Mapping Atomic Structure at Epitaxial Interfaces

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Opportunities for interface science at the ERL

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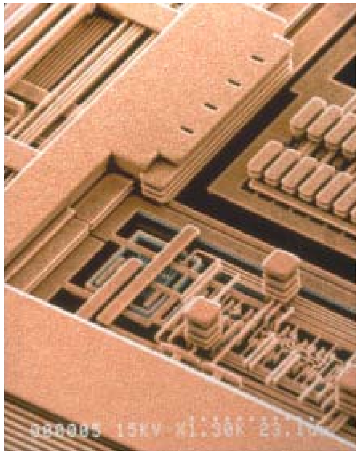
ERL X-ray Science Workshop:
Almost Impossible Materials Science, June 16, 2006

Outline

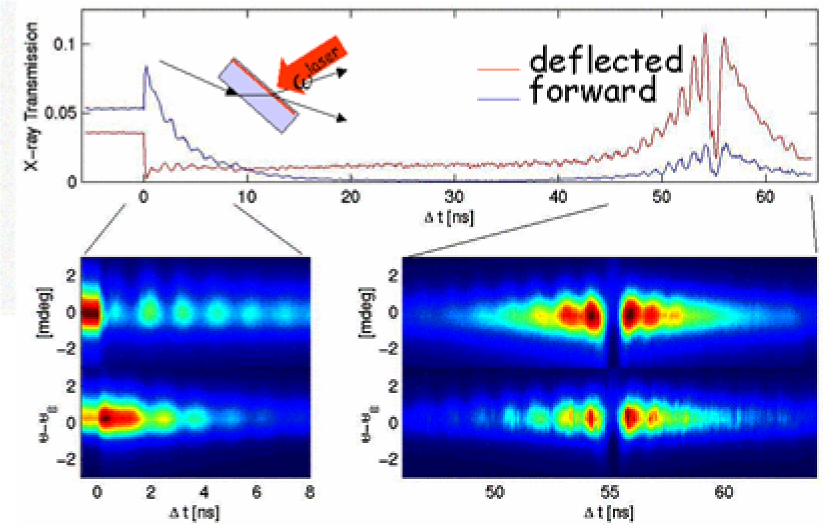
At nanoscale, interfaces are everything



- ***Possible now:***

-3D maps of static thin-film/interface structure with atomic resolution

-Some dynamic information, including strain, phonons, domain walls…



DeCamp, Reis et al. Nature, PRL

- ***Opportunities for ERL:***

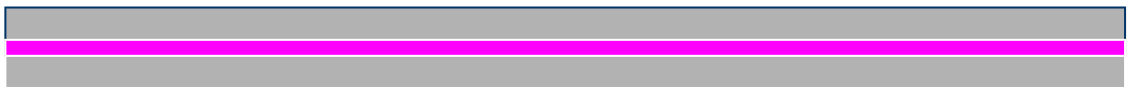
- ultrafast imaging at atomic scale

- tracking growth, deposition processes

- local probe of nano-structures

Epitaxial Nanostructures

Van der Merwe layer-by-layer growth



Quantum wells,
Superlattices,
Tunneling devices

Stransky-Krastanov mixed growth

Quantum dots,
self-assembly

Volmer-Weber island growth

Surface nano-
patterning

Epitaxial Nanostructures
(example: “6.1Å system”)

No-common-atom superlattices

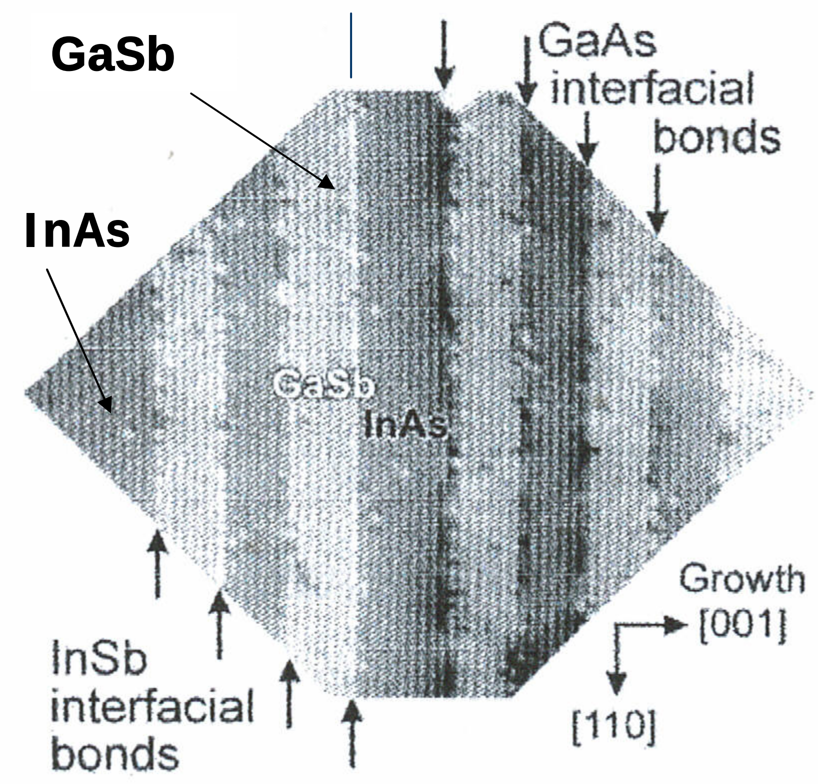
<u>InAs-on-GaSb:</u>

...Sb-Ga-Sb-**Ga-As** In-As-In-As...

<u>GaSb-on-InAs:</u>
(“inverted interface”):

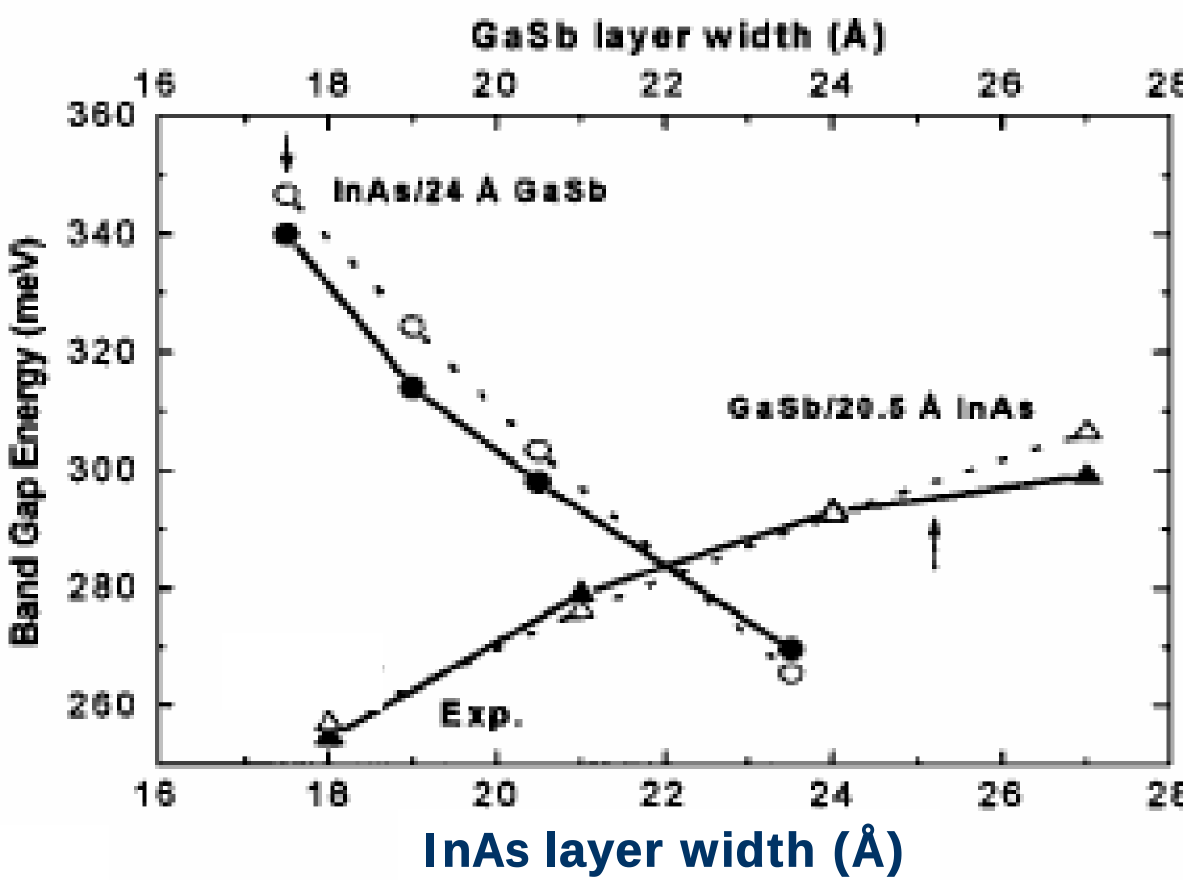
...As-In-As-**In-Sb**-Ga-Sb-Ga...

Band-gap tunability 0.2eV to 1.3 eV for IR applications – but difficult to control growth

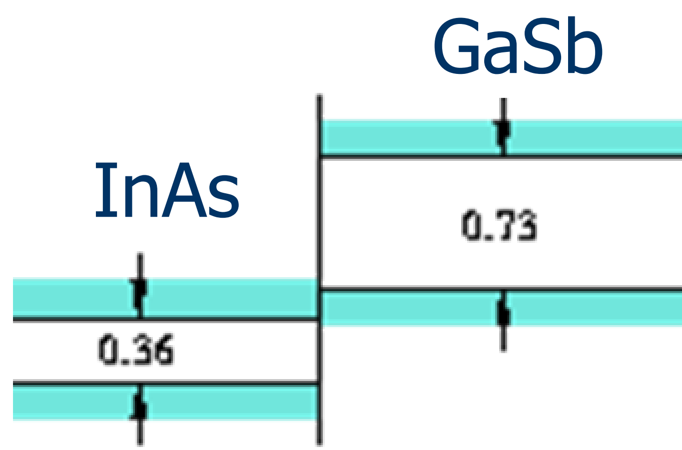


Nosho, Barvosa-Carter, Yang, Bennett,Whitman Surf. Sci. 465, 361 (2000).

