P, Sb and Sn Ion Implantation with Laser Melt-LPC (Liquid Phase Crystallization) For High Activation n+ Ultra-Shallow Junction in Ge Epilayer and Surface Strain-Ge Formation For Mobility Enhancement

John Borland[1], Joshua Herman[2], Steve Novak[2], Hiroshi Onoda[3], Yoshiki Nakashima[3], Karim Huet[4], Walt Johnson[5] and Abhijeet Joshi[6]

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IWJT-2015 June 11-12, 2015 Kyoto, Japan

&

Semicon/West July 16, 2015

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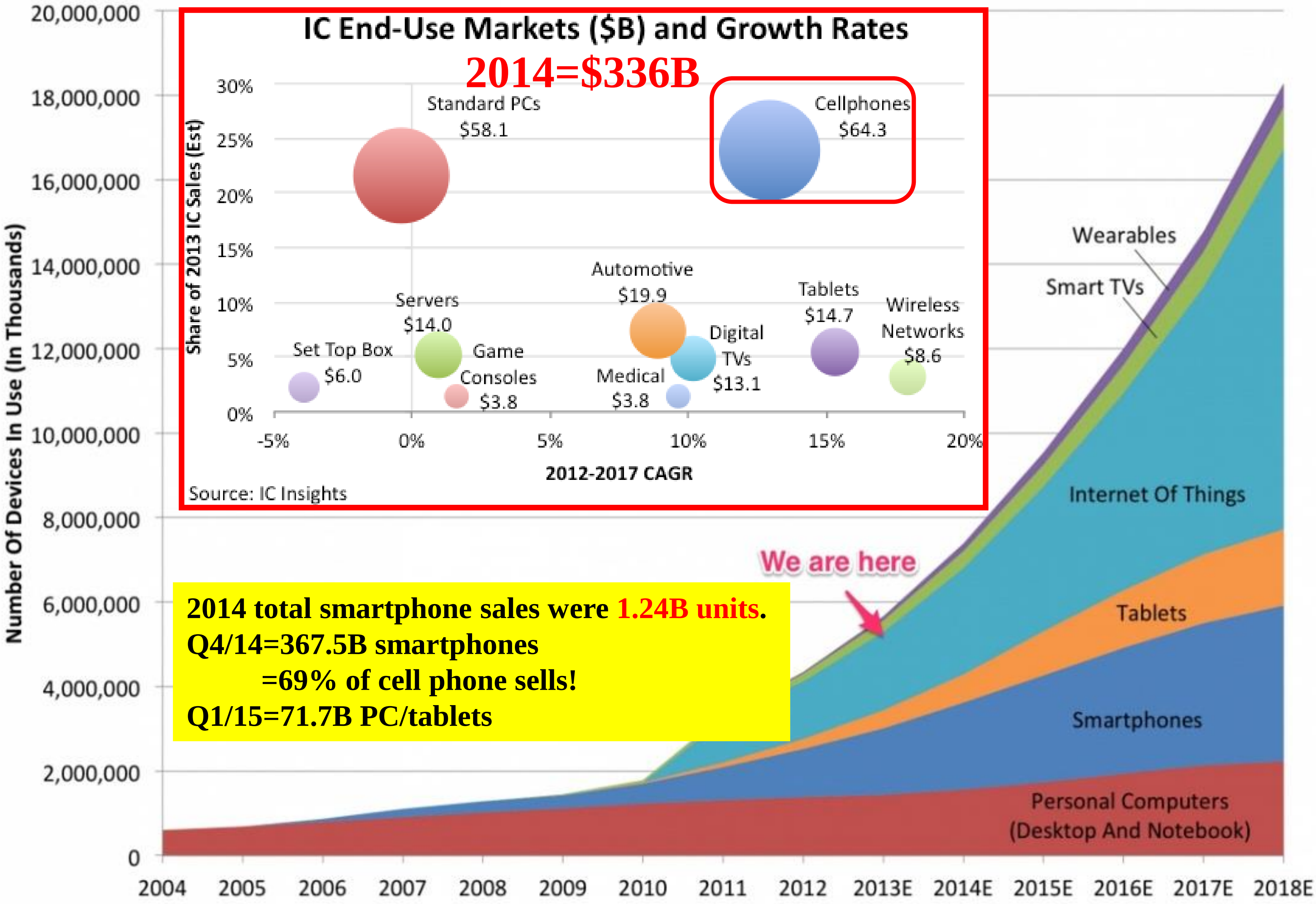
Outline

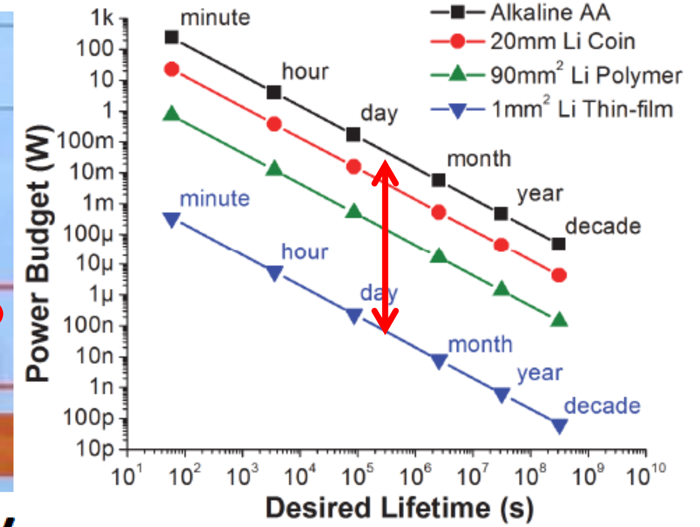
- Introduction
  - Device Roadmap to High Mobility Channels at 7/10nm Node
  - Issues with Ge n+ USJ Formation & High Dopant Activation
  - Strain-Ge High Mobility Channel Material
- Experimentation
  - 70nm Ge-epi/SiGe-buffer/Si P(100) wafer
  - P, Sb and Sn Implantation
  - 308nm Eximer Laser Annealing
- Results
  - Rs Dopant Activation
  - SIMS Dopant Profiles
  - XRD Strain-Ge Analysis
  - Differential Hall Mobility Depth Profiles
- Summary

Global Internet Device Installed Base Forecast



Smart Watch User Case	40LP	28SLP	FinFet	FD	FD+FBB
Power @ ISO Freq	1	0.71	0.39	0.33	0.23
Freq. @ ISO power	1	1.56	2.80	2.55	2.97
mW/Day (active and static)	334	238.6	131.2	109.7	76.3
Battery Life (Days)	4.55	6.37	11.58	13.85	19.91
Battery Life ISO	1	1.4	2.5	3.0	4.4

~5x battery life increase from 4 to ~20 days



gure 1. Average power draw constraint as a function of
etime and battery size

Rated and Actual Energy Use and Battery Energy Storage for Conventional Smart Phones

	Product Name	Mfg. Standby	Vendor reported Run Time	Actual Run Time *1	Installed Battery
1	HTC Dream	406 h	5h 20 minutes	2 ~ 3.5 h	Li-Ion 1150 mAh
2	Google Nexus One	290 h	7h	3.5 ~ 5.5 h	Li-Ion 1400 mAh
3	Apple IPhone 5	225 h	8h	3 ~ 5 h	Li-Po 1440 mAh (5.45 Wh)
4	Samsung Galaxy 5	375 h	6.45 h	2.5 ~ 4.5 h	1200 mAh
5	Nokia Lumen 1520	32 days	24 h	9 ~ 10.8h	3400mAh *2
	Motorola Droid		48 hrs		

Morris Chan chairman of TSMC wants 1 week cell phone battery life so need low leakage devices!

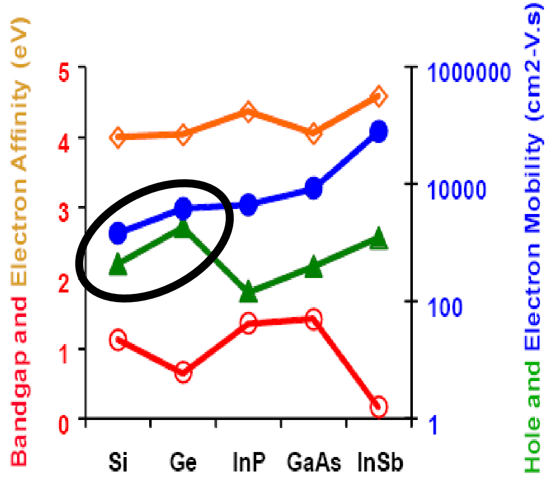
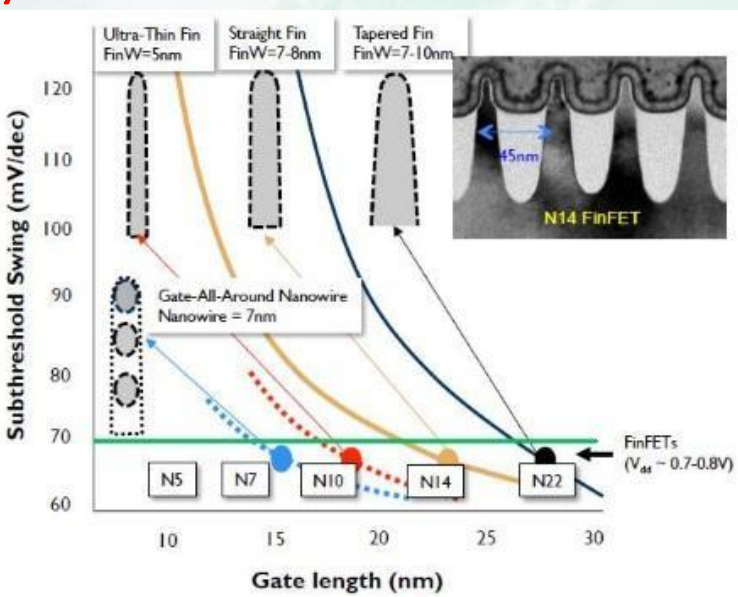


Figure 16. Key electronic parameters for major semiconductors.
Note the improved mobility for Ge vs Si, along with the degraded bandgap (47).

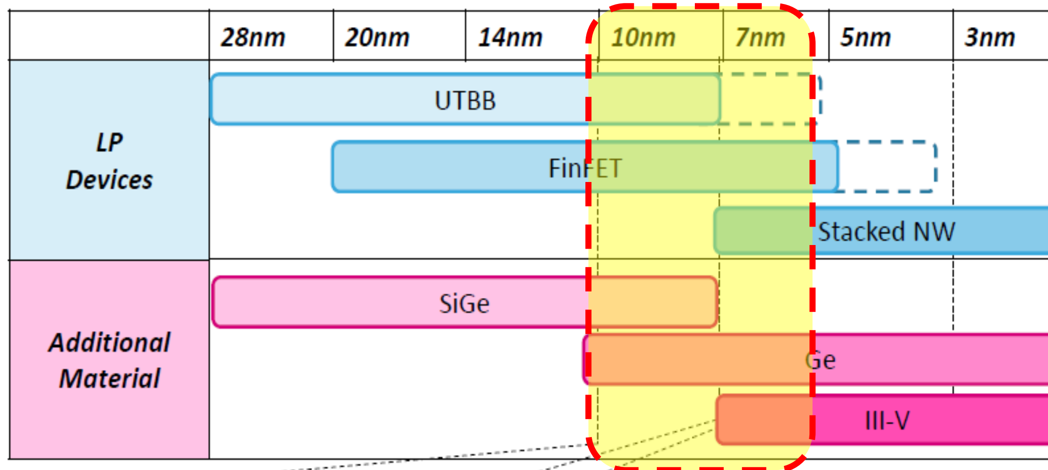
***2016: >50%SiGe→100%Ge-FinFET at 10nm**

***2018: Nano-wire at 5nm (Si, SiGe and Ge)**



Conclusion

IEDM-2013 short course



Challenges at 10nm

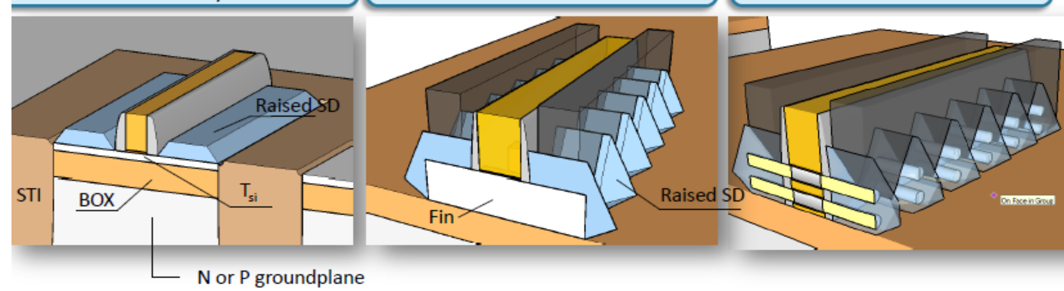
- « Conventional » boosters efficiency
- Variability sources (metal gate) for Vmin
- Low Parasitics

Challenges at 7nm (and below)

- Integration of new Device structure (SNW)
- Electrostatic control with new channel materials (s-Ge, III-V)
- Variability sources for Vmin < 0.5V

Transistor Structure for 10nm and 7nm nodes

UTBB Ultra Thin Body & BOX	FinFET/Trigate	Nanowire



UTBB
- Undoped channel
- Back-gate control using thin BOX capacitive coupling
- Raised S/D

FinFET/Trigate
- « Vertical » double gate
- Undoped or doped channel
- Multi-Fin
- Raised S/D

Nanowire
- Gate-All-Around
- Undoped channel
- Multi-wires
- Raised S/D

100nm Ge Thermal Surface Loss at 600C

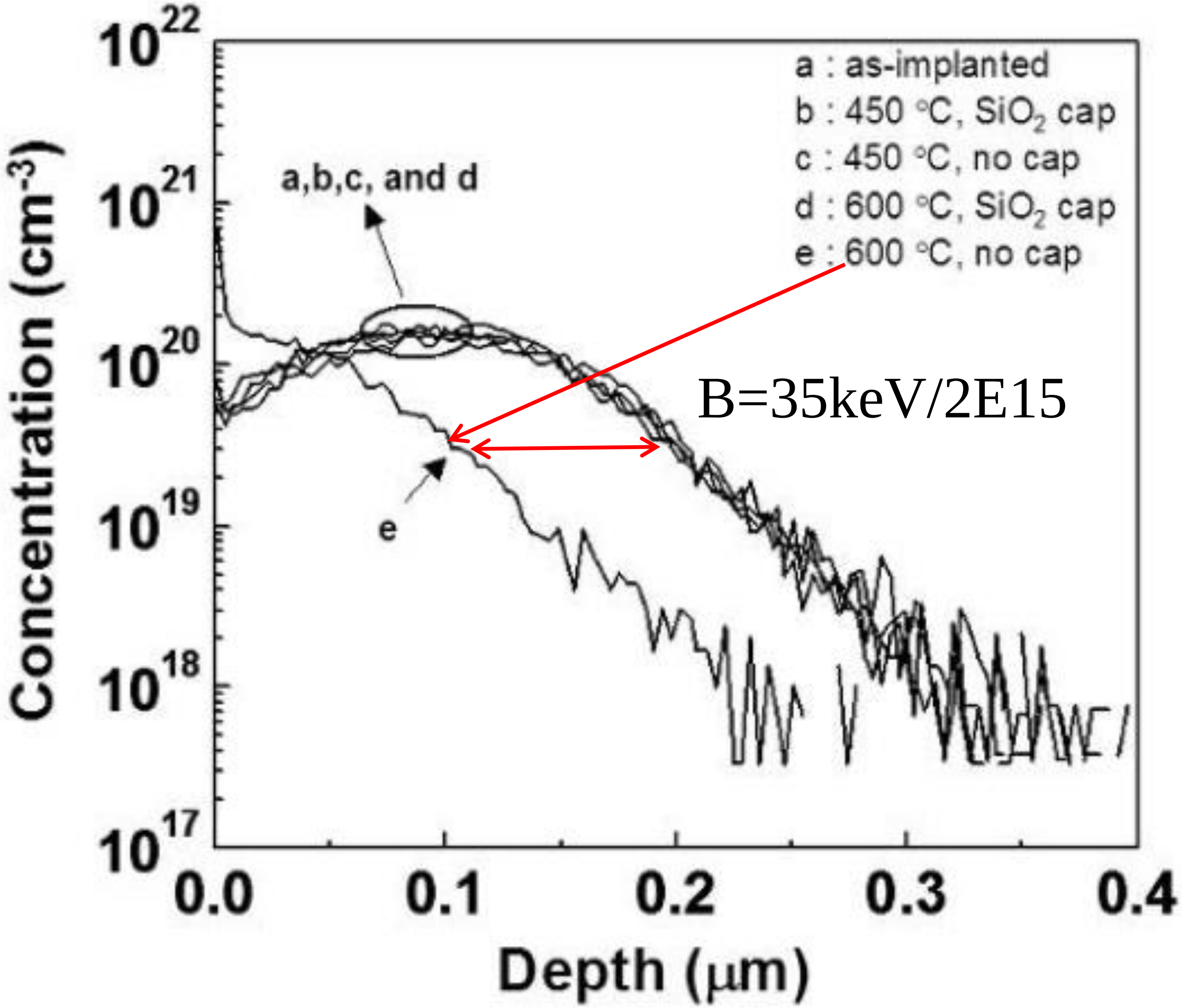


Fig. 4. SIMS profiles of ion-implanted boron in the Ge wafer with/without an SiO_2 cap layer as a function of temperature.

Oh & Campbell, Univ of Texas, J. Electronic Mats., vol.33, no.4, p. 364, 2004.

Anneals appear to have caused Ge loss

Assuming repeatable anneal conditions….

Following High Temp Anneals Only:

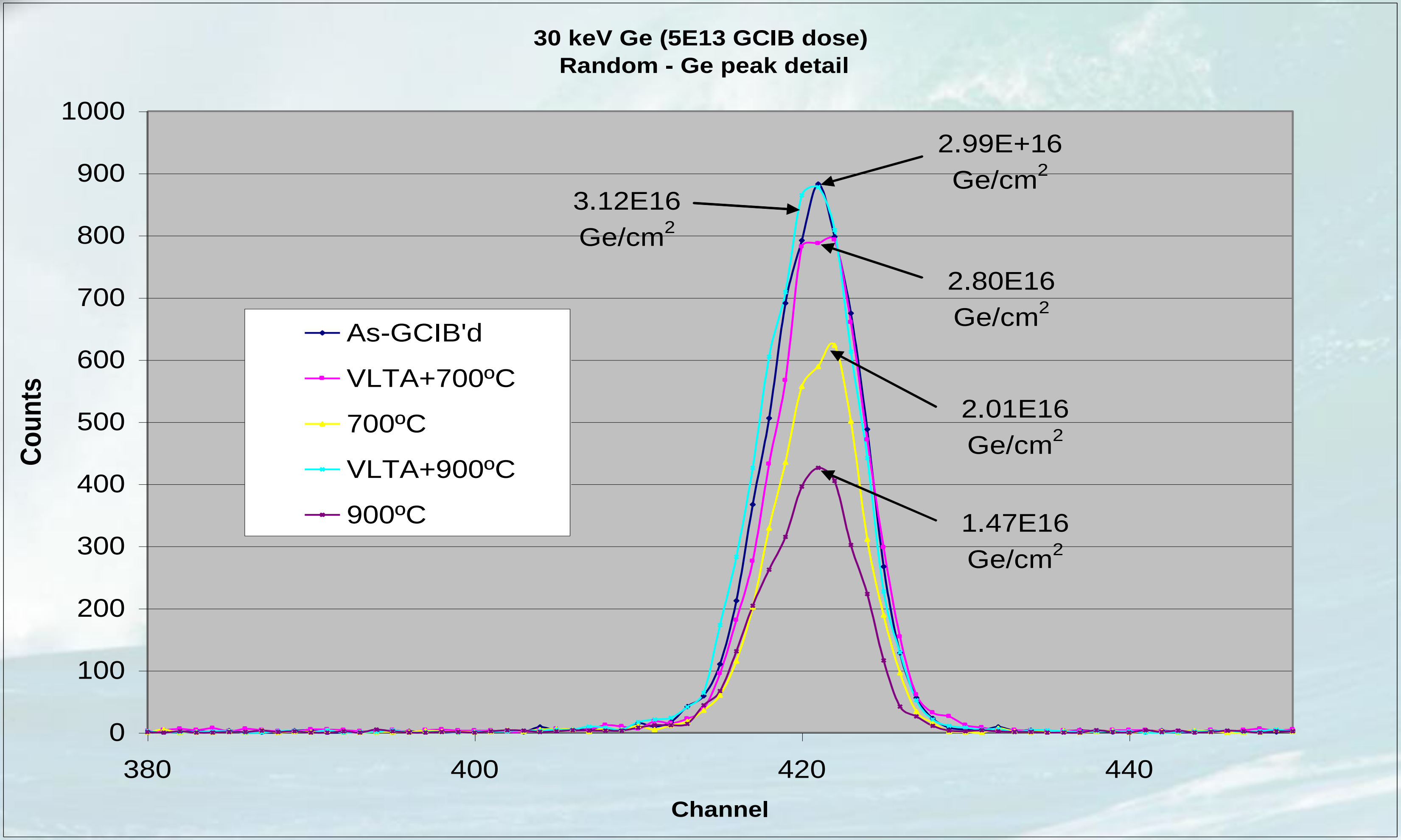
- 700 ºC loss is 33%
- 900 ºC loss is 50%

  Very low temperature anneal (375 ºC) prior to high temp. anneal greatly mitigates Ge loss.

Following Very Low Temp Anneals (*375 ºC*) + High Temp Anneal:

- 700 ºC loss is 7%
- 900 ºC loss is ~ 0%

Random RBS channel



375C then 900C anneal shows no Ge loss 900C alone shows 50% Ge loss

Epion & J.O.B. Technologies, 2004

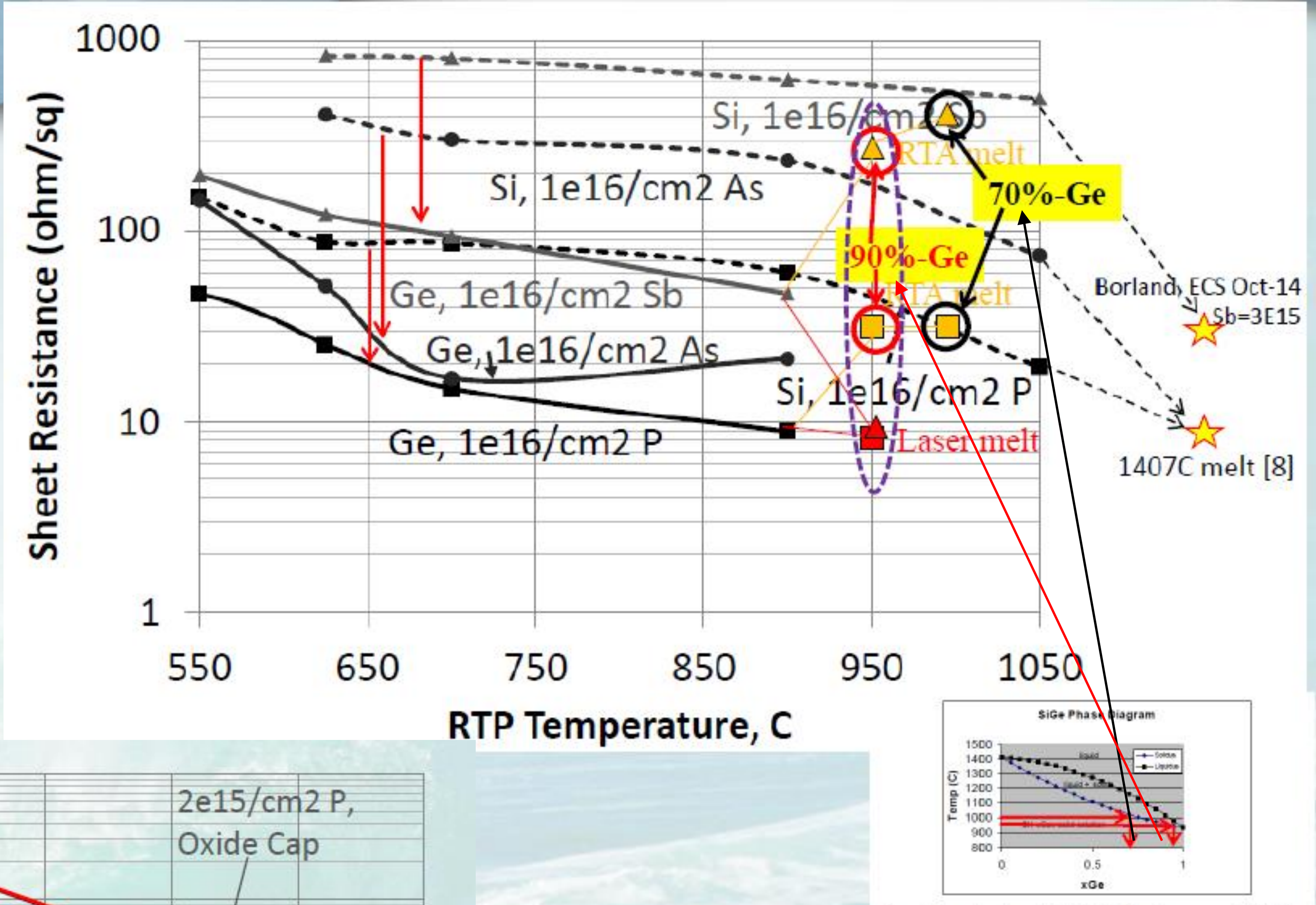
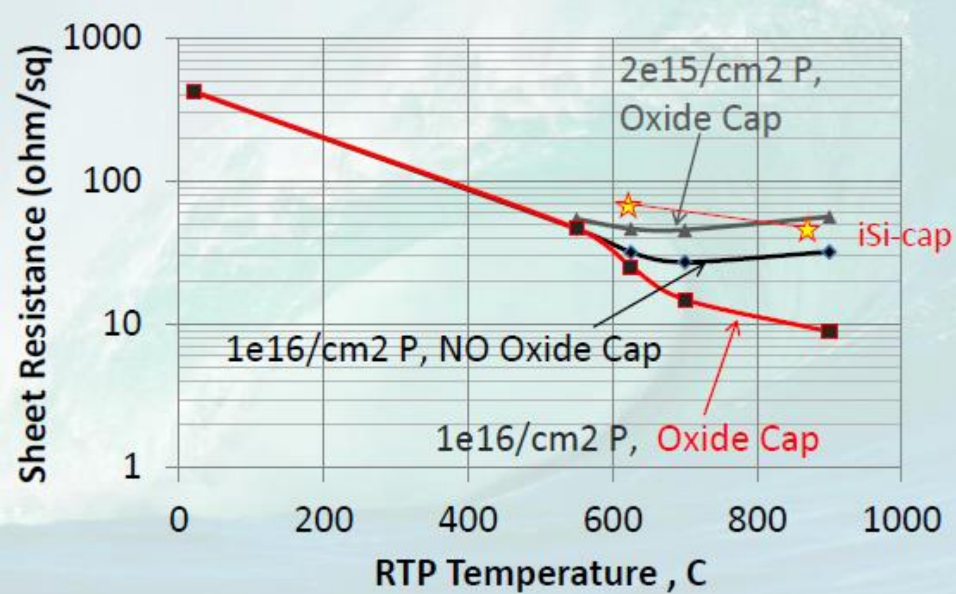
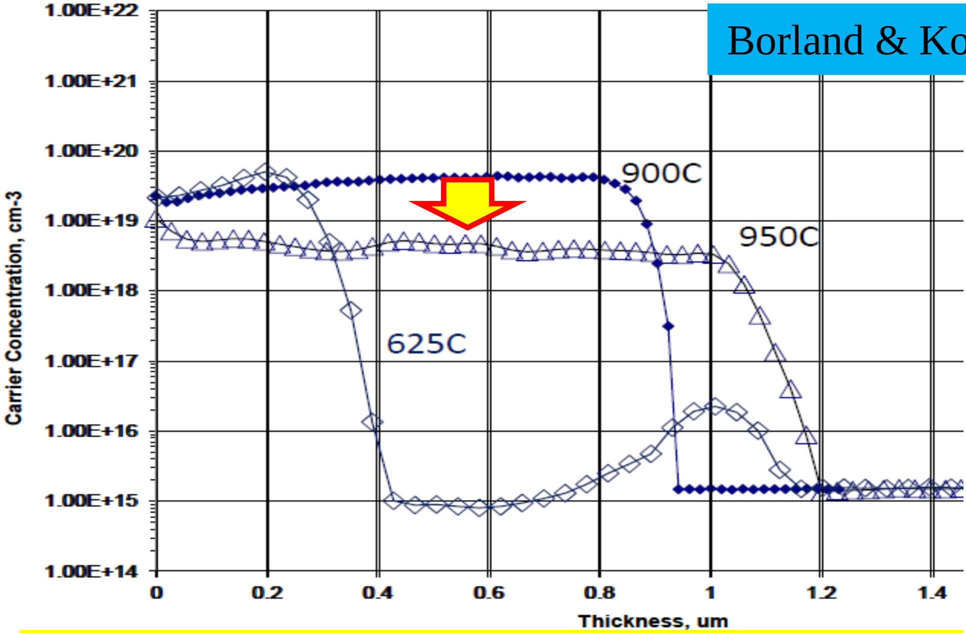


Figure 1. Binary phase diagram for Si-Ge. Note the continuous range of solid solutions for SiGe alloys, which form random solid solutions in a diamond cubic structure.

