Fab 5 Colorado Springs

Advanced Technique for $Si_{1-x}Ge_x$ Characterization: Infrared Spectroscopic Ellipsometry

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Joint work with
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ATMEL, Colorado Springs, CO

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Presenter: Richard Sun (rsun@angstec.com)

Outline

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1. Introduction
2. Epilayer Growth
3. Methodology - Characterization of SiGe films
4. Results and Discussion (IRSE vs. Xrd)
   - SiGe Box
   - Si Capped-box layers
   - Graded layers
   - Boron doped SiGe
   - Carbon alloyed SiGe with and without boron doped
5. Summary

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Introduction

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- $Si_{(1-x)}Ge_x$ and $Si_{(1-x-y)}Ge_xC_y$ films are top contenders for a wide range of high speed devices.
- Pseudomorphic growth of sub-50 nm SiGe films poses significant challenges for semiconductor manufacturers especially related to process development and control for enhanced manufacturability.
- Fast, reliable acquisition of in-line parametric data is critical to develop and sustain a manufacturable SiGe process.
  - %Ge, growth rate, dopant concentration, sheet resistance, strain effect
  - Across wafer uniformity
- Typical measurements are with Xrd, SIMS, and FPP which can be costly, “noisy”, and time consuming for in-line qualifications.
- Spectroscopic ellipsometry is a non contact, non-destructive technique, which is suitable for both thin film and bulk characterization. Through accessing dielectric properties of the film, other properties can be extracted accordingly, such as physical, chemical and electrical properties.

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Growth of Strained SiGe

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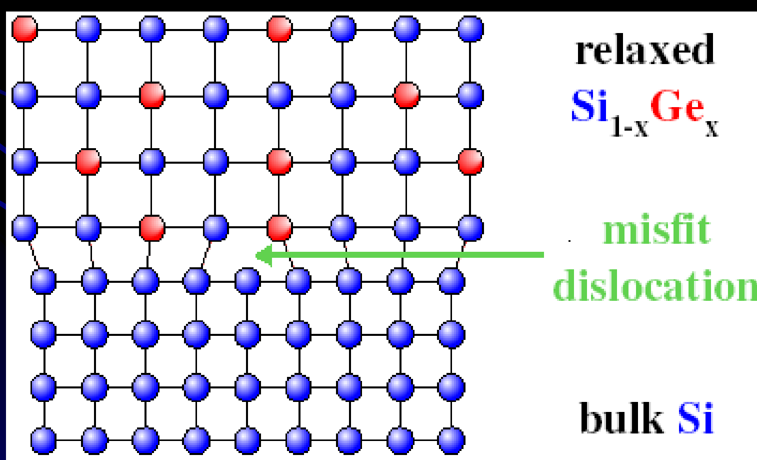
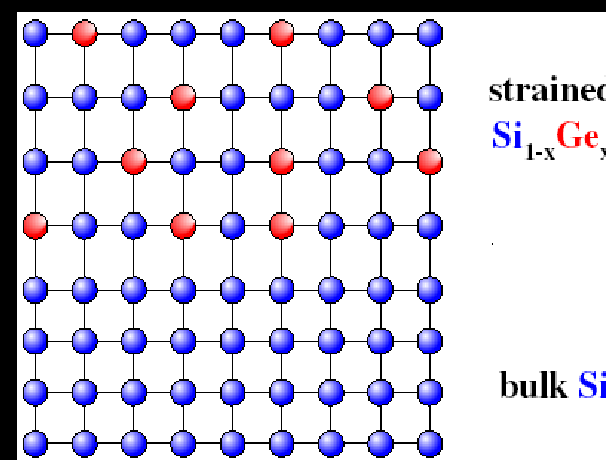
- **LPCVD (low pressure chemical vapor deposition) is performed in an AMAT 5200 Epi Centura Reactor.**
- **Pseudomorphic (lattice matched), sub-50 nm SiGe grown by thermal decomposition of silane (SiH_4), germane (GeH_4), methyl silane (CH_3SiH_3), and diborane (B_2H_6) in a H_2 ambient at ~600 ºC.**
  - SiH_4 + GeH_4 are Si and Ge sources for crystal growth
  - B_2H_6 is p-type dopant source for HBT base region.
  - CH_3SiH_3 is carbon source to minimize boron outdiffusion (captures Si interstitials) and provide strain compensation (reduces compressive strain)





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Comparison between Different Techniques for SiGe

Technique	Strength	Weakness
Xrd	• repeatable, reliable, sub-20 nm capability, • sensitive to lattice parameter variations, • indicates strain relaxation, • non-destructive • medium cost	• time consuming, • large spot size, not capable for product measurement, • dopant incorporation may result in low Ge measurement due to lattice parameter reduction
FPP	• fast • low cost • good indicator of active dopant	• difficulty for sub-50nm films • influenced by dopants from adjacent layers • not capable for product measurement, • destructive
SIMS	• sub-20 nm capability • great indicator of dopant profiles and concentrations • good measure of contaminants such as oxygen	• time consuming • high cost • does not indicate active or substitutional dopant incorporation • destructive

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Methodology - Characterization of SiGe

- **UV-Visible Spectroscopic Ellipsometry (SE) measurement and analysis yield:**
  - Thickness of SiGe layer and Si cap layer
  - Ge concentration in both box and graded SiGe layers
  - **Infrared SE (IR-SE) measurement and analysis yield:**
  - Dopant concentration and electrical properties
- **Both UV-Vis SE and IR-SE capabilities are integrated into IRSE tool (refer to presentation)**

Model and Its Analyses

$$\rho = \frac{R^P}{R^S} = Tan\psi \cdot e^{j\Delta} = f(n_i, k_i, d_i \cdots)$$

Measured Data

TanΨ λ

CosΔ λ

Physical Model

Estimated sample structure

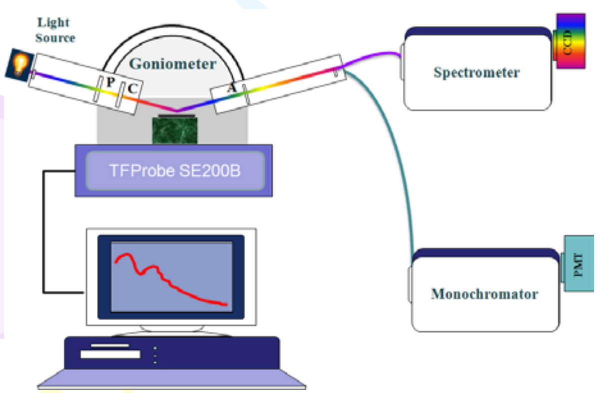
- Film Stack and structure
- Material n, k, dispersion
- Composition Fraction of Mixture

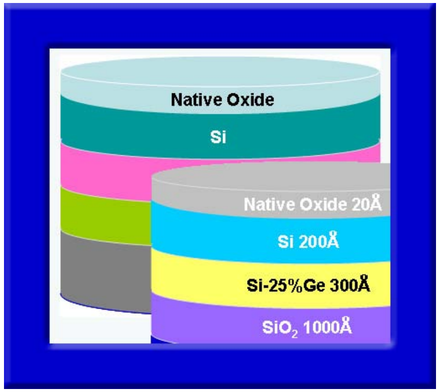
Measurement = Calculation ?

