ADVANCED INTEGRATED PHOTONICS, INC.

Implant Dopant Activation Comparison Between Silicon and Germanium Wafers

IIT-2014

June 30, 2014

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Advanced Integrated Photonics

Honolulu, HI

AIP Facility Overview

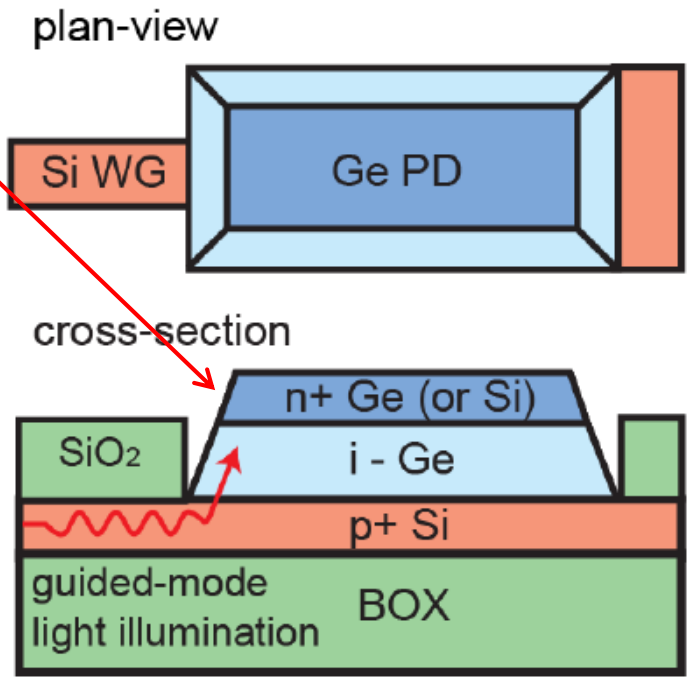
Located on the island of Oahu in the city of Kaka'ako, M3PF was established in 2004 in a joint effort combining APIC and The State of Hawaii's vision on establishing high tech capabilities in the Pacific.

The facility encompasses 10000sf^{2}of which 5000sf^2 is dedicated to class 100, 1000 and 10000 clean room space and 2000sf^2 of support equipment space that facilitates multiple support systems to maintain safety, environmental control and operations.

Capabilities include Lithography, wet chemistry, gas etch, PECVD, metal sputter deposition, metrology, Si/Glass wafer aligning, bonding and metal electro less plating.

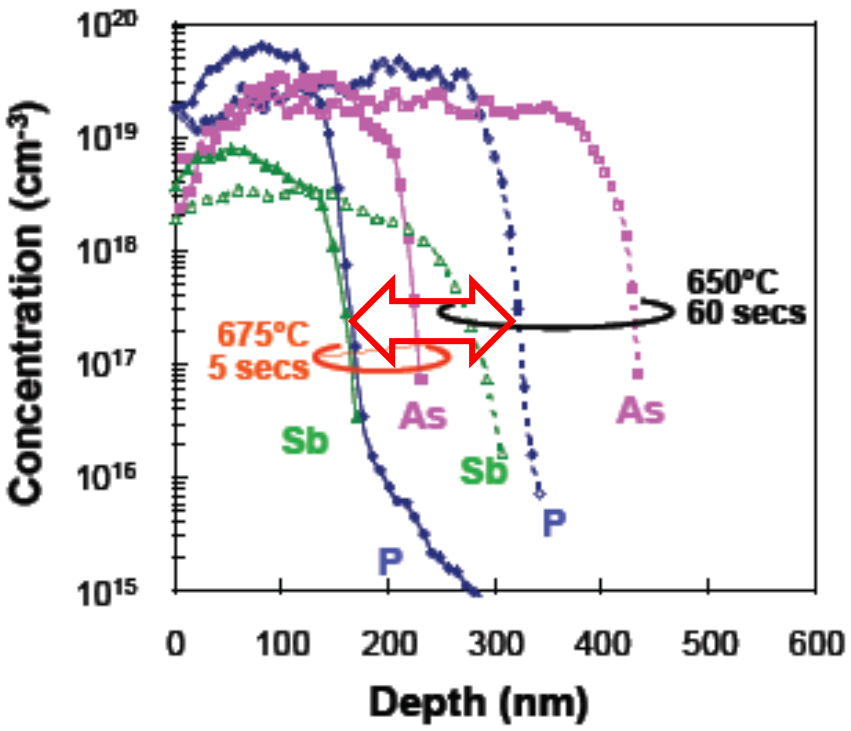
Outline

- Introduction
  - Sub-10nm node CMOS will use Ge high mobility channels for pMOS and nMOS
    - B-implant in Ge results in high dopant activation and minimal dopant diffusion
    - P, As or Sb implant in Ge results in poor dopant activation and significant n-type dopant diffusion
  - AIP Si-Photonics uses Ge-PD with n+ Ge contact
- Experimentation
- Results
- Summary/Conclusion