Band-gap tuning



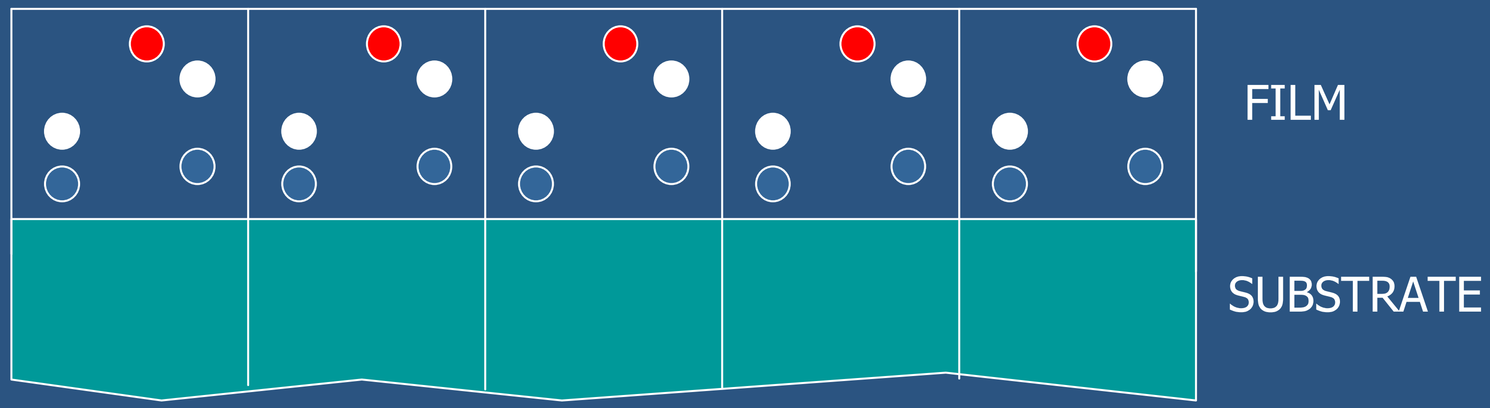
Type II band alignment

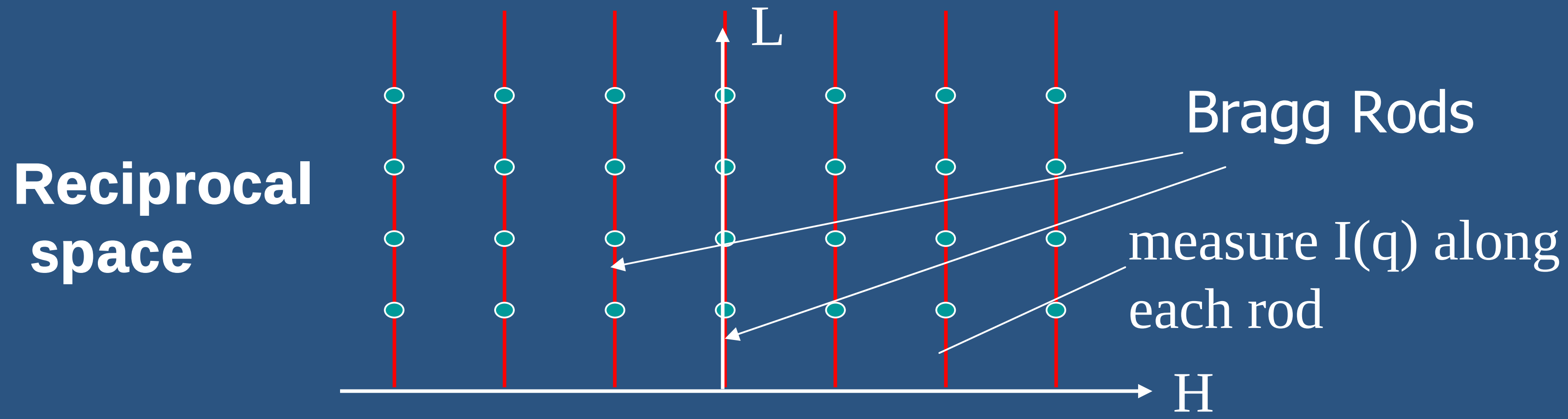


Haugen et al. J. Appl. Phys. 96 (2004)

Epitaxy and 2D periodicity

2D periodic structure coherent with the substrate (aka "epitaxial film")

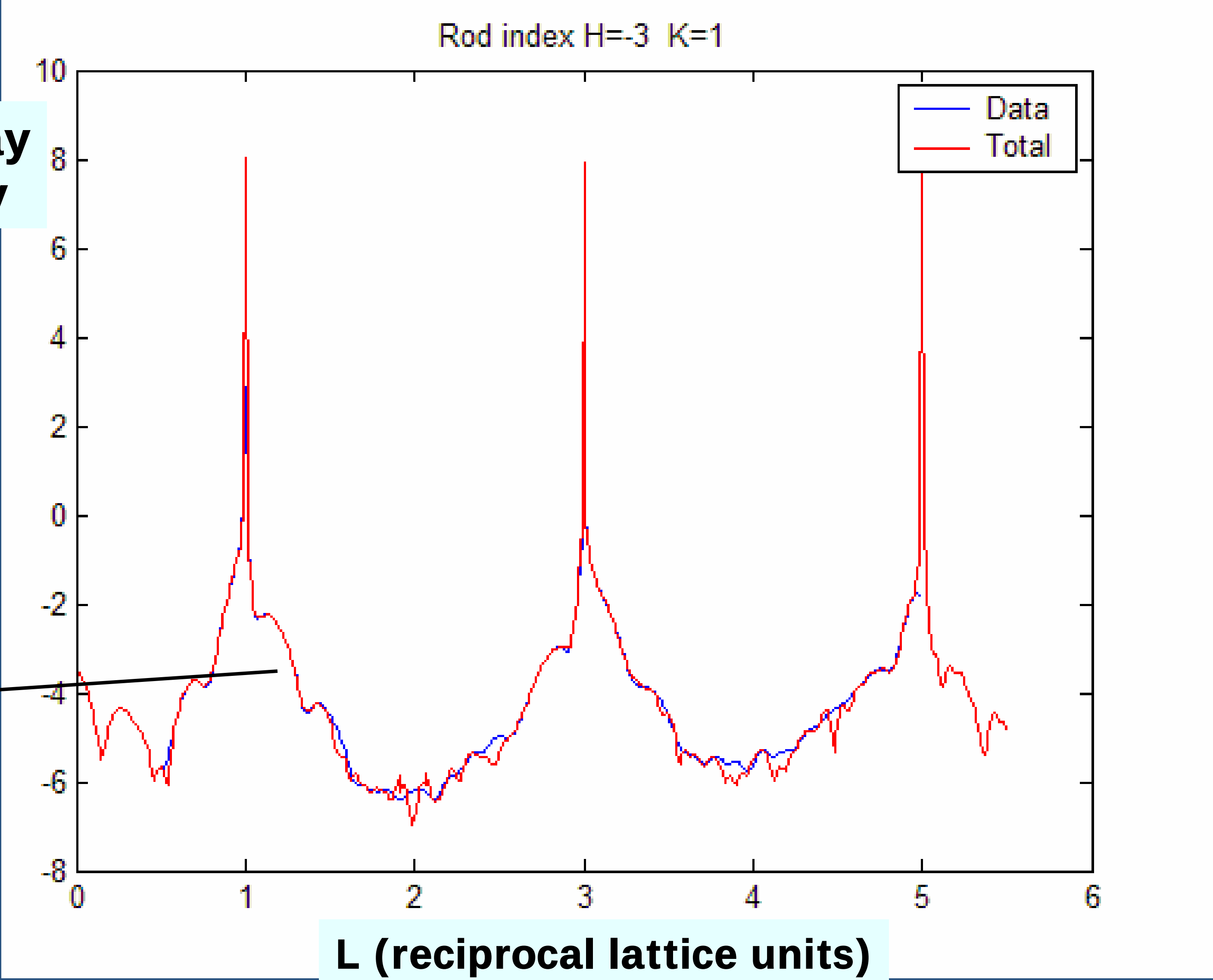




If film and substrate are coherent then get interference fringes along the rods:

Coherent Bragg Rod Analysis (COBRA)

-31L Bragg Rod Profile for sample 811 (InAs on GaSb)



Log x-ray Intensity

L (reciprocal lattice units)

Weak fringes contain info on film and interface structure

(APS, undulator beam line ~ 2hrs/rod need ~ 10 rods)

- large dynamic range: 14 orders!

total

reference (substrate)

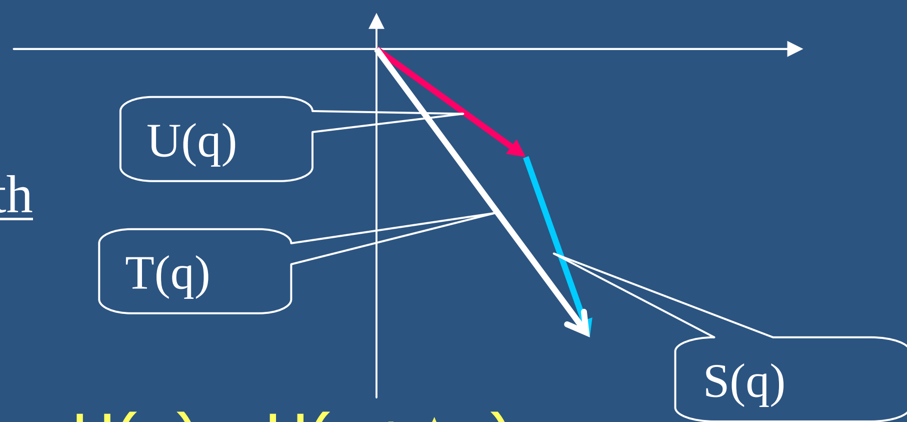
Unknown (film)