No

Yes

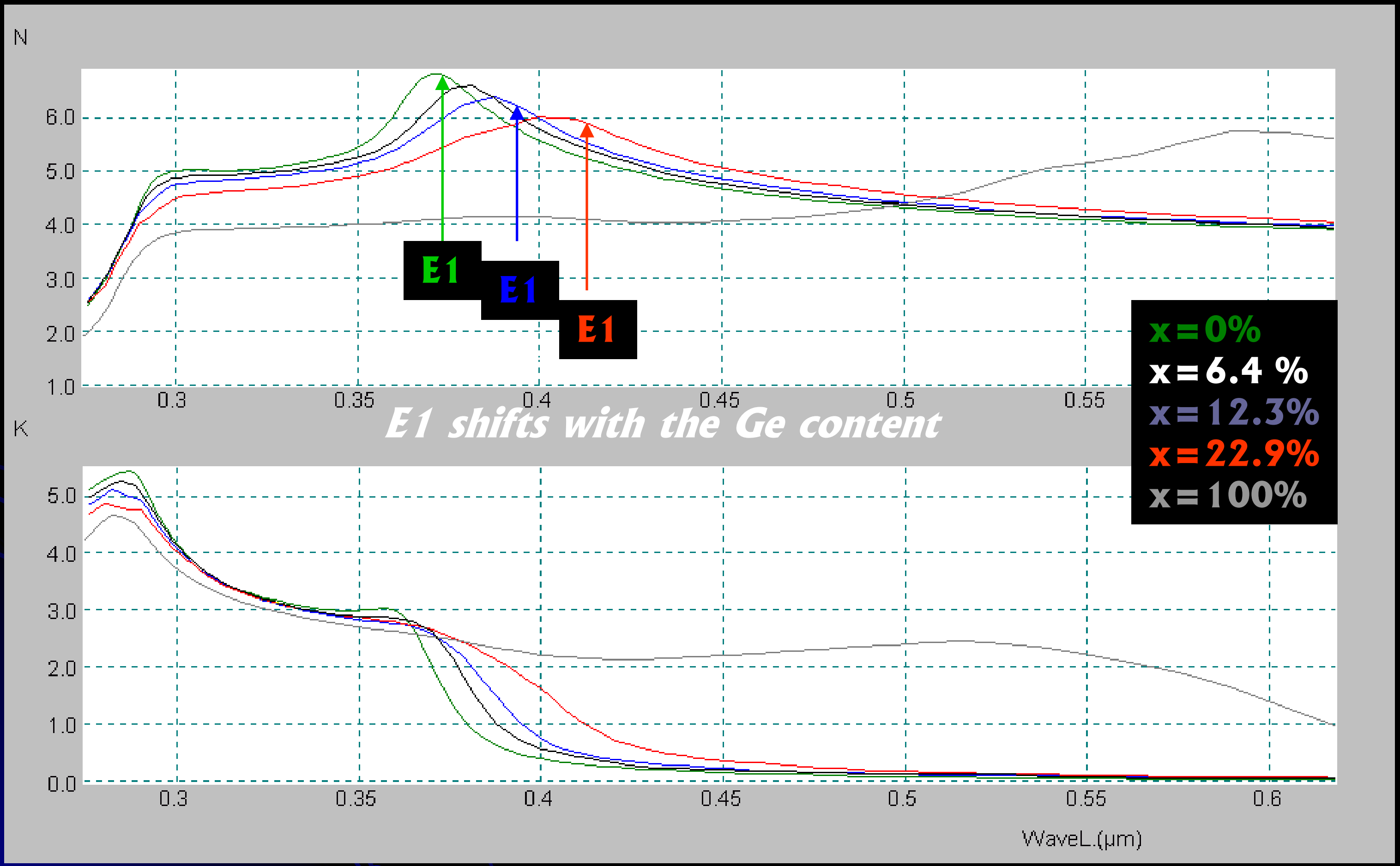
T_i, n_i, k_i





Introduction to Alloy Model (2)

Transition Energy as a function of Ge content



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Principle of Dopant Concentration Characterization (Drude Model)

$$\varepsilon_1(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - \omega_\tau^2}$$

$$\varepsilon_2(\omega) = \frac{\omega_p^2 \omega_\tau}{\omega(\omega^2 - \omega_\tau^2)}$$

ω_p: plasma frequency

ω_τ: scattering frequency

- the conductivity of the material

$$\sigma = \varepsilon_0 \frac{\omega_p^2}{\omega_\tau}$$

- the free carrier density N

$$N = m^* \frac{\varepsilon_0 \omega_p^2}{e^2}$$

where m* is the effective mass

- the free carrier mobility

$$\mu = \frac{e}{m^* \omega_\tau}$$

Sample Description

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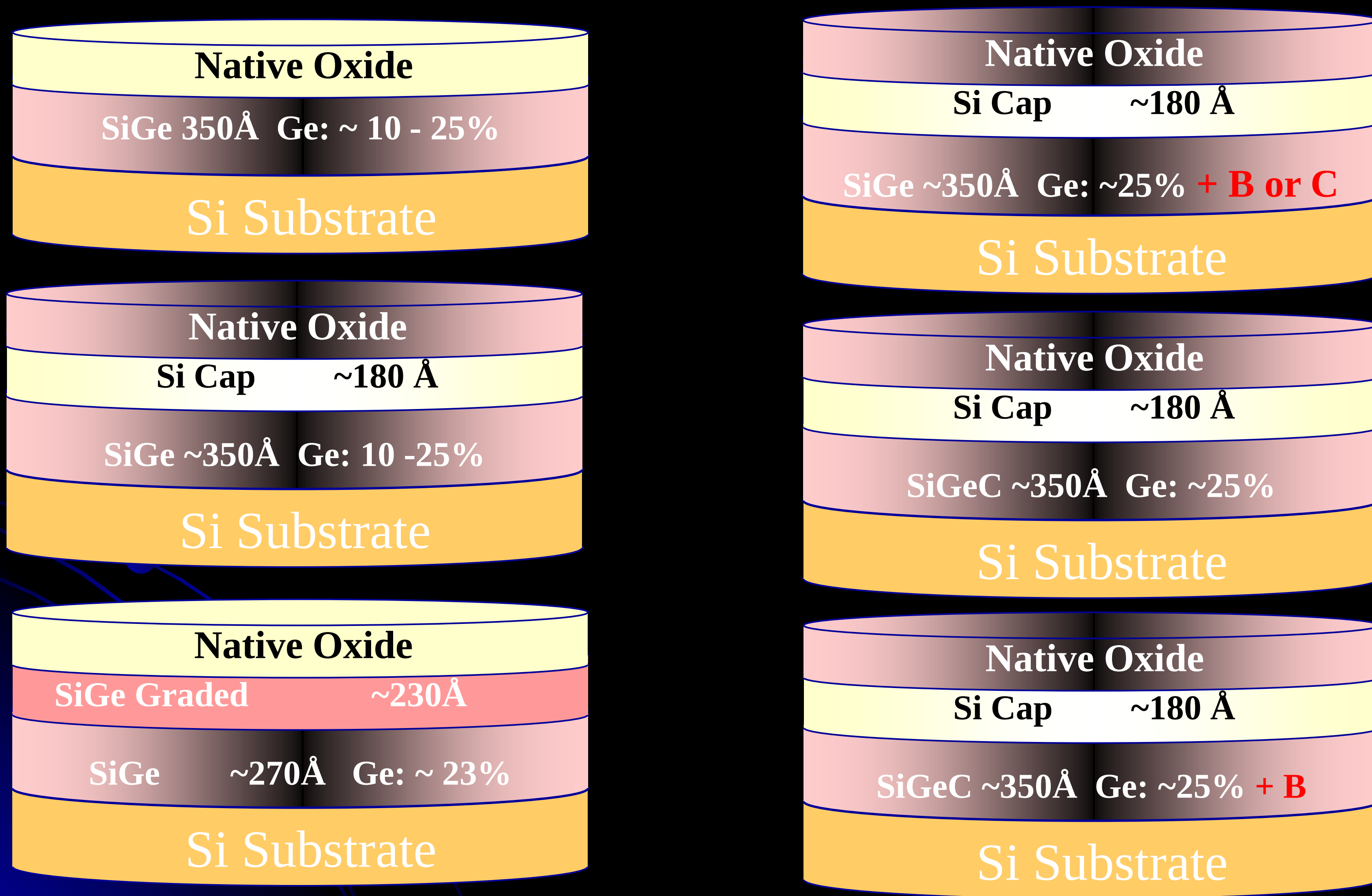