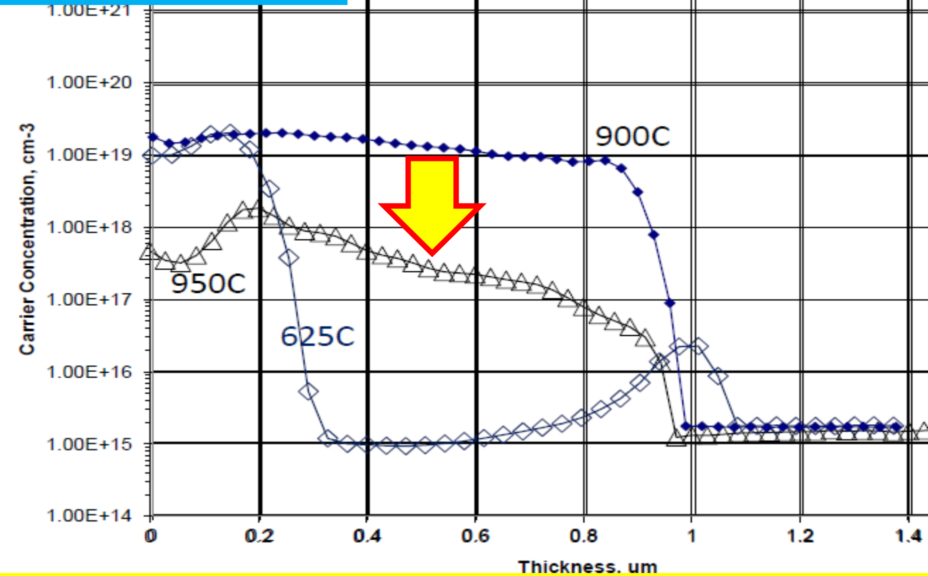


Borland & Konkola, AIP, IIT-2014

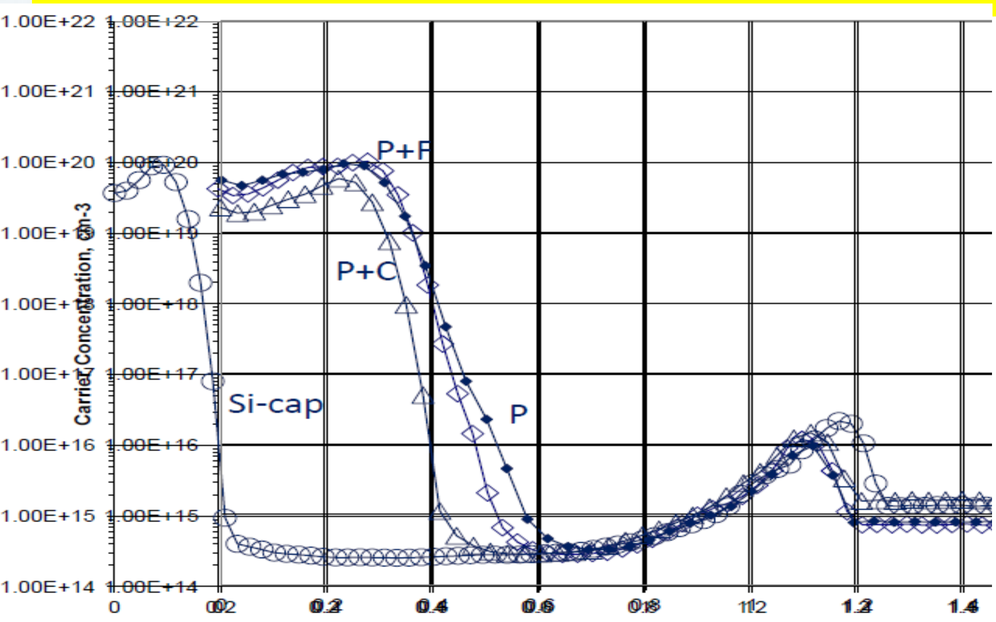
Borland & Konkola, IIT-2014



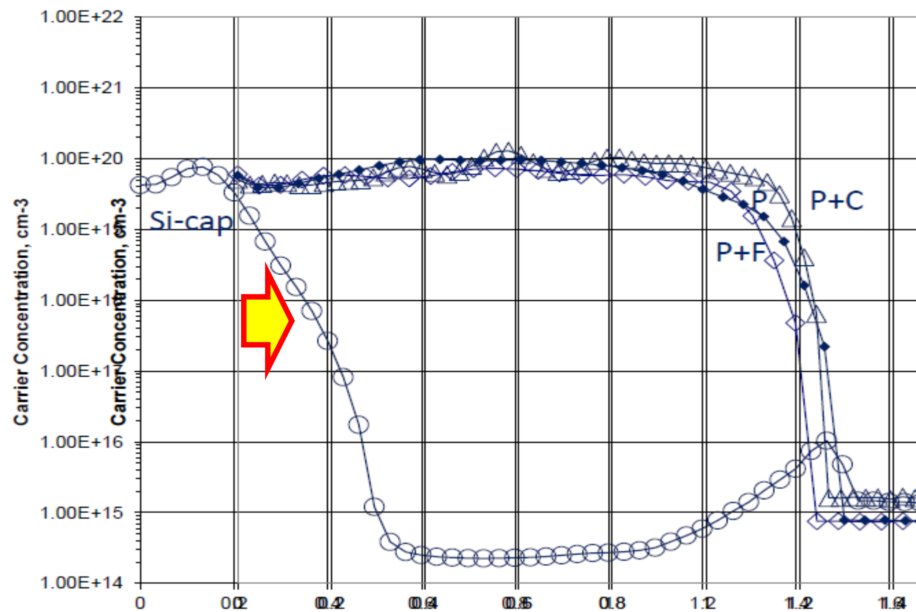
SRP for As-implant 1um Ge-epi wafers after RTA annealing



SRP for Sb-implant 1um Ge-epi wafers after RTA annealing

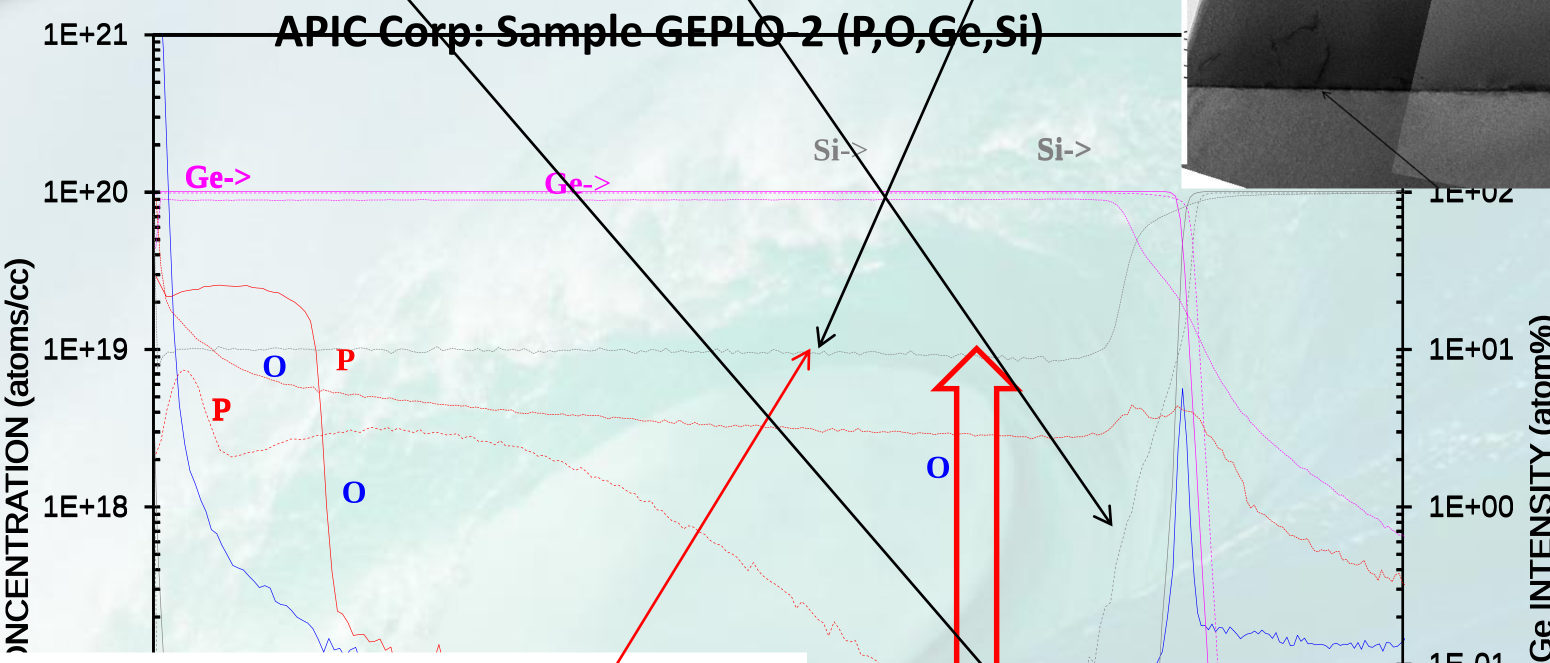


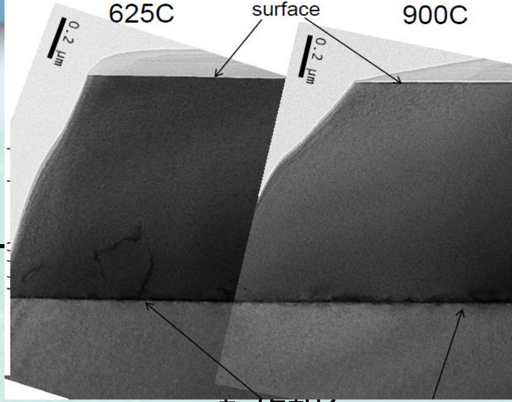
SRP for P-implant and co-implant in 1um Ge-epi wafers after 625°C RTA annealing

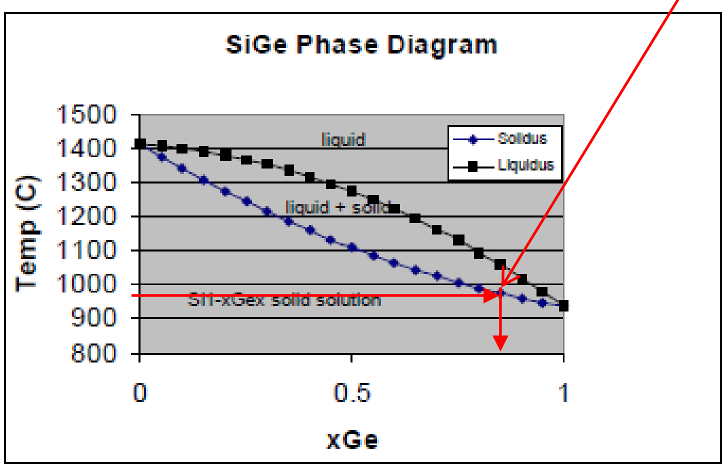


SRP for P-implant and co-implant in 1um Ge-epi wafers after 900°C RTA annealing

P=2E15 (625C & 900C & 950C)







Kennel, Intel, ECS Oct 2012 paper 3124

Figure 1. Binary phase diagram for Si-Ge. Note the continuous range of solid solutions for SiGe alloys, which form random solid solutions in a diamond cubic structure.

Borland & Konkola, IIT-2014

IEDM-2012 Paper 23.3: YJ Lee of NDL on "Full Low Temperature Microwave Processed Ge CMOS Achieving Diffusion-Less Junction and Ultrathin 7.5nm Ni Mono-Germanide".

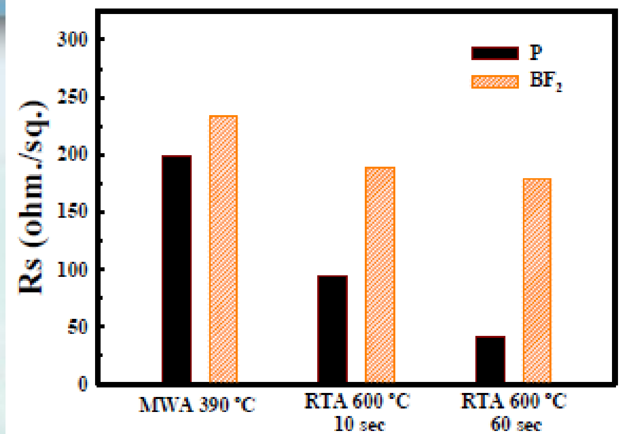


Fig. 4 The comparisons of the Rs between MWA and RTA in (100) Ge. The deep junction of P formed by RTA results in the low Rs.

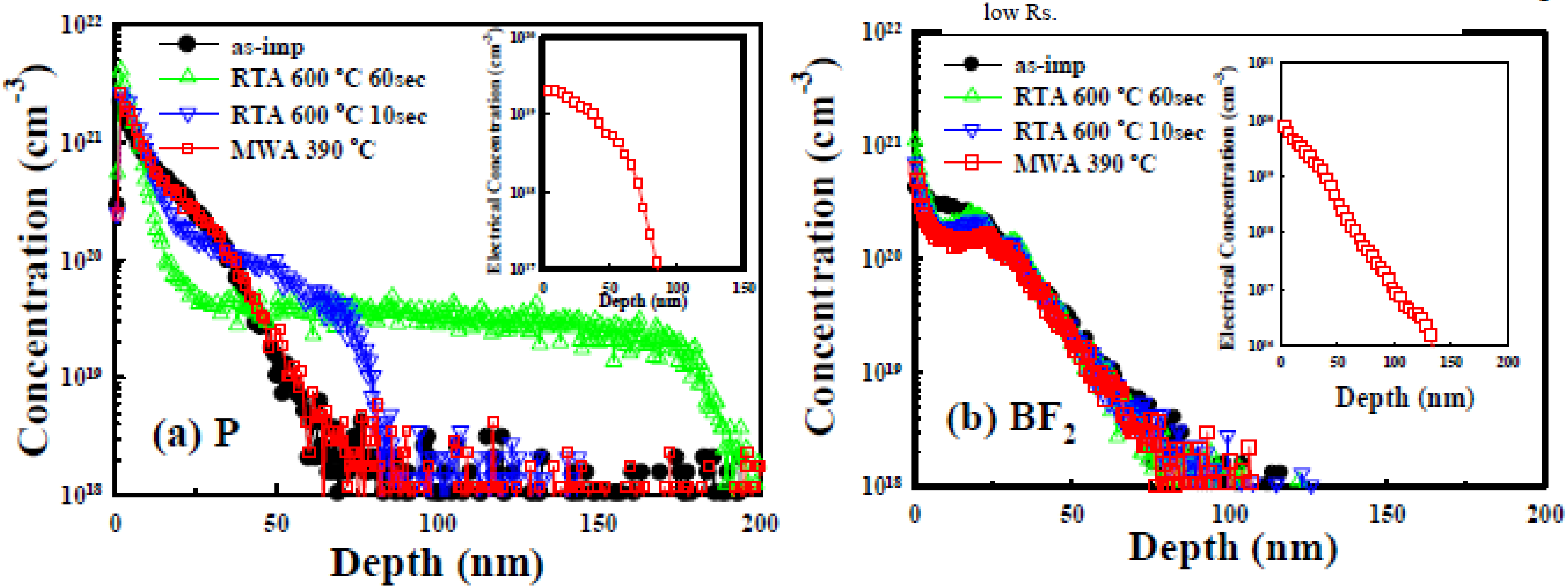
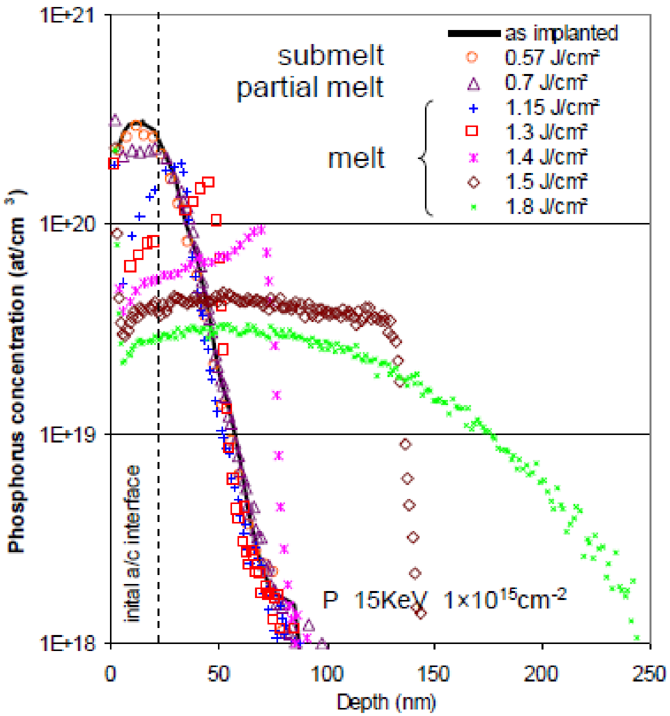
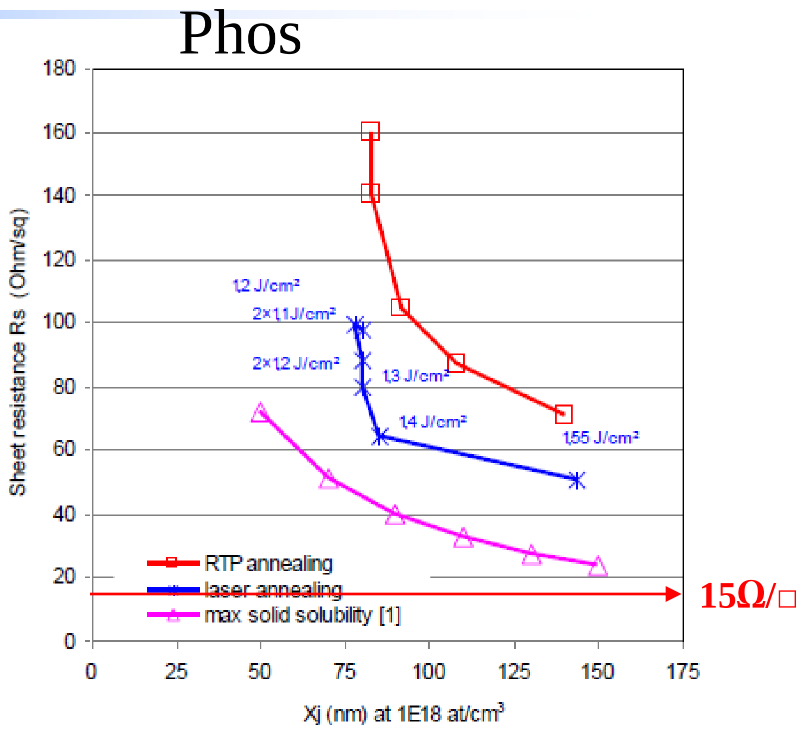


Fig. 3 SIMS and SRP profiles of (a) P and (b) BF_2 at 1×10^{15} cm^{-2} in (100) Ge. The P distribution after MWA is identical to as-implanted, but not after RTA. All boron distribution profiles are close to as-implanted. The insets show the activated levels of P and B by SRP are 2×10^{19} cm^{-3} and 7.5×10^{19} cm^{-3}.

DIFFUSION & ACTIVATION ANALYSIS





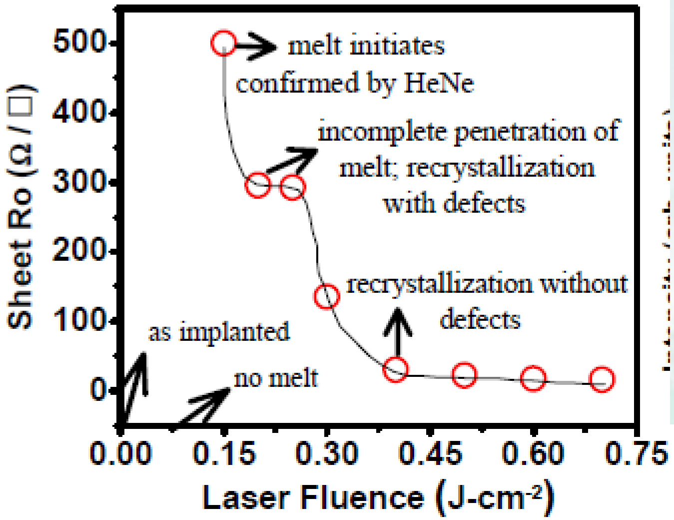
- Submelt: no modification of SIMS profile
- Melt < 1.4 J/cm²: no diffusion at $1\times10^{18}cm^{-3}$
- Abruptness : from 28 to 8 nm/dec

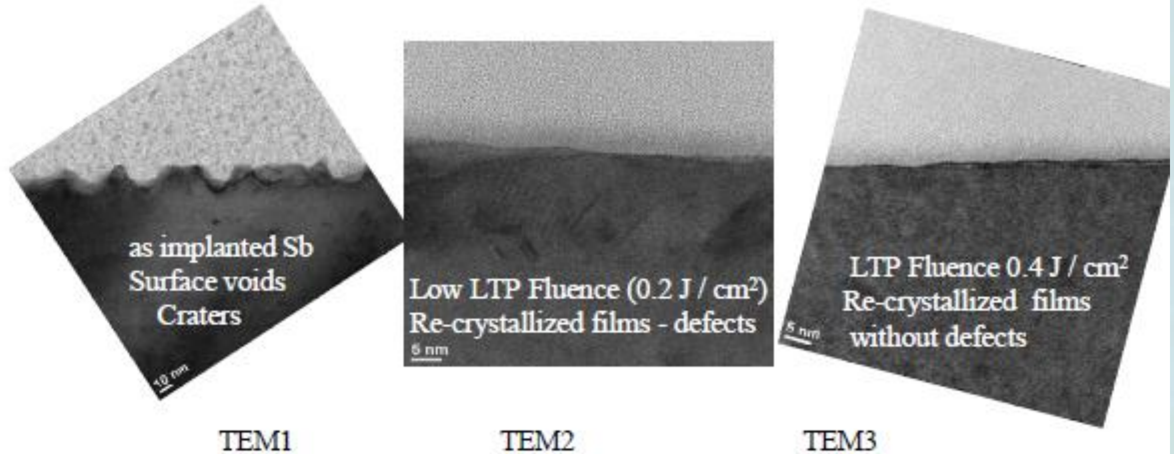
- LTA vs RTP: reduced Rs at same Xj depth
- Extracted **Nact = $1.2\times10^{20}cm^{-3}$** with 1.3 J/cm²
- Energy >1.3 J/cm² :100% dose activated
- No positive contribution of multi pulse laser

[1] F. A. Trumbore, Elec. Soc., 205-233 (1959)

Mazzocchi et al., IEEE-RTP 2009

Thareja et al., Stanford, IEDM-2010 ref 11





Thareja, 2010, P, As, and Sb implant with ~40 nm junction depth

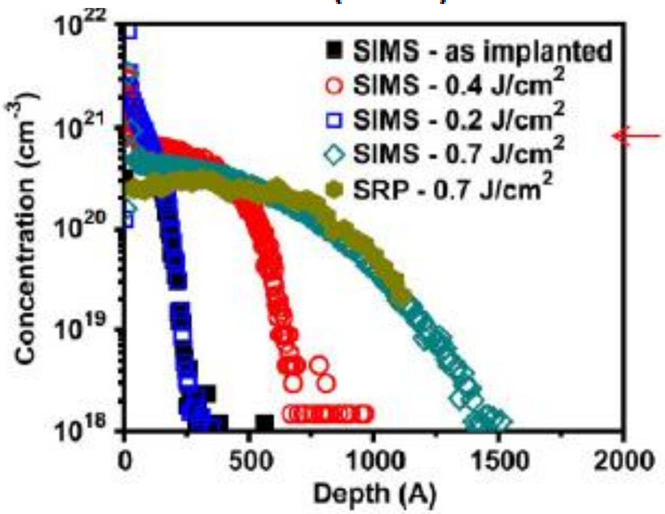


Fig. 2. Concentration profiles (SIMS and SRP) of as-implanted and laser-annealed samples.

Note very good SRP result

Sb Laser Anneal shows better activation than P or As

n of
an

ρ_s measured using Capres MicroRsp

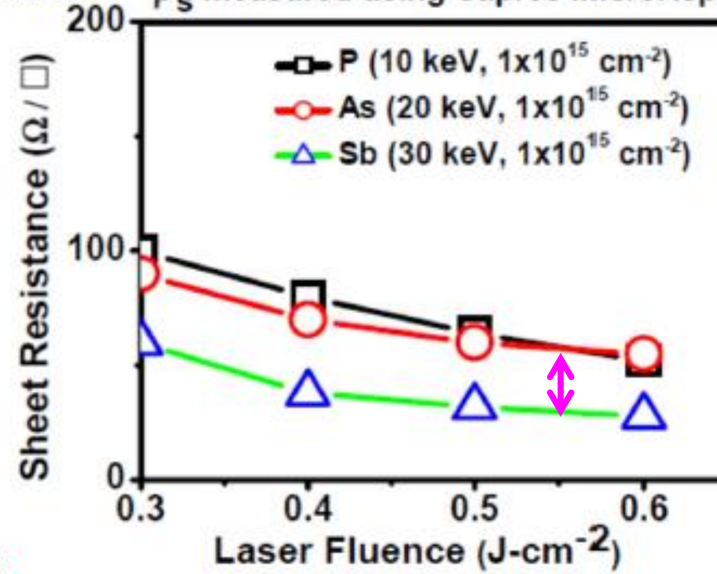
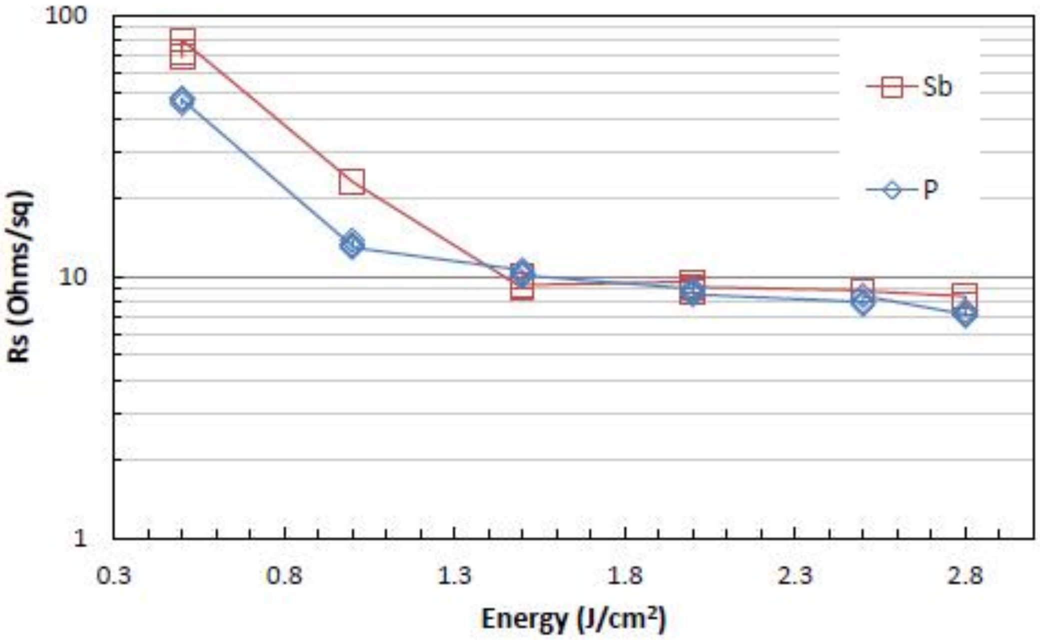
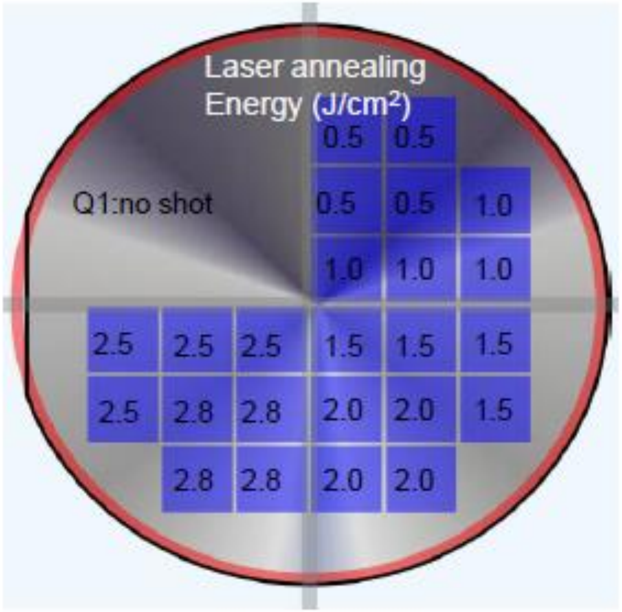


Fig. 13 : Reduction in ρ_S as laser fluence is increased from 0.3 - 0.5 J-cm^{-2}. Sb provides the lowest ρ_S

