

Recent Advances in Implant Metrology with the Shallow Probe LEXES Tool

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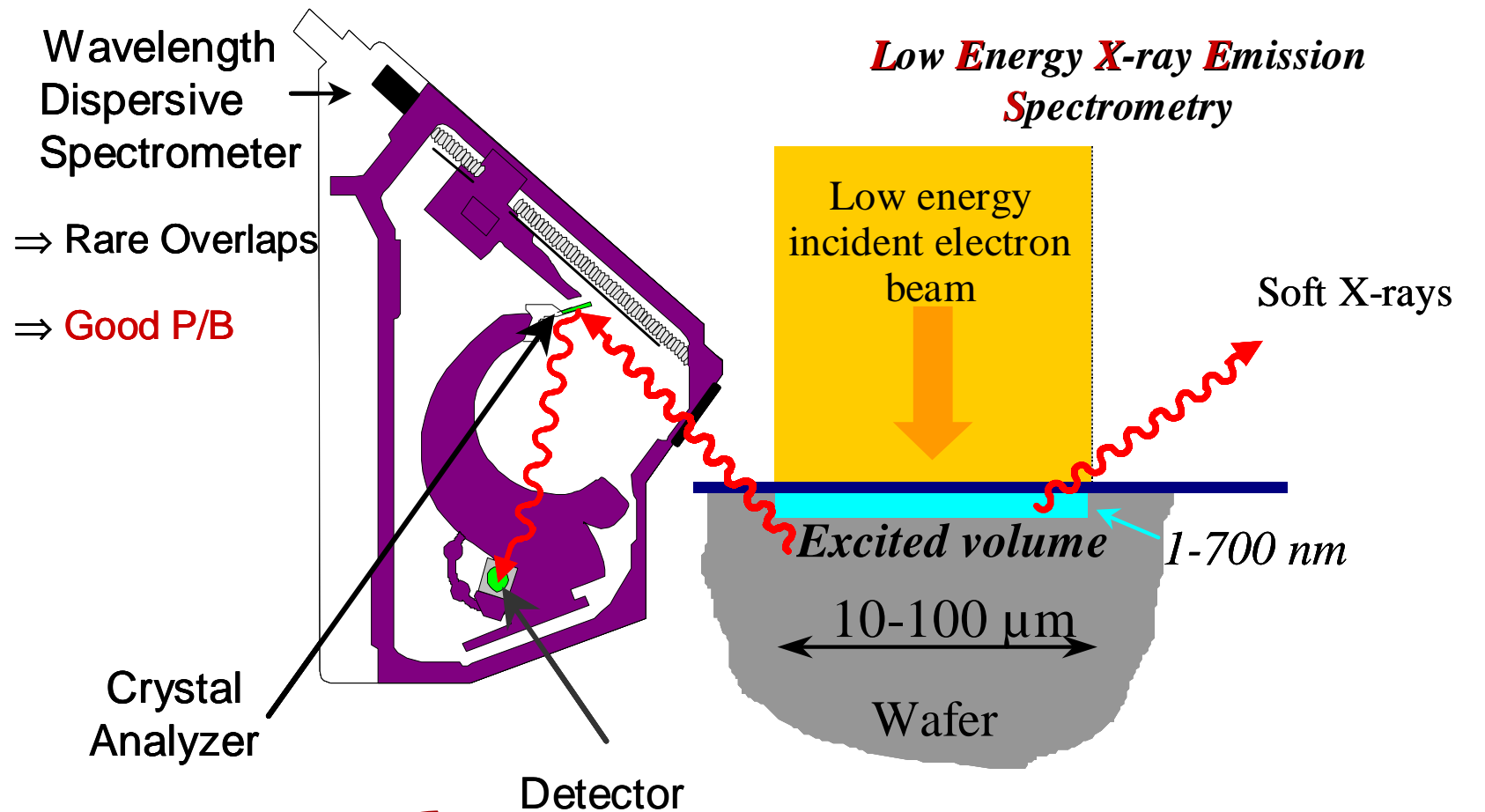
P.-F. Staub; C. Hombourger; M. Schuhmacher

Cameca, France



Theory of the analytical method: the LEXES technique

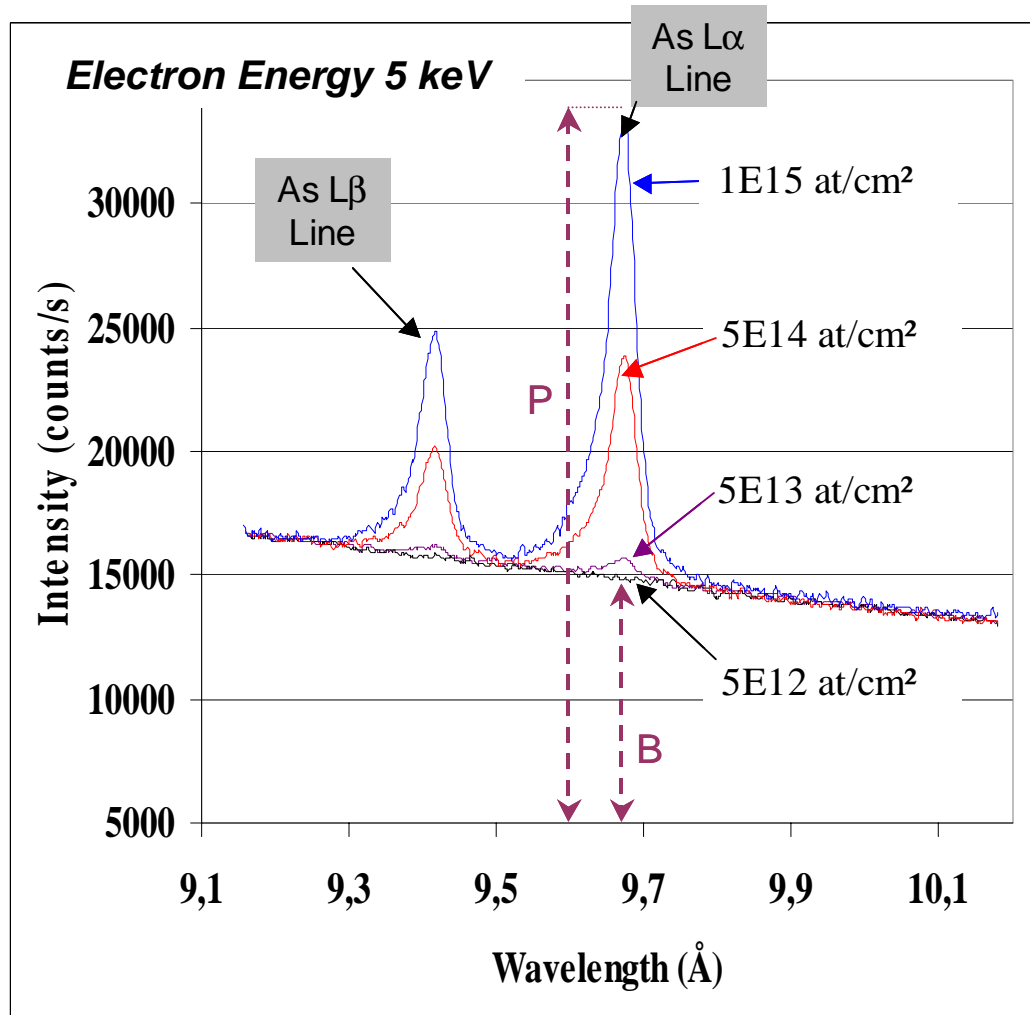
Sample Excitation & Detection



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.

