-Parameter Minimization)

3D X-ray Structural Microscopy with μm Resolution

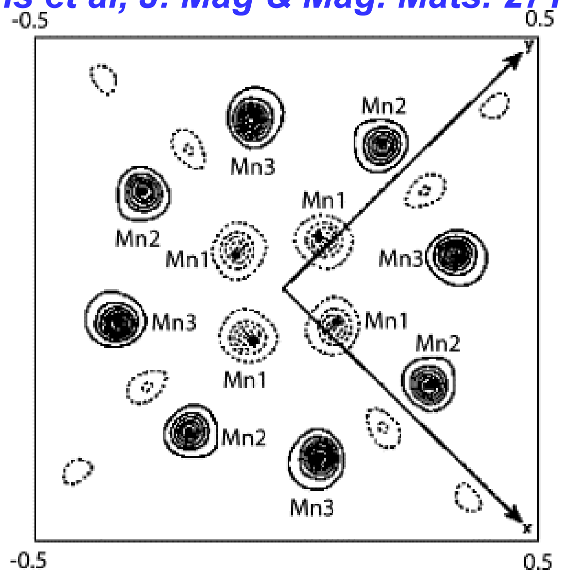


B.C. Larson et al, Nature 415, 887 (2002)

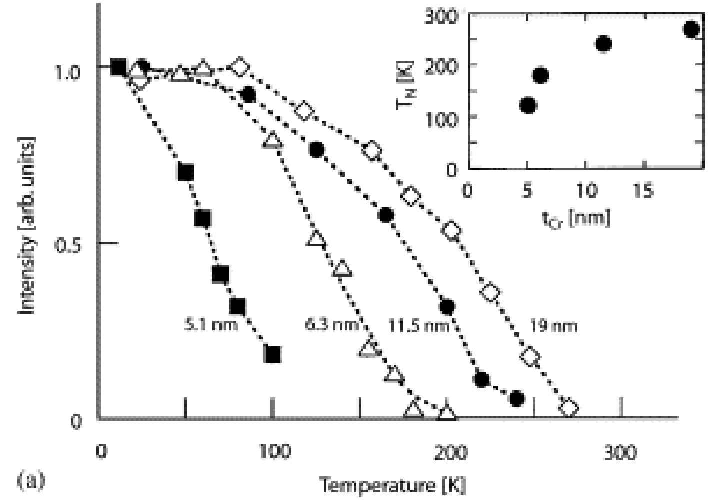
Neutron Scattering from Magnetic Nanostructures

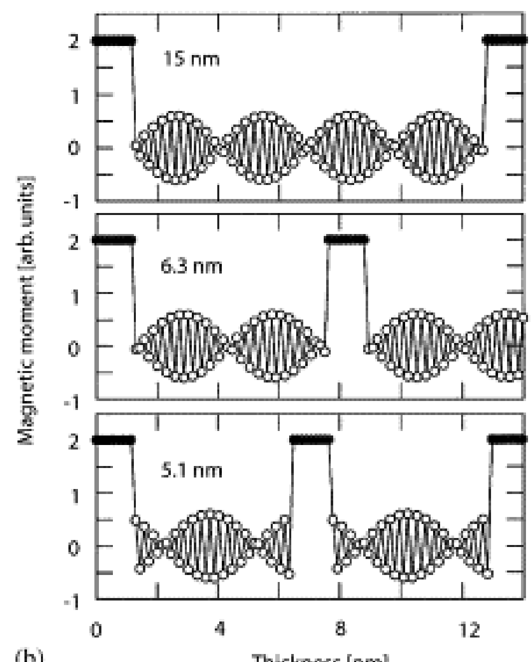


Fitzsimmons et al, J. Mag & Mag. Mats. 271, 103 (2004)



Spin density map in Mn_{12}-acetate, Robinson et al J. Phys. Con. Matt. 12, 2805 (2000)