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Typical SE Spectra (box only)

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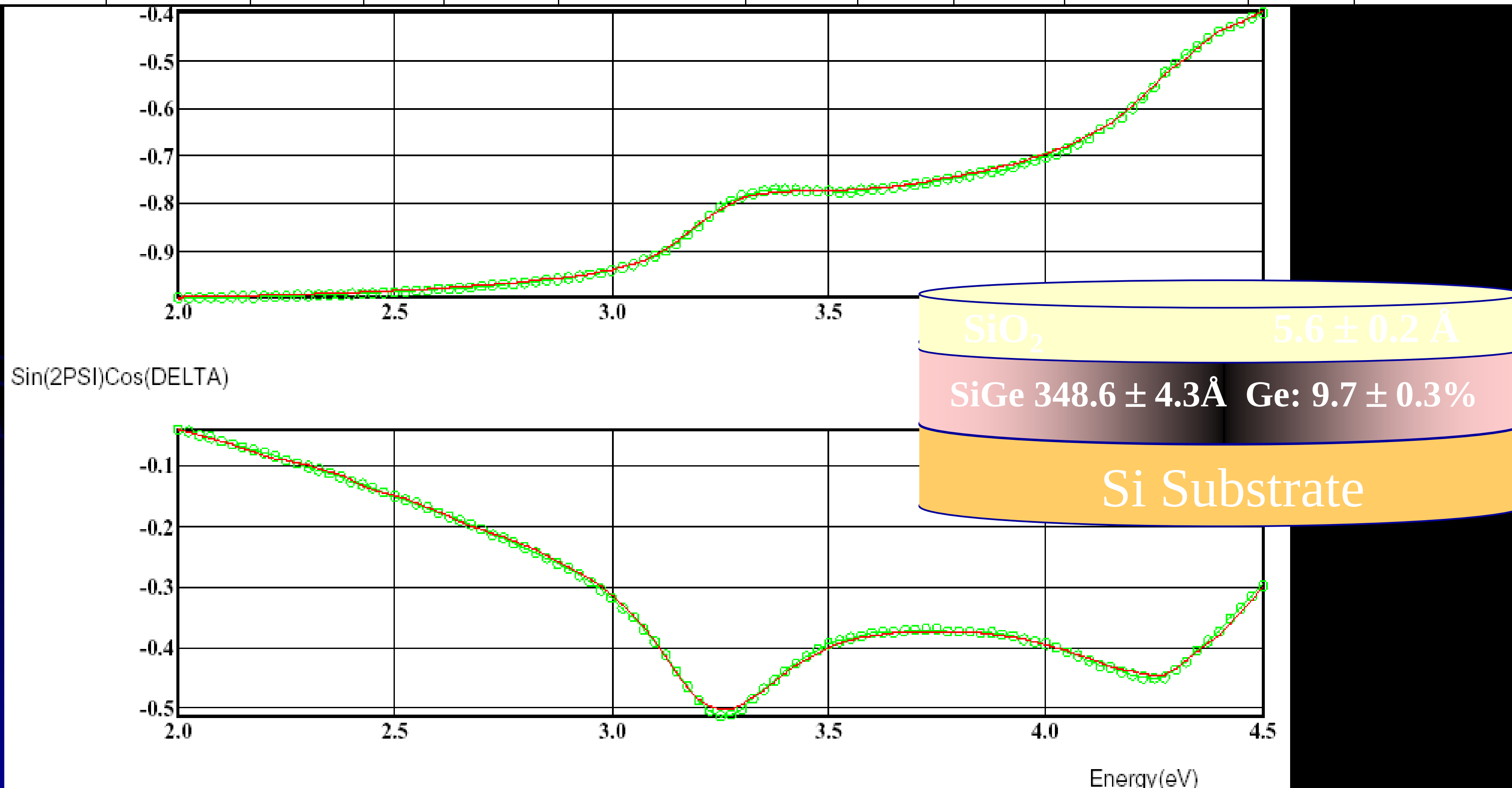
Sample ID	Ge Concentration				Thickness (Angstroms)						
	%Ge Box		%Ge Graded		SiGe Box		Graded SiGe		Si Cap		Native Oxide
	IRSE	Norminal	IRSE	Norminal	**IRSE**	Norminal	IRSE	Norminal	IRSE	Norminal	IRSE
ww01010	**9.7 ± 0.3**	9.8			**348.6 ± 4.3**	344					**5.6 ± 0.2**



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Typical Spectra (with cap)