Scattering factor $T(\mathbf{q}) = S(\mathbf{q}) + U(\mathbf{q})$

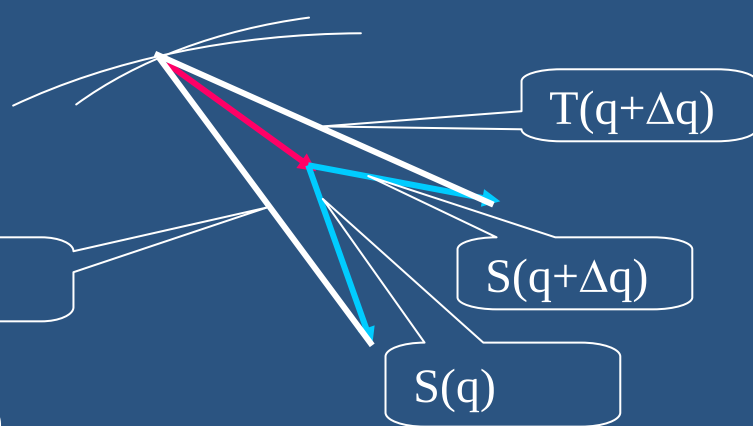
Fourier transform of $T(q)$
=> electron density

In the complex plane

know only <u>length</u>
of $T(q)$
from intensity



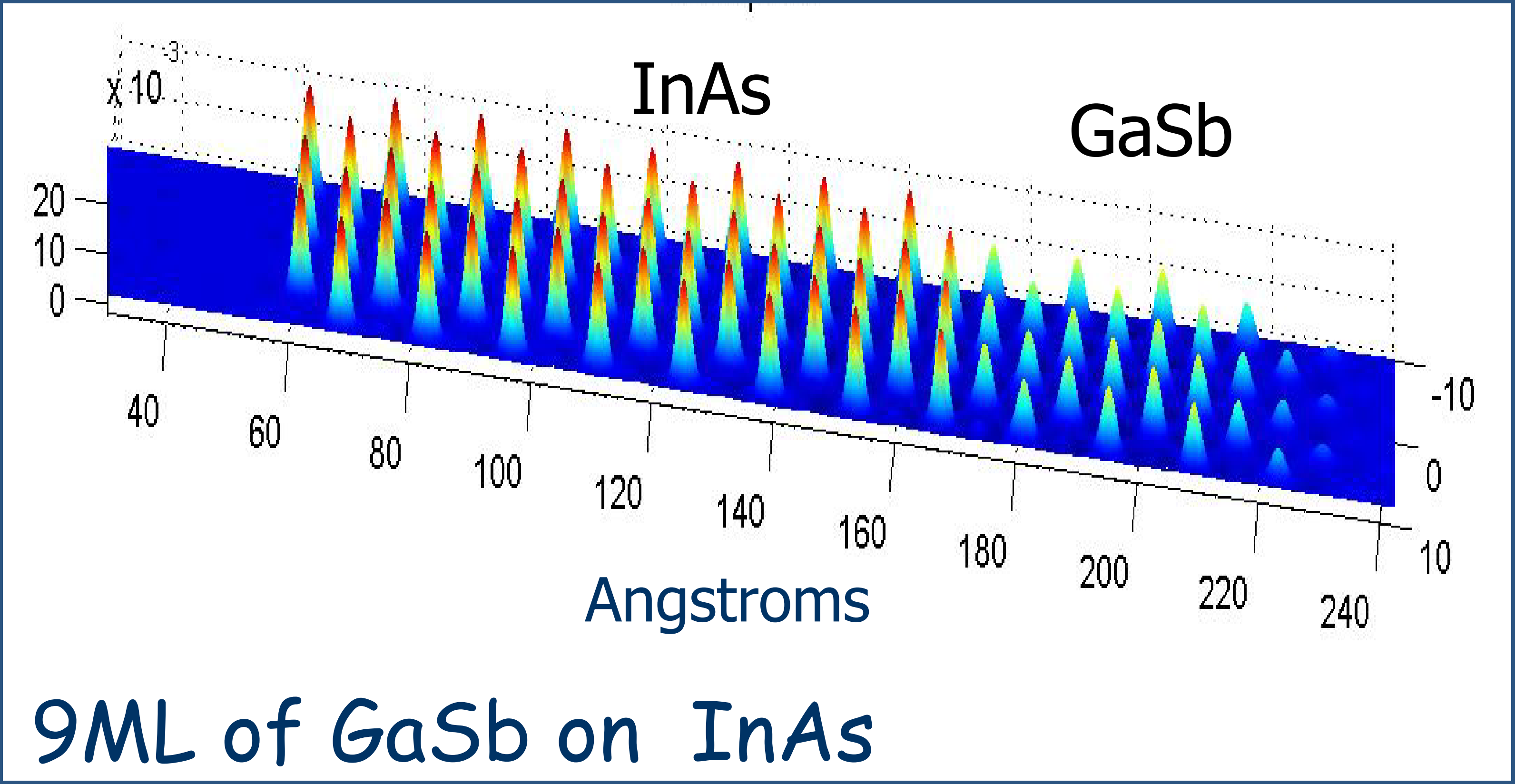
Approximation: $U(q) = U(q+\Delta q)$



COBRA METHOD

Sowwan et al. *Phys. Rev. B* 66, 205311 (2002).

COBRA MAP of Group III (In,Ga) plane

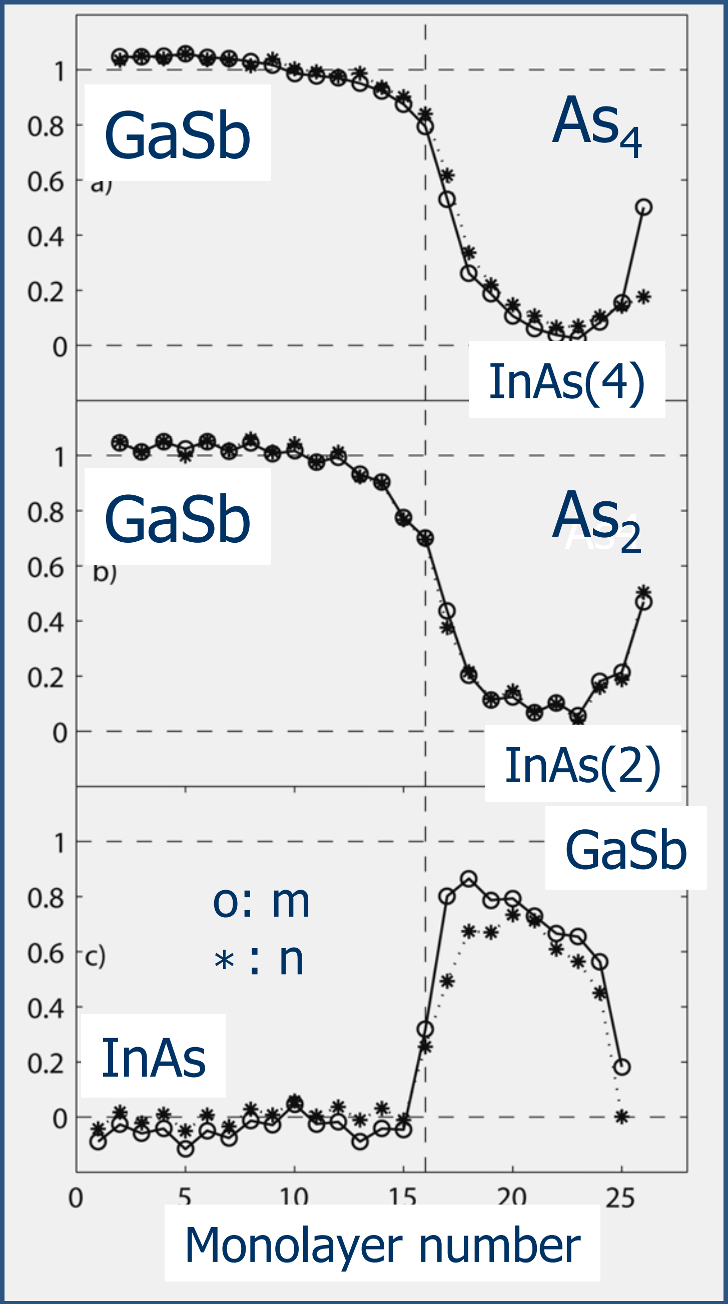


- very coherent interface
- surface roughness ~ 3ML

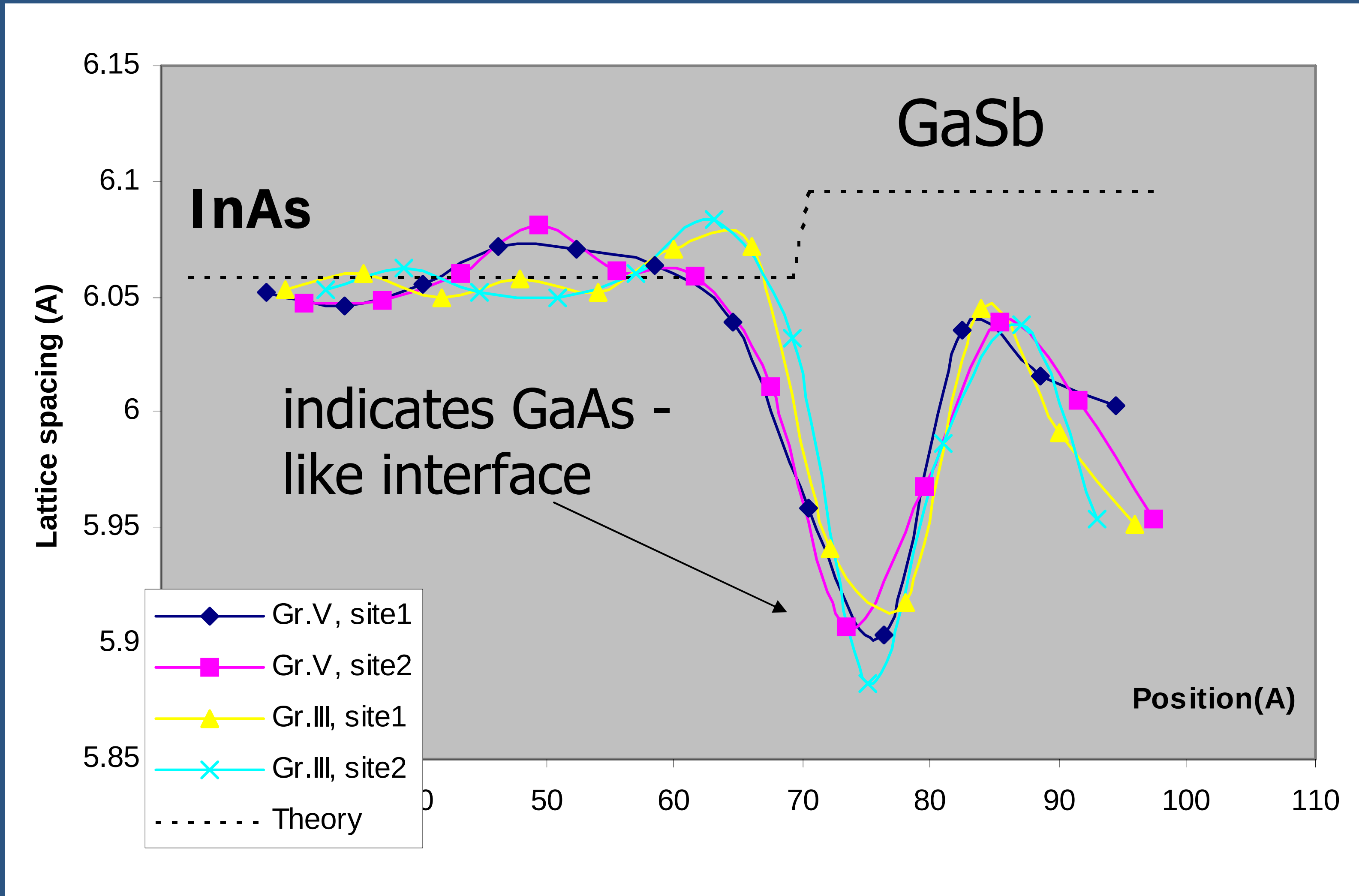
Composition profiles determined from COBRA electron density maps