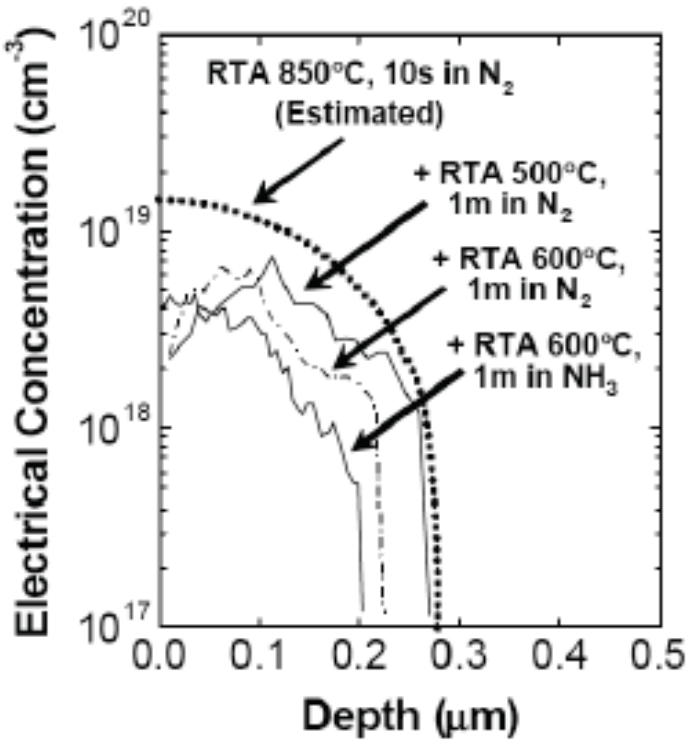


N Type Doping in Ge

Ion Implantation Doping

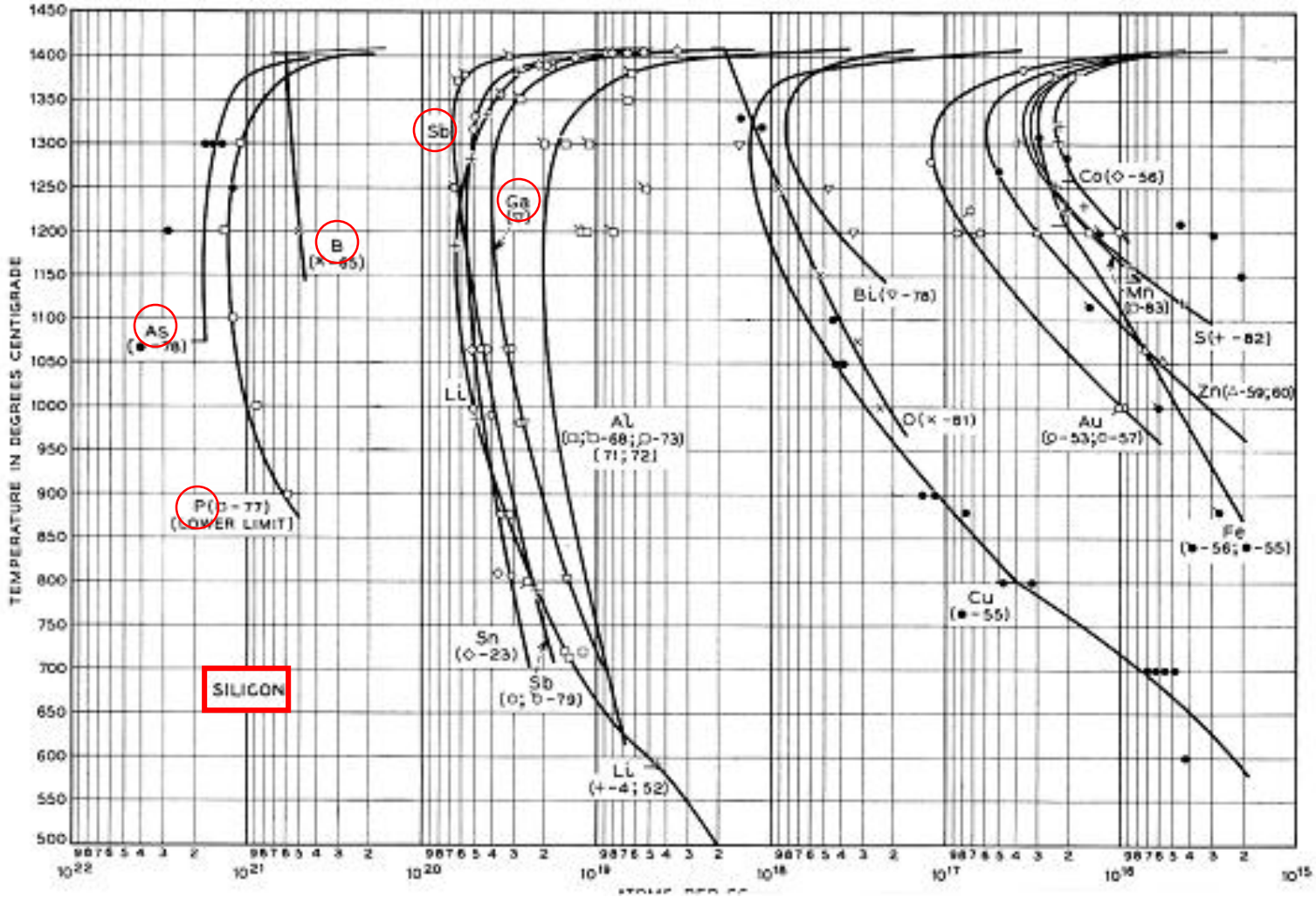


Deactivation at lower T

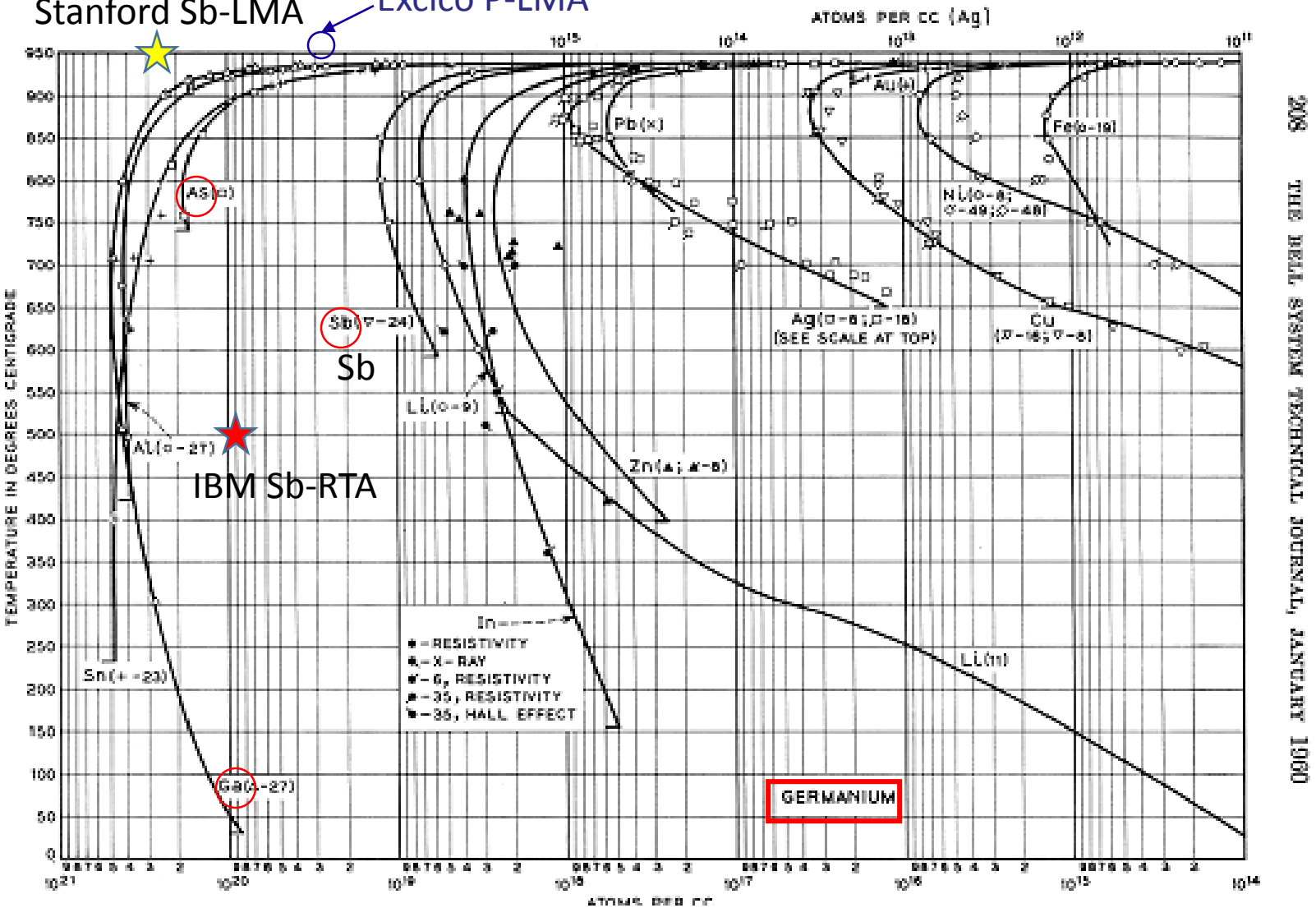


- ☹ Lower solid solubility - High S/D resistance
- ☹ High diffusivity - Shallow junctions??
- ☹ Deactivation at lower T
- ☹ Problems for NMOS

Trumble, Bell Labs, 1959



Trumble, Bell Labs, 1959



Outline

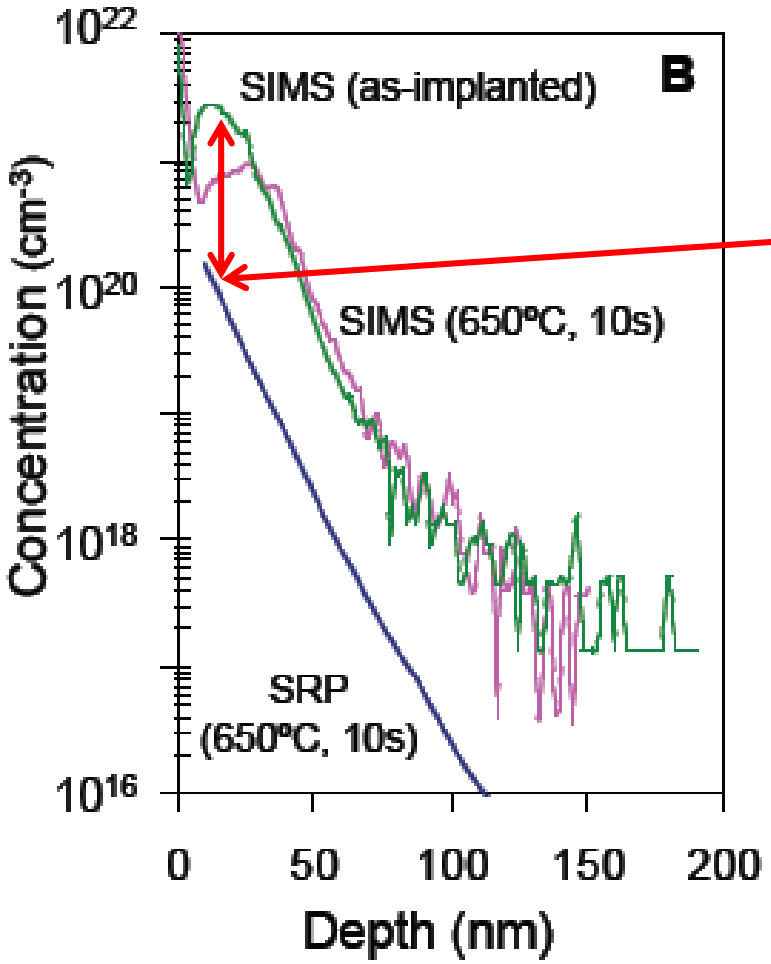
- Introduction
- Experimentation
  - 150mm wafers
    - Si-Cz P(100) & N(100)
    - Ge-Cz N(100)
    - 1um intrinsic Ge-epi on Si P(100)
    - 200nm Si-cap on Ge-epi
  - B, BF2, As, Sb, P, P+Sb, P+F, P+C implantation
  - RTA anneal (400C-1050C) and laser anneal
- Results
- Summary/Conclusion

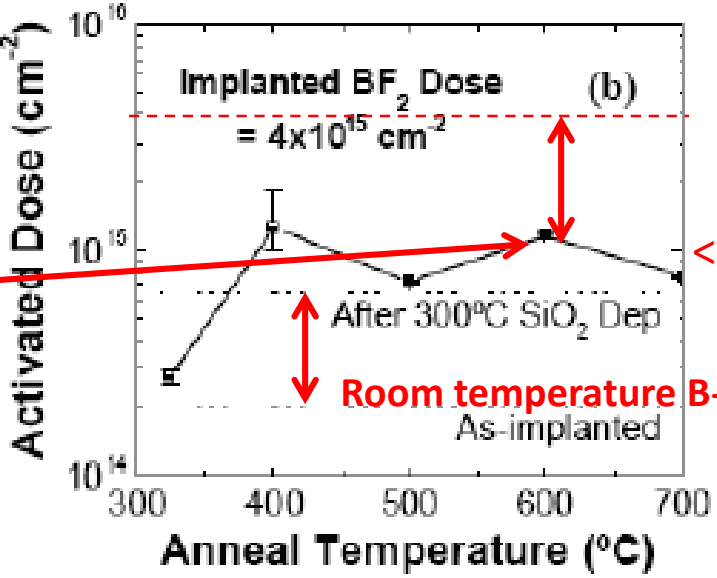
Substrates	Implant Specie	Dose (1/cm2)	Energy (keV)
Ge & Si	B	5.0E+15	30
Ge & Si	B	5.0E+14	30
Ge & Si	BF2	5.0E+14	150
1 micron Ge-epi on Si & 200 nm silicon-epi on 1 micron Ge-epi on Si & Si	P	1.0E+16	20
1 micron Ge-epi on Si & Si	P	2.0E+15	20
1 micron Ge-epi on Si & Si	As	1.0E+16	20
1 micron Ge-epi on Si & Si	Sb	1.0E+16	20
1 micron Ge-epi on Si & Si	P	1.0E+16	20
	C	2.0E+15	40
1 micron Ge-epi on Si & Si	P	2.0E+15	20
	C	2.0E+15	40
1 micron Ge-epi on Si & Si	P	1.0E+16	20
	F	2.0E+15	40
1 micron Ge-epi on Si & Si	P	2.0E+15	20
	F	2.0E+15	40
1 micron Ge-epi on Si & Si	P	1.0E+16	20
	Sb	1.0E+16	20
1 micron Ge-epi on Si & Si	P	2.0E+15	20
	Sb	1.0E+16	20

