High Mobility Ge-Channel Formation By Localized/Selective Liquid Phase Epitaxy (LPE) Using Ge+B Plasma Ion Implantation And Laser Melt Annealing

IWJT-2013, June 6-7, 2013

John Borland[1], Shu Qin[2], Peter Oesterlin[3], Karim Huet[4], Walt Johnson[5], Lauren Klein[6], Gary Goodman[6], Alan Wan[6], Steven Novak[7], Thomas Murray[7], Richard Matyi[7], Abhijeet Joshi[8] and Si Prussin[8]

[1]J.O.B. Technologies & APIC, Honolulu, Hawaii, [2]Micron Technology, Boise, Idaho, [3]Innovavent, Gottingen, Germany, [4]Excico, Paris, France, [5]KLA-Tencor, Milpitas, California, [6]EAG, East Windsor, New Jersey, [7]CNSE, Albany, New York, [8]UCLA, Los Angles, California

Outline

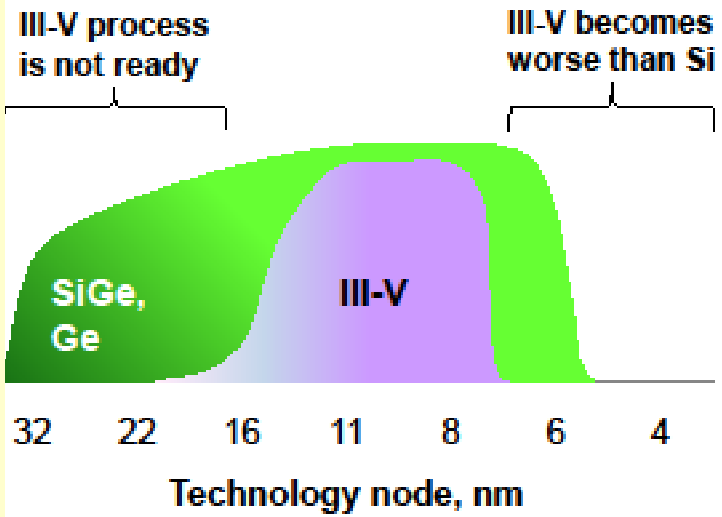
- Introduction
- Experimentation
  - **Micron** for Ge+B Plasma Implantation/Deposition Doping
  - **Innovavent**/Germany for 515nm laser annealing
  - **Excico**/France for 308nm laser annealing
- Results
  - **KT**/Shanghai for Hx-4PP and TW analysis
  - **EAG**/NJ for SIMS analysis
  - **CNSE**/Albany for SIMS, XRD & X-TEM analysis
  - **UCLA** differential Hall analysis for mobility and carrier density depth profiles
- Summary

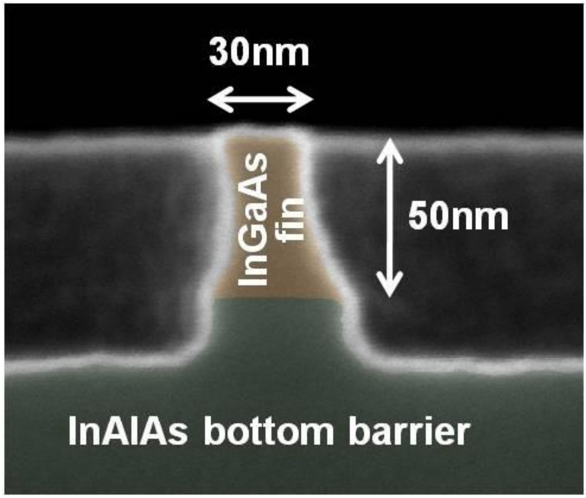
Outline

- Introduction
  - SiGe & Ge High Mobility Channel Formation Methods
- Experimentation
- Results
- Summary

Opportunity Window for Non-Si Channel

Material	μ_e (cm²/Vs)	μ_h (cm²/Vs)
Diamond	2200	1800
Si	1350	480
Ge	3900	1900
InP	5400	200
GaAs	8500	400
InGaAs (53%)	12000	300
InAs	40000	500
GaSb	3000	1000
InSb	77000	850





- Any new technology has to last at least 2 nodes
- SiGe channel is easier to manufacture
- High Ge content SiGe or even pure Ge to follow
- III-V materials have a narrow opportunity window

Paper 13.5: A. Khakifirooz of IBM on "Strain Engineered Extremely Thin SOI (ETSOI) for High Performance CMOS". Said ET-SOI needed for 20nm and beyond but ET-SOI is not compatible with eSiGe and eSiGe is limited with scaling they need something different. Finally shows a better way to integrate sSOI for nMOS with SiGe for pMOS by using an sSOI wafer with localized Ge condensation or thermal mixing for the pMOS as shown below. For 6nm ET-SOI they reported thermal mixing results in only 11% Ge while condensation method results in 23% Ge. This improves drive current by 35%.

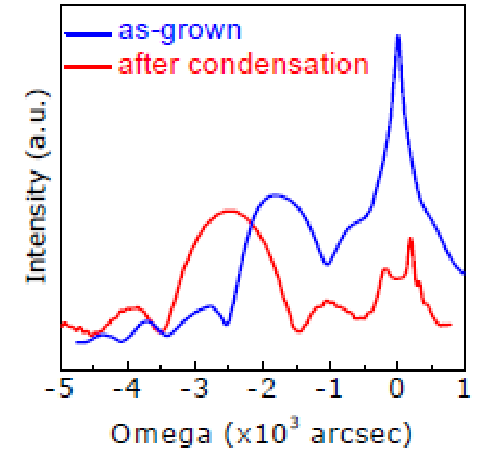
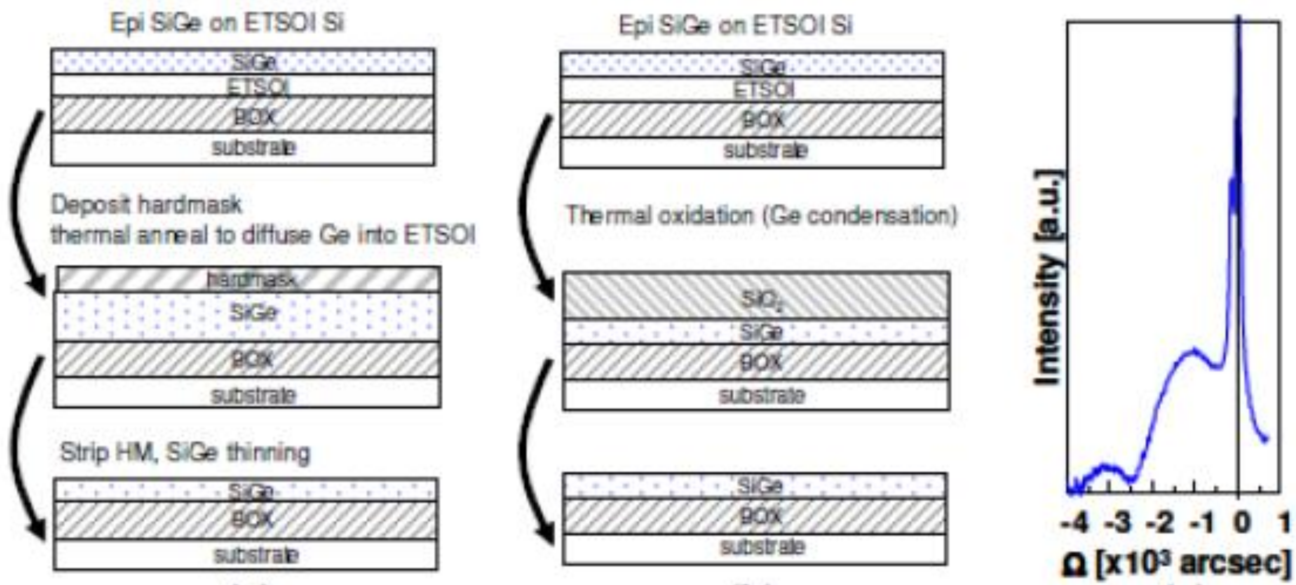


Fig. 6 XRD spectra showing fully compressively strained SiGe after epitaxy growth (20% Ge) on ETSOI Si and after condensation process (27% Ge).



(a) (b) (c)

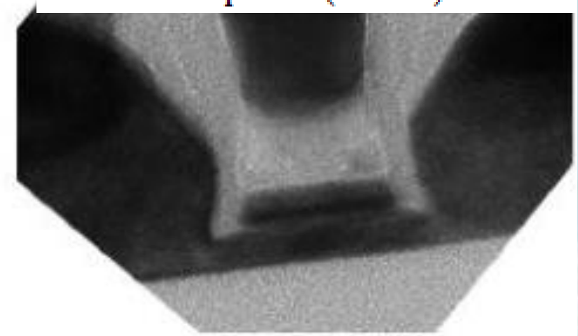


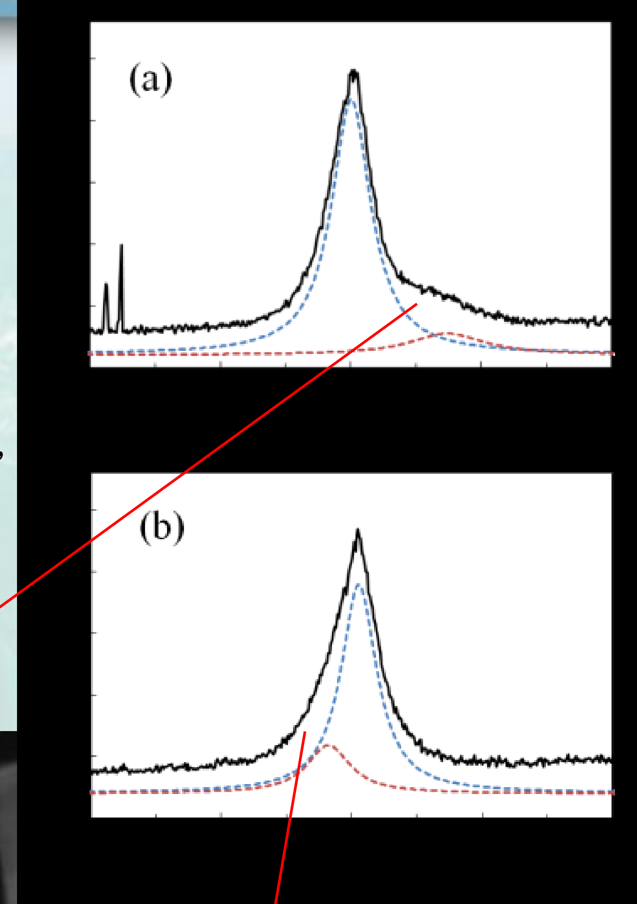
Fig. 6 Schematic process flow to form SiGe-channel ETSOI (a) thermal mixing (b) condensation. (c) HRXRD data showing compressively strained SGOI with 23% of Ge.

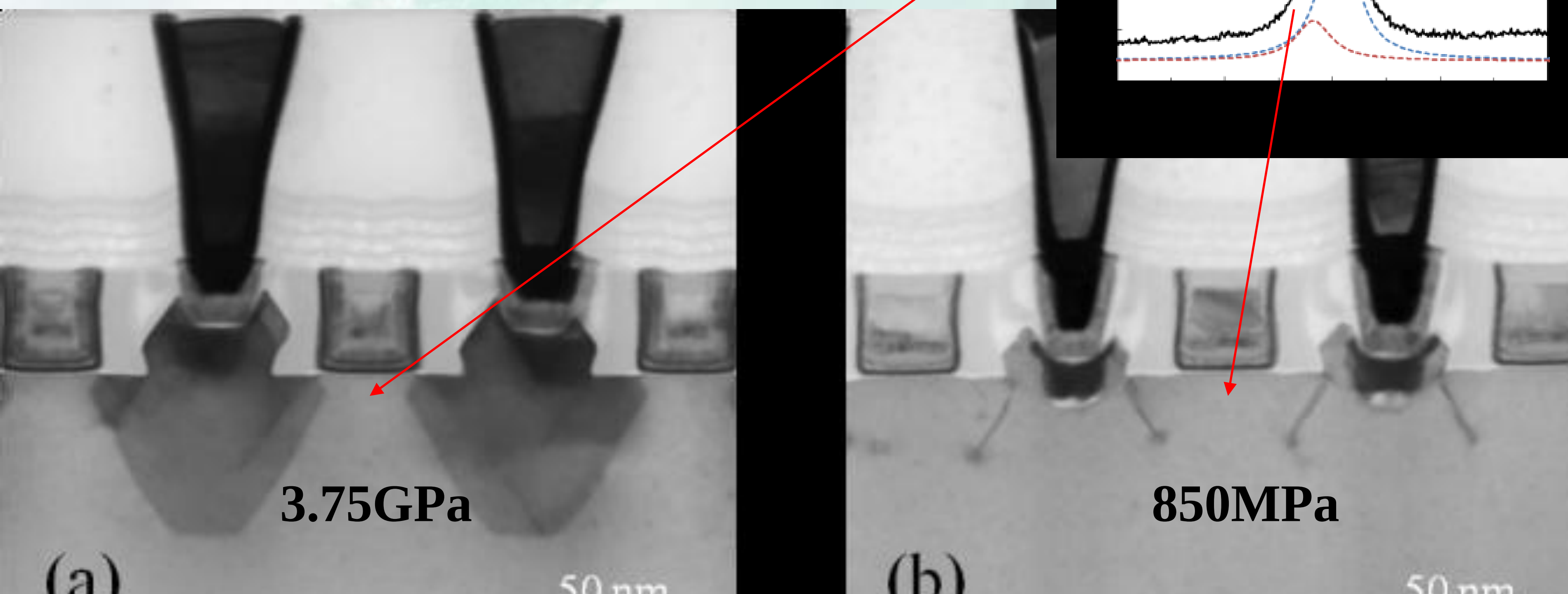
Fig. 7 TEM cross-section of SiGe channel ETSOI with a channel thickness of 6 nm.

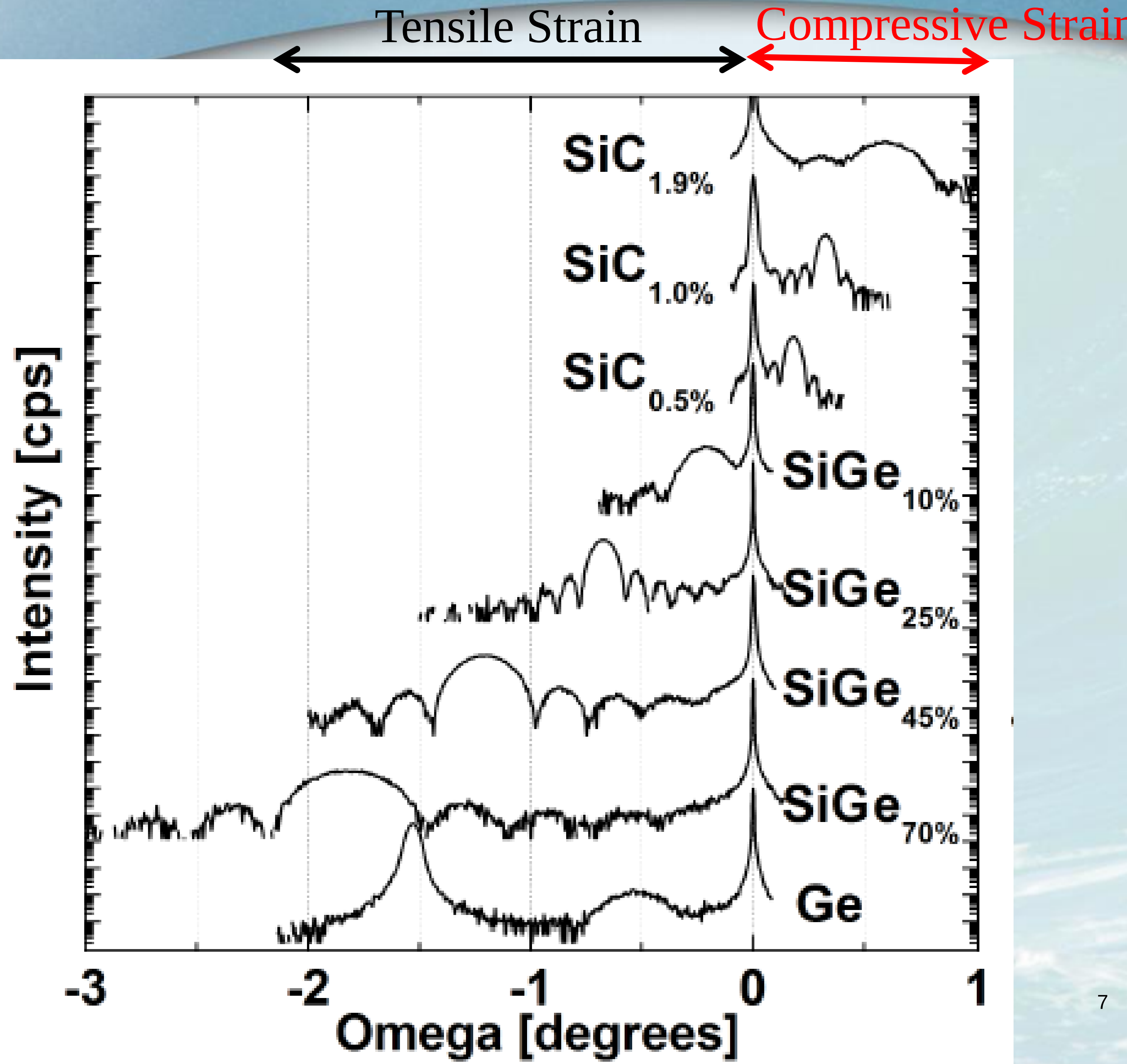
SSDM-2011: Apple iPhone 4

Channel strain measurements in 32nm-node CMOSFETs

Munehisa Takei1, Hiroki Hashiguchi1, Takuya Yamaguchi1, Daisuke Kosemura1, Kohki Nagata1, 2, and Atsushi Ogura1
1School of Science and Technology, Meiji University, 1-1-1 Higashimita, Tama-ku, Kawasaki, 214-8571, Japan
Phone/Fax: +81-44-934-7324, E-mail: m_takei@ meiji.ac.jp

