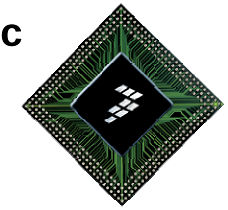
Metrology of Silicide Contacts for Future CMOS

Stefan Zollner, Rich Gregory, Mike Kottke, Victor Vartanian, Xiang-Dong Wang, Michael Canonico, David Theodore, Peter Fejes, Mark Raymond, Xiaoyan Zhu, Dean Denning, Scott Bolton, Kyuhwan Chang, Ross Noble, Mo Jahanbani, Marc Rossow, Darren Goedeke, Stan Filipiak, Ricardo Garcia, Dharmesh Jawarani, Bill Taylor, Bich-Yen Nguyen, Phil Crabtree, Aaron Thean
Freescale Semiconductor, Inc., ATMC, Austin, TX 78721



2007 Int. Conference on Frontiers of Characterization and Metrology for Nanoelectronics
Gaithersburg, MD, March 28, 2007

freescale™
semiconductor

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2007.

Outline

Current silicide device topics

- **NiSi contacts** for 45nm and 32nm CMOS
- Fully silicided gates (FUSI)
- Low-resistance Ohmic contacts (**PtSi for PMOS**, $ErSi_2$ for NMOS, etc)
- Schottky-barrier S/D devices
- Barrier height tuning by interface engineering

(1) Metal thickness metrology using x-ray fluorescence (XRF)

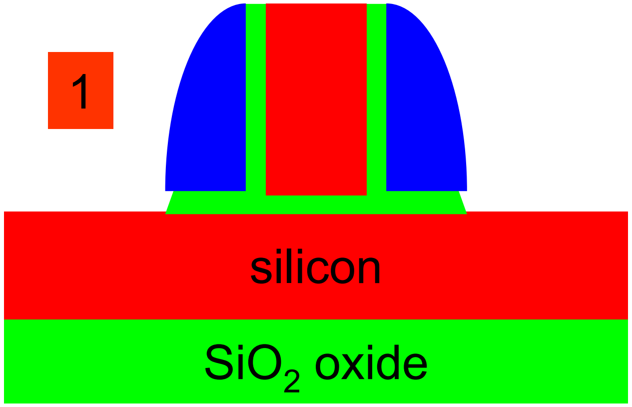
- Why XRF?
- XRF standards (RBS, TEM, etc)
- XRF results and issues

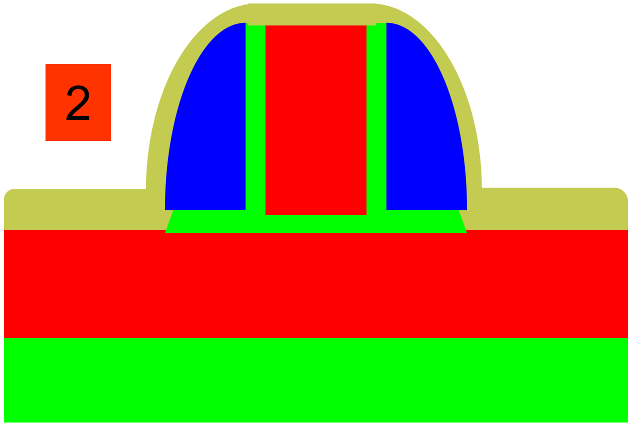
(2) Silicide materials properties

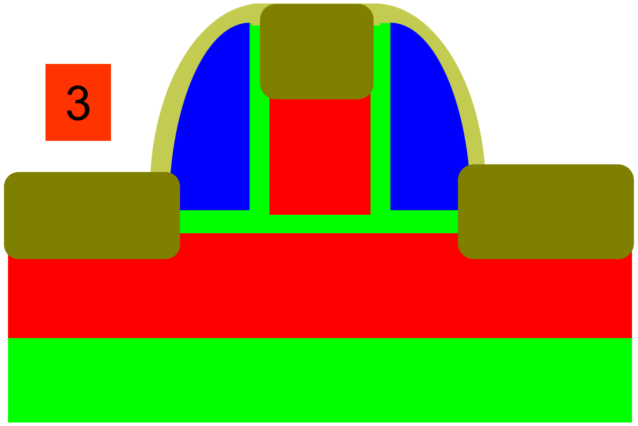
- Transformation and crystal structure (X-ray diffraction)
- Depth profiles (Auger spectrometry)
- Influence of surface preparation (X-ray reflectivity)

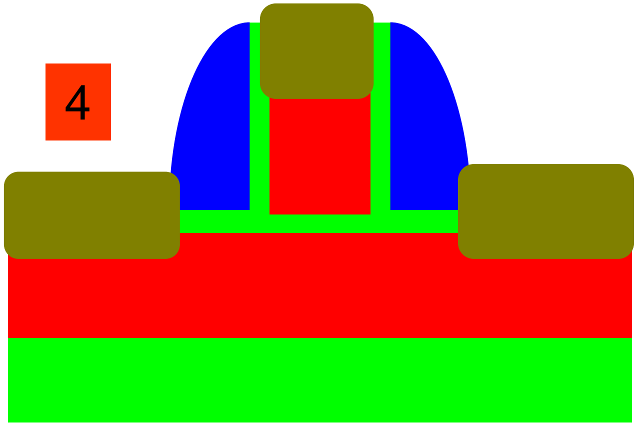
Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Self-aligned silicide (salicide) formation process flow



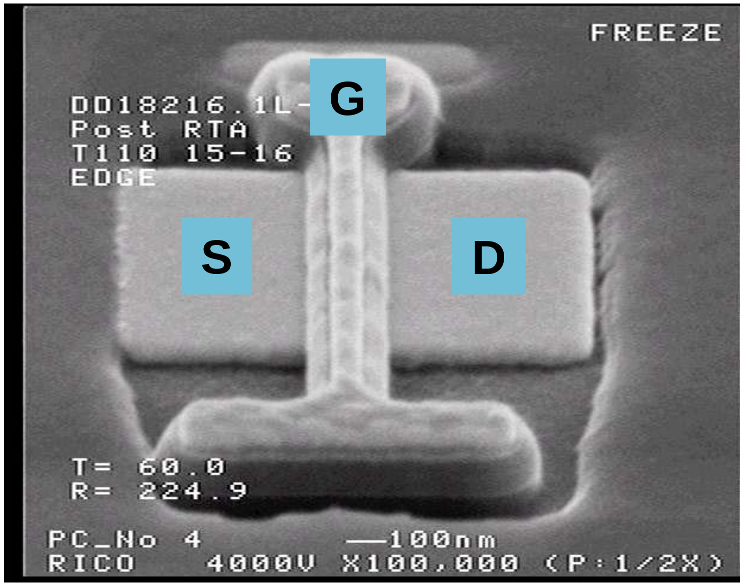






1. Silicide preclean
2. Blanket metal deposition
3. Silicide anneal
4. Selective etch

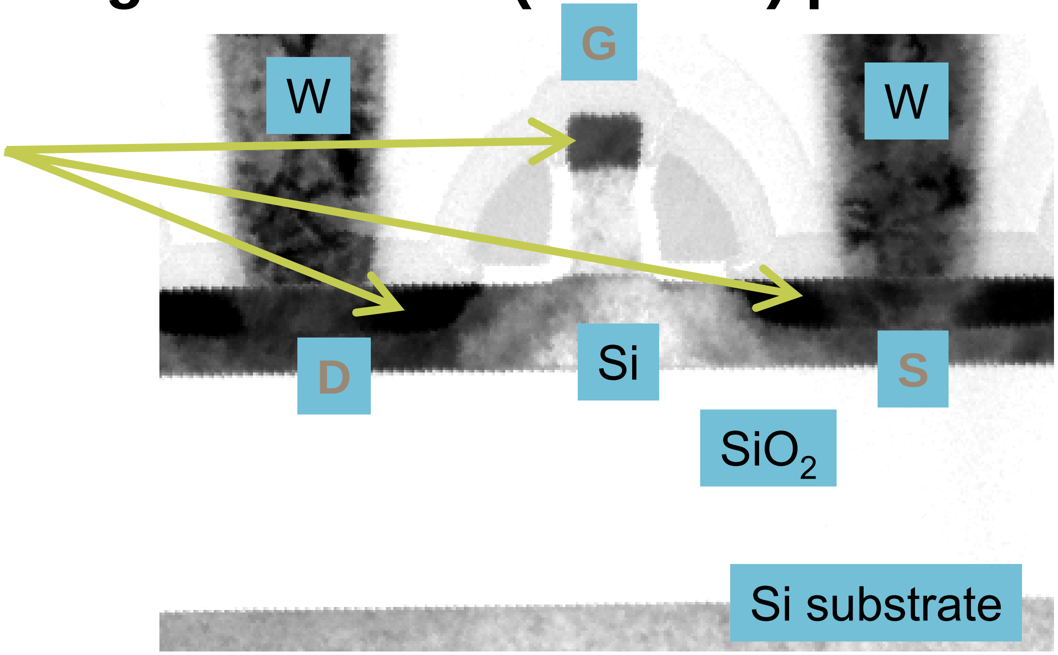
- Silicide anneal



Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Self-aligned silicide (salicide) process

1. Blanket metal deposition
2. Thermal annealing (RTA1)
3. Selective etch to remove unreacted metal
4. Thermal annealing (RTA2)

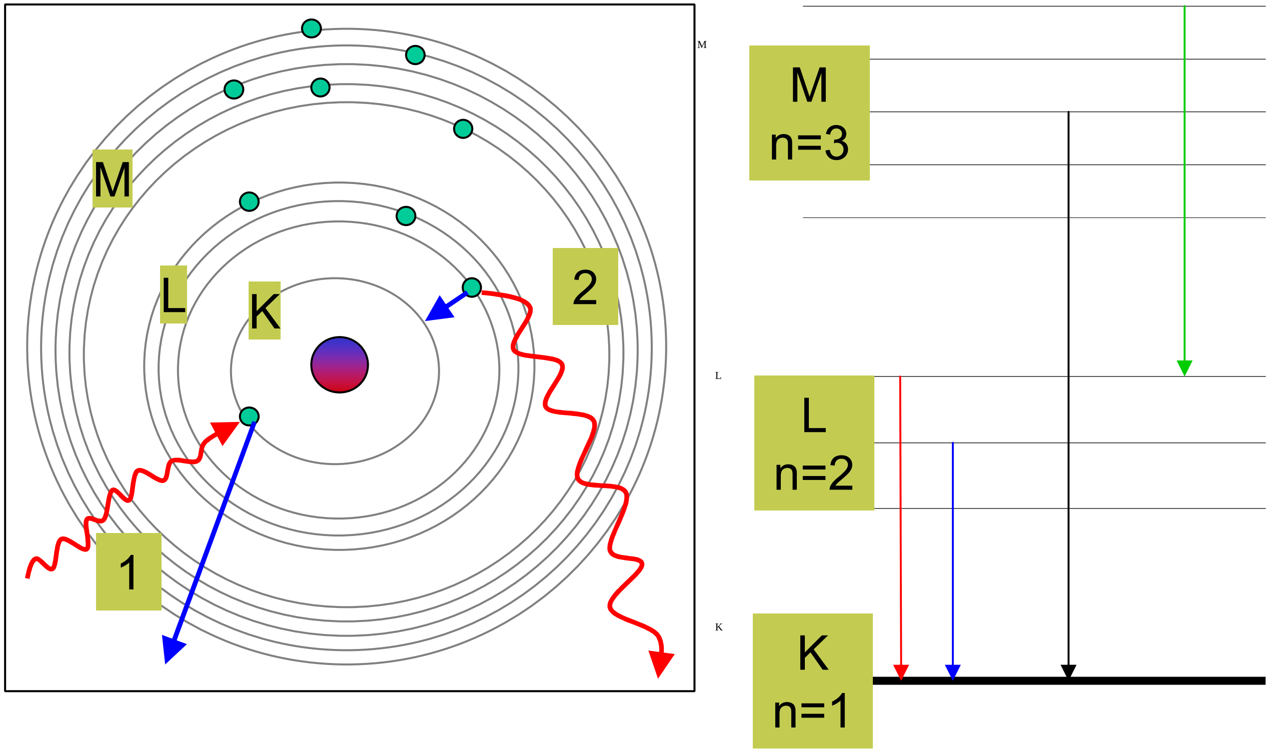


Process issues needing metrology:

- Process control for **blanket metal film thickness (~10 nm)**
- Formation of thin silicide on narrow active and poly **lines** (<50 nm)
- Optimizing the silicide **preclean** process (ICMI 2006, UCPSS 2006)
- Choosing **anneal** temperature and time (ICMI 2006, MAM 2006)
- **Selective etch** development (ICMI 2006)

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF Measurement Principle



$$E_K - E_{L_3} \Rightarrow K\alpha_1$$

$$E_K - E_{L_2} \Rightarrow K\alpha_2$$

$$E_K - E_{M3} \Rightarrow K\beta_1$$

$$E_{L_3} - E_{M_5} \Rightarrow L\alpha_1$$

(1) A primary x-ray photon ejects an electron from an inner shell, leaving behind a hole.
(2) This hole is filled by an electron from an outer shell, leading to the emission of a secondary characteristic x-ray photon.

Source: Dileep Agnihotri, Jesus Gallegos, Jeremy O’Dell

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Thin-film metrology for metals: Why XRF?

Why not ellipsometry?

Proven optical thin-film metrology techniques such as ellipsometry or reflectometry measure **transparent films** such as dielectrics or thin silicon. They do not work well for metals (including silicides).

Why X-ray fluorescence (XRF)?

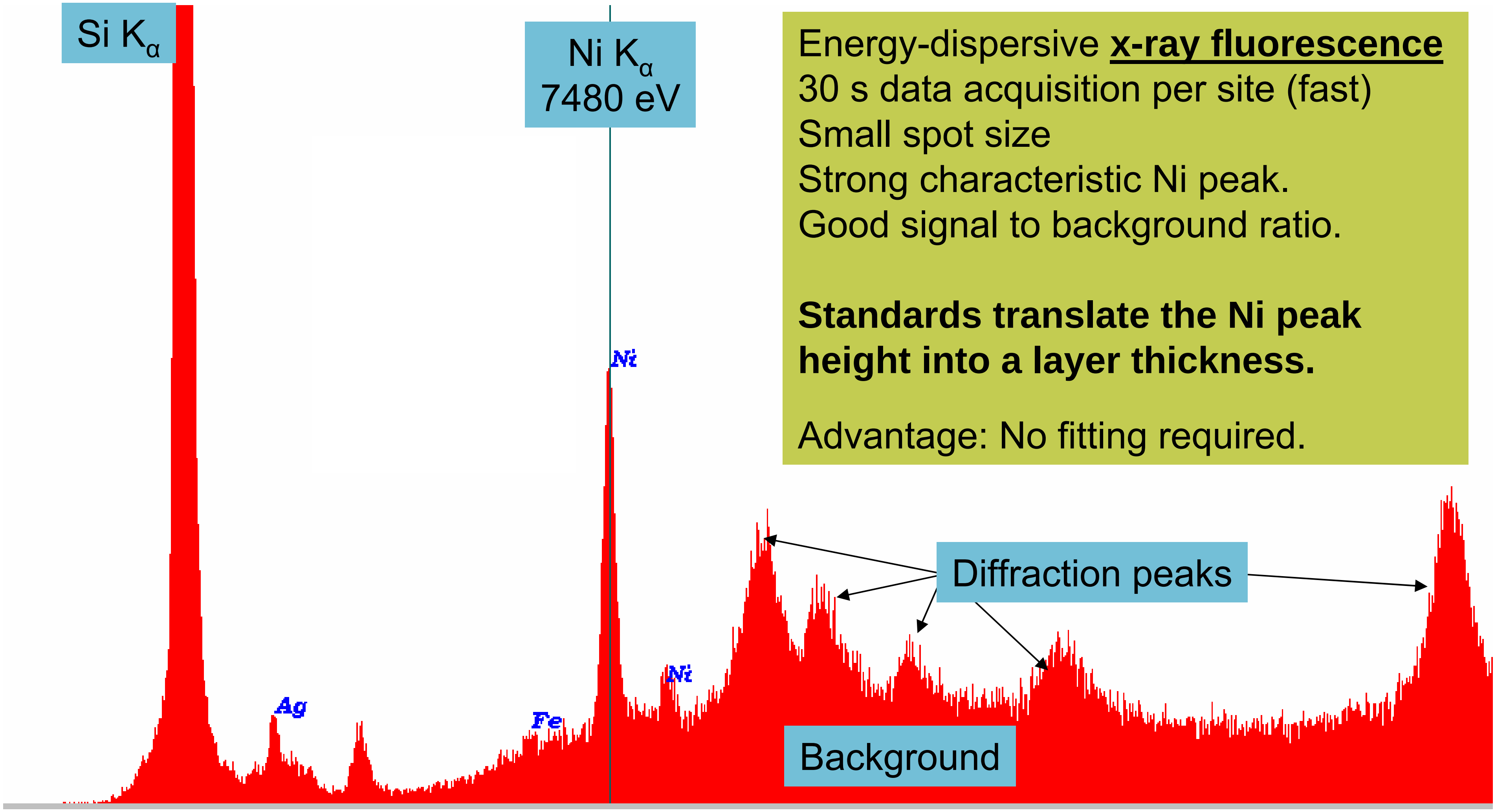
- Commercial fab tools available.
- High throughput (10 s per site for 10 nm Ni)
- Small spot size (~50 µm) with pattern recognition achievable
- Robust (areal density independent of chemical composition)
- No fitting or models required.

What are XRF issues?