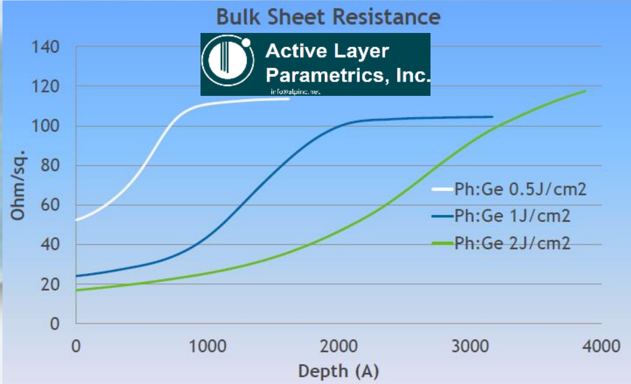
Rs results: Slot 11 (P) and Slot 13 (Sb)

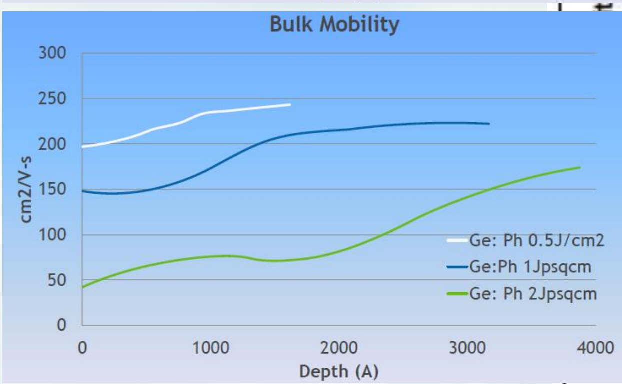


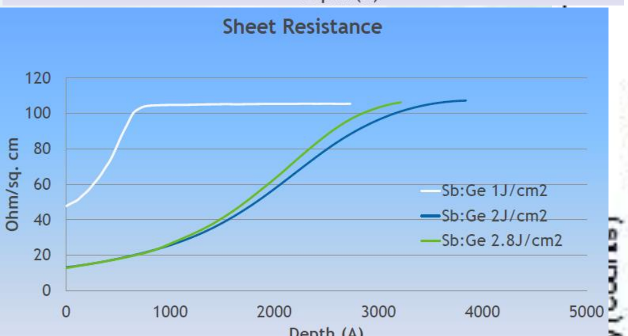


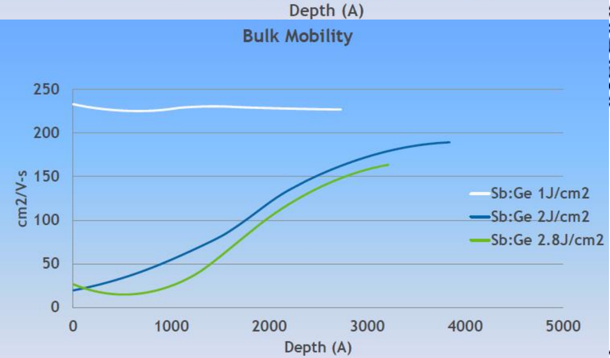
- Rs decrease with laser-annealing energy.
  - Reach saturation at high energy

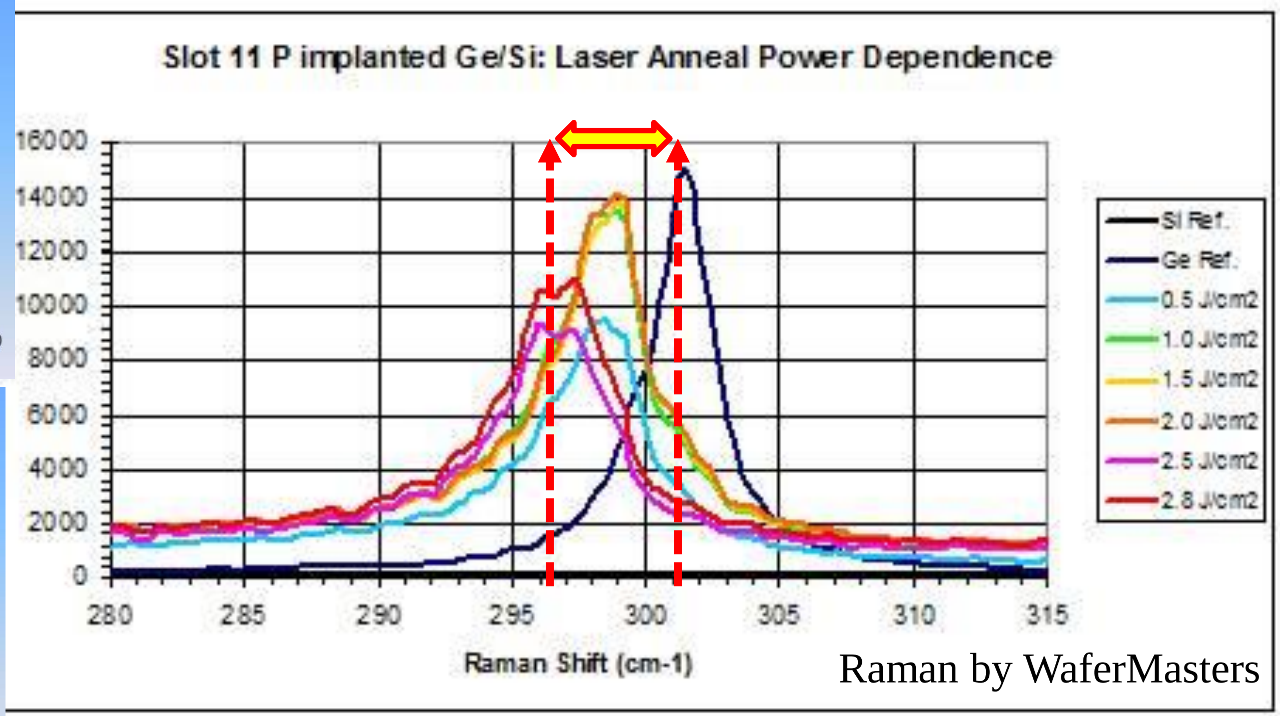
Rs (Ohms/sq)	Slot 11	Slot 13
Edge	741.53	538.49
No-anneal	701.77	494.59
Substrate	100.72	85.21

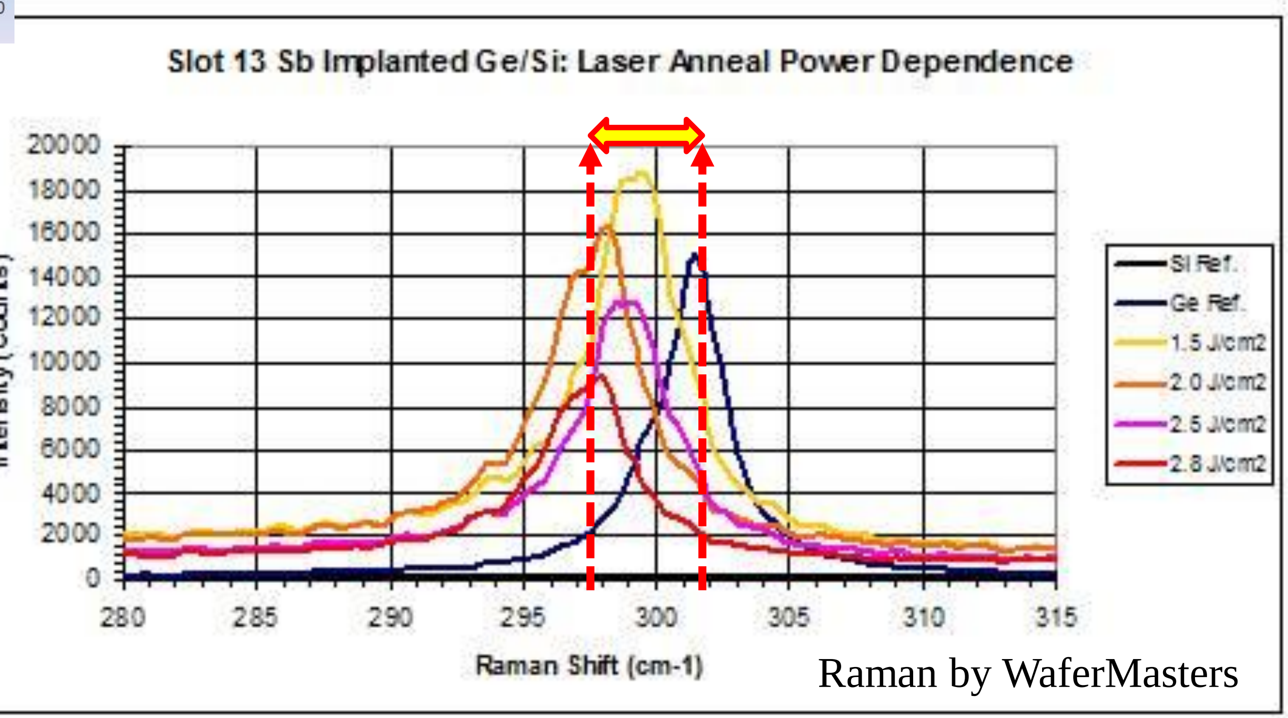

Bulk Sheet Resistance
Active Layer Parametrics, Inc.
Ohm/sq.
Depth (A)
Ph:Ge 0.5J/cm2
Ph:Ge 1J/cm2
Ph:Ge 2J/cm2

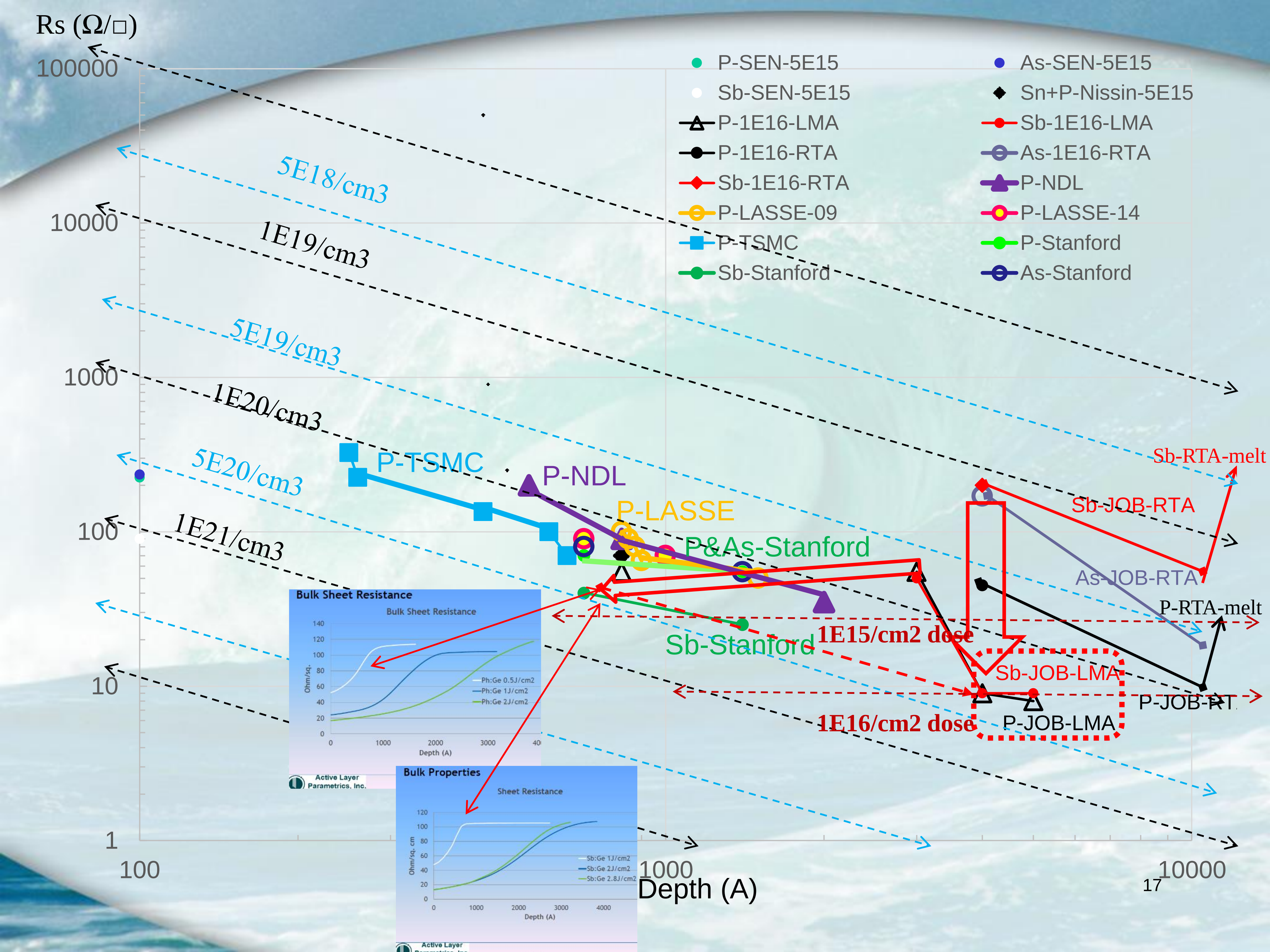

Bulk Mobility
cm2/V-s
Depth (A)
Ge: Ph 0.5J/cm2
Ge:Ph 1Jpsqcm
Ge: Ph 2Jpsqcm


Sheet Resistance
Ohm/sq. cm
Depth (A)
Sb:Ge 1J/cm2
Sb:Ge 2J/cm2
Sb:Ge 2.8J/cm2

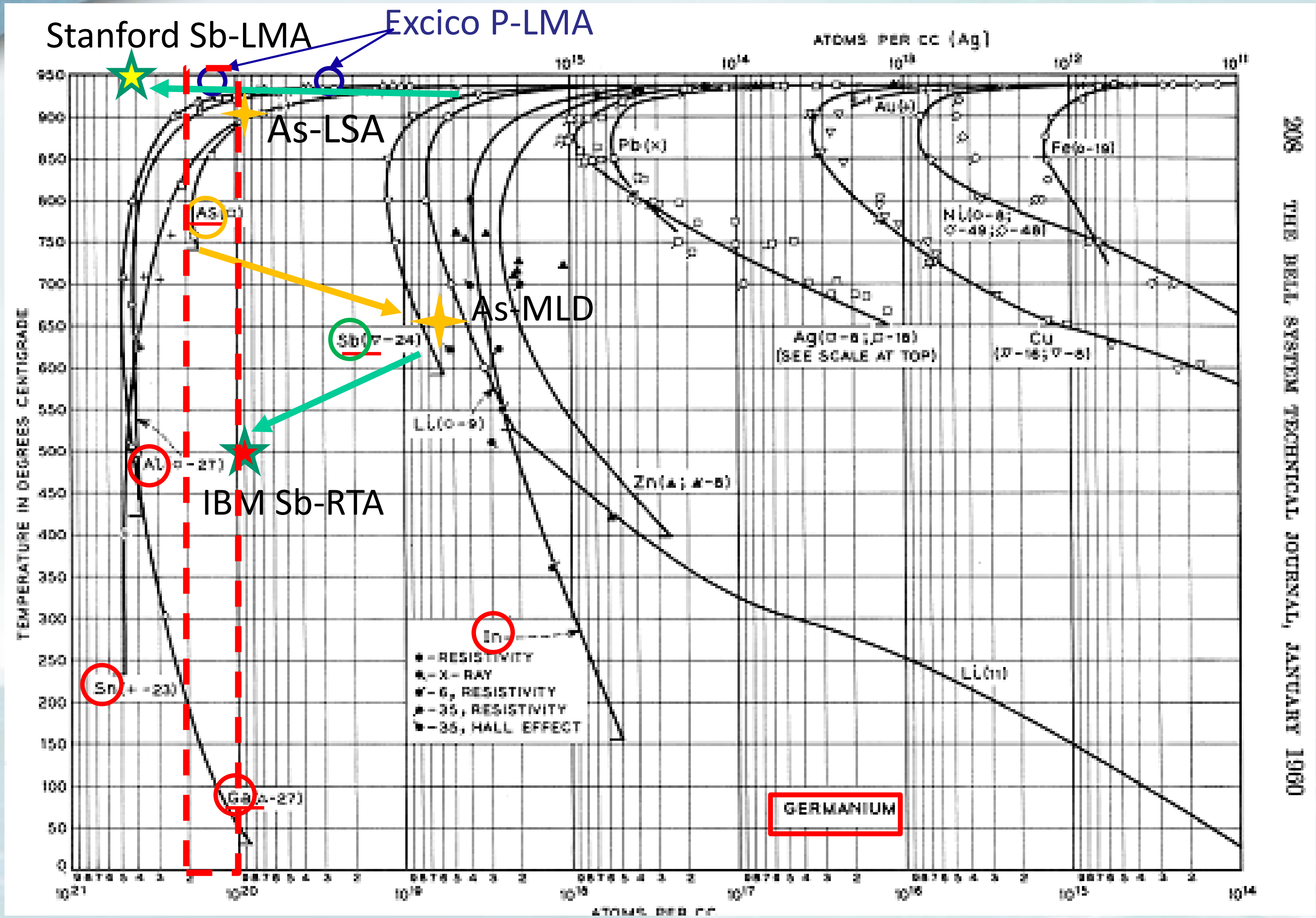

Bulk Mobility
cm2/V-s
Depth (A)
Sb:Ge 1J/cm2
Sb:Ge 2J/cm2
Sb:Ge 2.8J/cm2


Slot 11 P implanted Ge/Si: Laser Anneal Power Dependence
Raman Shift (cm-1)
Si Ref.
Ge Ref.
0.5 J/cm2
1.0 J/cm2
1.5 J/cm2
2.0 J/cm2
2.5 J/cm2
2.8 J/cm2
Raman by WaferMasters


Slot 13 Sb Implanted Ge/Si: Laser Anneal Power Dependence
Raman Shift (cm-1)
Si Ref.
Ge Ref.
1.5 J/cm2
2.0 J/cm2
2.5 J/cm2
2.8 J/cm2
Raman by WaferMasters


Rs (Ω/□)
100000
10000
1000
100
10
1
100
1000
10000
Depth (A)
P-SEN-5E15
As-SEN-5E15
Sb-SEN-5E15
Sn+P-Nissin-5E15
P-1E16-LMA
Sb-1E16-LMA
P-1E16-RTA
As-1E16-RTA
Sb-1E16-RTA
P-NDL
P-LASSE-09
P-LASSE-14
P-TSMC
P-Stanford
Sb-Stanford
As-Stanford
5E18/cm3
1E19/cm3
5E19/cm3
1E20/cm3
5E20/cm3
1E21/cm3
P-TSMC
P-NDL
P-LASSE
P&As-Stanford
Sb-Stanford
1E15/cm2 dose
1E16/cm2 dose
Sb-RTA-melt
Sb-JOB-RTA
As-JOB-RTA
P-RTA-melt
Sb-JOB-LMA
P-JOB-RT
P-JOB-LMA
Bulk Sheet Resistance
Bulk Sheet Resistance
Ohm/sq.
Depth (A)
Ph:Ge 0.5J/cm2
Ph:Ge 1J/cm2
Ph:Ge 2J/cm2
Active Layer Parametrics, Inc.
Bulk Properties
Sheet Resistance
Ohm/sq. cm
Depth (A)
Sb:Ge 1J/cm2
Sb:Ge 2J/cm2
Sb:Ge 2.8J/cm2
Active Layer

Trumble, Bell Labs, 1959



Growing Ge Channels

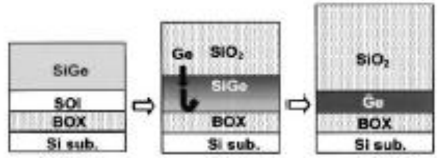
Blanket Ge-layer first then Ge-Fin etch

Selective Ge-epi Fin

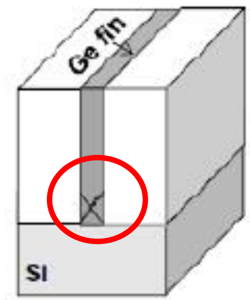
Ge on Si Bulk using SRB	GeOI using Wafer Bonding	GeOI using Enrichement	Aspect Ratio Trapping (ART)

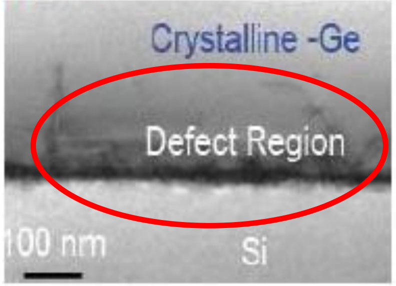
Currie et al., APL 1998 (MIT)

C. Deguet, ECS Proceeding 2005 (LETI)

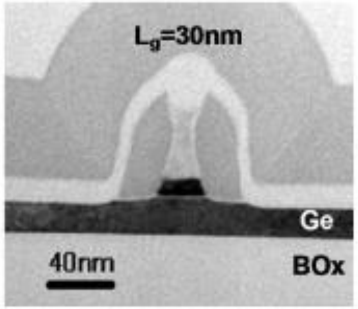


Nakaharai et al., APL 2003

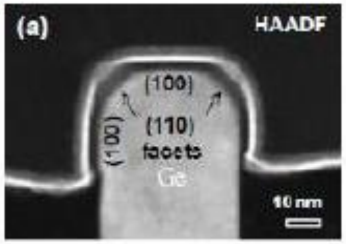




Nayfeh et al., APL 2004 (Stanford)



L. Hutin *et al.* IEEE EDL



M. Van Dal et al., TSMC, IEDM

IEDM-2013 short course

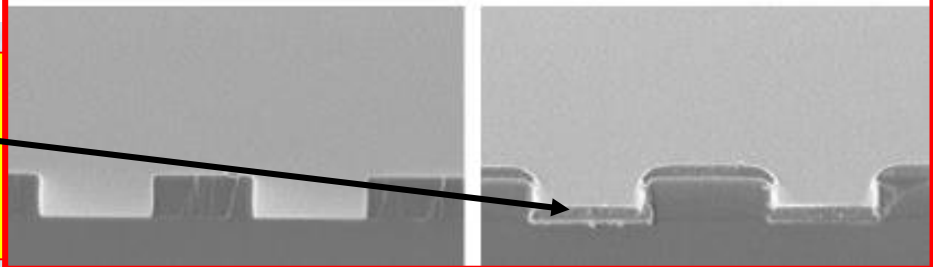
Borland: Localized Ge-LPE by Laser Melt

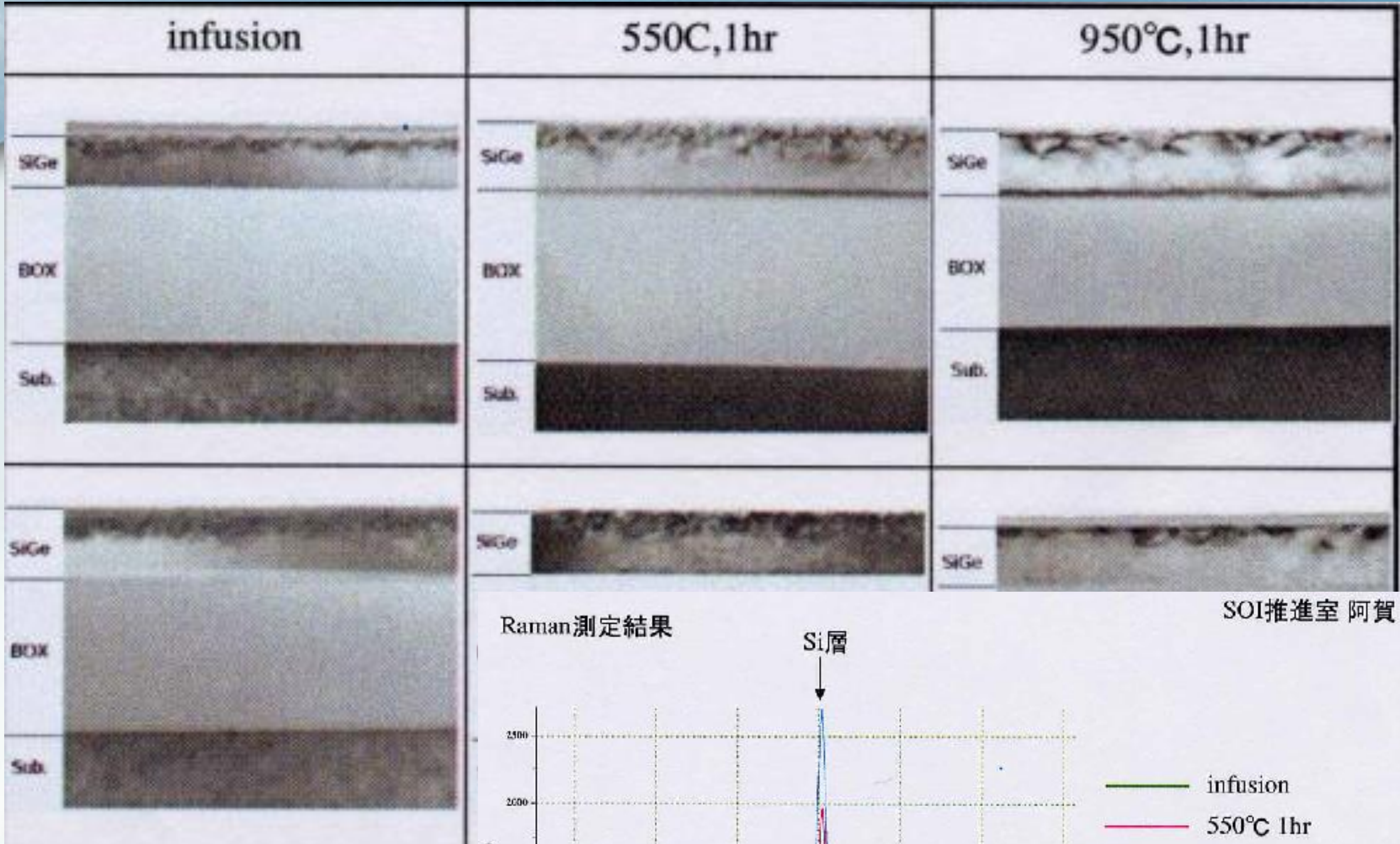
Oct 2004 ECS: Ge-GCIB/Infusion (E17/cm2)

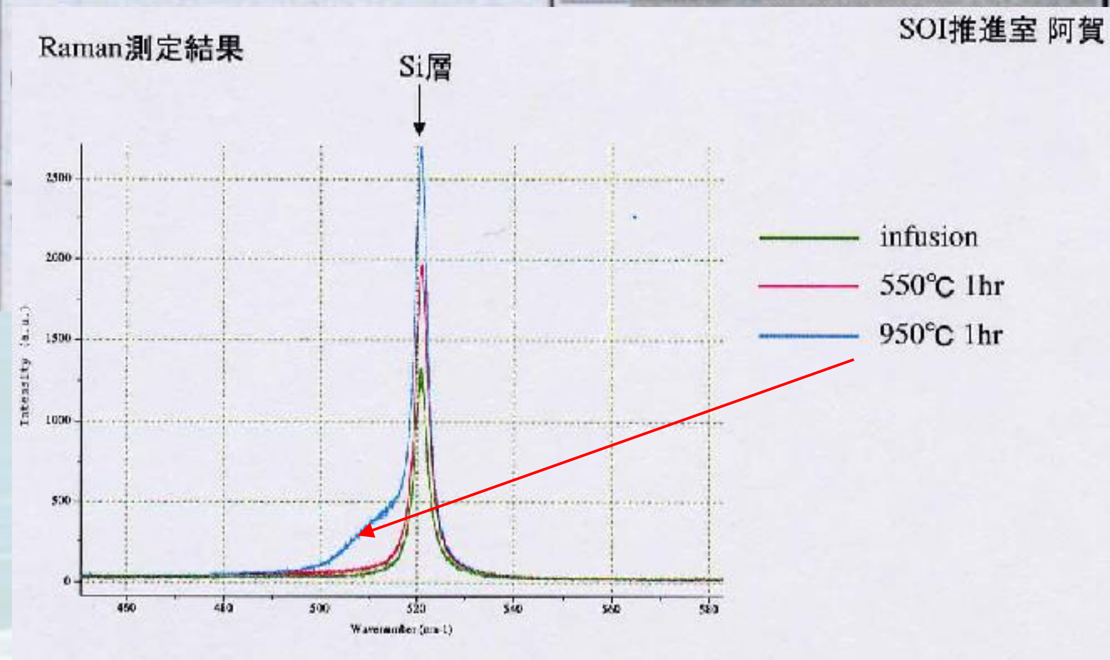
June 2013 IWJT: Ge-plasma implant (1E17/cm2)

Oct 2014 ECS: Ge-beamline implant (5E16/cm2)

200nm Ge Infusion Deposition On Photo Resist







infusion後と550℃アニール後ではSi層以外からの信号は検出されない。
950℃では、SiGe層からの信号有るが非常にブロード（濃度分布？）。

HF-vs-No HF Cleaning For Ge Infusion

J.O.B. Technologies (Strategic Marketing, Sales & Technology)

Localized/Selective Ge & SiGe Formation By Liquid Phase Epitaxy (LPE) Using Ge+B Plasma Ion Implantation And Laser Melt Anealing