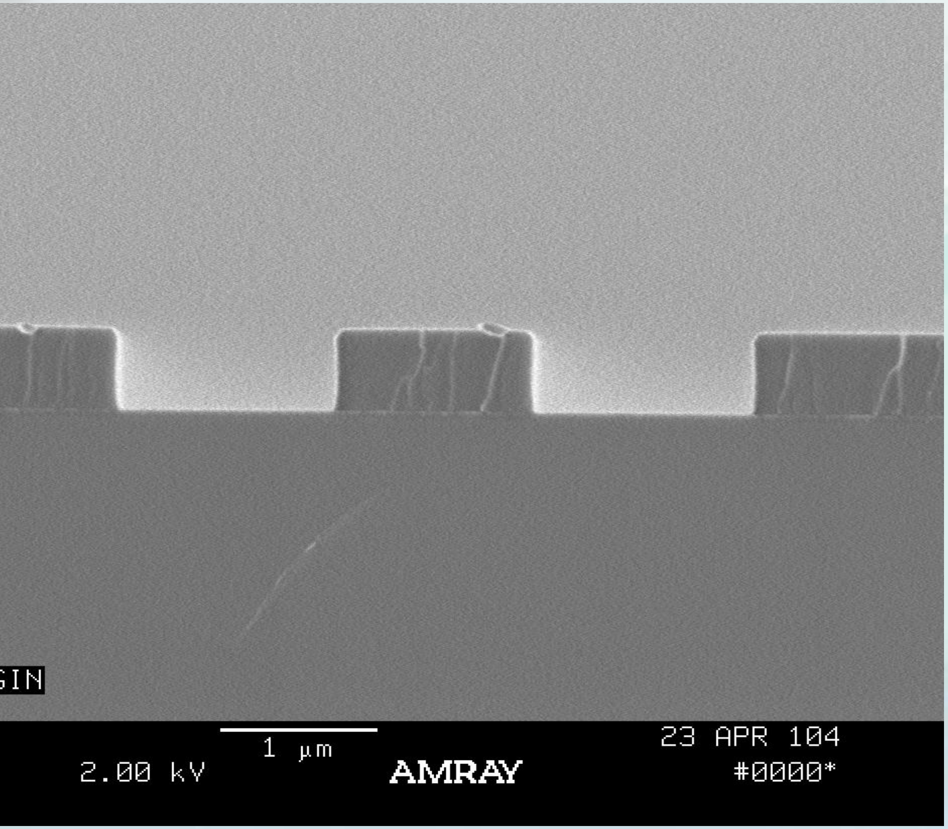


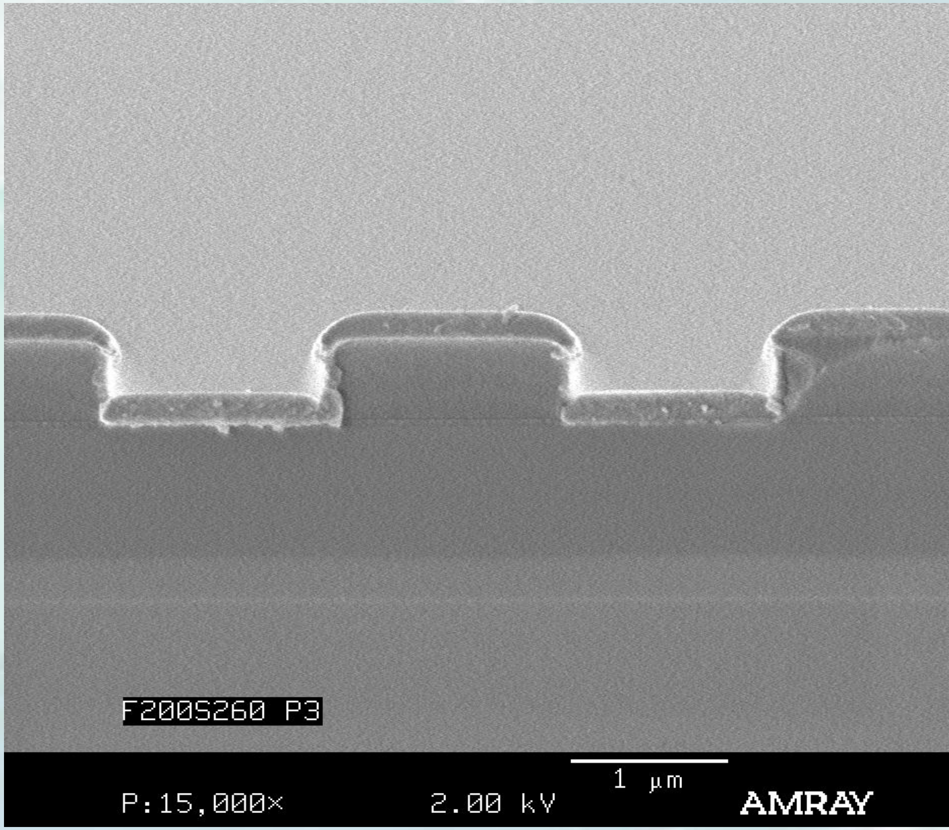



Tensile Strain
Compressive Strain
SiC 1.9%
SiC 1.0%
SiC 0.5%
SiGe 10%
SiGe 25%
SiGe 45%
SiGe 70%
Ge
Intensity [cps]
-3
-2
-1
0
1
Omega [degrees]

200nm Ge Infusion Deposition On Photo Resist

4/23/04



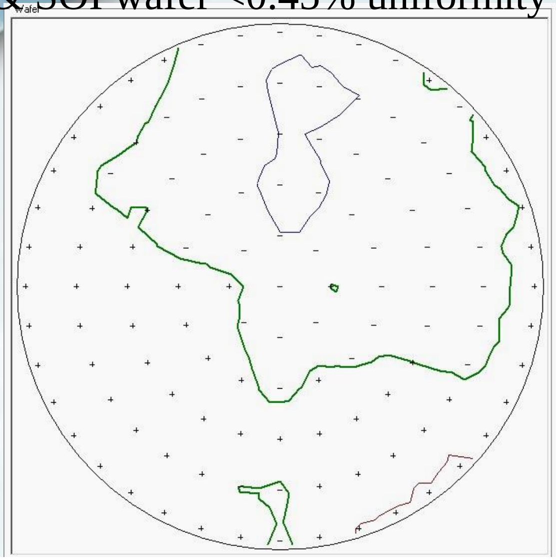


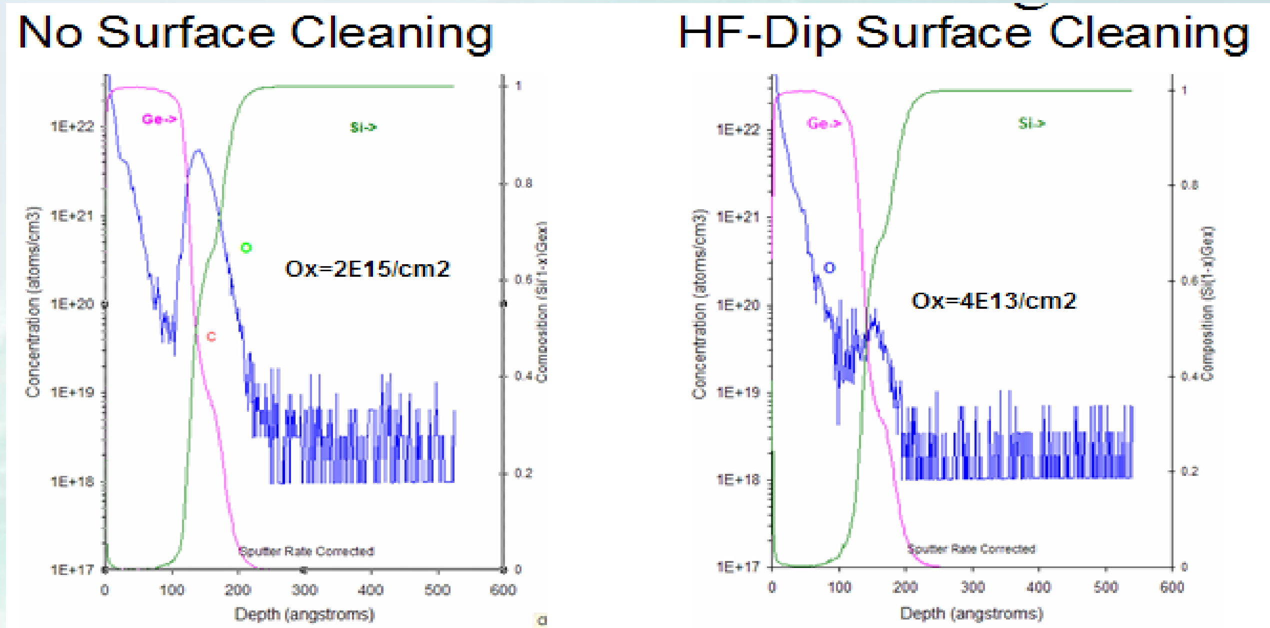
Borland et al., J.O.B. Technologies & Epion, ECS SiGe Sym., PV 2004-07, p. 769, Oct. 6, 2004

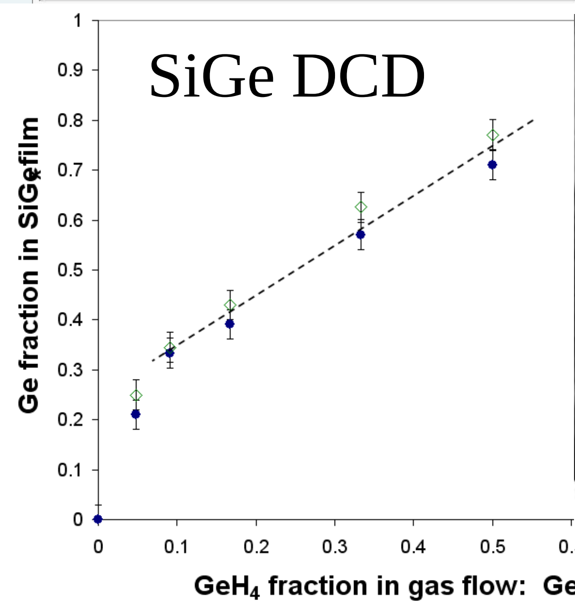
Infusion Ge-Doping/Deposition (Increasing Dose)

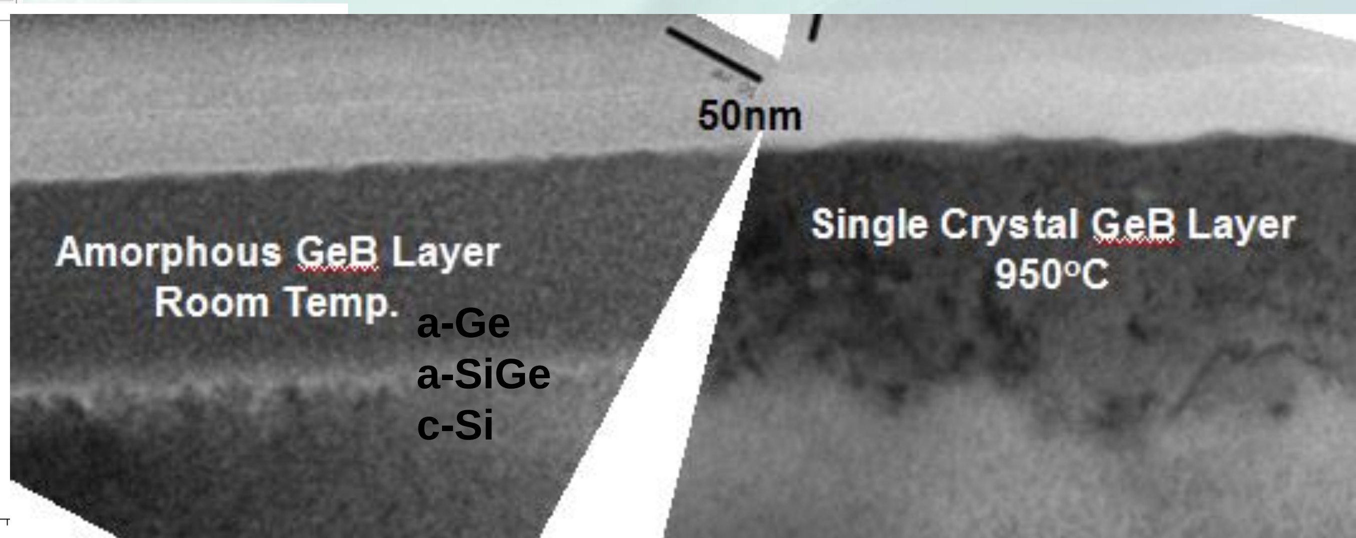
Medium Dose Increase Bss, High Dose Dose Controlled Deposition (DCD)

70nm Ge-DCD on 300mm bulk & SOI wafer <0.45% uniformity







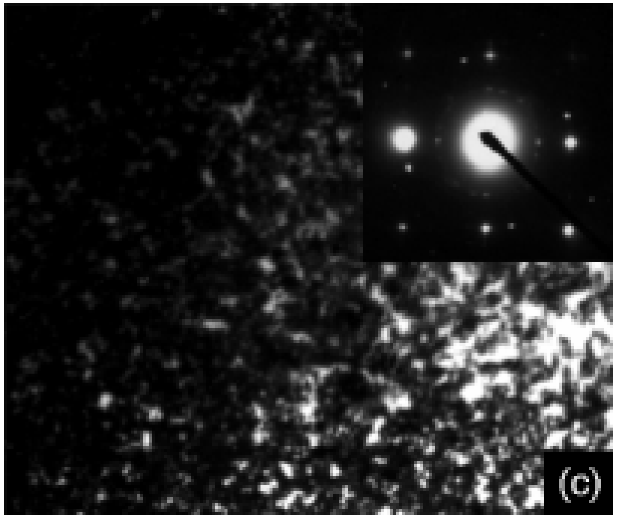


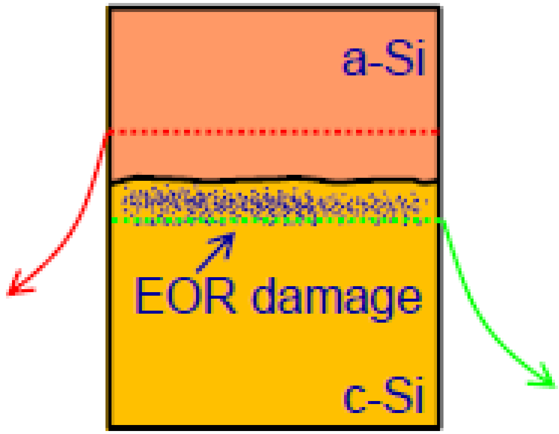
Borland et al., J.O.B. Technologies & Epion, ECS SiGe Sym., PV 2004-07, p. 769, Oct. 6, 2004

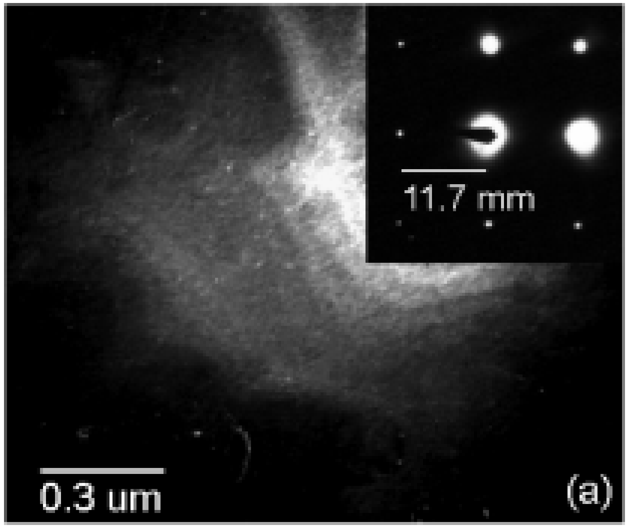
Melt Laser anneals of PAI USJs

Data from PhD Thesis of M.H. Clark, Univ. of Florida, 2004

- PAI: 15 keV Si^+ (a-thick. ~30 nm)
- XeCl laser (308 nm), 18 ns pulse, 0.68-0.76 J/cm^2