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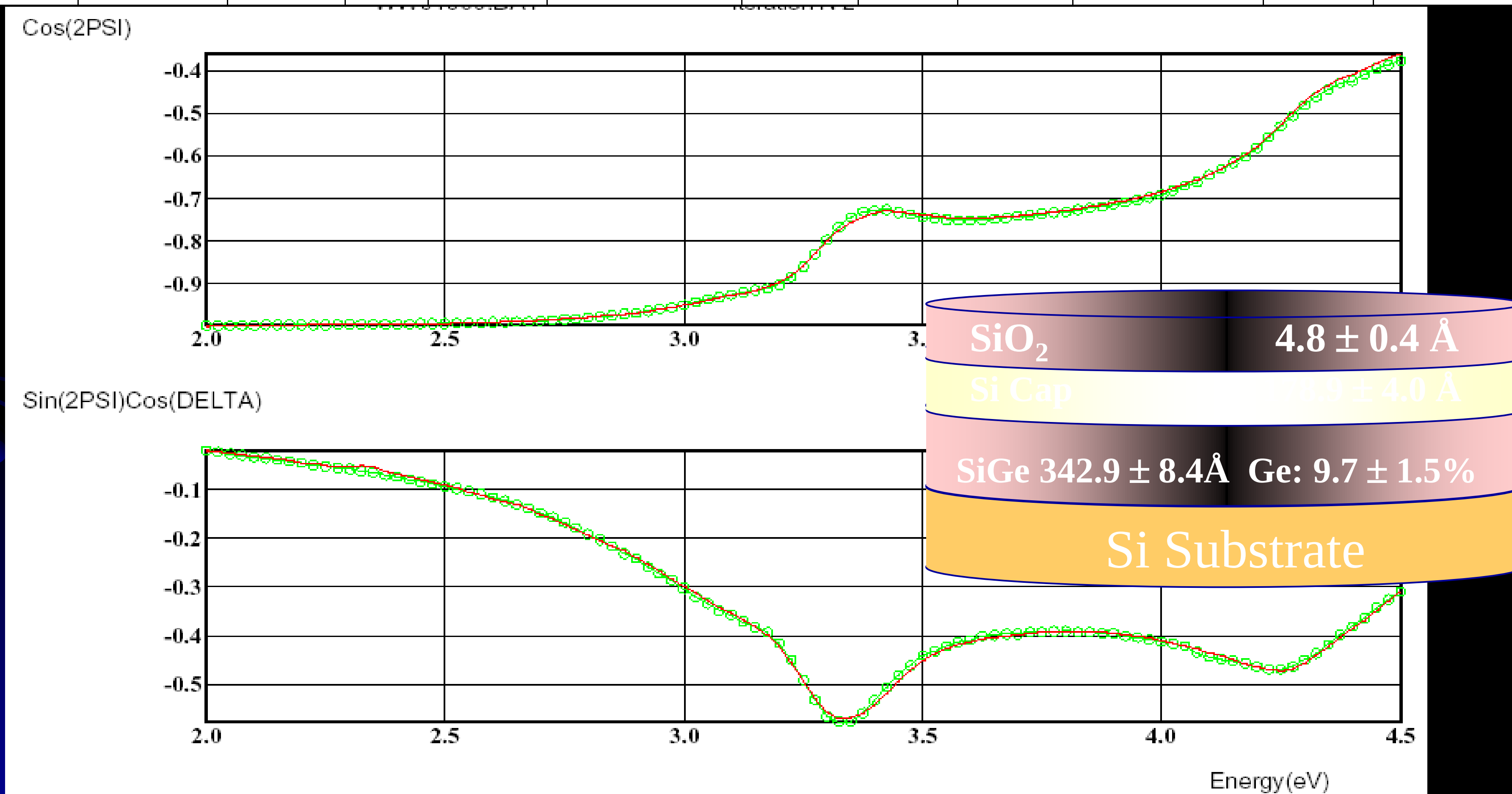
Sample ID	Ge Concentration				Thickness (Angstroms)						
	%Ge Box		%Ge Graded		SiGe Box		Graded SiGe		Si Cap		Native Oxide
	IRSE	Norminal	IRSE	Norminal	**IRSE**	Norminal	IRSE	Norminal	IRSE	Norminal	IRSE
ww01009	**9.7 ± 1.5**	9.8			**342.9 ± 8.4**	349			**178.9 ± 4.0**	180	**4.8 ± 0.4**



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Graded SiGe

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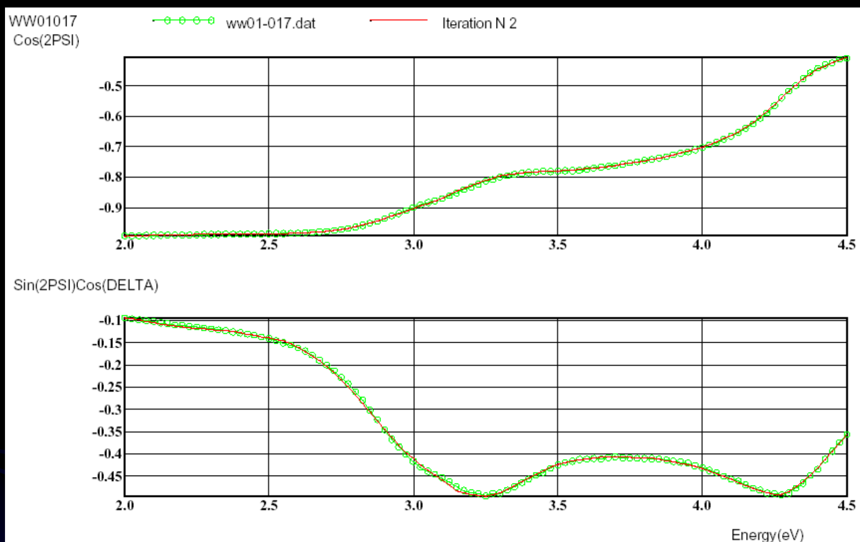
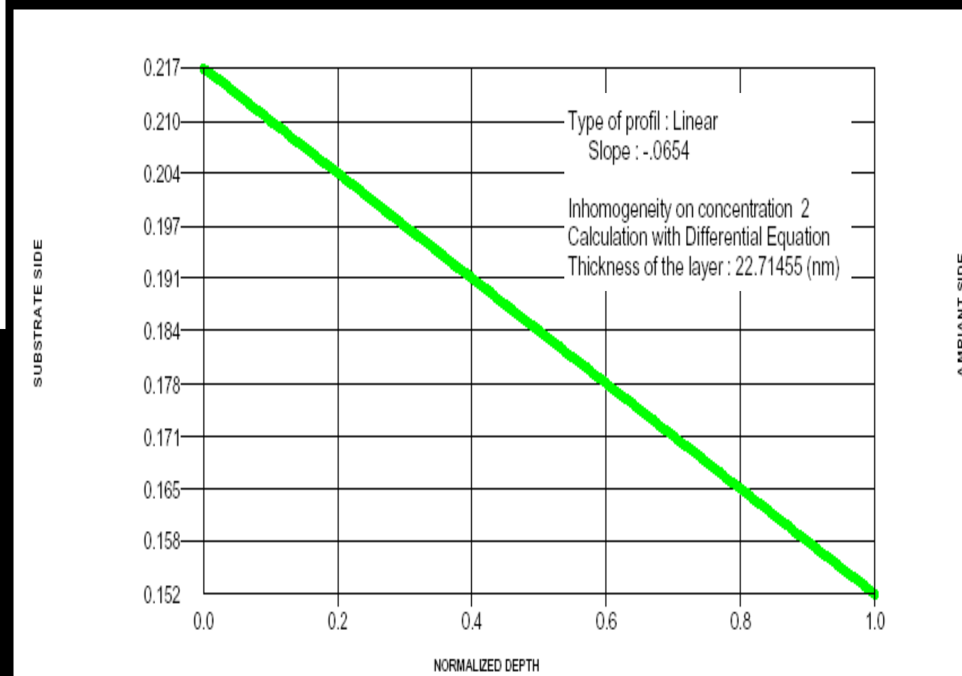
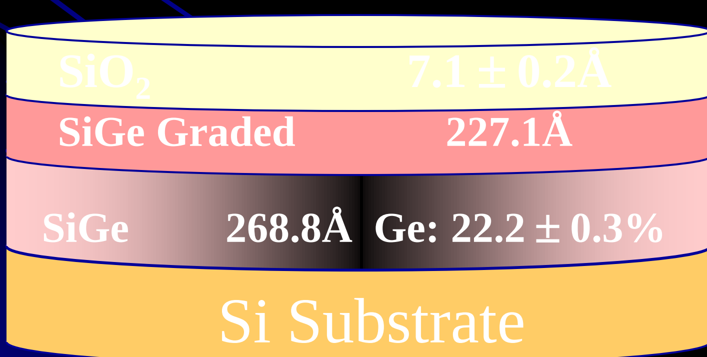
Sample ID	Ge Concentration				Thickness (Angstroms)						
	%Ge Box		%Ge Graded		SiGe Box		Graded SiGe		Si Cap		Native Oxide
	IRSE	Norminal	IRSE	Norminal	**IRSE**	Norminal	IRSE	Norminal	IRSE	Norminal	IRSE
ww01017	**22.2 ± 0.3**	24.1	**15.2**	15.2	**268.8**	260	**227.1**	234			**7.1 ± 0.2**