Assumes quaternary system:

$Ga_mIn_{1-m}Sb_nAs_{1-n}$



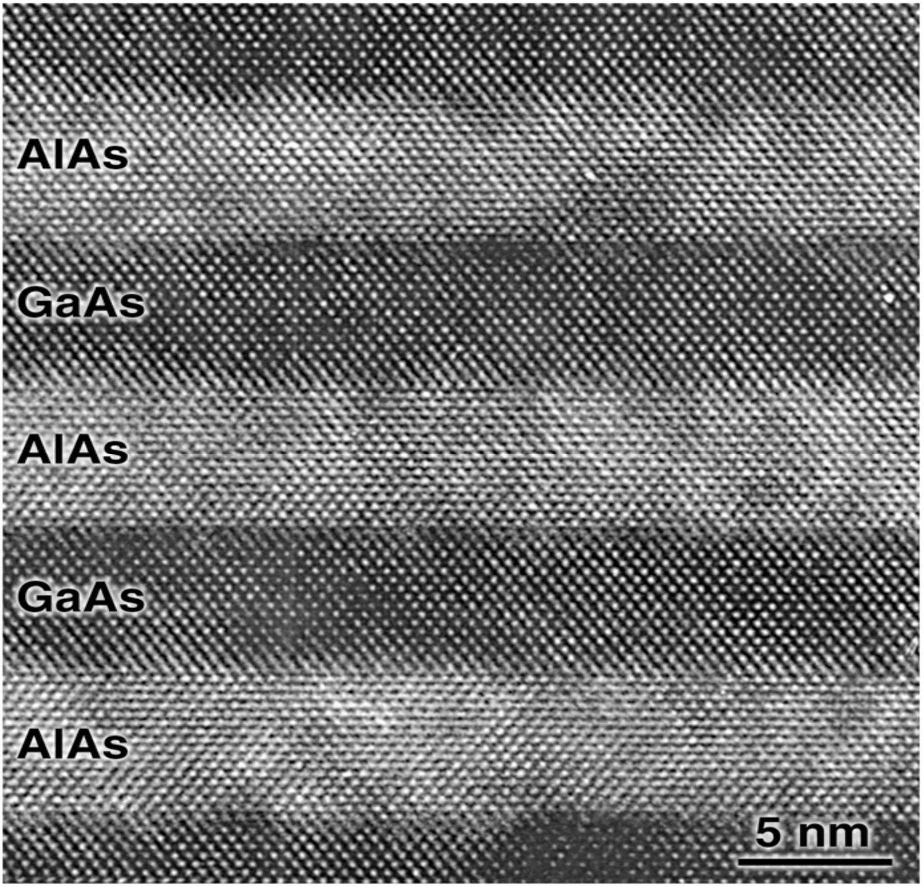
GaSb on InAs lattice spacing



(Determined from Gaussian fit to electron density peaks)

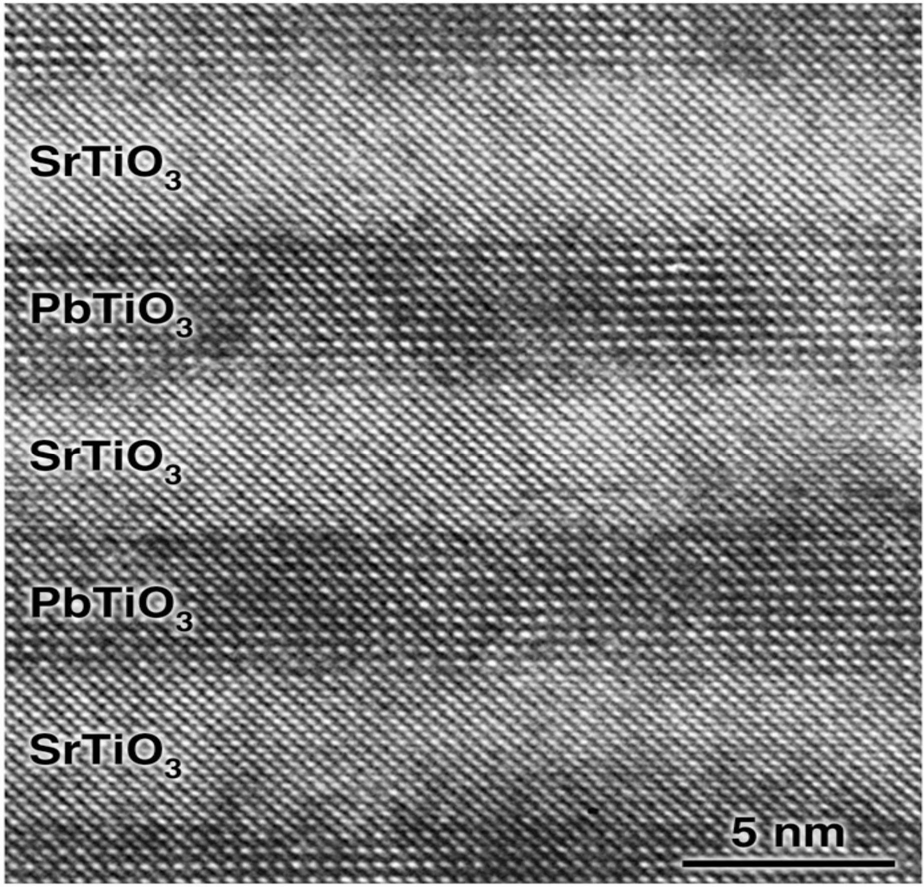
Ferroelectric nanostructure

AlAs / GaAs Superlattice



A. K. Gutakovskii *et al.*,
Phys. Stat. Sol. (a) **150** (1995) 127.

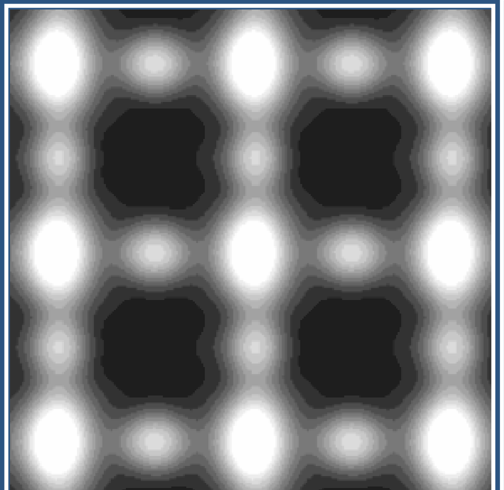
$PbTiO_3$ / $SrTiO_3$ Superlattice



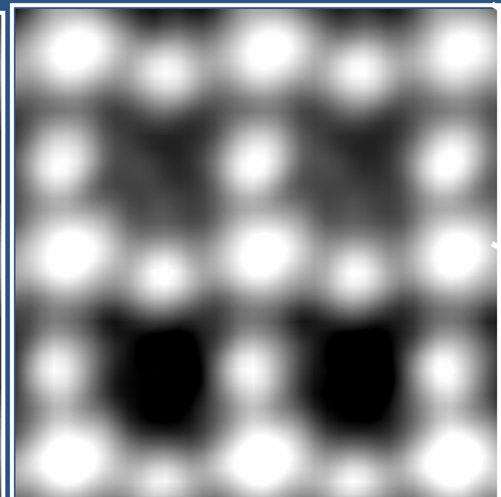
Film – Schlom Group (Penn State)
HRTEM – Pan Group (Univ. Michigan)

Jiang et al., APL 74, 2851 (1999).