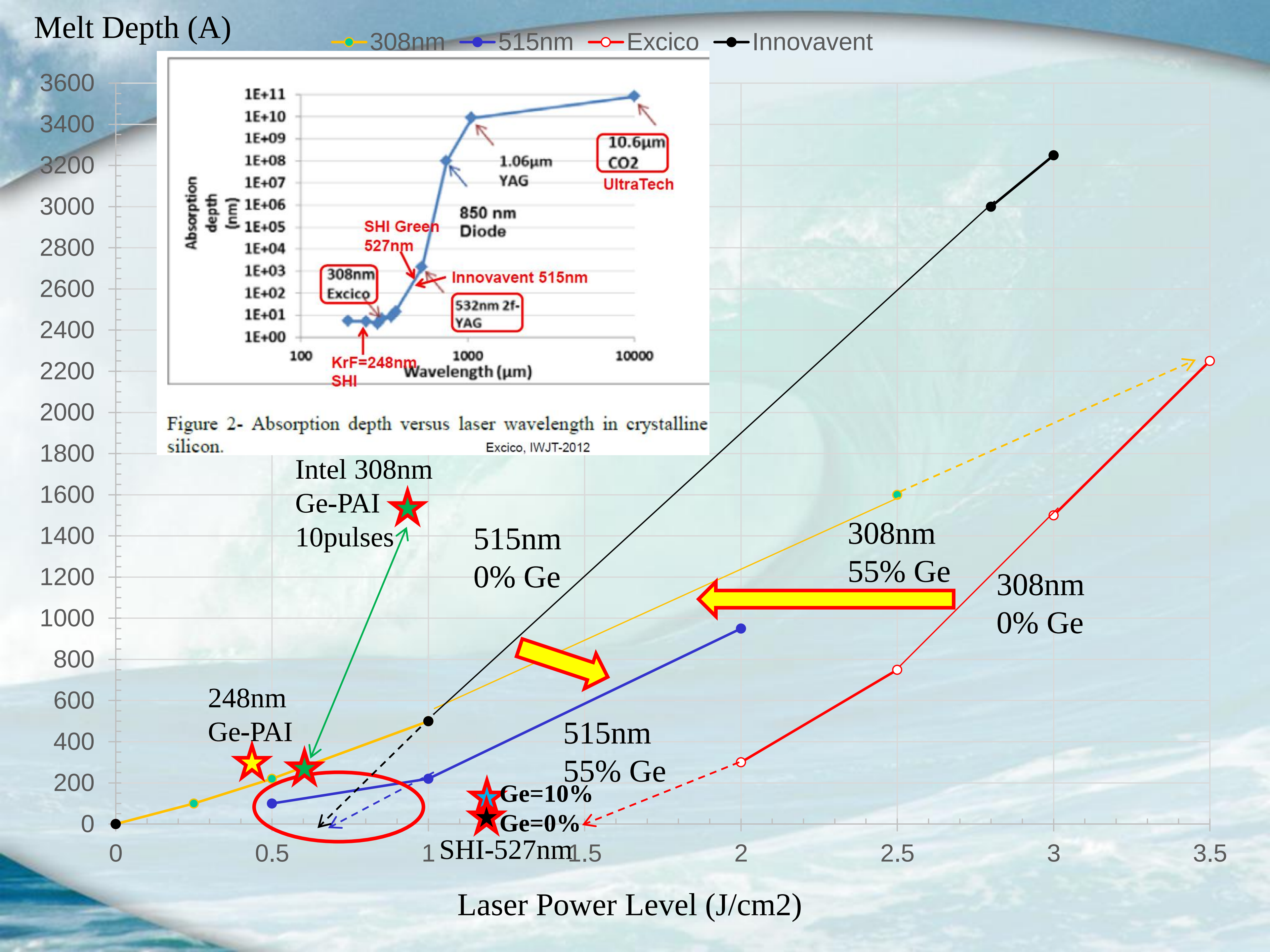
IWJT June 6, 2013

JOB Technology, Micron, Innovavent, Excico, KLA-Tencor, CNSE, EAG & UCLA

Ge 3keV (~7nm) at 1E16/cm2 & 1E17/cm2

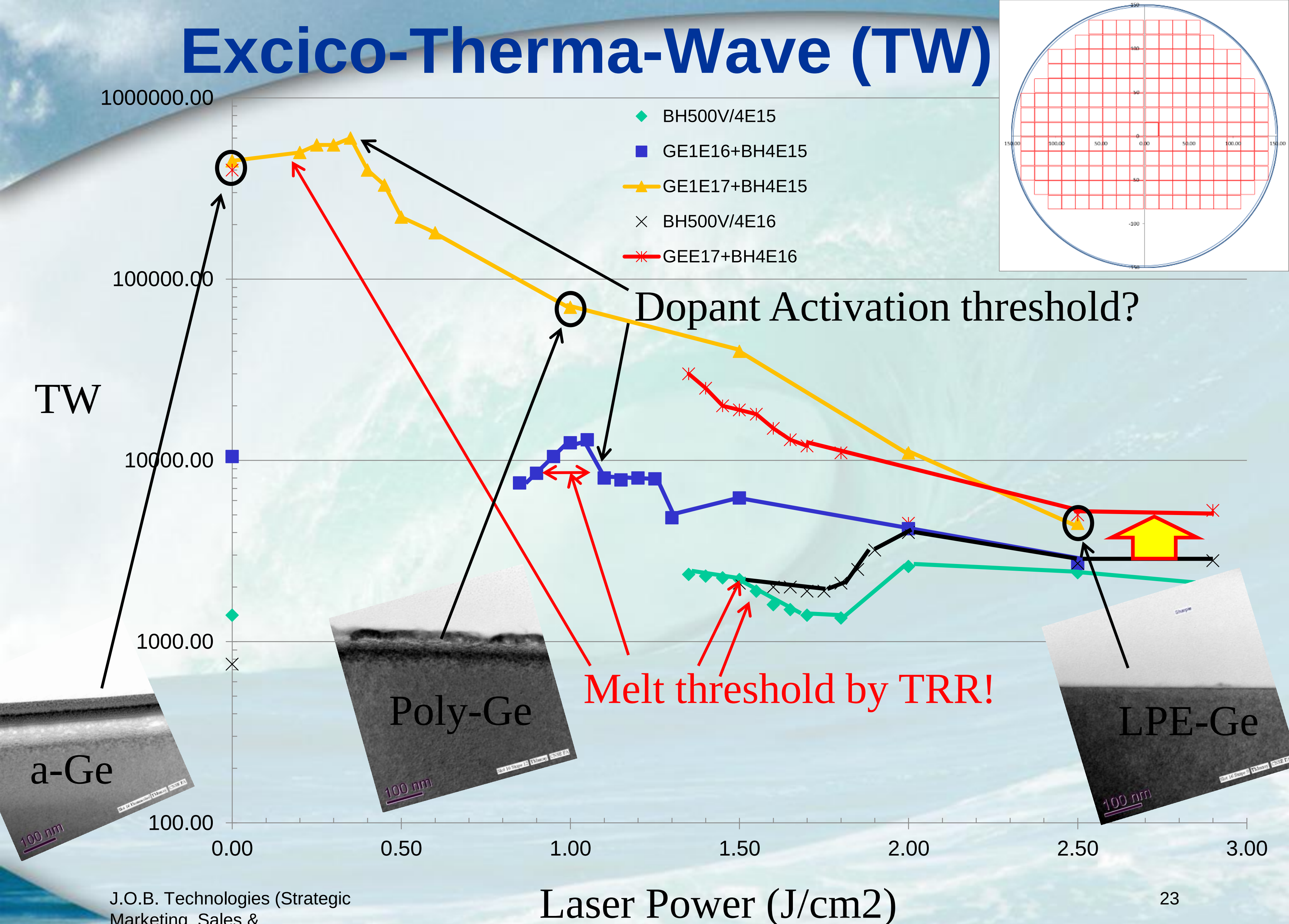
B2H6 500V (~7nm) at 4E15/cm2 & 4E16/cm2

Ge+B Plasma Implanted Wafers Provided by Micron
Laser Melt Annealing Provided by Innovavent & Excico

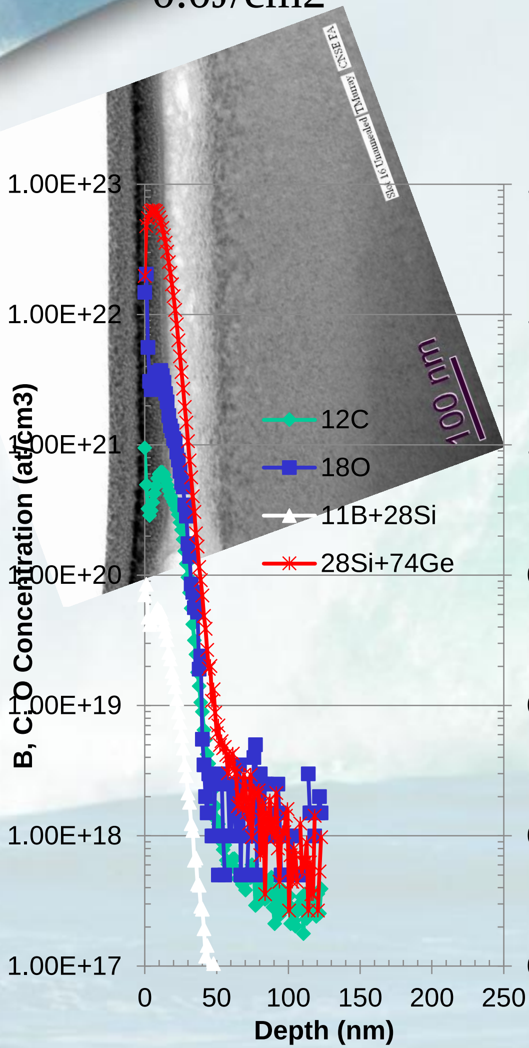


Melt Depth (A)
308nm
515nm
Excico
Innovavent
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
0.5
1
1.5
2
2.5
3
3.5
Laser Power Level (J/cm2)
Absorption depth (nm)
1E+11
1E+10
1E+09
1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
100
1000
10000
Wavelength (µm)
10.6µm CO2
UltraTech
1.06µm YAG
850 nm Diode
SHI Green 527nm
Innovavent 515nm
308nm Excico
532nm 2f-YAG
KrF=248nm SHI
Figure 2- Absorption depth versus laser wavelength in crystalline silicon.
Excico, IWJT-2012
Intel 308nm Ge-PAI 10pulses
515nm 0% Ge
308nm 55% Ge
308nm 0% Ge
248nm Ge-PAI
515nm 55% Ge
Ge=10%
Ge=0%
SHI-527nm

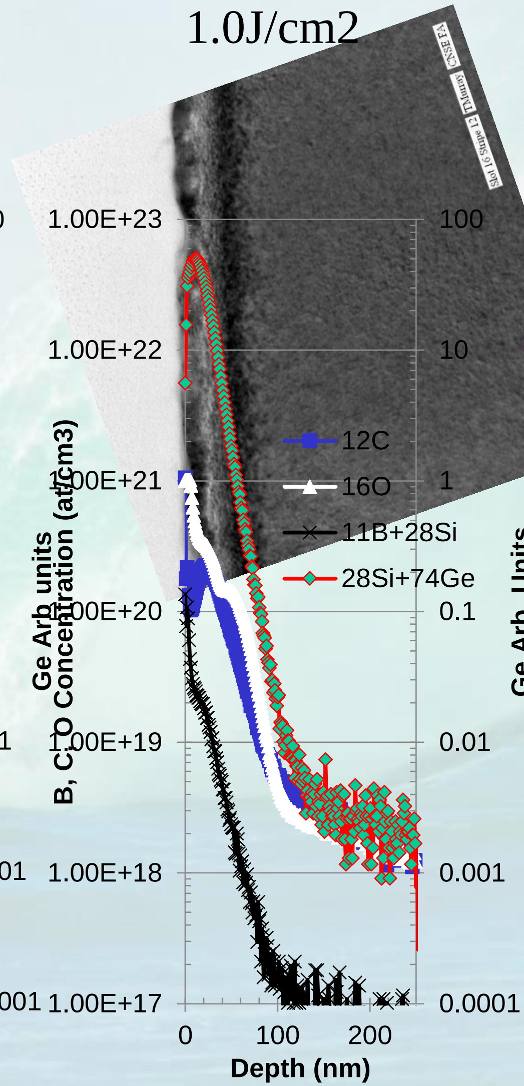
Excico-Therma-Wave (TW)



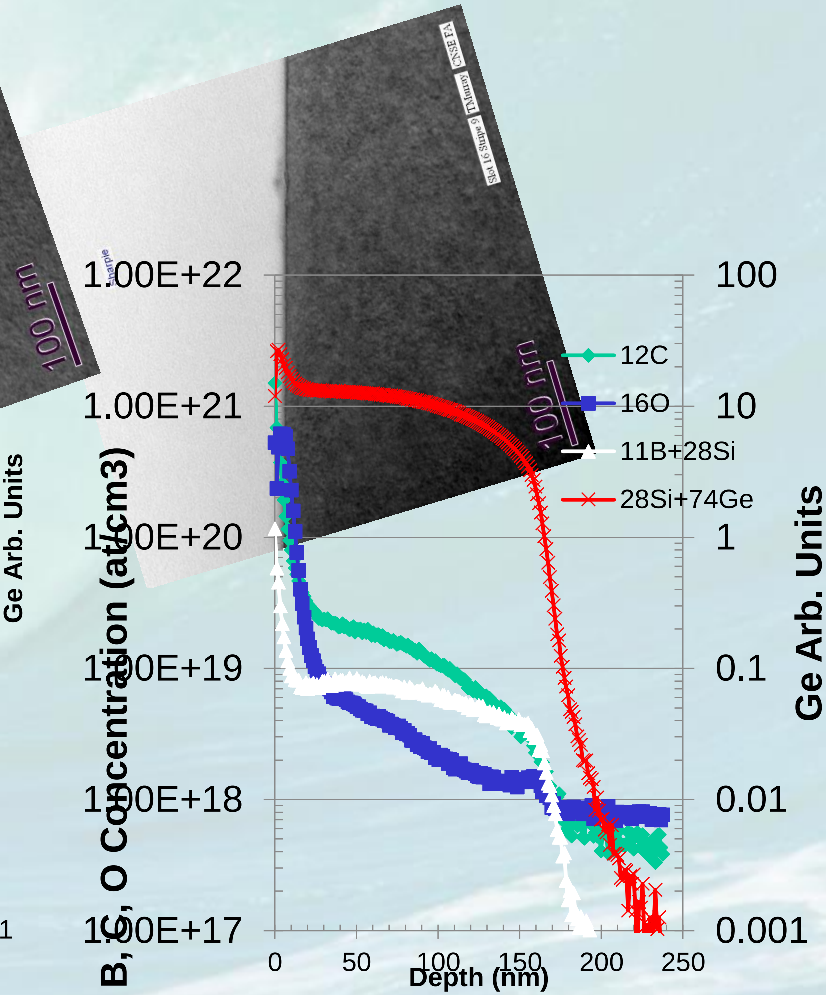
0.0J/cm2



1.0J/cm2

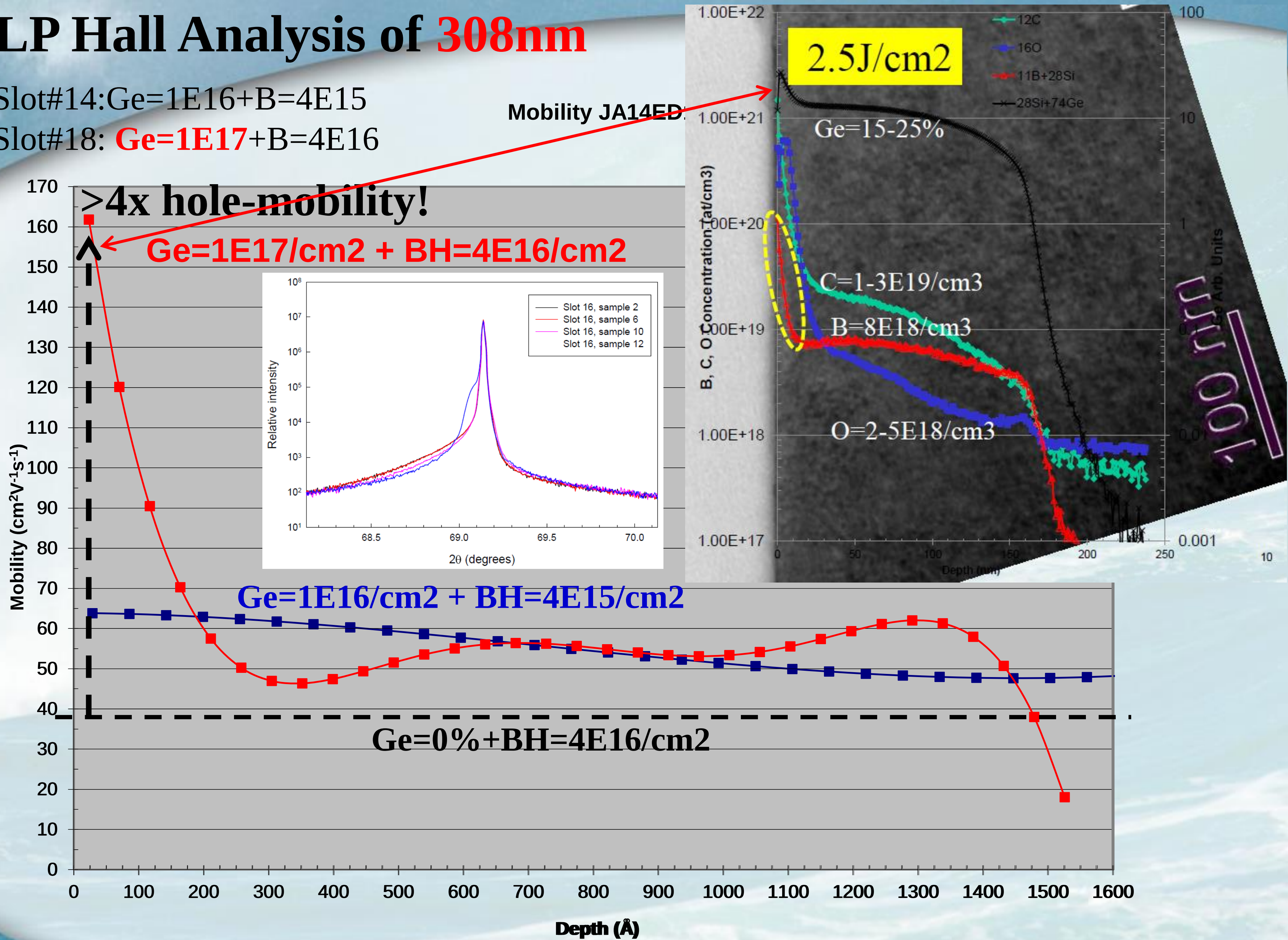


2.5J/cm2



ALP Hall Analysis of 308nm

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



Borland et al., IWJT-2013

Liquid Phase Epitaxy (LPE) Formation of Localized High Quality/Mobility Ge & SiGe by High Dose Ge-Implantation with Laser Melt Annealing for 10nm and 7nm Node

Oct 6, 2014 ECS Conference on SiGe & Ge Technology

John Borland[1,2], Michiro Sugitani[3], Peter Oesterlin[4], Walt Johnson[5], Temel Buyuklimanli[6], Robert Hengstebeck[6], Ethan Kennon[7], Kevin Jones[7] & Abhijeet Joshi[8]

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[2]AIP, Honolulu, Hawaii

[3]SEN, Shinagawa, Tokyo, Japan

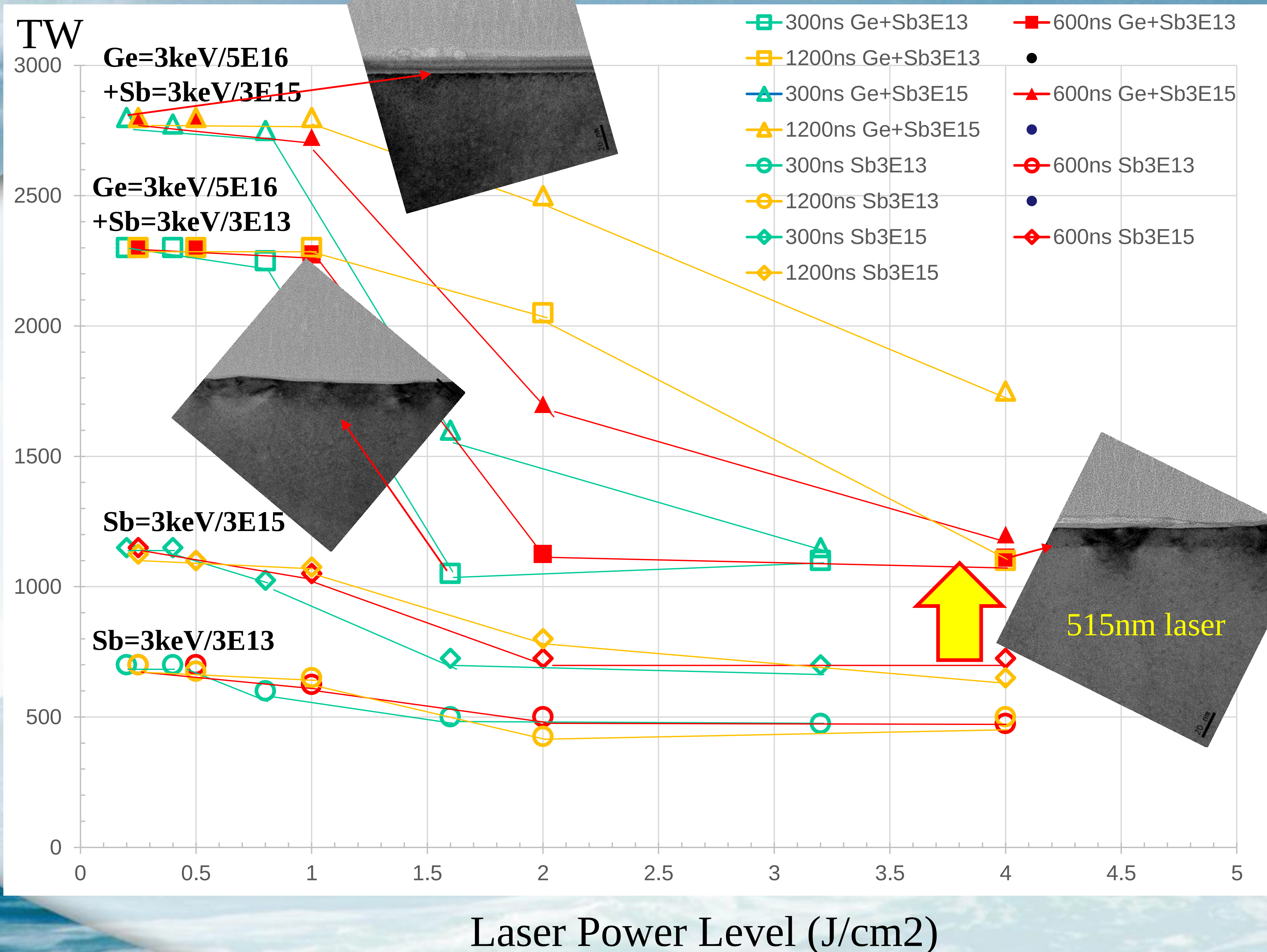
[4]Innovavent, Gottingen, Germany

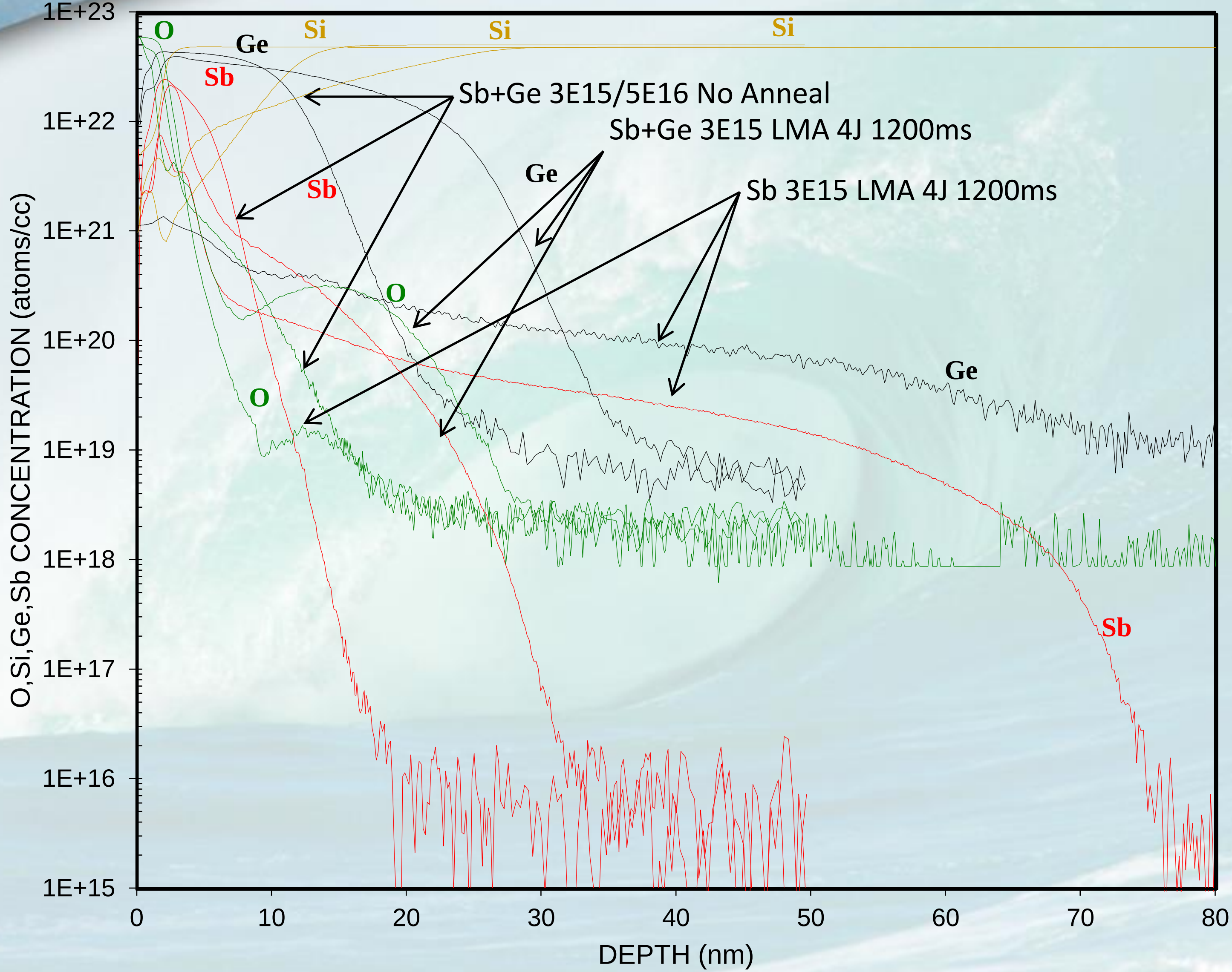
[5]KLA-Tencor, Milpitas, California

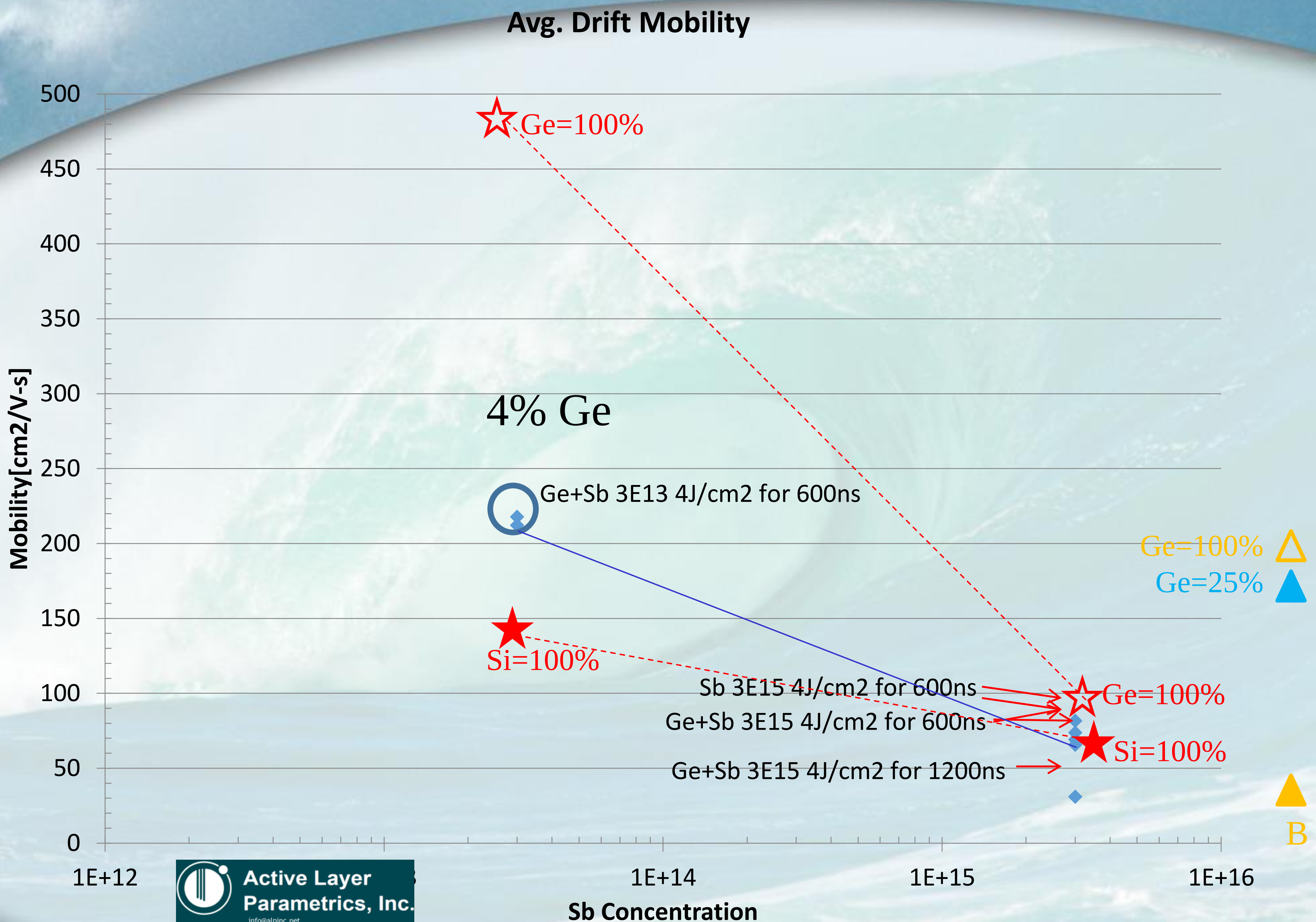
[6]EAG, East Windsor, New Jersey

[7]University of Florida, Gainsville, FL

[8]Active Layer Parametrics, LA, CA


TW
Ge=3keV/5E16
+Sb=3keV/3E15
Ge=3keV/5E16
+Sb=3keV/3E13
Sb=3keV/3E15
Sb=3keV/3E13
515nm laser
300ns Ge+Sb3E13
600ns Ge+Sb3E13
1200ns Ge+Sb3E13
300ns Ge+Sb3E15
600ns Ge+Sb3E15
1200ns Ge+Sb3E15
300ns Sb3E13
600ns Sb3E13
1200ns Sb3E13
300ns Sb3E15
600ns Sb3E15
1200ns Sb3E15
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Laser Power Level (J/cm2)


1E+23
1E+22
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
O,Si,Ge,Sb CONCENTRATION (atoms/cc)
0
10
20
30
40
50
60
70
80
DEPTH (nm)
O
Ge
Si
Si
Si
Sb
Sb+Ge 3E15/5E16 No Anneal
Sb+Ge 3E15 LMA 4J 1200ms
Sb
Ge
Sb 3E15 LMA 4J 1200ms
O
O
Ge
Sb



Borland et al., ECS Oct 2014

IEDM-2013 Stanford/Synopsys paper: 4%GeSn-channel for pMOS & 100%Ge-channel nMOS

with 32% Si and 8% Sn is lattice-matched to Ge and has a bandgap of 0.87eV.