Outline

- Introduction
- Experimentation
- Results
  - Boron implant into Si & Ge
    - Rs 4PP measurements for p-type dopant activation
    - SRP carrier depth profiling
  - As, P & Sb implant into Si & Ge
    - Rs 4PP measurements for n-type dopant activation
    - SRP carrier depth profiling
    - SIMS dopant depth profiles
    - X-TEM residual implant damage
- Summary/Conclusion

P Type Doping in Ge

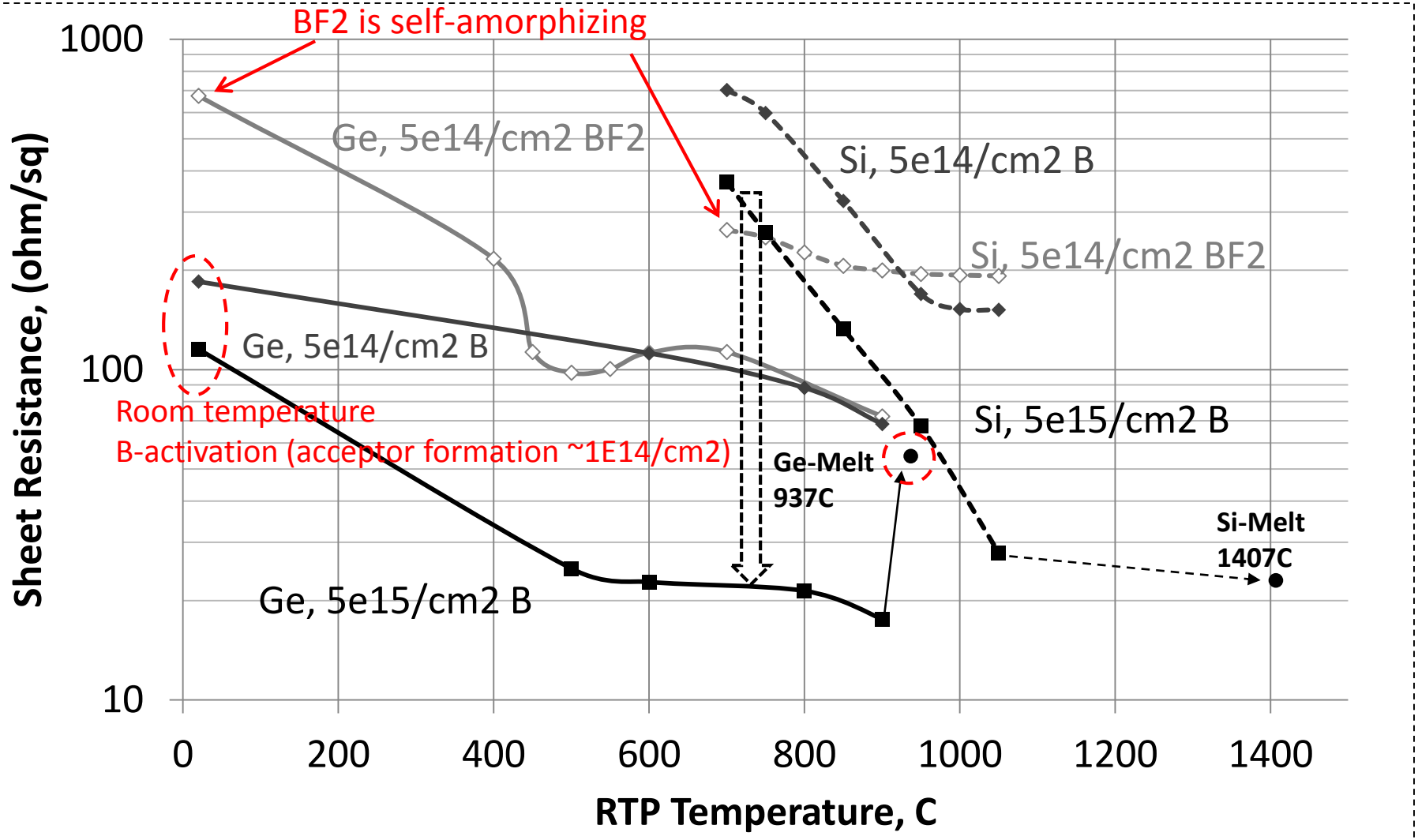




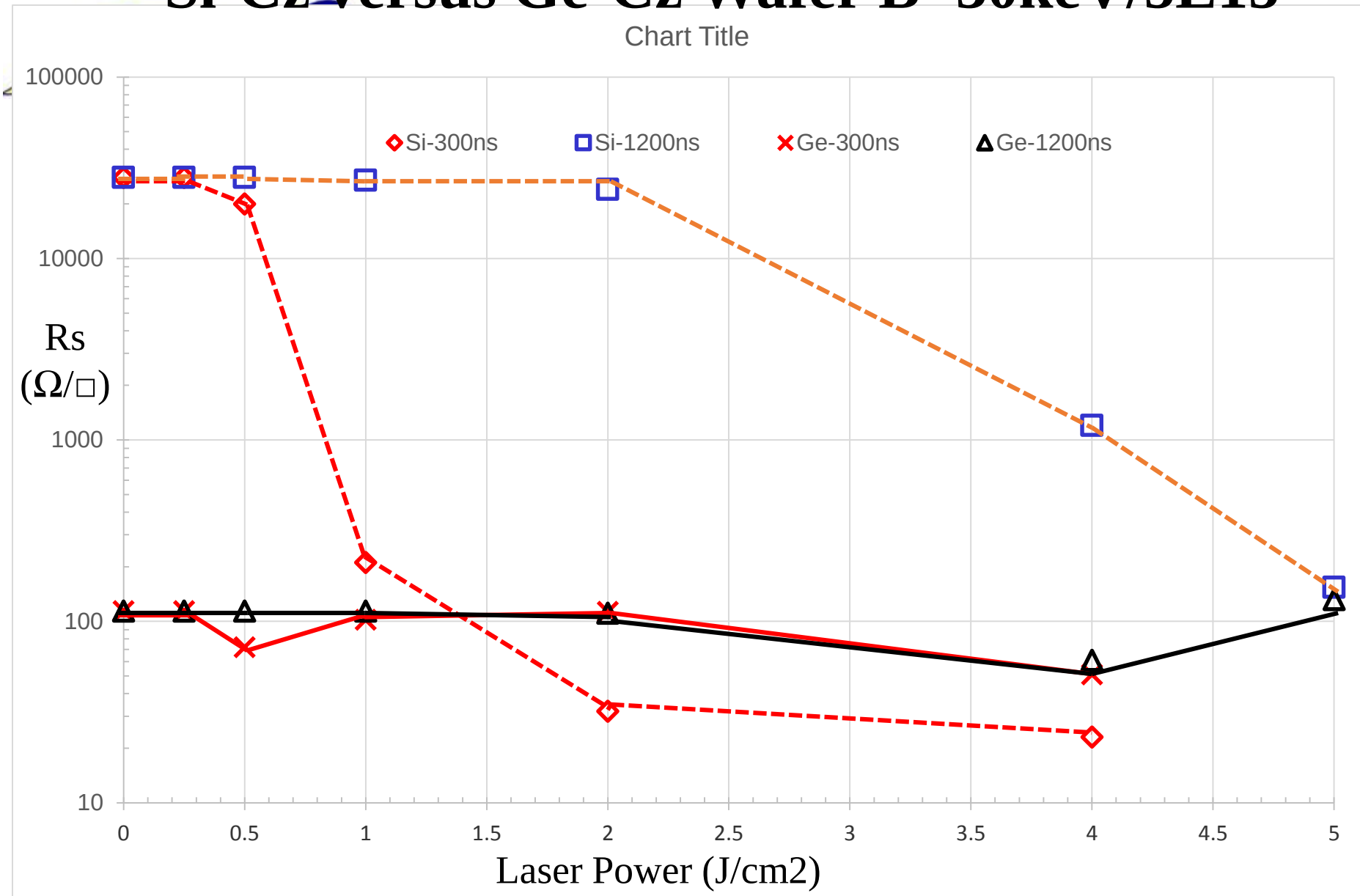
<25% active!