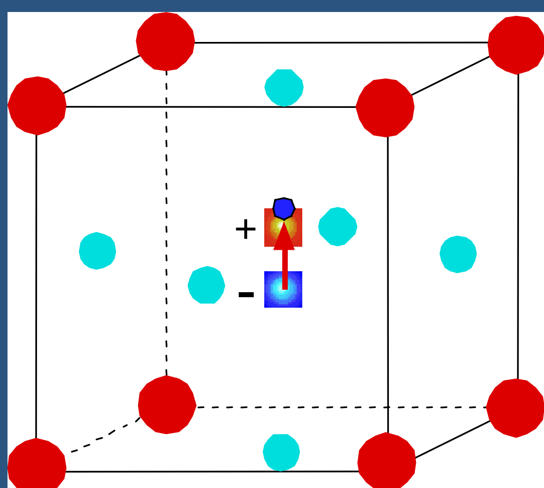
Ferroelectrics: Superlattice- Strain Effect

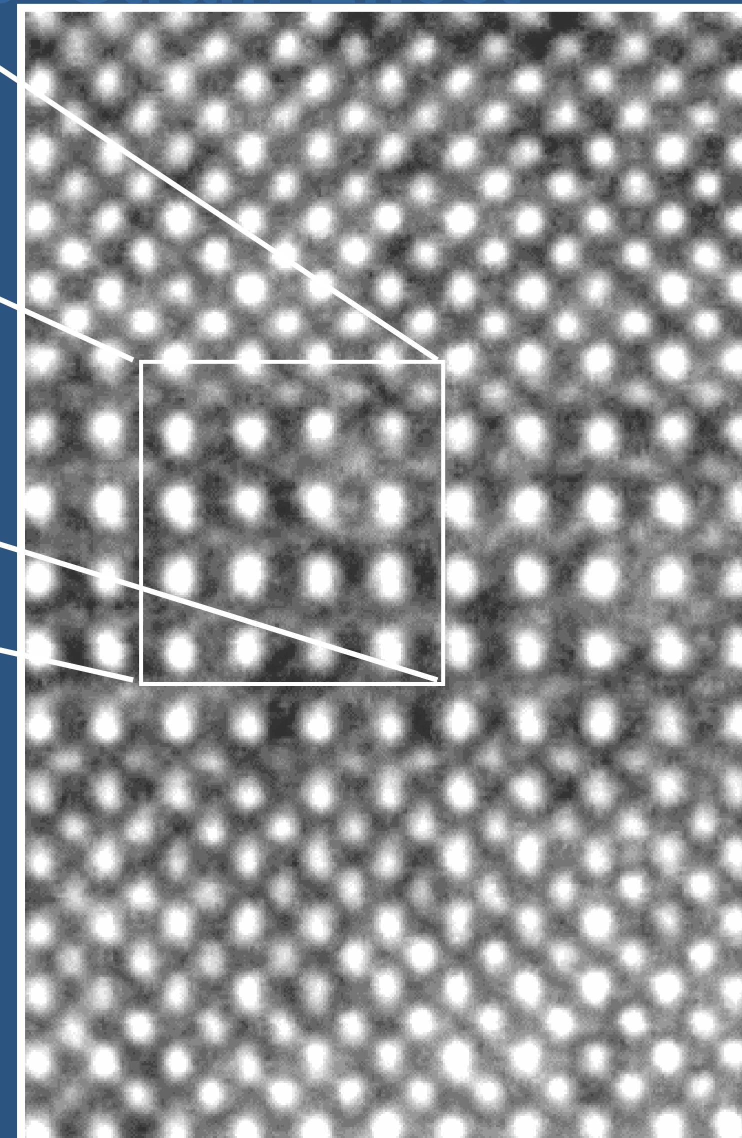


bulk $BaTiO_3$



strained $BaTiO_3$

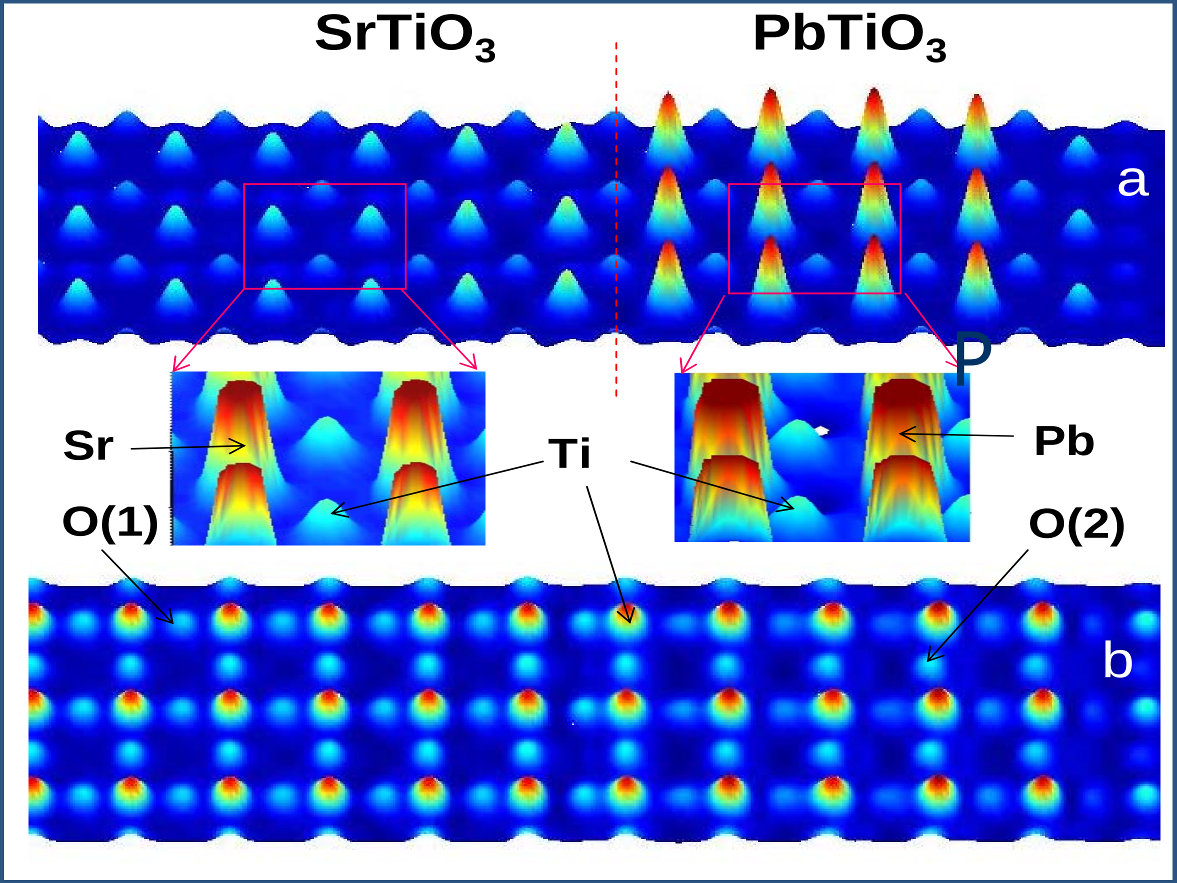




HRTEM image

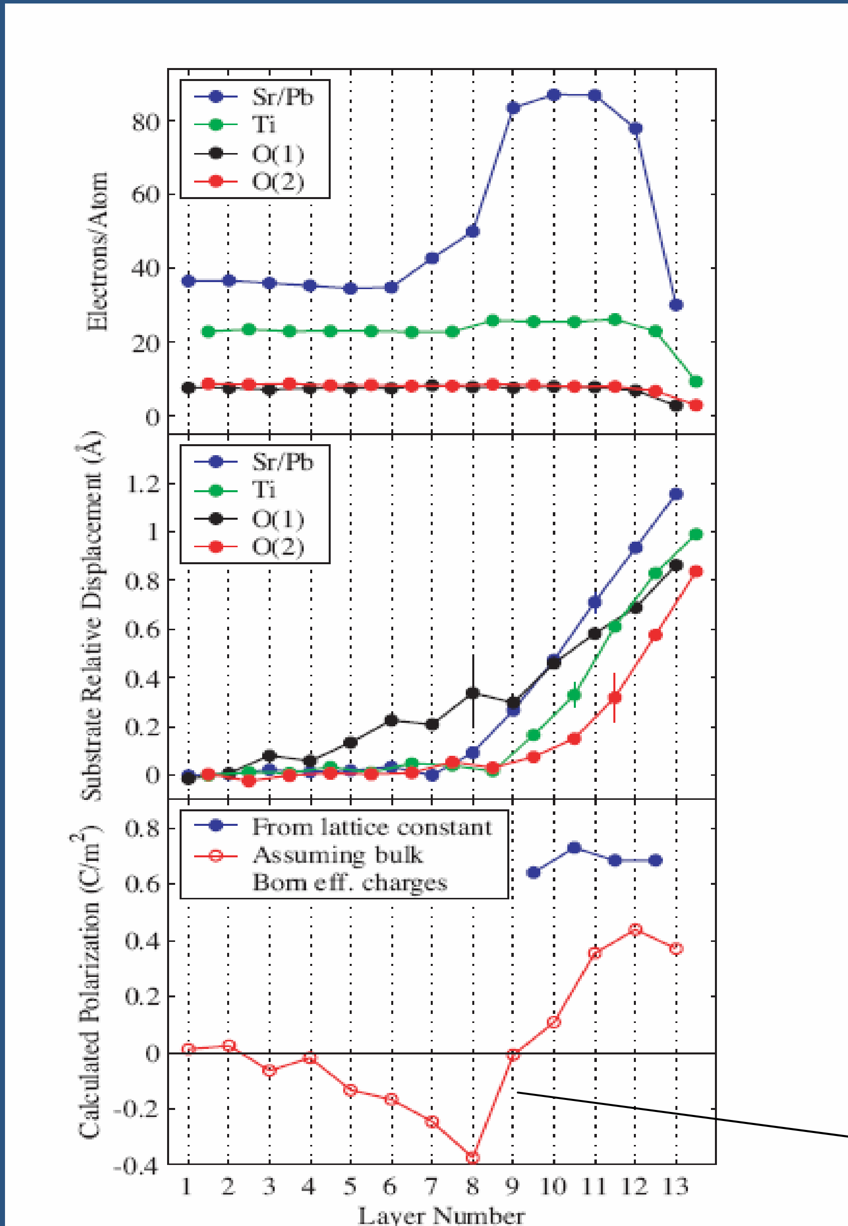
$[(BaTiO_3)_6/(SrTiO_3)_5]_{20}$

COBRA MAP OF FERROELECTRIC INTERFACE



E

Sample made by MOCVD, Stephenson group –in-situ facility, APS



COBRA results on ultrathin film of $PbTiO_3$

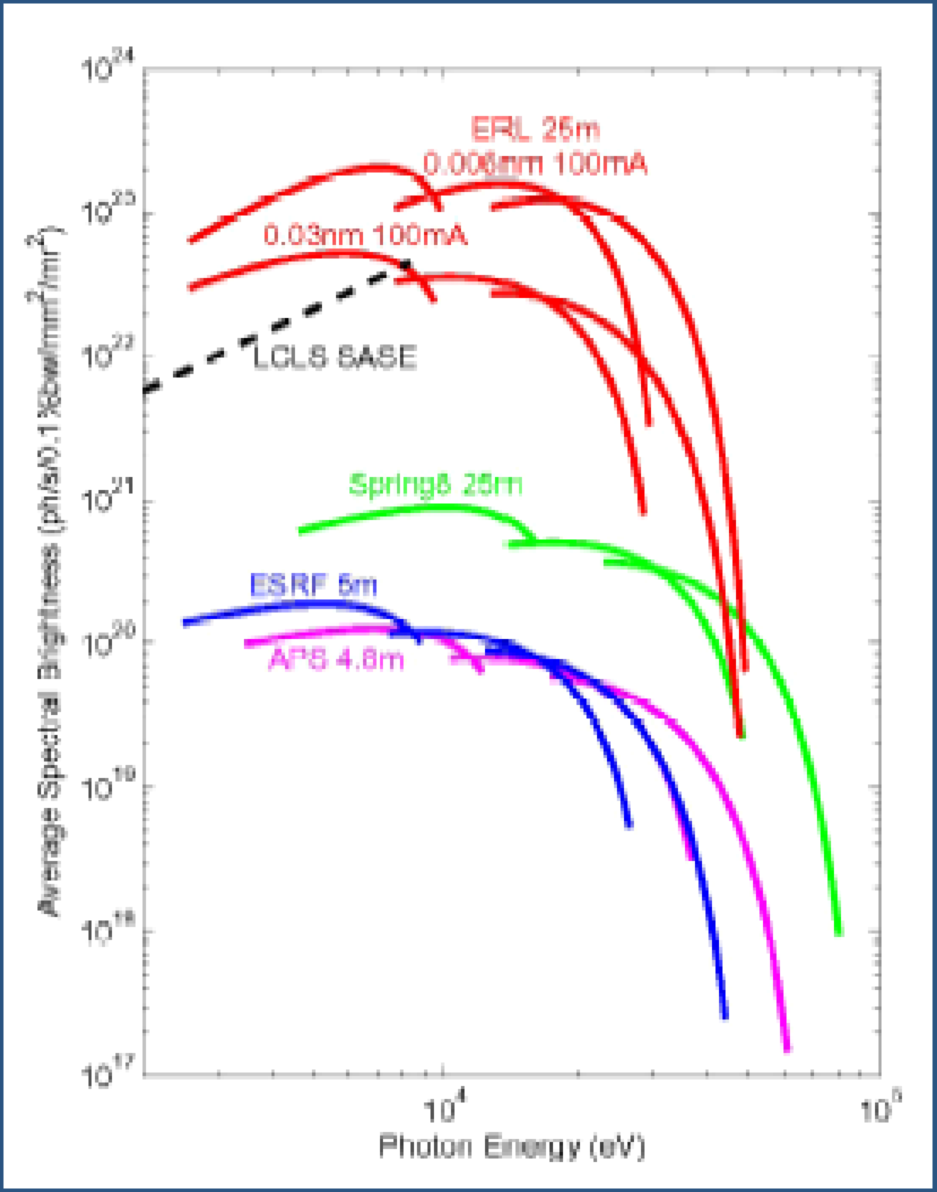
Fong, Cionca, Yacoby, Stephenson, Eastman, Fuoss, Streiffer, Thompson, Clarke, Pindak, Stern,   PRB 2005

Interface polarization reversal ?

Towards the EFL…

Smaller and faster
→ nm : fs

High rep-rate
and tunability are
great features!!