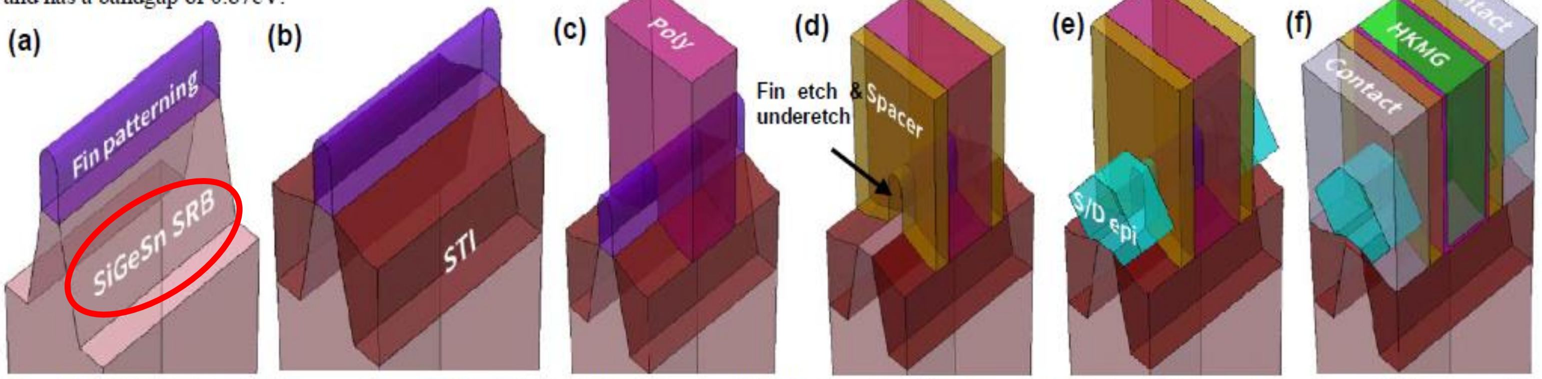
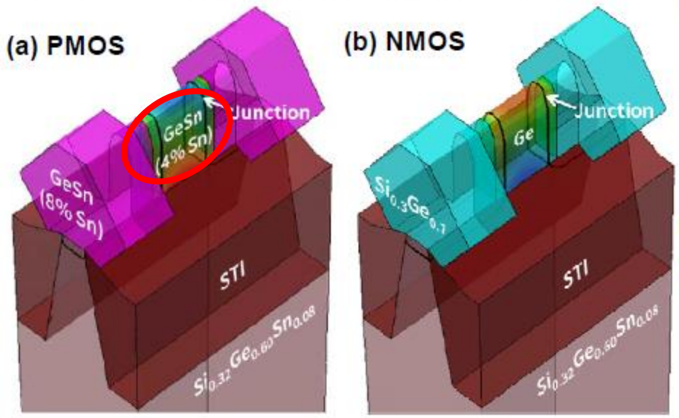


Fig. 3 MOSFET fabrication process flow (a) Fin, SiGeSn SRB patterning (b) STI formation (c) Poly gate definition (d) Spacer formation and S/D recess (e) *In-situ* doped S/D epitaxial re-growth, (f) Gate last high-κ metal gate.



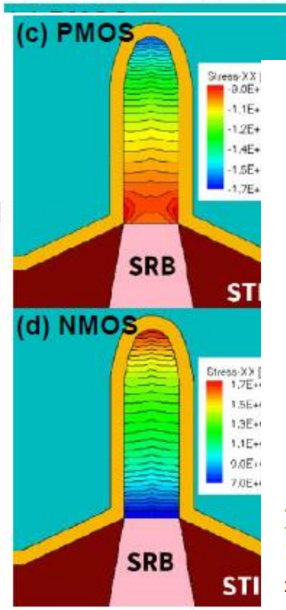


Fig. 4 (a, b) PMOS and NMOS devices (gate stack, spacers, contacts omitted) fabricated using '7nm' design rules. PMOS: GeSn (4% Sn) channel, *in-situ* doped GeSn (8% Sn) S/D. NMOS: Ge channel, *in-situ* doped $Si_{0.3}Ge_{0.7}$ S/D (c, d) Longitudinal stress distribution (σ_{xx}) for PMOS and NMOS. Other components of stress were found to be less than 10% of σ_{xx}.

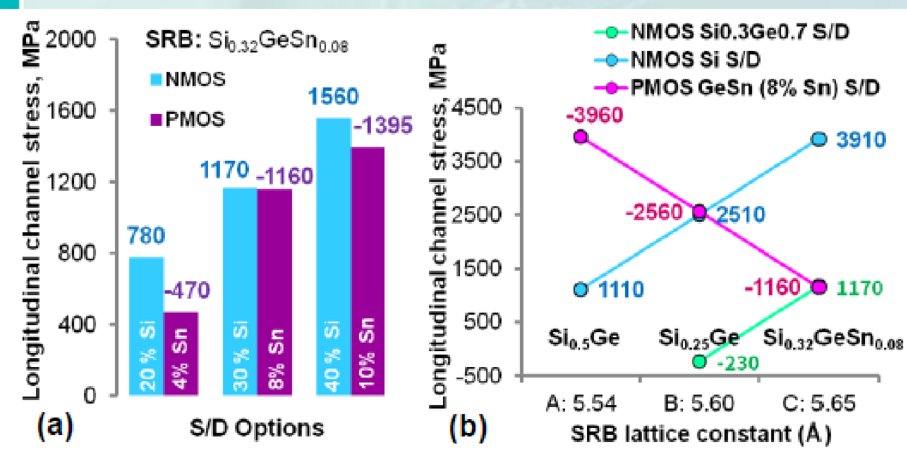
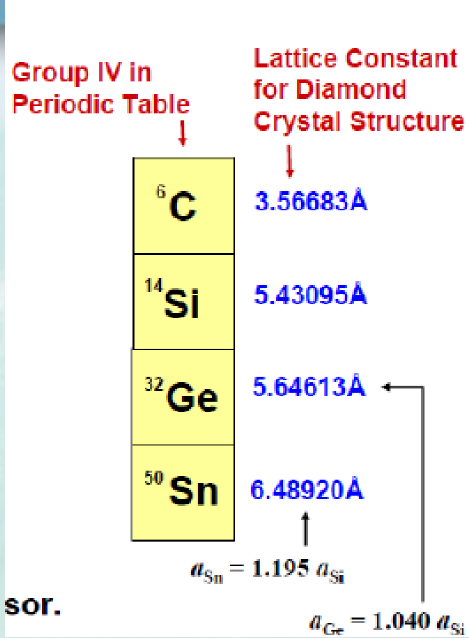
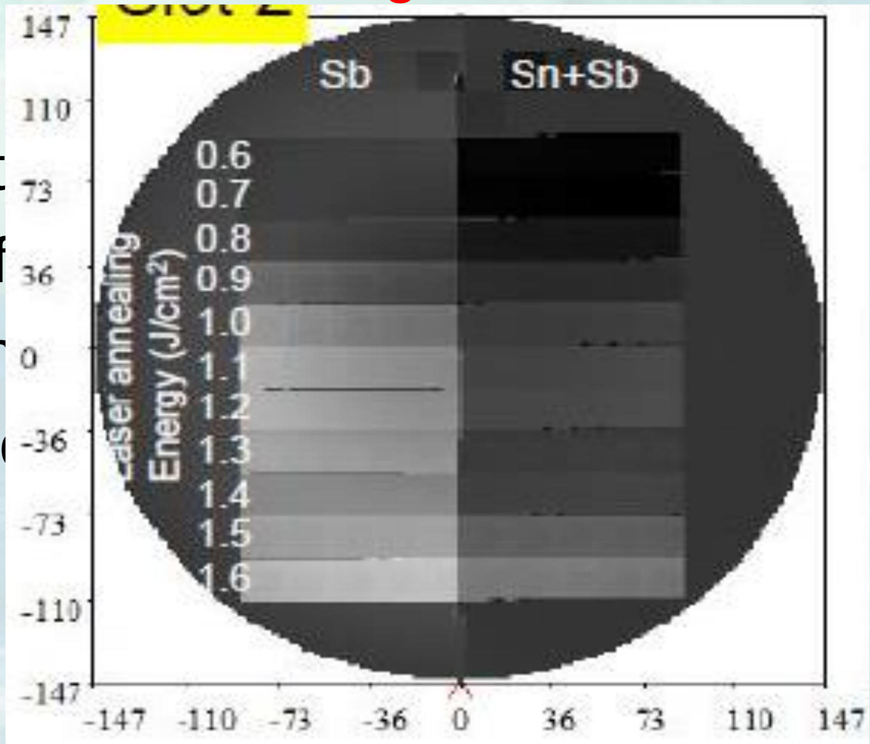


Fig. 12 Different options for tuning the channel stress: (a) Si content in NMOS S/D stressor, Sn content in PMOS S/D stressor (b) Lattice constant of the common SRB. Channel material kept invariant: GeSn (4% Sn) (PMOS) and Ge (NMOS), '7nm' design rules.

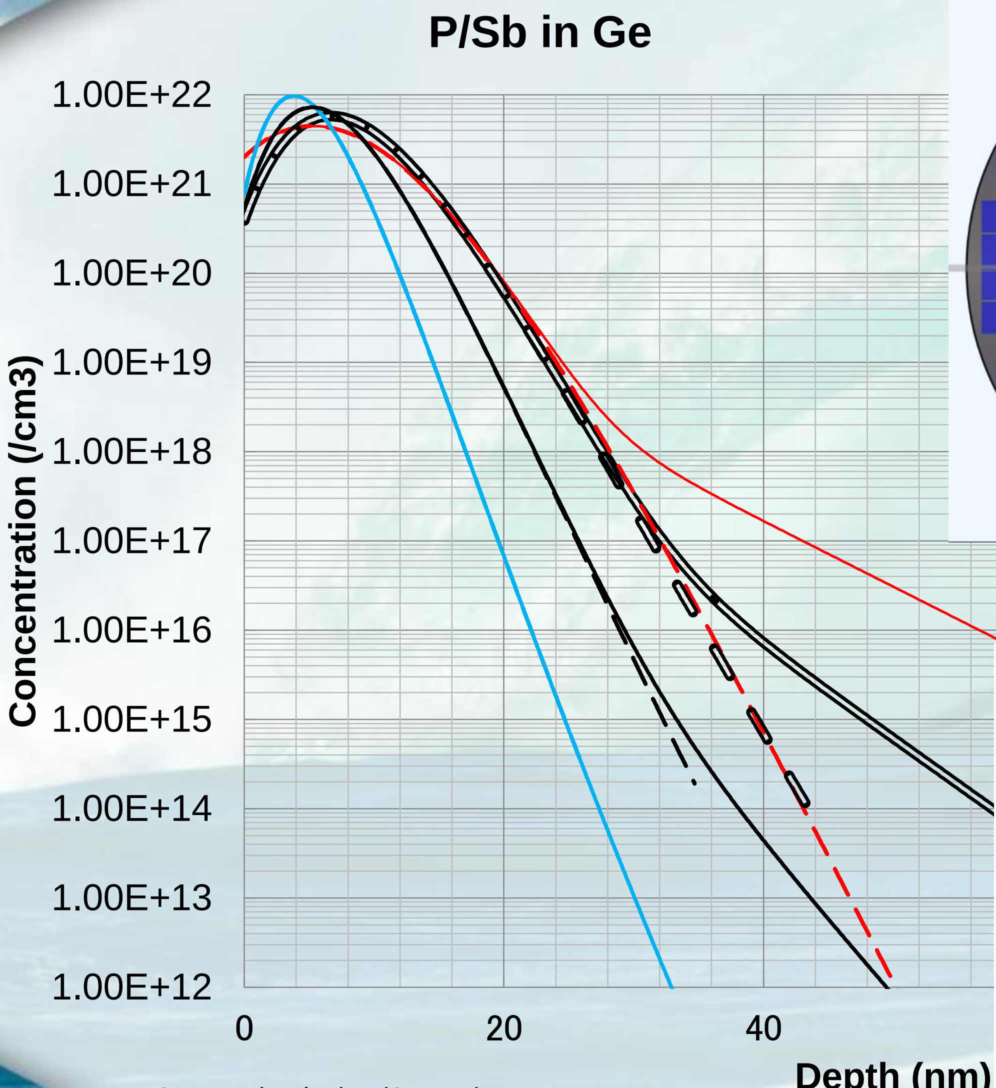
Outline

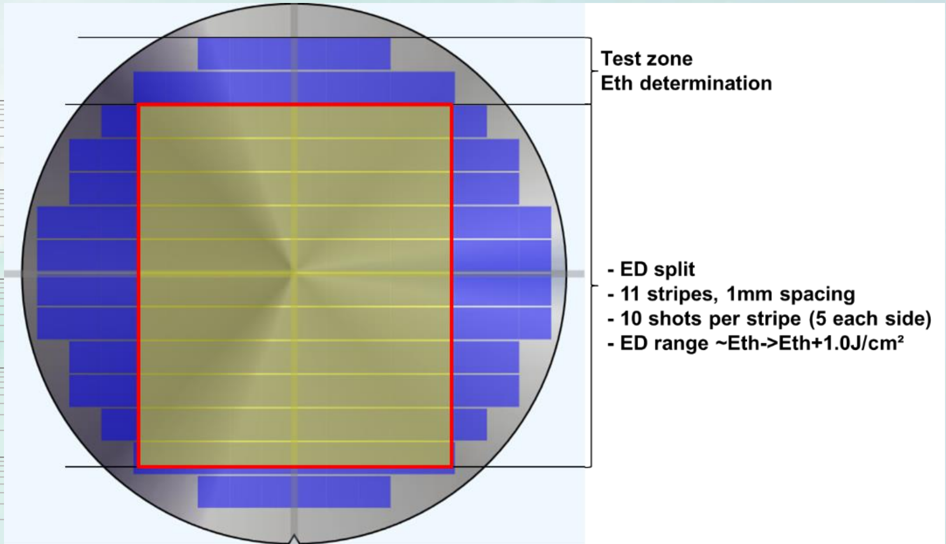
- Introduction
- Experimentation
  - 70nm Ge-epi/SiGe-buffer/Si P(100) wafer
  - P, Sb and Sn Implantation at 5E15/cm2
    - P=4keV, Sb=11keV & Sn=10keV
    - P, Sn+P, Sb and Sn+Sb
  - 308nm Excimer Laser Annealing 0.6-1.6J/cm2
- Results
  - Rs Dopant Activat
  - SIMS Dopant Prof
  - XRD Strain-Ge Ar
  - Differential Hall M
- Summary



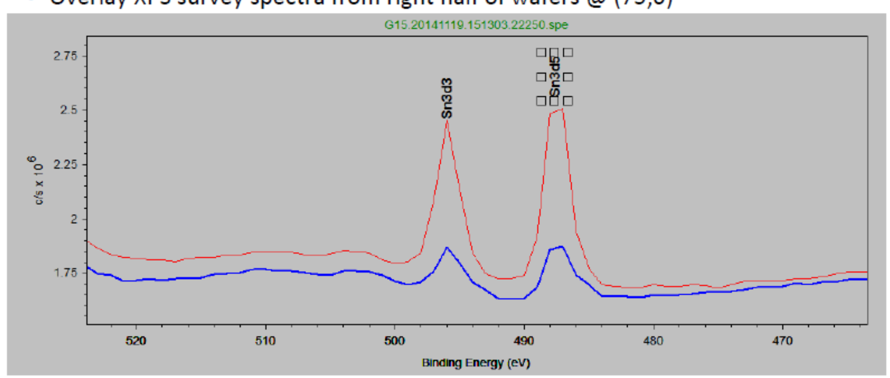


Half-Wafer Sn-Implant 5E15/cm2
Full Wafer P or Sb 5E15/cm2 Implant





- Overlay XPS survey spectra from right half of wafers @ (75,0)



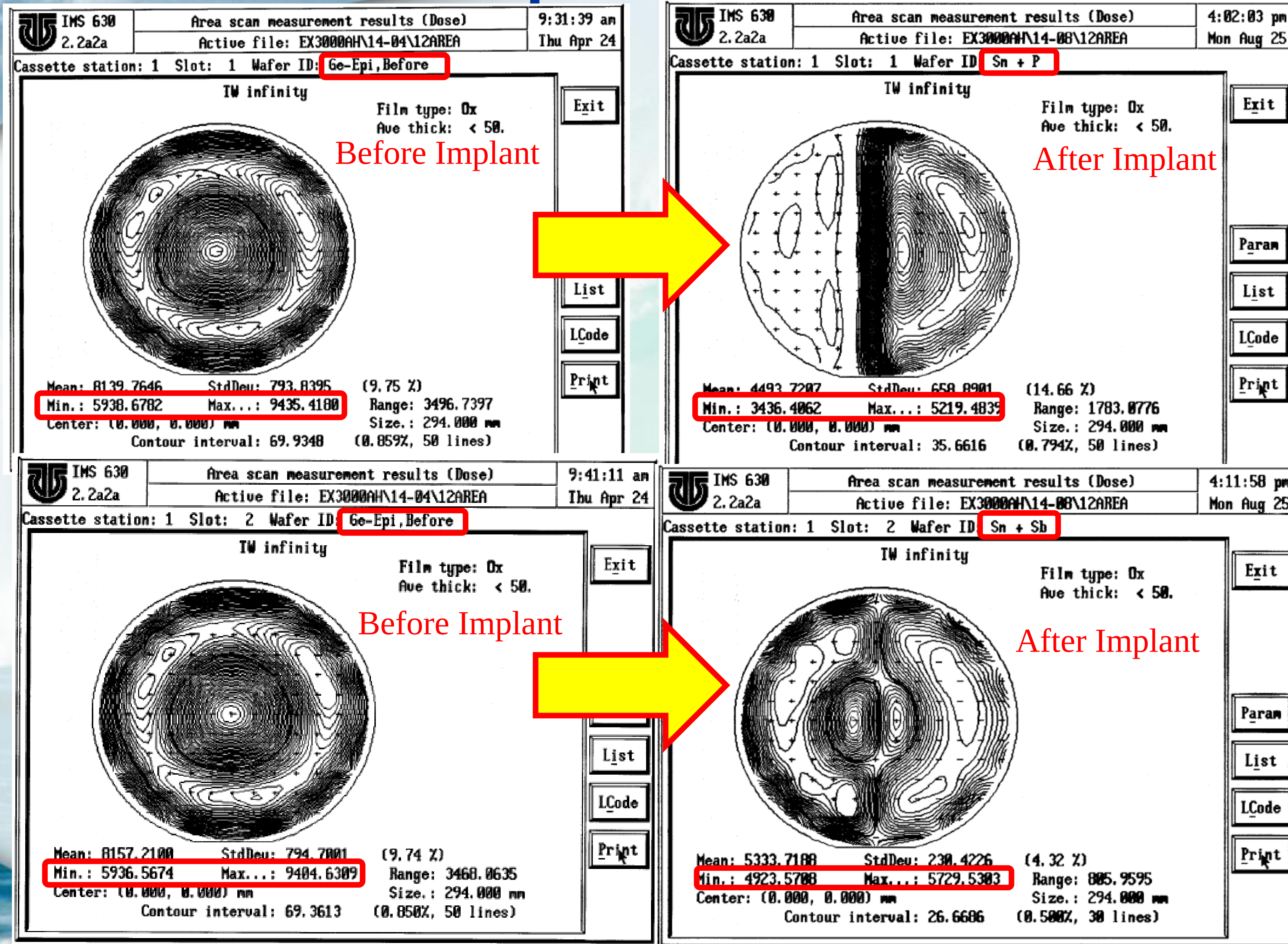
- Rough quantification:
  - Wafer 1: 10.4 at% Sn, 89.6% Ge
  - Wafer 2: 2.5 at% Sn, 97.5% Ge

Sn+P-SIMS, Sn=12.5% ~4.5E15/cm2
Sn+Sb-SIMS, Sn=4.5% ~2.3E15/cm2
Maybe due to retrograde surface with Sb co-implant!

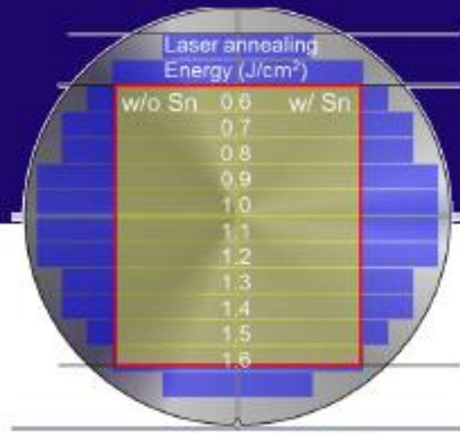
ReVera

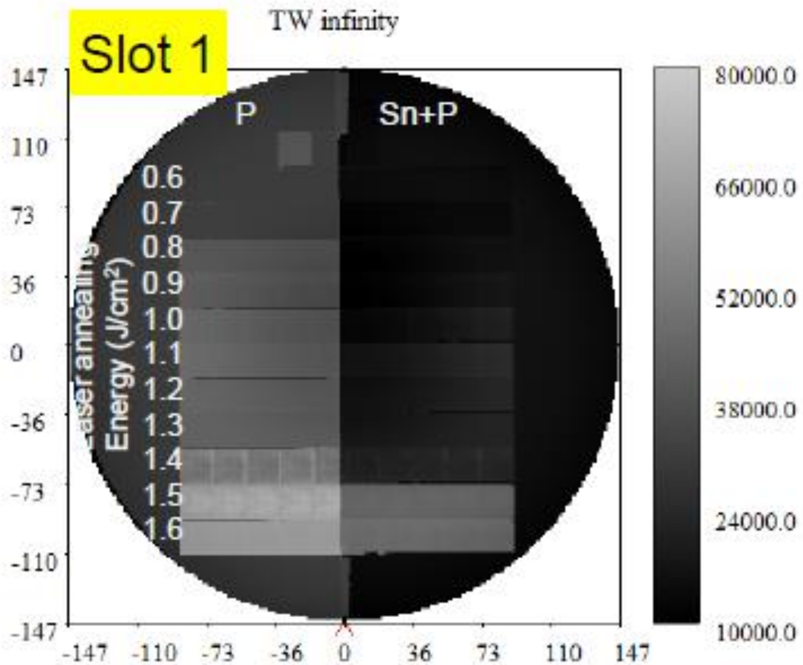
J.O.B. Technologies (Strategic Marketing, Sales & Technology)

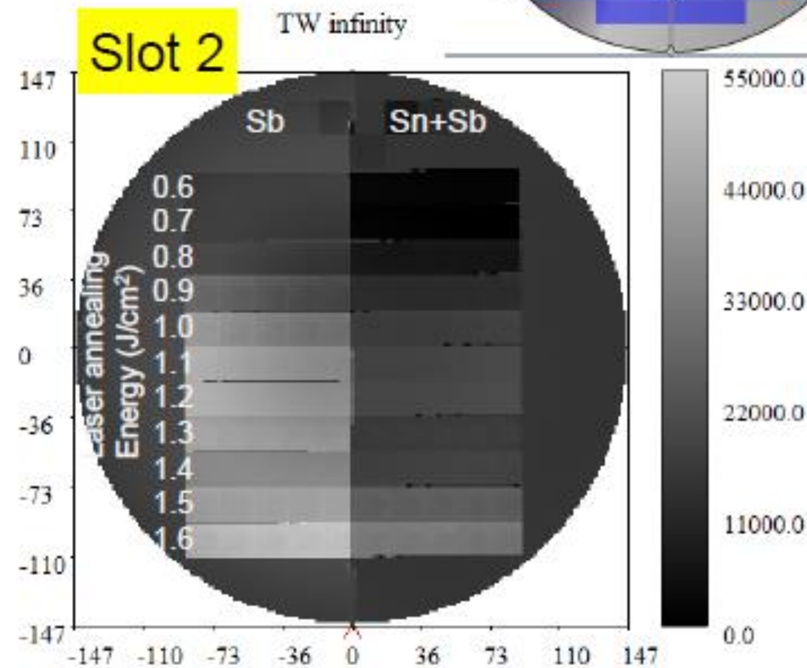
Half-Wafer Sn-Implant 5E15/cm2



µ-uniformity mapping (µMap)

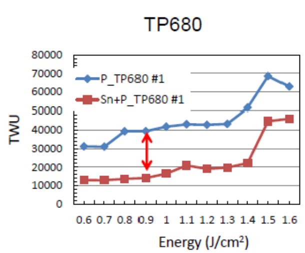


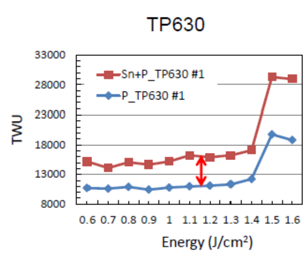


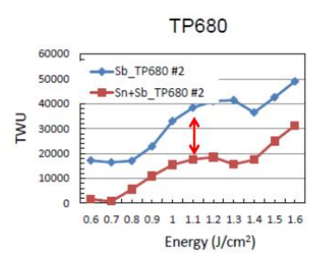


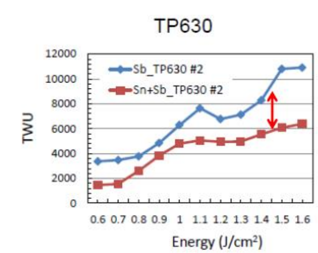
Slot 1 (P, Sn+P)

Slot 2 (Sb, Sn+Sb)









- TWU increase with laser-annealing energy

- TWU increase with laser-annealing energy

IWJT-2015 Paper S5-2 by Nishimura of **Univ of Tokyo** on "Recent Progress of Junction Technology for Germanium CMOS". In Fig.4 below they used Raman analysis to quantify implant annealing damage recovery from the P=30keV/3E15 implant in to Ge-Cz wafers. They commented that even after high temperature annealing at 850°C the Raman Ge peak did not recover to the reference Ge-Cz wafer level concluding there still remains some residual implant damage. Fig.5 shows the effects of P implant dose from 1E13/cm^2 to 3E15/cm^2 on resistivity and FWHM Raman Ge-peak with 600°C 5 min SPC (solid phase crystallization) annealing and the critical P-implant dose is <2E14/cm^2 to be defect free after annealing.

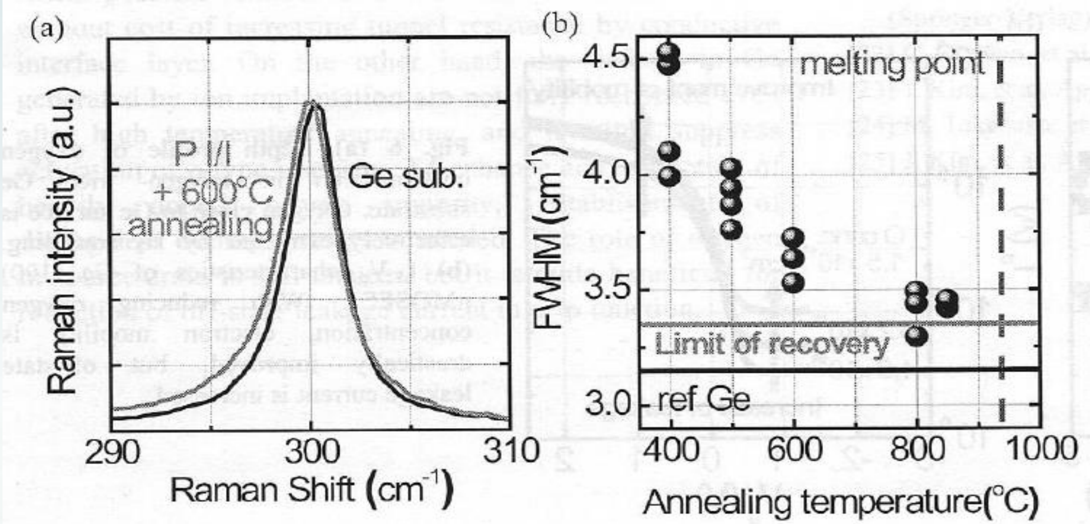


Fig. 4 (a) Typical Ge Raman peaks (around 300 cm^{-1}) before and after P ion implantation with a dose of 3 x10^{15} /cm^2 and thermal annealing. **(b)** Annealing temperature dependence on crystallinity recovery of Ge. Although the annealing temperature was increased up to 850°C, still crystallinity is still worse than that of initial Ge substrate.