- ✓ P type dopant activation in Ge could be accomplished at temperatures as low as 400°C
- ✓ Solid solubility of B is very high in Ge
- ✓ Diffusion of B in Ge is very slow
- ✓ It is possible to get very shallow junctions for PMOS

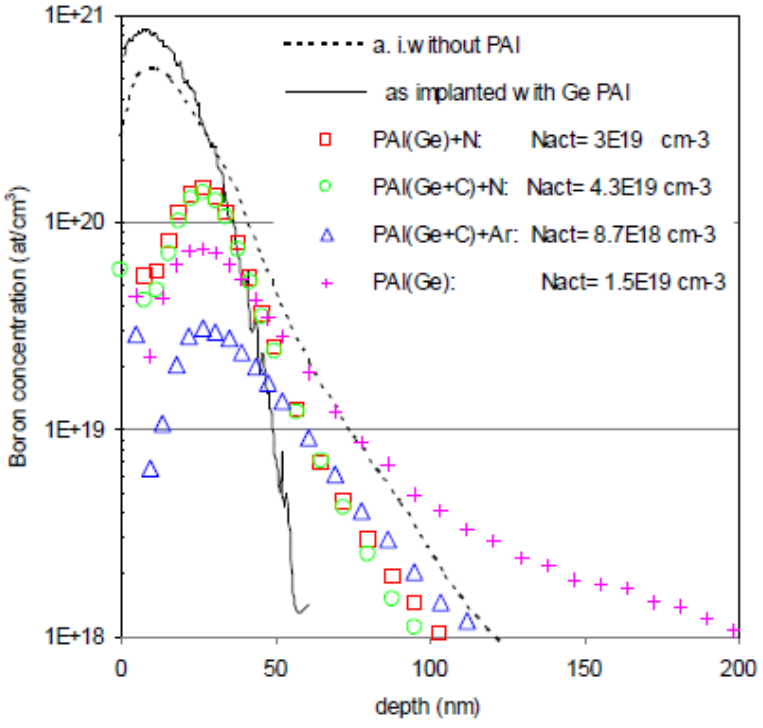
Boron Activation in Si & Ge



Si-Cz versus Ge-Cz Wafer B=30keV/5E15



BORON WITH PAI



B 4KeV $2\times10^{15}cm^{-2}$, 1.6 to 1.8 j/cm² laser annealing

- Necessary to use anneal condition to melt beyong a/c interface
- Carbon improves the N_{act}
- Argon enhances the dopant loss and reduces the N_{act}
- Nitrogen limits dopant diffusion and improves N_{act}
- max $N_{act} = 4.3\times10^{19}cm^{-3}$

⇩

PAI results are below previoulsy published results [1]

[1] A. Satta et al., Appl. Phys. Lett., 87, 172109 (2005).

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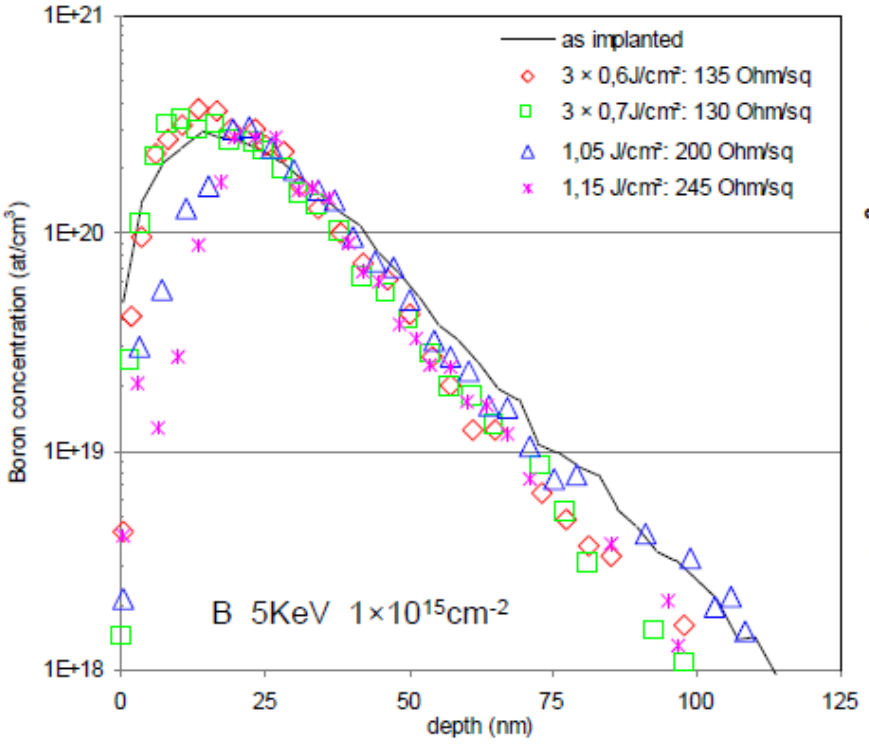
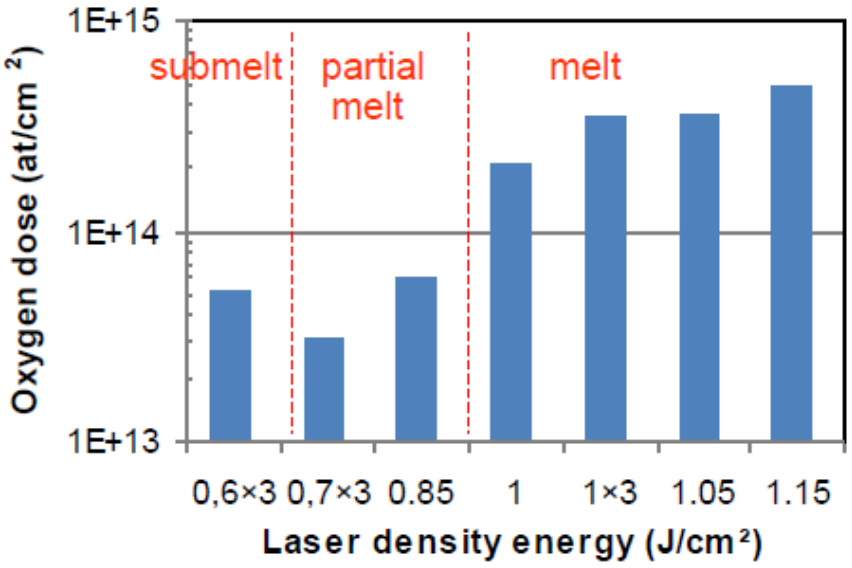
BORON WITHOUT PAI





- Submelt regime: no dopant loss, N_{act} level = 1.1×10^{20} cm^{-3}
- TRR signal: melt threshold of c-Ge = 0.95 J/cm²
- Melt regime: N_{act} decreases and dopant loss increases
- Increasing presence of Oxygen in the bulk with laser energy in melt regime

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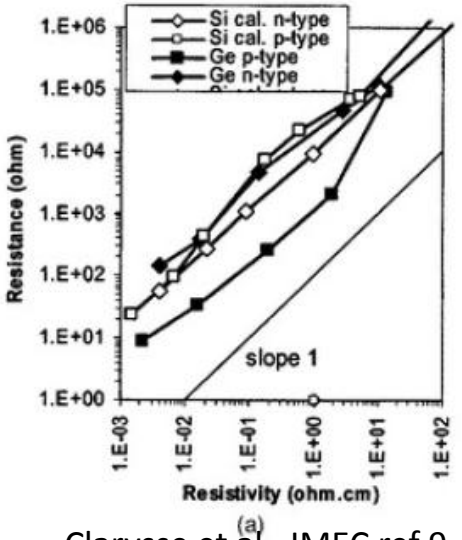
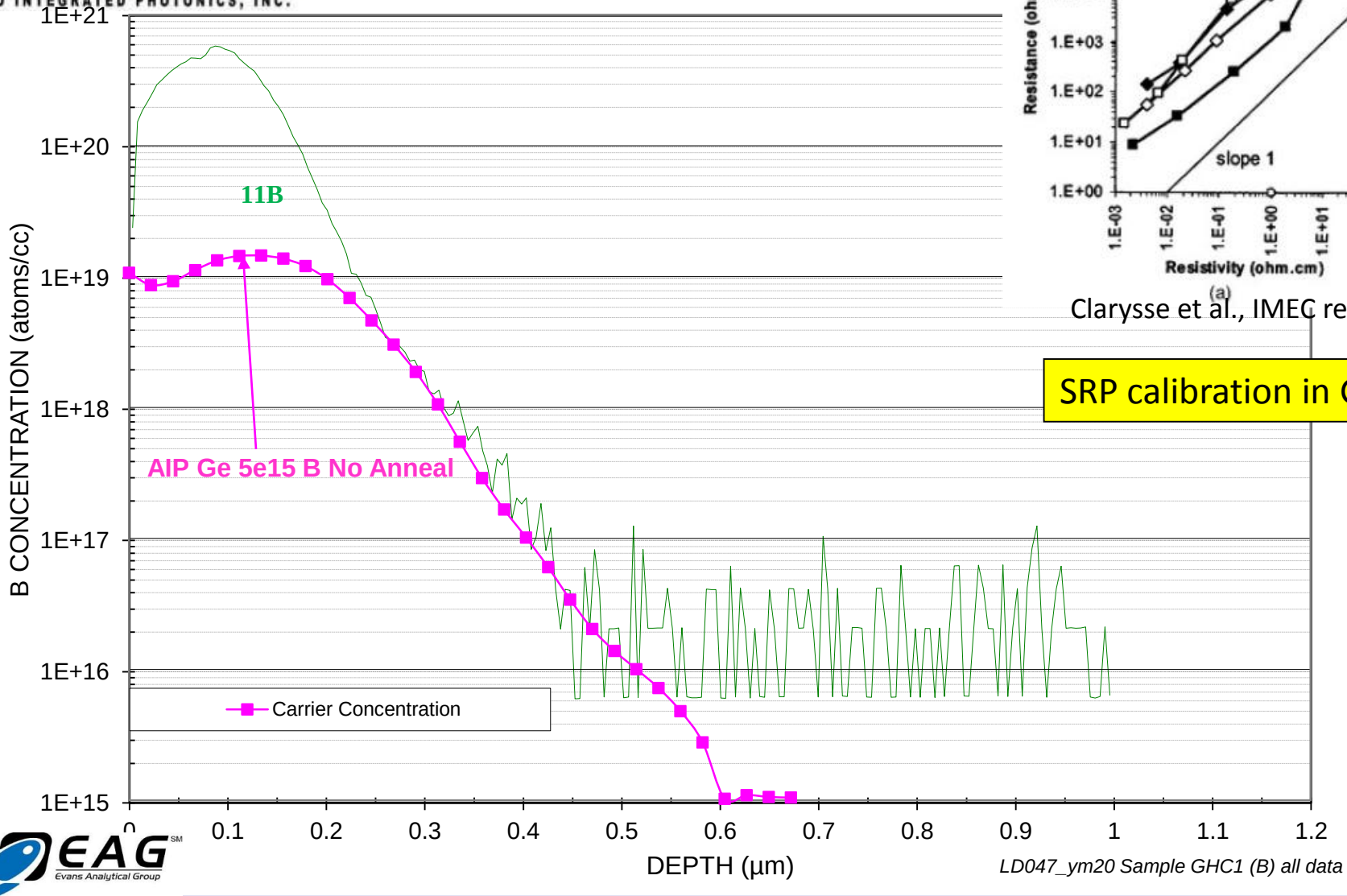


