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Recent Advances in Implant Metrology with the Shallow Probe LEXES Tool

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Theory of the analytical method: the LEXES technique

Sample Excitation & Detection

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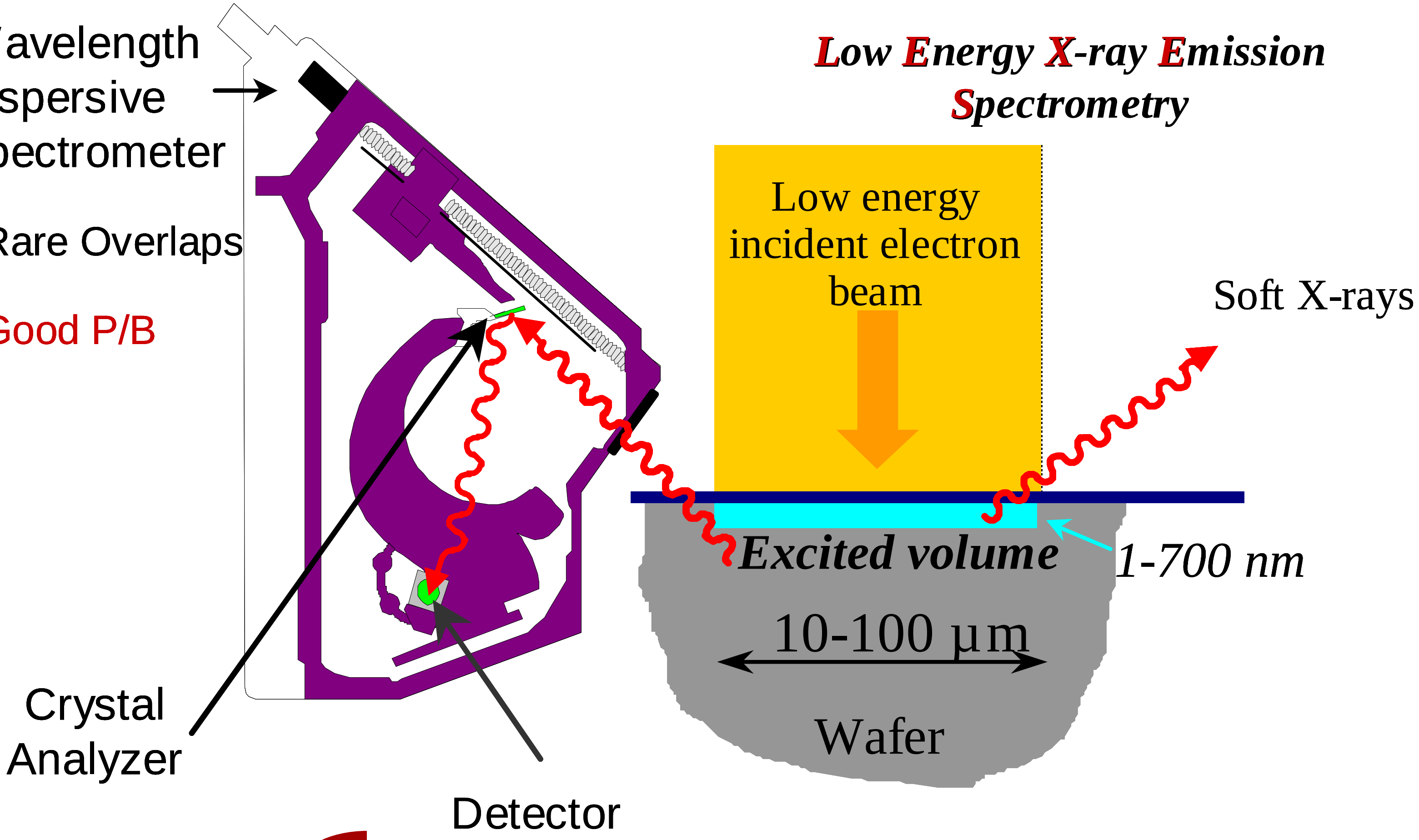
Wavelength
Dispersive
Spectrometer

⇒ Rare Overlaps

⇒ Good P/B

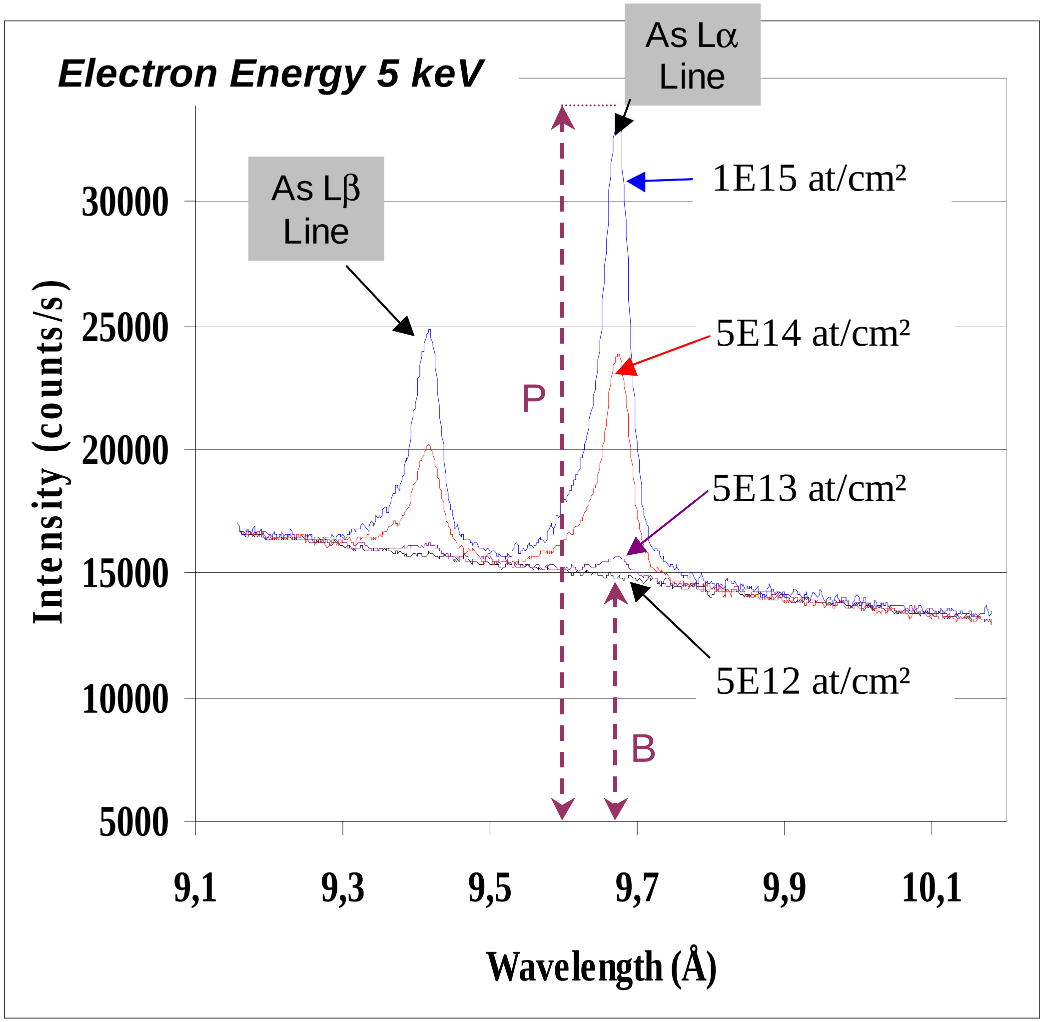
Low Energy X-ray Emission Spectrometry



Intensity (background subtracted) at Element X-ray position is proportional to Dose or film thickness.

Signal Variation with Dose, and illustration of Detection Limit issues.

Case of 5keV As implants in Si.



Uncertainty on dopant signal :