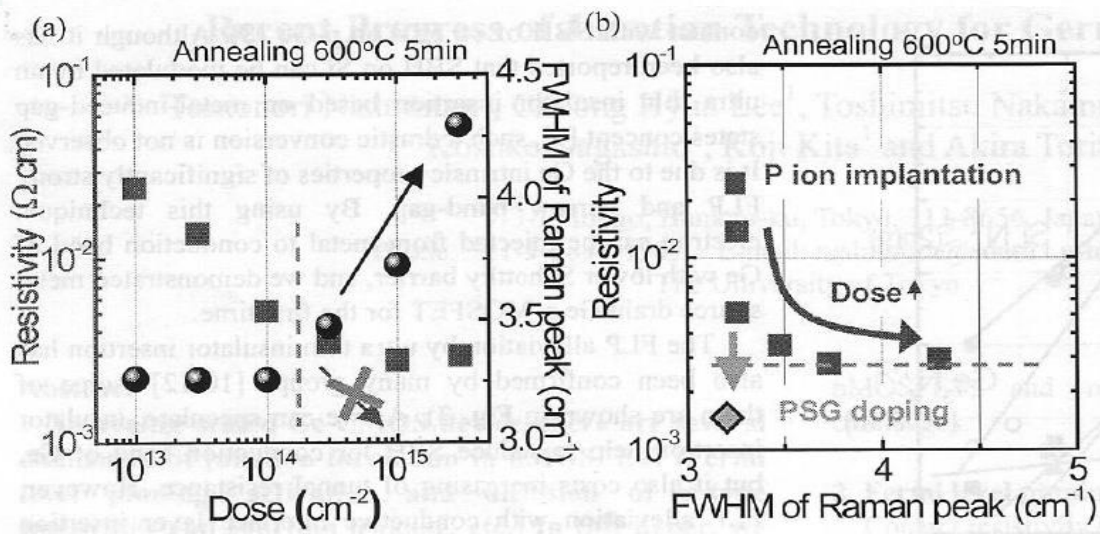
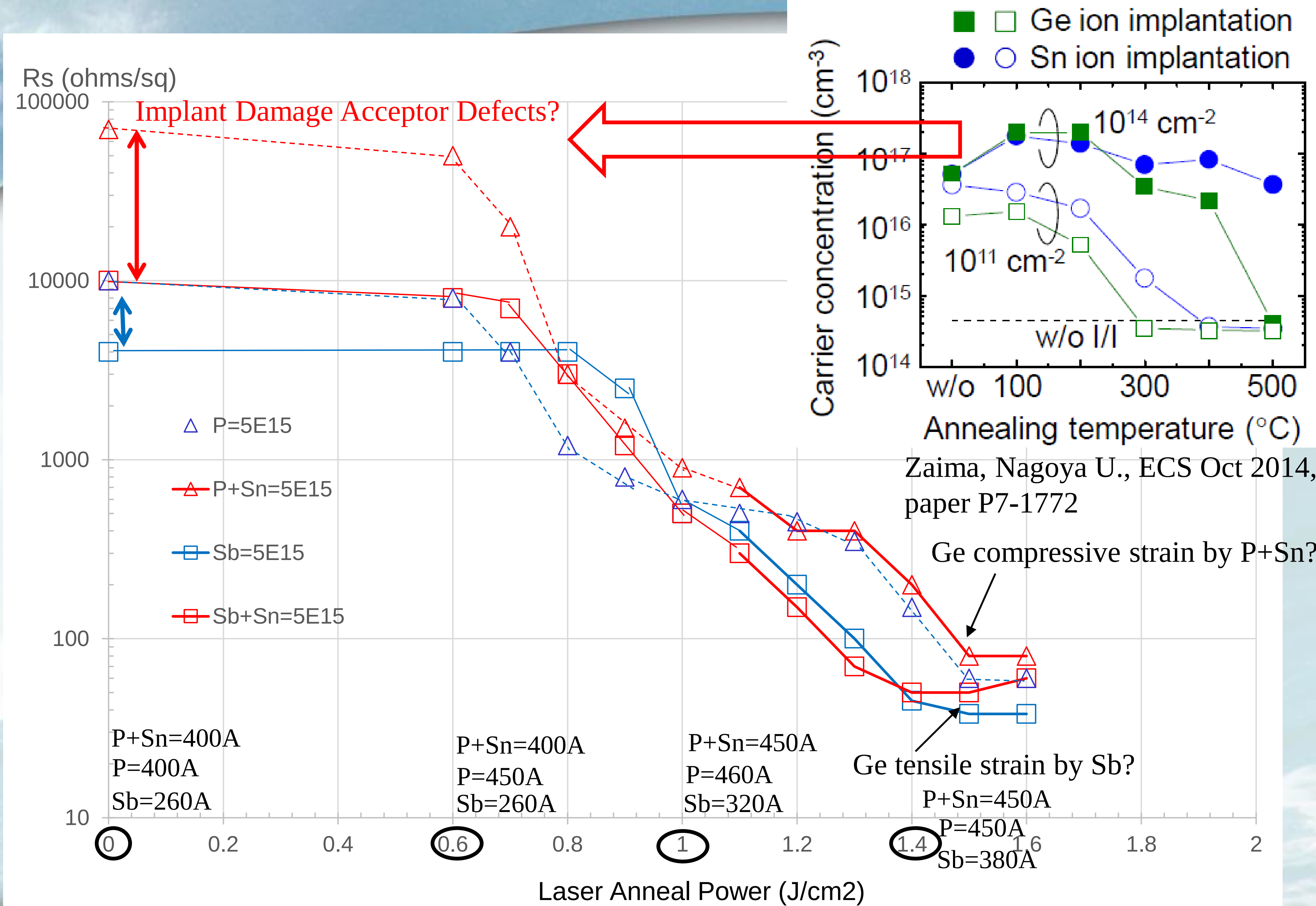
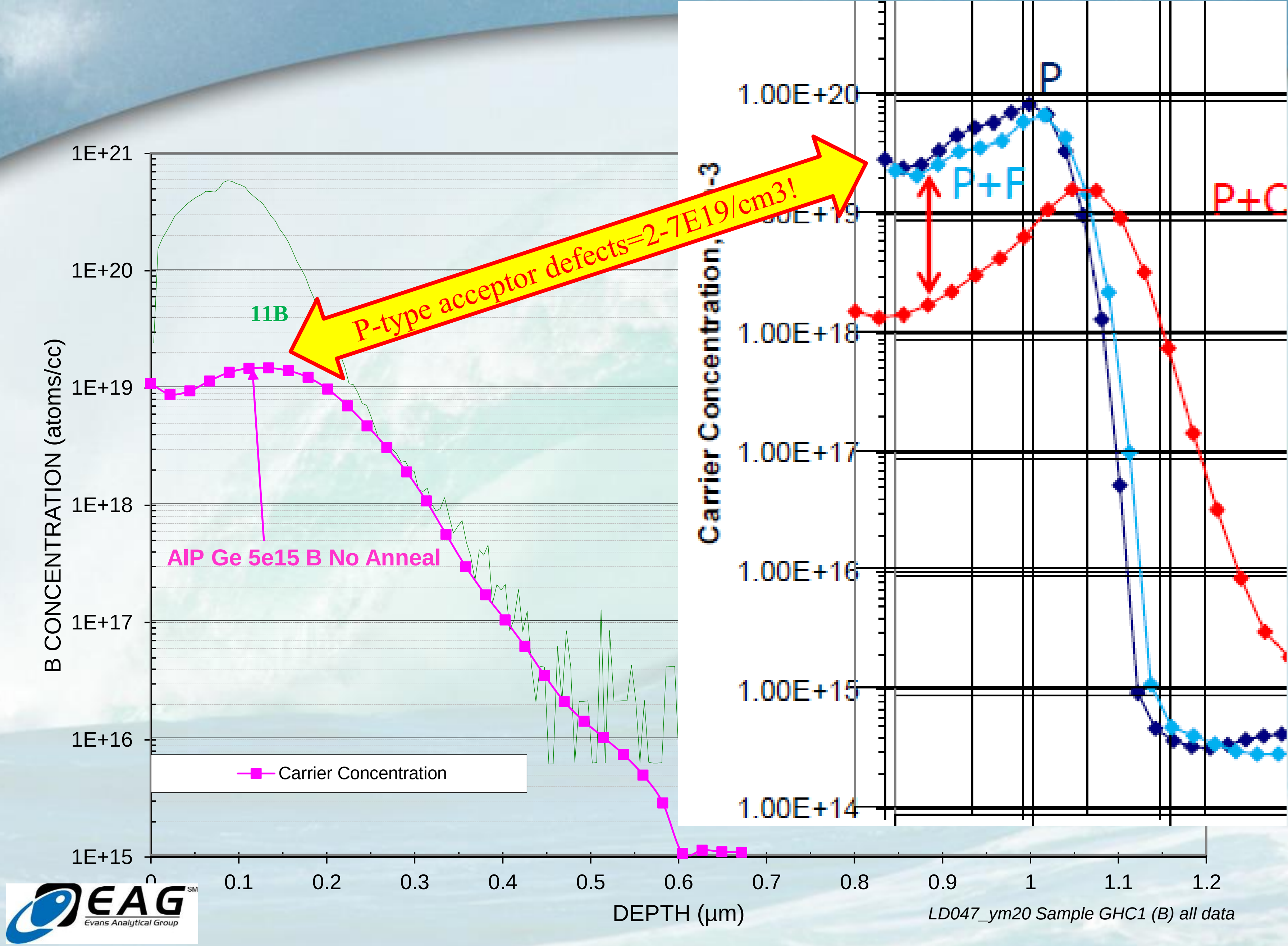


Fig. 5 (a) Resistivity and FWHM of Raman peak of P implanted GeOI as a function of implantation dose. Above 3 x10^{14} /cm^2, FWHM of Raman peak is increased and reduction of resistivity is saturated. **(b)** Correlation between resistivity and FWHM of Raman peak. By solid phase diffusion with phosphorous silicate glass (PSG), further reduction of resistivity is achieved without increasing FWHM of Raman peak.

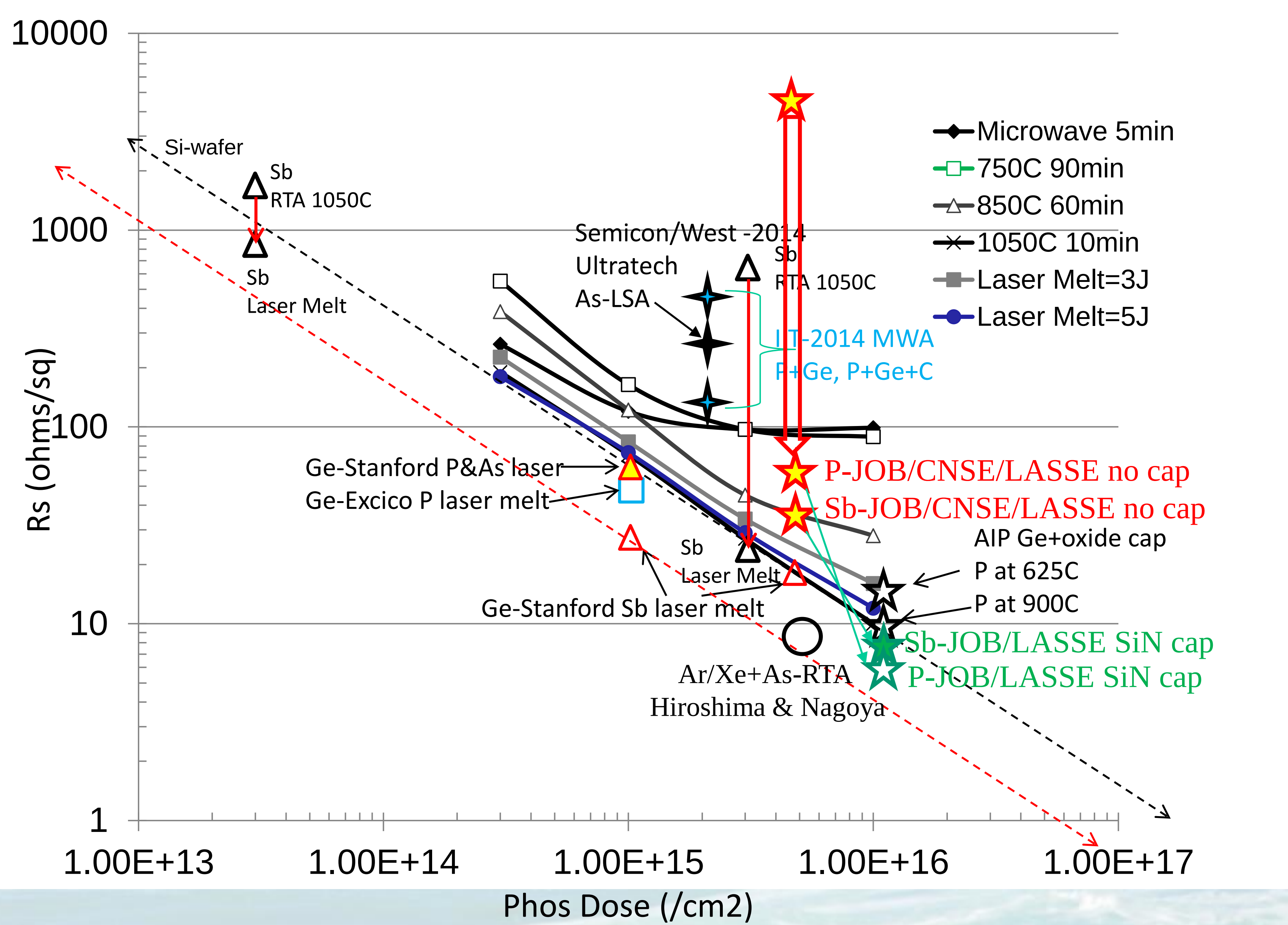
Outline

- Introduction
  - Issues with Ge n+ USJ Formation & High Dopant Activation
  - Strain-Ge High Mobility Channel Material
- Experimentation
  - 70nm Ge-epi/SiGe-buffer/Si P(100) wafer
  - P, Sb and Sn Implantation
  - 308nm Eximer Laser Annealing
- Results
  - Rs Dopant Activation
  - SIMS Dopant Profiles
  - XRD Strain-Ge Analysis
  - Differential Hall Mobility Depth Profiles
- Summary

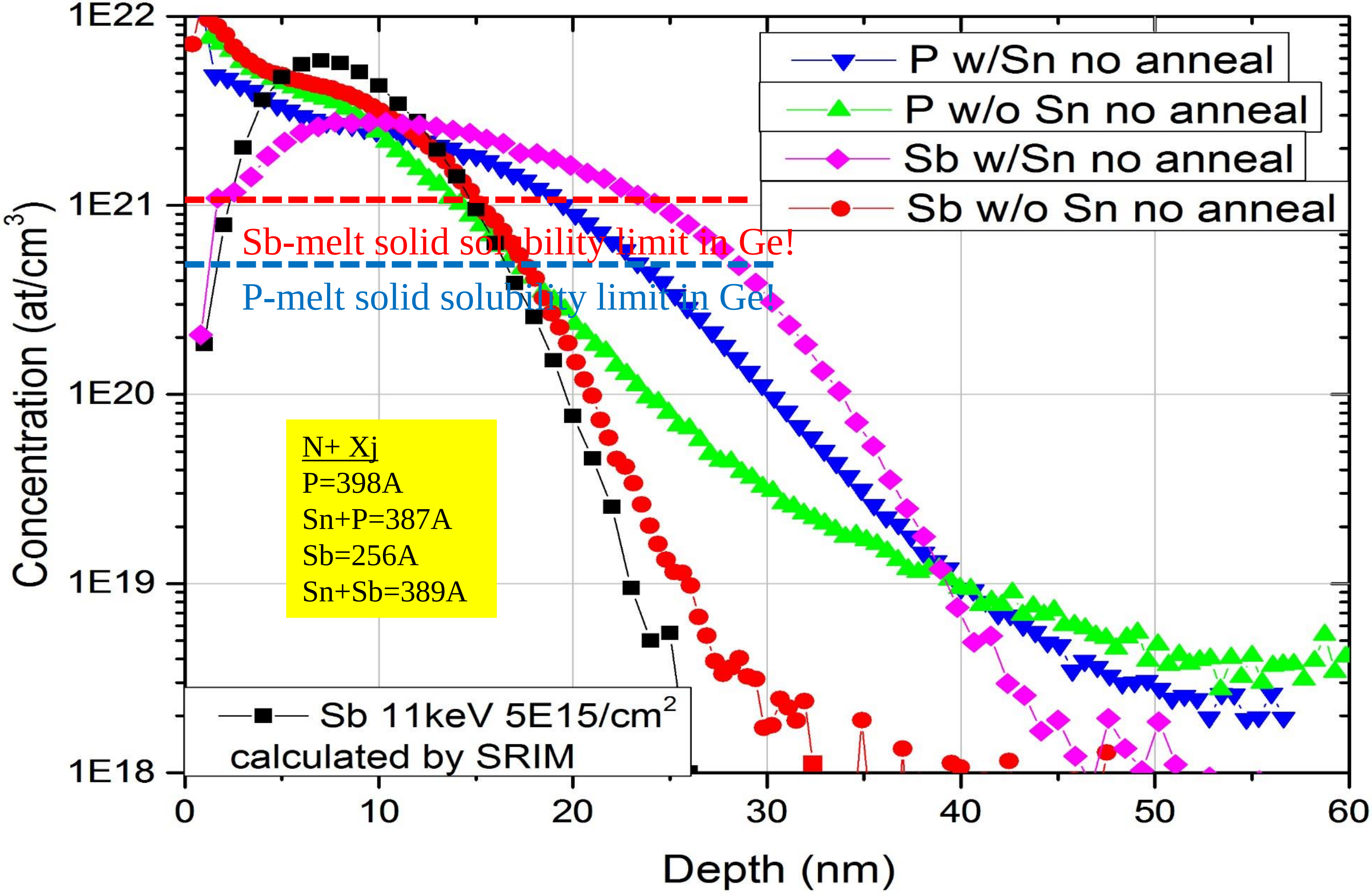

Rs (ohms/sq)
100000
10000
1000
100
10
Implant Damage Acceptor Defects?
P=5E15
P+Sn=5E15
Sb=5E15
Sb+Sn=5E15
P+Sn=400A
P=400A
Sb=260A
P+Sn=400A
P=450A
Sb=260A
P+Sn=450A
P=460A
Sb=320A
P+Sn=450A
P=450A
Sb=380A
Ge compressive strain by P+Sn?
Ge tensile strain by Sb?
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Laser Anneal Power (J/cm2)
Ge ion implantation
Sn ion implantation
Carrier concentration (cm-3)
10^18
10^17
10^16
10^15
10^14
10^14 cm-2
10^11 cm-2
w/o I/I
w/o
100
300
500
Annealing temperature (°C)
Zaima, Nagoya U., ECS Oct 2014,
paper P7-1772



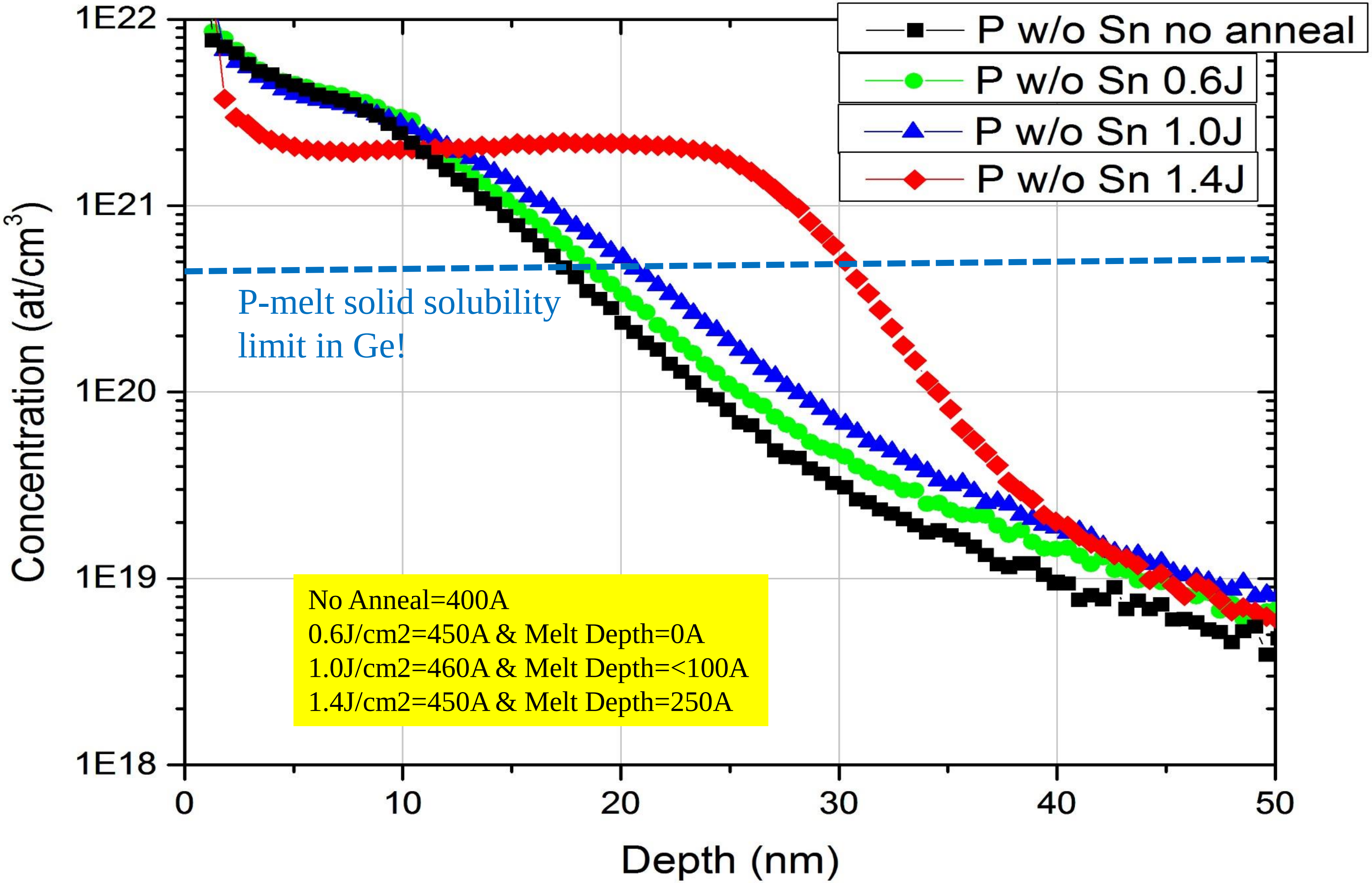
Borland & Konkola, AIP, IIT-2014



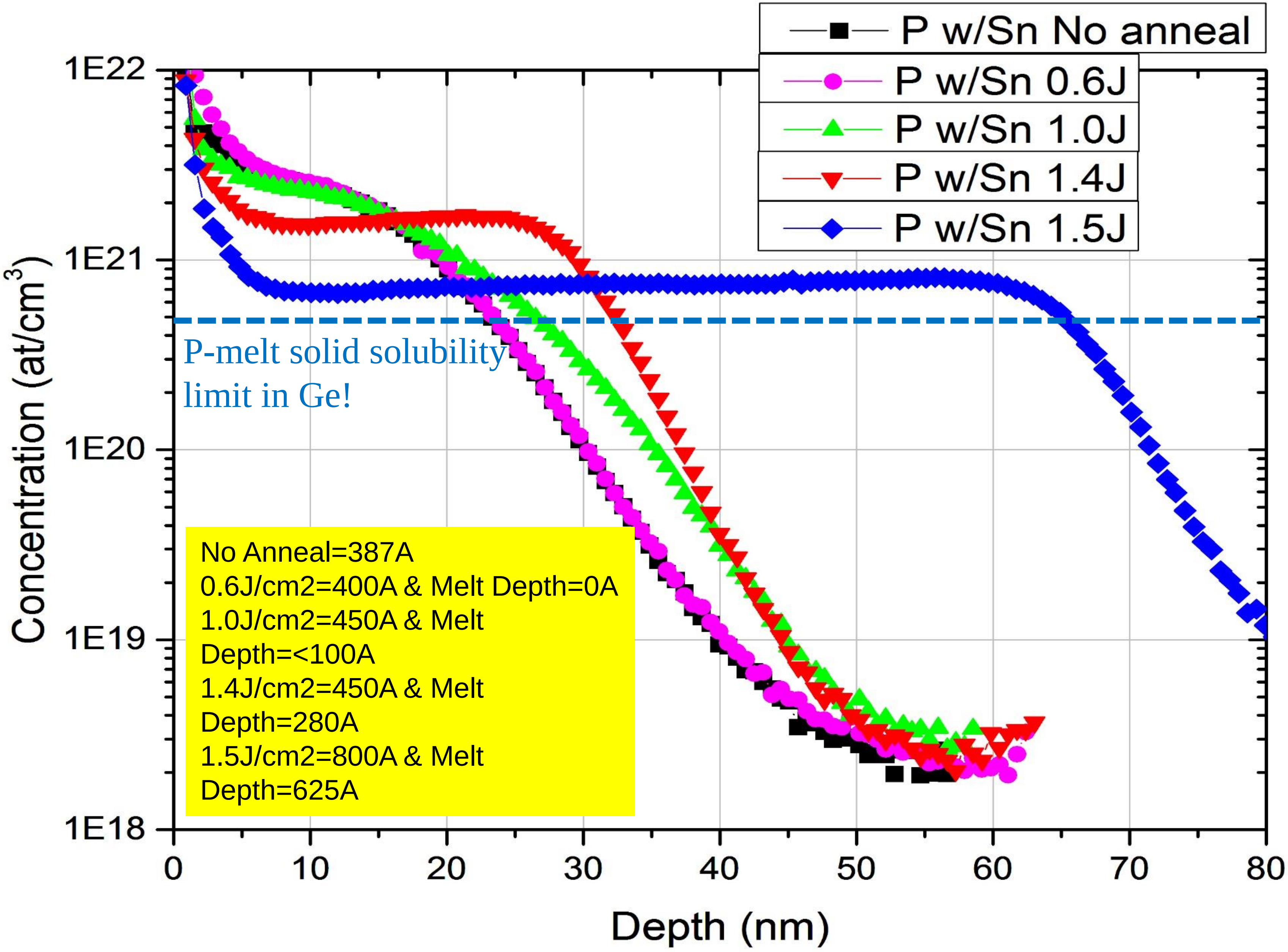
10000
1000
100
10
1
Rs (ohms/sq)
1.00E+13
1.00E+14
1.00E+15
1.00E+16
1.00E+17
Phos Dose (/cm2)
Microwave 5min
750C 90min
850C 60min
1050C 10min
Laser Melt=3J
Laser Melt=5J
Si-wafer
Sb
RTA 1050C
Sb
Laser Melt
Semicon/West -2014
Ultratech
As-LSA
Sb
RTA 1050C
IIT-2014 MWA
P+Ge, P+Ge+C
Ge-Stanford P&As laser
Ge-Excico P laser melt
P-JOB/CNSE/LASSE no cap
Sb-JOB/CNSE/LASSE no cap
AIP Ge+oxide cap
P at 625C
P at 900C
Sb
Laser Melt
Ge-Stanford Sb laser melt
Sb-JOB/LASSE SiN cap
P-JOB/LASSE SiN cap
Ar/Xe+As-RTA
Hiroshima & Nagoya