Clarysse et al., IMEC ref 9

SRP calibration in Ge



EAG SM Evans Analytical Group

LD047_ym20 Sample GHC1 (B) all data

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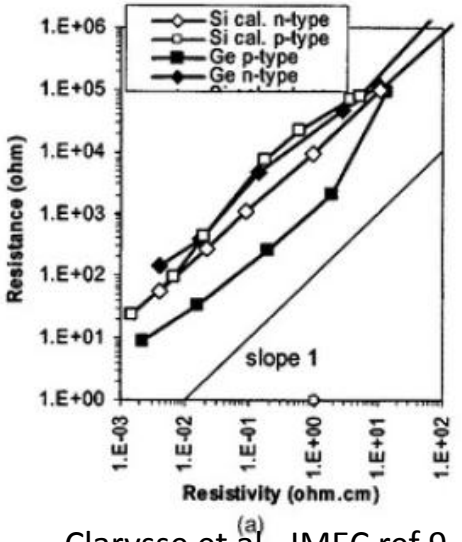


(a)

Clarysse et al., IMEC ref 9

AIP Ge 5e15 B LMA 0.5J

AIP Ge 5e15 B RTA 900C

11B

AIP Ge 5e15 B RTA 600C

B-dose loss with laser

AIP Ge 5e15 B LMA 2J

SRP calibration in Ge

AIP Ge 5e15 B No Anneal

Carrier Concentration

B CONCENTRATION (atoms/cc)

1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2

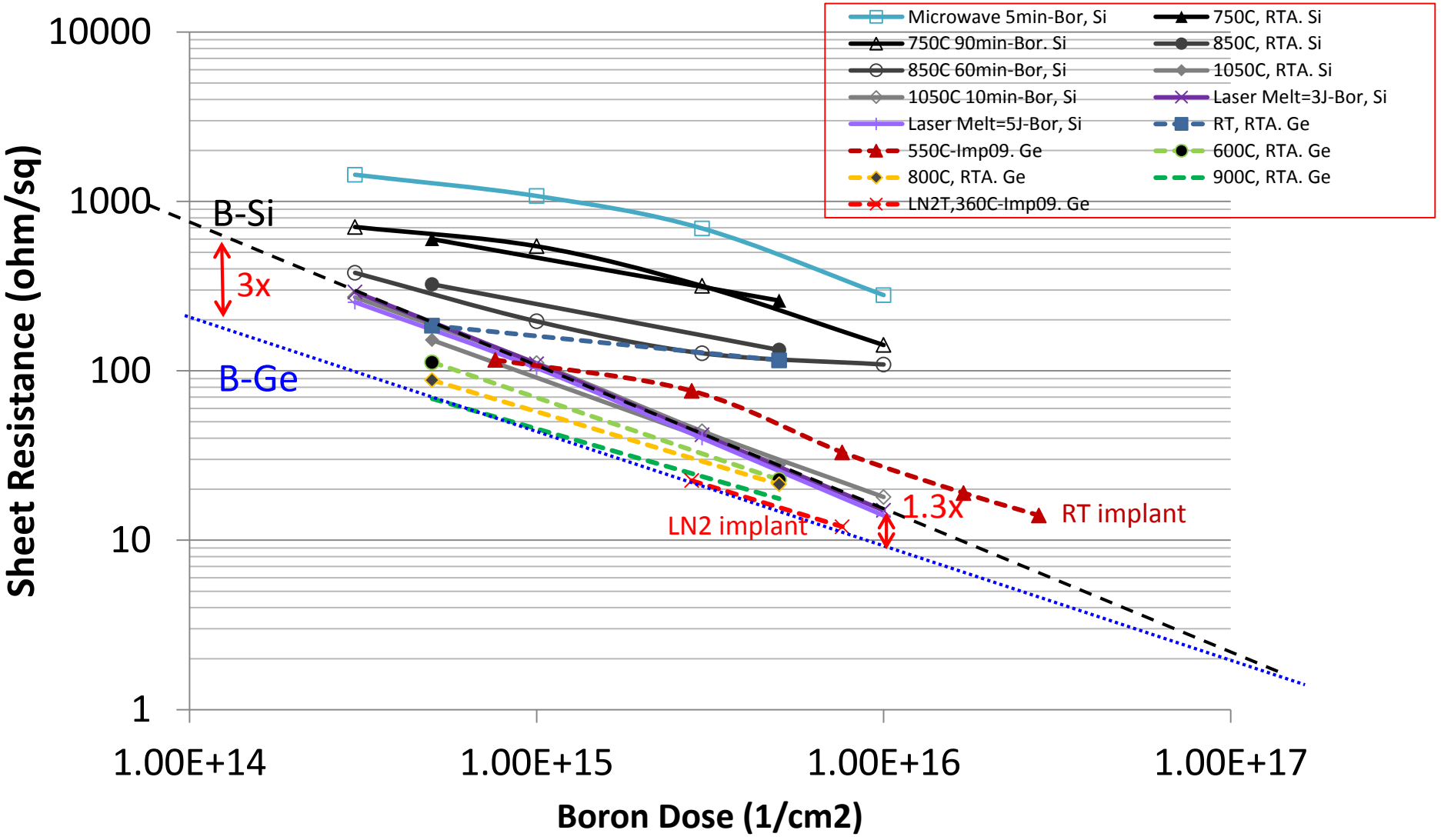
DEPTH (µm)

EAG Evans Analytical Group

LD047_ym20 Sample GHC1 (B) all data

Borland et al. (ref #8) & Impellizzeri et al. (ref#7)

B-Implant Results



JOURNAL OF APPLIED PHYSICS 105, 063533 (2009)

B activation and clustering in ion-implanted Ge

G. Impellizzeri,[a] S. Mirabella, E. Bruno, A. M. Piro, and M. G. Grimaldi
MATIS CNR-INFM and Dipartimento di Fisica e Astronomia, Università di Catania, Via S. Sofia 64, I-95123 Catania, Italy

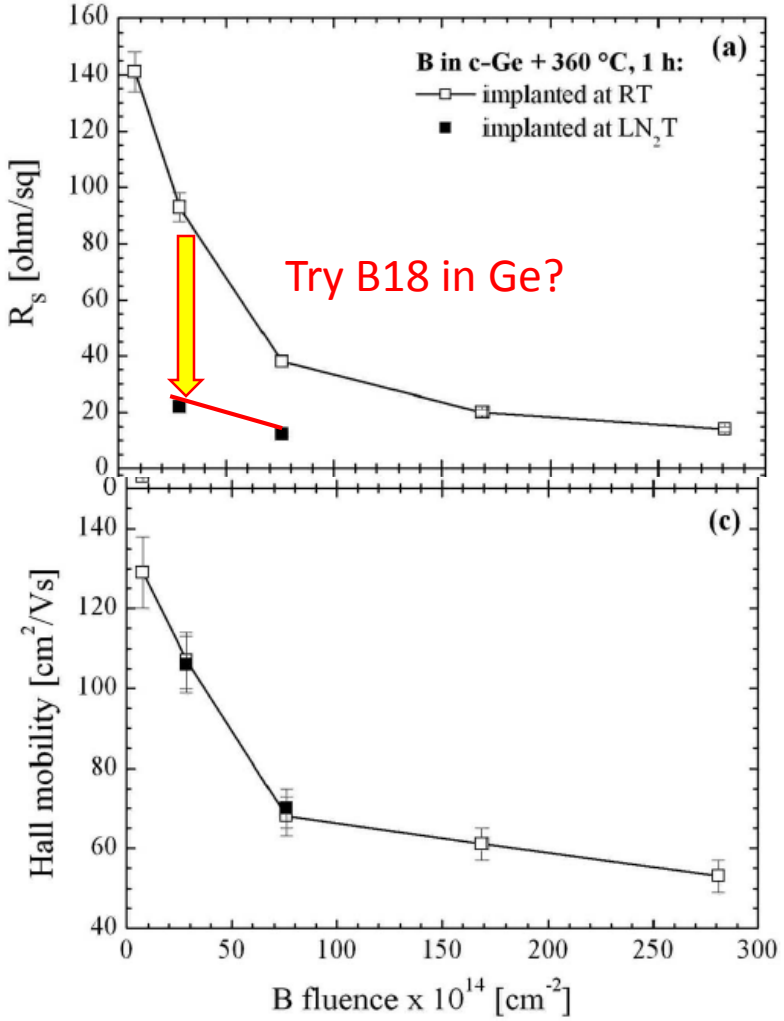


FIG. 3. (a) Sheet resistance (R_S), (b) carrier Hall fluence, and (c) Hall mobility vs B fluence (measured by NRA) for B implanted in c-Ge at RT (open squares) or LN_2T (closed squares) and annealed at 360 °C for 1 h.