$$\sigma_I(cps) = \sqrt{\frac{P}{t_P} + \frac{B}{t_B}}$$

LEXES Probing of Nanometric Depths in Silicon

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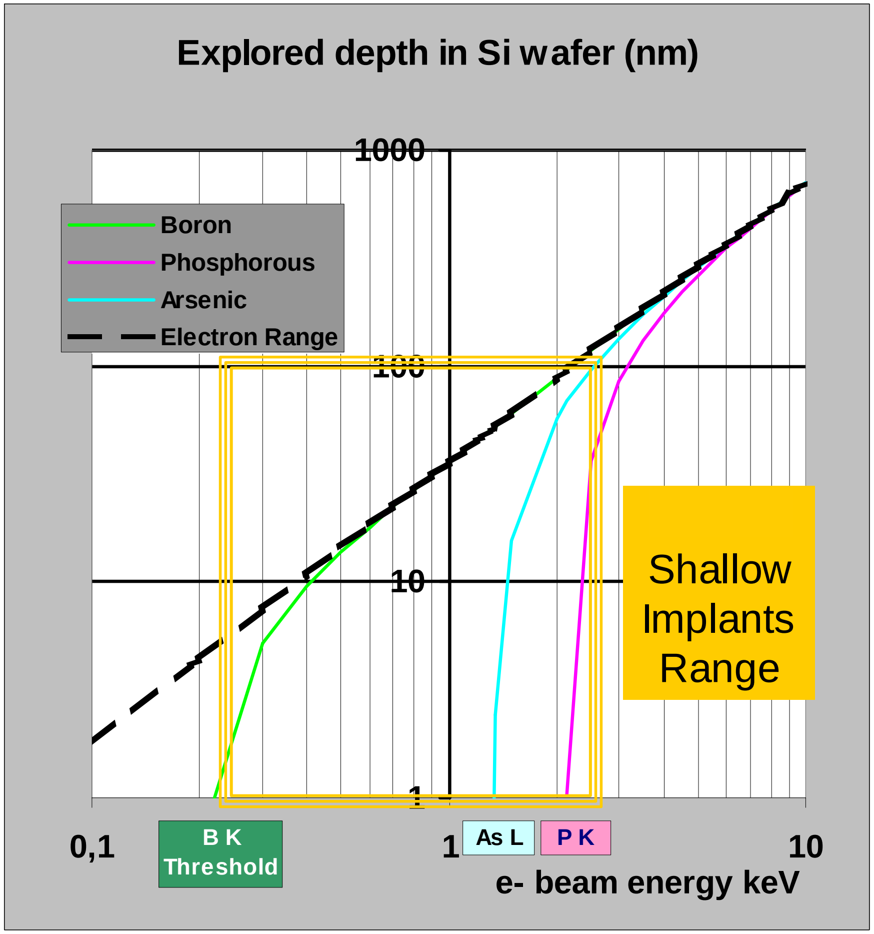
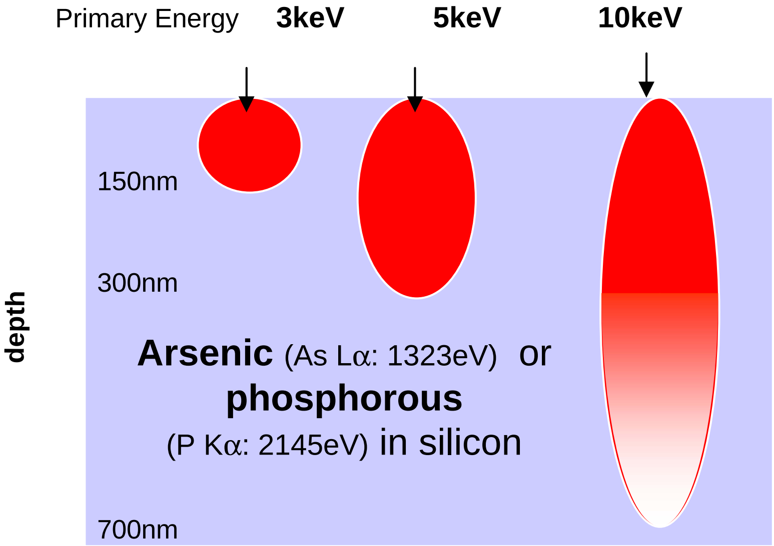
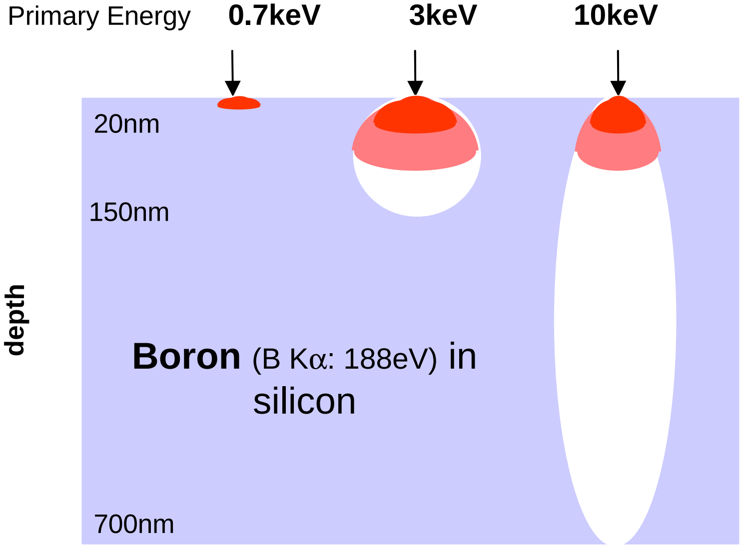




Arsenic (As Lα: 1323eV) or **phosphorous** (P Kα: 2145eV) in silicon



Boron (B Kα: 188eV) in silicon

Quantification Procedure

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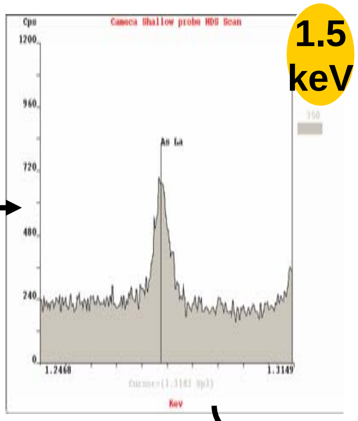
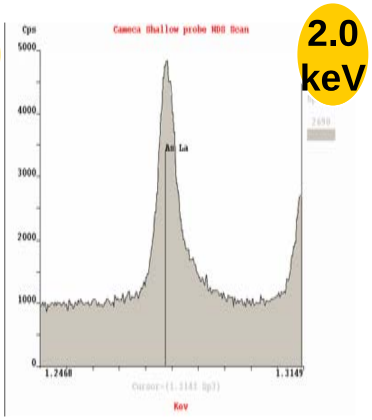
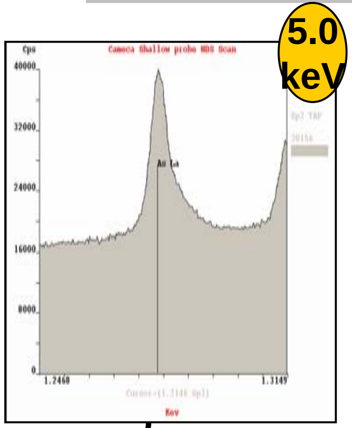
Peak & Background measurements on the ***Unknown Sample*** *at various primary energies*



1.5 keV



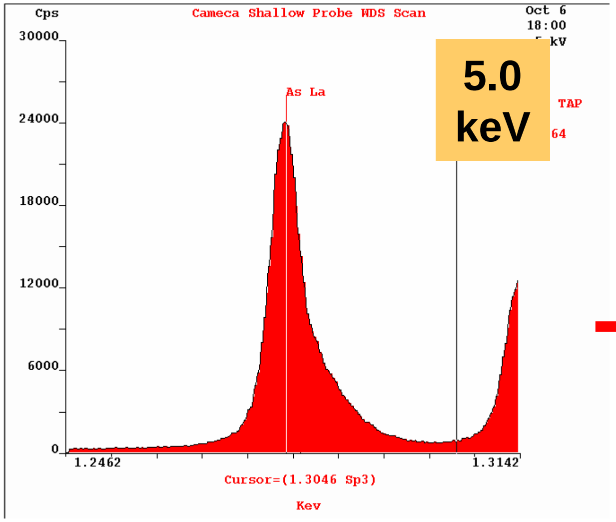
2.0 keV



5.0 keV

\+

Peak & Background measurements on the ***Standard*** (GaAs, GaP, InP, …)



5.0 keV

Calibration

Profile Extraction (Physical Model)

Absolute Dose Determination

Example of Quantification

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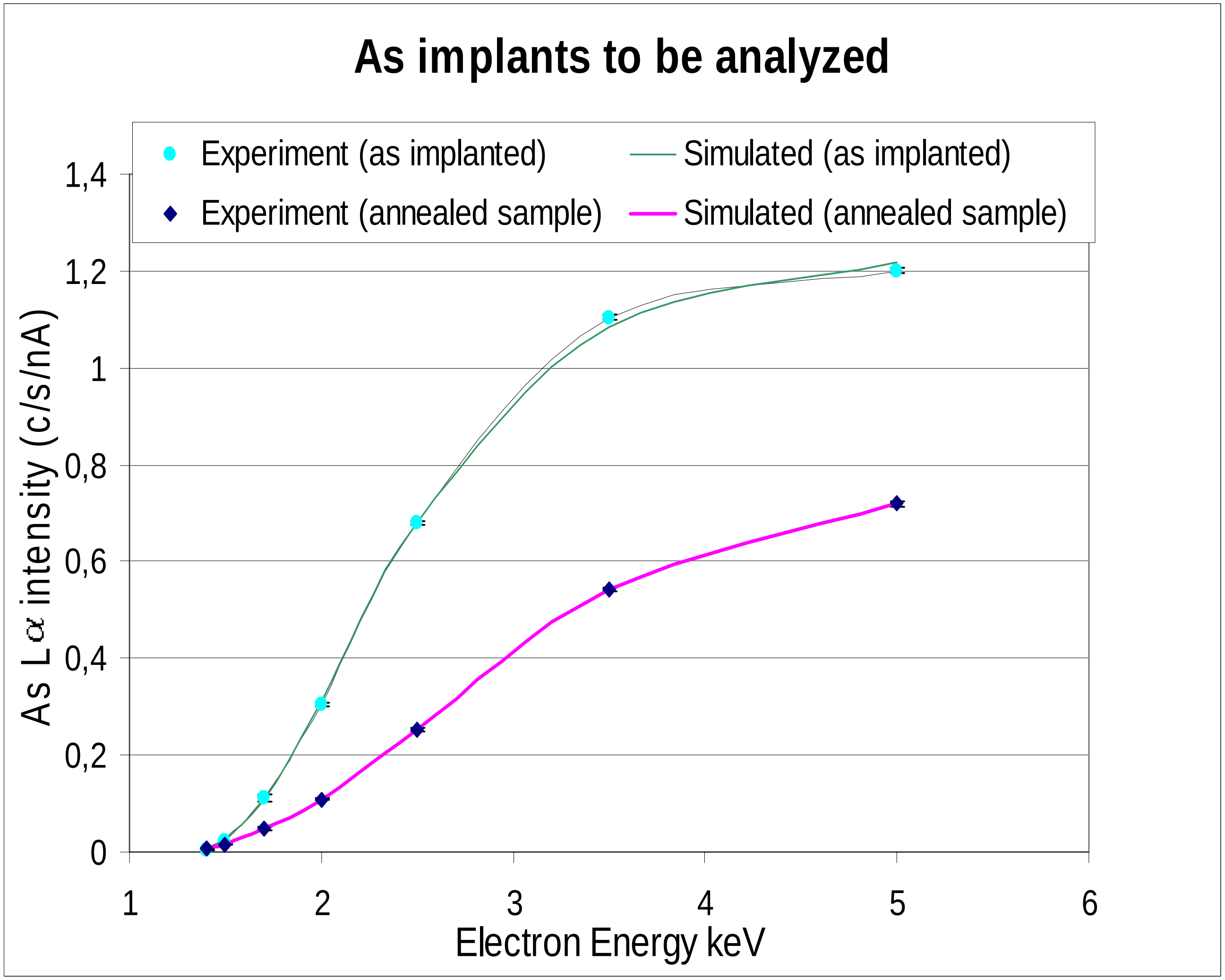
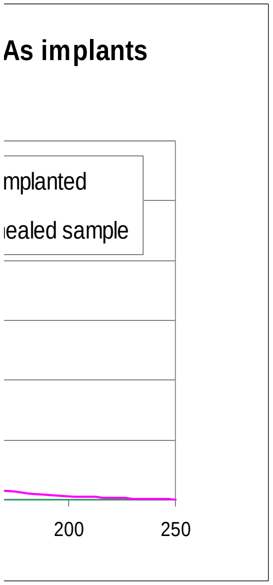