- XRF needs standards
- Interference issues (different element, same peak energy)
- Diffraction background depends on substrate type

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Why XRF standards? XRF spectrum for 10 nm Ni on oxide



Energy-dispersive **x-ray fluorescence**
30 s data acquisition per site (fast)
Small spot size
Strong characteristic Ni peak.
Good signal to background ratio.

Standards translate the Ni peak height into a layer thickness.

Advantage: No fitting required.

Diffraction peaks independent of notch rotation for Si (100) surface!

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF standards

XRF standards translate XRF peak intensity into film thickness.

Two standards are often sufficient:

(1) Bare Si substrate (0 nm standard)
(2) Metal film of known thickness (10 to 100 nm)

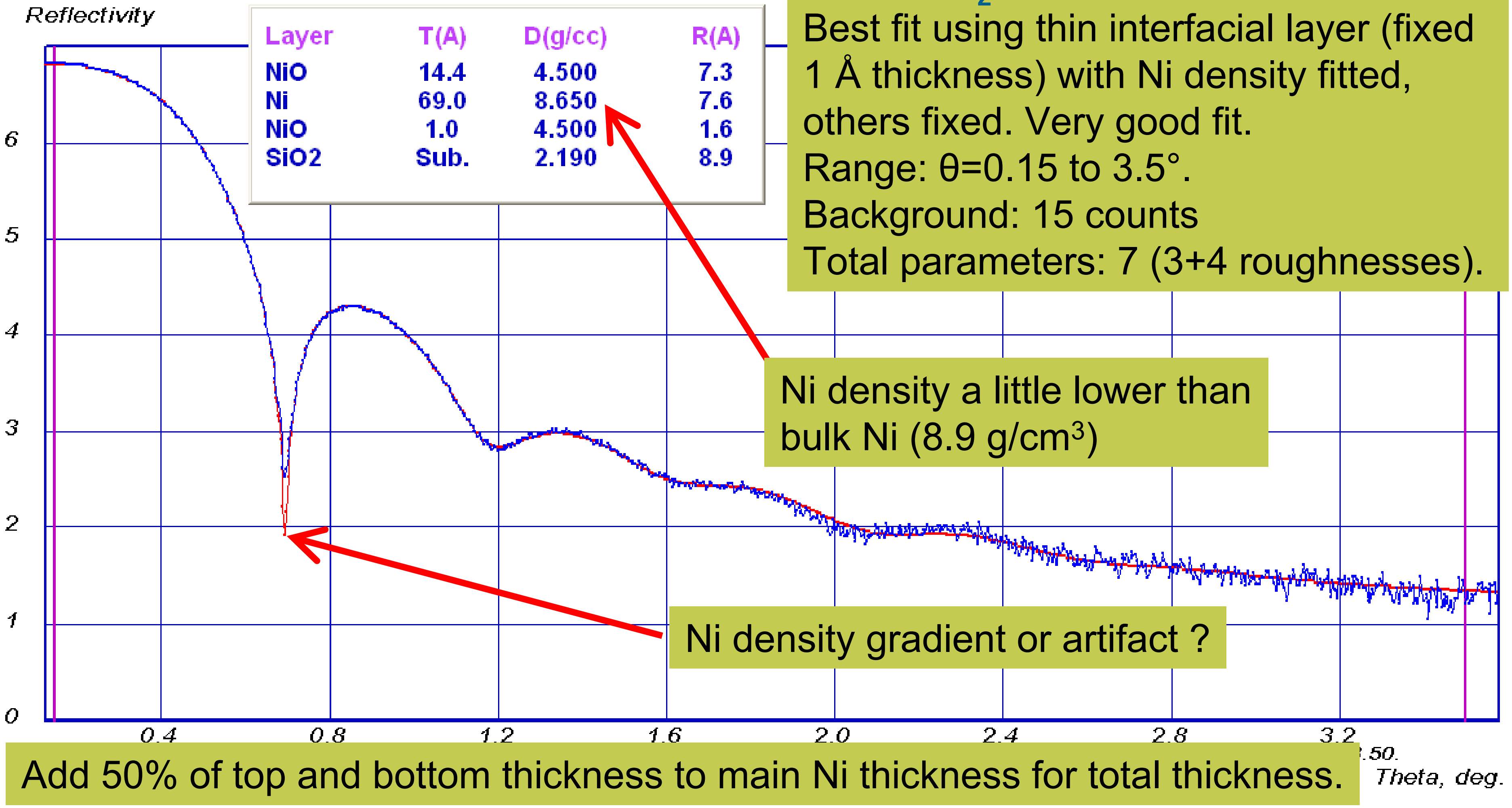
How do we obtain a metal film of “known” thickness?

(1) Does “known” mean NIST-traceable?
(2) Match other existing metrology (“golden” wafer).
(3) Sheet resistance measurement (assume bulk resistivity).
(4) SEM or TEM microscopy: Consider calibration errors!
(5) Rutherford backscattering: Very good for transition metals!
(6) X-ray reflectivity (XRR) of metal film on oxide.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

X-ray reflectivity: Ni on oxide as XRF standard

Ni on SiO_2:
Best fit using thin interfacial layer (fixed 1 Å thickness) with Ni density fitted, others fixed. Very good fit.
Range: θ=0.15 to 3.5°.
Background: 15 counts
Total parameters: 7 (3+4 roughnesses).



Layer	T(A)	D(g/cc)	R(A)
NiO	14.4	4.500	7.3
Ni	69.0	8.650	7.6
NiO	1.0	4.500	1.6
SiO2	Sub.	2.190	8.9

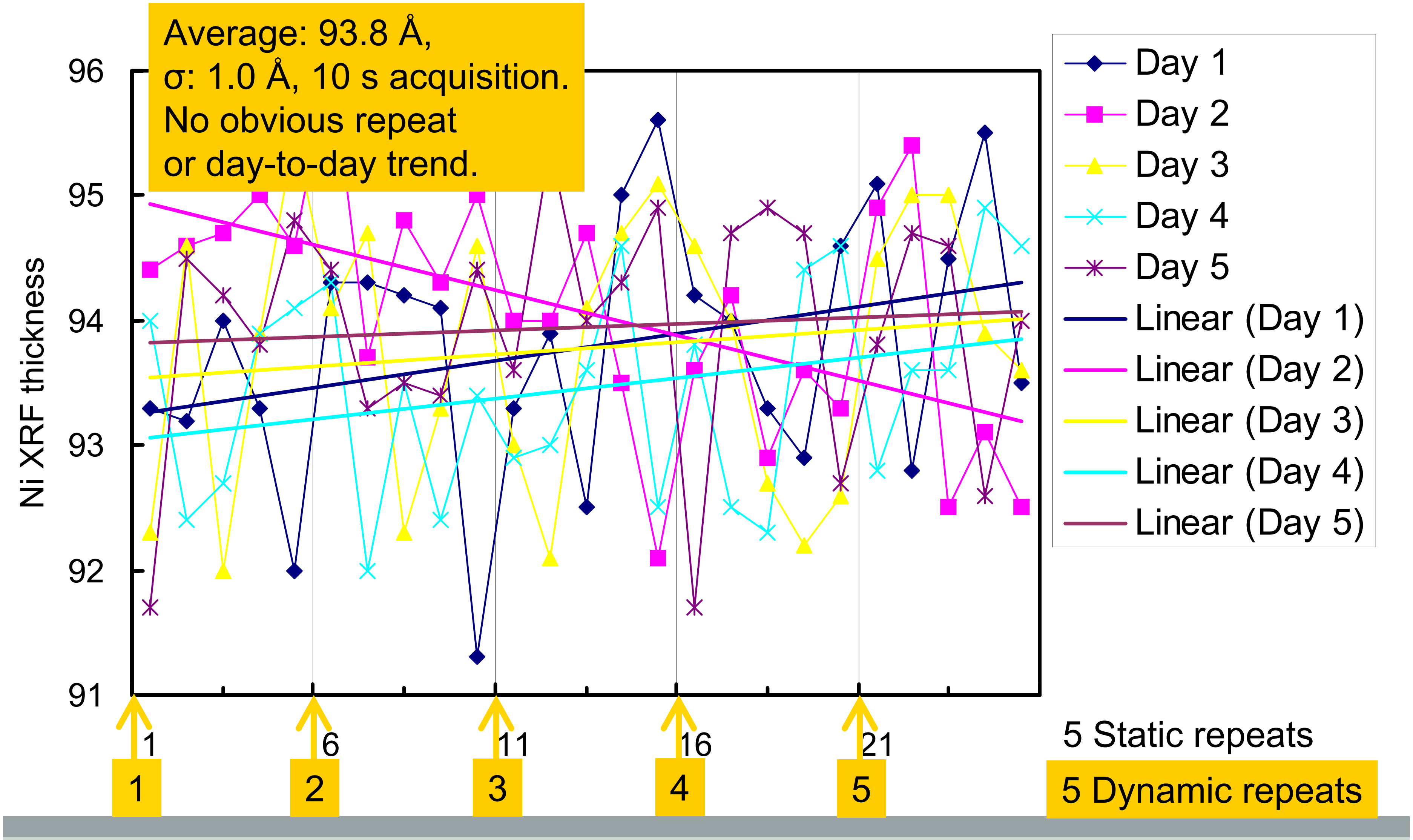
Ni density a little lower than bulk Ni (8.9 g/cm^3)

Ni density gradient or artifact ?

Add 50% of top and bottom thickness to main Ni thickness for total thickness.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF measurement results: 10 nm Ni on SiO$_2$



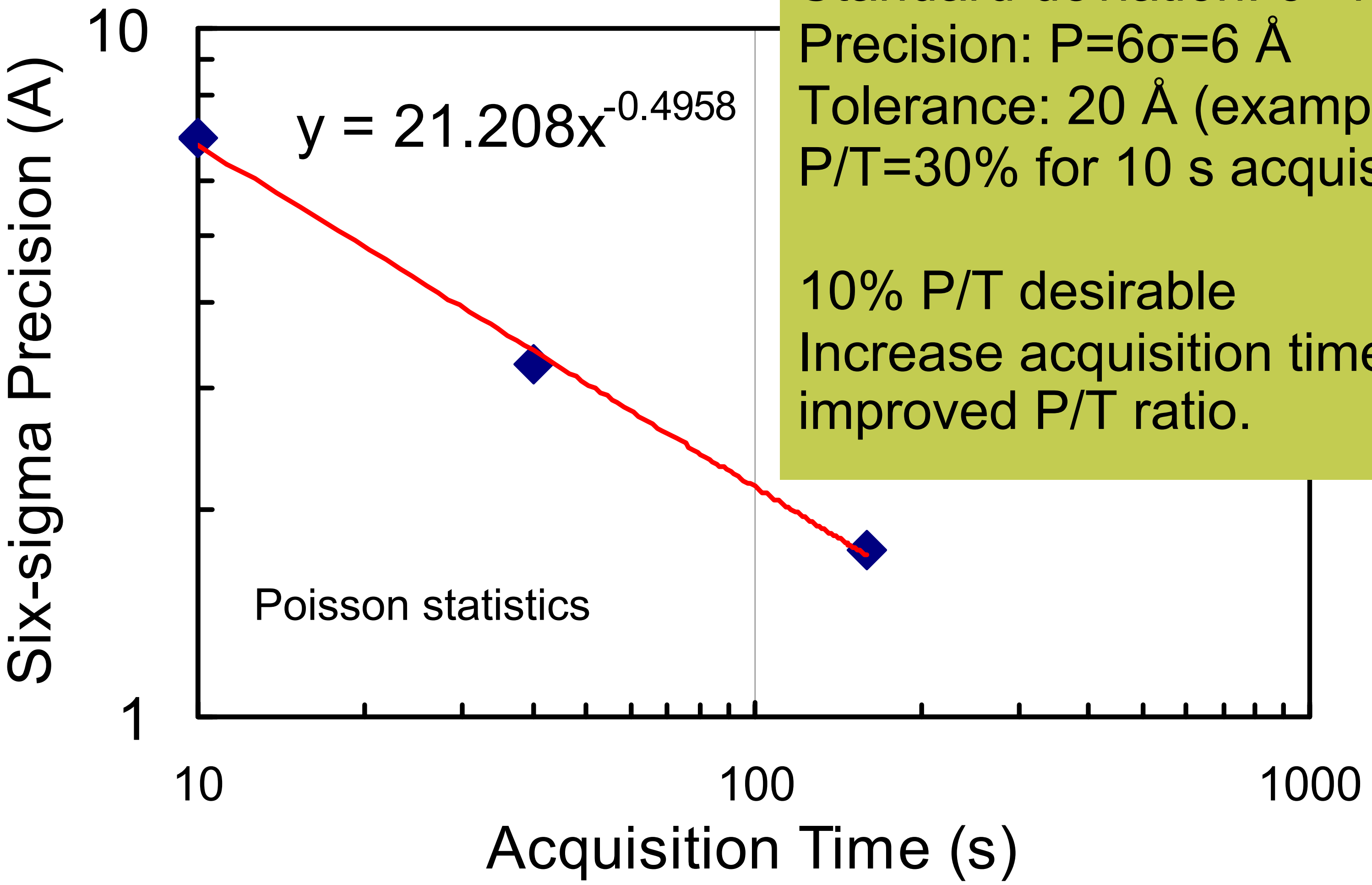
Average: 93.8 Å,
σ: 1.0 Å, 10 s acquisition.
No obvious repeat
or day-to-day trend.

5 Static repeats

5 Dynamic repeats

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF Precision is shot-noise limited

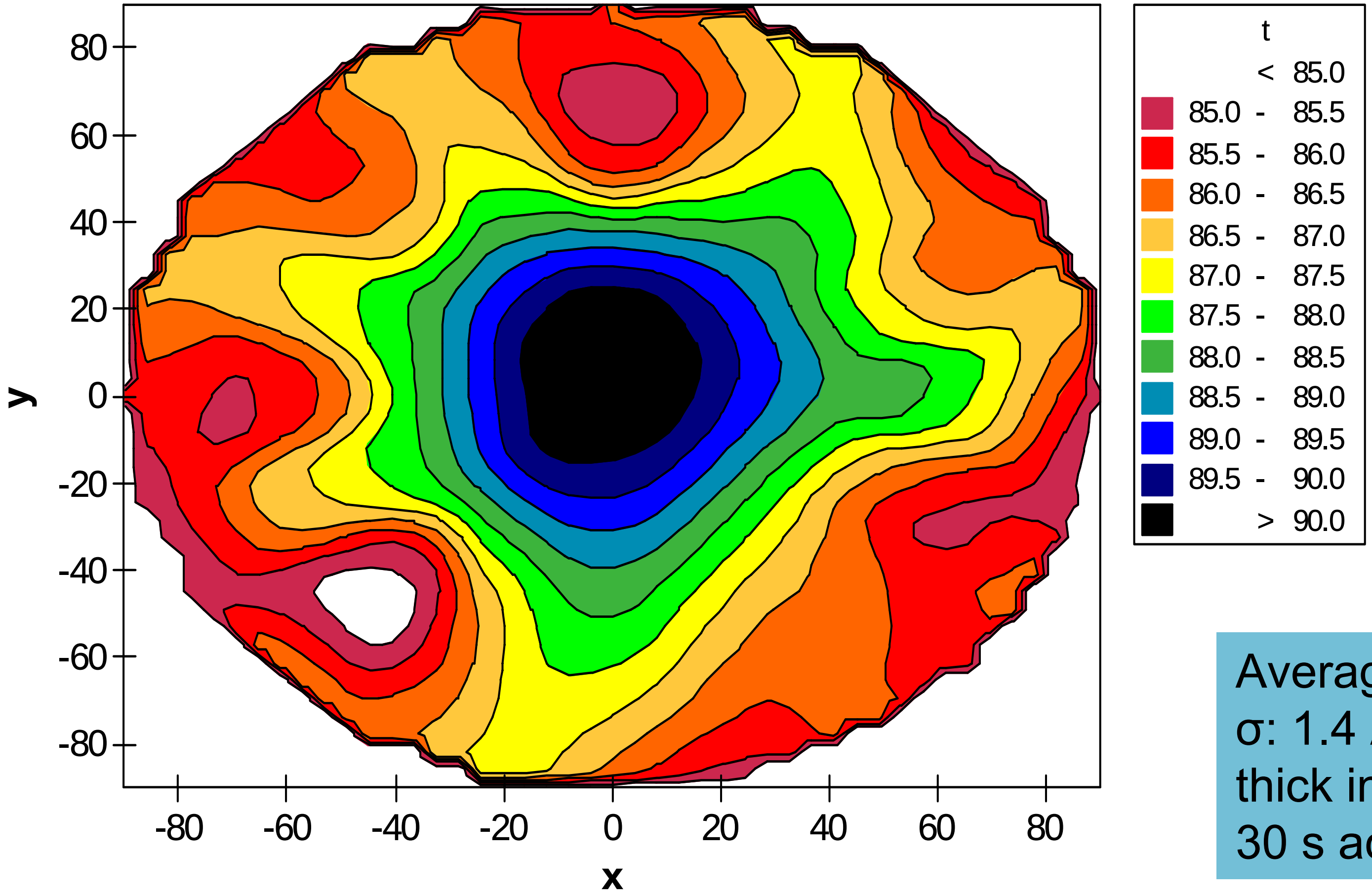


Standard deviation: $\sigma=1$ Å
Precision: $P=6\sigma=6$ Å
Tolerance: 20 Å (example)
P/T=30% for 10 s acquisition time

10% P/T desirable
Increase acquisition time for improved P/T ratio.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF application: 49-point wafer map