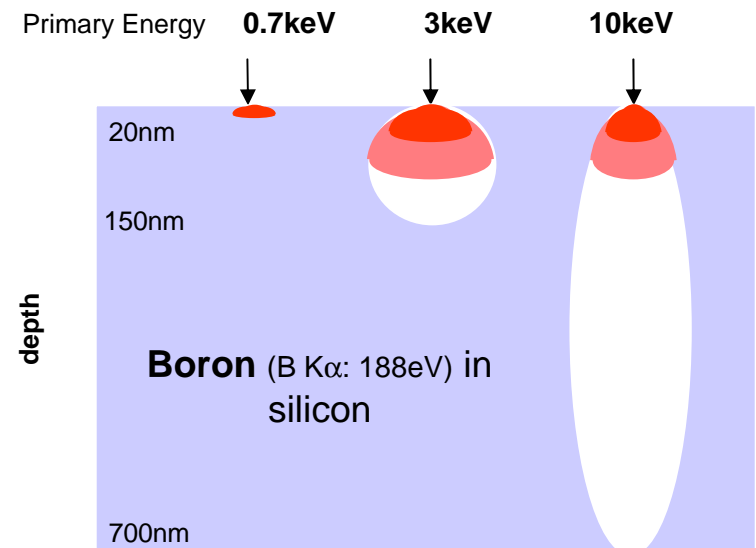
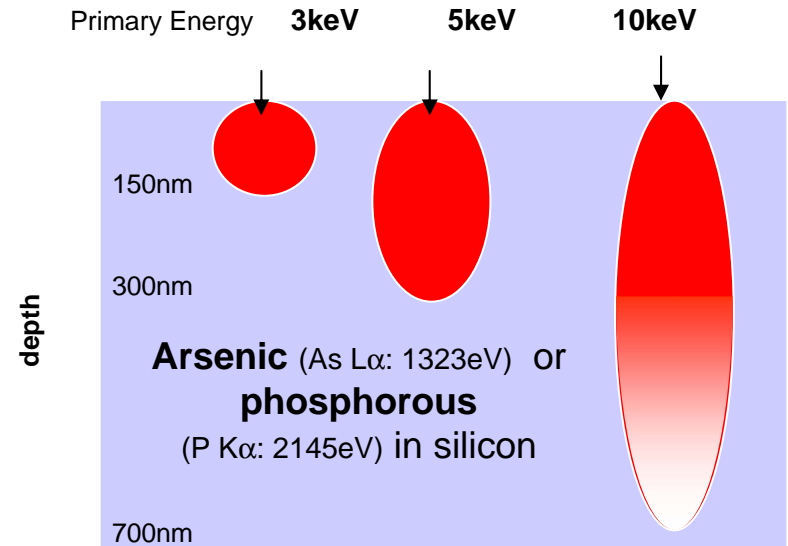
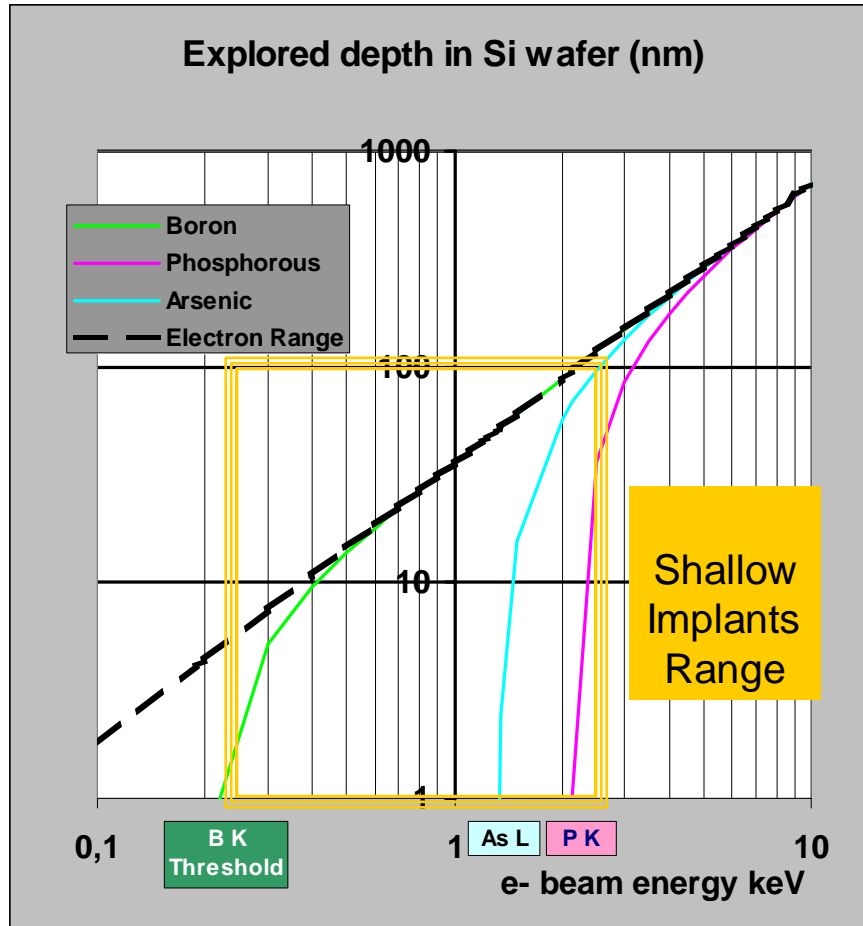
Case of 5keV As implants in Si.



Uncertainty on dopant signal :

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

LEXES Probing of Nanometric Depths in Silicon

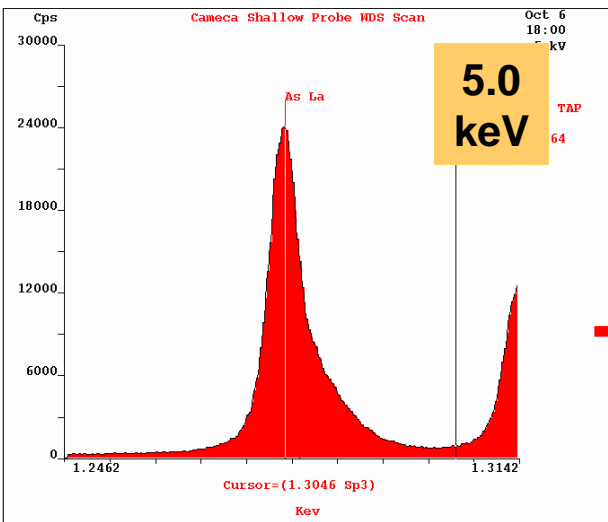
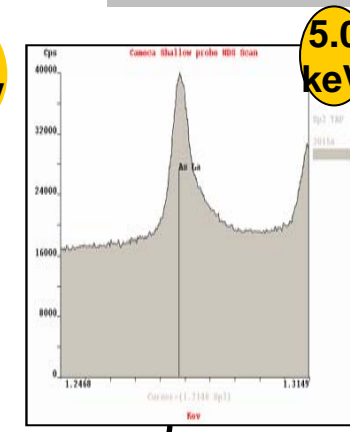
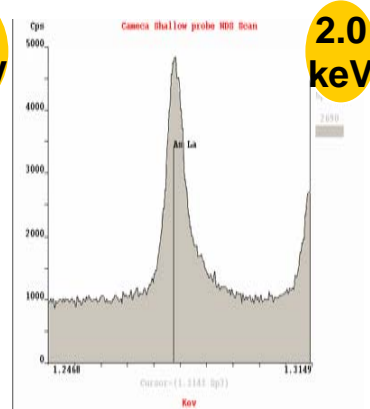
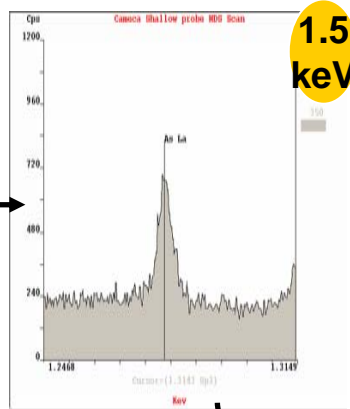


Quantification Procedure

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



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



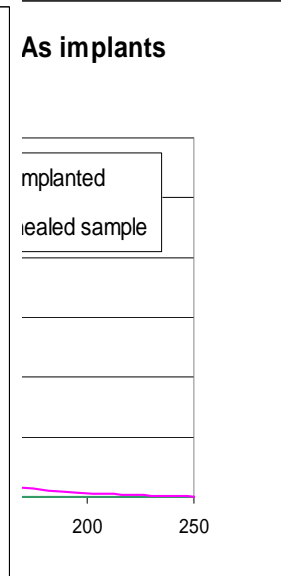
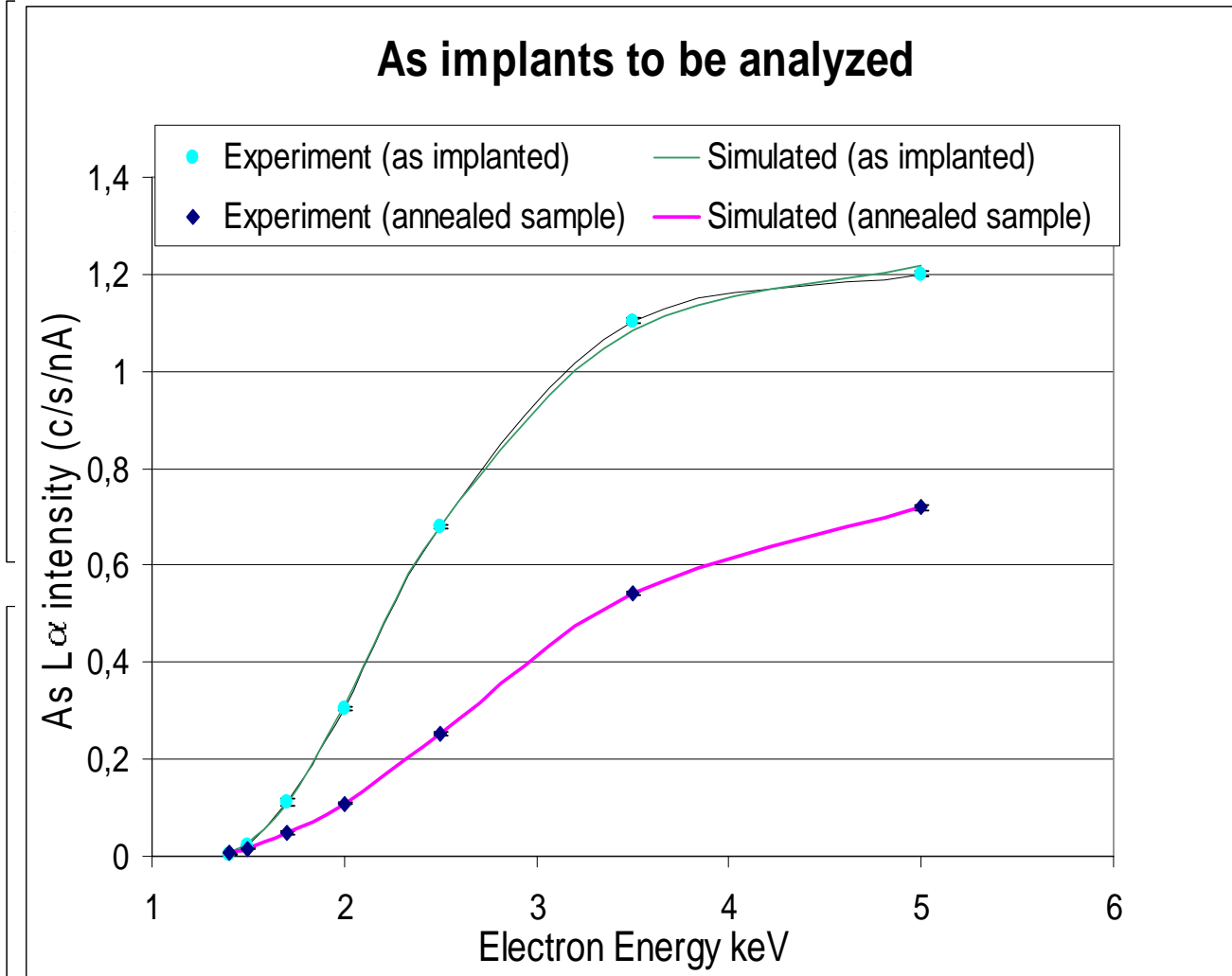
Profile Extraction (Physical Model)