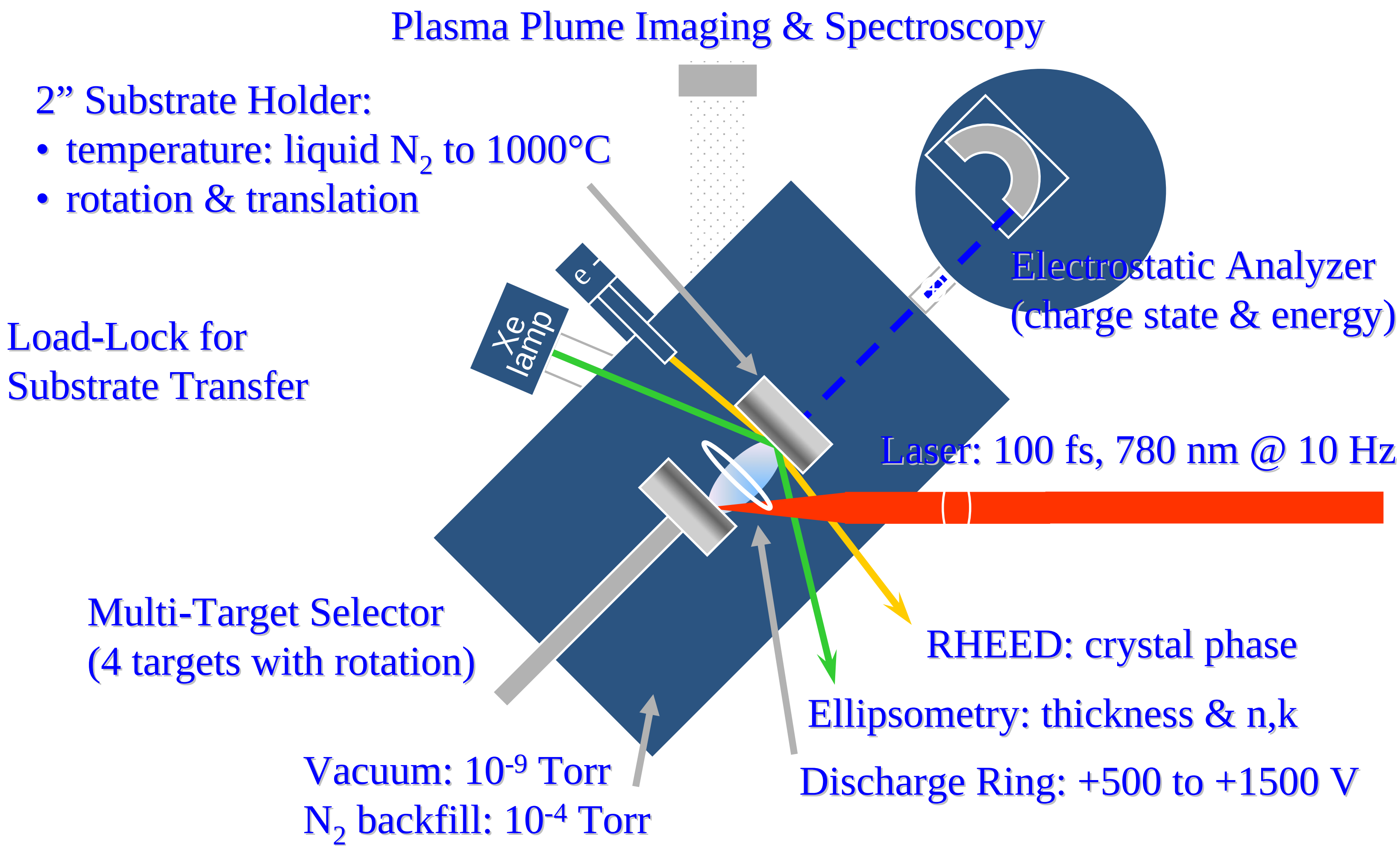
ERL characteristics for in-situ materials dynamics studies

	Short-Term Goals			Long-Term Goals		
Modes:	(A) Flux	(B) High-Coherence	(C) Short-Pulse	(D) Ultra High-Coherence	(E) Ultra Short-Pulse	Unit
Energy	5	5	5	5	5	GeV
Macropulse current	100	25	1	100	1	mA
Bunch charge	77	19	1000	77	10000	pC
Repetition rate	1300	1300	1	1300	0.1	MHz
Transverse emittance (norm. rms)	0.3	0.08	5.0	0.06	5.0	mm.mrad
Transverse emittance (geometric at 5GeV)	31	8.2	511	6.1	511	pm
Bunch length (rms)	2000	2000	50	2000	20	fsec
intrabunch Energy spread (fractional;rms)	2E-4	2E-4	3E-3	2E-4	3E-3	
Beam power	500	125	5	500	5	MW
Beam loss	< 1	< 1	< 1	< 1	< 1	μA

kW average power (fiber) lasers on the horizon (mJ/pulse at 1MHz)