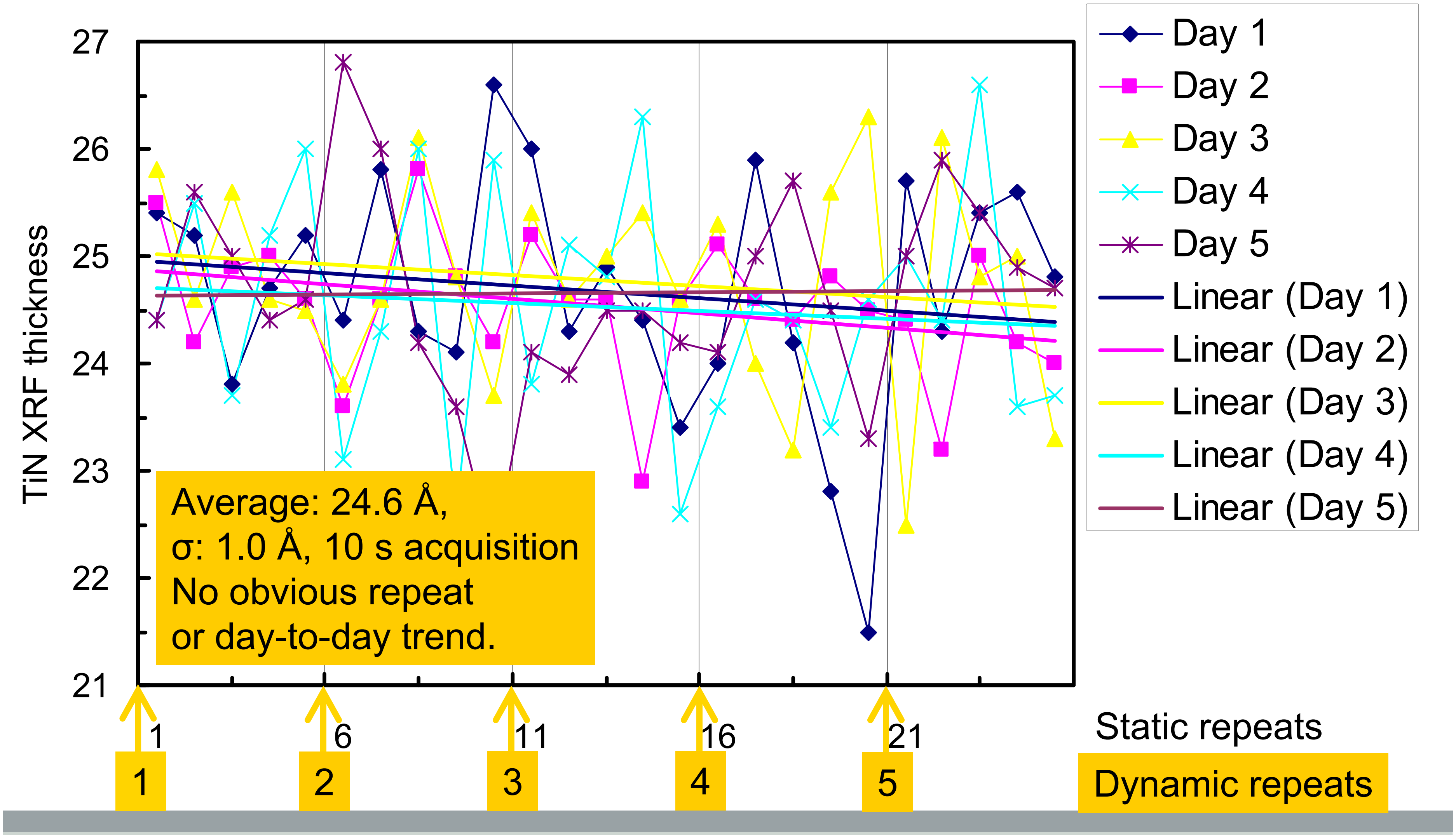


Average: 86.8 Å
σ: 1.4 Å across wafer
thick in center
30 s acquisition

49-point map with 0.5 Å contours: 9 nm Ni on oxide

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

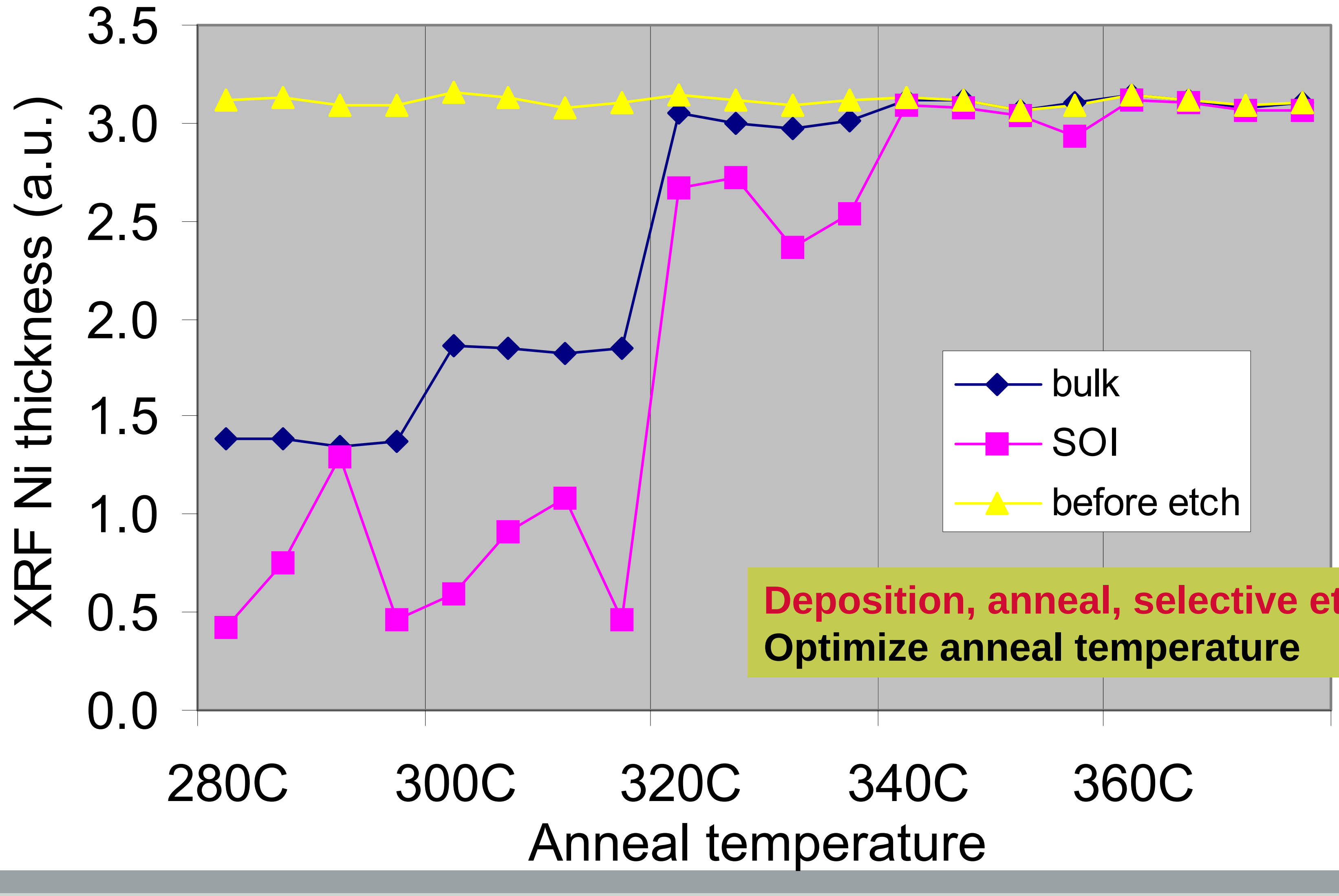
XRF measurement results: 2 nm TiN on SiO_2



Average: 24.6 Å,
σ: 1.0 Å, 10 s acquisition
No obvious repeat
or day-to-day trend.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

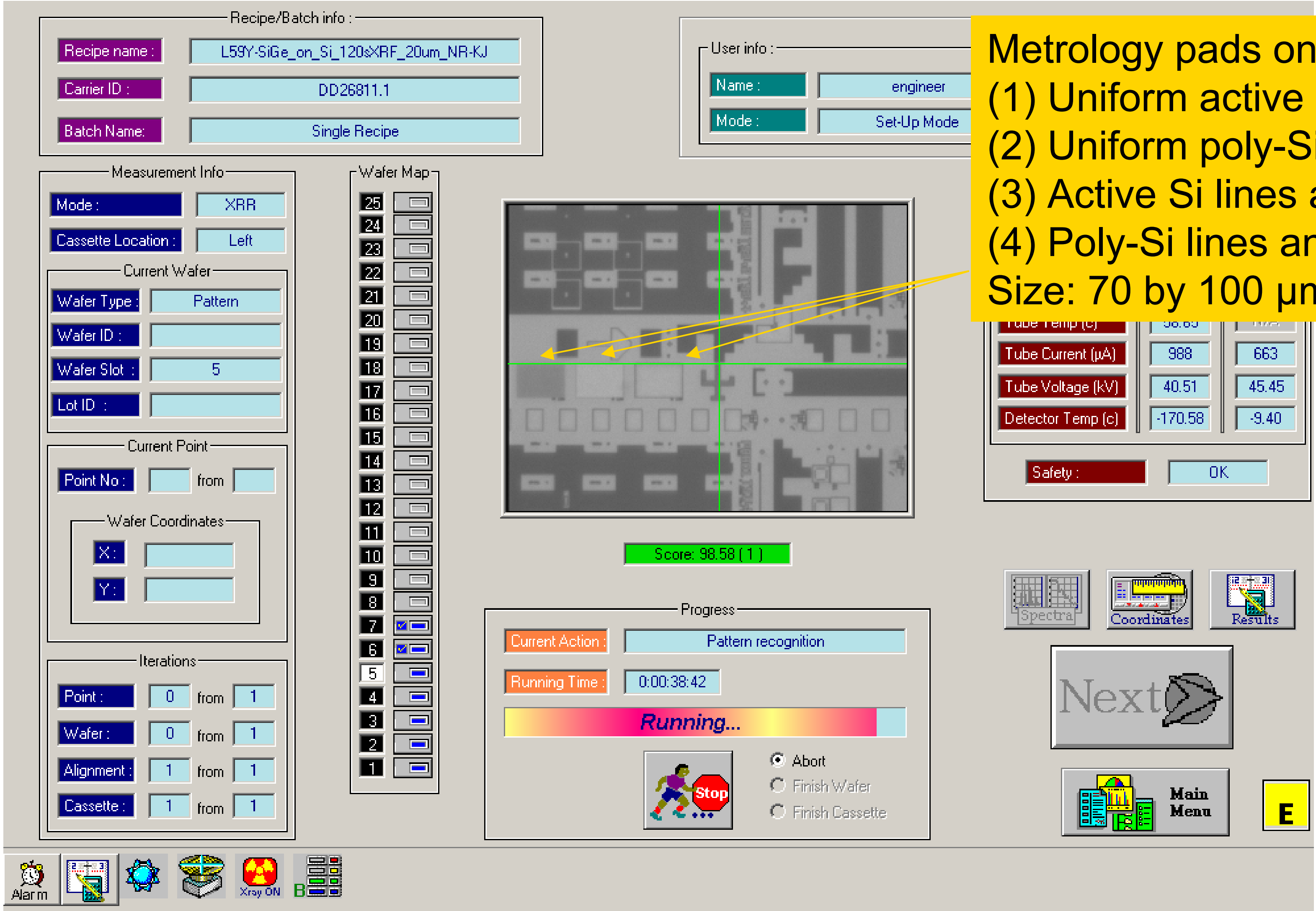
XRF application: Anneal and selective etch development



Deposition, anneal, selective etch
Optimize anneal temperature

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF application to patterned wafers



Recipe/Batch info :

Recipe name : L59Y-SiGe_on_Si_120sXRF_20um_NR-KJ
Carrier ID : DD26811.1
Batch Name: Single Recipe

User info :

Name : engineer
Mode : Set-Up Mode

Measurement Info

Mode : XRR
Cassette Location : Left

Current Wafer

Wafer Type : Pattern
Wafer ID :
Wafer Slot : 5
Lot ID :

Current Point

Point No : from

Wafer Coordinates

X :
Y :

Iterations

Point : 0 from 1
Wafer : 0 from 1
Alignment : 1 from 1
Cassette : 1 from 1

Score: 98.58 (1)

Progress

Current Action : Pattern recognition
Running Time : 0:00:38:42

Running...

● Abort
○ Finish Wafer
○ Finish Cassette

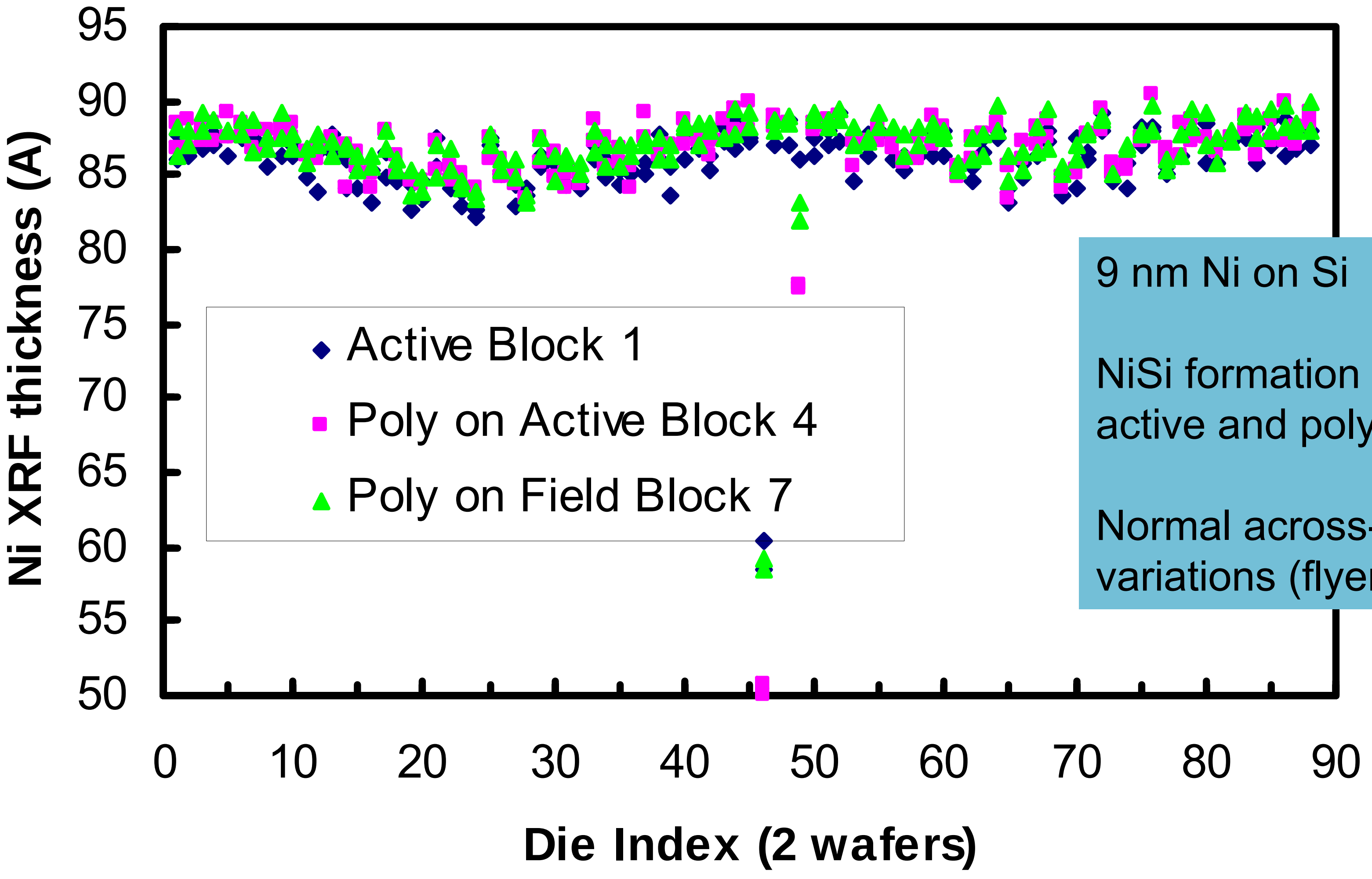
Tube Current (µA)	988	663
Tube Voltage (kV)	40.51	45.45
Detector Temp (c)	-170.58	-9.40

Safety : OK

Metrology pads on mask sets:
(1) Uniform active Si block
(2) Uniform poly-Si block
(3) Active Si lines and spaces
(4) Poly-Si lines and spaces
Size: 70 by 100 µm.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF application to patterned wafers: Uniform block