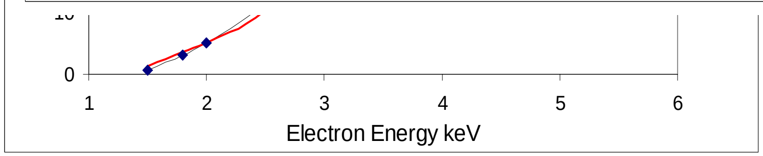
.5 at/cm² +/- 0,81%

15 at/cm² +/- 1,10%

$_{Dose}$, as follows:

ignal

Intensity



$$\frac{1}{\sigma^2_{Signal}} = \sum_{Energies"i"} \left(\frac{1}{\sigma^{2}_{Intensity"i"}} \right)$$

Range of Applications

Sample Types	***Monitored Species***	***Thickness***	***Precision (1RSD)***	***Detection Limits***
Implants and diluted species	Dopants (B, N, F, As, P, In, …) Metals	from Surface (contamination) to 1 µm in-depth	0.1 to 1% for dose D>1E15at/cm²; 0,5-2% for 1E14<D<1E15at/cm², 1,5-10% for D<1E14at/cm²	5E12-1E13 at/cm²
Dielectric & Oxide films	N, O, Metals (Hf, Ta, Zr, .)	Sub-nm to 1µm thick	0.5-2% on nm range thickness	<1/100 monolayer
SiGe	Ge, B, C, …	typically nm to 100 nm (or more)	0.1-0.4% on Ge, 0.5-2% for B with dose >1E15at/cm²	5E12at/cm² for Ge, 5E13 for B

Shallow Probe System Description

- ➡ ◆ System configuration
- ◆ System performance

System configuration

Must comply with :

- Clean room compatibility
- Full 300 mm wafer analysis capability
- High performance in terms of
  - ⇒ Precision
  - ⇒ Accuracy of Quantitation
  - ⇒ Repeatability & Reproducibility
- High level of automation
- Low cost of ownership

Shallow Probe SP 300 :

Instrument Body

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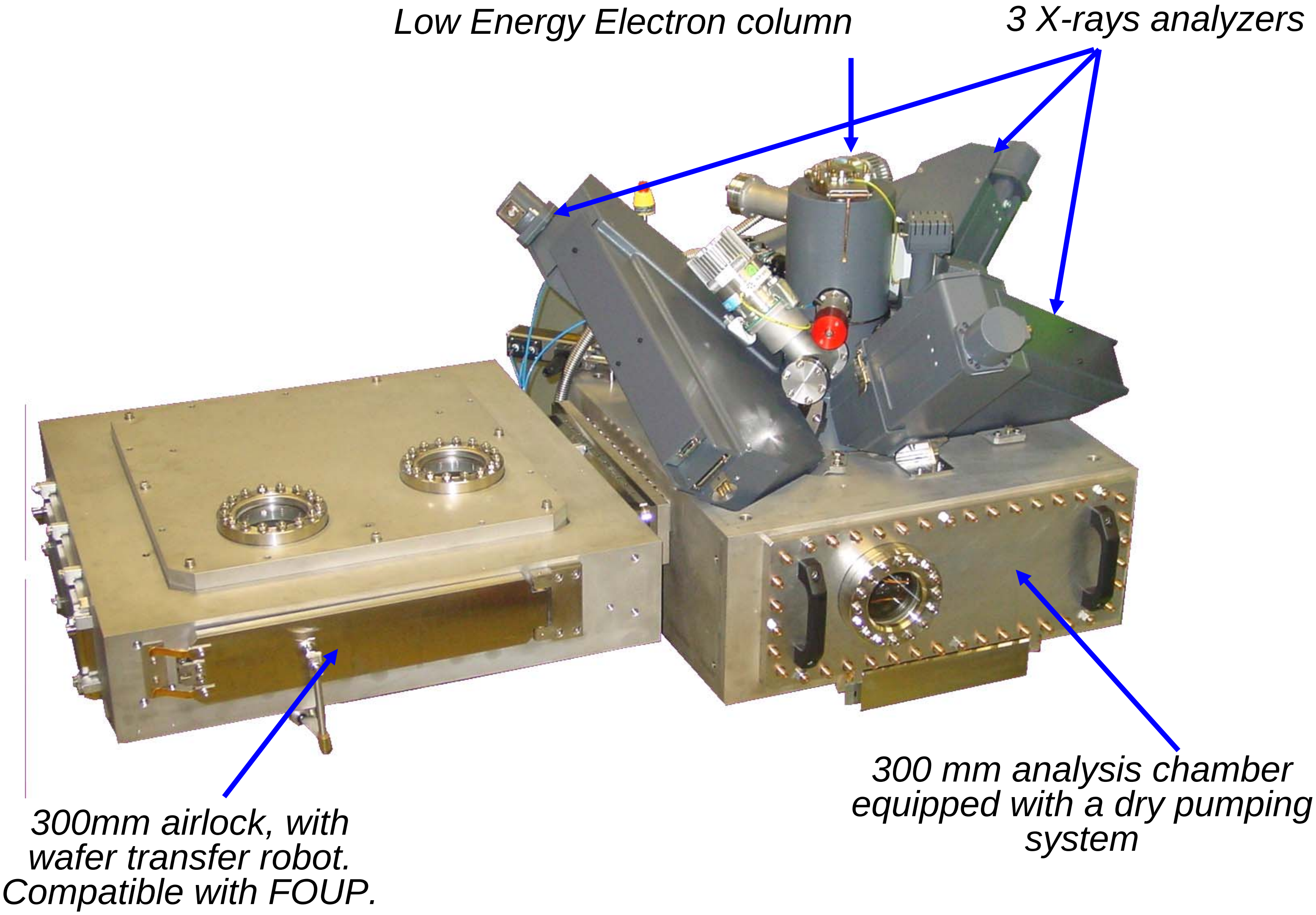


Low Energy Electron column

3 X-rays analyzers

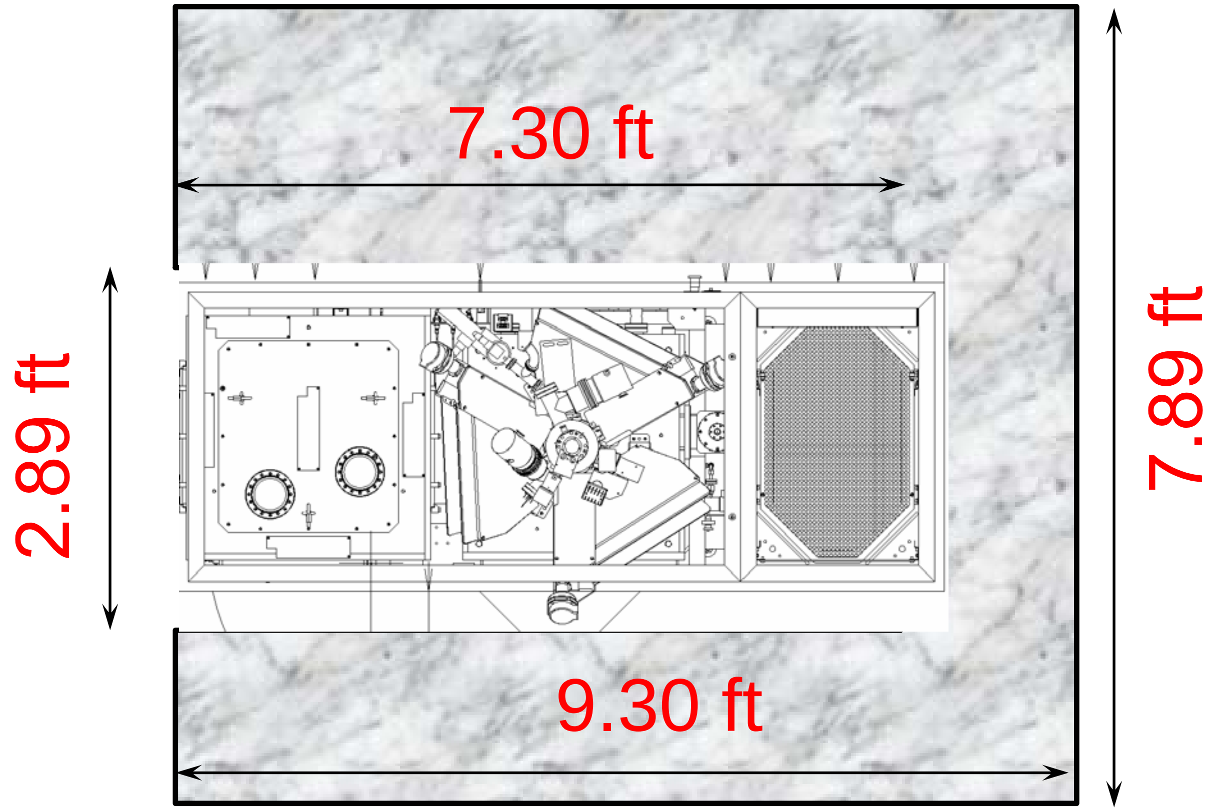
*300mm airlock, with
wafer transfer robot.
Compatible with FOUP.*