Absolute Dose Determination

Calibration



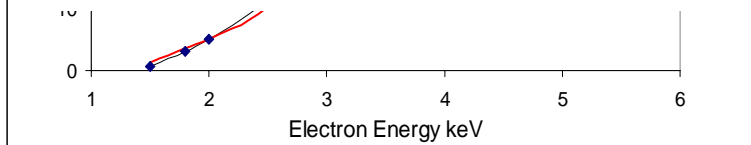
Example of Quantification



5 at/cm² +/- 0,81%
 15 at/cm² +/- 1,10%

σ_{Dose} , as follows:

$$\frac{\sigma_{signal}}{Intensity}$$




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

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 $D > 1\text{E}15\text{at}/\text{cm}^2$; 0,5-2% for $1\text{E}14 < D < 1\text{E}15\text{at}/\text{cm}^2$, 1,5-10% for $D < 1\text{E}14\text{at}/\text{cm}^2$	$5\text{E}12$ - $1\text{E}13$ at/ cm^2
Dielectric & Oxide films	N, O, Metals (Hf, Ta, Zr, .)	Sub-nm to 1 μm 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 $> 1\text{E}15\text{at}/\text{cm}^2$	$5\text{E}12\text{at}/\text{cm}^2$ for Ge, $5\text{E}13$ for B

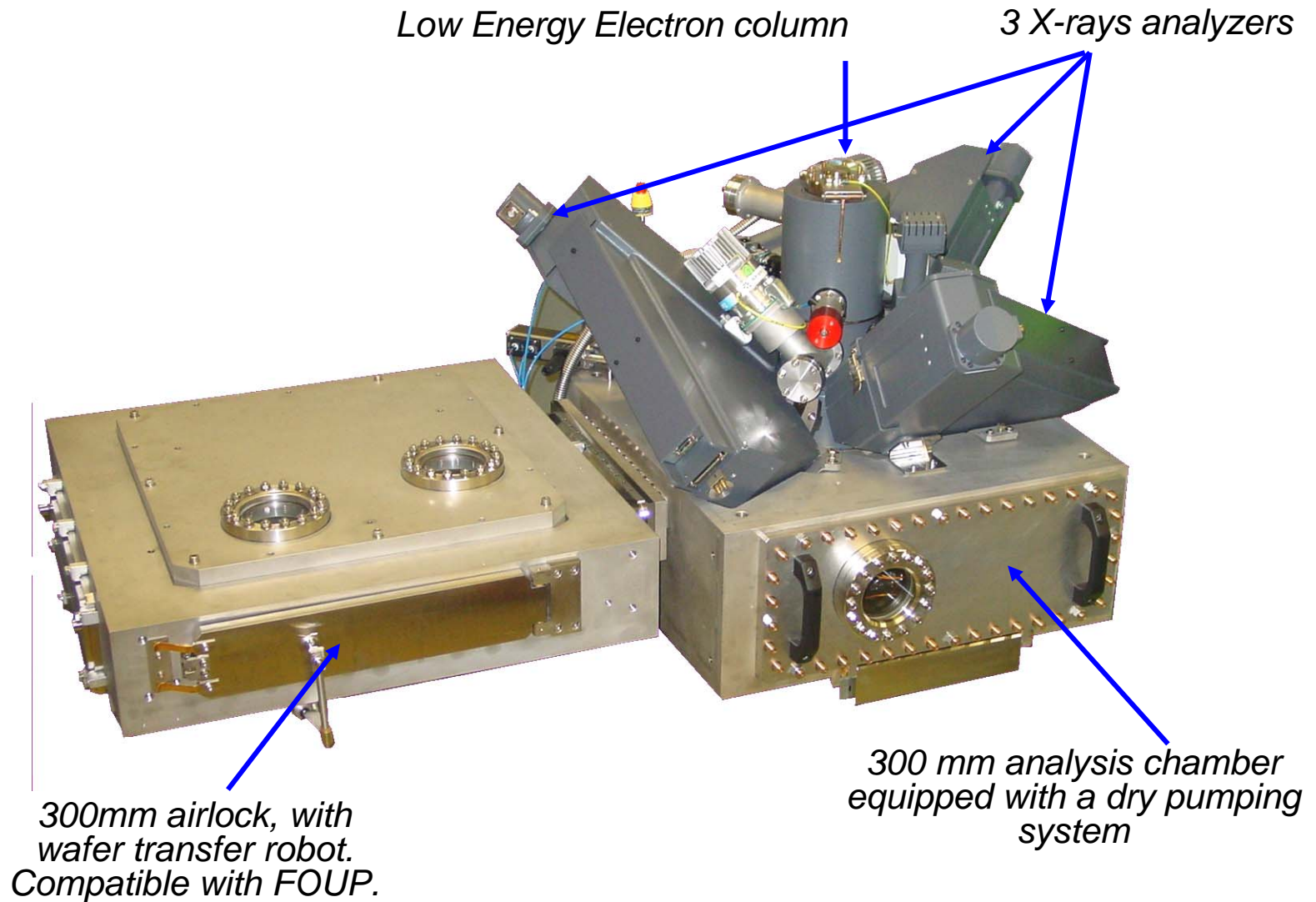
Shallow Probe System Description

- 
- ◆ 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*

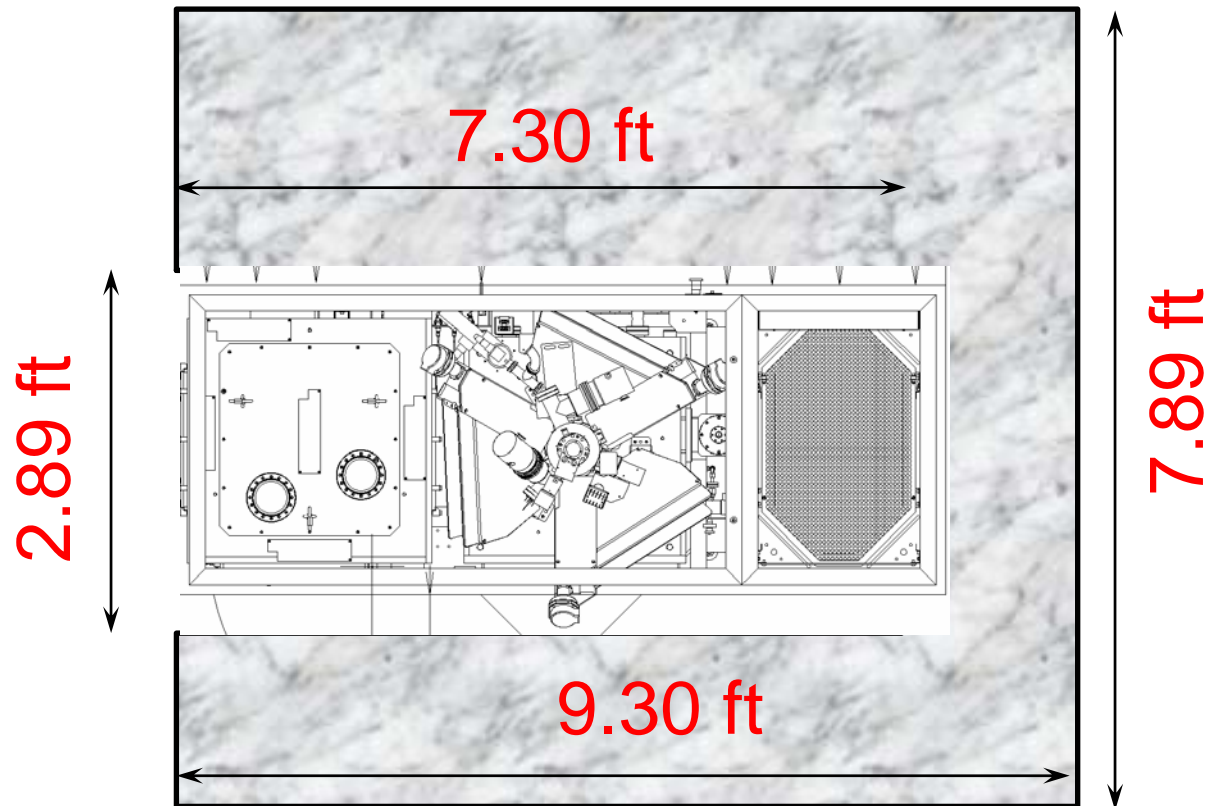
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Footprint