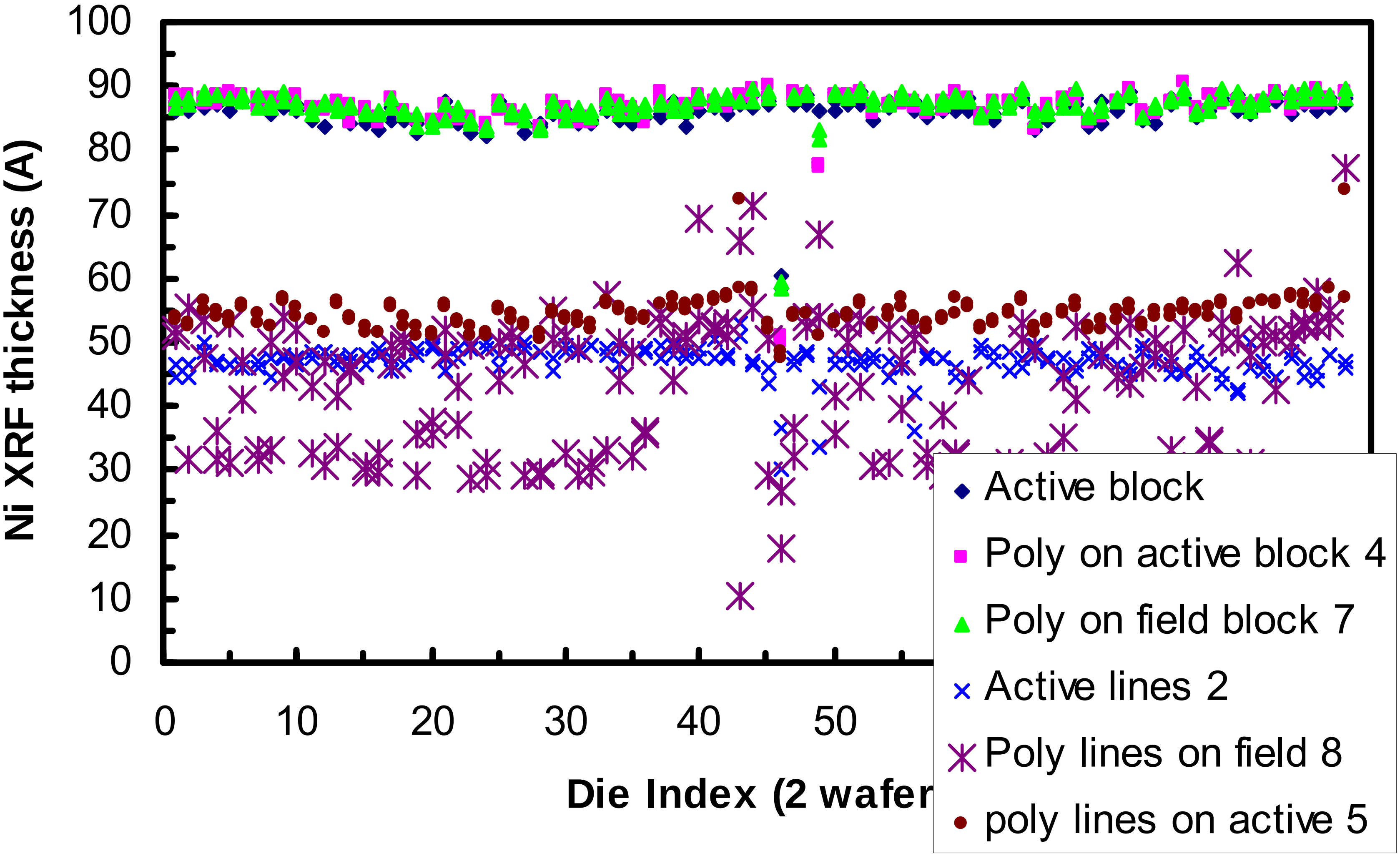
9 nm Ni on Si

NiSi formation similar on active and poly Si.

Normal across-wafer variations (flyers!).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF application to patterned wafers: Lines and spaces



Good uniformity for active Si lines and spaces.
Large variations in Ni coverage for poly-Si lines on oxide (patterning issue).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF issues

Light elements cannot be measured (Al or higher are practical).

Hard to measure low impurity levels (Example: 5% Pt in Ni)

XRF background depends on substrate choice.

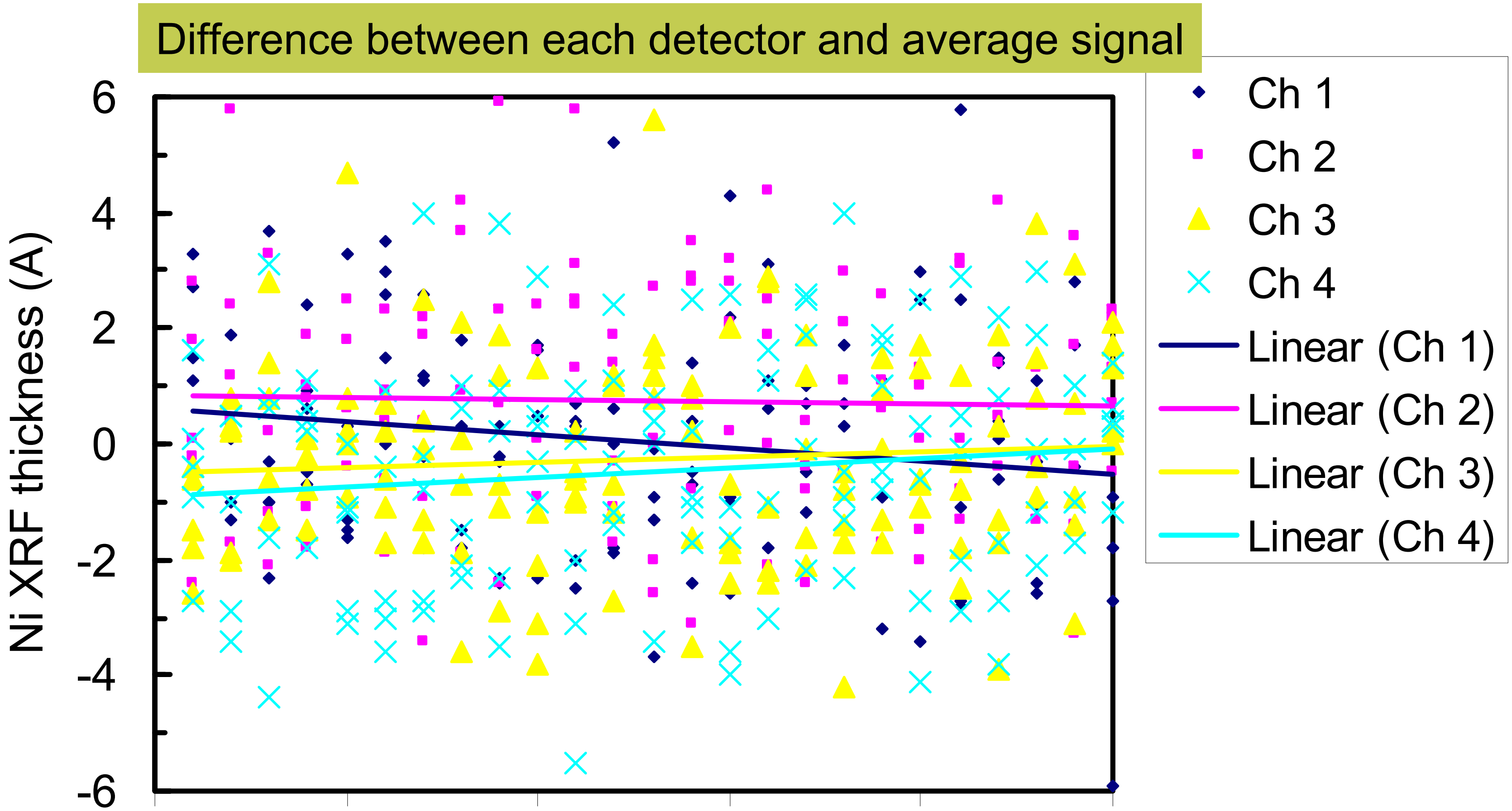
XRF is an excellent thin-film metrology technique, because
XRF does not get confused by details of materials science, such as

- Chemical reactions
- Chemical composition
- Surface and interface effects
- Crystal structure
- Crystal orientation and texture
- Interdiffusion of layers
- Surface roughness and agglomeration (evenly distributed across surface?)

This lack of sensitivity is also a limitation for XRF!

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

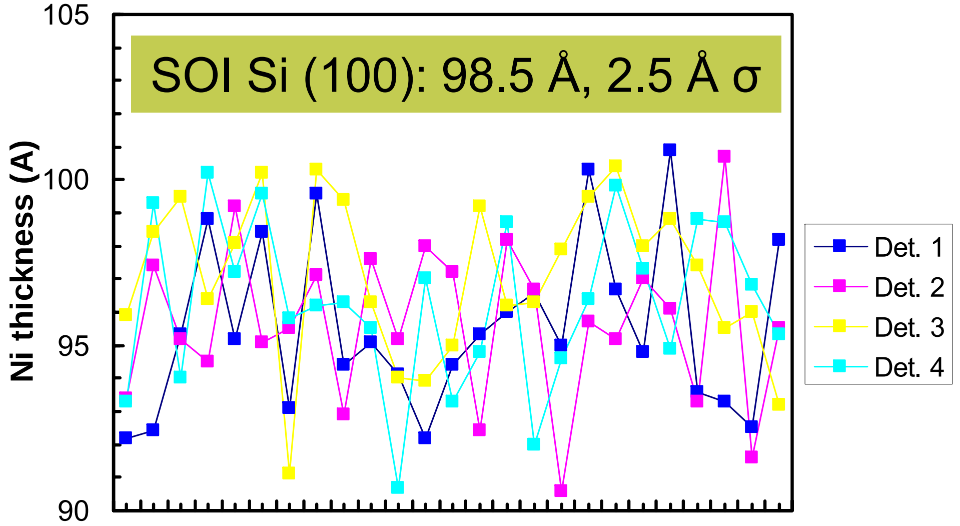
XRF experimental setup: Four detectors improve throughput

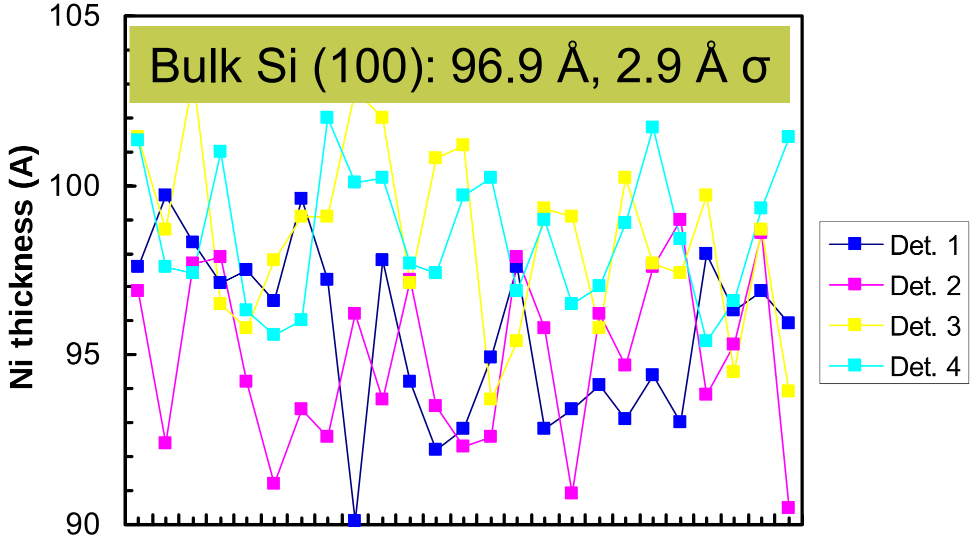


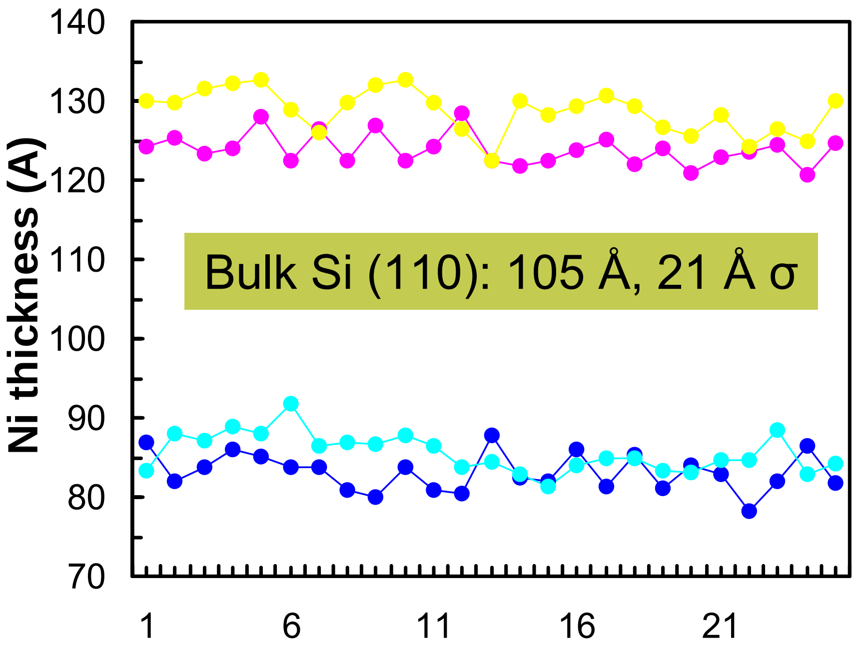
Random variations (up to ±5 Å, with σ=2 Å) between each detector and the average.
Systematic differences between four detector channels are smaller than 1 Å.
These measurements performed for Ni film on Si (100) surface (symmetric diffraction).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

XRF issues: Diffraction varies with surface orientation


SOI Si (100): 98.5 Å, 2.5 Å σ


Bulk Si (100): 96.9 Å, 2.9 Å σ

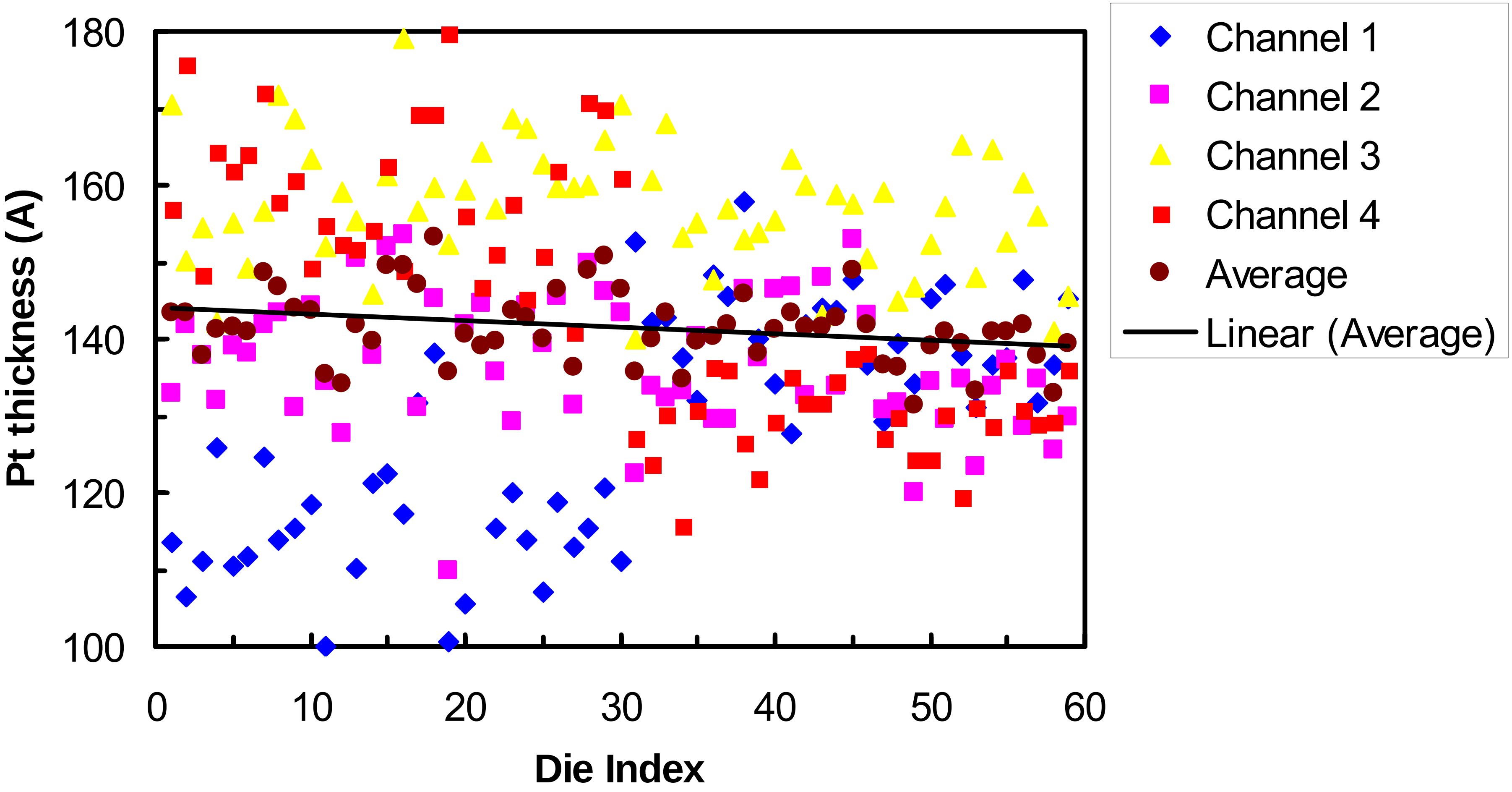

Bulk Si (110): 105 Å, 21 Å σ

Recipe optimized for Ni on Si (100) does not work for Ni on Si (110).