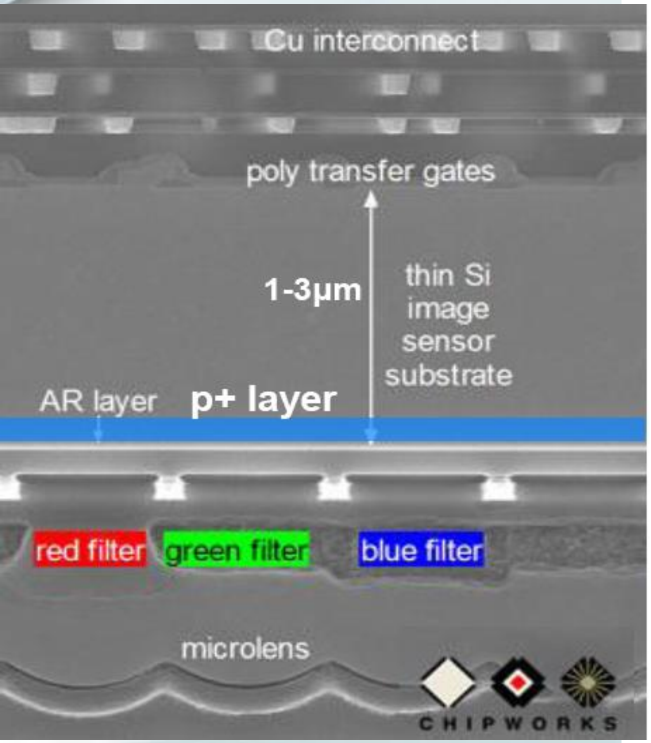




Amorphous layer is not fully melted → Poly-Si

Melt front exceeds a-Si and EOR damage → Fully recristallised Si (very few defects left)

0.9um Pixel CMOS Imager Sensor Technology with Backside Illumination



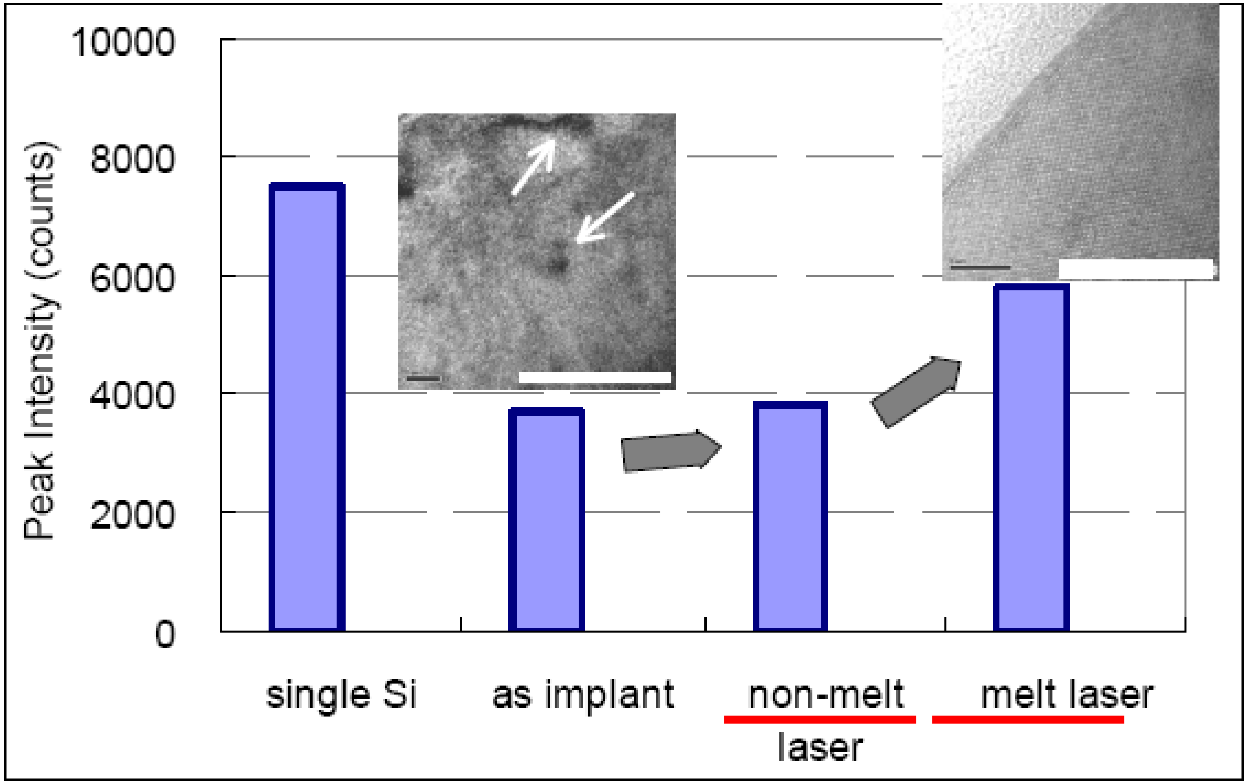
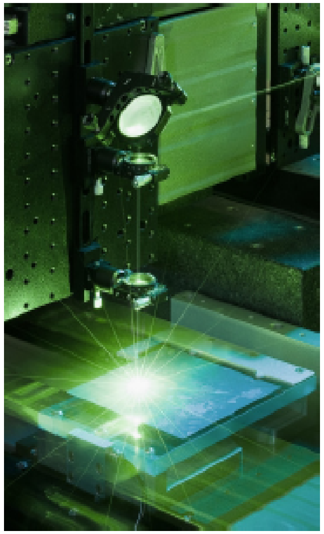


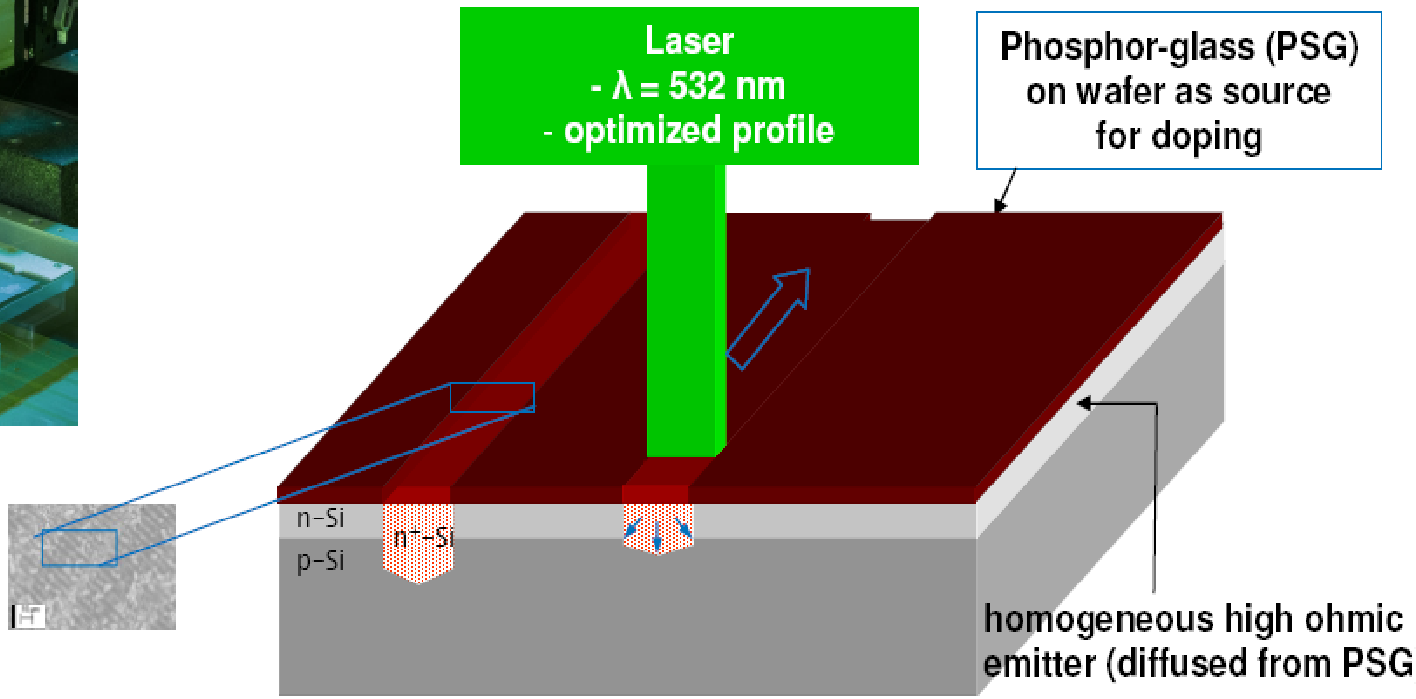
Figure 4. Photoluminescence and TEM study of laser anneal (higher peak intensity means better Si crystal quality)

TSMC, IEDM-2010, paper 14.1

Efficiency: selective emitter cell I

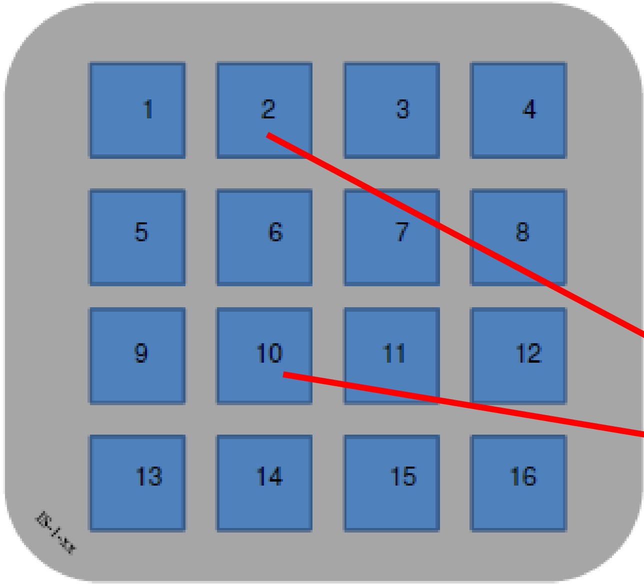


Laser process provides additional doping from PSG glass



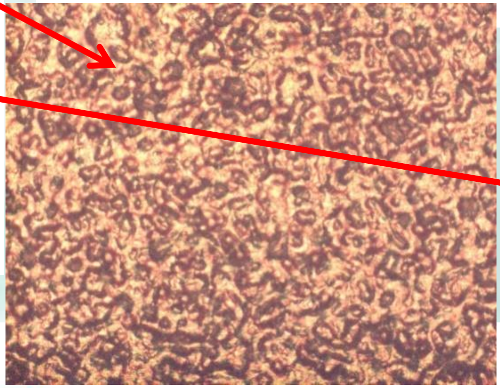
Only one laser process step added to mainstream cell process.
Optimisation of laser process (power/profile/pulse, no defects in silicon…) **essential**

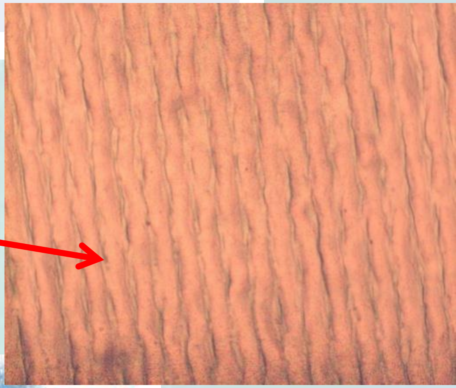
LLM used for both c-Si and multi-Si Solar Cells!



Mark in the lower left corner

area	energy density (J/cm²)		area	energy density (J/cm²)
1	2.75		9	4.75
2	3.0		10	5.0
3	3.25		11	5.25
4	3.5		12	5.5
5	3.75		13	5.75
6	4.0		14	6.0
7	4.25		15	6.25
8	4.5		16	[illegible]





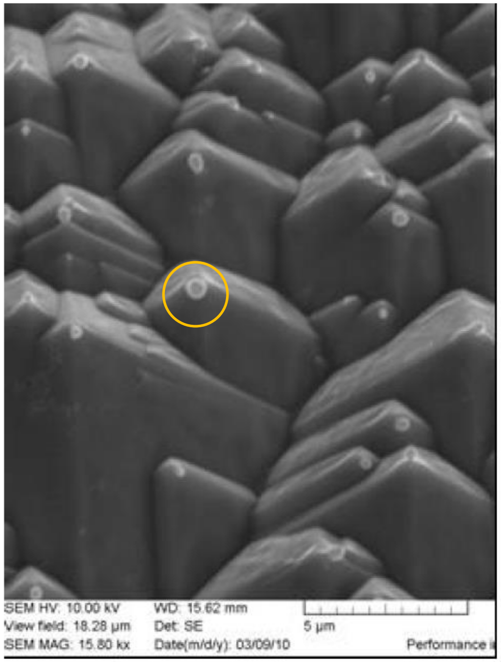
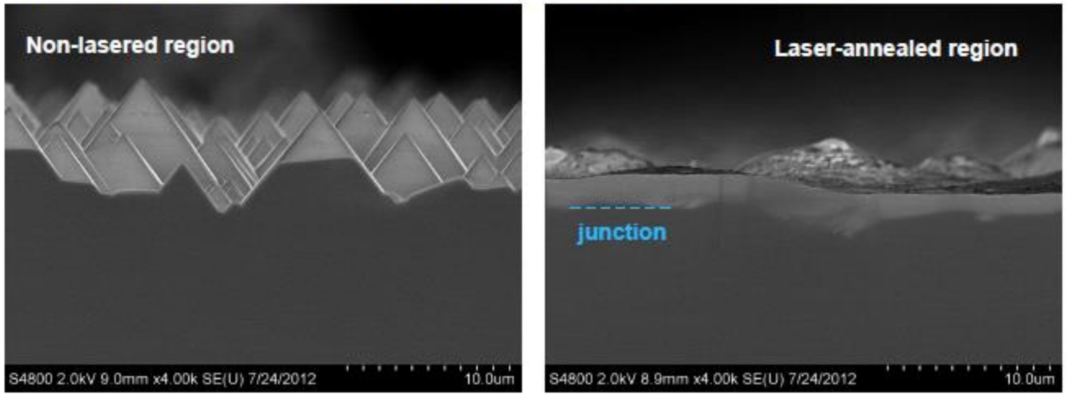


Figure 2: Wafer surface after laser treatment. Only the very tips of the pyramids were slightly molten.

SEM measurements

ISFH

X-SEM images from sample n-8 5 (*n*-type, Boron implant, 3.75 J/cm²)



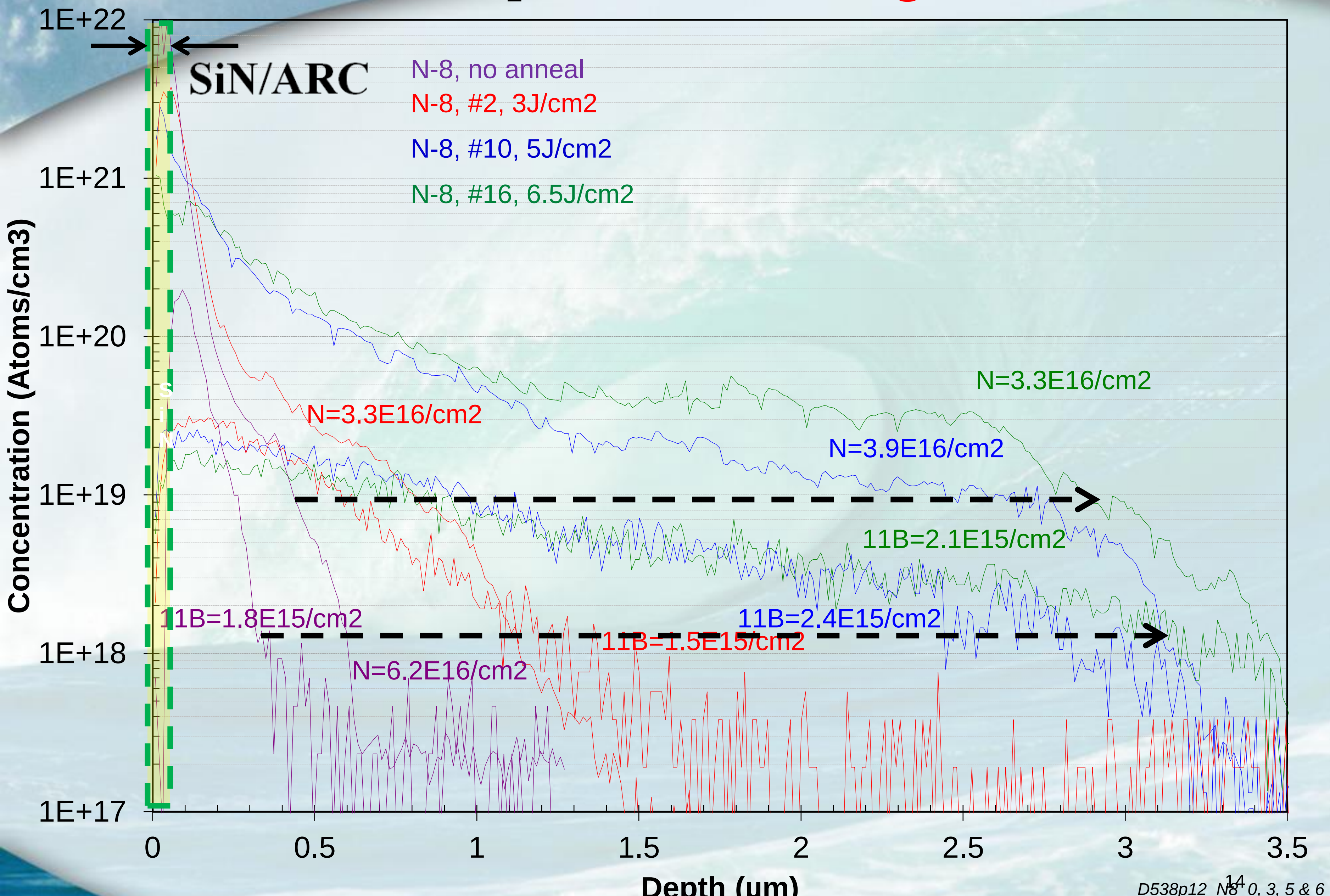
- *p*-doped regions visible by contrast (appear brighter)
- As-implanted junction much more shallow than after anneal (not surprising)
- Junction depth after anneal ~2µm → much deeper than reported in paper (~0.4µm)

Institut für Solarenergieforschung Hameln

Leibniz Universität Hannover

Borland et al, EU-PVSEC 2012

80nm SiN/ARC+B-implant: Note Nitrogen Melt Profile!