Ge Concentration Profile





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Mapping on Si Cap Thickness

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Wafer Size

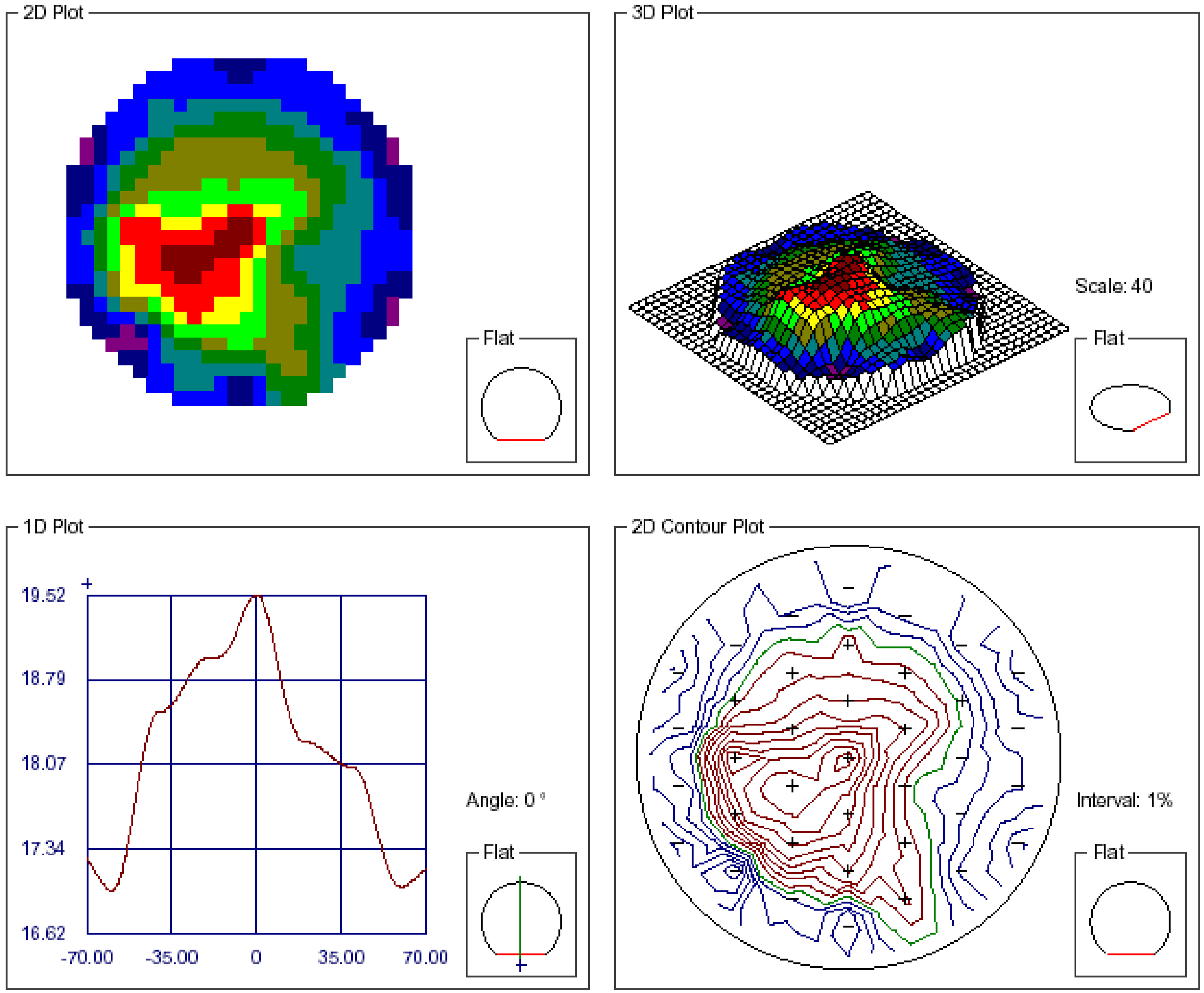
Wafer Diam: 150.00 mm
Test Diam: 140.00 mm
No. Sites: 37
Style: Flat

Wafer Statistics

Mean:	17.80
Maximum:	19.52
Minimum:	16.62
Std. Dev:	0.84
	4.72 %
Range:	2.90
Hi/Lo Var:	8.04 %
Unit:	nm

Legend

- 19.2 - 19.5
- 18.9 - 19.2
- 18.6 - 18.9
- 18.4 - 18.6
- 18.1 - 18.4
- 17.8 - 18.1
- 17.5 - 17.8
- 17.2 - 17.5
- 16.9 - 17.2
- 16.6 - 16.9



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Mapping on SiGe Layer Thickness

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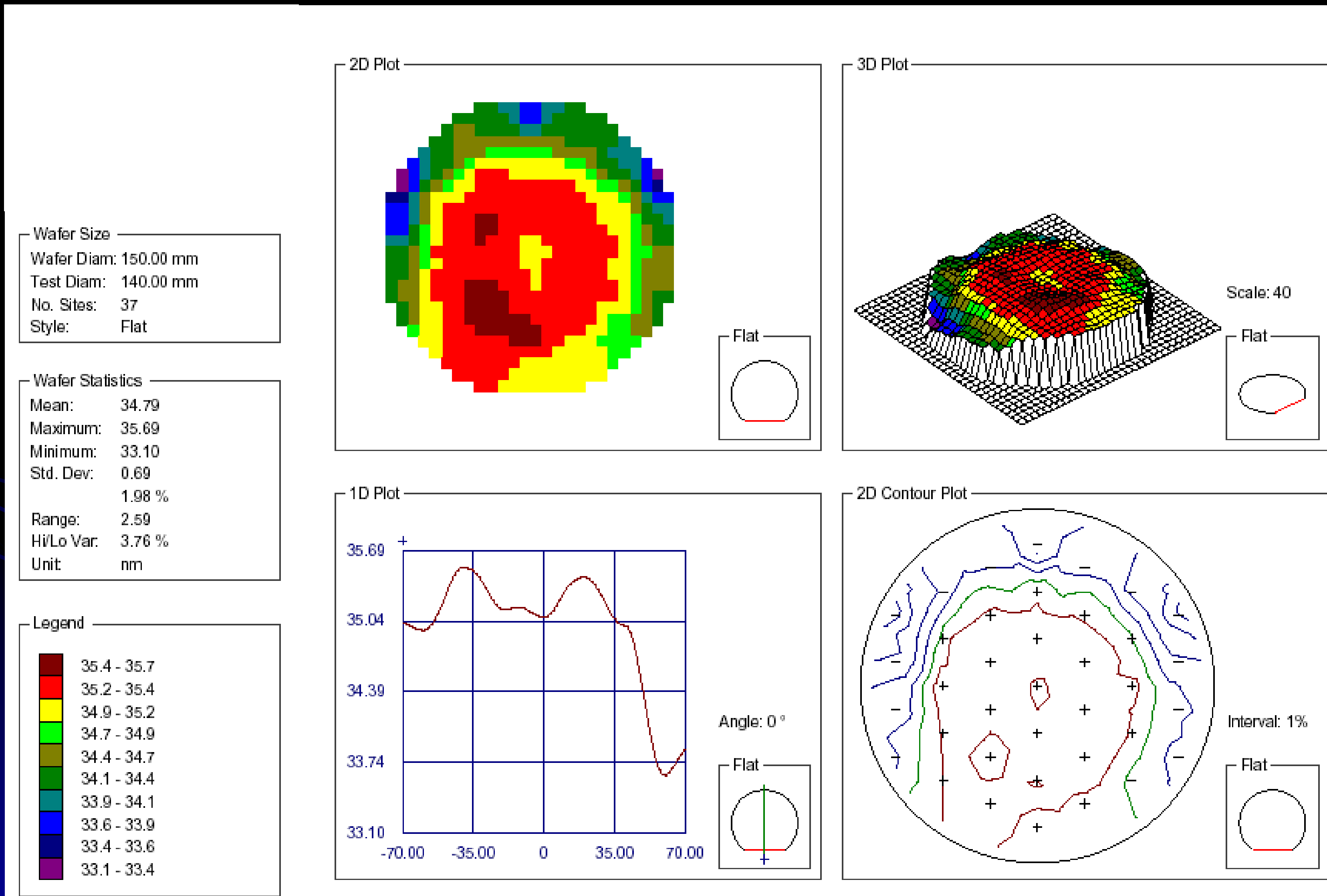