Similarly: Bare Si and TEOS test wafers show different results than Si test wafers with silicon nitride.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

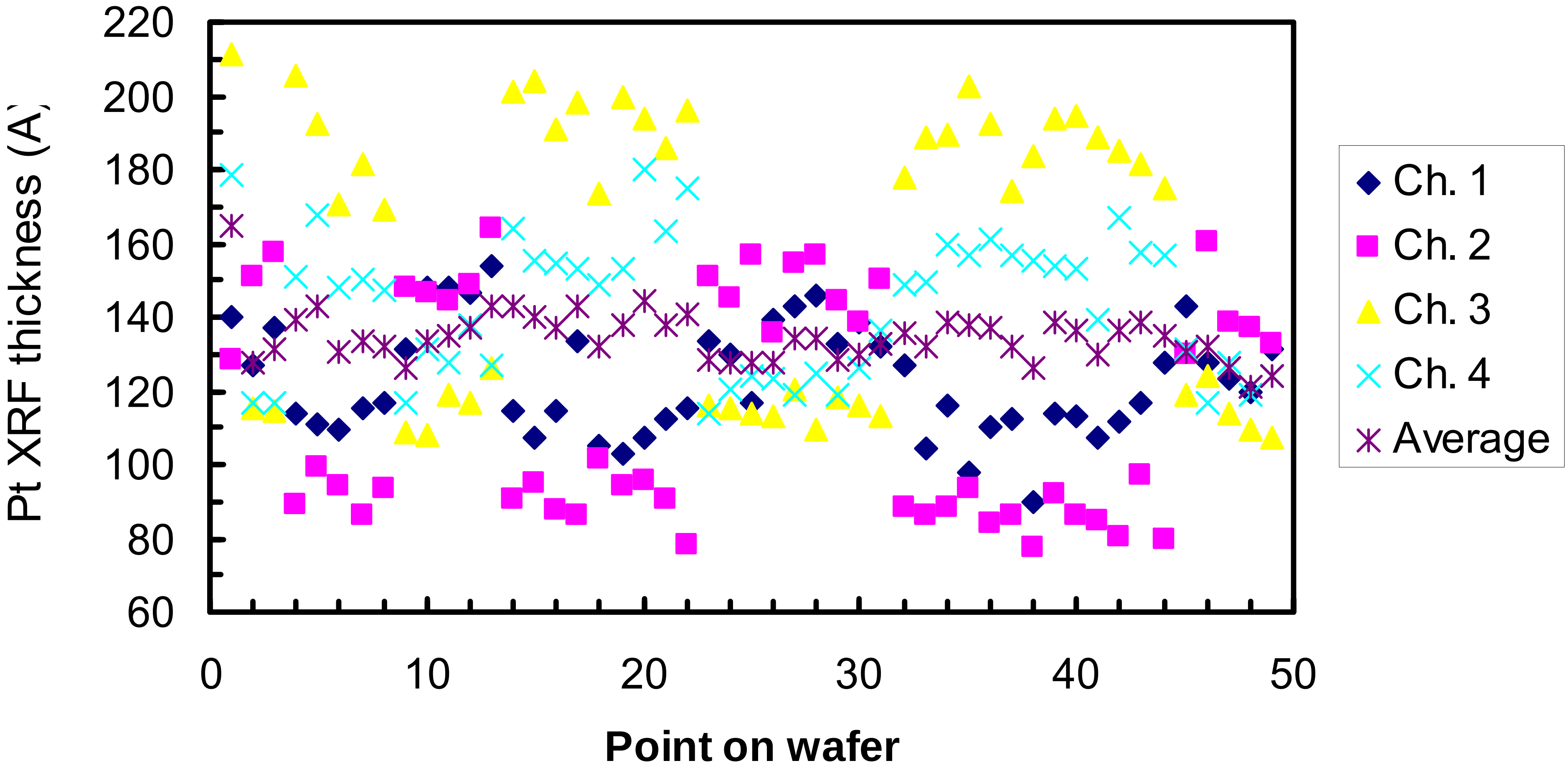
Pt thickness from XRF (patterned wafer)



Channel 2 and 3 signal independent of die and similar to average.
Channels 1 and 4 are high/low and show variation by die (instrument artifact).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

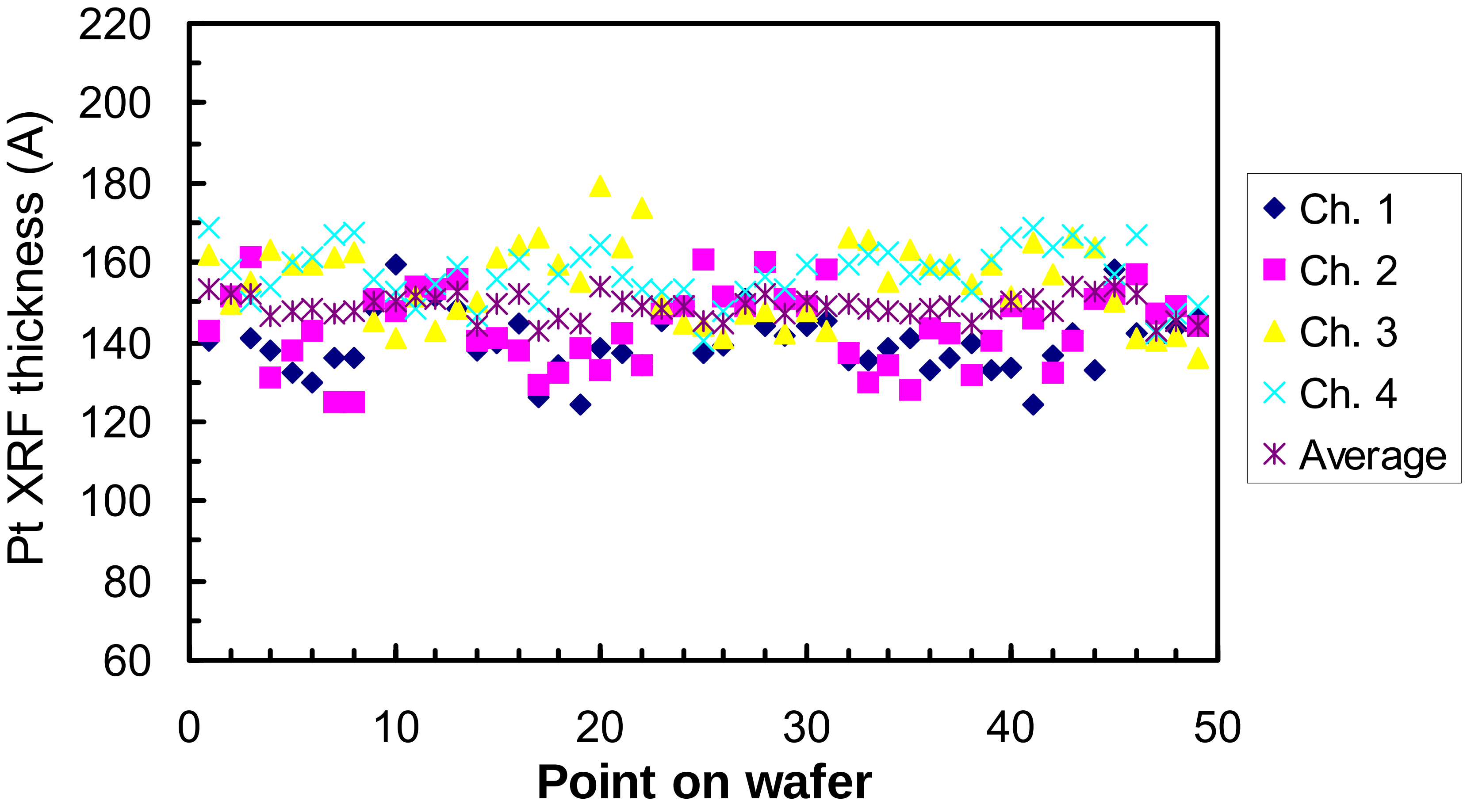
Pt thickness from XRF (blanket wafer)



Channel 2 and 3 signal independent of location and distributed around average.
Channels 1 and 4 are high/low and show variation by point (instrument artifact).
No background subtraction was used.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Pt thickness from XRF (blanket wafer)



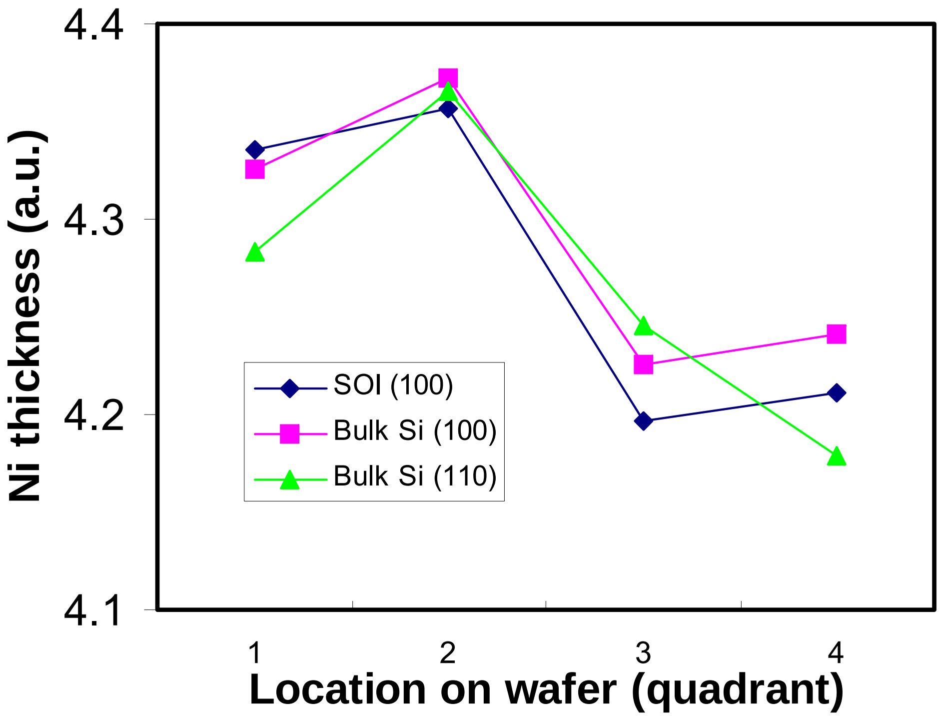
With background subtraction and digital filtering to find the peaks, the data look much cleaner, but there are still large variations.
Four-channel σ=11 Å. After averaging: σ=3 Å.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Wavelength-dispersive XRF

Wavelength dispersive XRF uses an x-ray crystal monochromator:

- Higher resolution
- Much larger spot size (~10 mm)
- Much lower throughput (5 min per data point)
- Less susceptible to background variations or interferences.



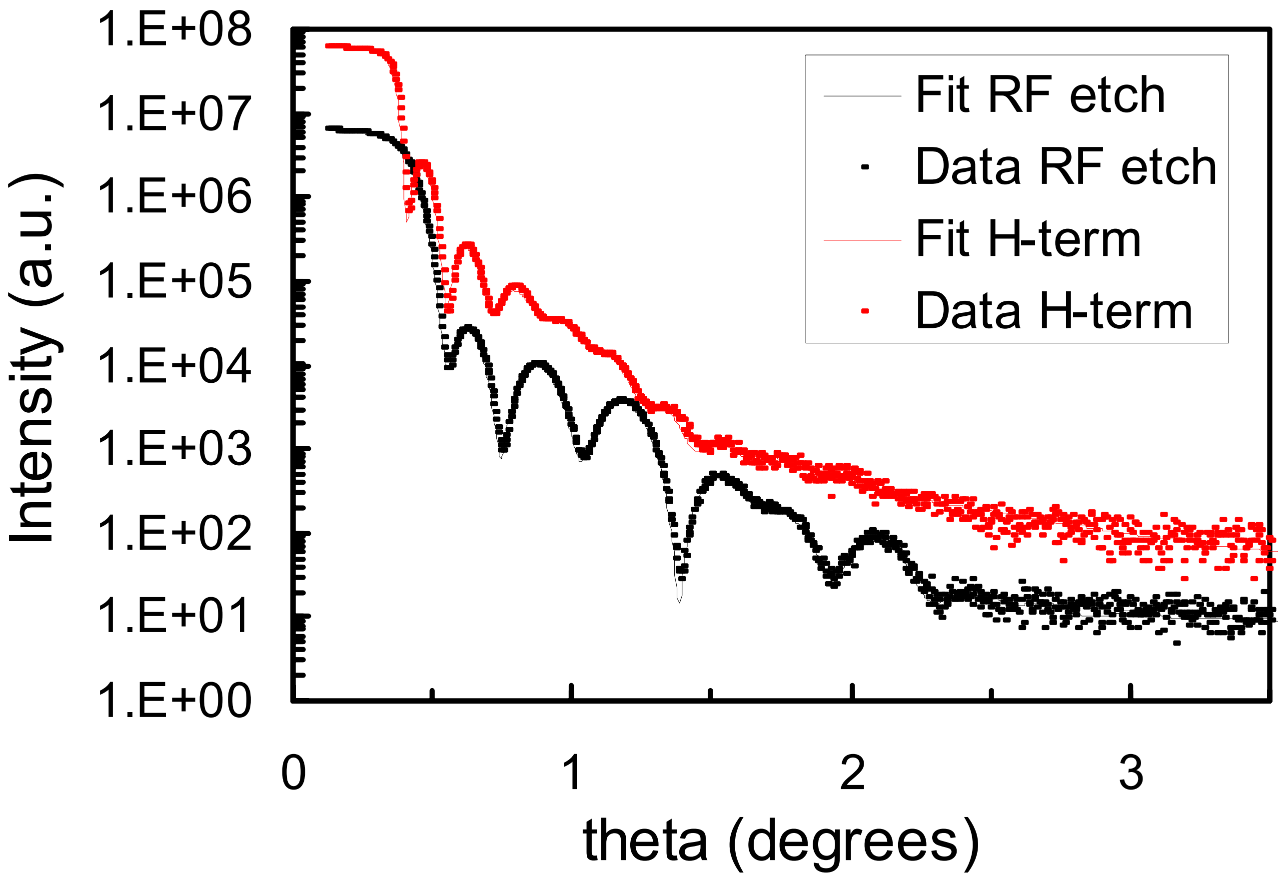
10 nm Ni on Si substrate with different surface orientations.

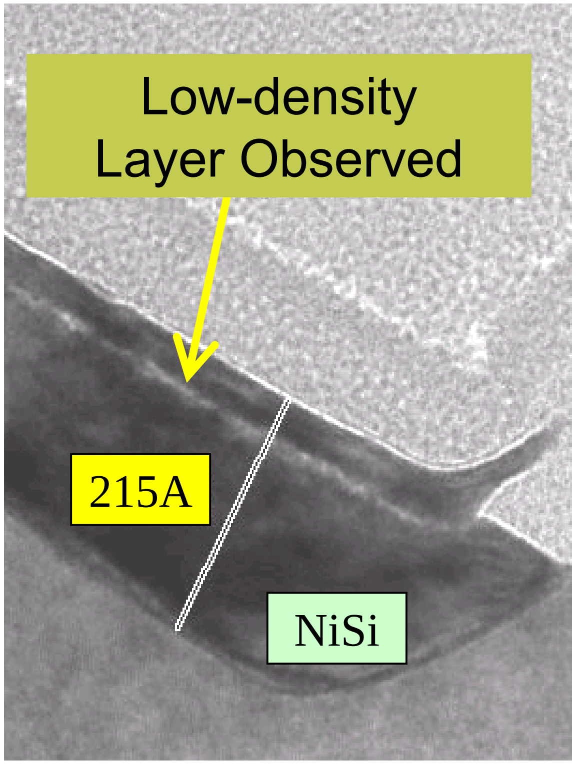
Energy-dispersive XRF yields consistent results without variations due to substrate orientations. Background subtraction was used.

(No standards were used for this tool).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Why not X-ray reflectivity (XRR) ?