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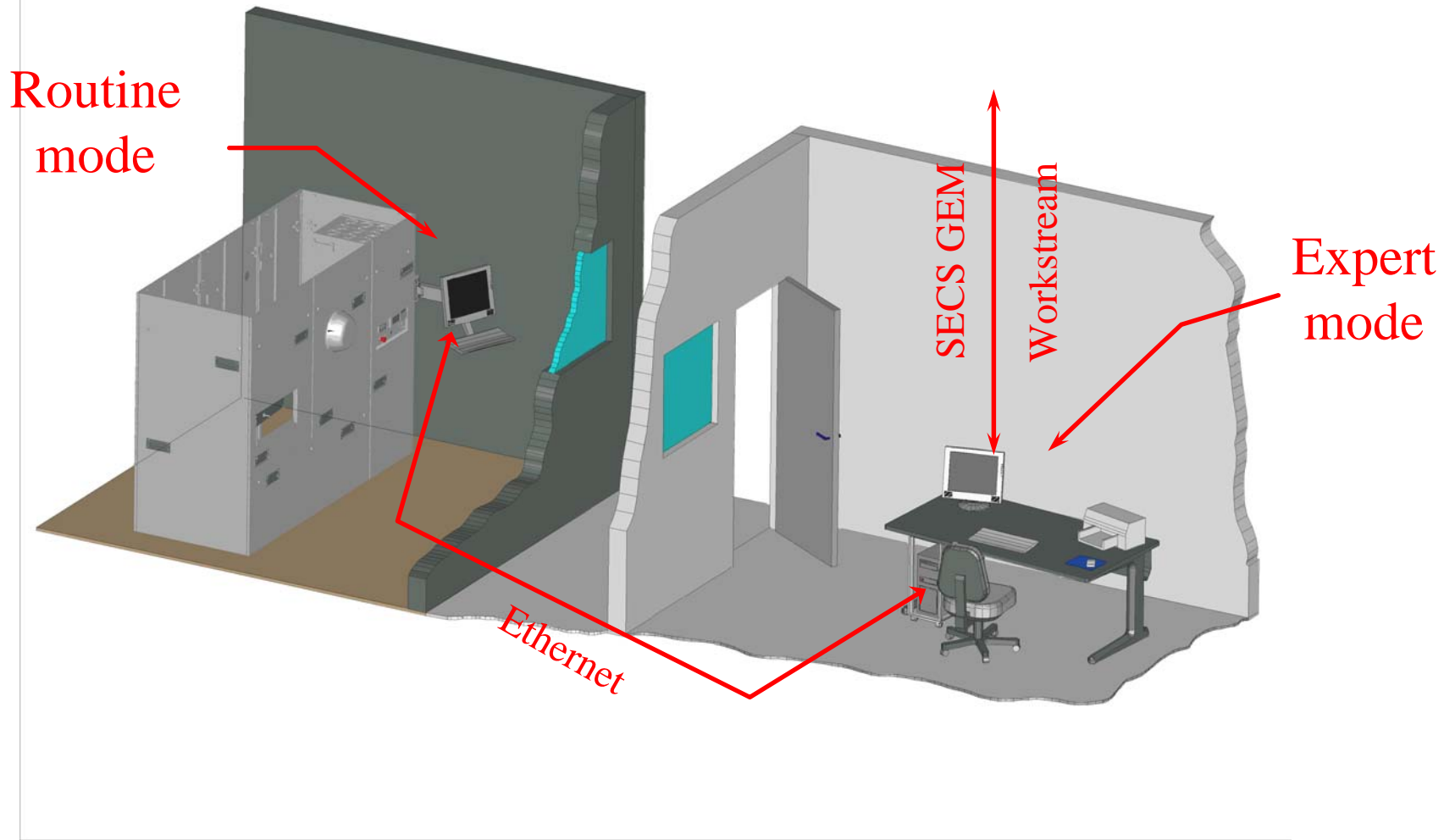
Physical envelope : **21 ft²**

With clearance : **73 ft²**



Clean Room Environment

Two control desks



Low Energy Electron Column

The logo for CAMECA, featuring the word "CAMECA" in a bold, sans-serif font with a red triangle above the letter 'A'.

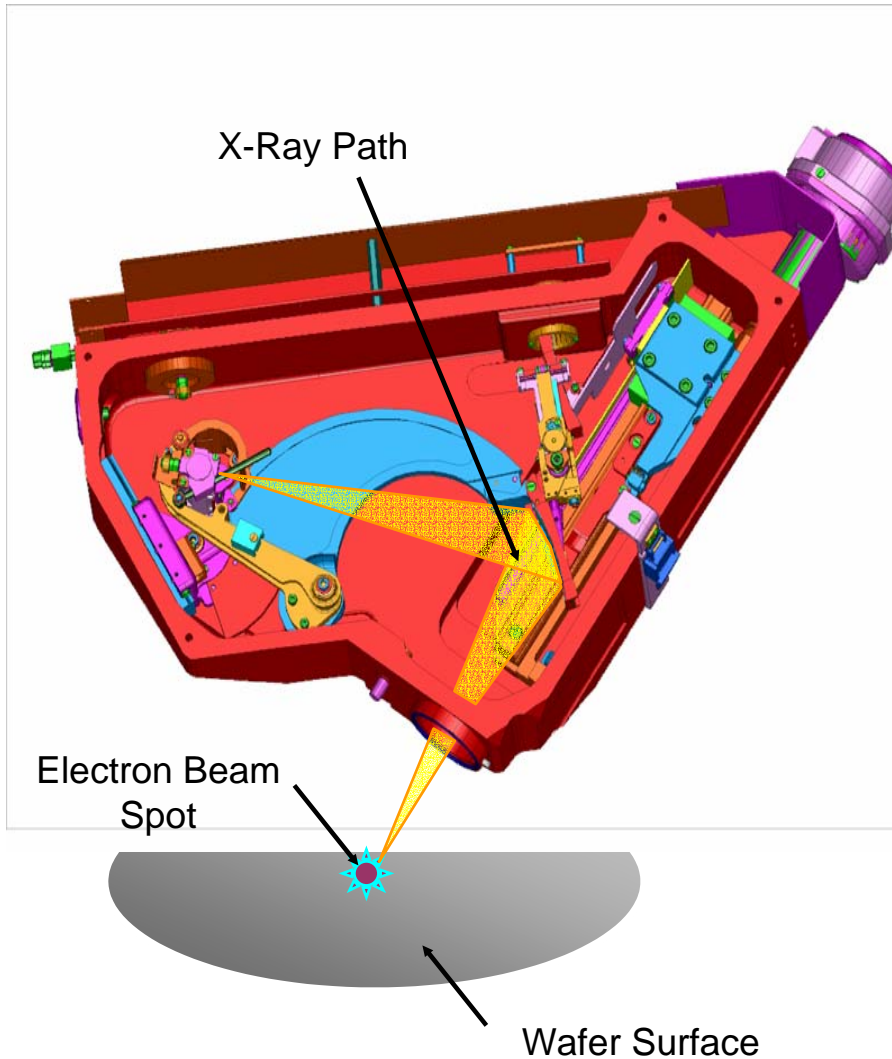
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- ◆ Derived from long established Cameca EPMA Expertise
- ◆ New Design to achieve Quantitative Electron Probe at very low Energy and high Current. (*patent pending*)
- ◆ Electron Beam 0.2 to 10keV, focused on spots 3-100 μ m. Beam Current from 10nA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

Wavelength Dispersive Spectrometers

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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