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Mapping on Ge % in SiGe Box

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Wafer Size

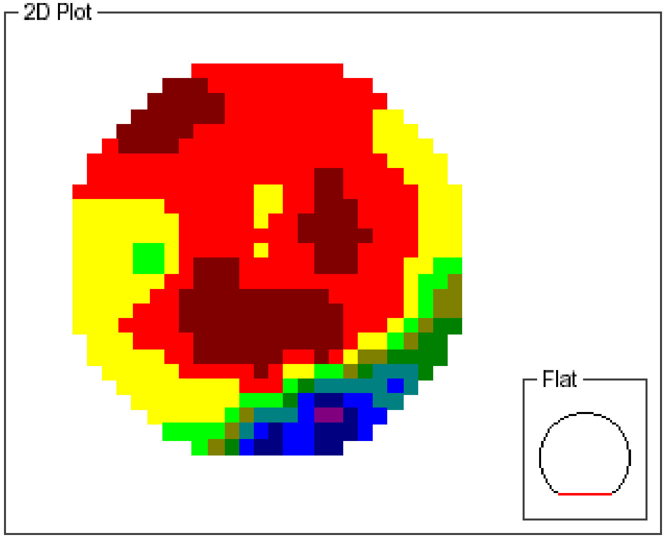
Wafer Diam:	150.00 mm
Test Diam:	140.00 mm
No. Sites:	37
Style:	Flat

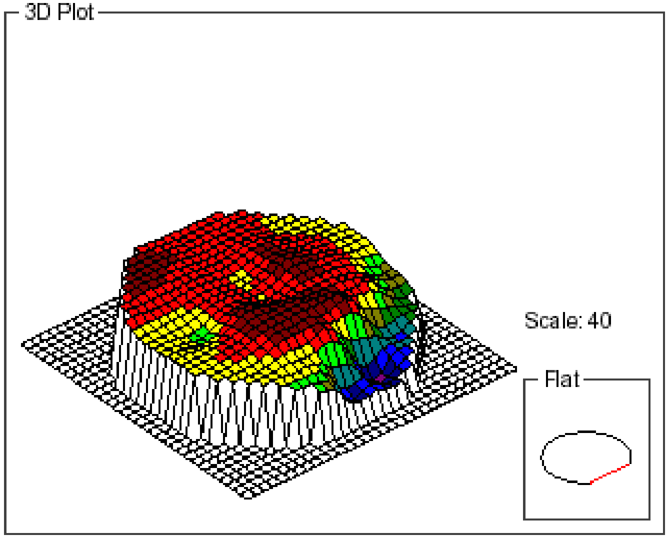
Wafer Statistics

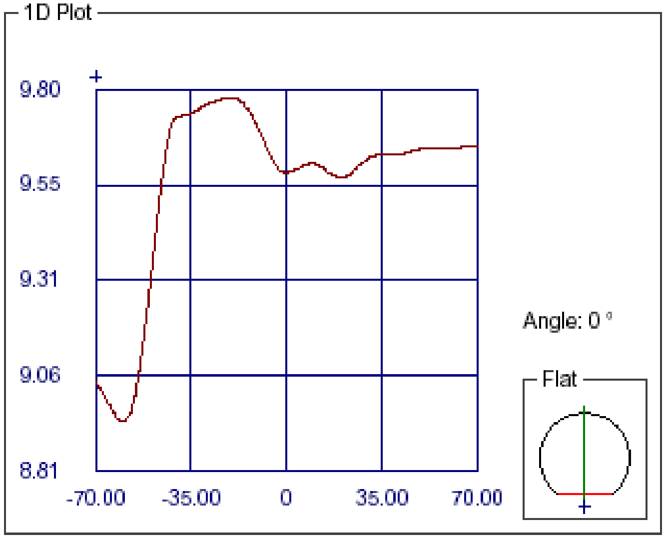
Mean:	9.57
Maximum:	9.80
Minimum:	8.81
Std. Dev:	0.22
	2.34 %
Range:	0.99
Hi/Lo Var:	5.31 %
Unit:	%

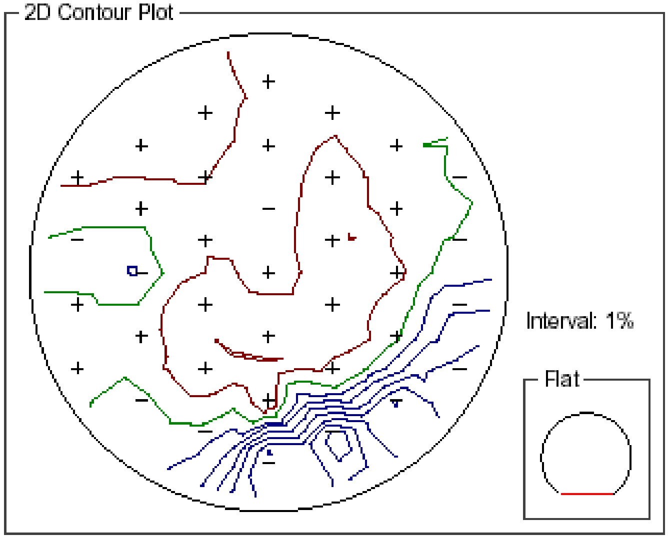
Legend

- 9.70 - 9.80
- 9.60 - 9.70
- 9.50 - 9.60
- 9.40 - 9.50
- 9.31 - 9.40
- 9.21 - 9.31
- 9.11 - 9.21
- 9.01 - 9.11
- 8.91 - 9.01
- 8.81 - 8.91









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Characterization – Summary Table