- XRR spectra for metal films vary with processing and depend on many factors (composition, interface and surface layers, processing, etc).
- Difficult line shape fitting is required for new film stacks.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Materials science of silicide formation

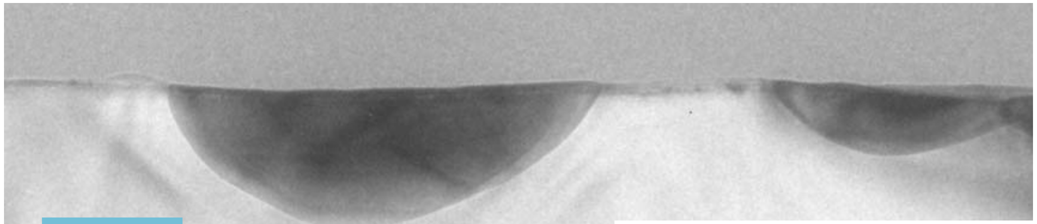
Need metrology techniques for

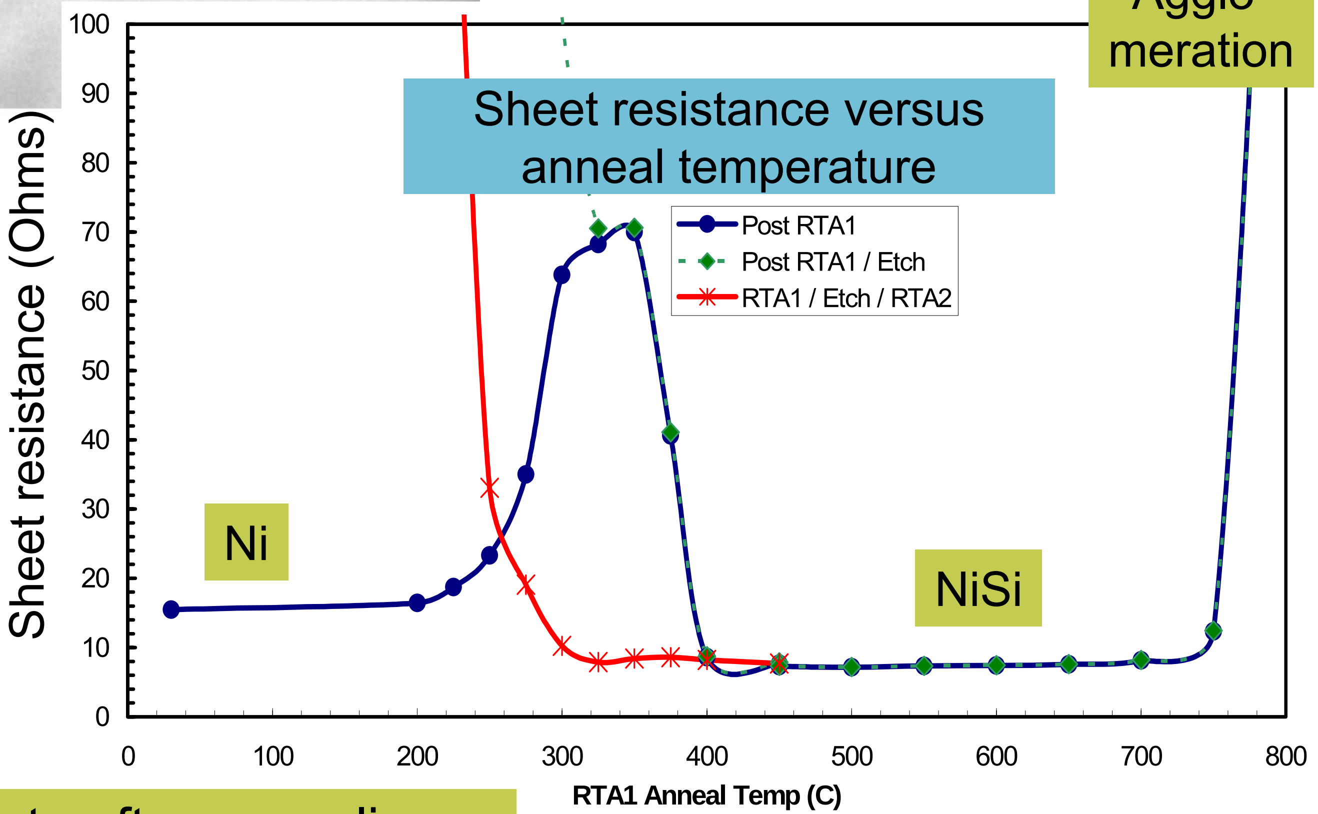
- Surface roughness and agglomeration (AFM, TEM, scatterometry, Raman, XRD)
- Chemical reactions
- Chemical composition
- Surface and interface effects
- Crystal structure (XRD)
- Crystal orientation and texture (XRD, lab or synchrotron, EBSD)
- Interdiffusion (SIMS or Auger depth profiling)

Many non-routine techniques are needed during process development.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Agglomeration: Formation of nano-islands





Surface energy vs. bulk energy

Ref:
Niranjan, PRB **73** & **75**

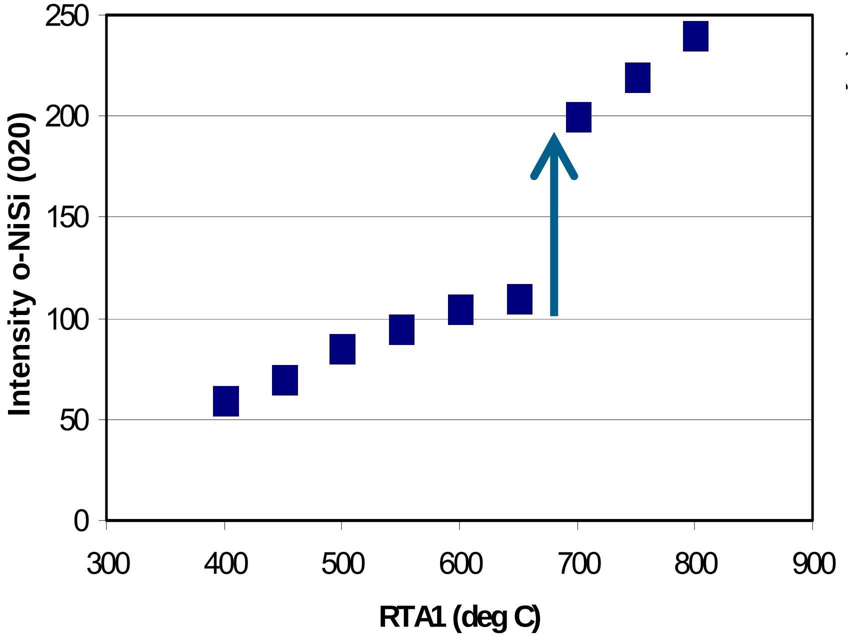
Thin Ni films agglomerate after annealing, do not form continuous silicide film.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

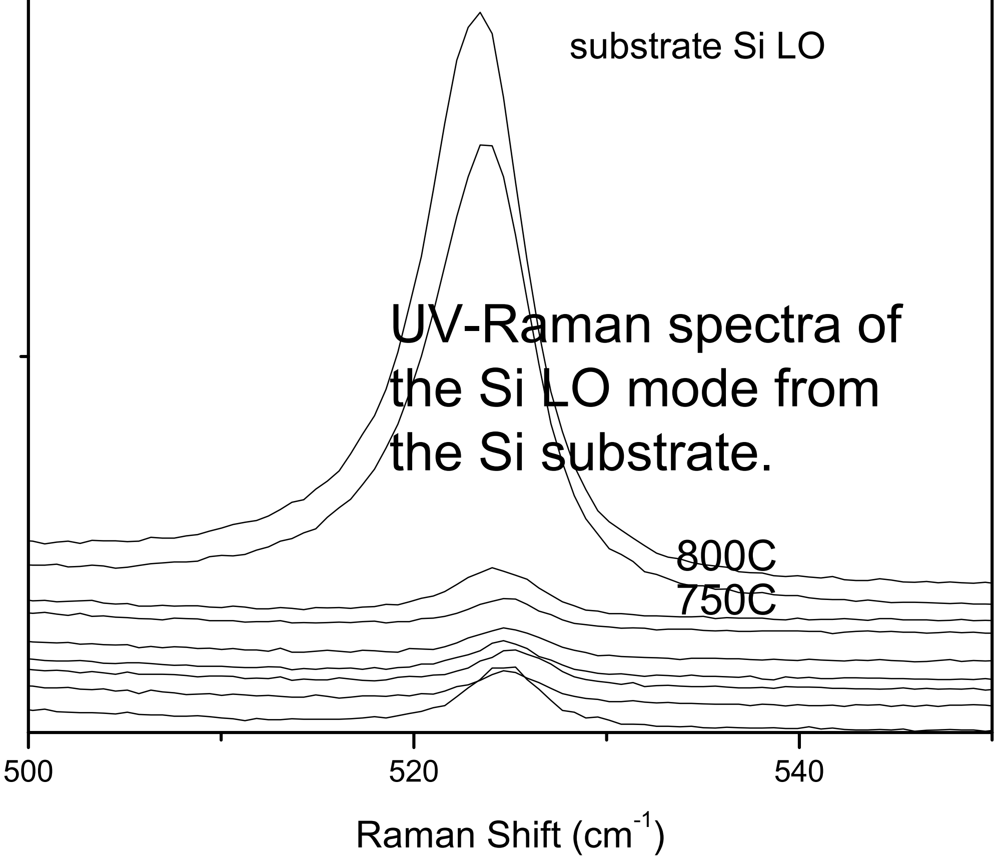
Agglomeration: Observed with UV Raman and XRD

TEM

NiSi XRD intensity: orthorhombic (020)



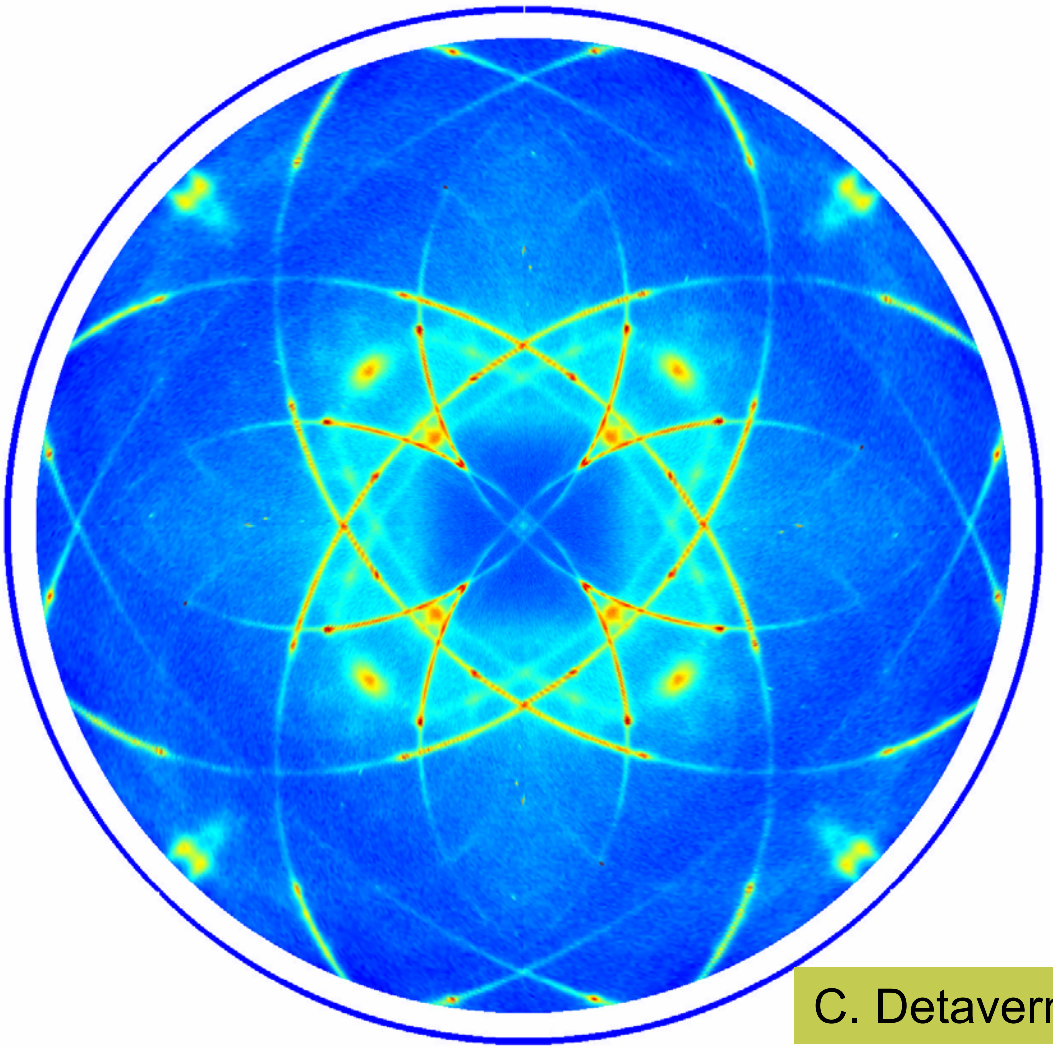
Si substrate LO Raman signal increases due to agglomeration.



UV-Raman spectra of the Si LO mode from the Si substrate.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

NiSi Crystal orientation influences agglomeration



NiSi (002) pole figure obtained using synchrotron x-ray diffraction.

Spots: epitaxial alignment
Rings: Conventional fiber texture
Arcs: Tilted fiber texture (axiotaxy)

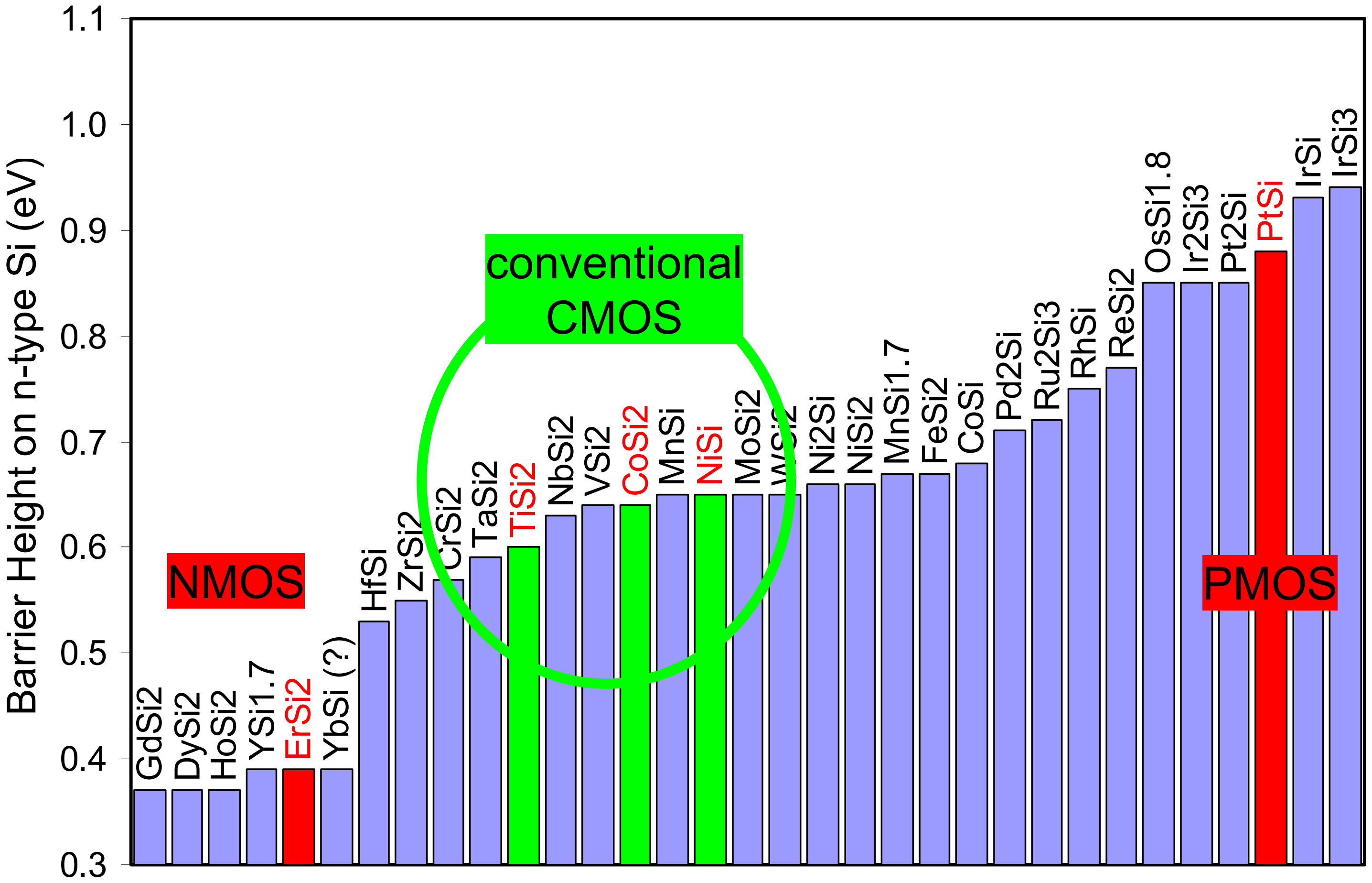
Texture is influenced by lattice constants of Si and NiSi.

Good lattice match produces tilted fiber texture, which leads to early agglomeration.

C. Detavernier *et al.*, Nature **426**, 641 (2003).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Reducing contact resistance and Schottky barrier height

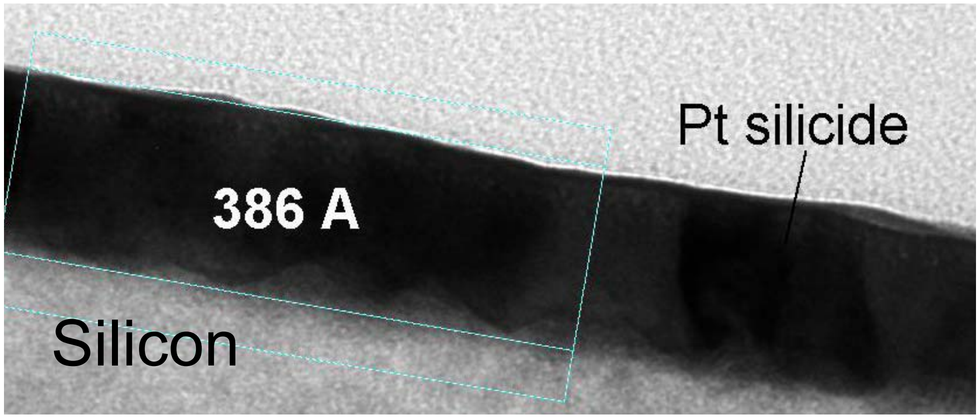


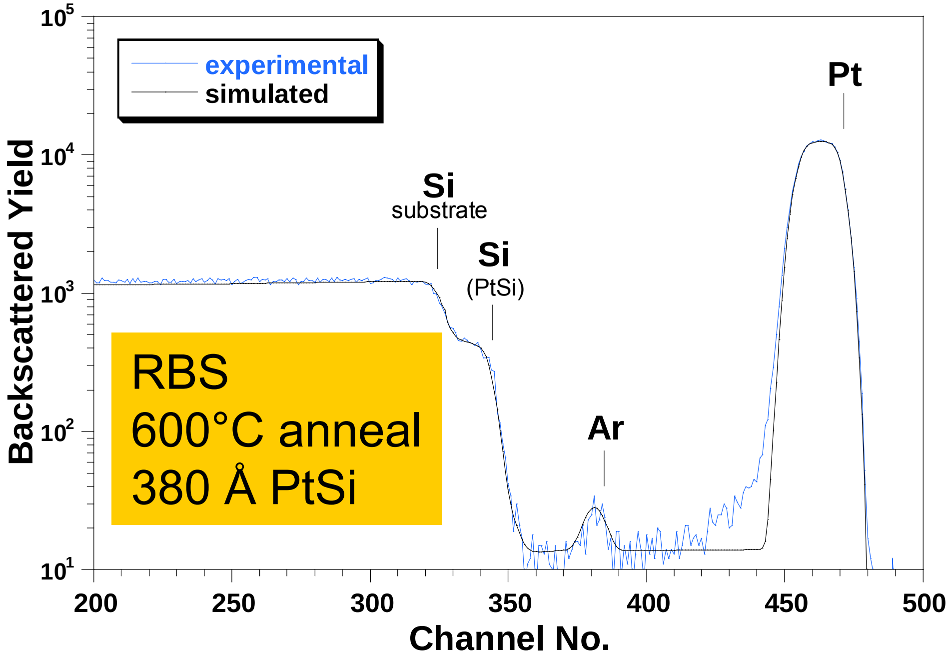
Future CMOS devices will lose 20% of their power in the contacts.
New materials for low-barrier contacts are crucial to reduce power.