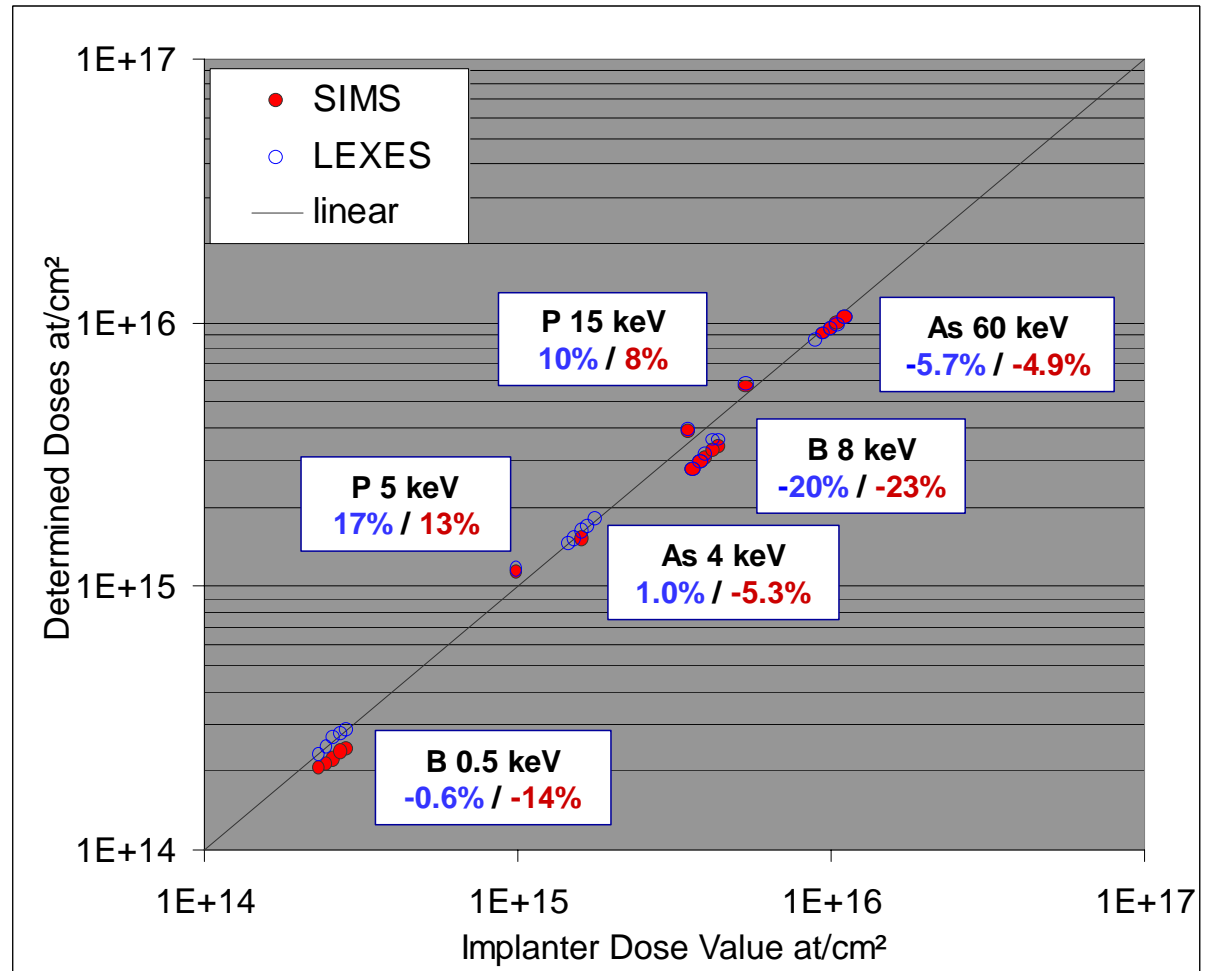
- ◆ System configuration
-  ◆ System performance (Implant Characterization)

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.

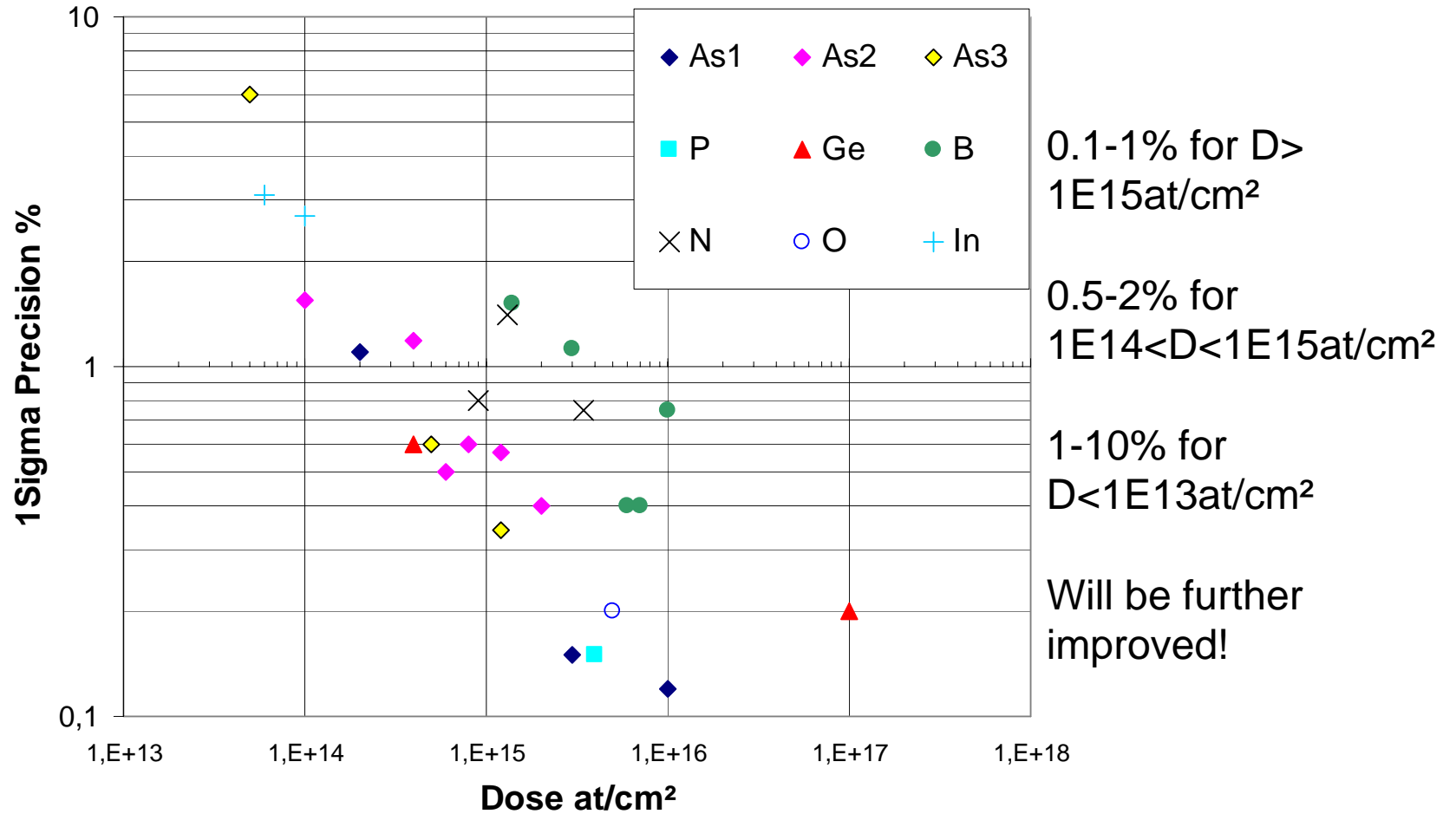


Samples provided by S. Corcoran from Intel Inc. and P. Ronsheim from IBM

Precision per point



Precision of counting as a function of Dose



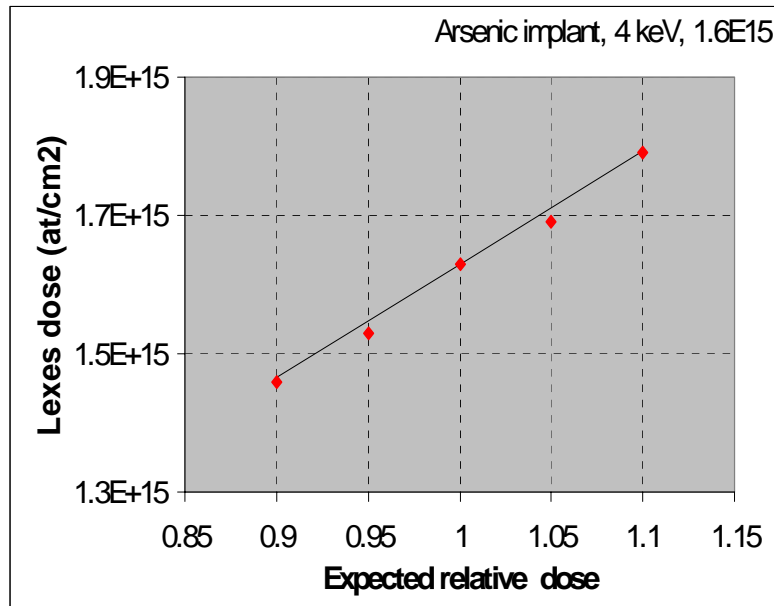
Resolving dose variations

Arsenic

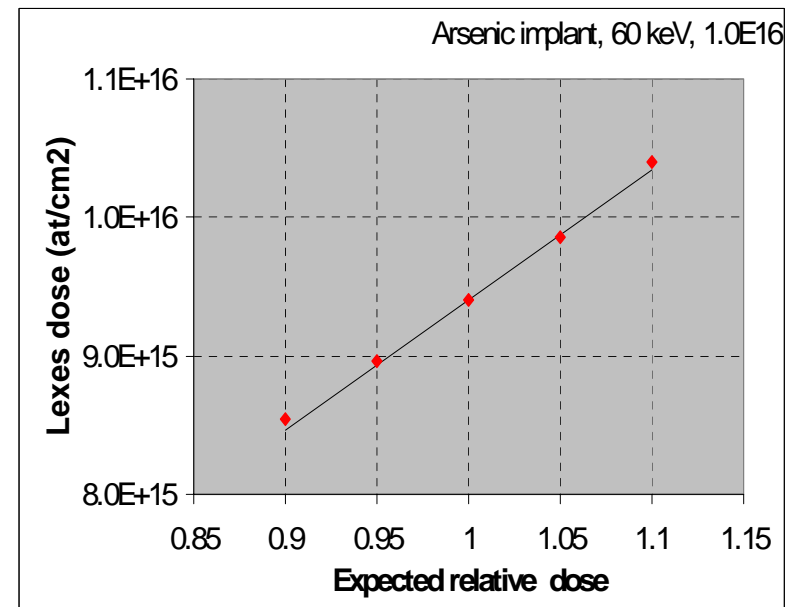
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Shallow Implants