*300 mm analysis chamber
equipped with a dry pumping
system*

Footprint

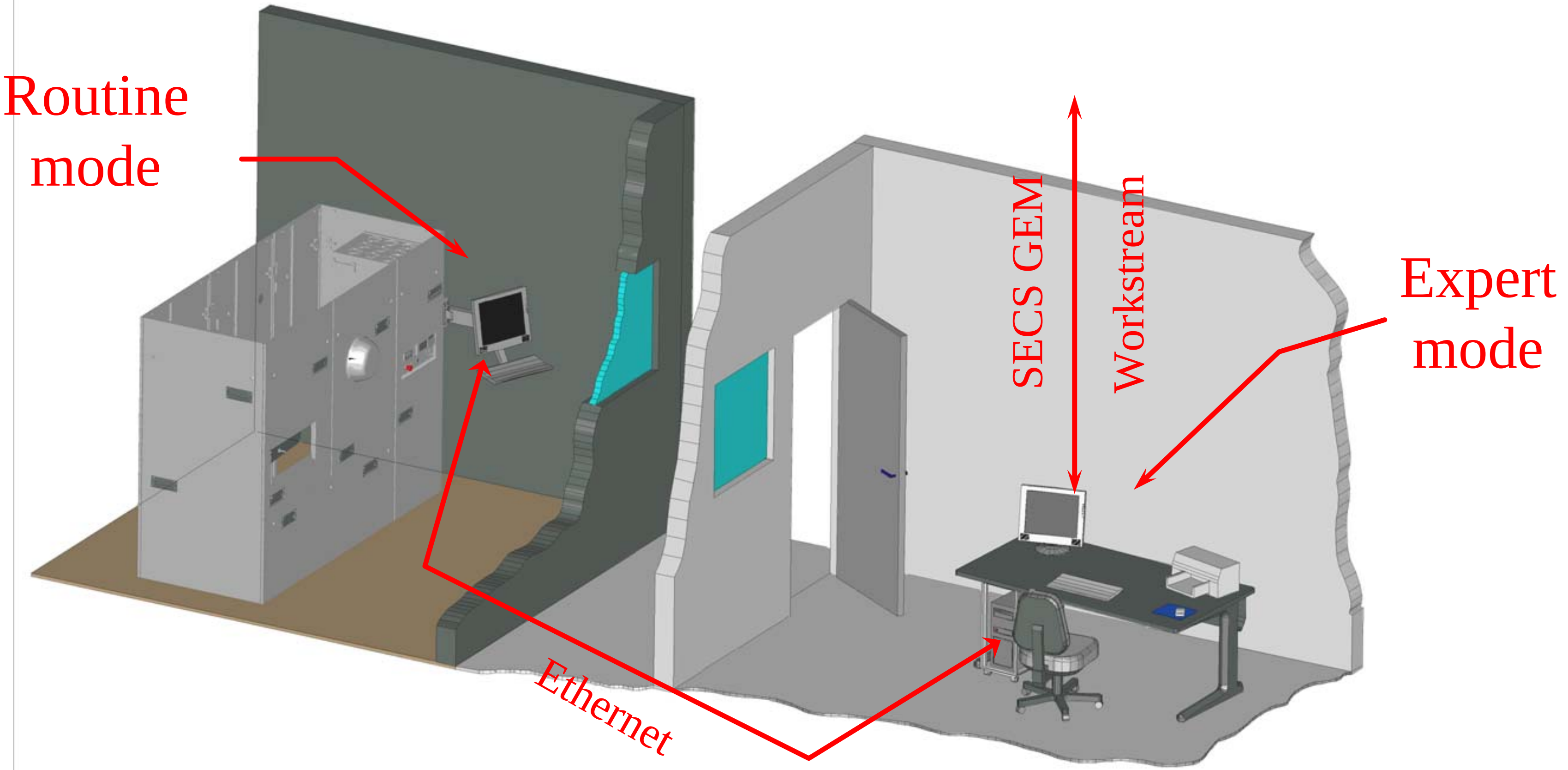
Physical envelope : 21 ft^2

With clearance : 73 ft^2



Clean Room Environment

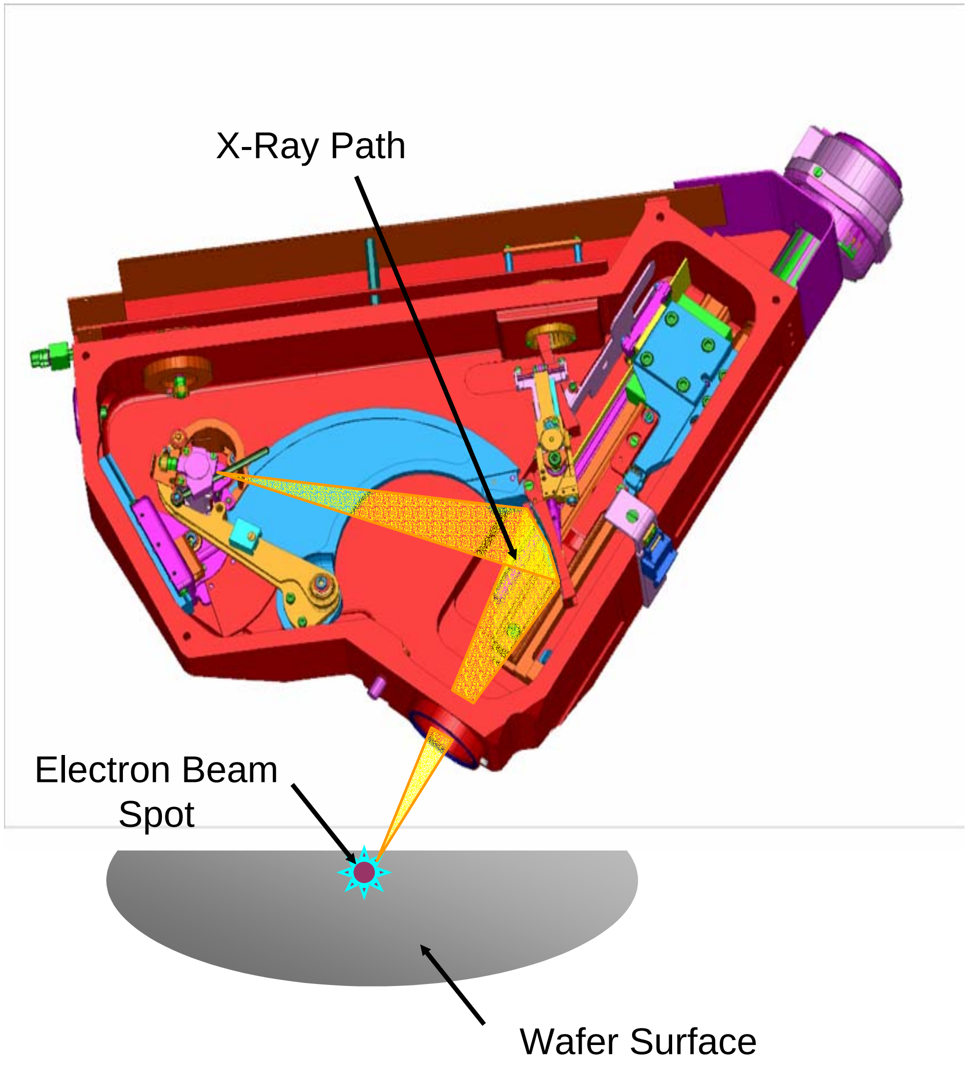
Two control desks



Low Energy Electron Column

- Derived from long established Cameca EPMA Expertise
- New Design to achieve Quantitative Electron Probe at very low Energy and high Current. ***(patent pending)***
- Electron Beam 0.2 to 10keV, focused on spots 3-100µm. Beam Current from 10nA to 500µA controlled with high performance electrometry.
- Fully Automated (Alignment, Aperture Positionning, Beam Current Monitoring, ..) and embedded as Setup in Analysis Recipes.

Wavelength Dispersive Spectrometers



Main Features

- **3 WD spectrometers**: Multiplies sensitivity by 3, or allows simultaneous detection of 3 different species.
- WD Spectrometers with large Rowland circle radii (160mm): ***high wavelength resolution*** and ***precise quantification (good Peak/Background)***.
- WD Spectrometers mounted in inclined orientation (40° take-off angle): ***strongly reduced sensitivity to sample height variation, which is good for Repeatability.***
- Absolute Positioning thanks to Optical Encoders: ***highest Reproducibility***.
- Analyzer design: trace level detection **without saturation from intense matrix signals.**