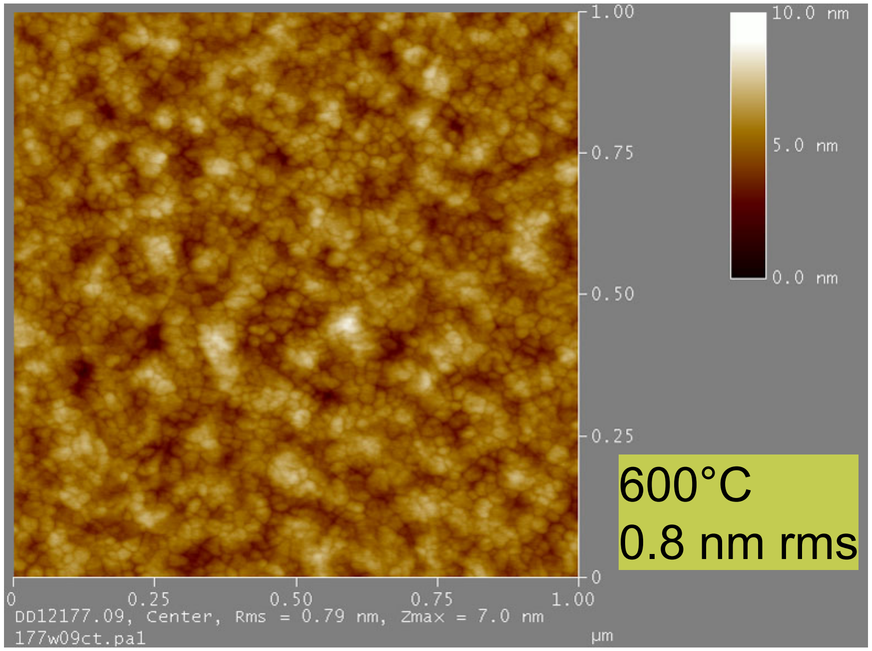
Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

PtSi film properties: TEM, RBS, AFM

PtSi formed by
- Si substrate preclean
- Pt sputtering (PVD)
- Thermal annealing
- Selective etch

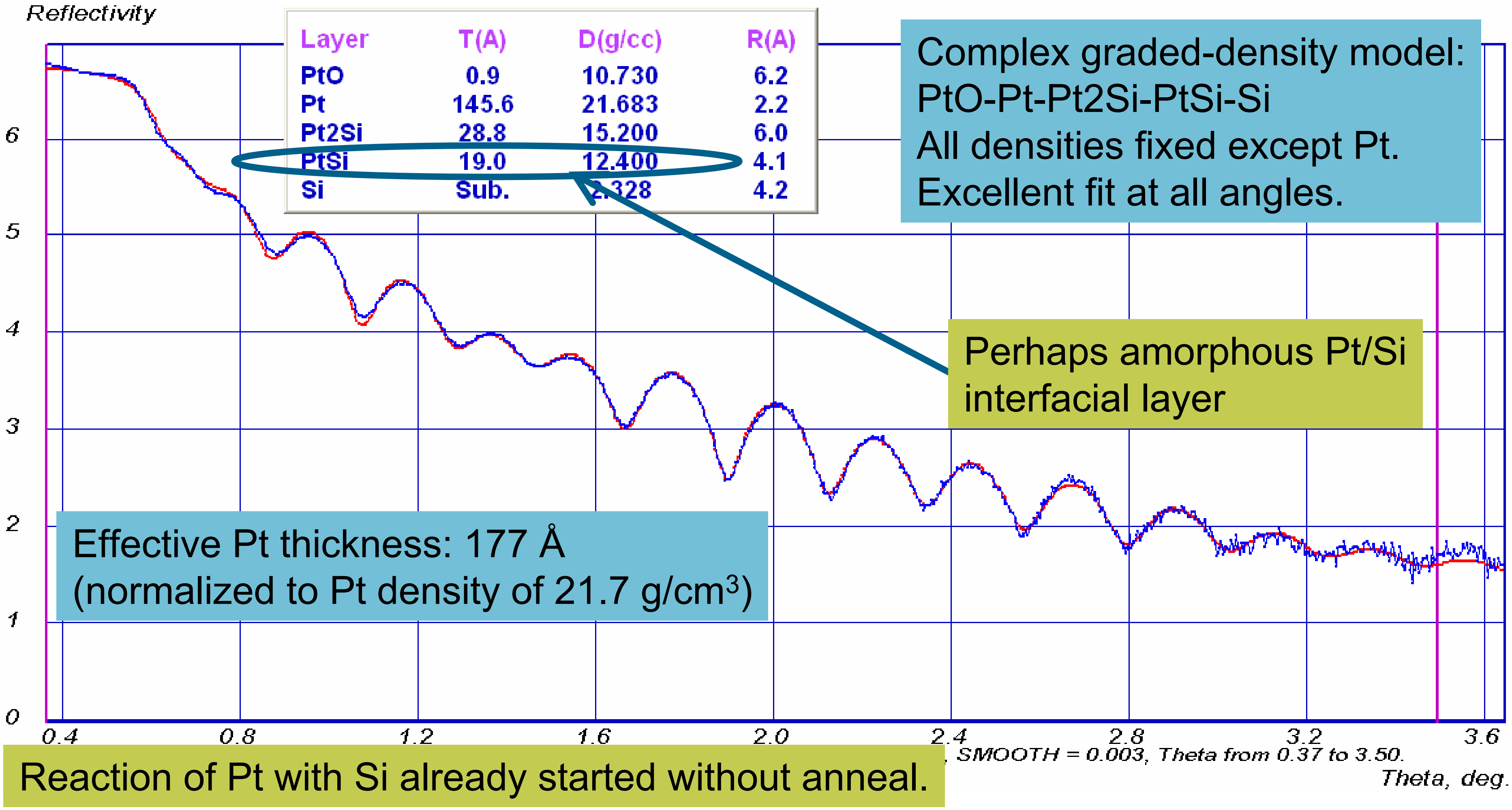






Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

X-ray reflectivity (XRR) of as-deposited Pt on Si



Layer	T(A)	D(g/cc)	R(A)
PtO	0.9	10.730	6.2
Pt	145.6	21.683	2.2
Pt2Si	28.8	15.200	6.0
PtSi	19.0	12.400	4.1
Si	Sub.	2.328	4.2

Complex graded-density model:
PtO-Pt-Pt2Si-PtSi-Si
All densities fixed except Pt.
Excellent fit at all angles.

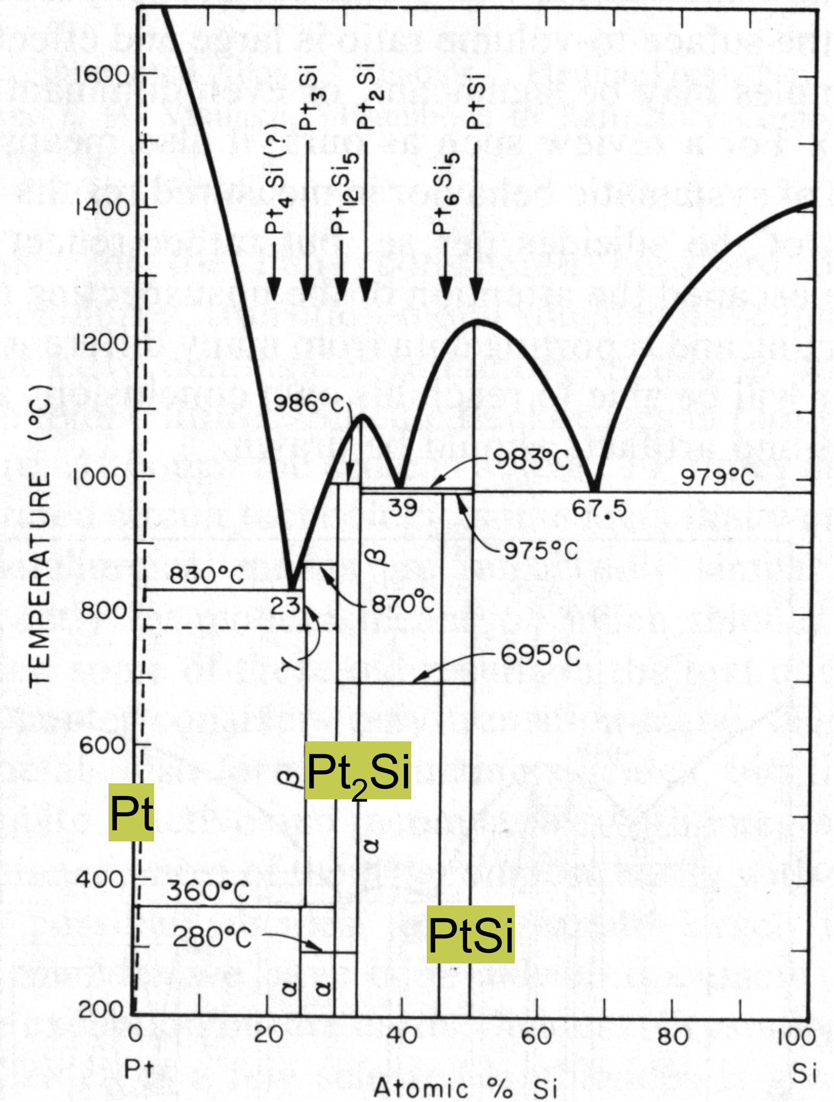
Perhaps amorphous Pt/Si interfacial layer

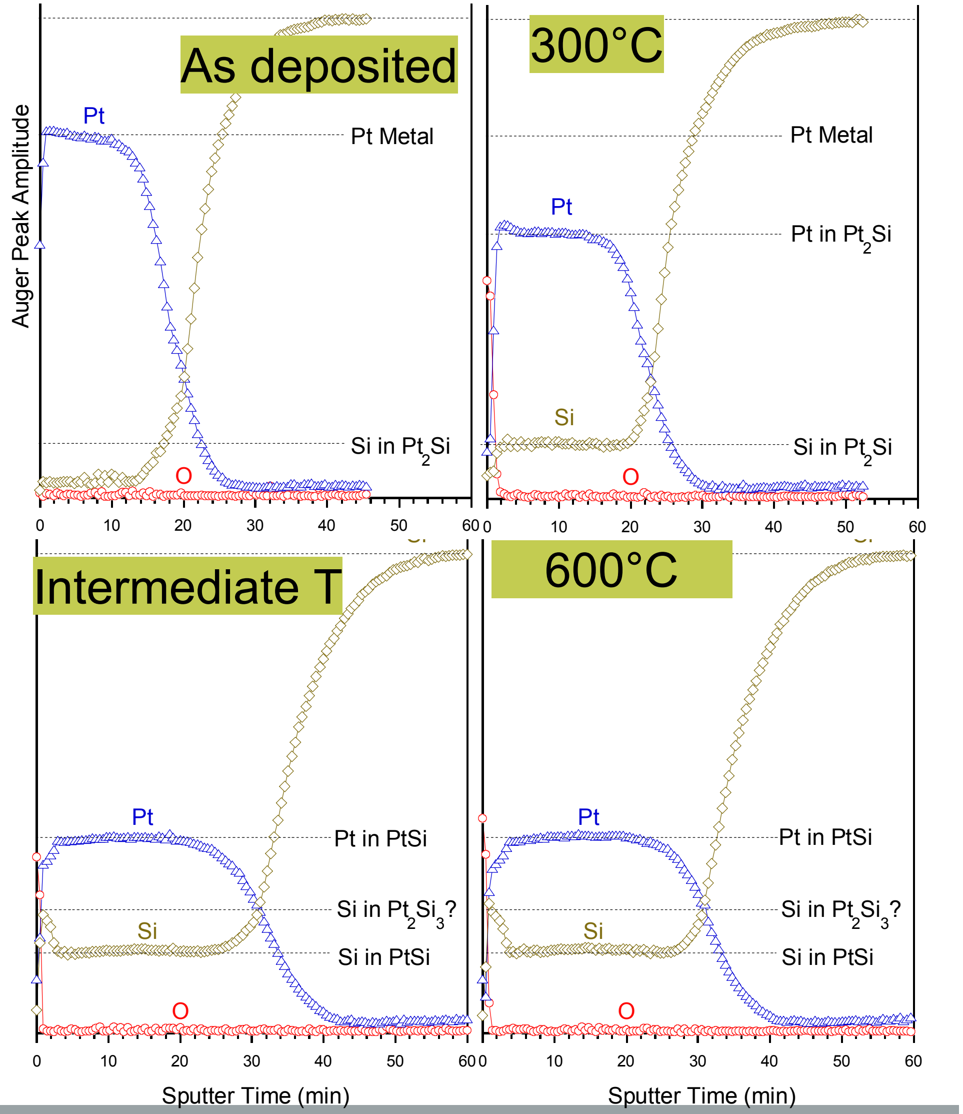
Effective Pt thickness: 177 Å
(normalized to Pt density of 21.7 g/cm^3)

Reaction of Pt with Si already started without anneal.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

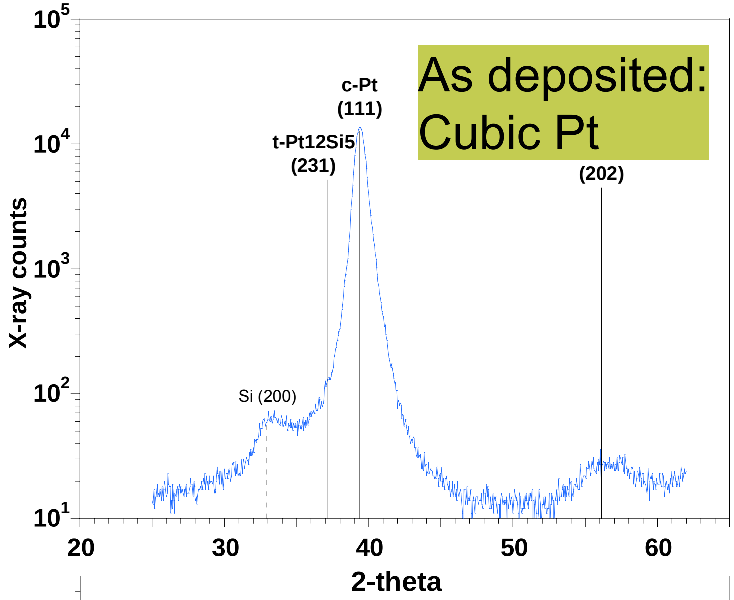
PtSi phase diagram and transformation

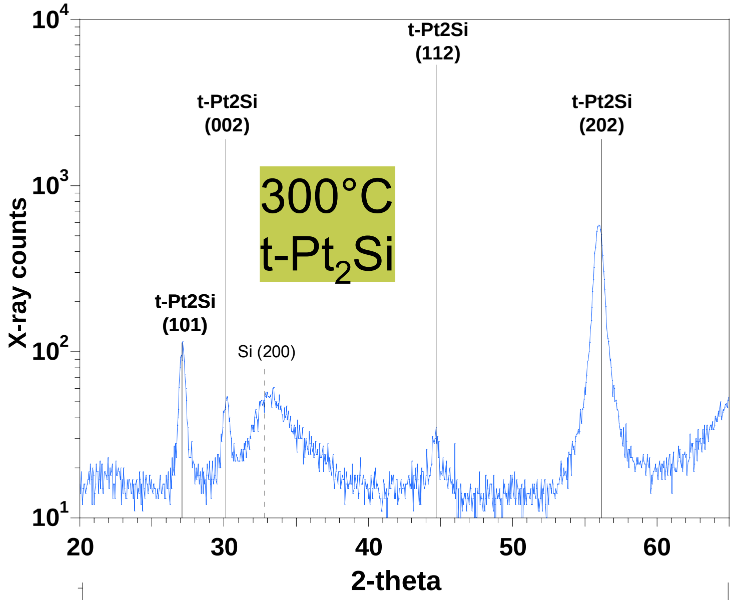


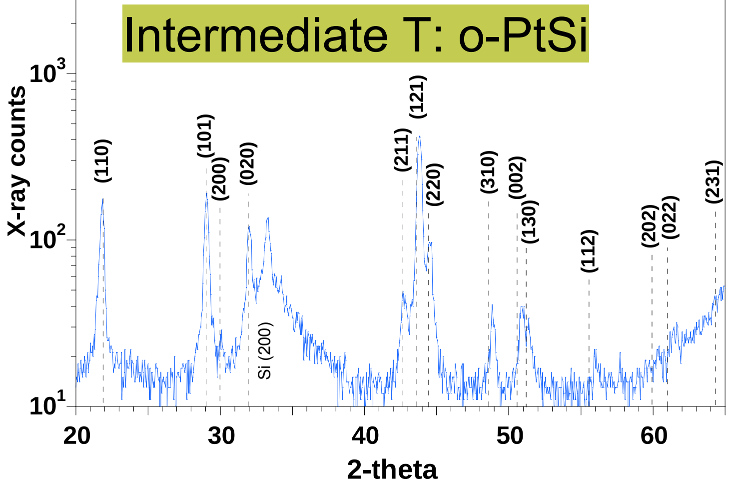


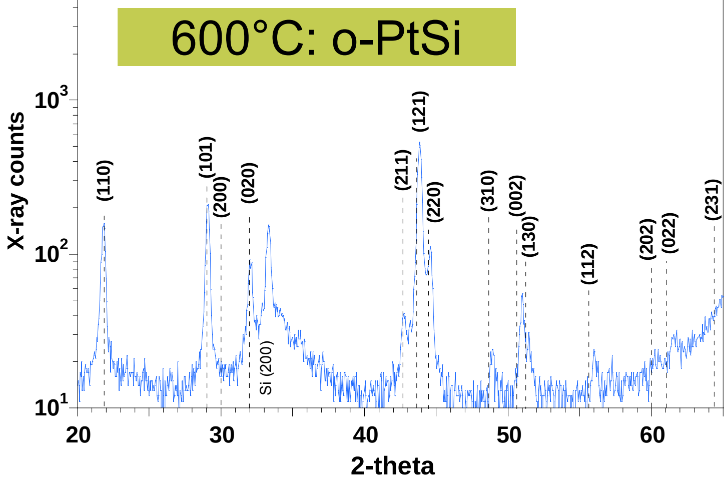
Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