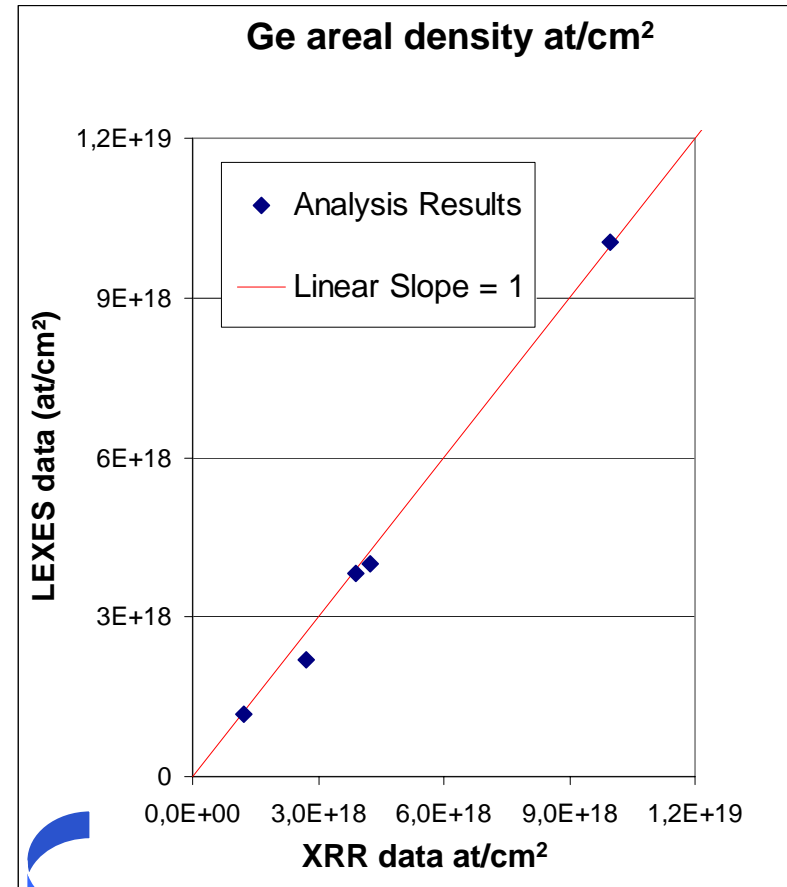
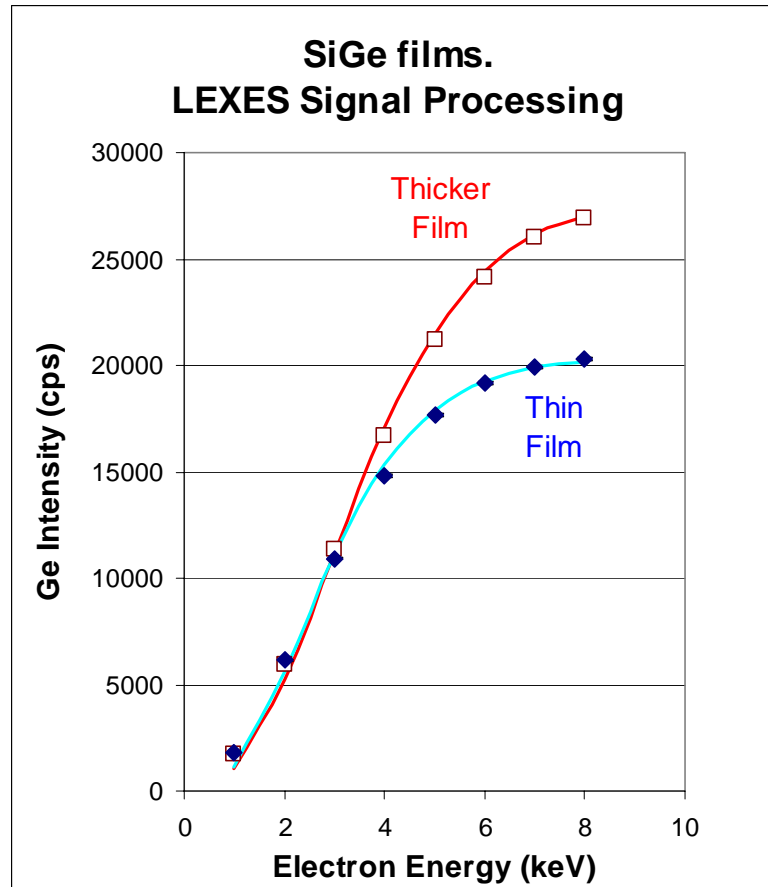
Medium Energy Implants



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

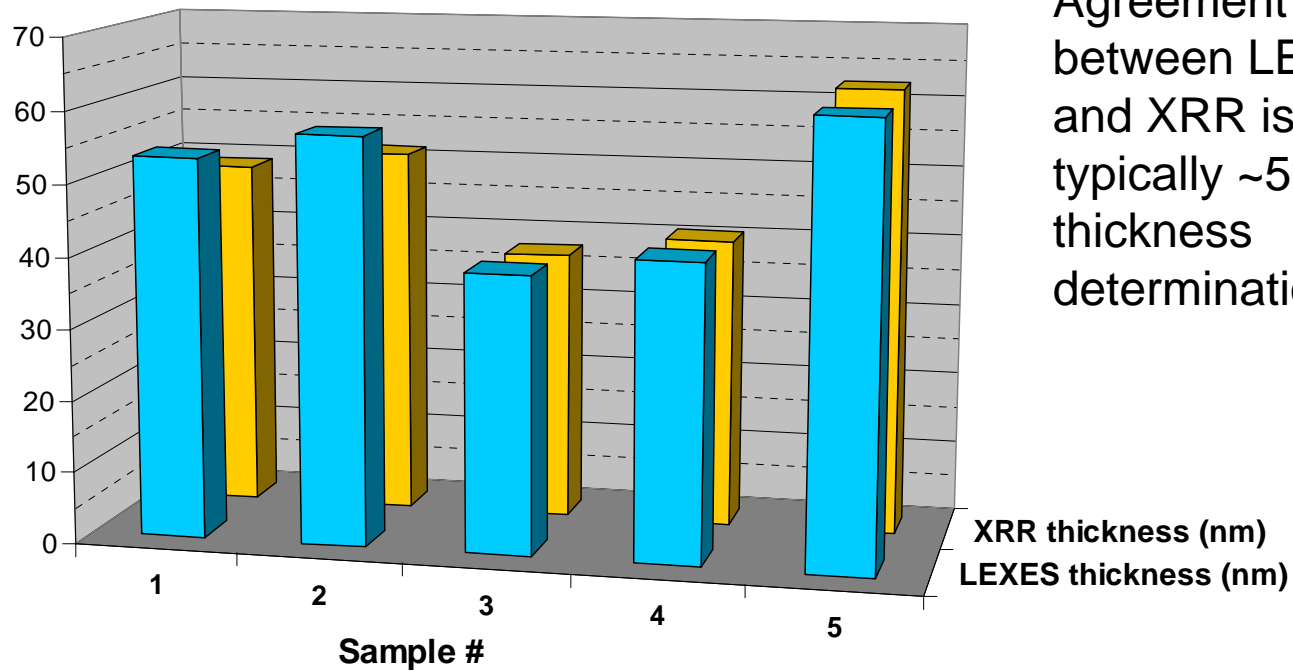
Uncertainty bars are smaller than the dots ($1\sigma < 0.5\%$).

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).