System Description

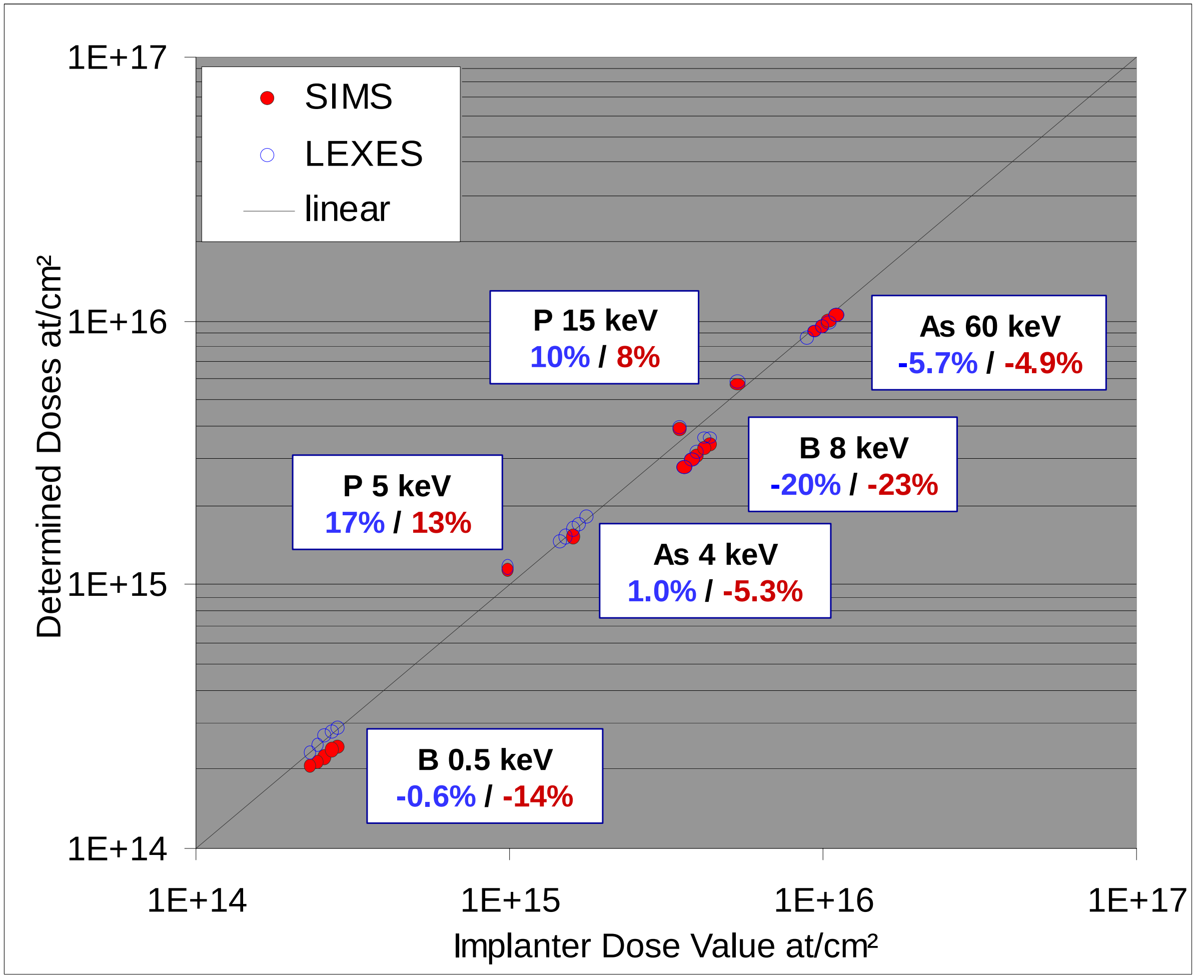
- System configuration
- ➡ System performance (Implant Characterization)

Accuracy of Dose determination:

comparison with SIMS values

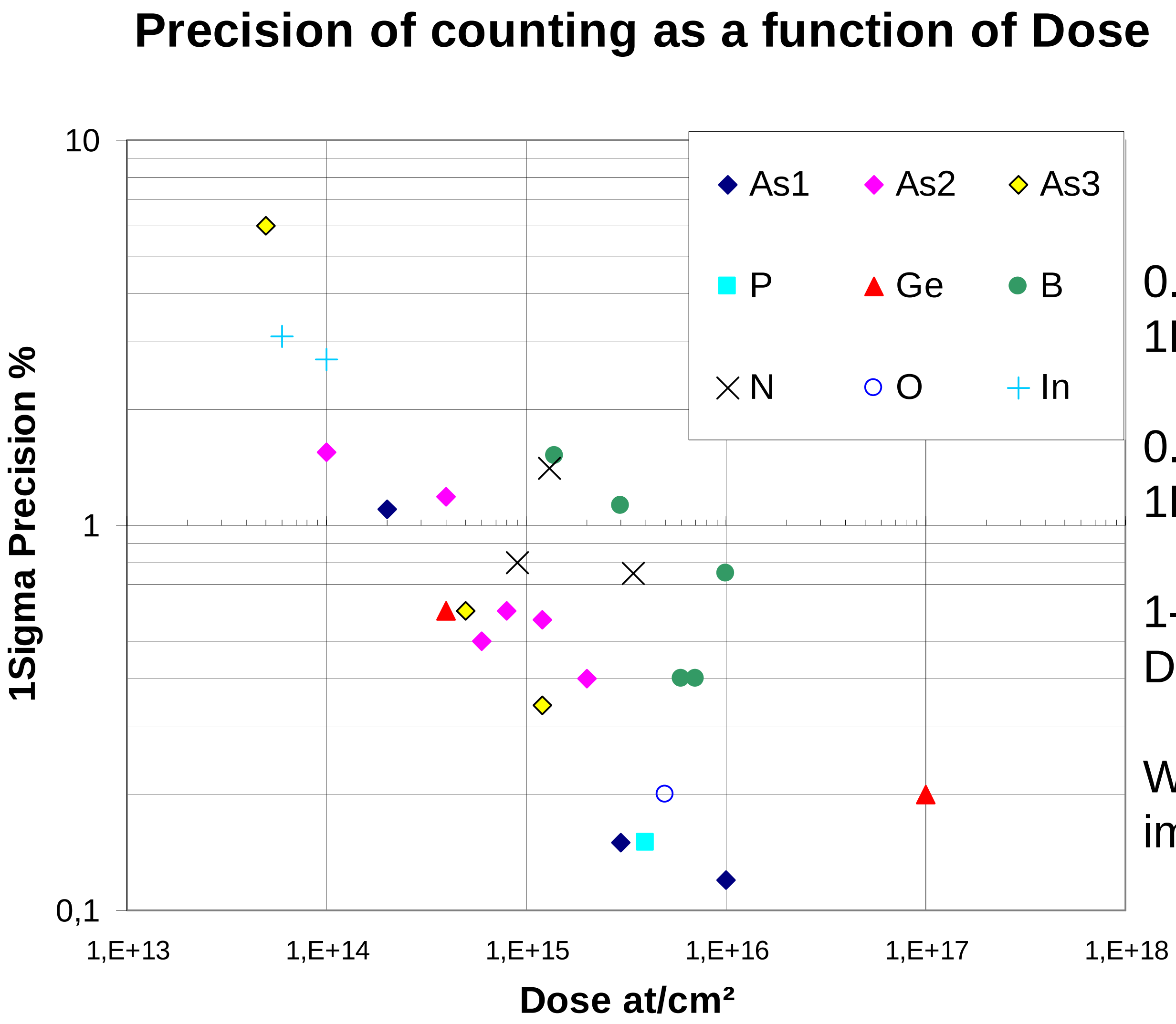
- Although completely independent, SIMS and LEXES typically agrees **within 5%,** whatever the dopant type and dose.
- Deviation between Implanter tool values and both techniques is about 5-20%.

SIMS data were recorded with CAMECA IMS 6f equipped with Accel-Decel option.



Samples provided by S. Corcoran from Intel Inc. and P. Ronsheim from IBM

Precision per point



0.1-1% for D> 1E15at/cm²

0.5-2% for 1E14<D<1E15at/cm²

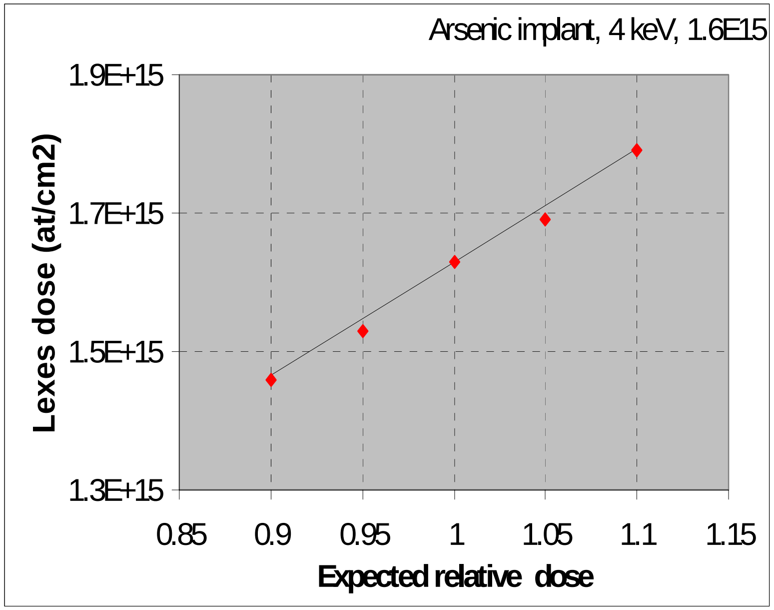
1-10% for D<1E13at/cm²

Will be further improved!