PtSi phase transformation by XRD


As deposited: Cubic Pt

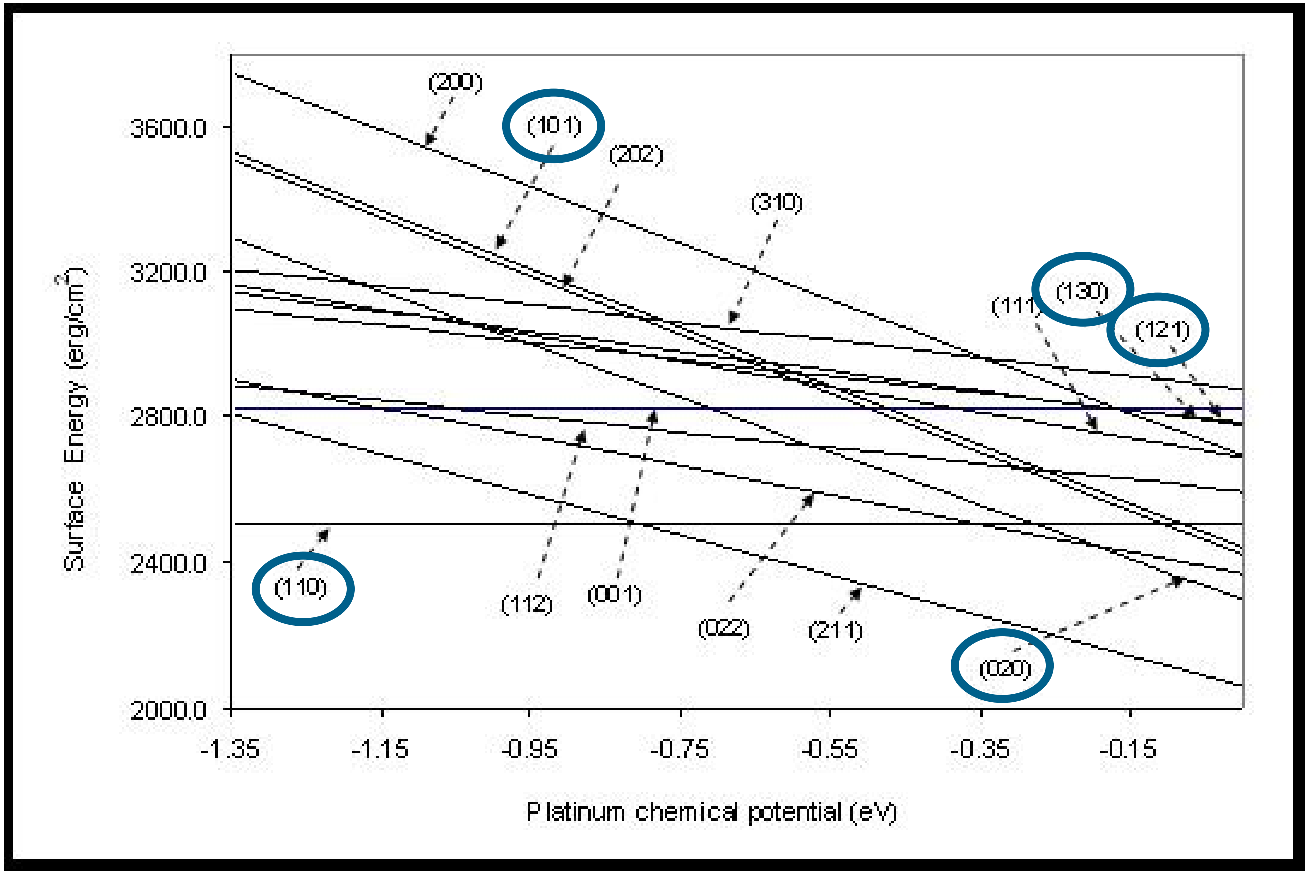

300°C t-Pt_2Si


Intermediate T: o-PtSi


600°C: o-PtSi

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

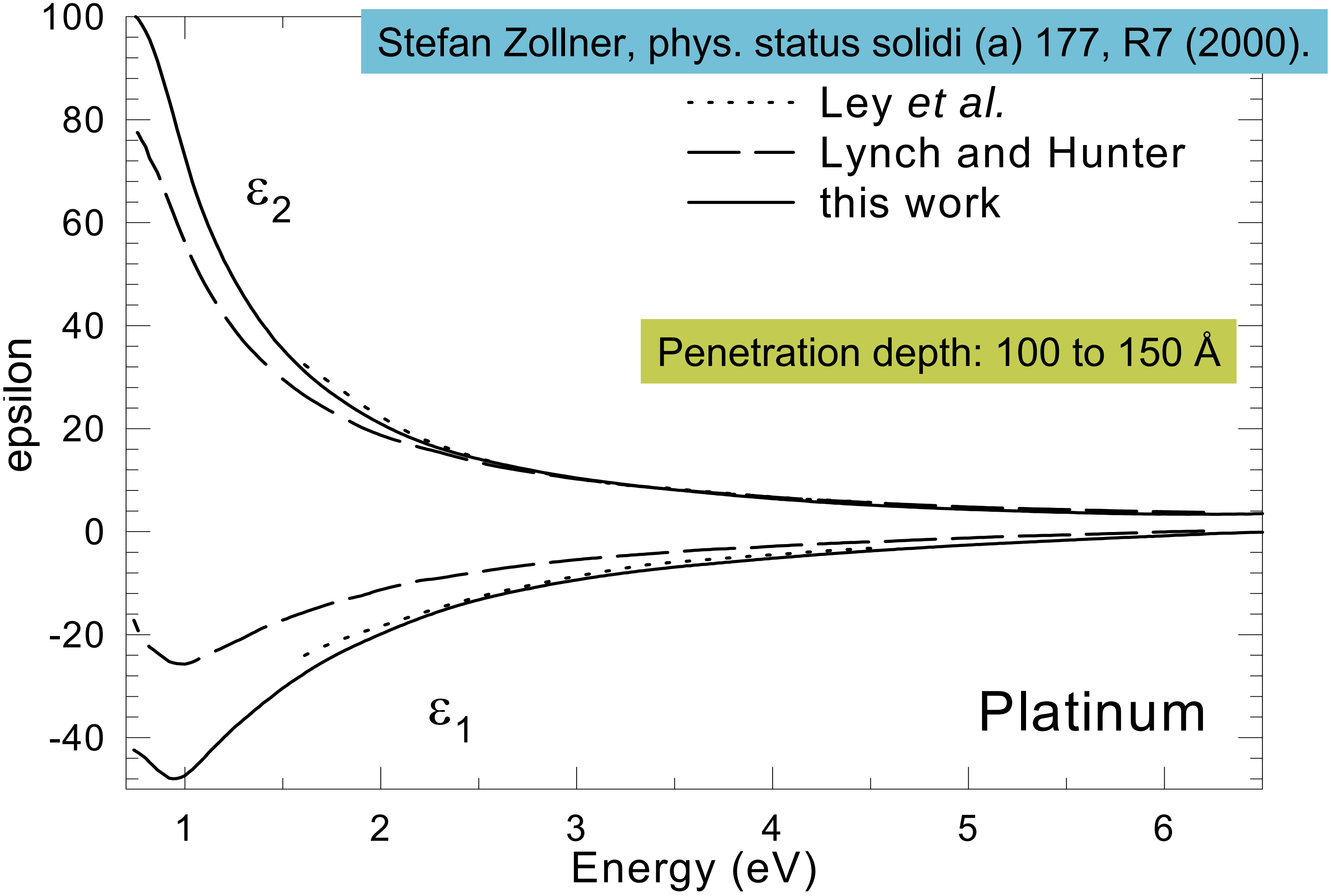
PtSi surface orientations



LDA structure calculations indicate many different surface orientations with similar surface energies (Niranjan, Demkov, Kleinman, PRB **73** & **75**).

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Optical properties of Pt

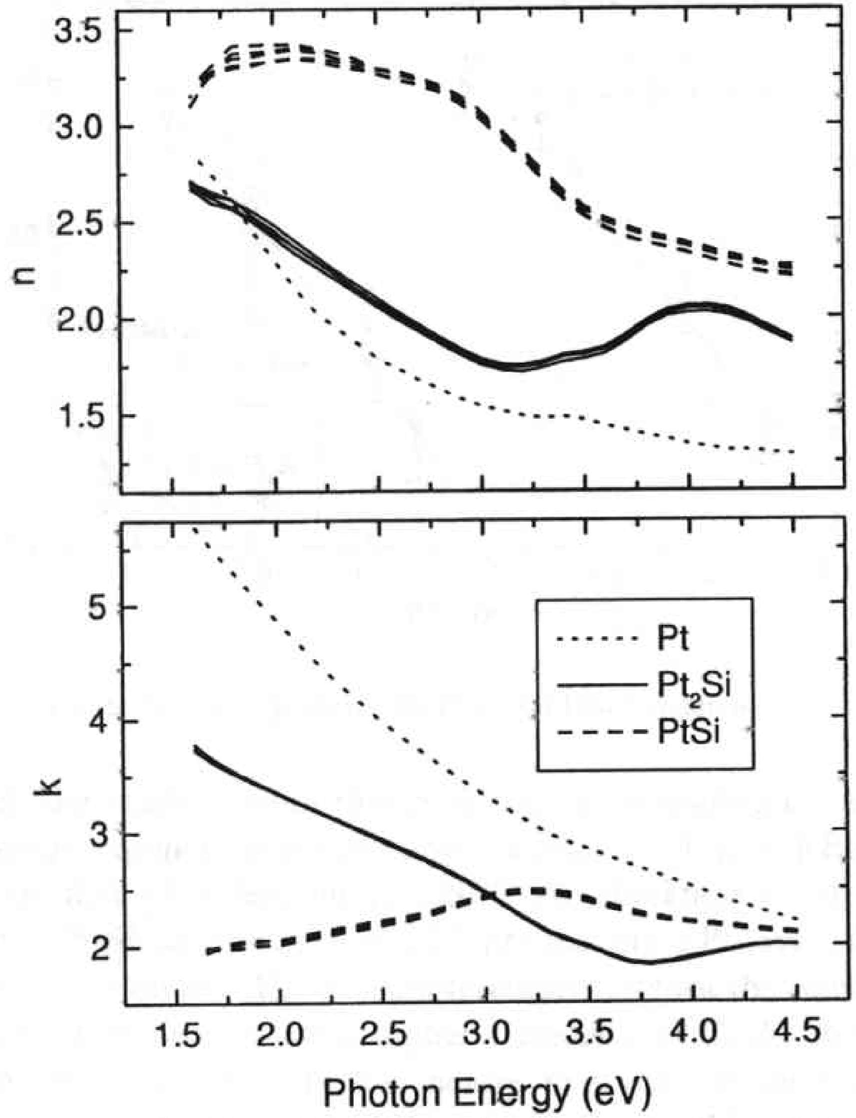


Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

Optical properties of Pt, Pt_2Si, and PtSi

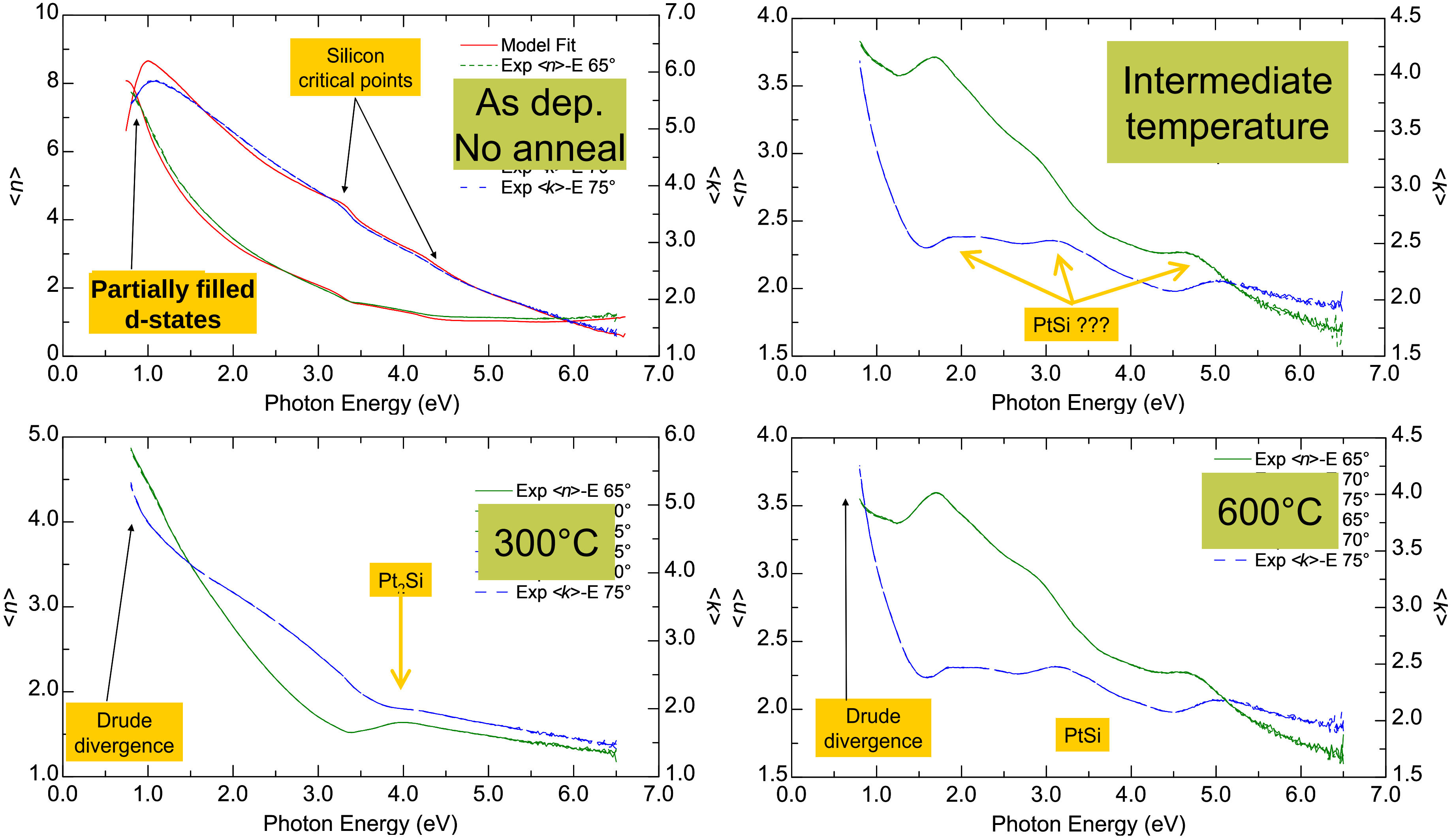
- Drude tail for Pt (diverges at E=0).
- Weaker divergence plus peak near 4 eV for Pt_2Si.
- Weak absorption plus peak near 3.2 eV for PtSi.

T. Stark et al.
Thin Solid Films **358**, 73 (2000).



Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

PtSi phase transformation by ellipsometry



Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.

freescale™ semiconductor

Summary: Silicide Nanowires

Modern CMOS devices need low-resistance current electrode contacts (between silicon transistor and metal interconnects)

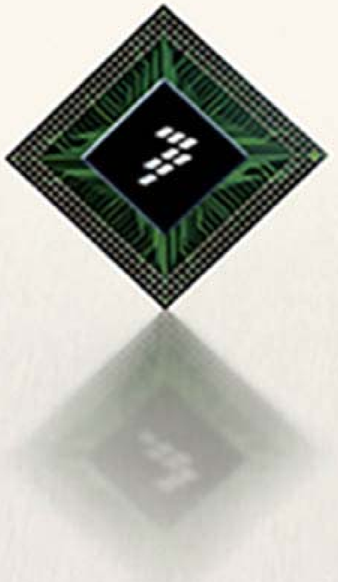
- PtSi for PMOS
- Rare earth silicides ($ErSi_{1.7}$) for NMOS
- Fermi level of silicide should be aligned with the conduction and valence bands of silicon, respectively.

Much silicide on THICK films was carried out many years ago.

Thin silicide films and narrow lines behave differently.

- Surface preparation (atomically clean, preamorphized, etc.)
- Bulk energy versus surface energy
  - Agglomeration
  - Crystal structure, texture
  - Measurement techniques, modeling using *ab initio* theory.

Freescale™ and the Freescale logo are trademarksof Freescale Semiconductor, Inc.
All other product or service names are the property of their respective owners. © Freescale Semiconductor, Inc. 2006.



It's science ~~fiction~~.

freescale™
semiconductor