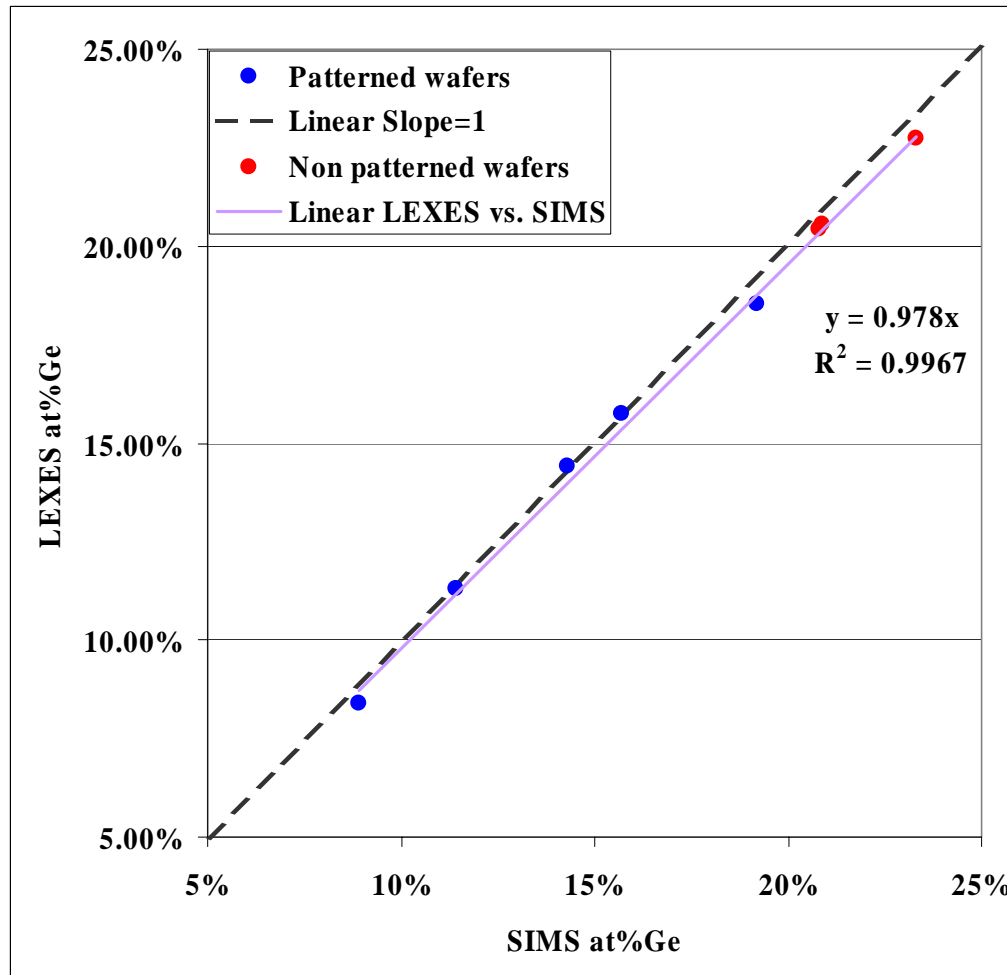
Characterization of Si-Ge thin films: *Comparison with X-Ray Analysis*

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

Si_xGe_{1-x} films composition

Comparison with SIMS

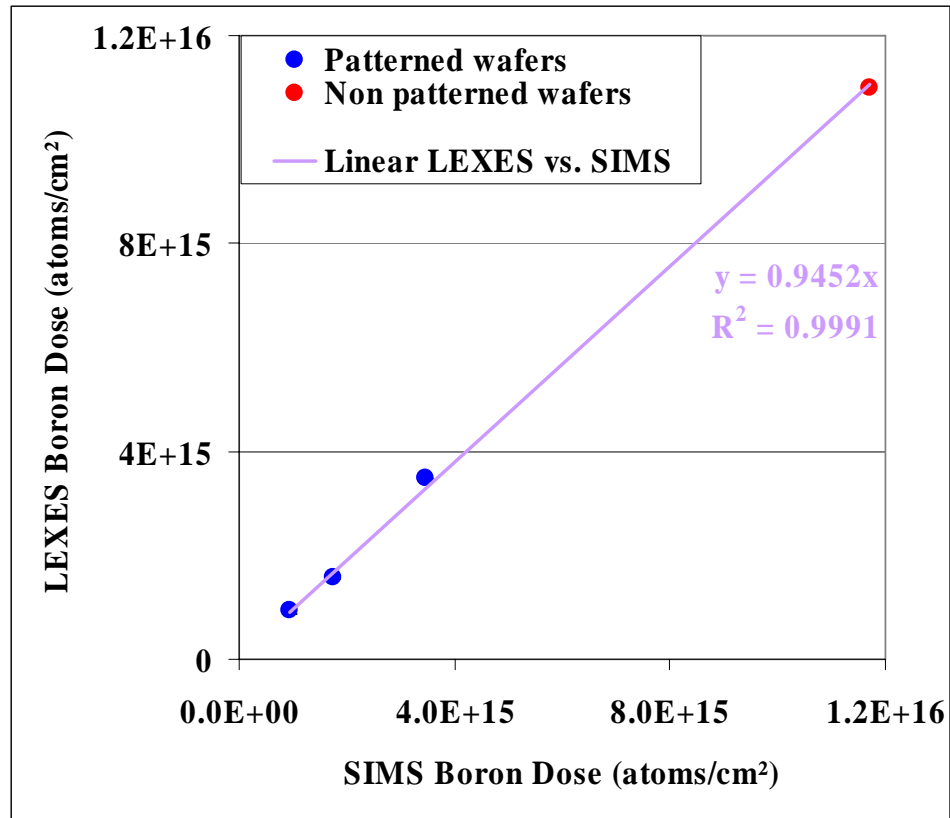
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Both techniques are matching within 2% (!)

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



Both techniques are matching within 5%

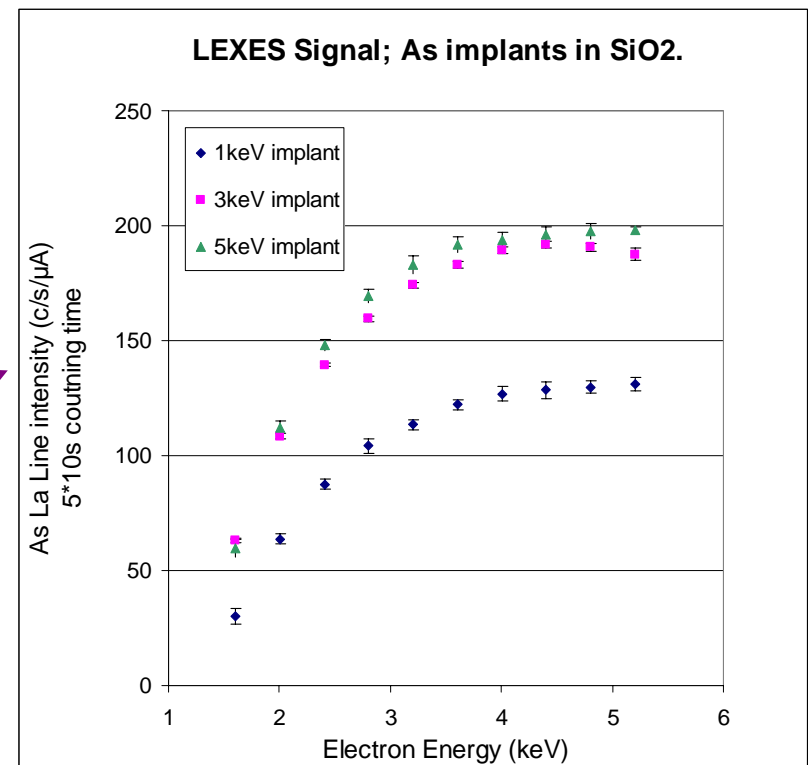
LEXES dose (atoms/cm ²)	Precision (%)	SIMS dose (atoms/cm ²)
Non patterned wafer		
1.10E16	0.75	1.17E16
Patterned wafers		
9.50E14	0.44	9.43E14
3.48E15	1.13	3.45E15
1.58E+15	1.52	1.75E15