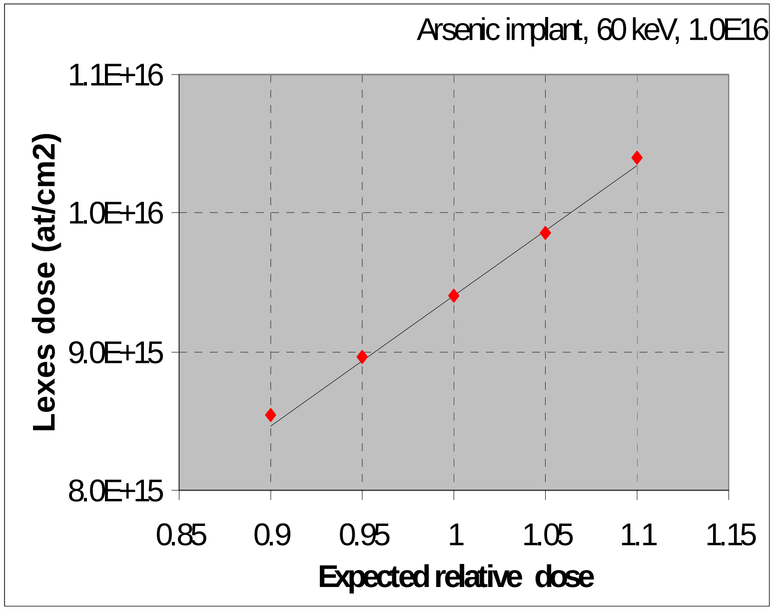
Resolving dose variations

Arsenic

Shallow Implants



Medium Energy Implants

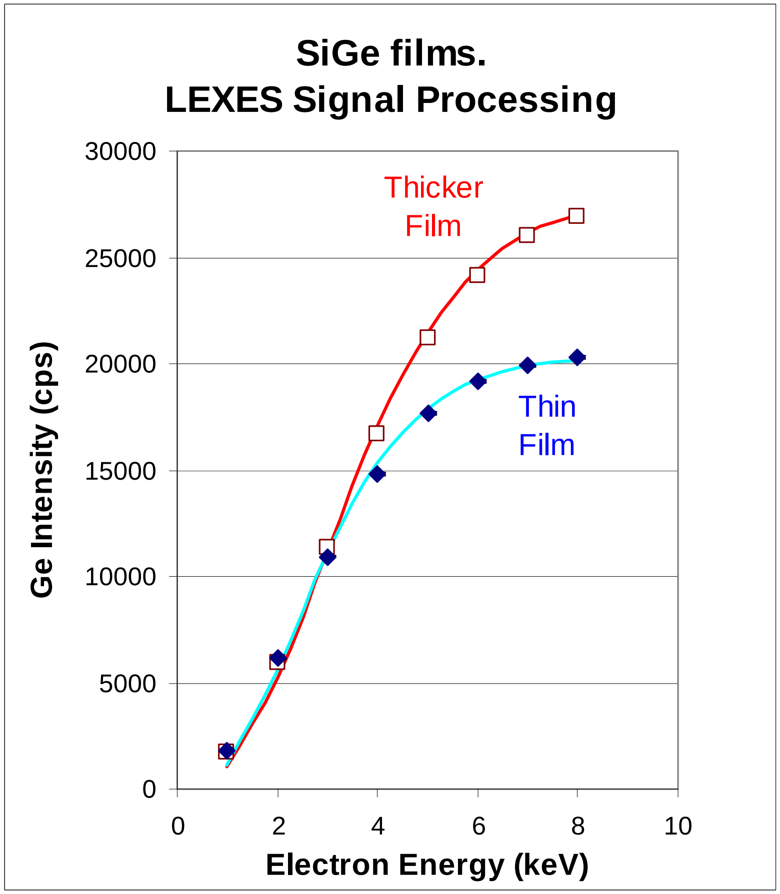


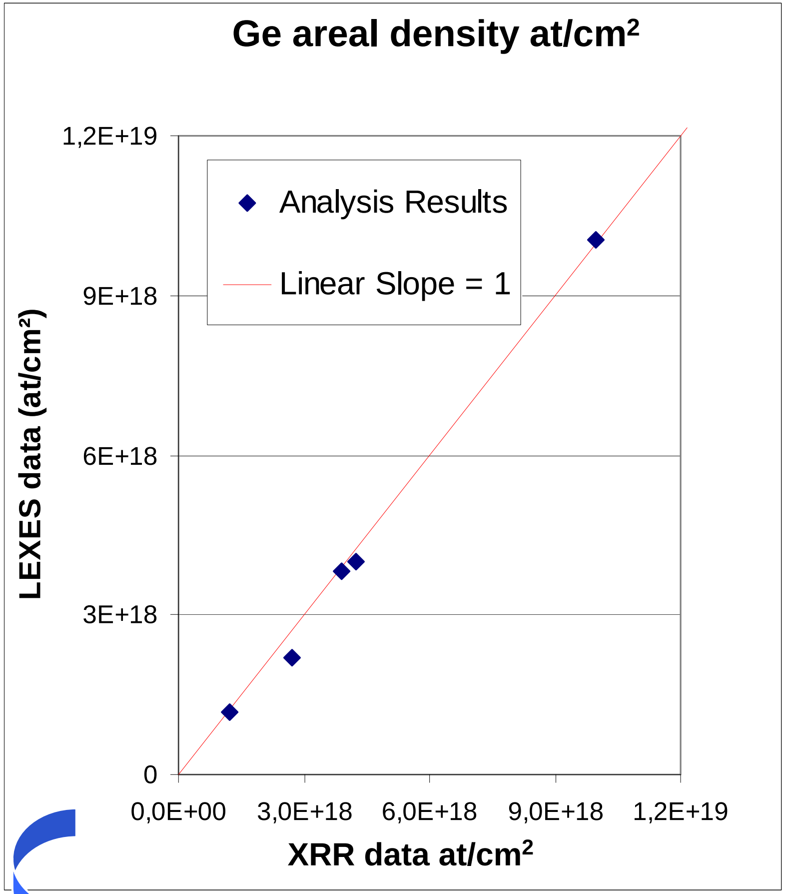
Shallow Probe easily discriminates dose gradations of 5%. Linearity is maintained even for very shallow implants or highly doped implants (E16 at/cm²).

Uncertainty bars are smaller than the dots (1σ<0.5%).

Characterization of Si-Ge thin films:

comparison with XRR





Agreement between LEXES and XRR is typically ~3% for atomic density per area unit. But Spatial resolution is much better with LEXES (test pattern analysis).

Characterization of Si-Ge thin films:

Comparison with X-Ray Analysis

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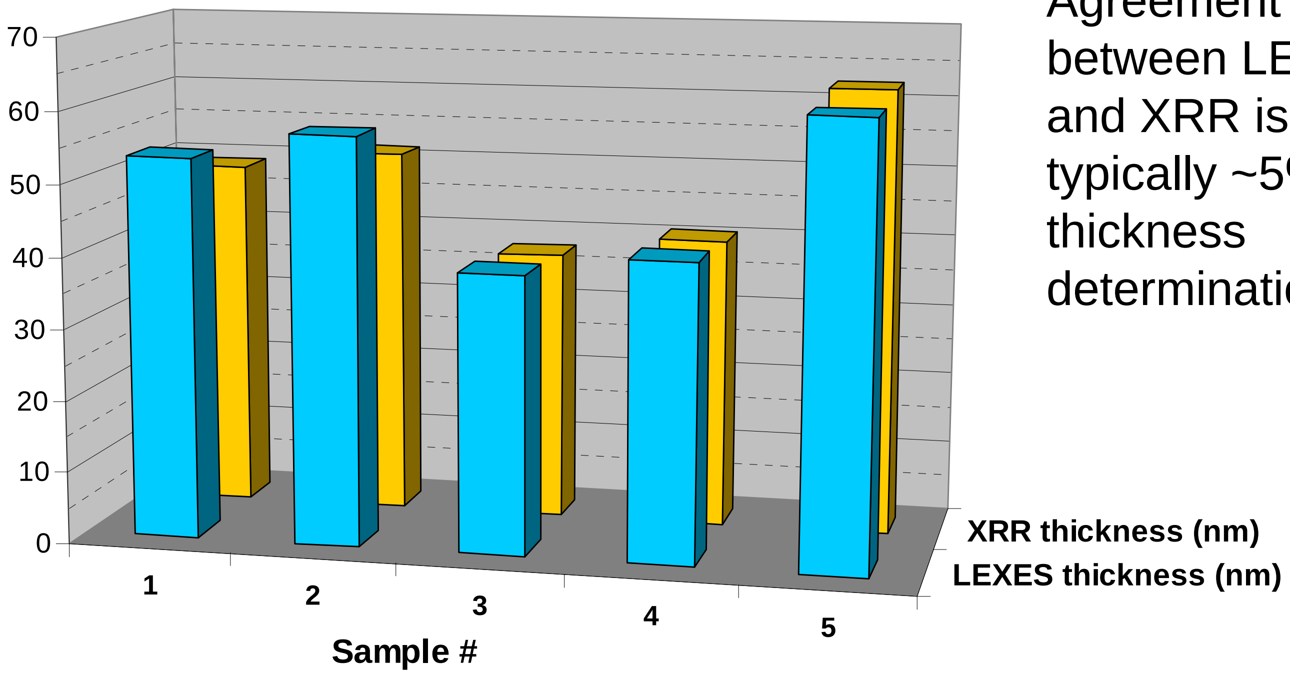
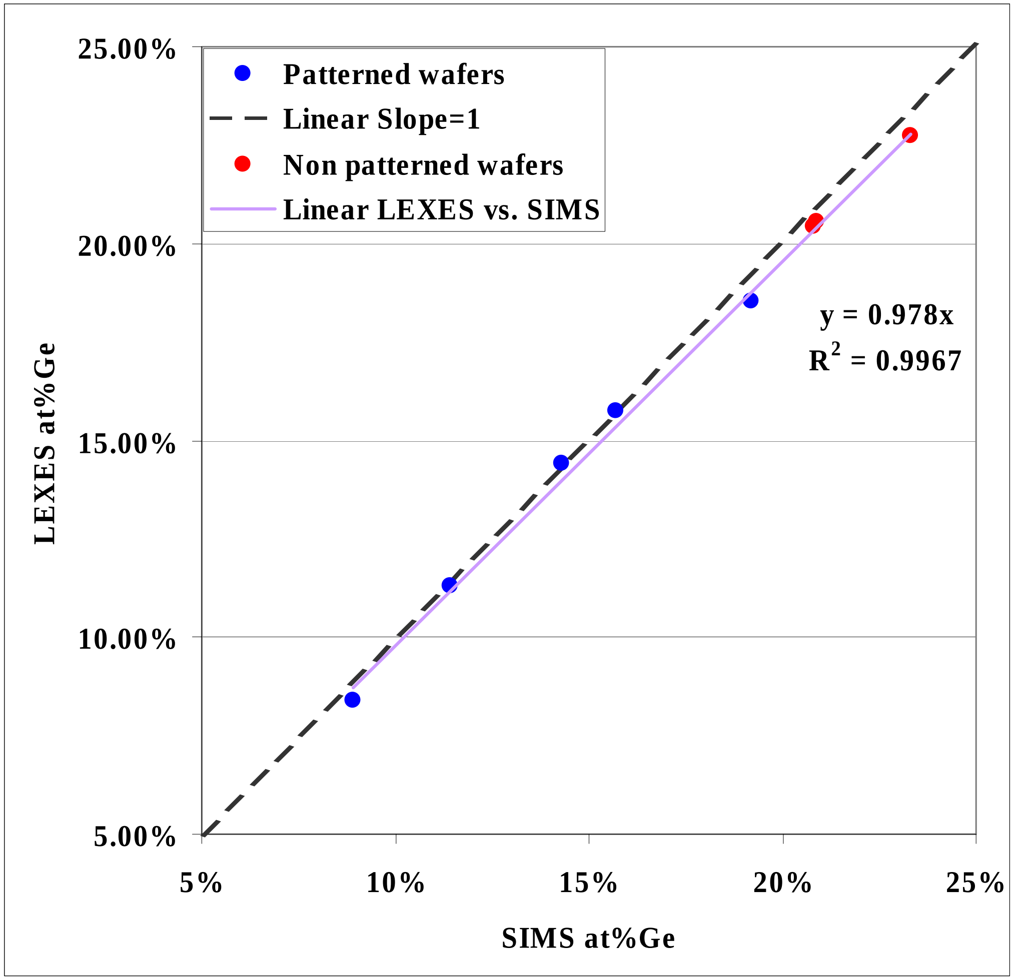


Agreement between LEXES and XRR is typically ~5% for thickness determination.