USING EVERY X-RAY PHOTON

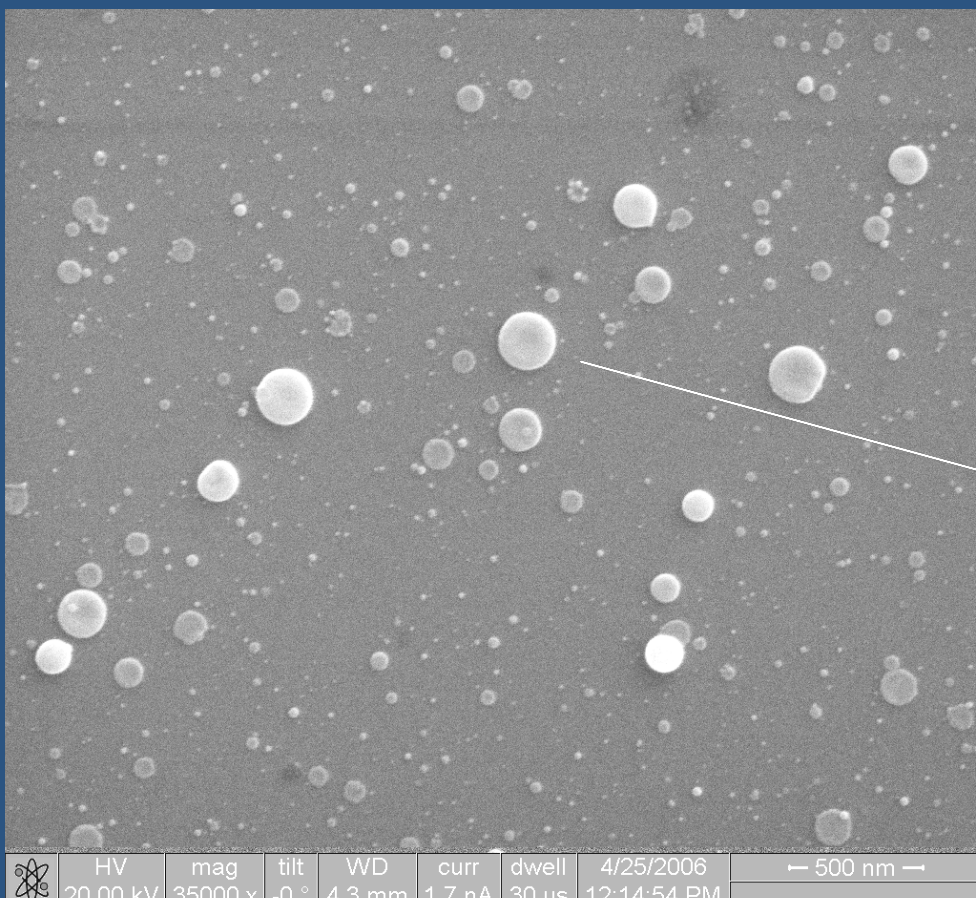
Ultrafast Laser Deposition

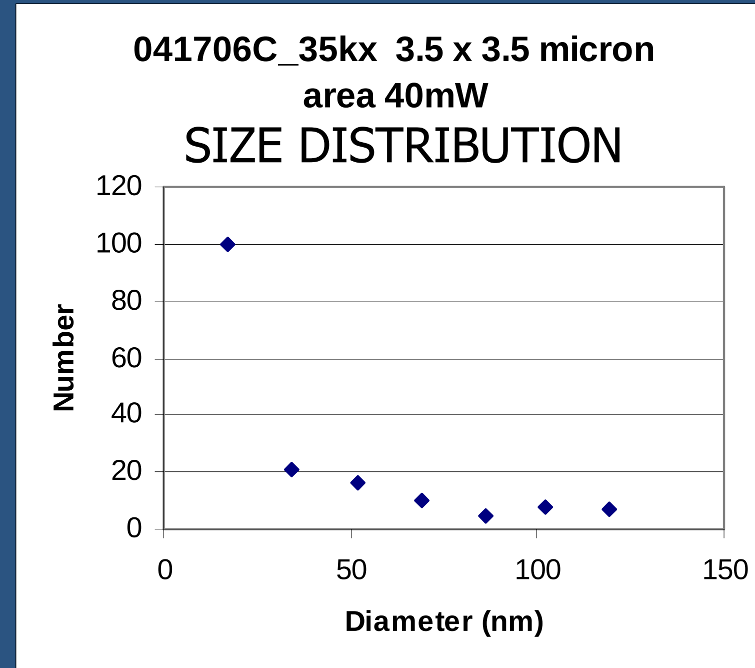


Co nano-disks on Si

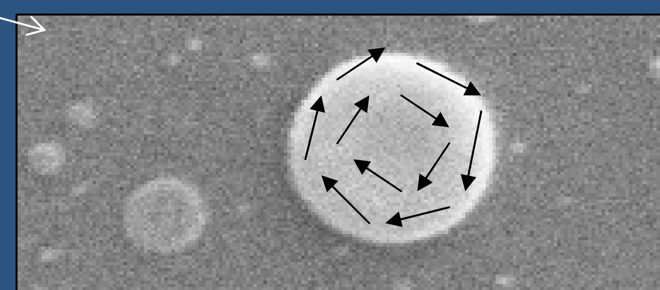
ultrafast laser deposition

810nm, 50 fs, 1mJ/pulse 1 kHz





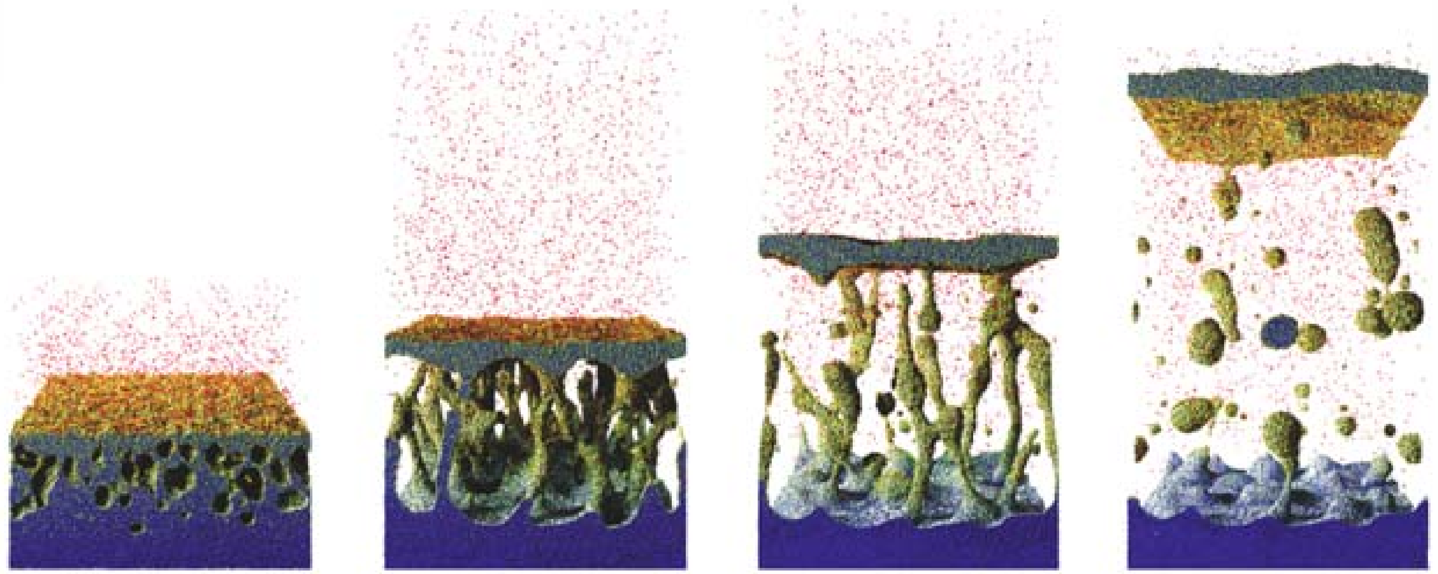
200nm



spin vortex state

35kx

Probing the initial stages of ultrafast ablation



Snapshots of MDCASK simulation of the ablation of Cu (From Gilmer et al., unpublished research)

Timescale of ERL matches simulation
Laser pump – x-ray (diffraction/XAFS) at high rep rates

Detectors !

- Investment lags source development
- Need fast, gated area detectors –badly!

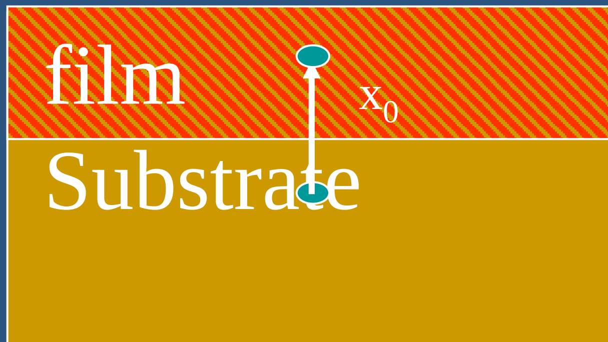
- efficient direct detection PADs
- x2 from cross-scan, more from // channels
- ≤ n sec gating
- 10^5 dynamic range
- multiple read architecture
- modular
- …..

Summary

- ERL source could enable dynamic imaging of atomic/spin motions associated with collective phenomena
(e.g. fast switching with laser impulse)

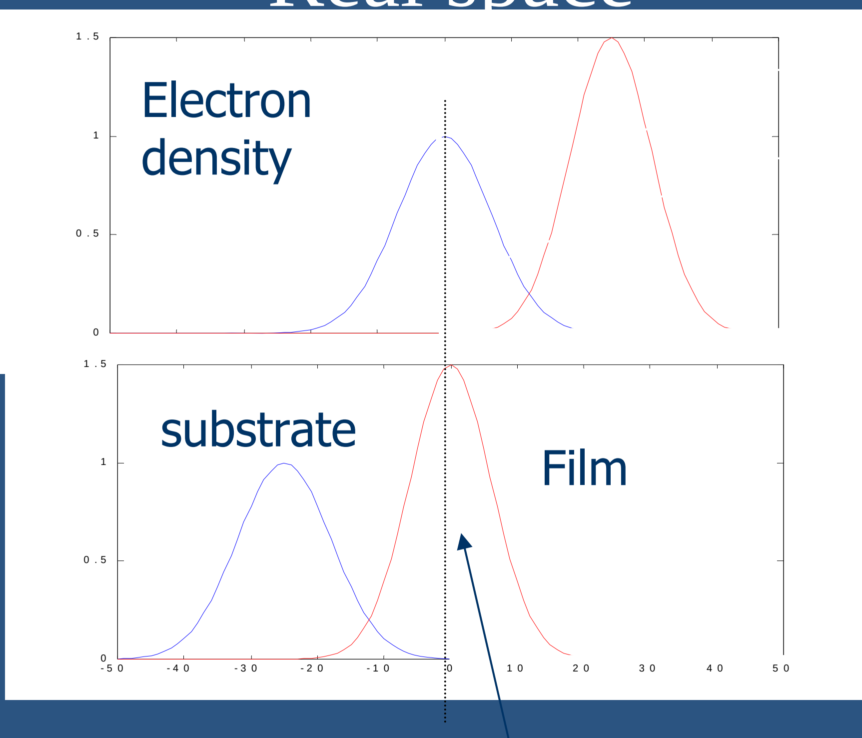
- deposition processes also, esp. for nanostructures