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

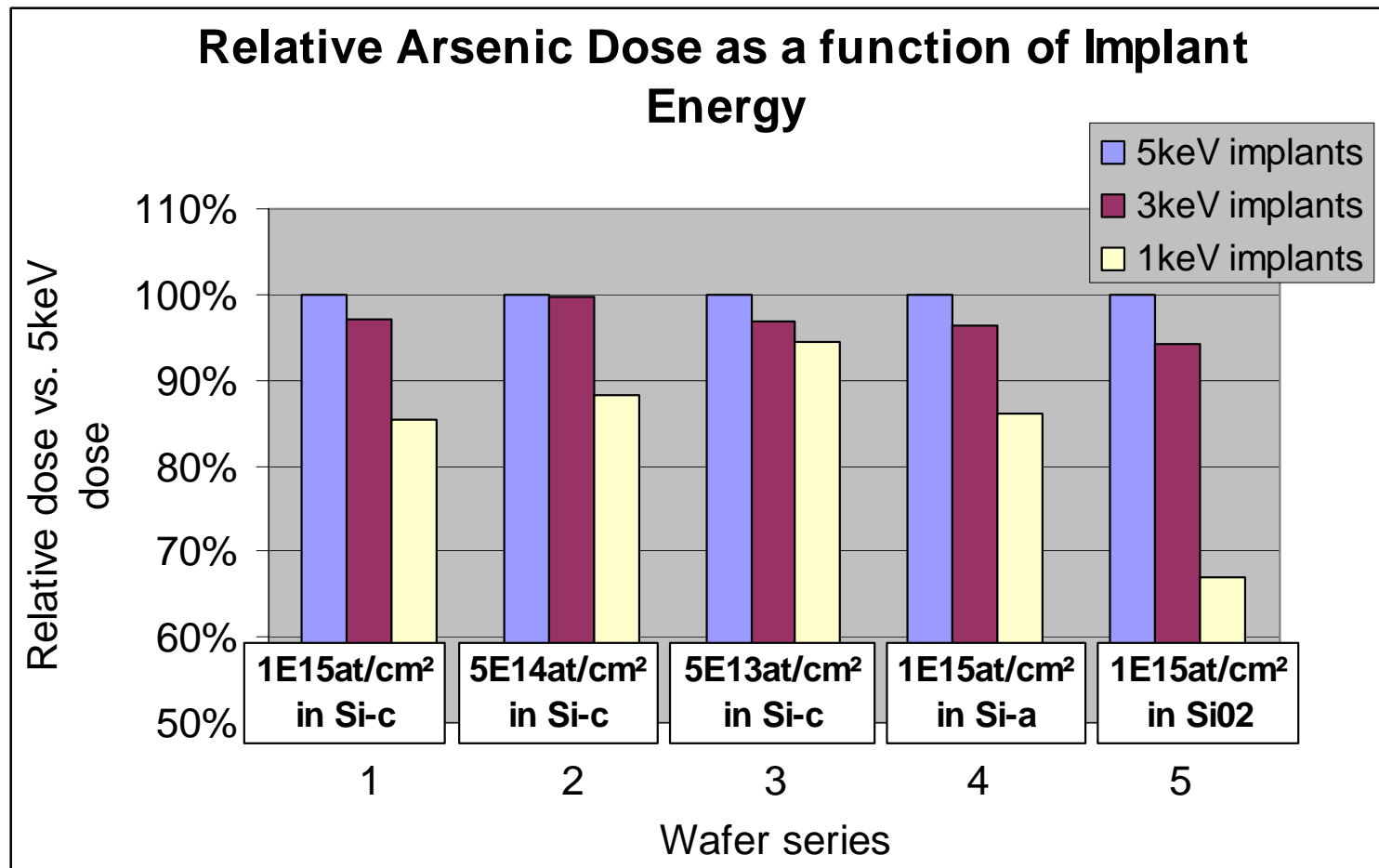
Example of LEXES signal from 1 sample set: samples are easily distinguished one another.



Samples provided by Y. Kataoka from Fujitsu Laboratories Ltd.

Characterization of Low Energy / High Current Implantation Process

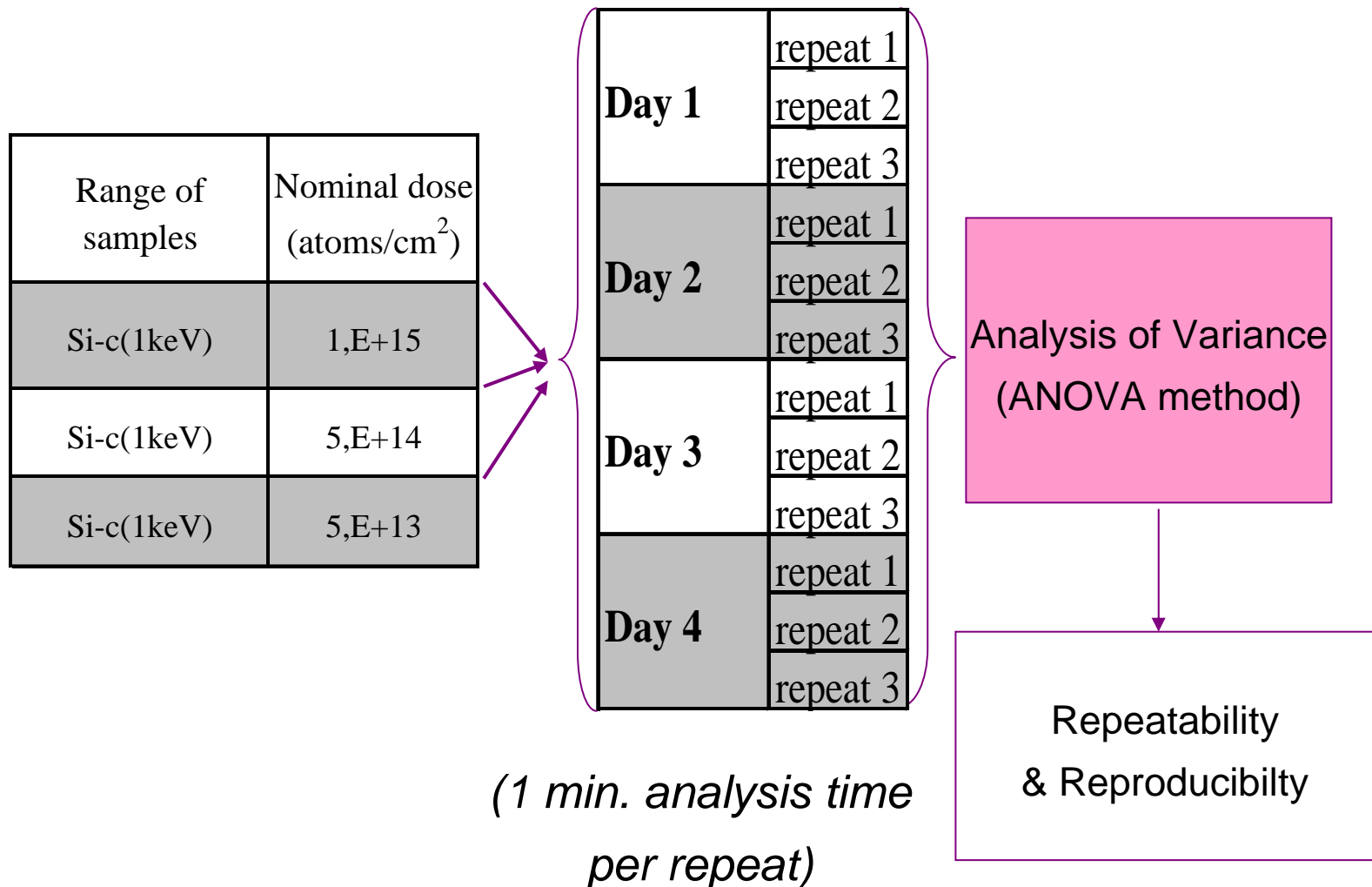
Arsenic.



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

Gauge Repeatability & Reproducibility Study

Case of 1 keV Arsenic implants



GRR Study; Case of 1 keV Arsenic implants.

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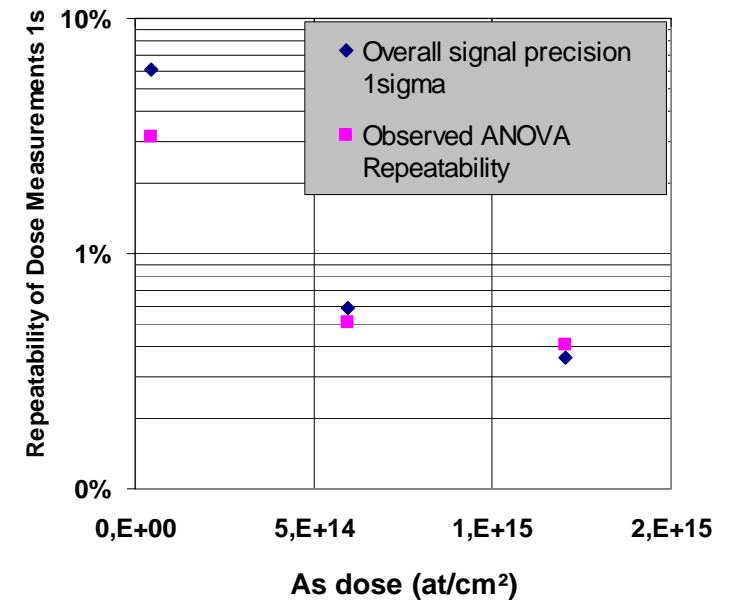
1E15 at/cm²	Measured Dose (at/cm²)	% of Mean Value
Mean value	1,21E+15	
Repeatability (Equipment Variation)	2,54E+13	0,41%
Reproducibility (Apraiser Variation)	3,89E+13	0,63%
Gage R&R (Measurement system repeatability&reproducibility)	4,65E+13	0,75%

5E14 at/cm²	Measured Dose (at/cm²)	% 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/cm²	Measured Dose (at/cm²)	% 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.

Expected & Observed Repeatabilities



Estimated System Throughput (combined with a 300mm FOUP)


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Boron dosimetry in Si, shallow implants, $1E15at/cm^2$, 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, $1E15at/cm^2$, 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/cm² (no upper dose limits) with typical accuracy $\sim 3\%$ and 1σ precision ~ 0.1 to 1% . Work is in progress to extend these capabilities to the $E13$ at/cm² range.
- ◆ Spatial Resolution (3-100 μ m) 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!