Si_xGe_{1-x} films composition

Comparison with SIMS

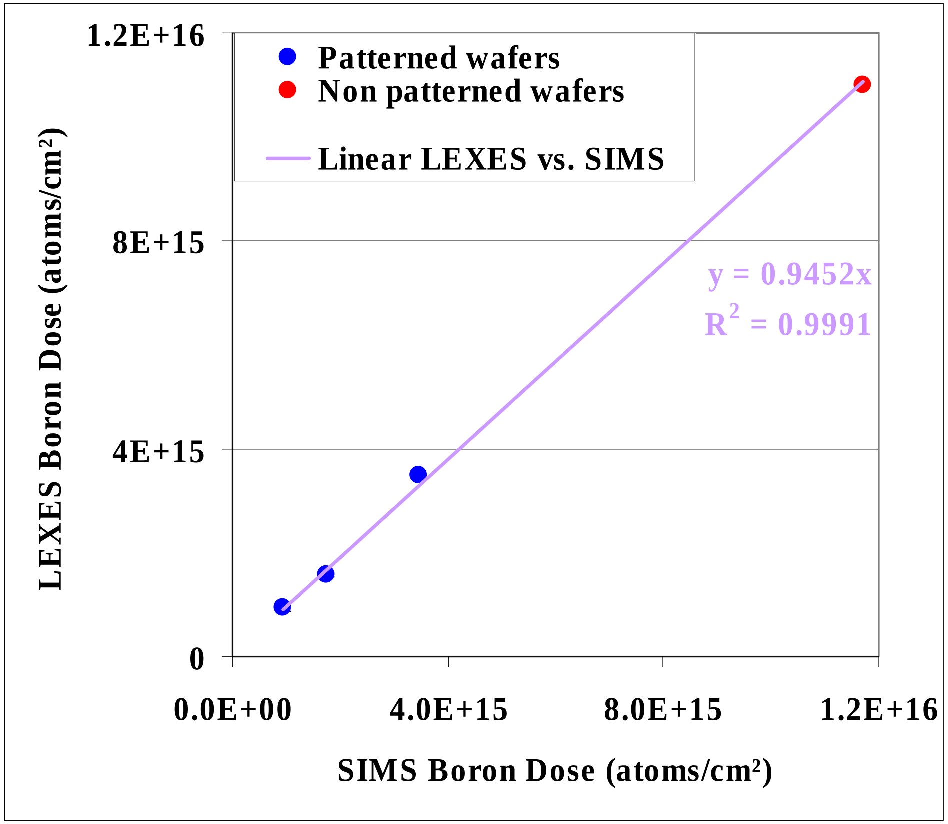


Both techniques are matching within 2% (!)

LEXES at% Ge	SIMS at% Ge
Patterned Wafers	
8.41%	8.90%
11.30%	11.40%
14.40%	14.30%
15.74%	15.70%
18.55%	19.20%
Non Patterned Wafers	
20.54%	20.90%
20.45%	20.80%
22.73%	23.30%

Boron dosimetry in SiGe films

Comparison with SIMS



LEXES dose (atoms/cm2)	Precision (%)	SIMS dose (atoms/cm2)
Non patterned wafer		
1.10E16	0.75	1.17E16
Patterned wafers		
9.50E14	0.44	9.43E14
3.48E15	1.13	3.45E15
1.58E+15	1.52	1.75E15

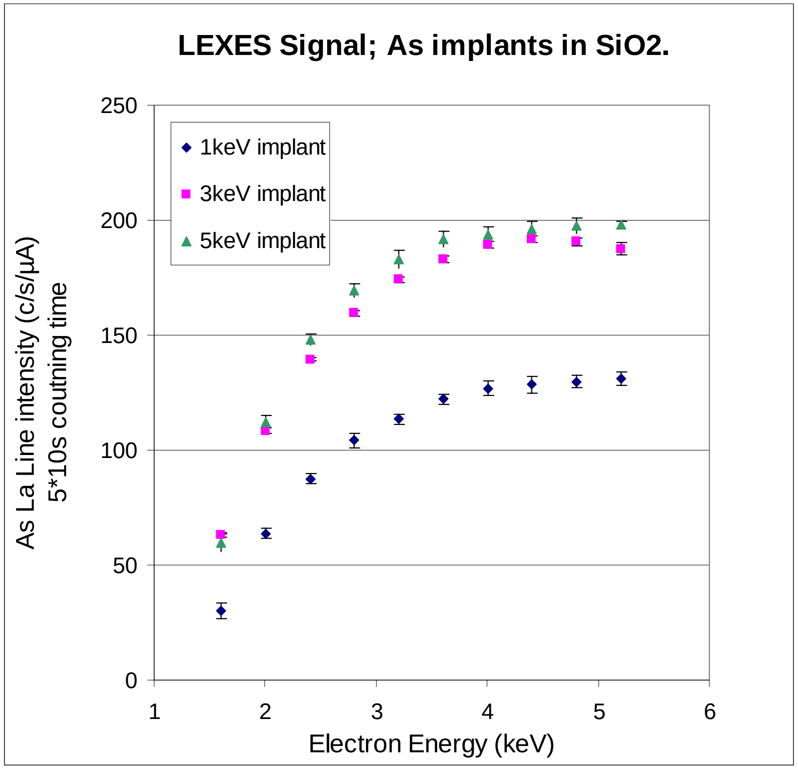
Both techniques are matching within 5%

Characterization of Low Energy / High Current Implantation Process

Arsenic.

Range of samples	Nominal dose (atoms/cm^2)
Si-c(1keV)	1,00E+15
Si-c(3keV)	1,00E+15
Si-c(5keV)	1,00E+15
Si-c(1keV)	5,00E+14
Si-c(3keV)	5,00E+14
Si-c(5keV)	5,00E+14
Si-c(1keV)	5,00E+13
Si-c(3keV)	5,00E+13
Si-c(5keV)	5,00E+13
Si-a(1keV)	1,00E+15
Si-a(3keV)	1,00E+15
Si-a(5keV)	1,00E+15
SiO$_2$(1keV)	1,00E+15
SiO$_2$(3keV)	1,00E+15
SiO$_2$(5keV)	1,00E+15

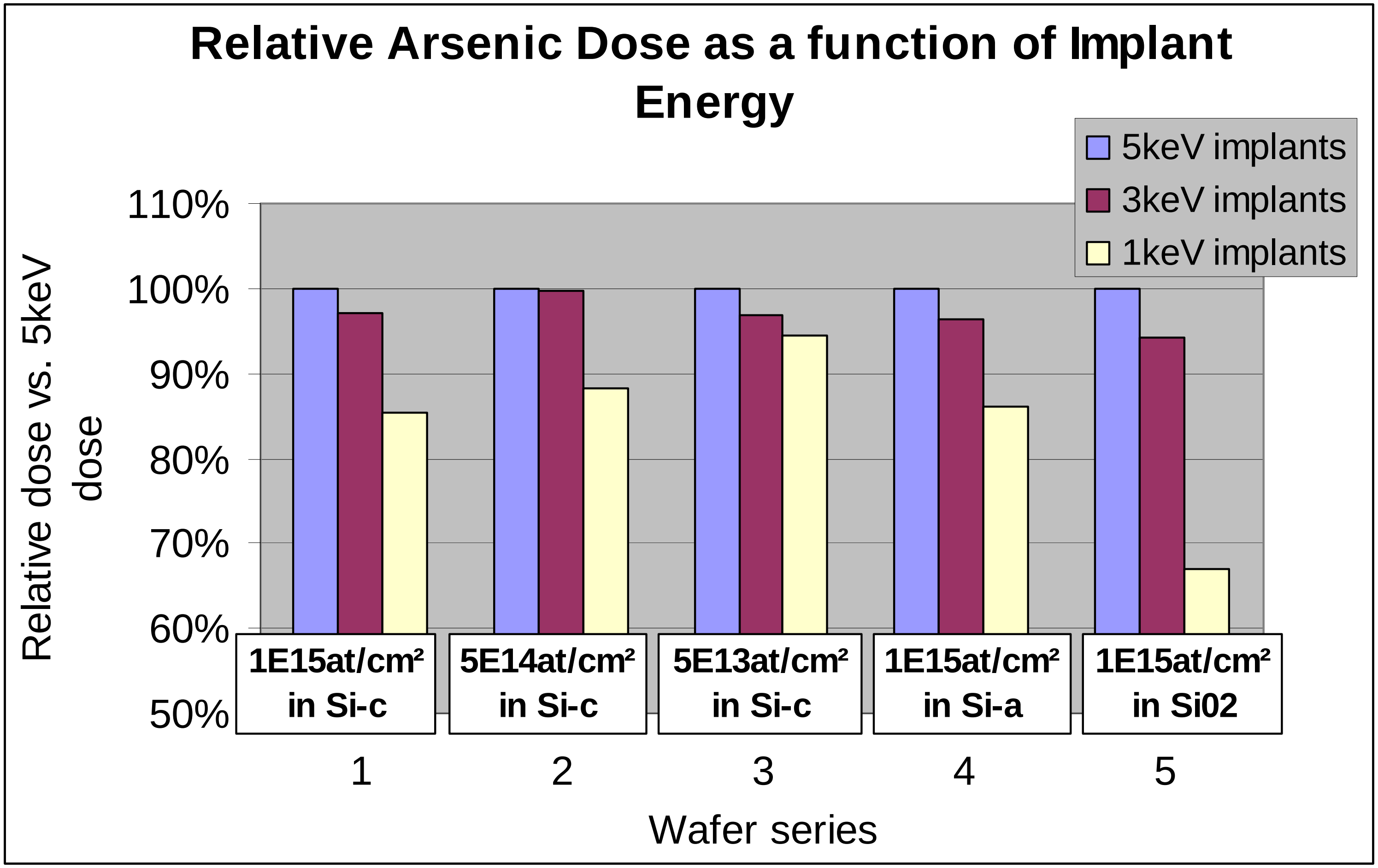
Example of LEXES signal from 1 sample set: samples are easily distinguished one another.