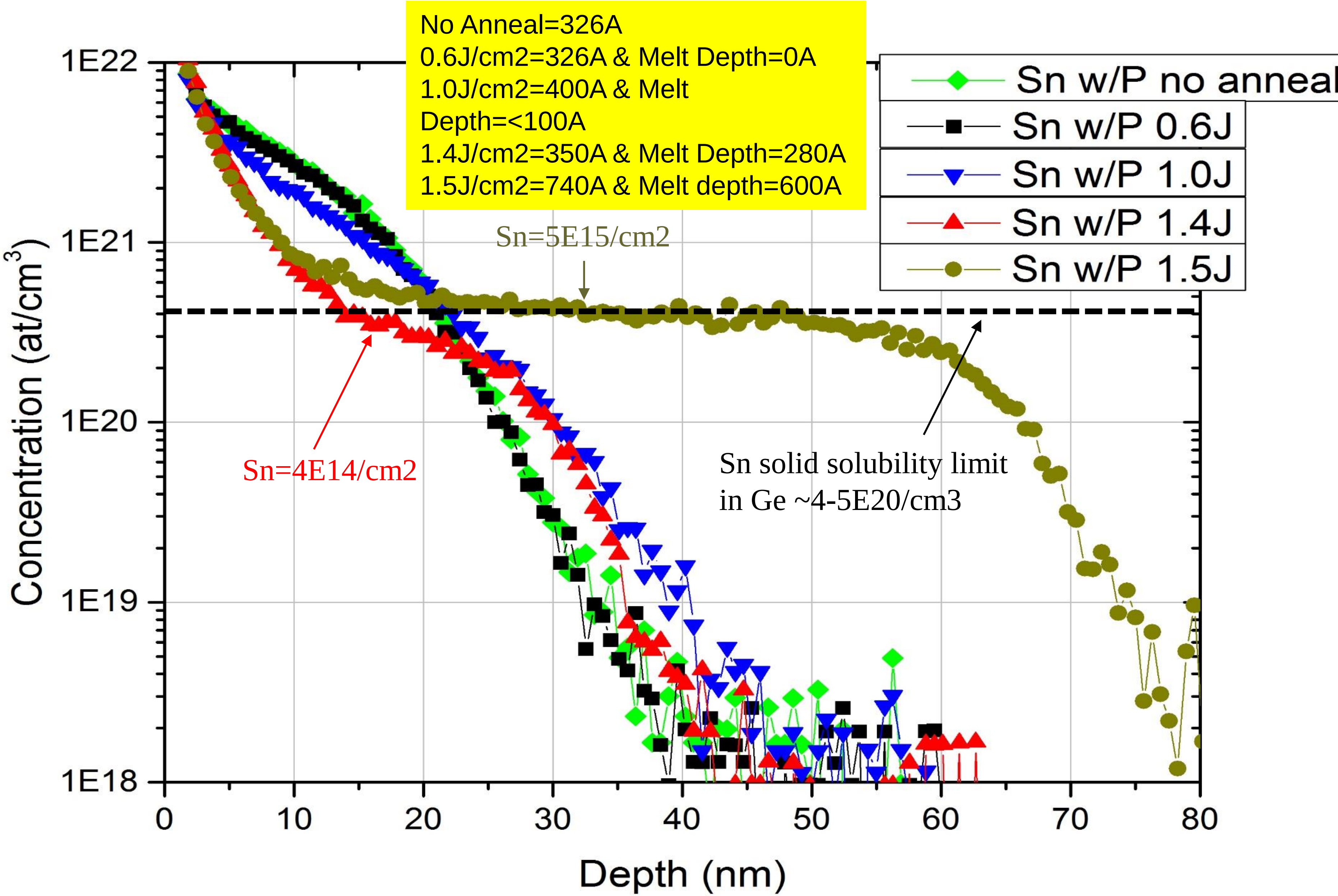
1E22
1E21
1E20
1E19
1E18
Concentration (at/cm^3)
0
10
20
30
40
50
60
Depth (nm)
P w/Sn no anneal
P w/o Sn no anneal
Sb w/Sn no anneal
Sb w/o Sn no anneal
Sb-melt solid solubility limit in Ge!
P-melt solid solubility limit in Ge!
N+ Xj
P=398A
Sn+P=387A
Sb=256A
Sn+Sb=389A
Sb 11keV 5E15/cm^2
calculated by SRIM

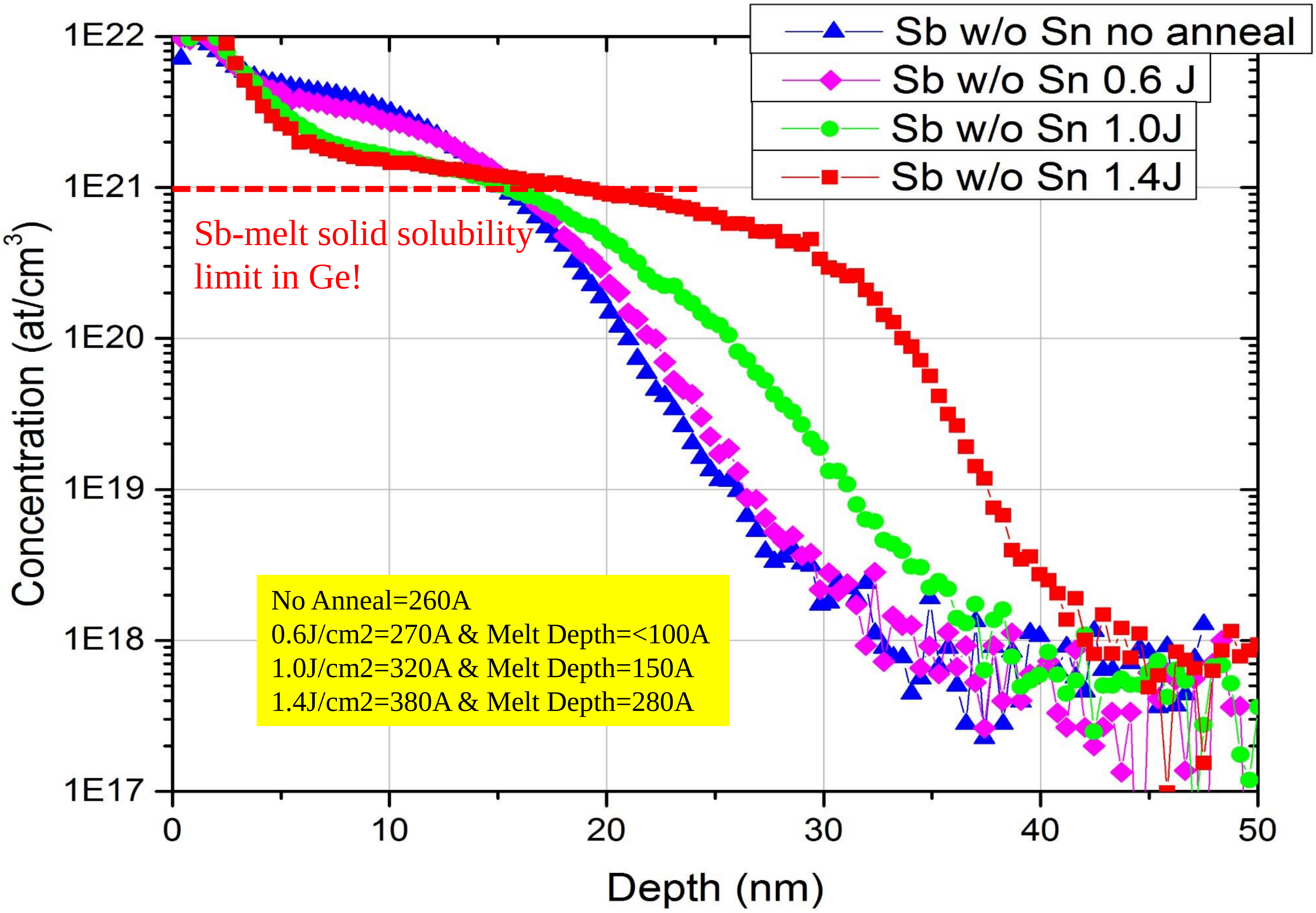


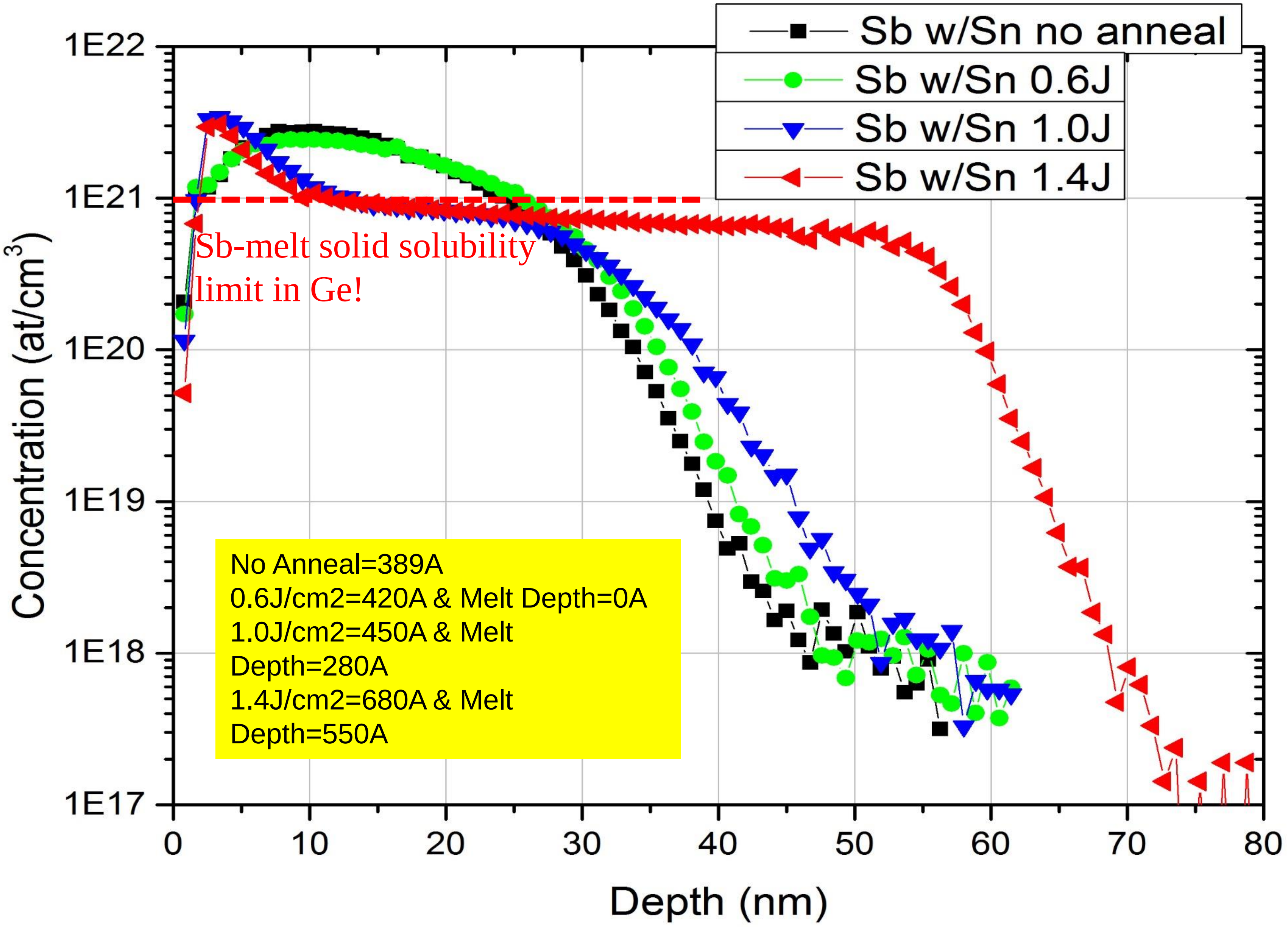
P w/o Sn no anneal
P w/o Sn 0.6J
P w/o Sn 1.0J
P w/o Sn 1.4J
1E22
1E21
1E20
1E19
1E18
Concentration (at/cm3)
0
10
20
30
40
50
Depth (nm)
P-melt solid solubility limit in Ge!
No Anneal=400A
0.6J/cm2=450A & Melt Depth=0A
1.0J/cm2=460A & Melt Depth=<100A
1.4J/cm2=450A & Melt Depth=250A

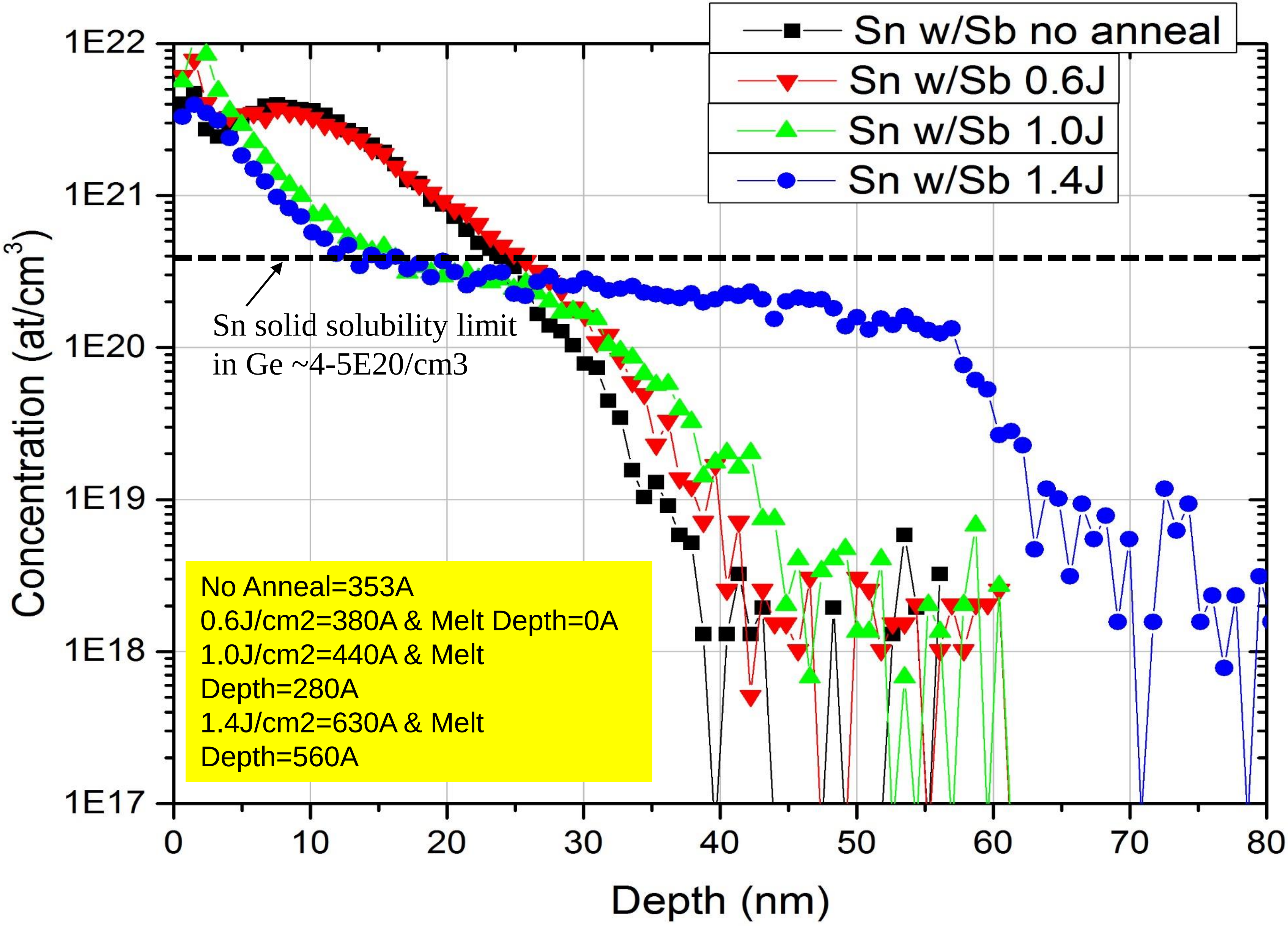


P w/Sn No anneal
P w/Sn 0.6J
P w/Sn 1.0J
P w/Sn 1.4J
P w/Sn 1.5J
1E22
1E21
1E20
1E19
1E18
Concentration (at/cm3)
0
10
20
30
40
50
60
70
80
Depth (nm)
P-melt solid solubility
limit in Ge!
No Anneal=387A
0.6J/cm2=400A & Melt Depth=0A
1.0J/cm2=450A & Melt
Depth=<100A
1.4J/cm2=450A & Melt
Depth=280A
1.5J/cm2=800A & Melt
Depth=625A

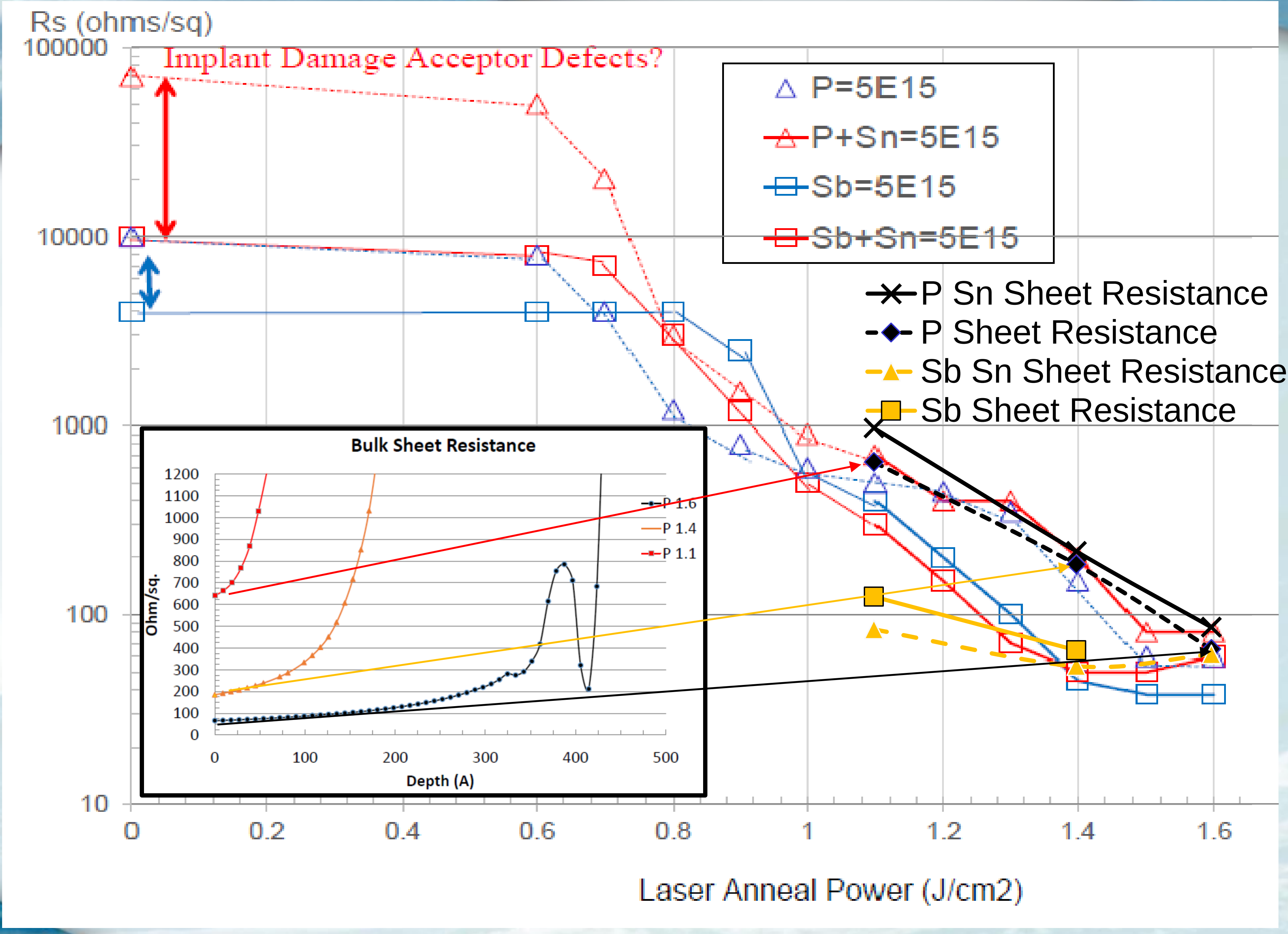

No Anneal=326A
0.6J/cm2=326A & Melt Depth=0A
1.0J/cm2=400A & Melt Depth=<100A
1.4J/cm2=350A & Melt Depth=280A
1.5J/cm2=740A & Melt depth=600A
Sn w/P no anneal
Sn w/P 0.6J
Sn w/P 1.0J
Sn w/P 1.4J
Sn w/P 1.5J
Sn=5E15/cm2
Sn=4E14/cm2
Sn solid solubility limit in Ge ~4-5E20/cm3
Concentration (at/cm3)
Depth (nm)
1E22
1E21
1E20
1E19
1E18
0
10
20
30
40
50
60
70
80


Sb w/o Sn no anneal
Sb w/o Sn 0.6 J
Sb w/o Sn 1.0J
Sb w/o Sn 1.4J
1E22
1E21
1E20
1E19
1E18
1E17
Concentration (at/cm^3)
Sb-melt solid solubility limit in Ge!
No Anneal=260A
0.6J/cm2=270A & Melt Depth=<100A
1.0J/cm2=320A & Melt Depth=150A
1.4J/cm2=380A & Melt Depth=280A
0
10
20
30
40
50
Depth (nm)

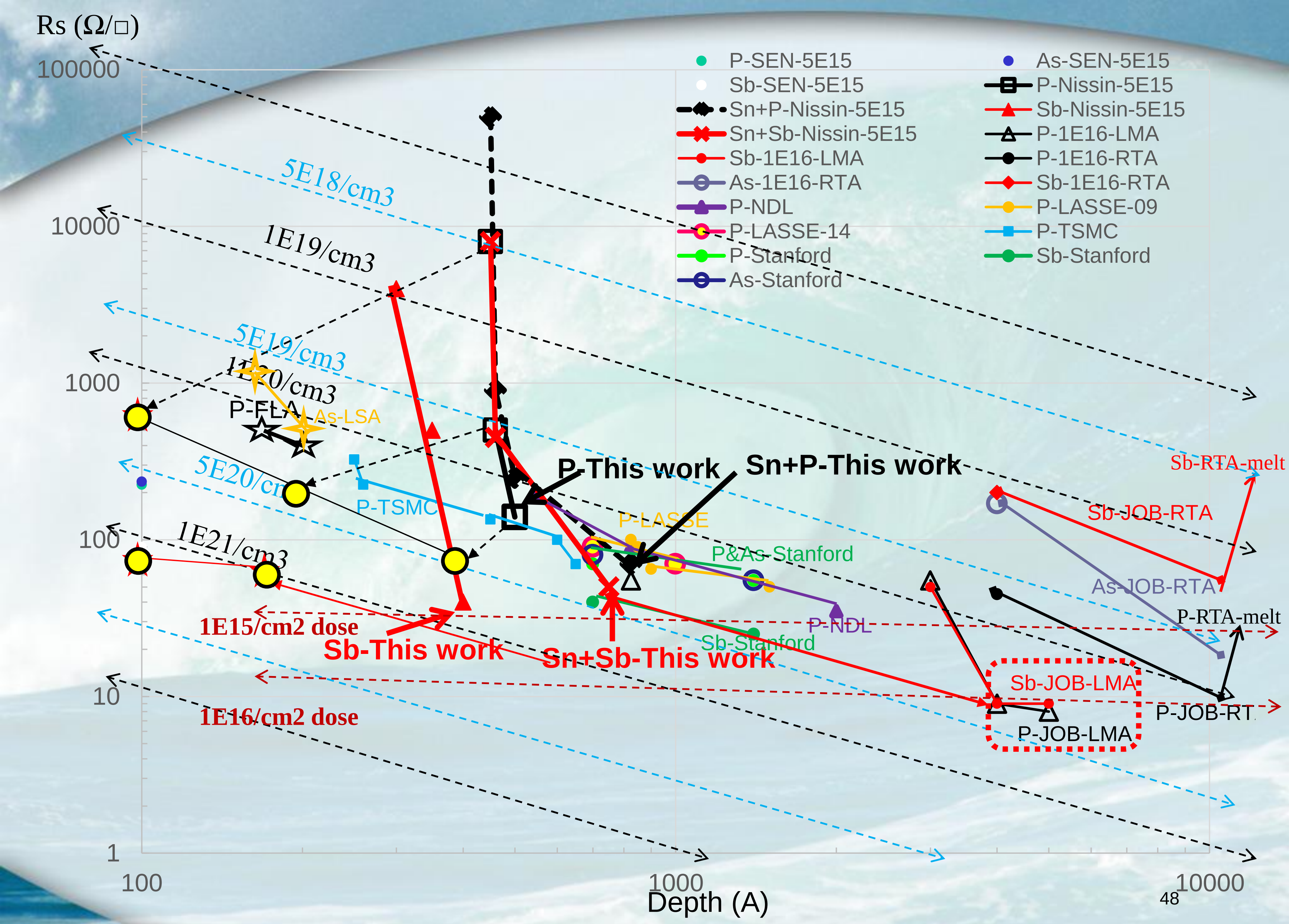

Sb w/Sn no anneal
Sb w/Sn 0.6J
Sb w/Sn 1.0J
Sb w/Sn 1.4J
1E22
1E21
1E20
1E19
1E18
1E17
Concentration (at/cm3)
0
10
20
30
40
50
60
70
80
Depth (nm)
Sb-melt solid solubility
limit in Ge!
No Anneal=389A
0.6J/cm2=420A & Melt Depth=0A
1.0J/cm2=450A & Melt
Depth=280A
1.4J/cm2=680A & Melt
Depth=550A



Sn w/Sb no anneal
Sn w/Sb 0.6J
Sn w/Sb 1.0J
Sn w/Sb 1.4J
Concentration (at/cm3)
Depth (nm)
1E22
1E21
1E20
1E19
1E18
1E17
0
10
20
30
40
50
60
70
80
Sn solid solubility limit
in Ge ~4-5E20/cm3
No Anneal=353A
0.6J/cm2=380A & Melt Depth=0A
1.0J/cm2=440A & Melt
Depth=280A
1.4J/cm2=630A & Melt
Depth=560A

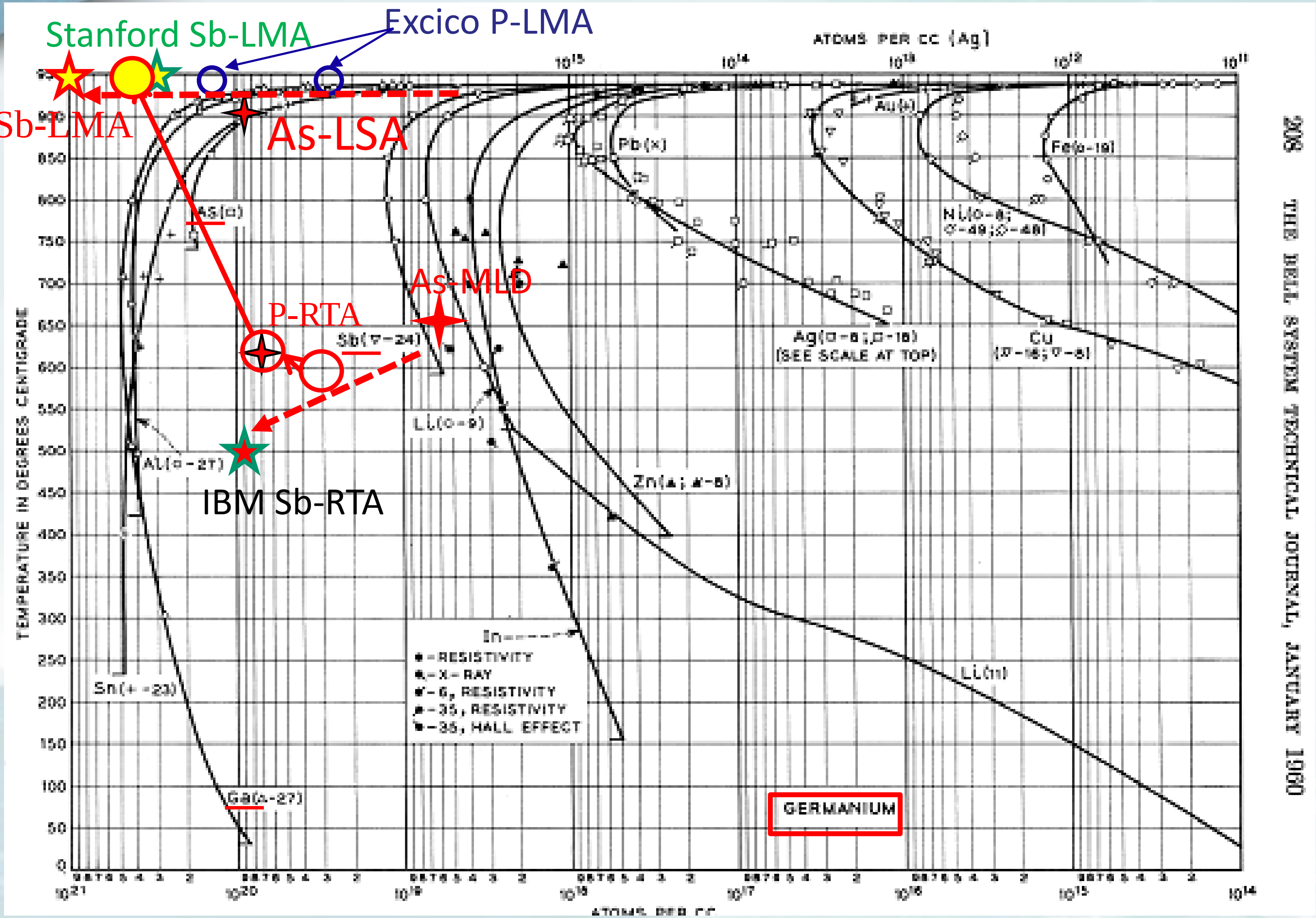


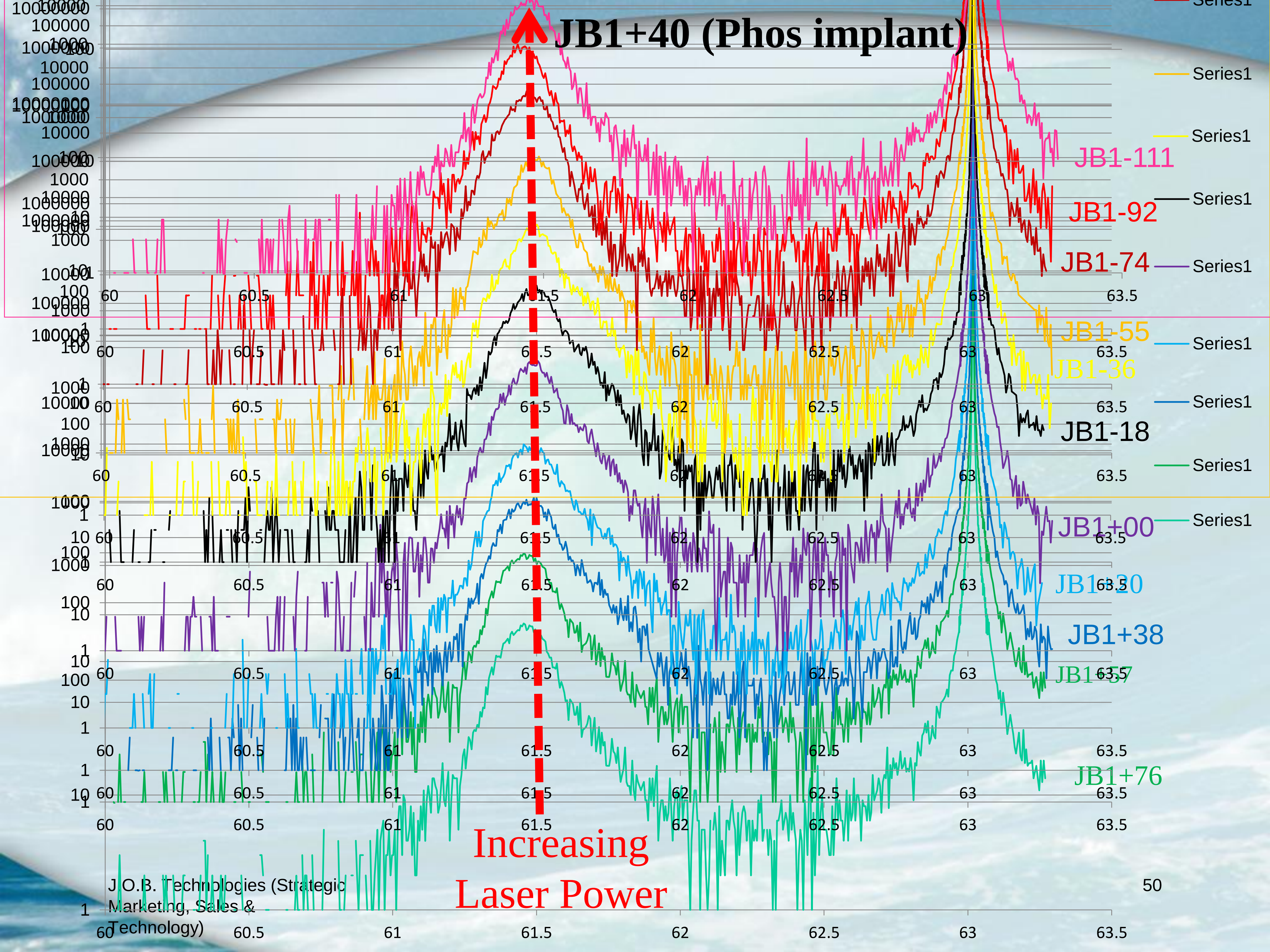
Rs (ohms/sq)
100000
10000
1000
100
10
Implant Damage Acceptor Defects?
P=5E15
P+Sn=5E15
Sb=5E15
Sb+Sn=5E15
P Sn Sheet Resistance
P Sheet Resistance
Sb Sn Sheet Resistance
Sb Sheet Resistance
Bulk Sheet Resistance
Ohm/sq.
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
P 1.6
P 1.4
P 1.1
0
100
200
300
400
500
Depth (A)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Laser Anneal Power (J/cm2)