Borland et al., EU-PVSEC 2012

IWJT-2011 S9-4 paper by Keio Univ/SEN/**SHI** on p+ USJ by non-melt KrF(248nm) and Green (527nm) laser annealing.

Table 2. Peak temperature for each laser energy density

KrF / Green laser (mJ/cm^2)	Peak Temperature (K)	
300 / 560	1078 K	**=805C**
350 / 655	1205 K	**=932C**
400 / 750	1323 K	**=1050C**
450 / 850	a-Si melting (1420K)	**=1147C**

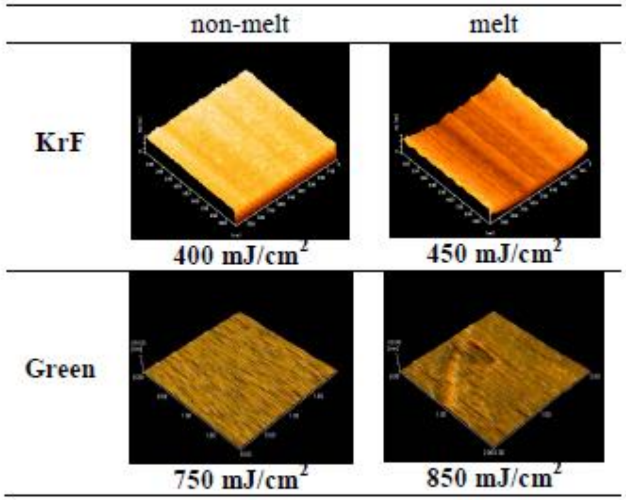


Fig. 2 AFM images for annealed samples

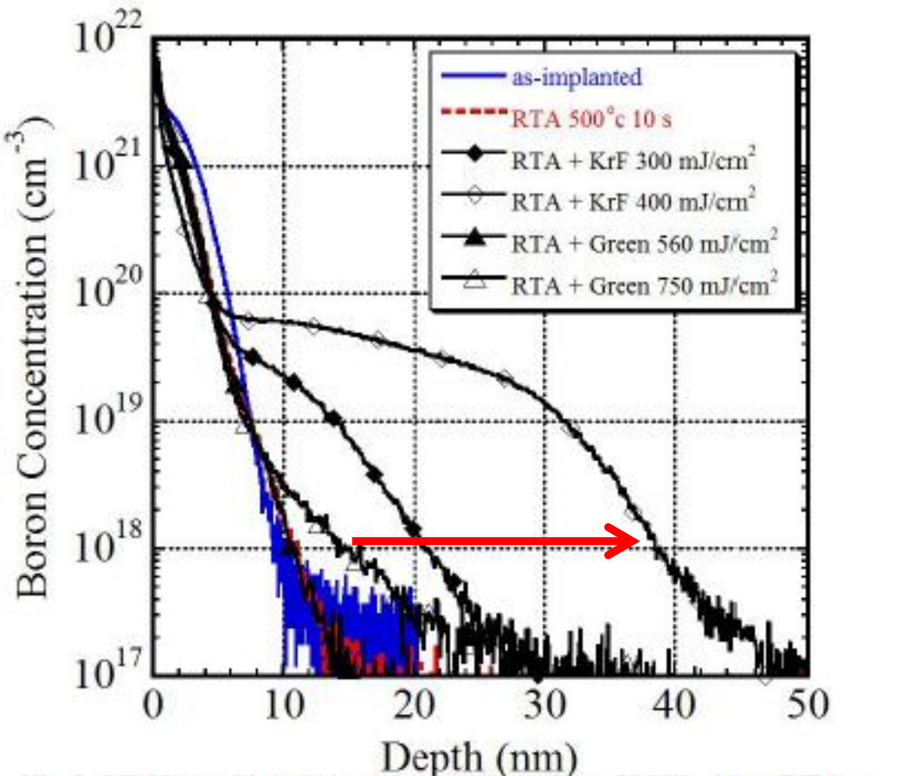
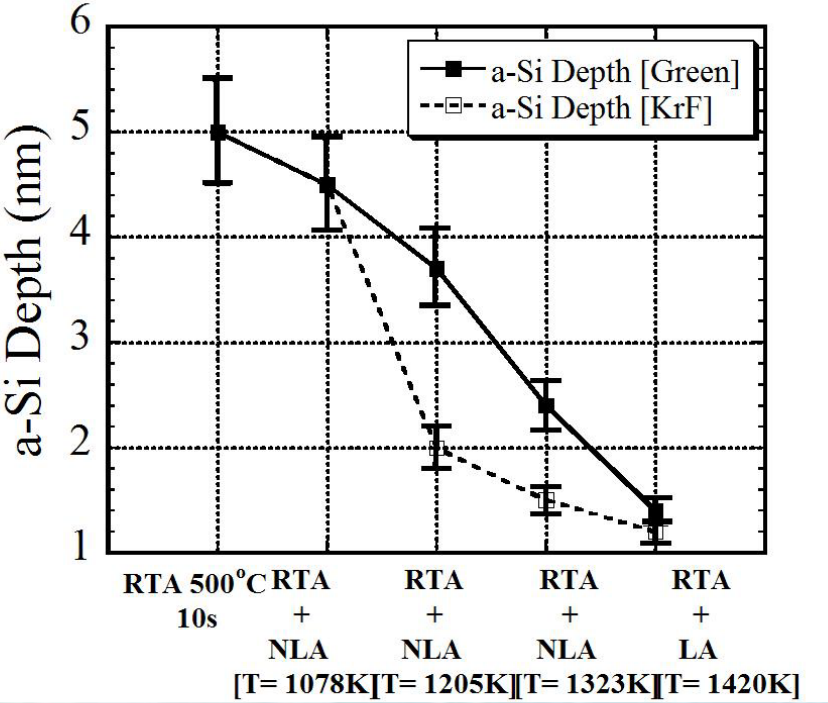


Fig.3 SIMS profile of samples subjected to 500°C, 10 s RTA + NLA by KrF and green laser

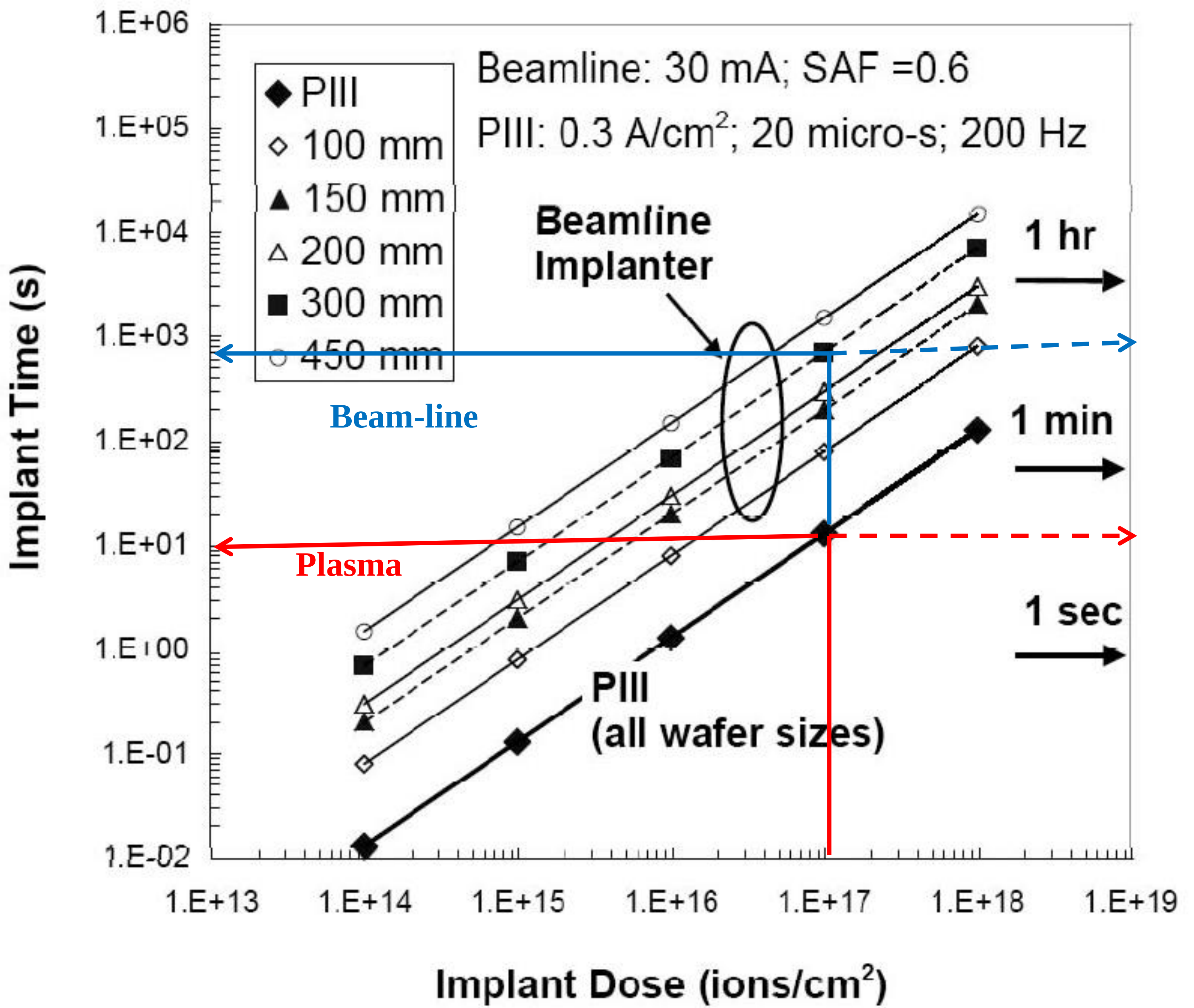


Marketing, Sales & Technology)

With KrF sees selective/localized Si-melt of amorphous region only!

Outline

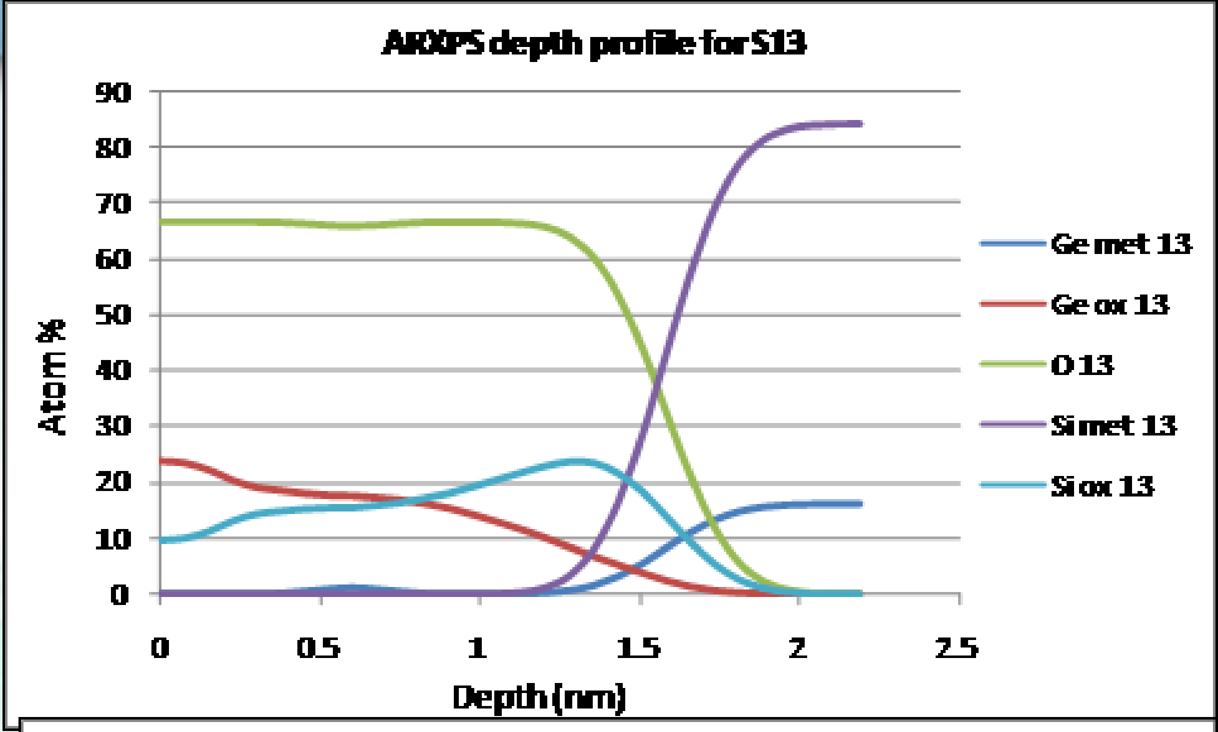
- Introduction
- Experimentation
  - Ge+B Plasma Implantation/Deposition Doping
    - Ge=3kV, 1E16/cm2 and 1e17/cm2 dose
    - B=500V, 4E15/cm2 and 4E16/cm2 dose
  - Laser Melt Annealing
    - Innovavent 515nm laser
    - Excico 308nm laser
- Results
- Summary



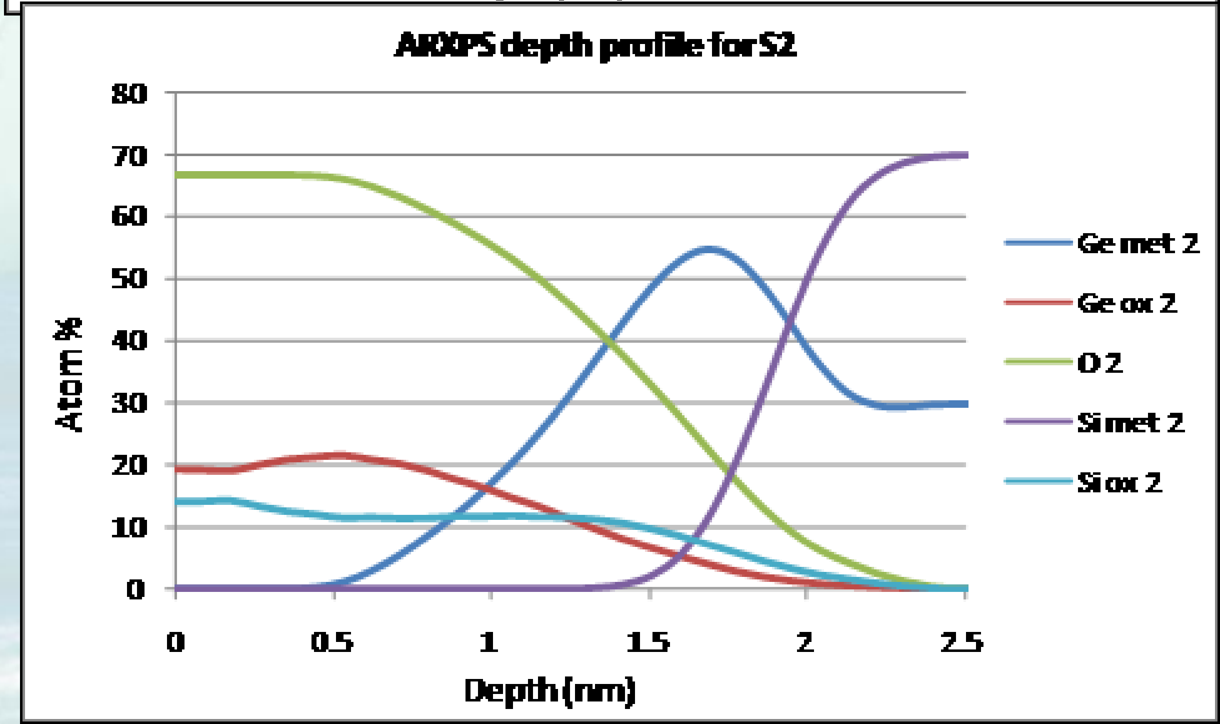
J.O.E
Mark
Tech

Micron Provided Wafers

#13, GEH3K1E16 **(8.6sec)** shows a ~20% Ge peak near Si surface, also shows a ~ 1.5nm native SiO2/GeOx layer.