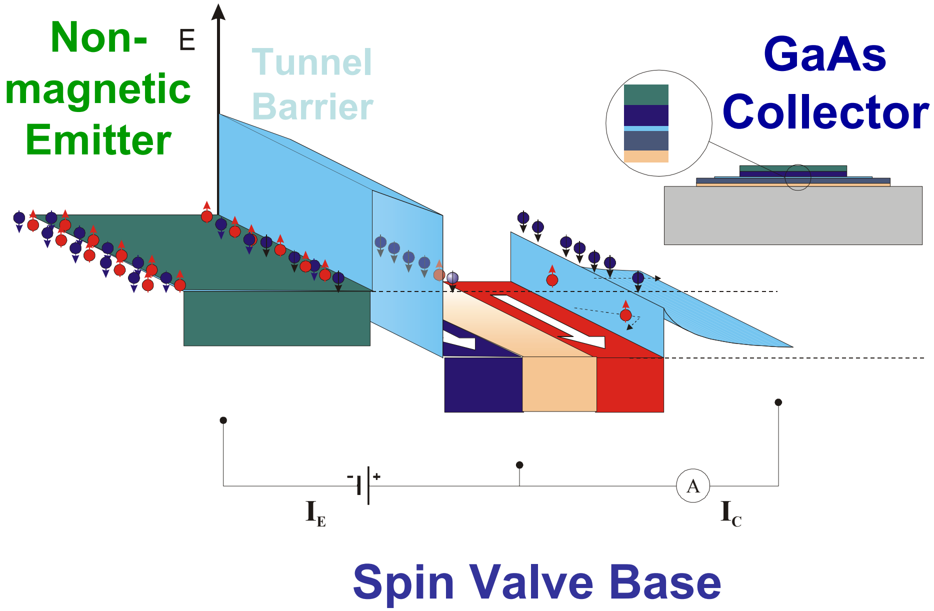
T-dependence of Cr Bragg reflection in Fe/Cr SL; variation of magnetic moments in Fe, Cr layers. Fullerton et al PRL 77, 1382 (1996)

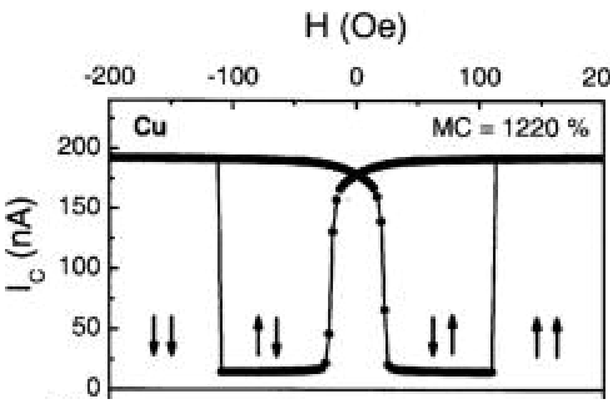
Spintronics

Ferromagnetic Semi-conductors GaMnAs

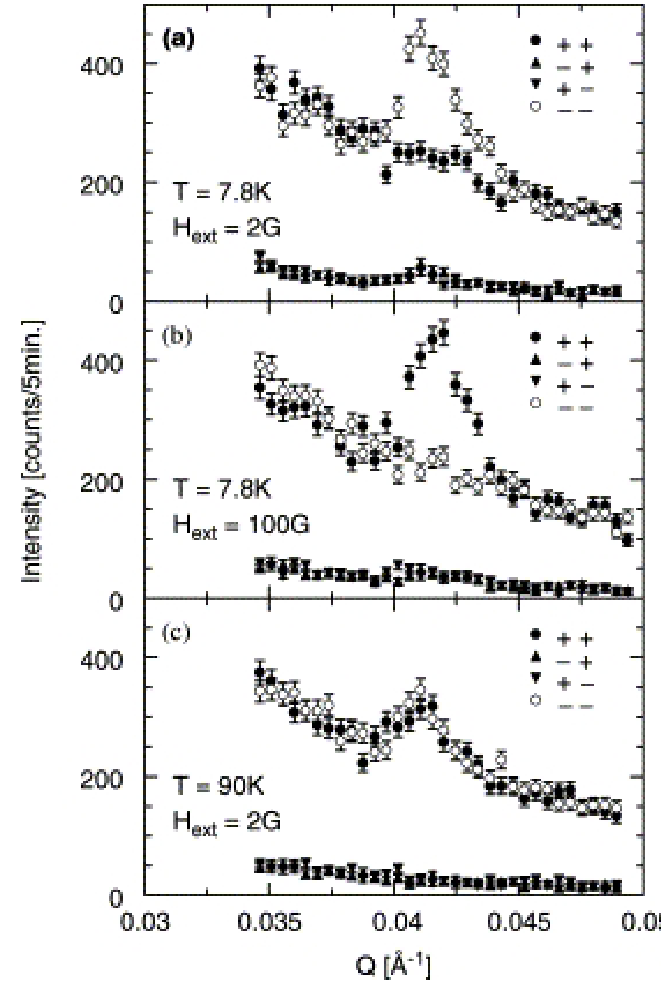
Three terminal magnetic tunnel transistor

GaAs(001)/5 nm $Co_{70}Fe_{30}$/4 nm Cu/5 nm $Ni_{81}Fe_{19}$/ 1.8 nm Al_2O_3/30 nm Au





Van Dijken, Jiang and Parkin Appl. Phys. Lett. 82, 775 (2003)



Polarized neutron reflectivity, Kepa et al Physica B335, 44 (2003)

Summary of Key Needs

- In-situ studies of evolution of individual objects down to the nanoscale
- Greater accessibility to in-situ experimentation
- Chemical analysis of nanoscale objects
- Direct detection of impurities / dopants
- Micro-probe $\rightarrow$ Nano-Probe Stress Analysis