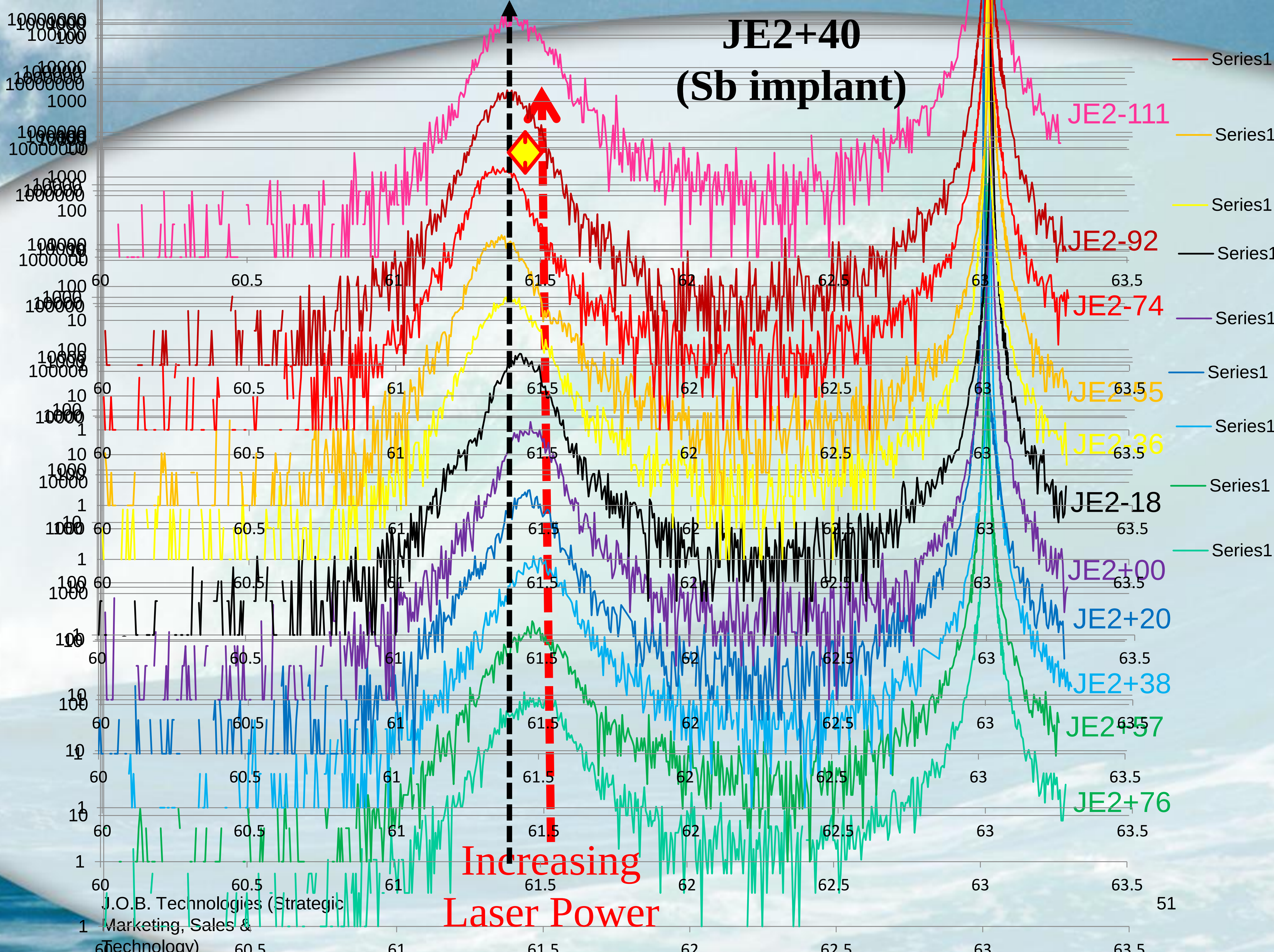
Rs (Ω/□)
100000
10000
1000
100
10
1
100
1000
10000
Depth (A)
P-SEN-5E15
As-SEN-5E15
Sb-SEN-5E15
P-Nissin-5E15
Sn+P-Nissin-5E15
Sb-Nissin-5E15
Sn+Sb-Nissin-5E15
P-1E16-LMA
Sb-1E16-LMA
P-1E16-RTA
As-1E16-RTA
Sb-1E16-RTA
P-NDL
P-LASSE-09
P-LASSE-14
P-TSMC
P-Stanford
Sb-Stanford
As-Stanford
5E18/cm3
1E19/cm3
5E19/cm3
1E20/cm3
5E20/cm3
1E21/cm3
P-FLA
As-LSA
P-TSMC
P-This work
Sn+P-This work
P-LASSE
P&As-Stanford
Sb-Stanford
P-NDL
1E15/cm2 dose
1E16/cm2 dose
Sb-This work
Sn+Sb-This work
Sb-RTA-melt
Sb-JOB-RTA
As-JOB-RTA
P-RTA-melt
Sb-JOB-LMA
P-JOB-LMA
P-JOB-RT.

Trumble, Bell Labs, 1959

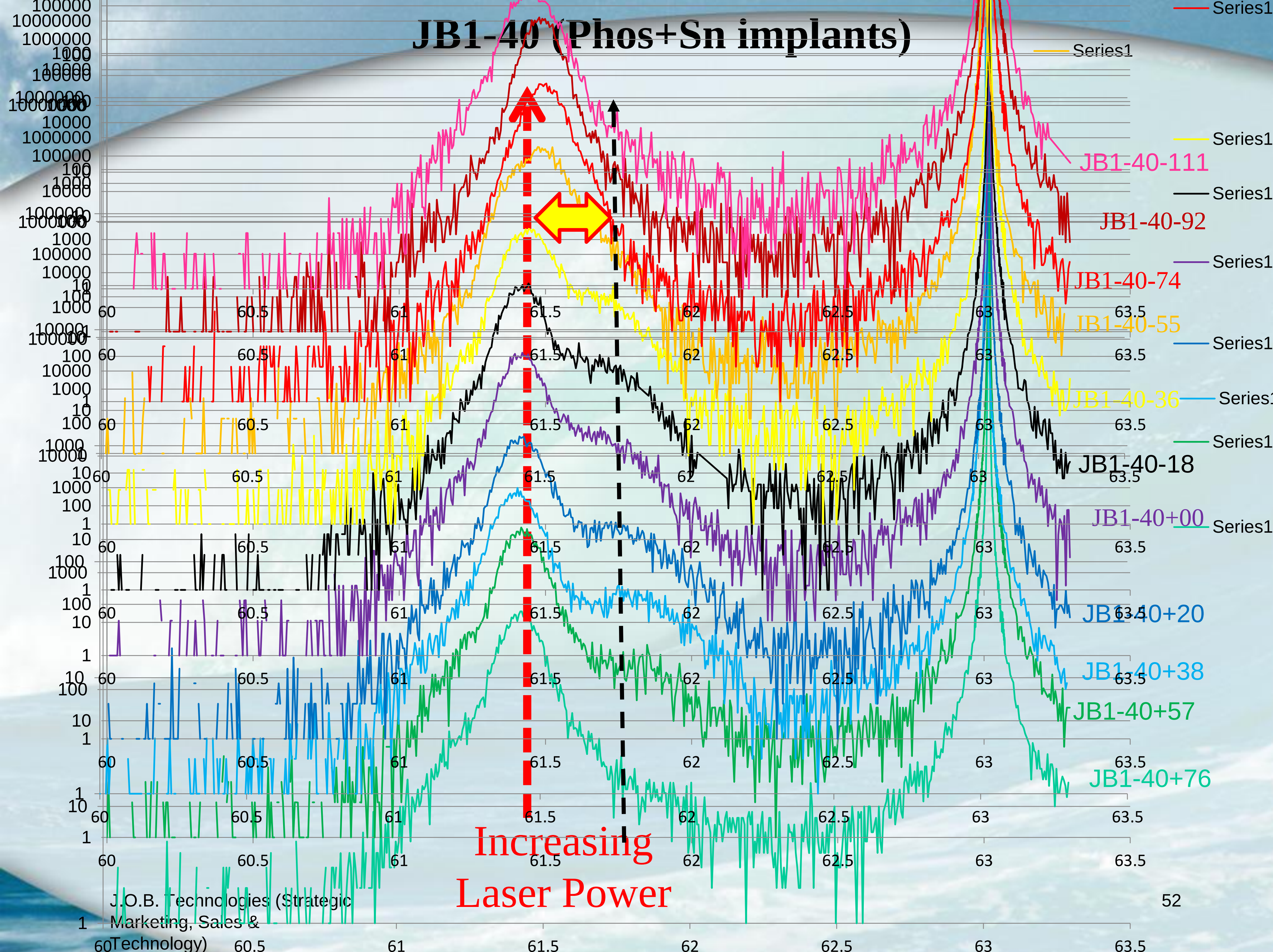


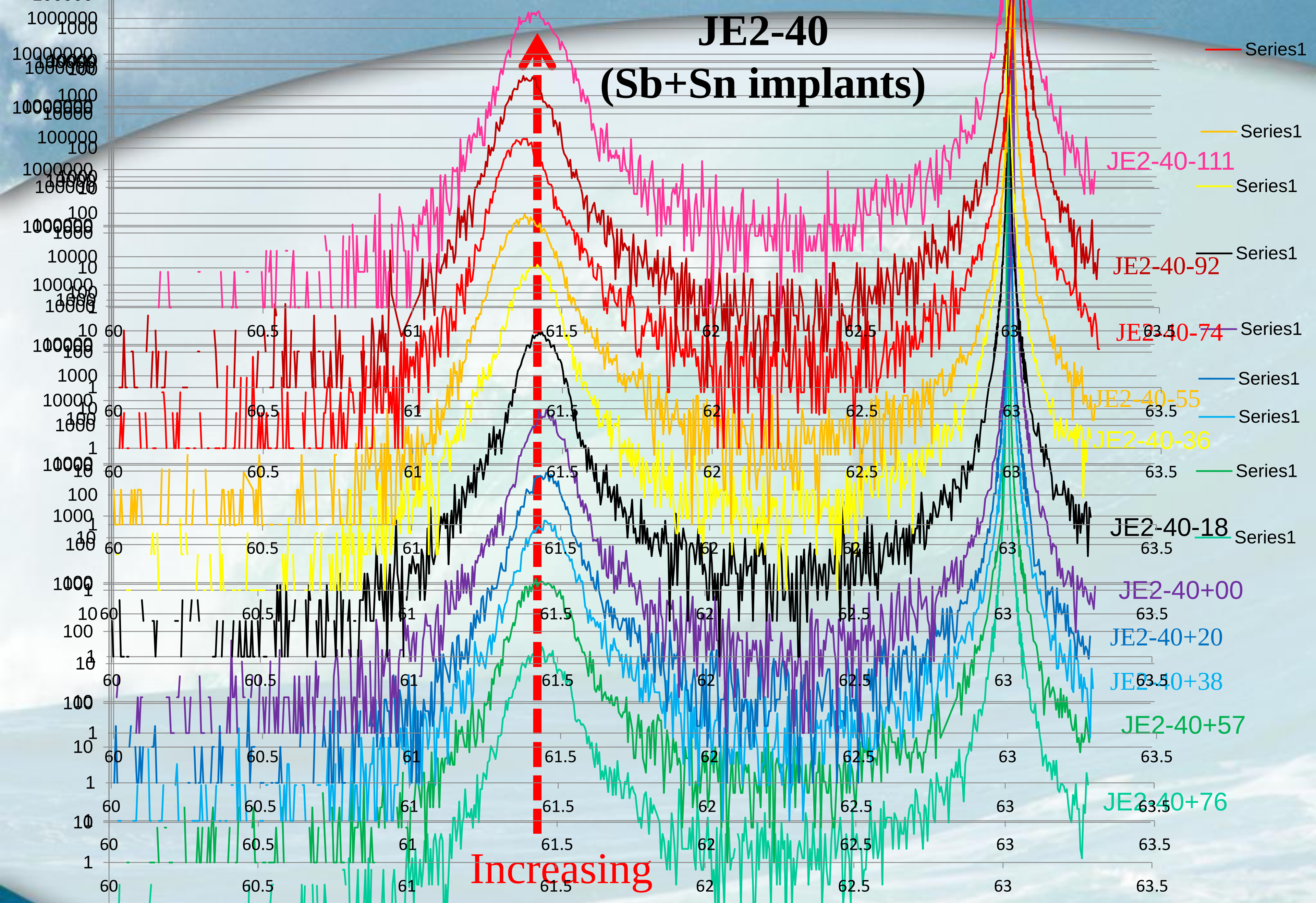

JB1+40 (Phos implant)
JB1-111
JB1-92
JB1-74
JB1-55
JB1-36
JB1-18
JB1+00
JB1+20
JB1+38
JB1+57
JB1+76
Series1
Increasing
Laser Power
60
60.5
61
61.5
62
62.5
63
63.5

JE2+40 (Sb implant)

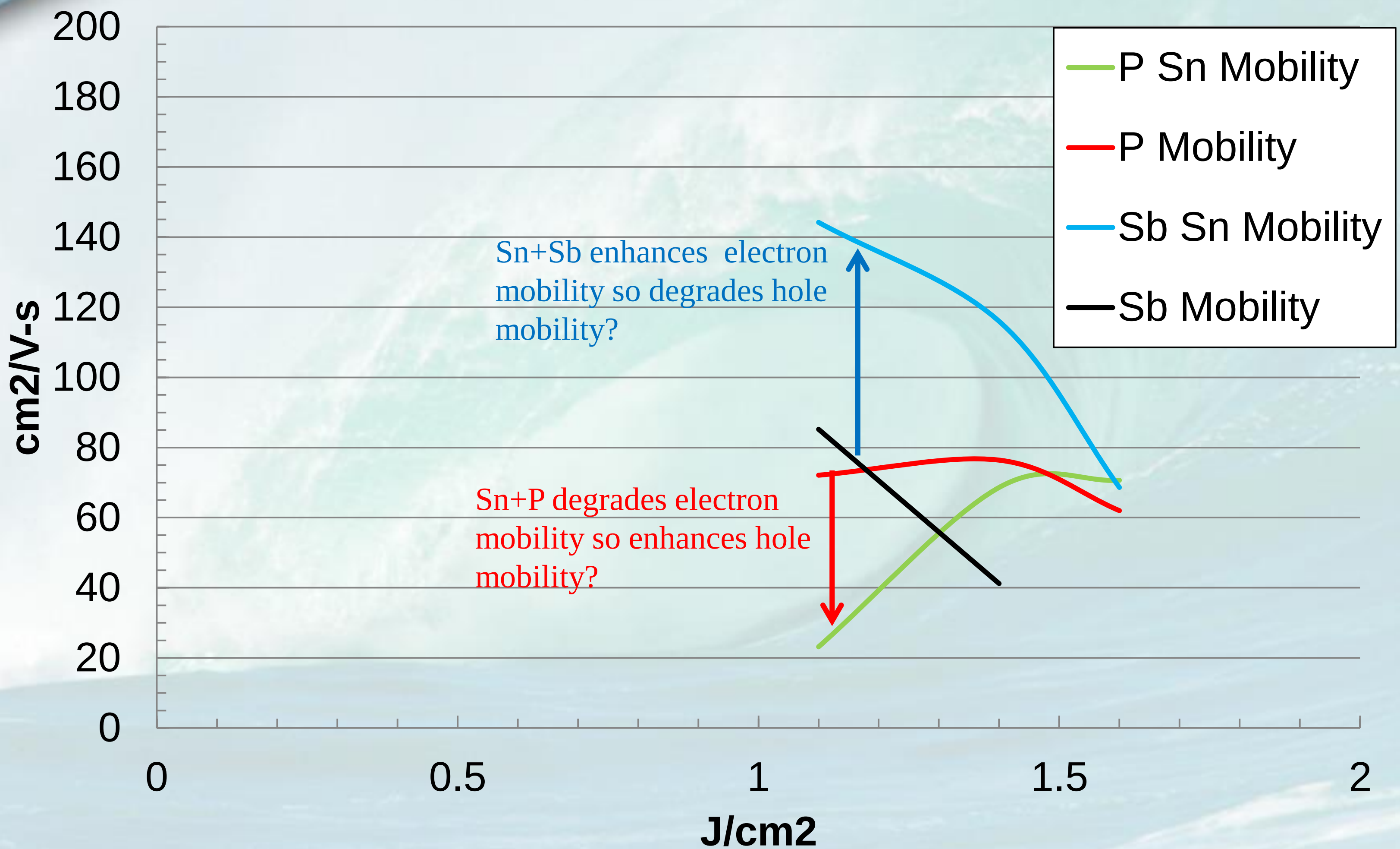


JB1-40 (Phos+Sn implants)



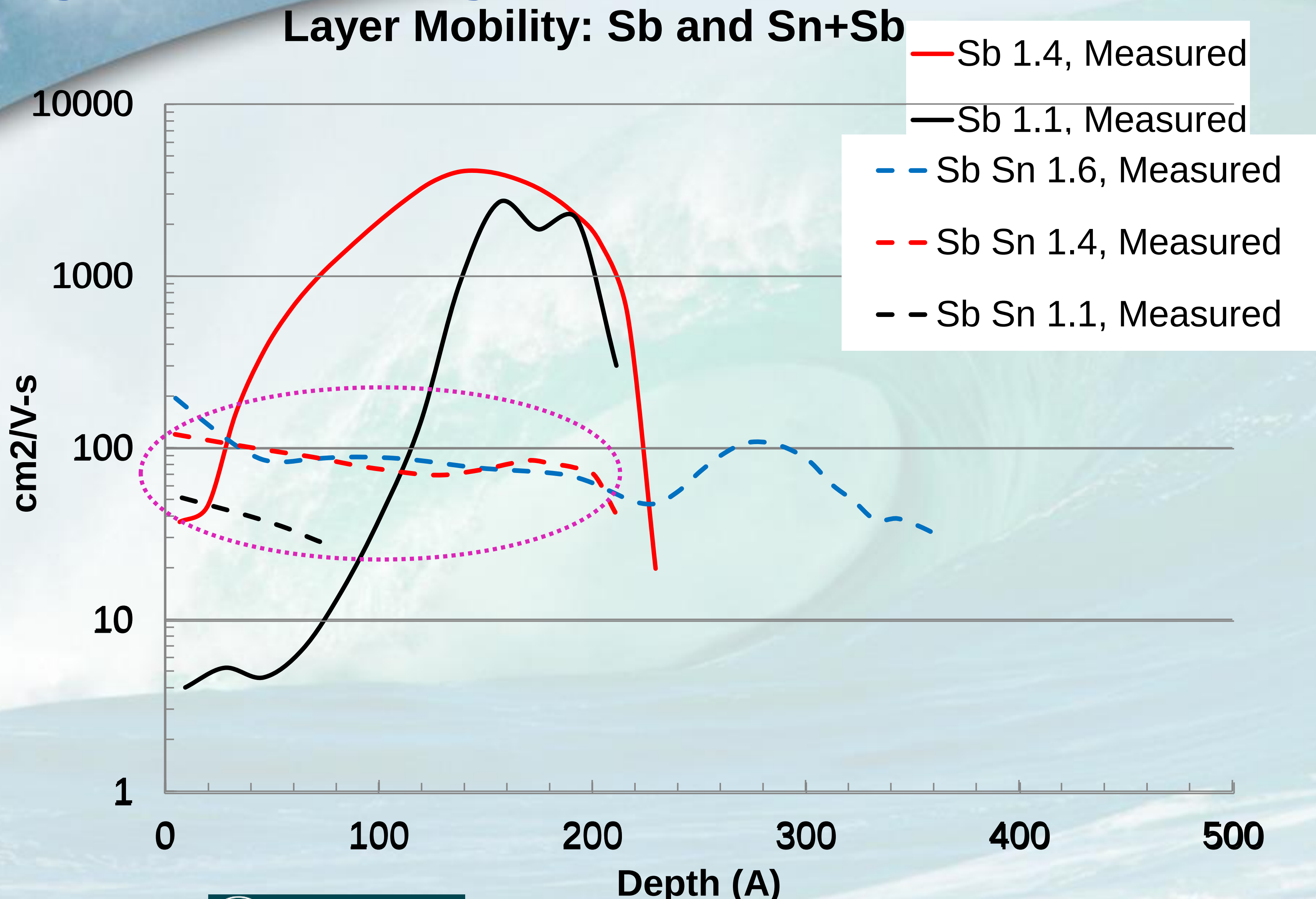

JE2-40
(Sb+Sn implants)
JE2-40-111
JE2-40-92
JE2-40-74
JE2-40-55
JE2-40-36
JE2-40-18
JE2-40+00
JE2-40+20
JE2-40+38
JE2-40+57
JE2-40+76
Series1
Increasing
Laser Power
60
60.5
61
61.5
62
62.5
63
63.5

Bulk Trends – Mobility

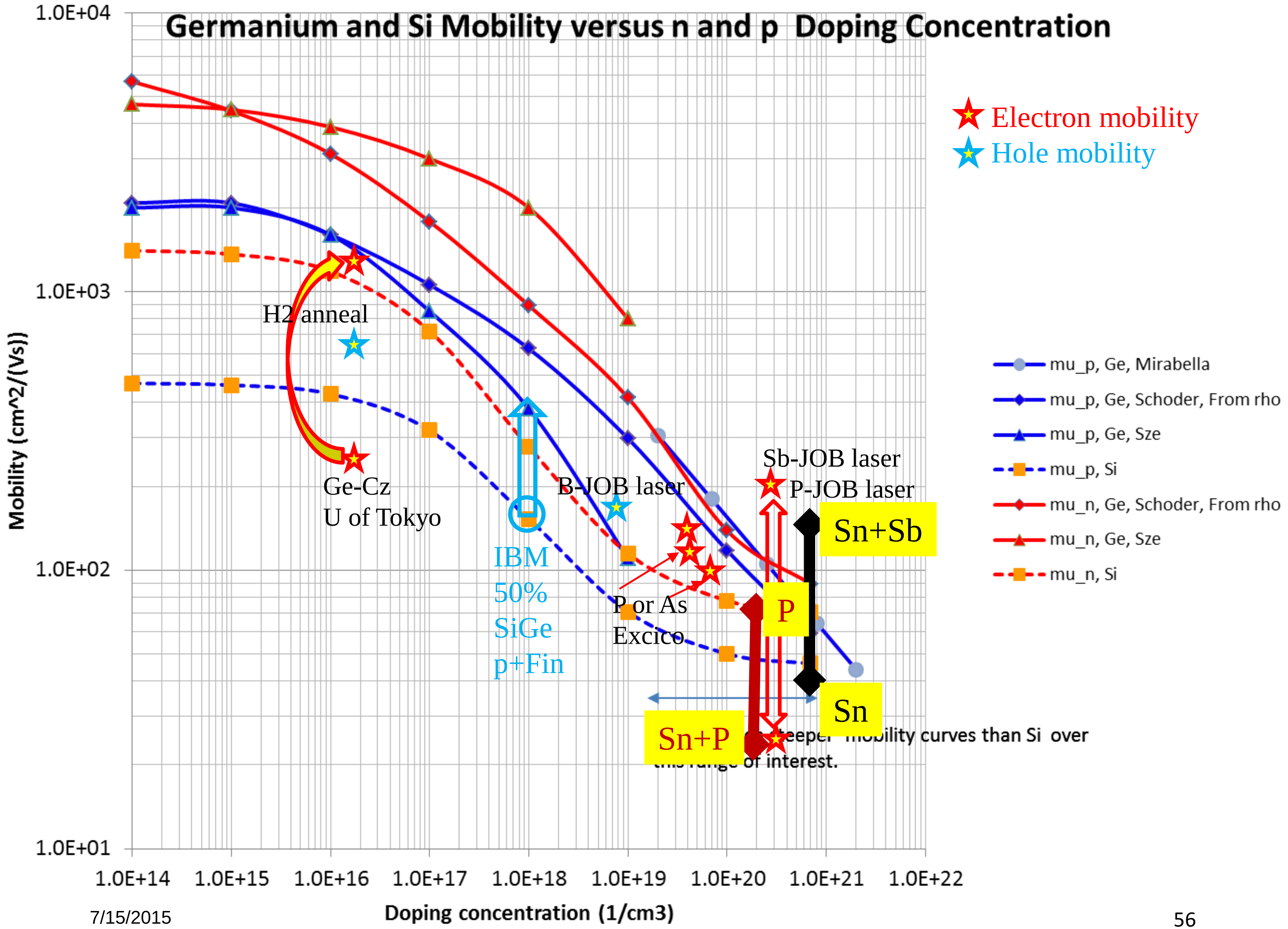


Active Layer Parametrics, Inc.
info@alpinc.net

Layer Mobility



Active Layer Parametrics, Inc.
info@alpinc.net



See large variation in reported Ge electron & hole mobilities reported in the literature!

Outline

- Introduction
- Experimentation
- Results
- Summary:
  - Laser-LPC (Liquid Phase Crystallization) critical to achieve controlled n+ USJ down to sub-10nm with high dopant activation without diffusion.
  - Best reported Ge n+ USJ activation level of 1E21/cm3 at 10nm is for Sb implant with laser-LPC
  - Best reported Ge n+ USJ activation level of 3-5E20/cm3 at 10-40nm is for P implant with laser-LPC.
  - Sn implant can be engineered to:
    - Improve Electron Mobility by 2x and uniform depth with Sb implant n+ doping
    - Is neutral to degrade Electron Mobility by 3x with P implant n+ doping.
  - Next try Sn implant for Ge p+ USJ Hole Mobility Enhancement (B, BF2, B18, In, Ga)