#15 (#2), GEH3K1E17 **(66 sec)** shows a ~55% Ge peak near Si surface, also shows a ~ 1.8nm native SiO2/GeOx layer.

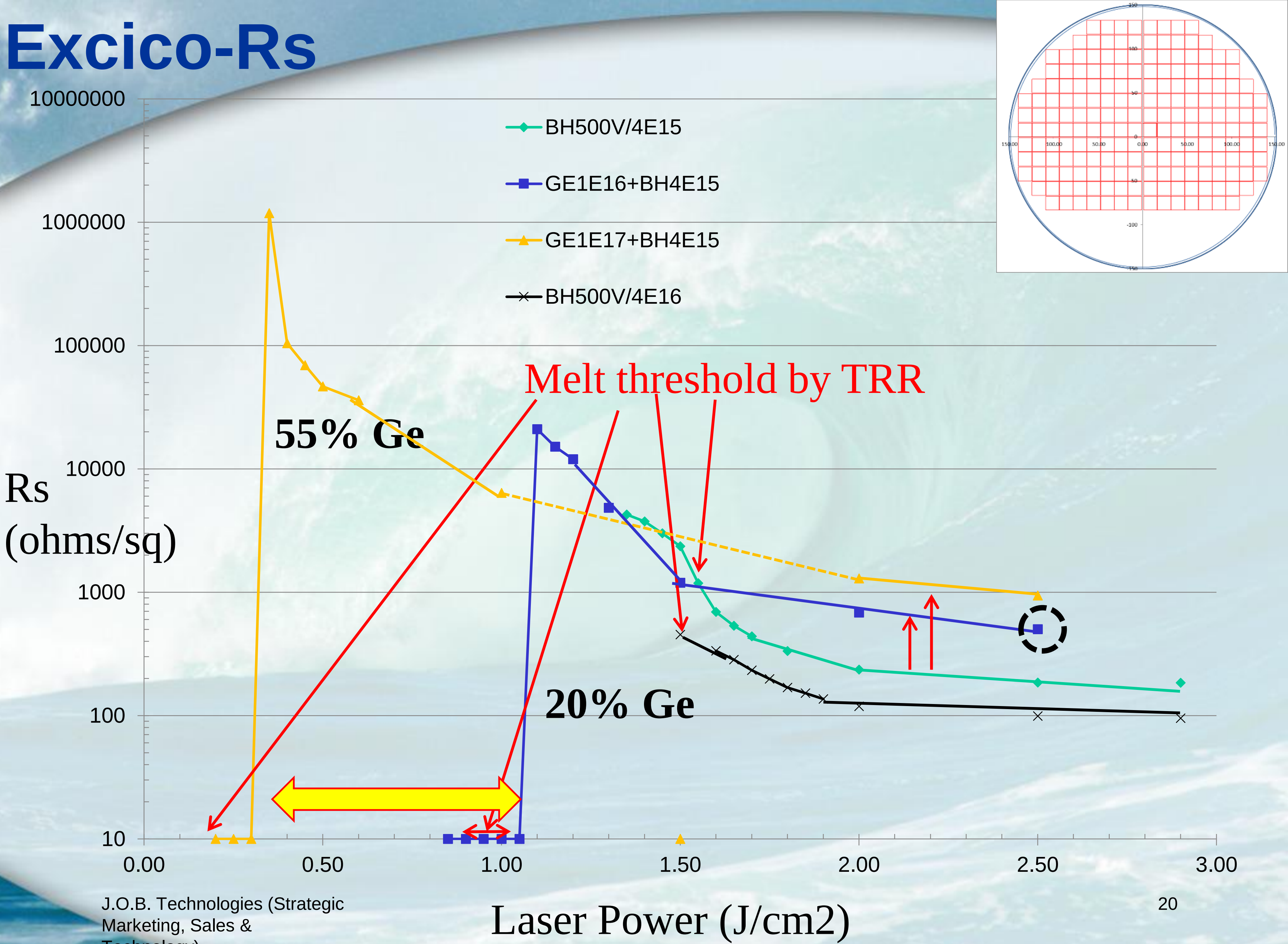


Why not 200%?

Outline

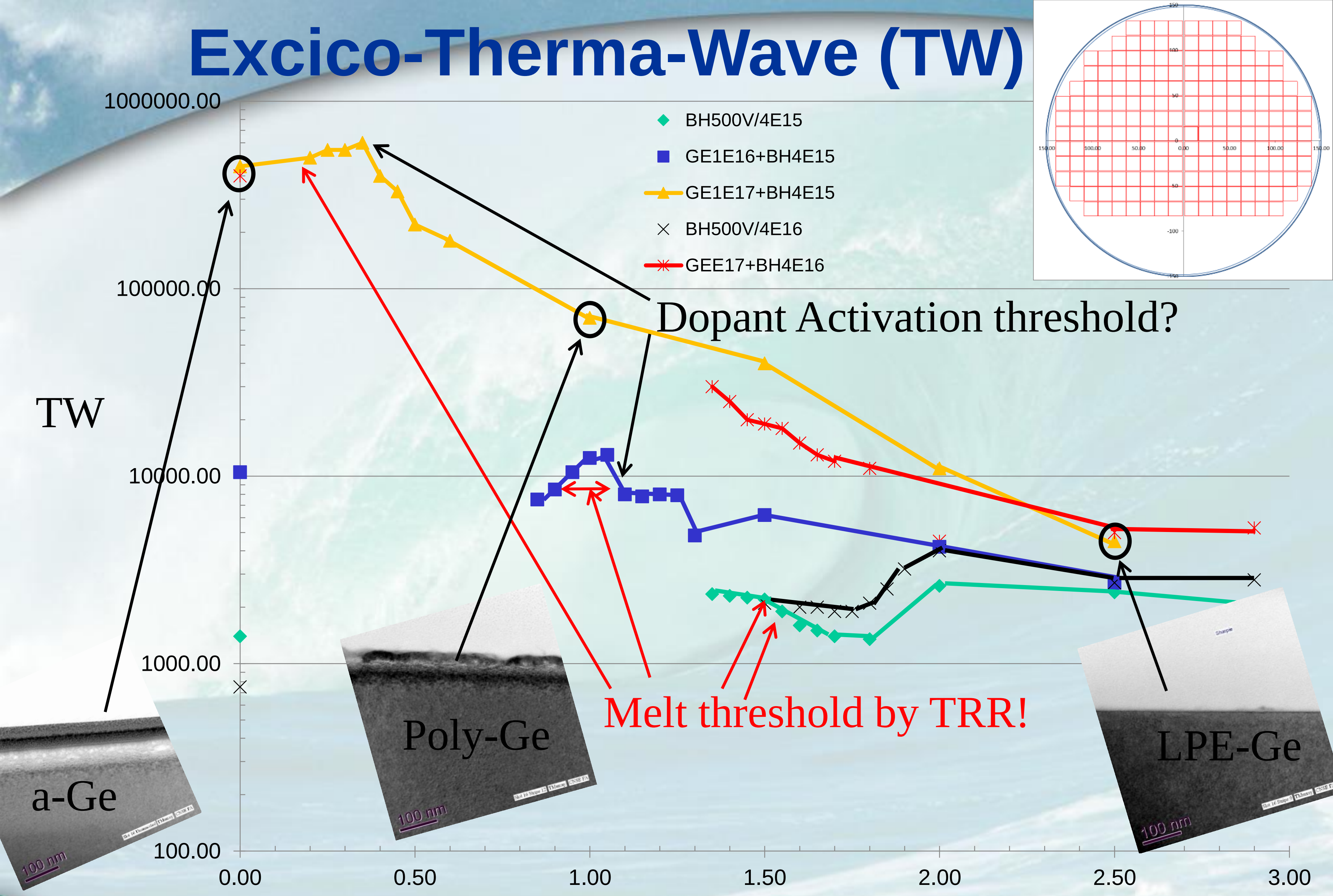
- Introduction
- Experimentation
- Results
  - 308nm Laser Anneal
  - 515nm Laser Anneal
- Summary

Excico-Rs

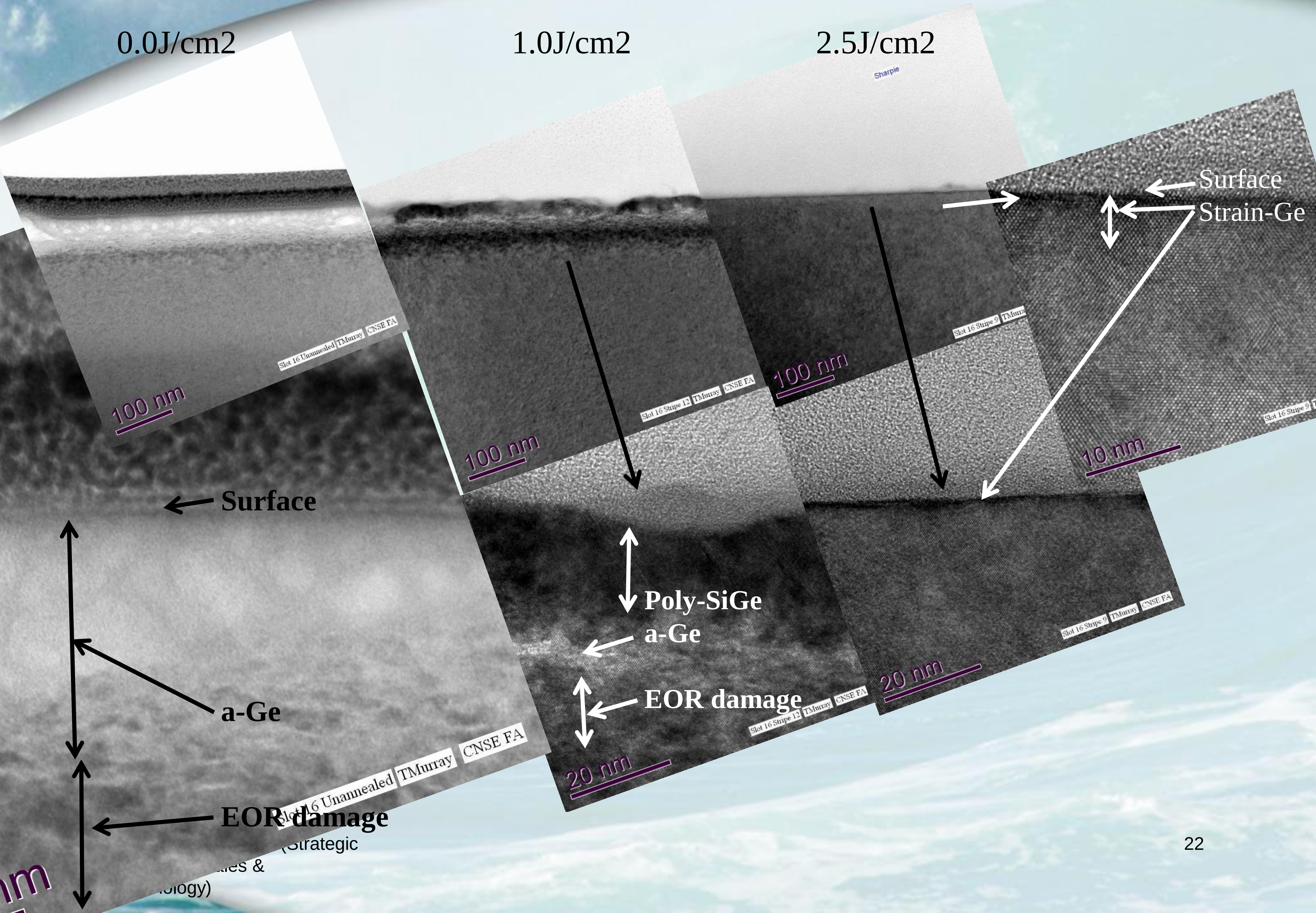


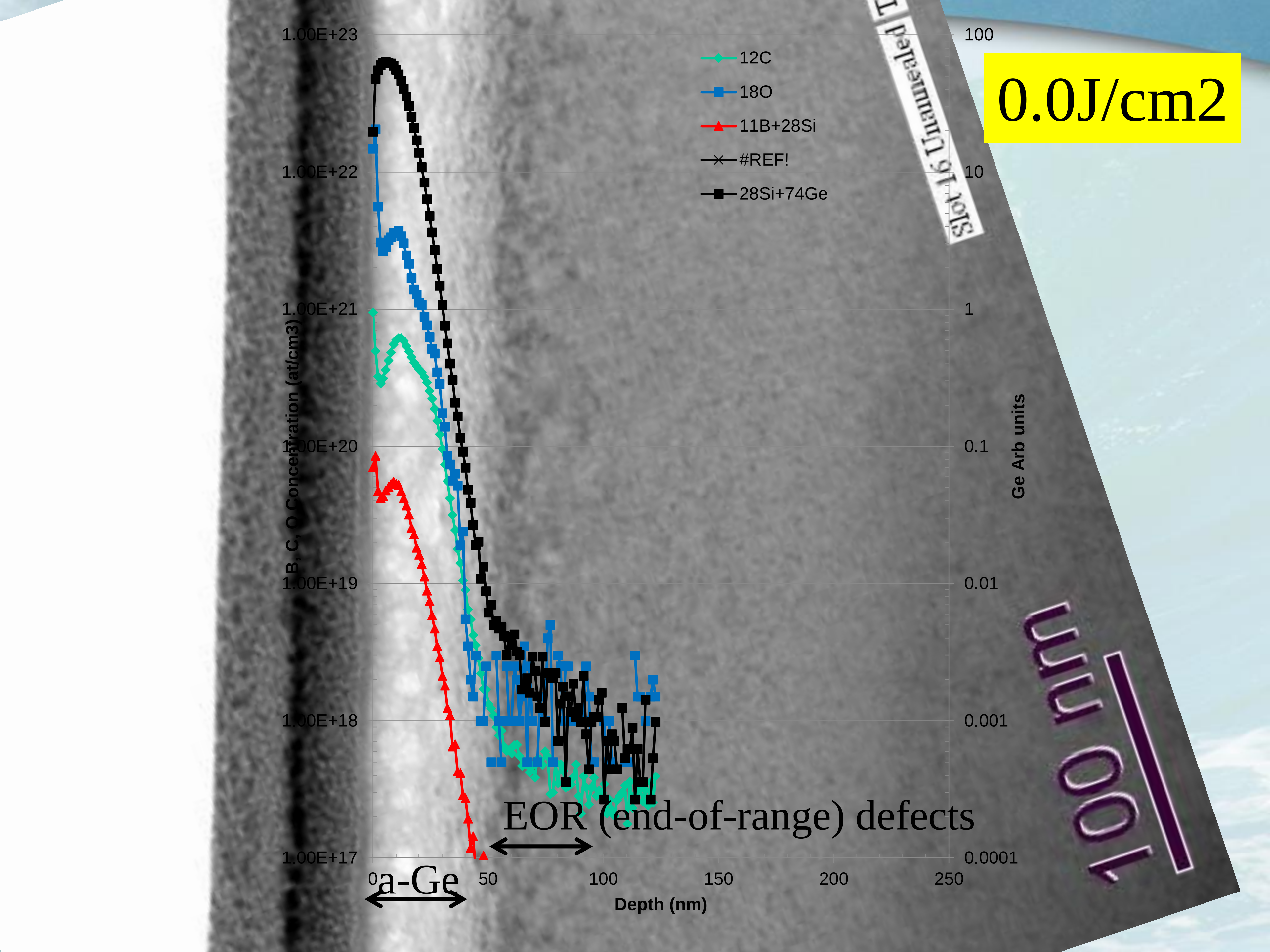
BH500V/4E15
GE1E16+BH4E15
GE1E17+BH4E15
BH500V/4E16
Melt threshold by TRR
55% Ge
20% Ge
Rs
(ohms/sq)
10000000
1000000
100000
10000
1000
100
10
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Laser Power (J/cm2)

Excico-Therma-Wave (TW)