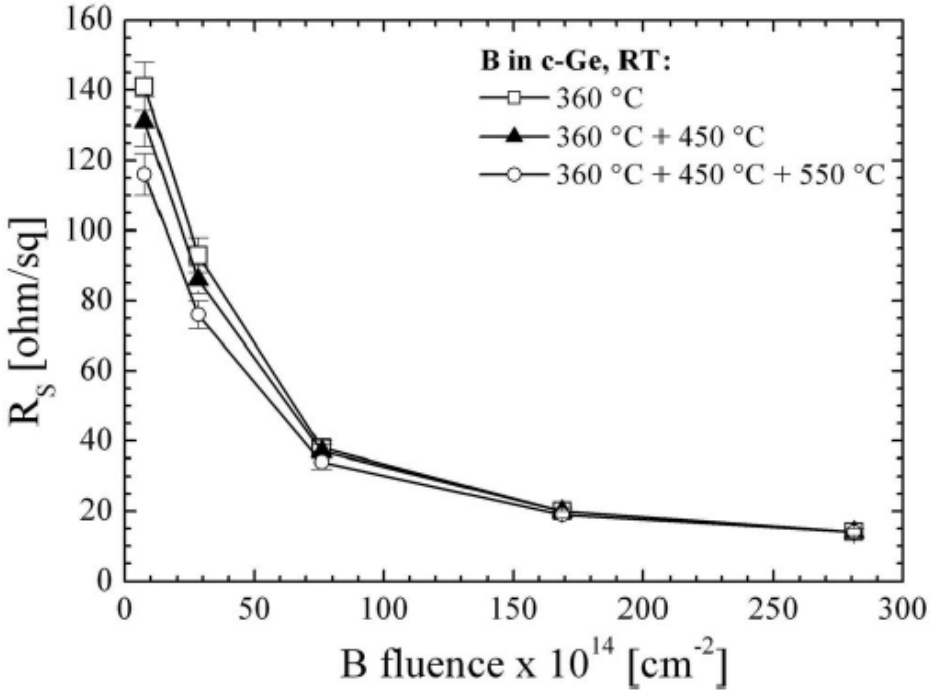


FIG. 4. Sheet resistance (R_S) vs B fluence (measured by NRA) for B implanted in c-Ge at RT and annealed at 360 °C for 1 h (open squares), 360 °C for 1 h plus 450 °C for 1 h (closed triangles) or at 360 °C for 1 h plus 450 °C for 1 h plus 550 °C for 1 h (open circles).

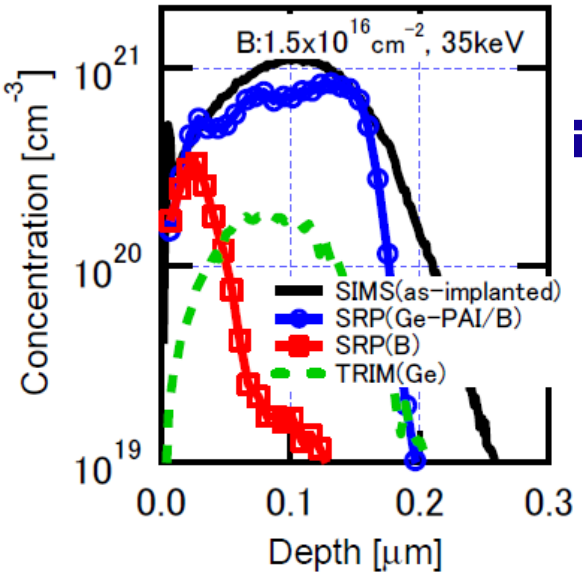


Fig. 6 SIMS/SRP profiles for B and Ge-PAI/B implanted

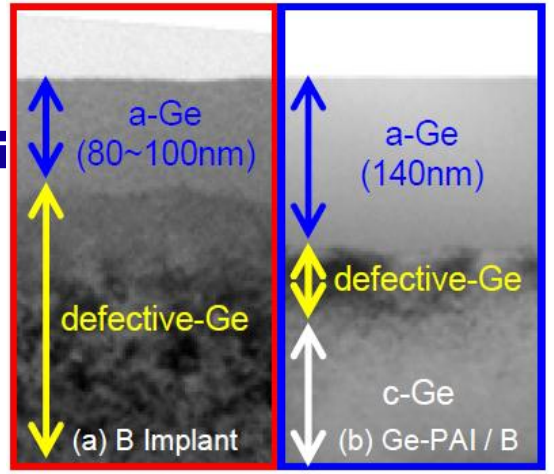


Fig. 7 TEM images of B implanted samples (a) w/o Ge-PAI and (b) with Ge-PAI before anneal. B activation is governed by amophization status before anneal.

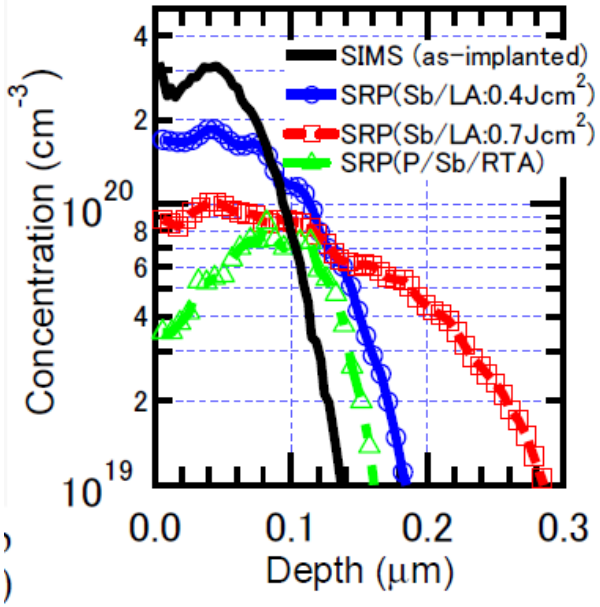


Fig. 9 SIMS/SRP profiles for Sb and P/Sb implanted samples before/after anneal.

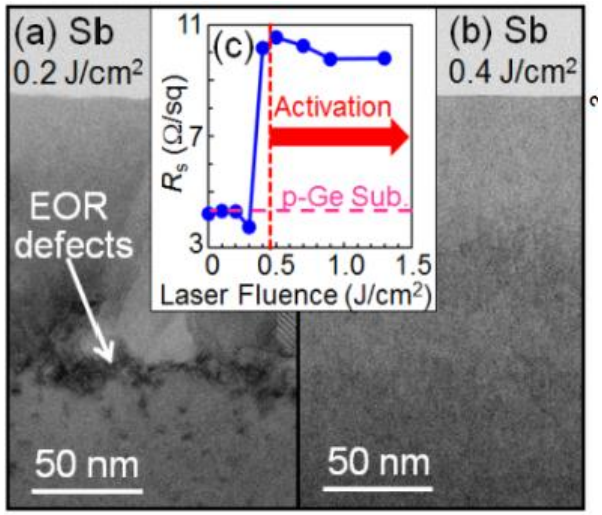
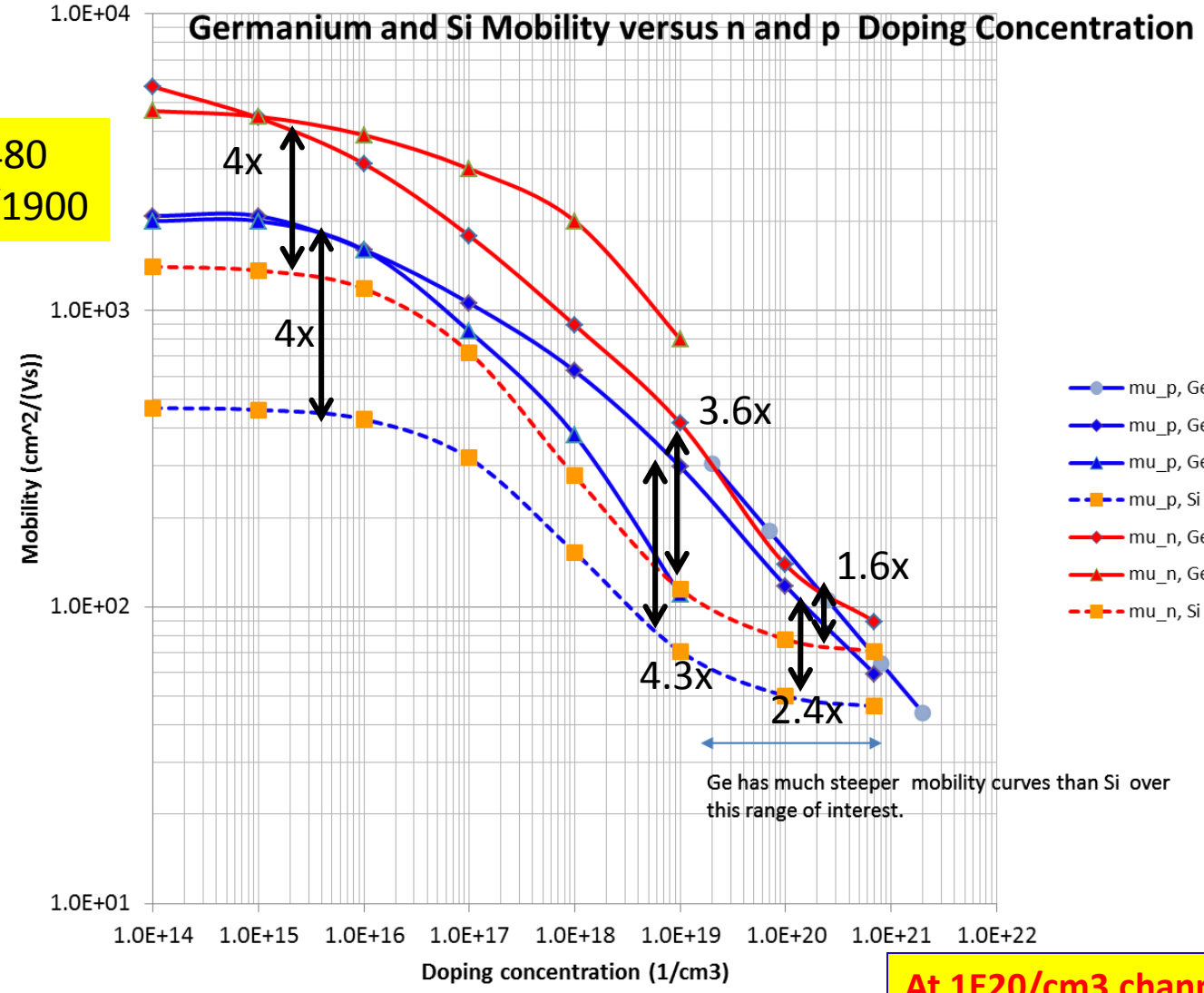


Fig. 8 TEM images of Sb implanted samples after LA at (a) 0.2J/cm^2 and (b) 0.4J/cm^2. (c) Laser fluence dependent sheet resistance (R_s).