Samples provided by Y. Kataoka from Fujitsu Laboratories Ltd.

Characterization of Low Energy / High Current Implantation Process

Arsenic.

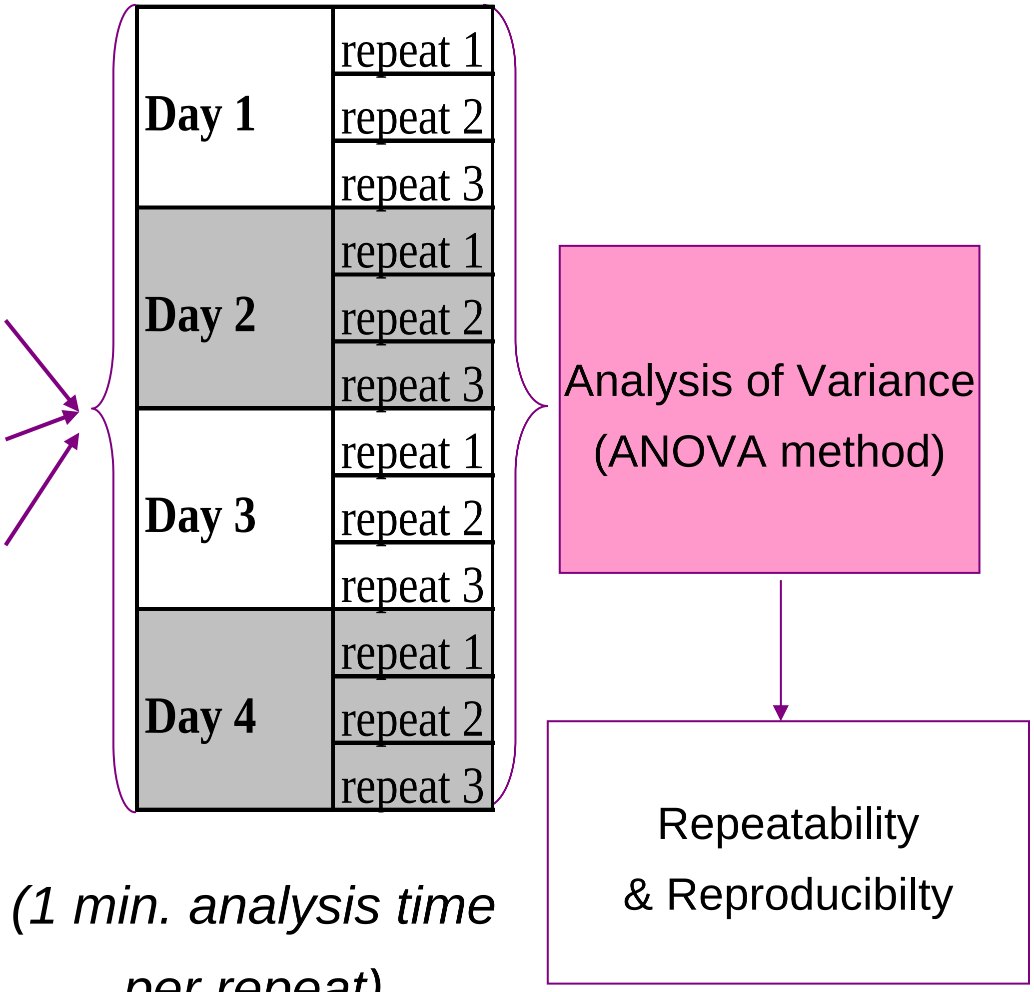


Ratio between Retained and Nominal dose decreases with decreasing implant energy and increasing implant dose.

Gauge Repeatabilty & Reproducibilty Study

Case of 1 keV Arsenic implants

Range of samples	Nominal dose (atoms/cm^2)
Si-c(1keV)	1,E+15
Si-c(1keV)	5,E+14
Si-c(1keV)	5,E+13



Day 1	repeat 1 repeat 2 repeat 3
Day 2	repeat 1 repeat 2 repeat 3
Day 3	repeat 1 repeat 2 repeat 3
Day 4	repeat 1 repeat 2 repeat 3

Analysis of Variance
(ANOVA method)

Repeatability
& Reproducibilty

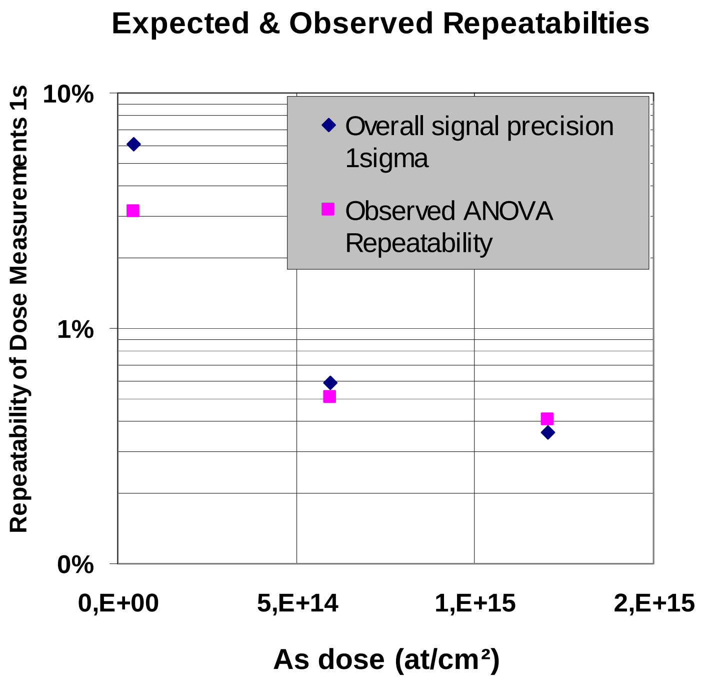
(1 min. analysis time per repeat)

GRR Study; *Case of 1 keV Arsenic implants.*

1E15 at/cm^2	Measured Dose (at/cm^2)	% of Mean Value
Mean value	1,21E+15	
Repeatability (Equipment Variation)	2,54E+13	**0,41%**
Reproducibility (Apraiser Variation)	3,89E+13	**0,63%**
Gage R&R (Measurement system repeatability&reproducibility)	4,65E+13	**0,75%**

5E14 at/cm^2	Measured Dose (at/cm^2)	% of Mean Value
Mean value	5,98E+14	
Repeatability (Equipment Variation)	1,57E+13	**0,51%**
Reproducibility (Apraiser Variation)	4,56E+13	**1,48%**
Gage R&R (Measurement system repeatability&reproducibility)	4,83E+13	**1,57%**

5E13 at/cm^2	Measured Dose (at/cm^2)	% of Mean Value
Mean value	4,51E+13	
Repeatability (Equipment Variation)	7,25E+12	**3,12%**
Reproducibility (Apraiser Variation)	1,59E+13	**6,83%**
Gage R&R (Measurement system repeatability&reproducibility)	1,74E+13	**7,51%**



Observed Repeatability and predicted Precision match consistently.

Estimated System Throughput

(combined with a 300mm FOUP)

Boron dosimetry in Si, shallow implants, 1E15at/cm², Precision <1%

Analysis Type	# points /wafer	Run Rate (w/h)
Full Quantitative	1	19
Full Quantitative	5	8
Uniformity Check	5	24
Uniformity Check	25	11

Arsenic dosimetry in Si, 1E15at/cm², Precision <0.5%

Analysis Type	# points /wafer	Run Rate (w/h)
Full Quantitative	1	11
Full Quantitative	5	4
Uniformity Check	5	21
Uniformity Check	25	8

Ge measurement in SiGe box, 20 at%, 100nm, Precision <0.3%

Analysis Type	# points /wafer	Run Rate (w/h)
Full Quantitative	1	30
Full Quantitative	5	12
Uniformity Check	5	27
Uniformity Check	25	13

Conclusion

- The ***Shallow Probe*** instrument provides real Quantitative & Elemental information on ULE to ME implants doses >1E14 at/cm^2 (no upper dose limits) with typical accuracy ~3% and 1σ precision ~ 0.1 to 1%. Work is in progress to extend these capabilities to the E13 at/cm^2 range.
- Spatial Resolution (3-100µm) makes the technique compatible with pattern analysis.
- Long Term Reproducibility about 1-2% and easiness of quantitation settings favor its use for Process Matching, especially for Low Energy/High Current Implanters.
- The instrument can be equipped with full wafer capability (up to 300mm) and is designed to be compatible with FOUP operation. High Throughput (10-20 w/h for 25 points mapping) associated with sub% Repeatability performance make it a serious candidate as an industrial Metrology tool. First 300mm instrument delivery scheduled by next fall.
- Your samples are welcome to evaluate the new tool!