Sample ID	Ge Concentration				Thickness (Angstroms)						
	%Ge Box		%Ge Graded		SiGe Box		Graded SiGe		Si Cap		Native Oxide
	IRSE	Norminal	IRSE	Norminal	**IRSE**	Norminal	IRSE	Norminal	IRSE	Norminal	IRSE
ww01010	**9.7 ± 0.3**	9.8			**348.6 ± 4.3**	344					**5.6 ± 0.2**
ww01012	**18.1 ± 0.2**	19.2			**383.8 ± 1.6**	392					**5.2 ± 0.2**
ww01014	**25.1 ± 0.5**	26.4			**406.4 ± 2.8**	404					**4.2 ± 0.3**
ww01009	**9.7 ± 1.5**	9.8			**342.9 ± 8.4**	349			**178.9 ± 4.0**	180	**4.8 ± 0.4**
ww01011	**19.0 ± 1.0**	19.2			**391.8 ± 13.9**	388			**178.9 ± 3.2**	181	**4.9 ± 0.6**
ww01013	**26.3 ± 1.2**	26.4			**411.6 ± 12.6**	407			**178.5 ± 2.6**	175	**4.6 ± 0.6**
ww01015	**22.2 ± 0.3**	24.2	**15.3**	15.6	**256.3**	251	**237.6**	236			**7.7 ± 0.2**
ww01016	**21.9 ± 0.3**	24.0	**15.2**	15.3	**273.3**	254	**225.3**	235			**3.9 ± 0.2**
ww01017	**22.2 ± 0.3**	24.1	**15.2**	15.2	**268.8**	260	**227.1**	234			**7.1 ± 0.2**

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IRSE - Spectra Comparison Doped vs. Non-doped Samples

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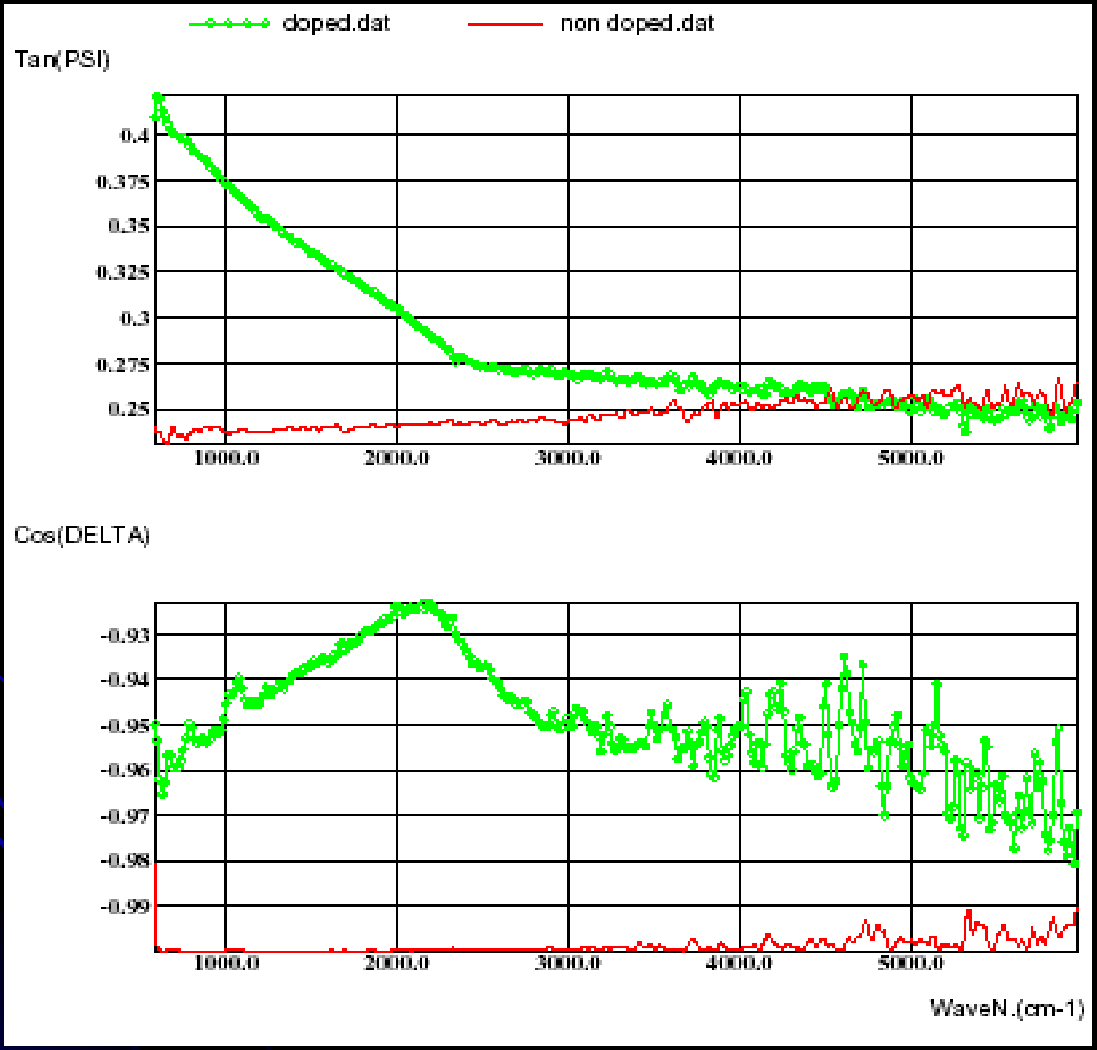

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Typical Fitting for Boron Doped Sample in IR Region

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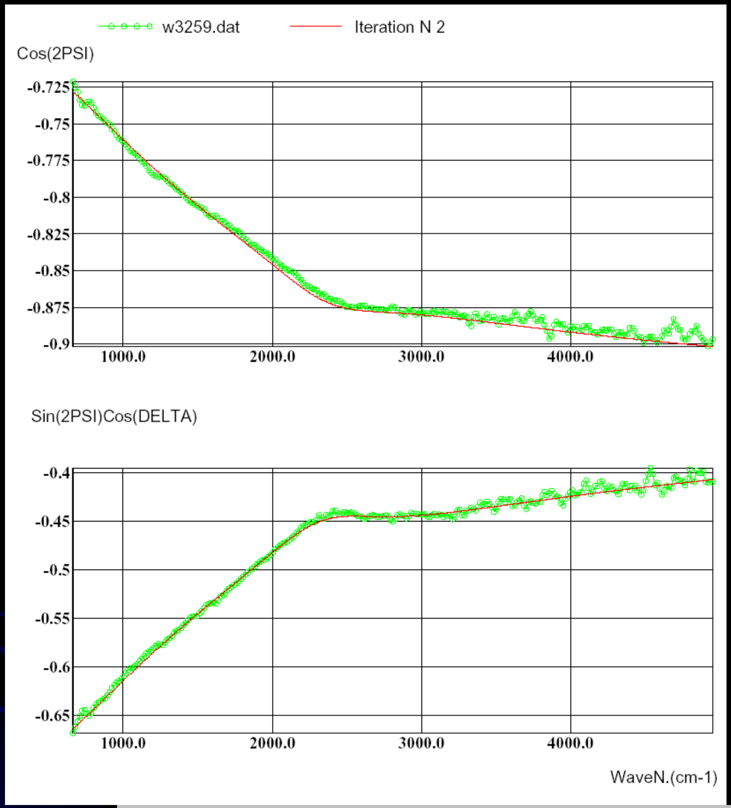