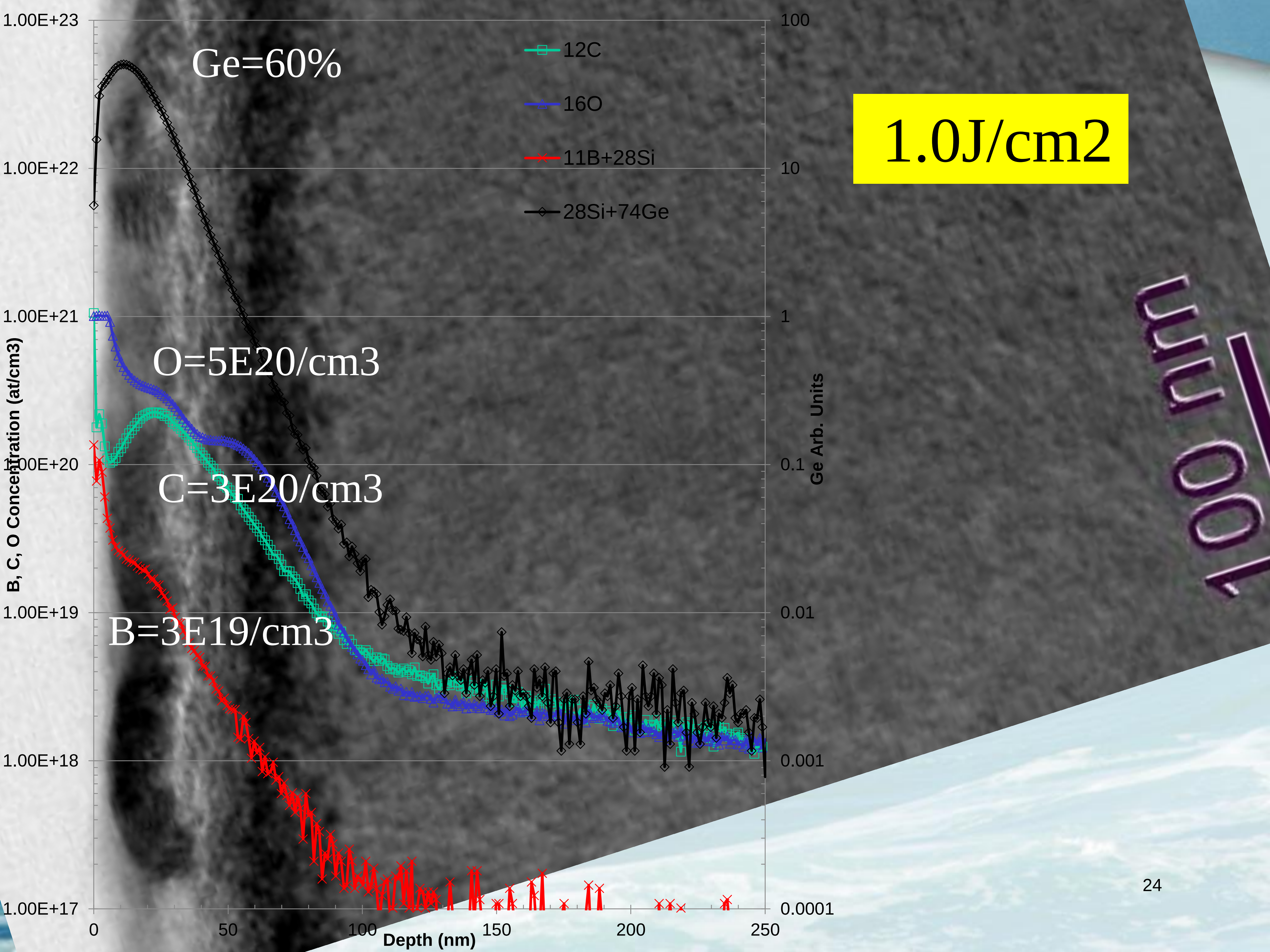


0.0J/cm2 1.0J/cm2 2.5J/cm2

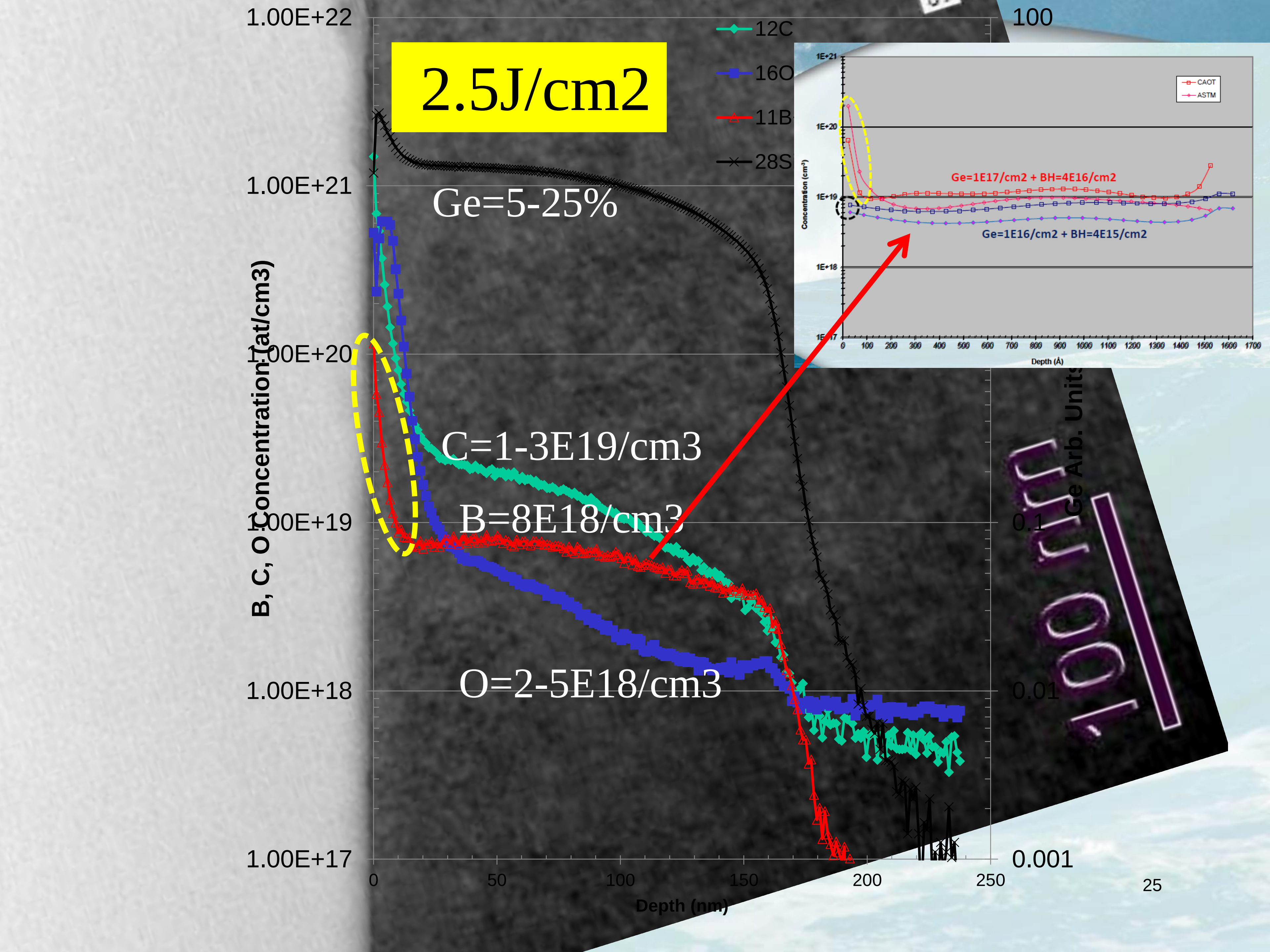




0.0J/cm2
12C
18O
11B+28Si
#REF!
28Si+74Ge
B, C, O Concentration (at/cm3)
Ge Arb units
Depth (nm)
EOR (end-of-range) defects
a-Ge
100 nm



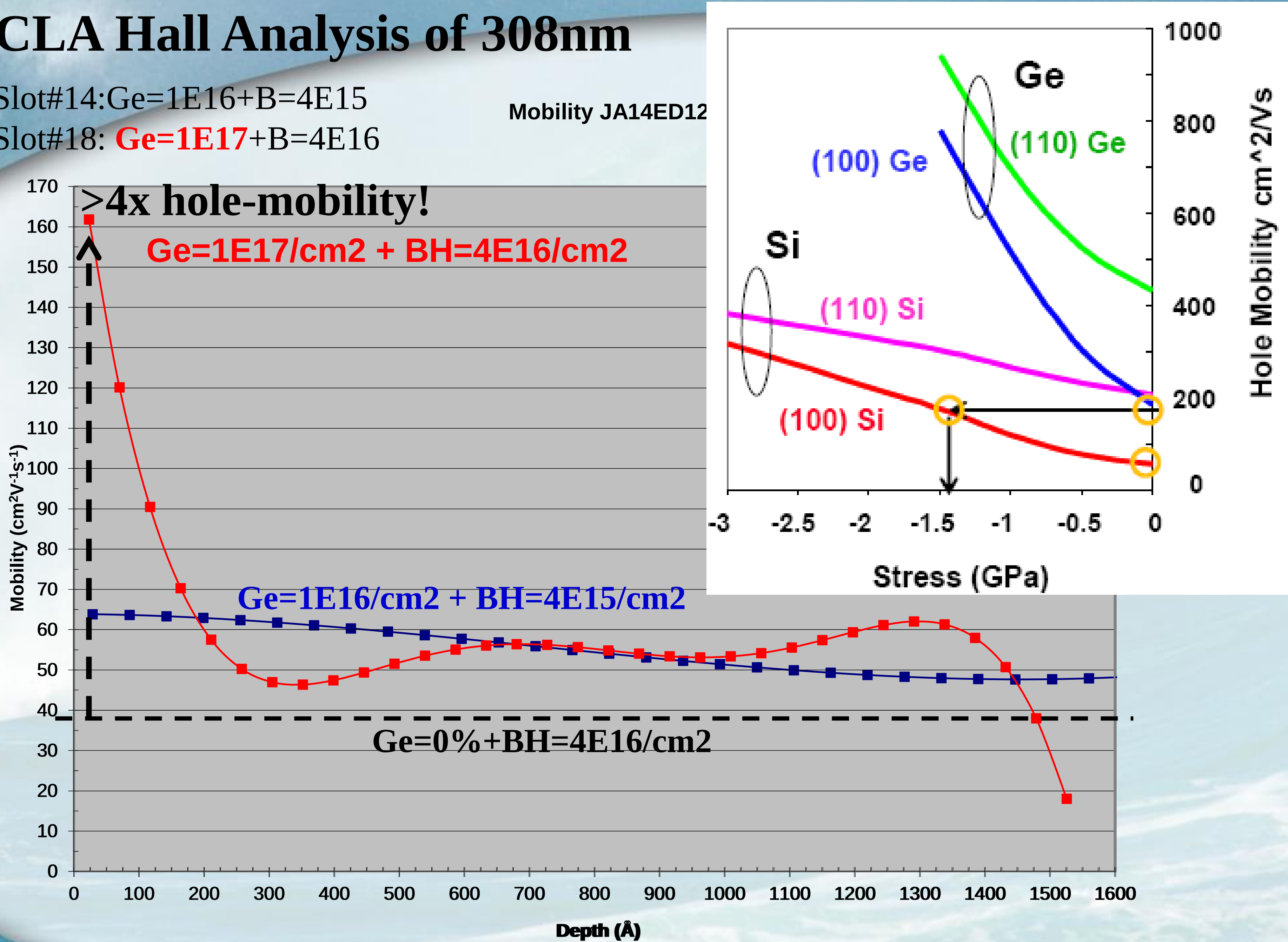
1.0J/cm2
Ge=60%
O=5E20/cm3
C=3E20/cm3
B=3E19/cm3
12C
16O
11B+28Si
28Si+74Ge
B, C, O Concentration (at/cm3)
Ge Arb. Units
Depth (nm)
1.00E+23
1.00E+22
1.00E+21
1.00E+20
1.00E+19
1.00E+18
1.00E+17
100
10
1
0.1
0.01
0.001
0.0001
0
50
100
150
200
250
100 nm



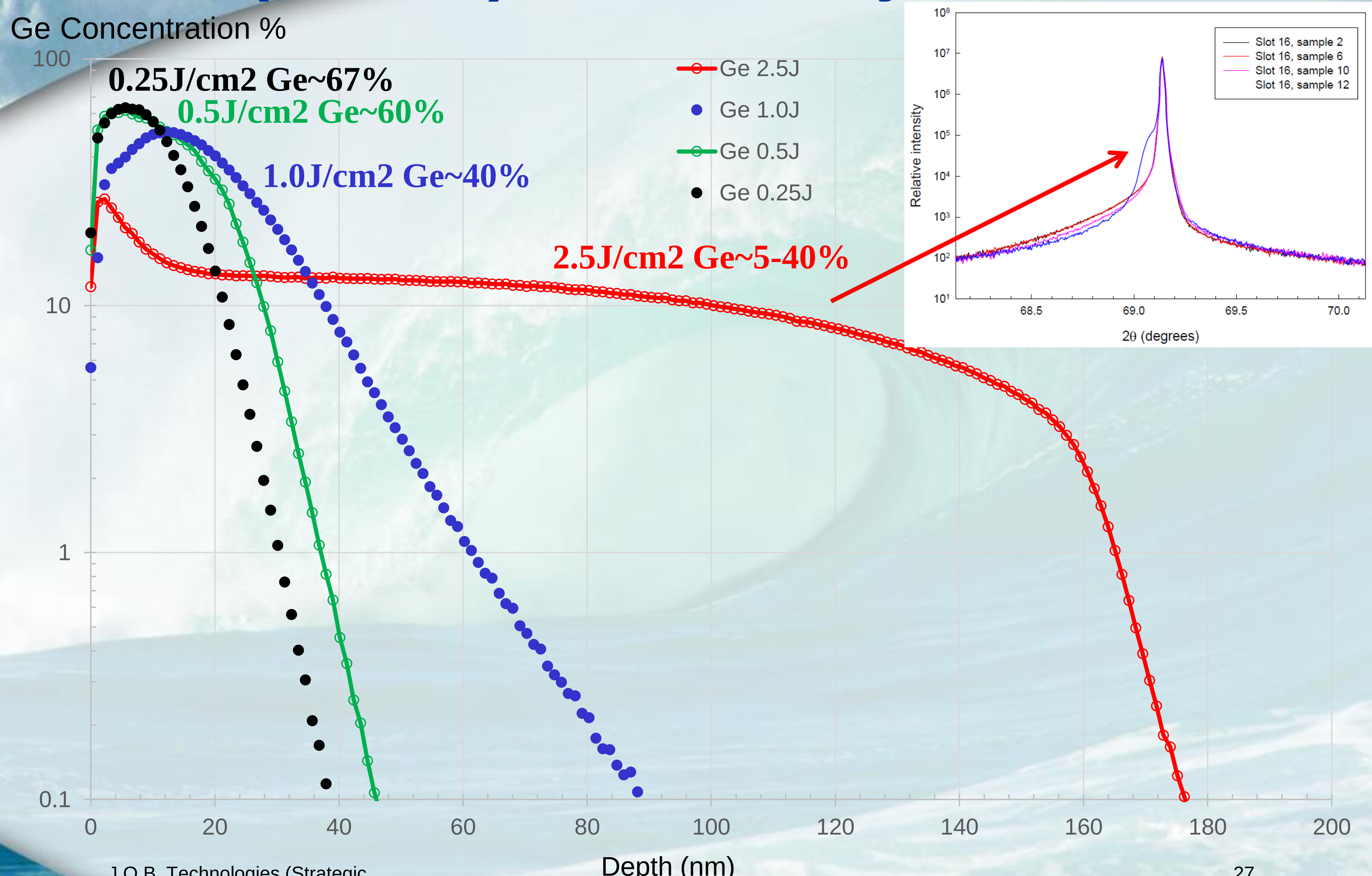
2.5J/cm2
Ge=5-25%
C=1-3E19/cm3
B=8E18/cm3
O=2-5E18/cm3
12C
16O
11B
28S
1.00E+22
1.00E+21
1.00E+20
1.00E+19
1.00E+18
1.00E+17
B, C, O Concentration (at/cm3)
0
50
100
150
200
250
Depth (nm)
100
0.1
0.01
0.001
Ge Arb. Units
100 nm
CAOT
ASTM
Ge=1E17/cm2 + BH=4E16/cm2
Ge=1E16/cm2 + BH=4E15/cm2
1E+21
1E+20
1E+19
1E+18
Depth (Å)