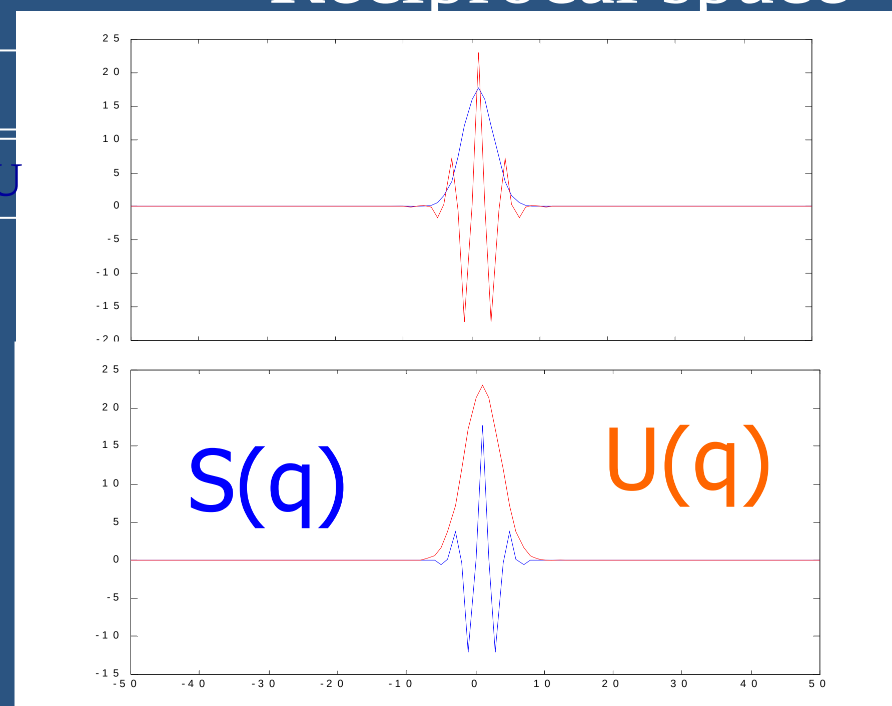
- combination of fast rep-rate and short pulse matches well to laser pump development
 (high average power fiber lasers)



Real space

Reciprocal space

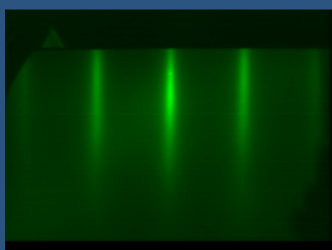




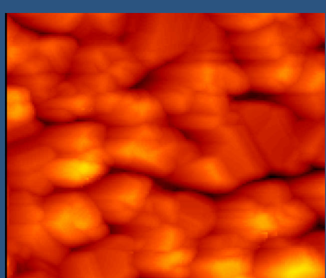
This choice of origin satisfies the COBRA approximation: slowly varying U(q)

MBE Growth and In-situ Analysis

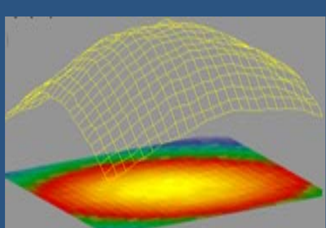
Integrated MBE/RHEED/STM/MOS capabilities:



RHEED: Real-time surface structure characterization (annealing)



STM: surface morphology, roughness, coarsening



MOSS: curvature mapping gives mismatch strain information.

Typical Growth Conditions

GaSb on InAs T_{sub}= 450C

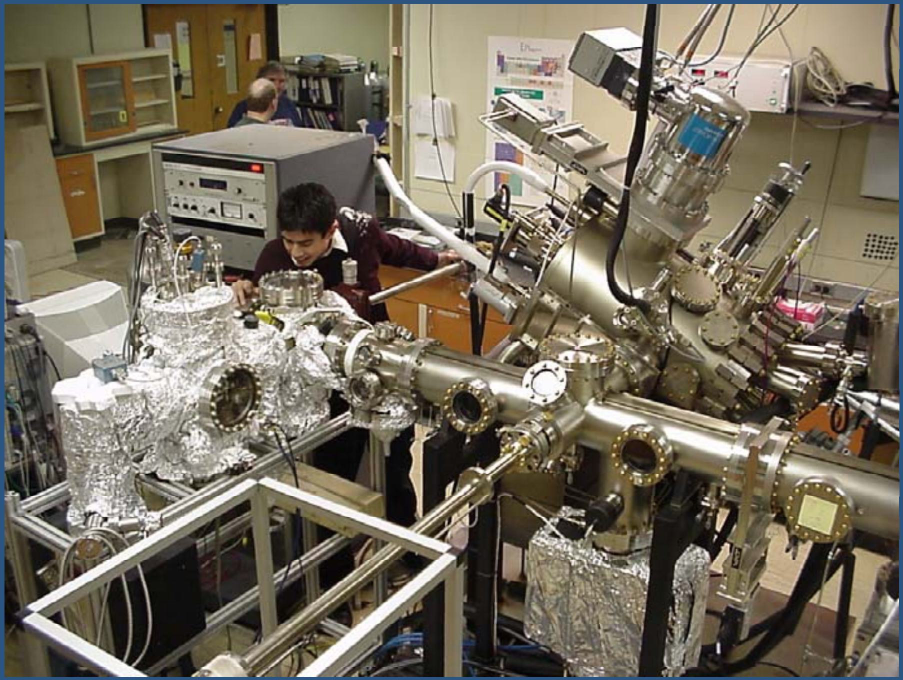
GaSb 9ML MBE (30sec)

Ga/Sb 1ML/1ML MEE (3s/2s)

Sb 1ML MEE (2s)

In 1ML MEE (2s)

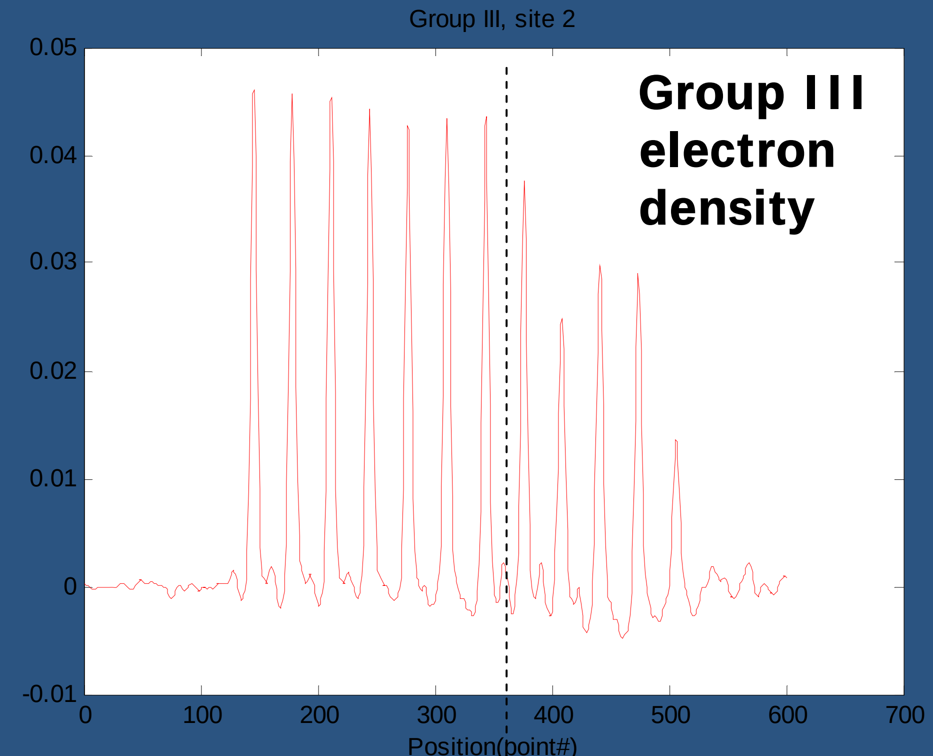
InAs 0.2 micron



Combined MBE growth chamber and STM chamber. Mirecki Millunchick Lab, University of Michigan

In-situ: k-Space Associates KSA 400 and MOSS

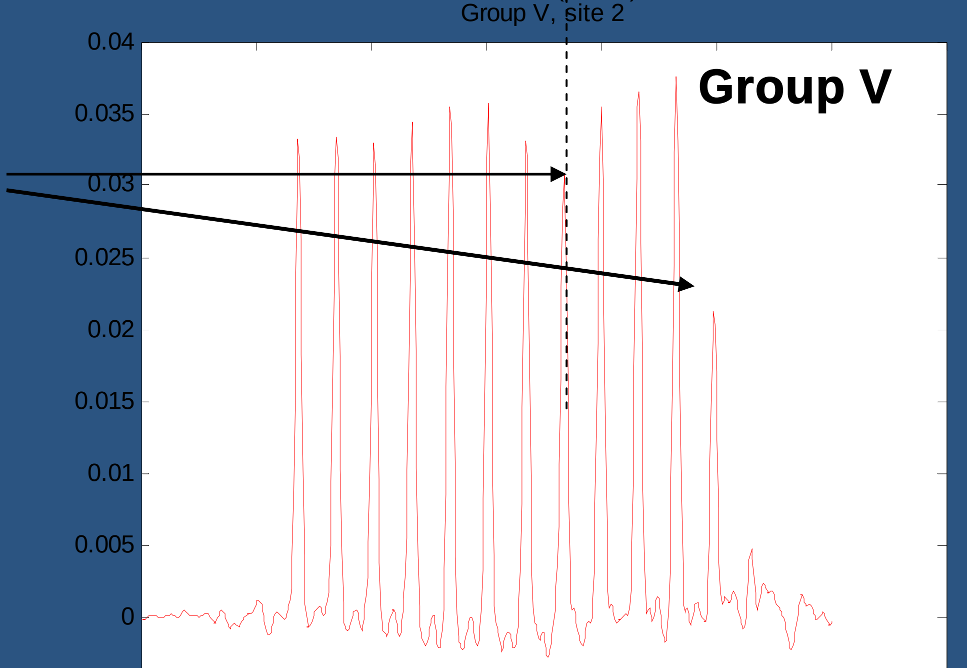
Sample 814 GaSb on InAs



In = 49
Ga = 31

Exp ratio ~ 1.6
Ideal = 1.6

Accumulation of As at interface



As = 33
Sb = 51

Exp ratio ~ 1
Ideal = 0.65