Si=1390/480
Ge=3900/1900



At 1E20/cm3 channel doping level Ge mobility only 2x of Si for electron and hole!

Oh & Campell ref 10 on Ge Thermal Surface Loss

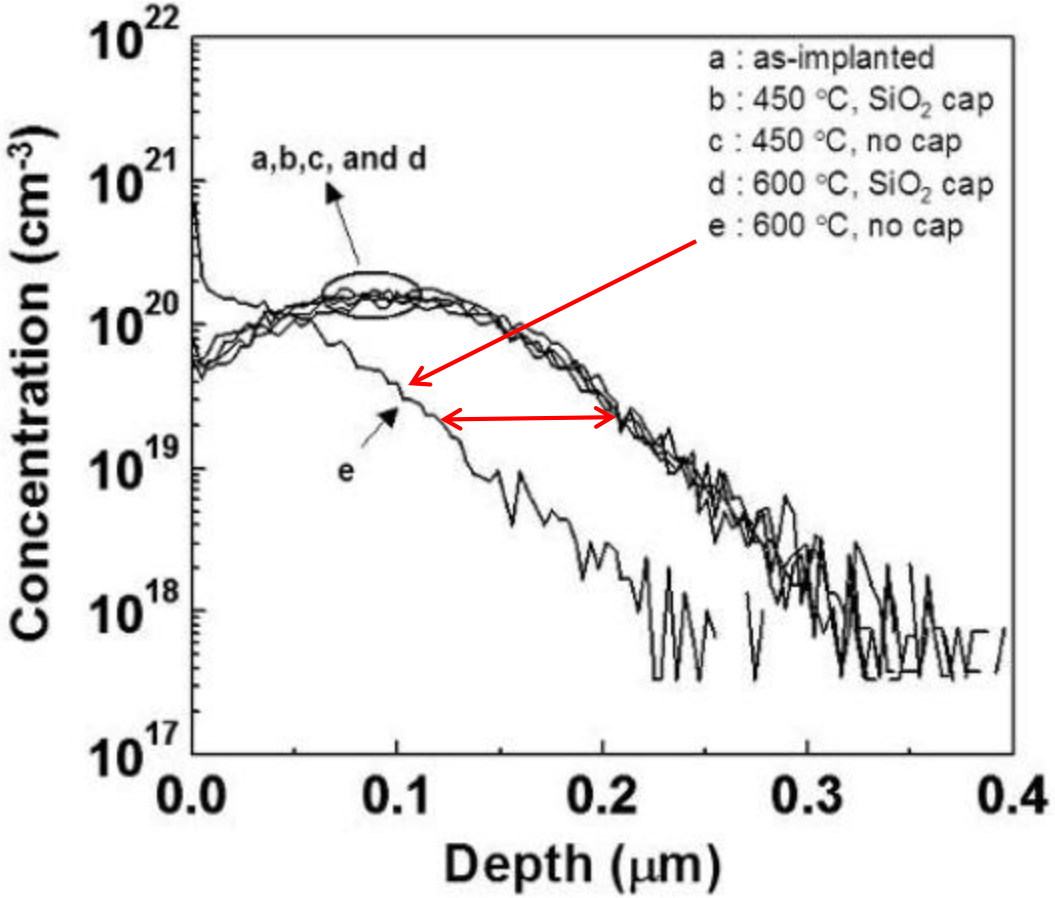
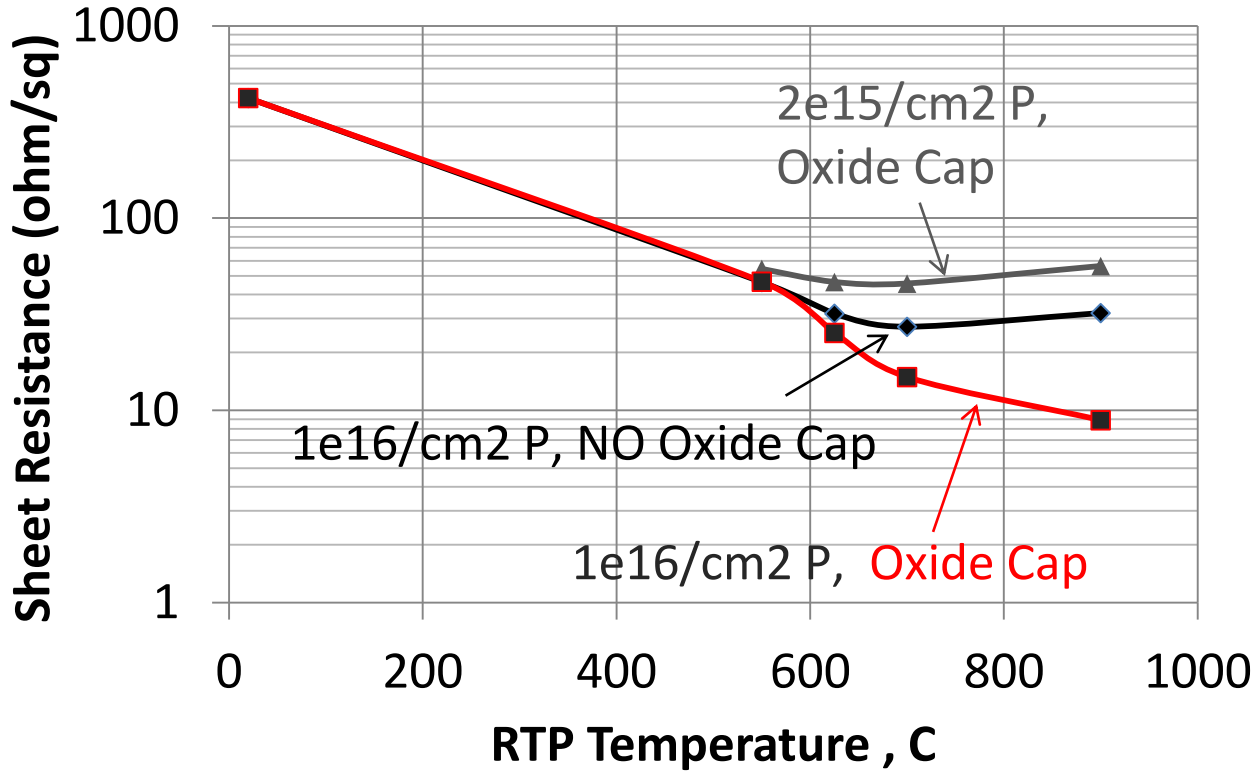
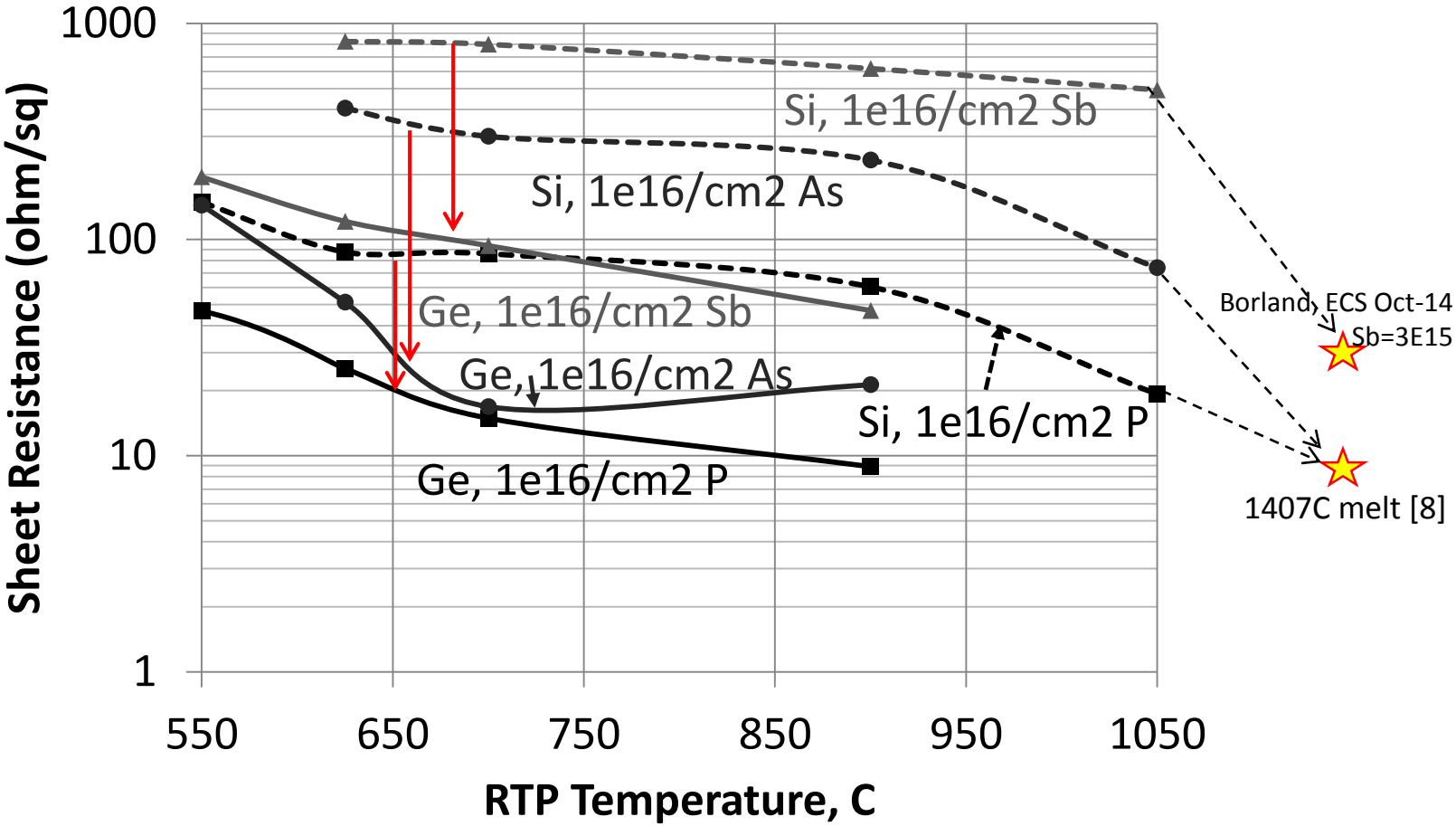