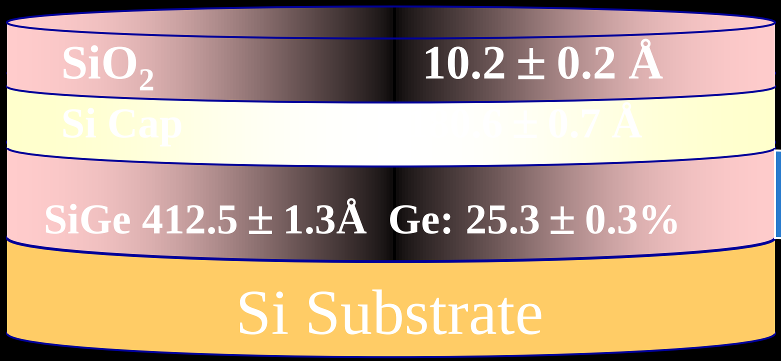

Sample	Resistance	Dopant Concentration
ww 3259 (plus boron)	228 ± 9 ohm/square	2.77 E+20 ± 4E+18

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Characterization Results from Infrared Channel

Sample	Resistance	Dopant Concentration
(undoped 24-25 %)	na	na
ww 3259 (plus boron)	228 ± 9 ohm/square	2.77 E+20 ± 4E+18
ww 3260 (plus carbon)	na	na
ww 3261 (plus boron and carbon)	263 ± 15 ohm/square	2.71 E+20 ± 5 E+18

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Characterization Results from Visible Channel

Sample ID	SiGe Layer	Si Cap Thickness (Å)	SiGe Thickness (Å)	Ge %	IRSE - %Chg in Ge	Xrd - %Chg in Ge
Sample 1	SiGe only	171.7	389.5	24.9	0.00%	0.00%
Sample 2	SiGe + B	180.6	412.5	25.3	1.61%	-14.12%
Sample 3	SiGe + C	175.9	374.5	25.0	0.40%	-8.24%
Sample 4	SiGe + B + C	184.1	391.7	24.6	-1.20%	-18.61%

Still Strained or Relaxed by Carbon Alloying?

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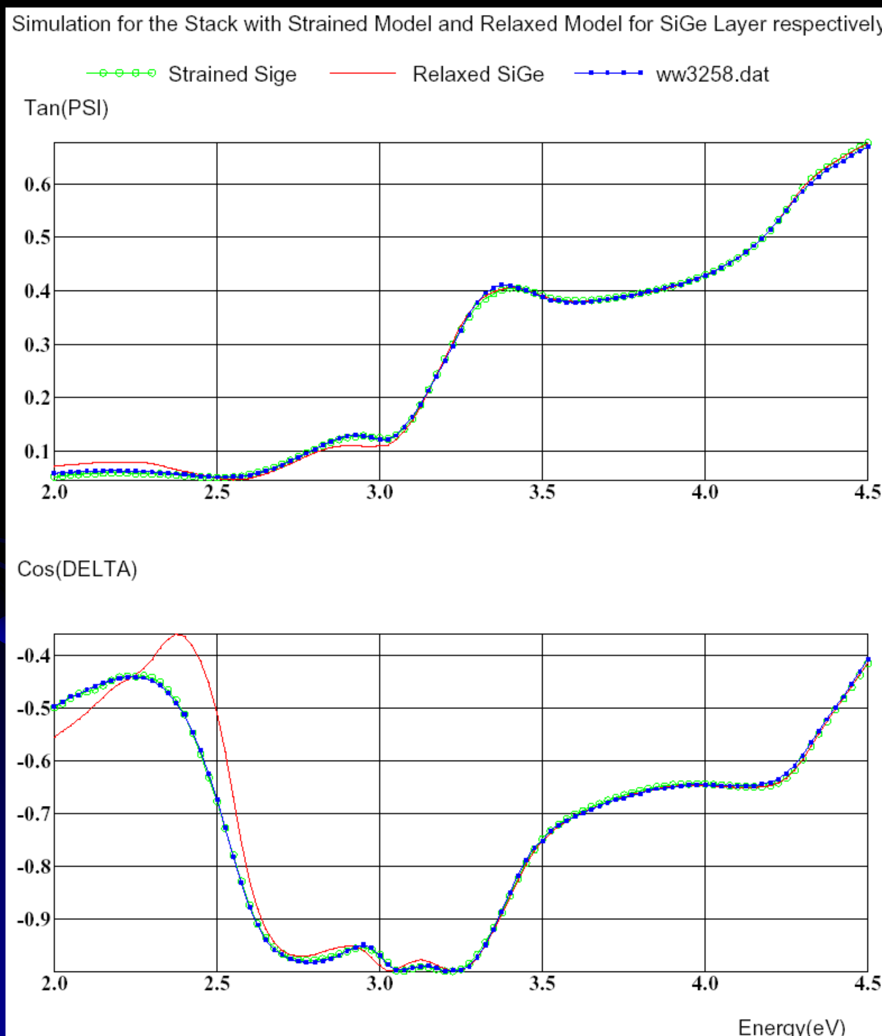

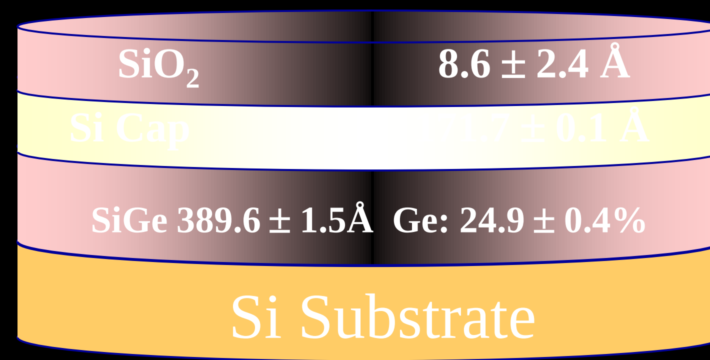

- Strained model matches measured real SE Data.
- It is possible to tell whether SiGe layer is strained or relaxed with SE technique.

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Summary

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Precise measurements have been obtained for:

- Si cap layer thickness
- Si:Ge box layer thickness
- Ge concentration in Si:Ge box layer
- Ge gradient and thickness for graded Si:Ge layer
- Doped boron concentration and electrical properties

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Summary (cont'd)

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- IRSE method can reduce process qualification times significantly.
  - **Typical Xrd "single point" measurements consume 1-2 hours/day** of potential production time.
    - **IRSE extracts single point measurement in minutes.**
  - **Typical Xrd "multipoint" measurements require 10 – 12 hours** for 20+ points
    - **IRSE extracts multipoint measurements in minutes**
    - Weekly multipoint measurements are important for manufacturing control, but are difficult with Xrd due to time constraints.
  - **Four Point Probe sheet resistance measurements on thin SiGe films are "noisy" and difficult** due to probe contact problems, leakage to substrate, and probe conditioning issues.
    - **IRSE is contact-less and offers improved reliability and speed.**

- Fast, accurate determination of %Ge, thickness, sheet resistance, and dopant concentrations offers to increase production time, and enhance process development activity.

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Further Information Available

- **For any further information, please contact:**

Email: **info@angstec.com**

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