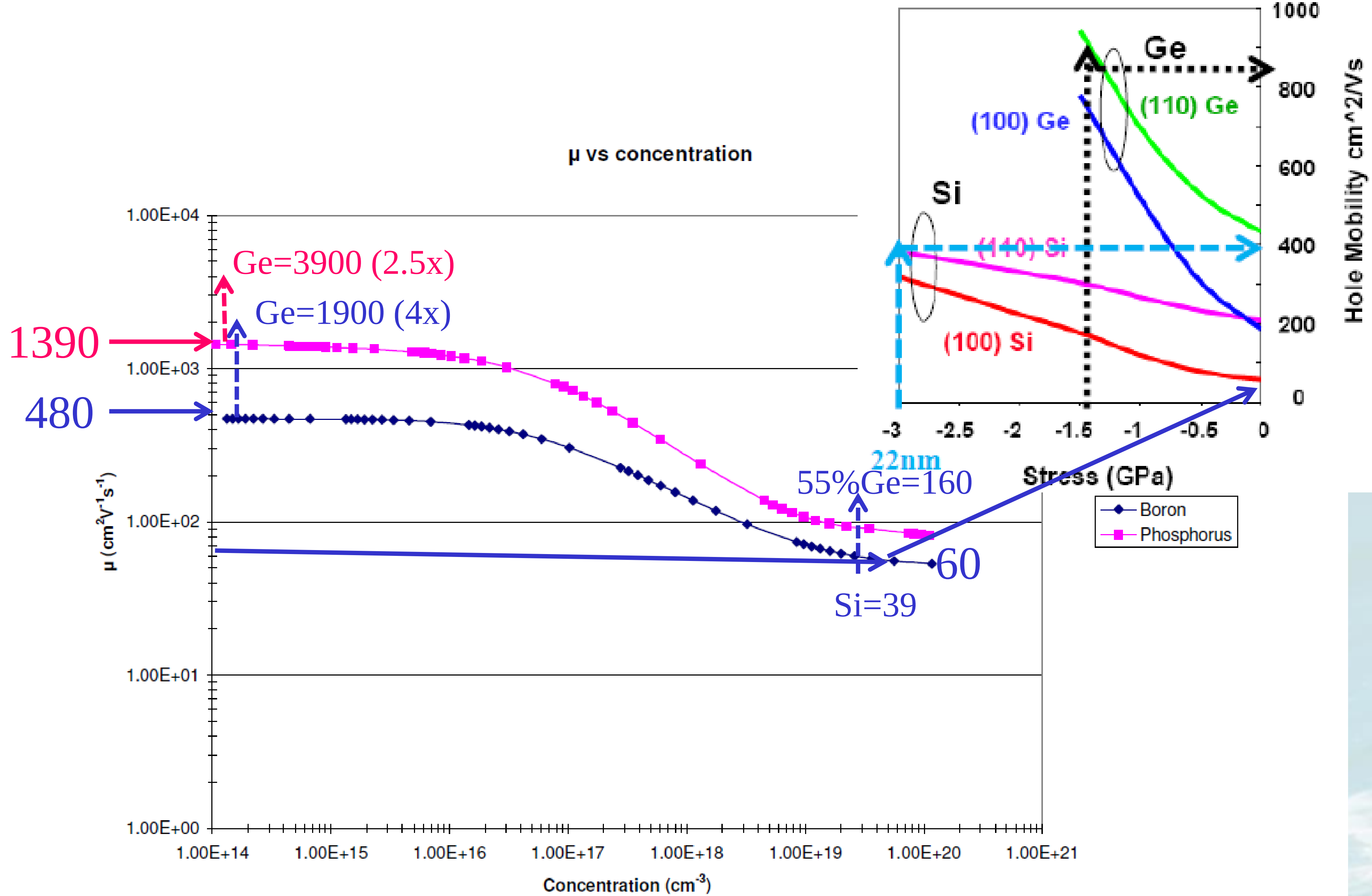
UCLA Hall Analysis of 308nm

Slot#14:Ge=1E16+B=4E15
Slot#18: **Ge=1E17**+B=4E16

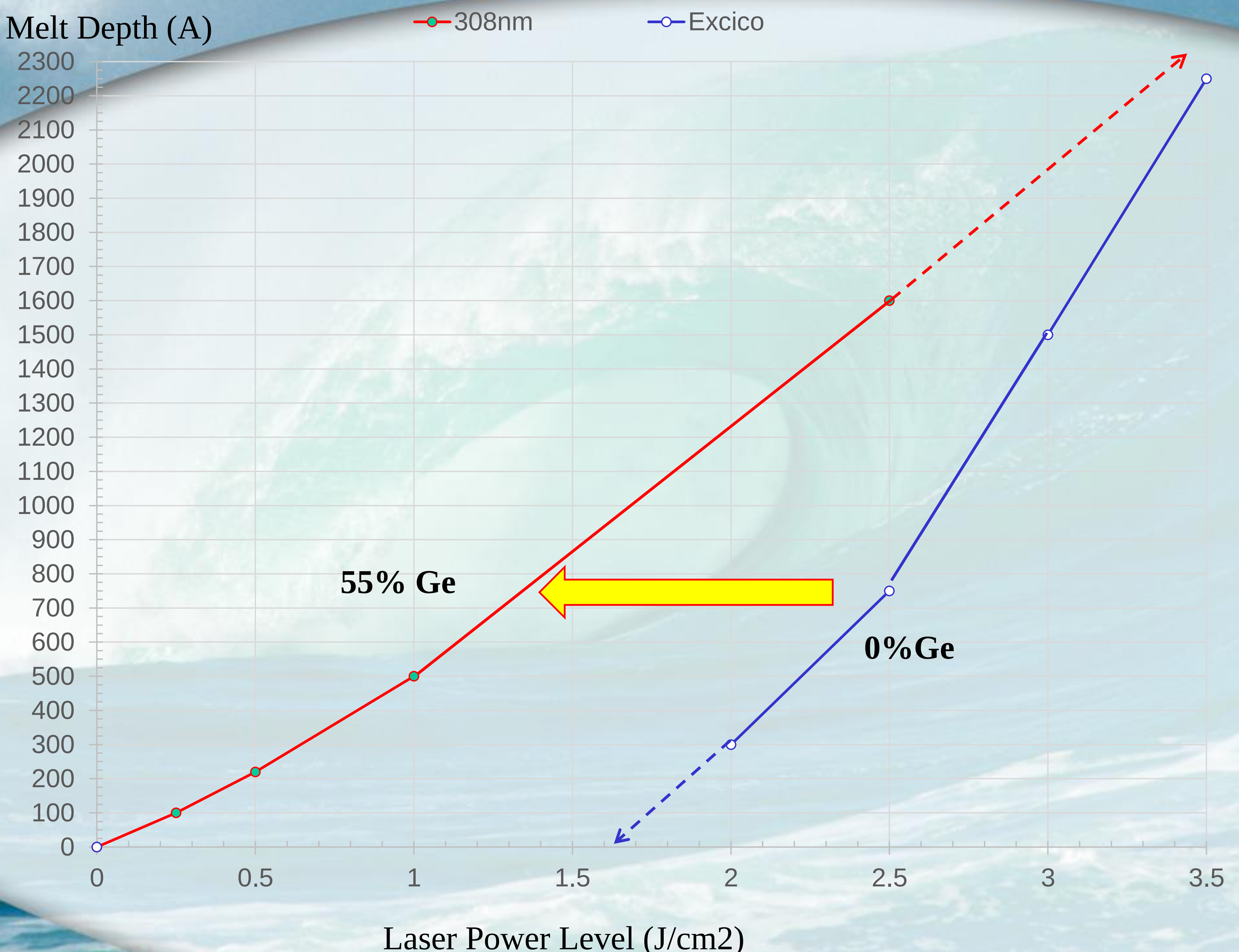


Excico (308nm) Ge-SIMS by CNSE



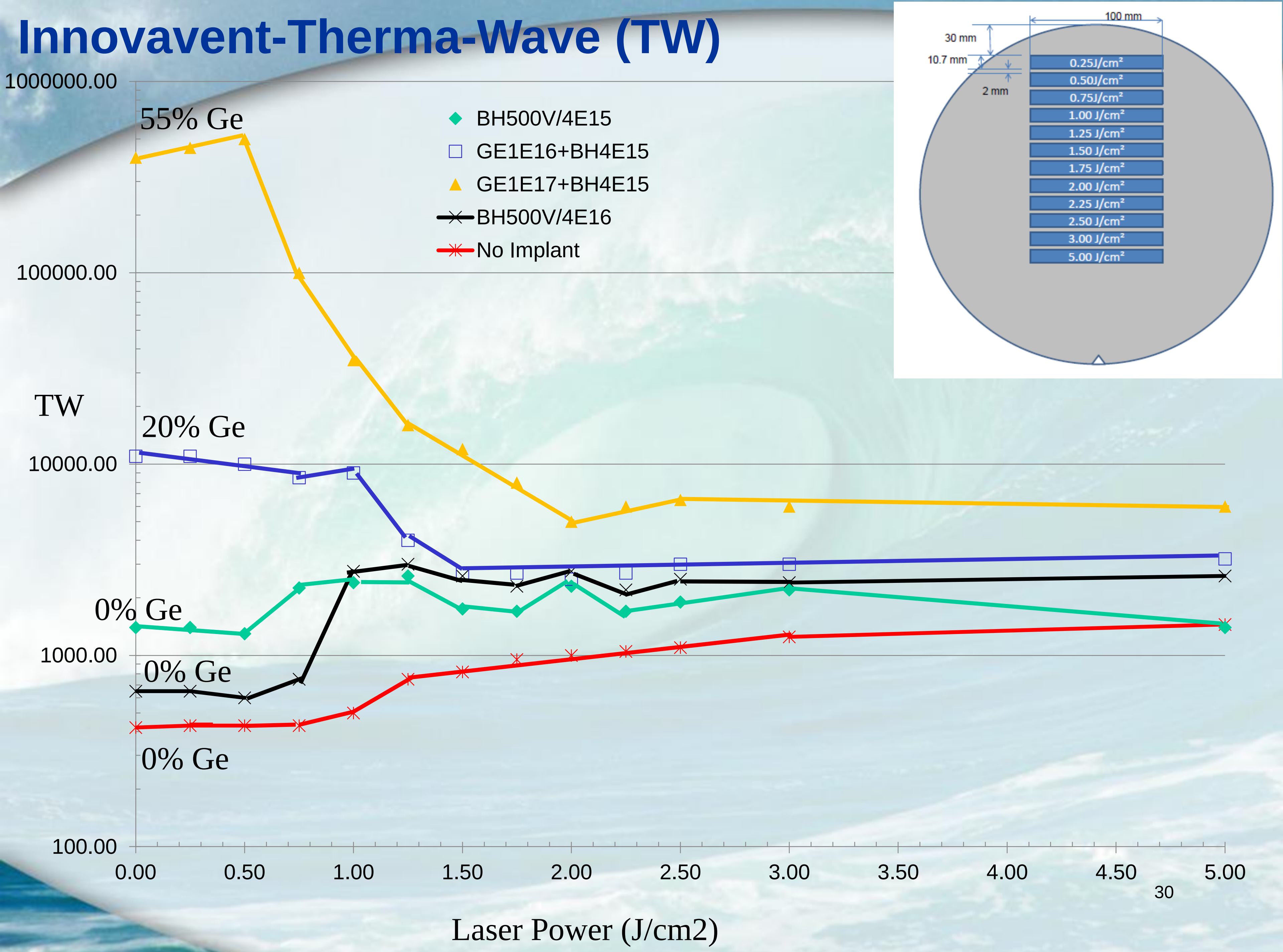


μ vs concentration
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
μ (cm²V⁻¹s⁻¹)
1.00E+14
1.00E+15
1.00E+16
1.00E+17
1.00E+18
1.00E+19
1.00E+20
1.00E+21
Concentration (cm⁻³)
Ge=3900 (2.5x)
Ge=1900 (4x)
1390
480
22nm
55%Ge=160
60
Si=39
Boron
Phosphorus
Ge
Si
(100) Ge
(110) Ge
(110) Si
(100) Si
1000
800
600
400
200
0
Hole Mobility cm^2/Vs
-3
-2.5
-2
-1.5
-1
-0.5
0
Stress (GPa)

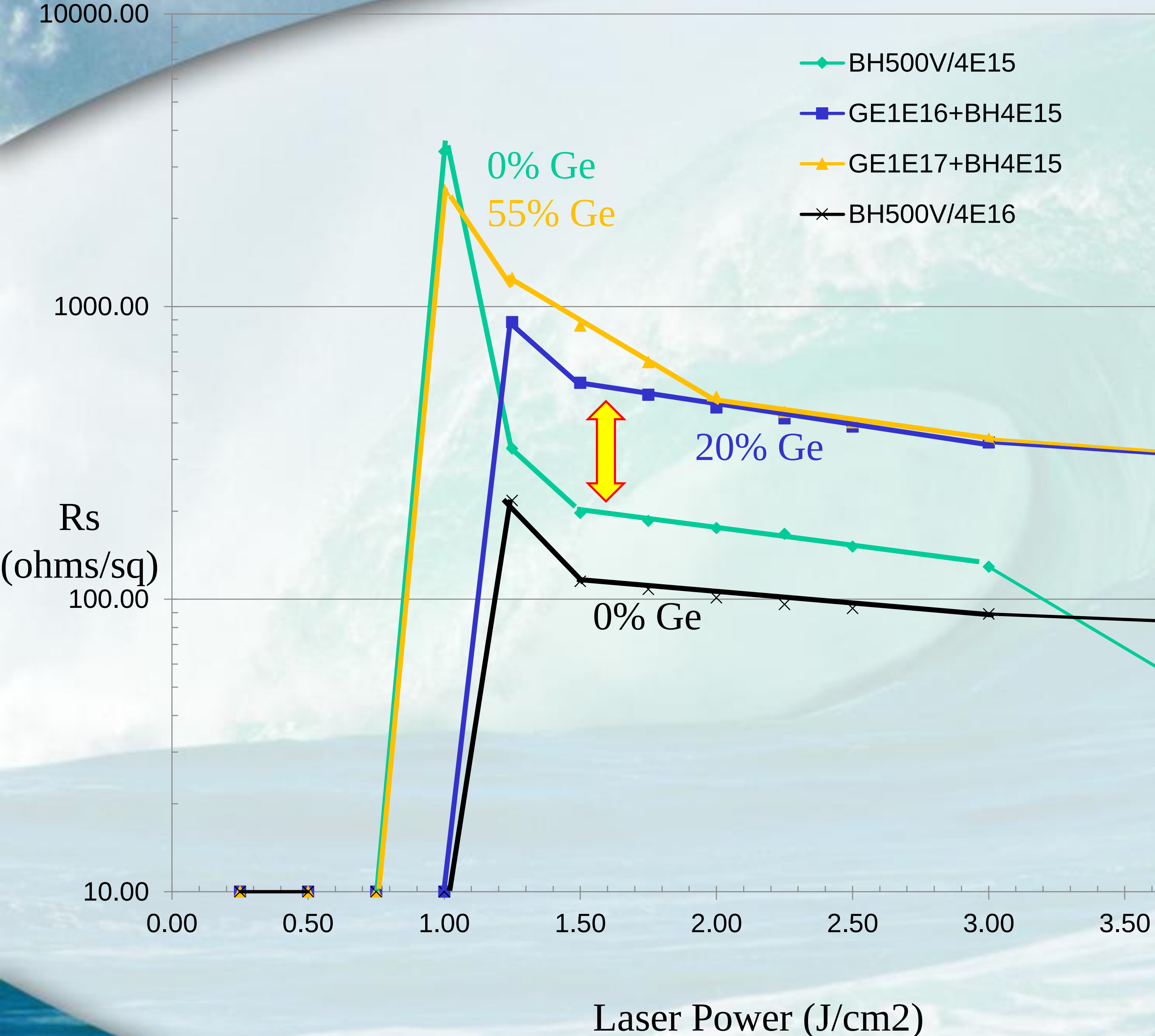


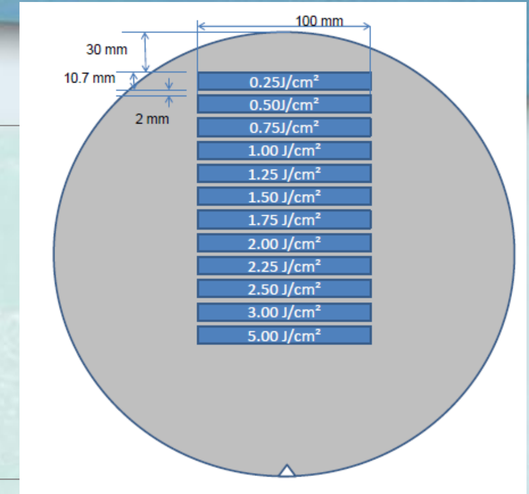
Melt Depth (A)
308nm
Excico
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
55% Ge
0%Ge
0
0.5
1
1.5
2
2.5
3
3.5
Laser Power Level (J/cm2)

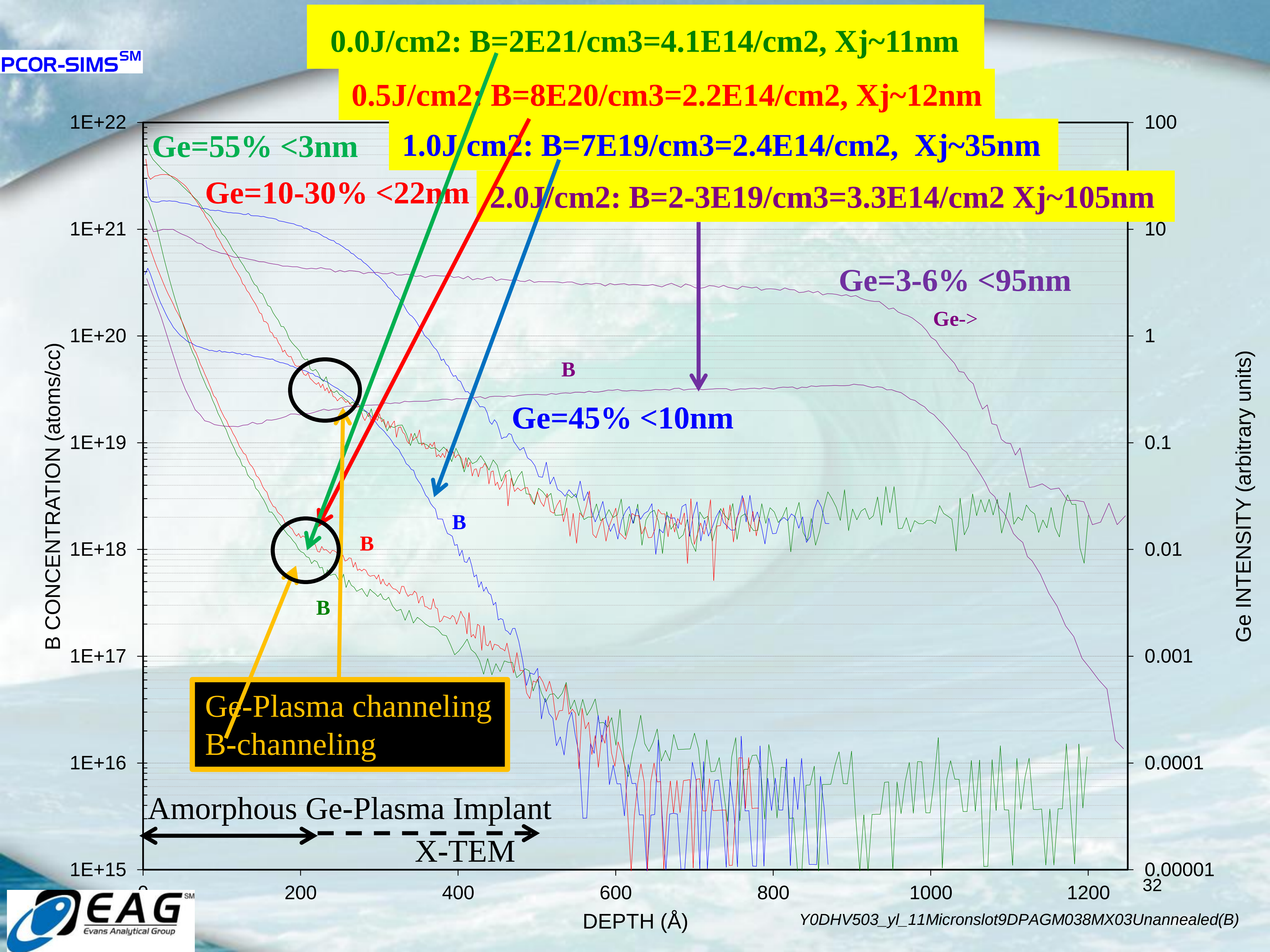
Innovavent-Therma-Wave (TW)



Innovavent-Rs

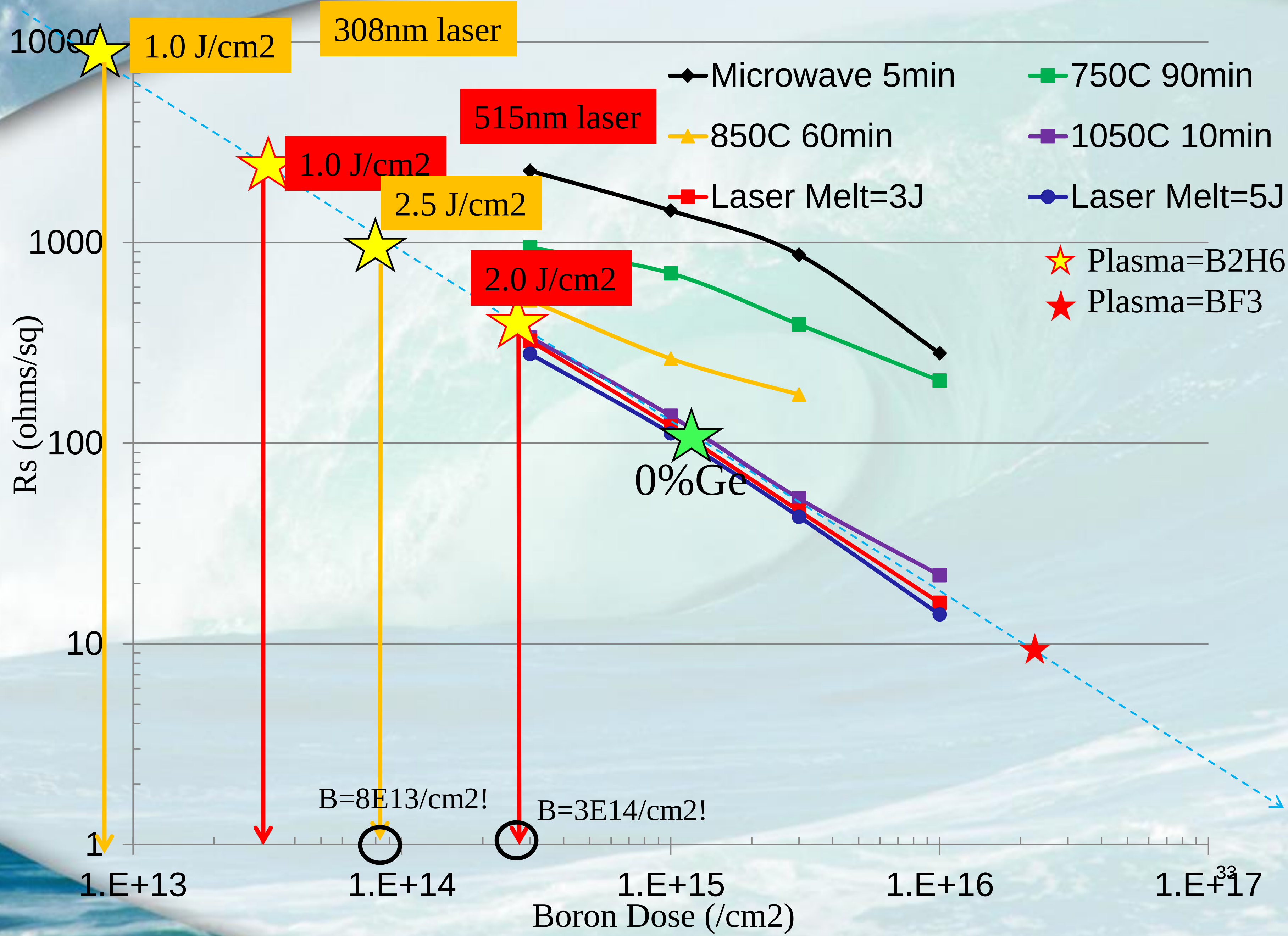


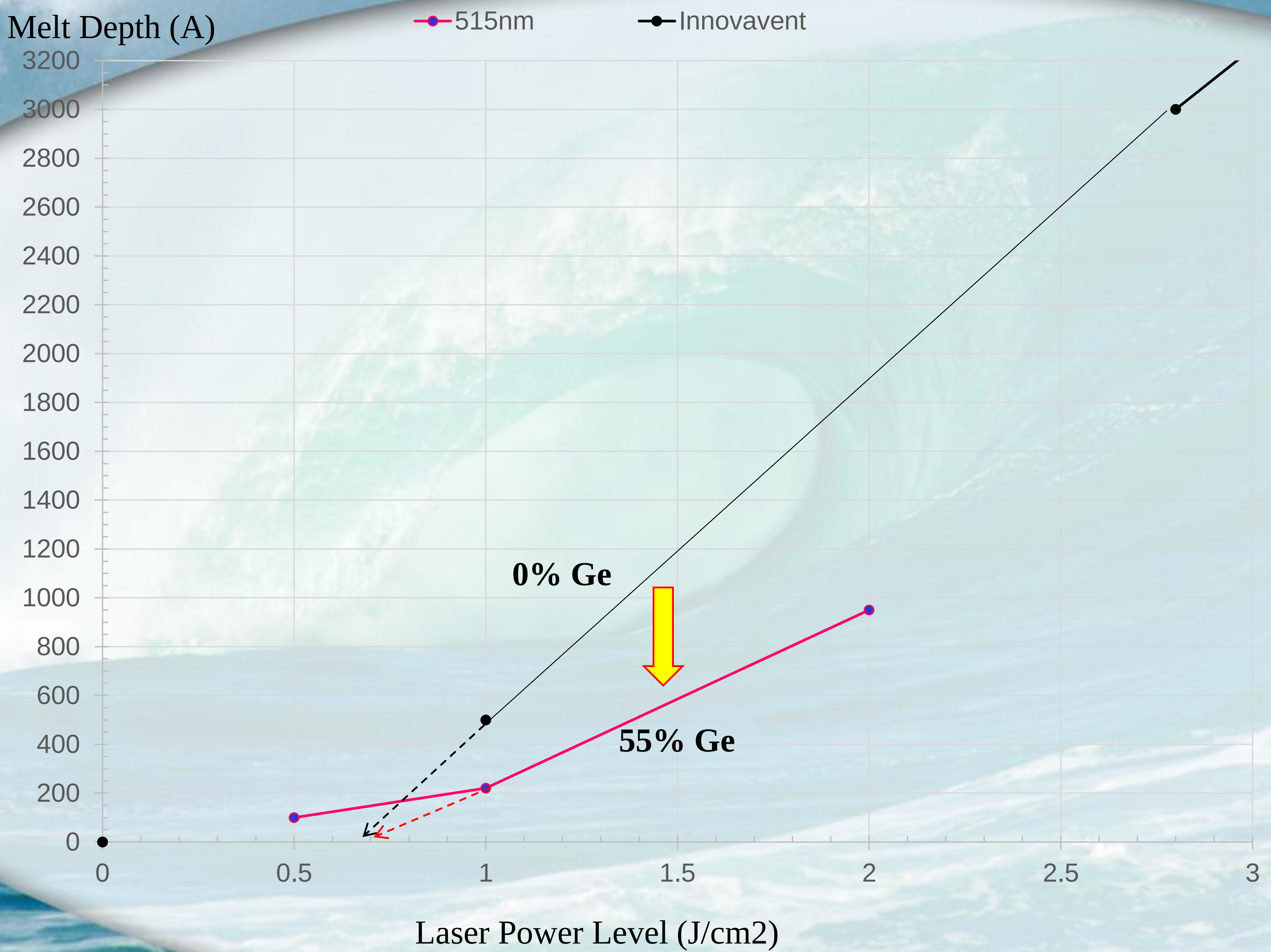




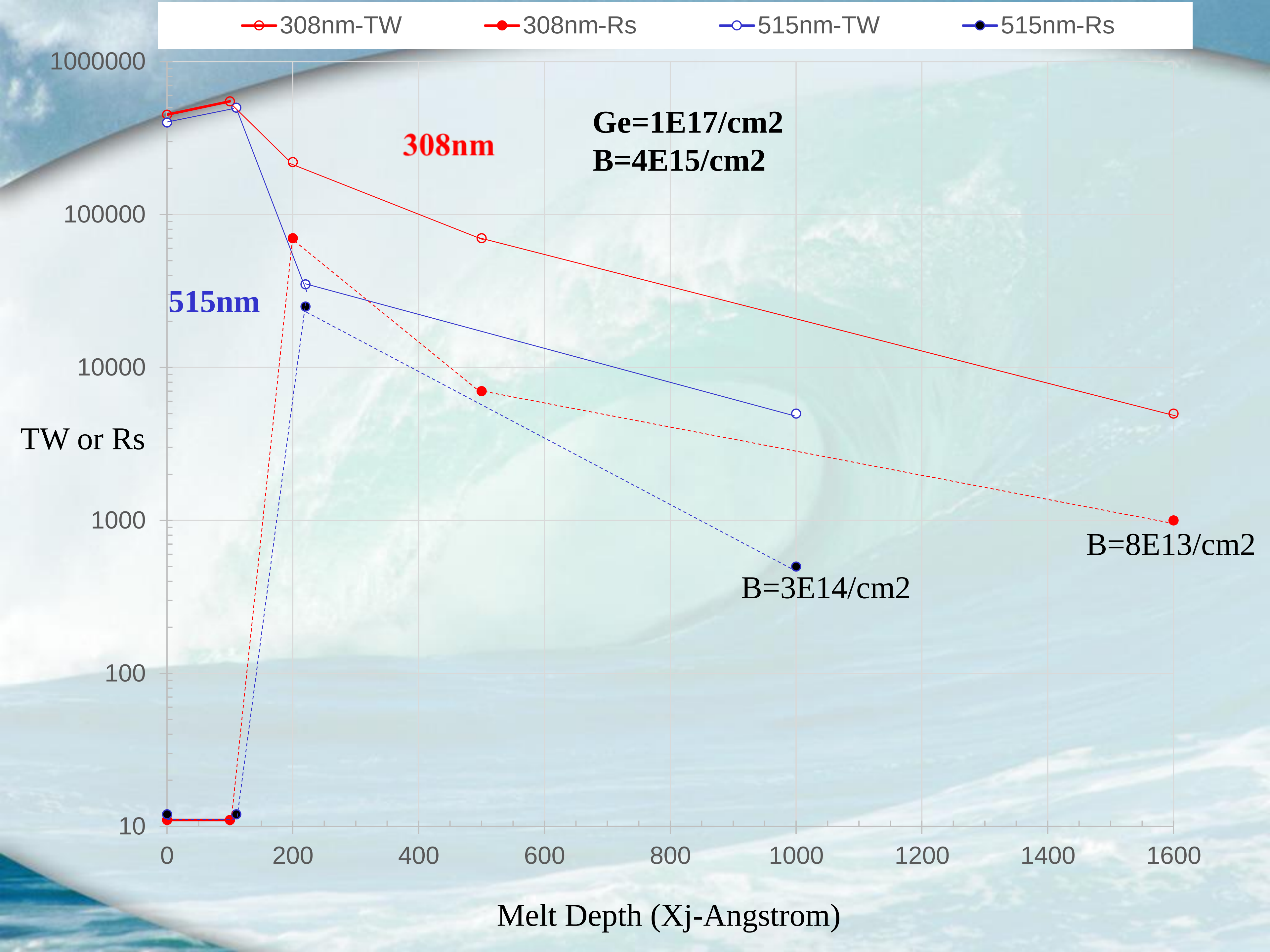
PCOR-SIMS SM
0.0J/cm2: B=2E21/cm3=4.1E14/cm2, Xj~11nm
0.5J/cm2: B=8E20/cm3=2.2E14/cm2, Xj~12nm
1.0J/cm2: B=7E19/cm3=2.4E14/cm2, Xj~35nm
2.0J/cm2: B=2-3E19/cm3=3.3E14/cm2 Xj~105nm
Ge=55% <3nm
Ge=10-30% <22nm
Ge=3-6% <95nm
Ge->
Ge=45% <10nm
B
B
B
B
Ge-Plasma channeling
B-channeling
Amorphous Ge-Plasma Implant
X-TEM
B CONCENTRATION (atoms/cc)
Ge INTENSITY (arbitrary units)
DEPTH (Å)
1E+22
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0
200
400
600
800
1000
1200
Y0DHV503_yl_11Micronslot9DPAGM038MX03Unannealed(B)
EAG Evans Analytical Group

Boron Implant





Melt Depth (A)
515nm
Innovavent
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0% Ge
55% Ge
0
0.5
1
1.5
2
2.5
3
Laser Power Level (J/cm2)



308nm-TW
308nm-Rs
515nm-TW
515nm-Rs
Ge=1E17/cm2
B=4E15/cm2
308nm
515nm
TW or Rs
B=8E13/cm2
B=3E14/cm2
1000000
100000
10000
1000
100
10
0
200
400
600
800
1000
1200
1400
1600
Melt Depth (Xj-Angstrom)

Summary & What Next?:

- High quality Ge-Epitaxy was achieved from 1e17/cm2 amorphous Ge-plasma implantation when using LPE (liquid phase epitaxy) by both 308nm and 515nm laser melt annealing.
- This resulted in a 4x increase in surface hole-mobility.
  - Try lower B dose <5E12/cm2 and look at electron mobility next.
- The 308nm laser melt annealing process achieved shallow <10nm selective localized melting of amorphous-Ge and amorphous-Si regions but showed higher Rs dopant activation.
  - Why >3x lower B electrical activation or B retained dose? Loss of surface Ge doping reported with Ge-RMG without surface cap!
- The 515nm laser melt annealing process showed lower Rs dopant activation (higher B retained dose) but was not selective to amorphous-Ge or amorphous-Si regions.
  - Try longer pulse duration next.
- Next: Ge, SiGe & Si hole (B) and electron (P, As & Sb) mobility
  - Ge beam-line implantation at 5E16/cm2 dose
  - Ge-Epilayer on Si-bulk, SiGe-buffer and SOI wafers