Fig. 4. SIMS profiles of ion-implanted boron in the Ge wafer with/without an SiO_2 cap layer as a function of temperature.

Phosphorus Implant into Ge-epi

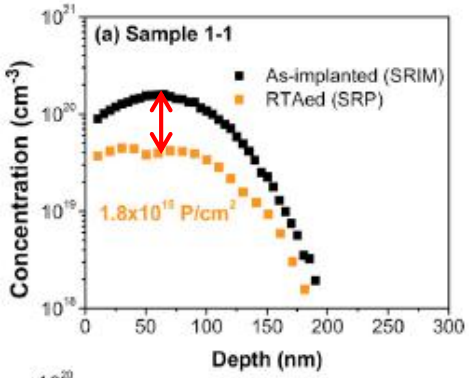


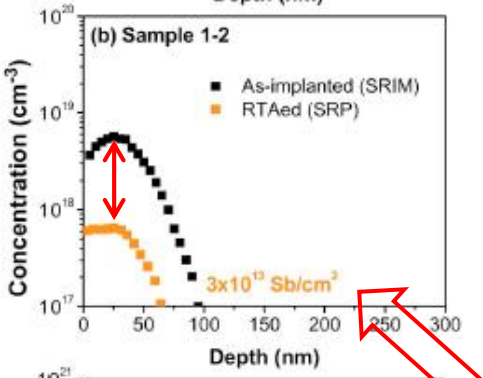
N-type Implants into Ge & Si

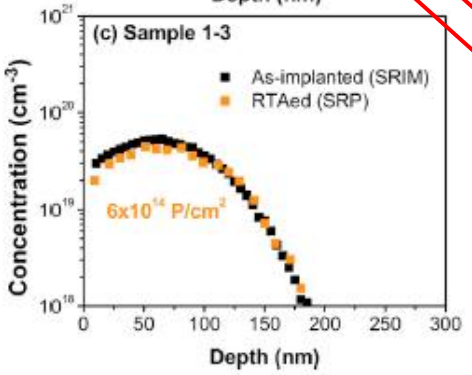


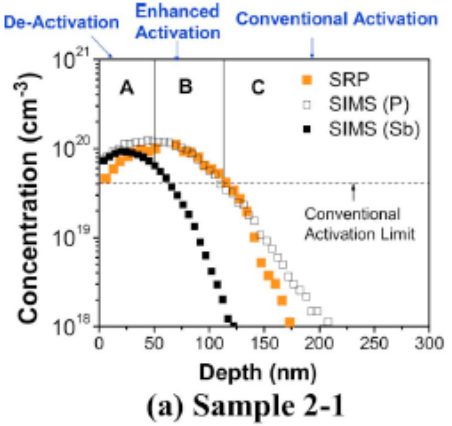
Kim, IBM ref 2: P+Sb Co-Implant

RTA=500C 10sec and 60sec

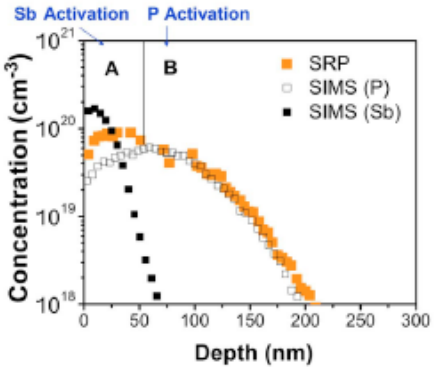




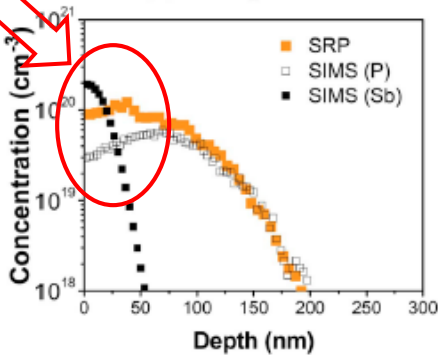




(a) Sample 2-1

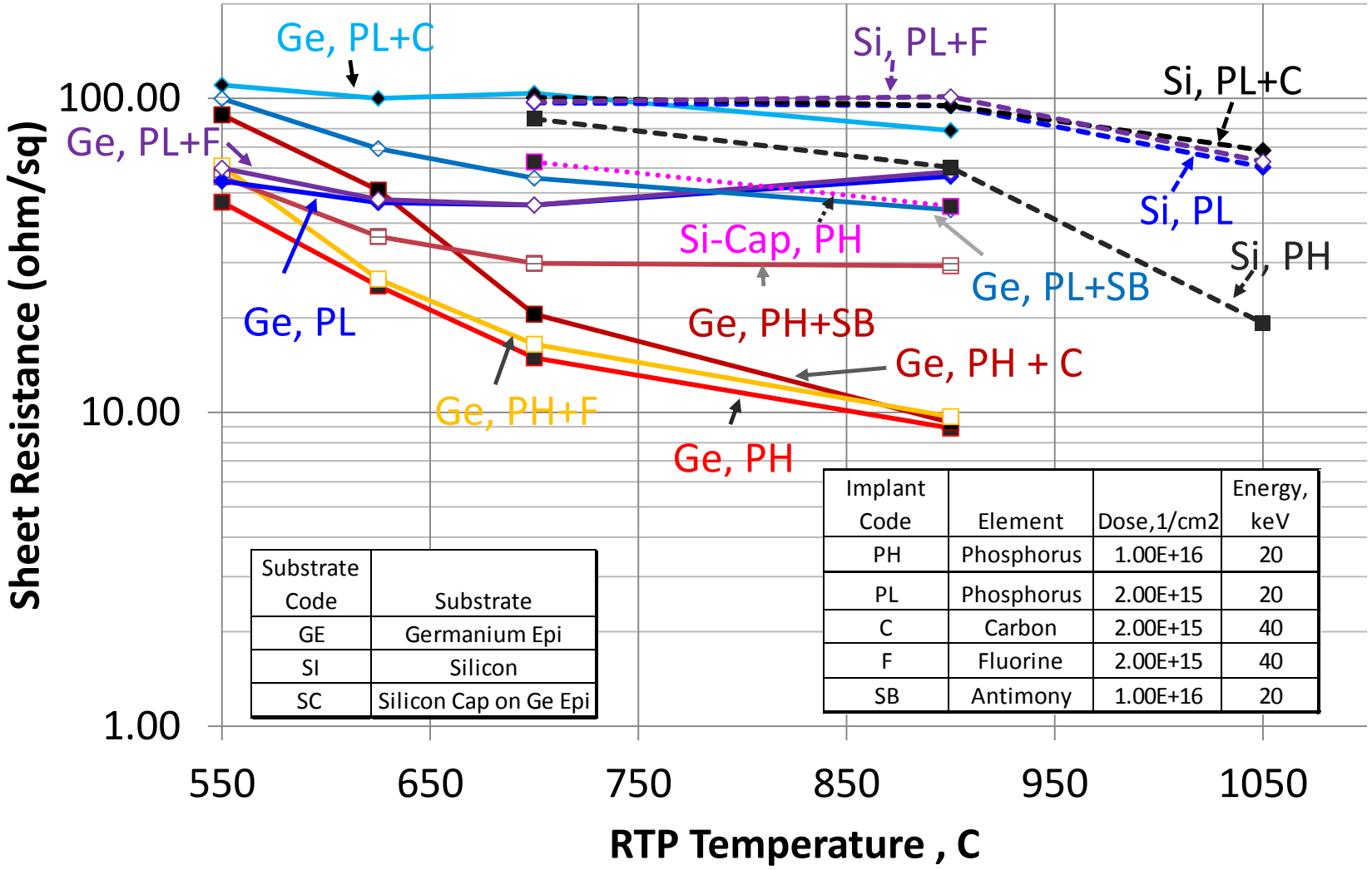


(b) Sample 2-2



(c) Sample 2-3

N-type co-implants and lower dose



Substrate Code	Substrate
GE	Germanium Epi
SI	Silicon
SC	Silicon Cap on Ge Epi

Implant Code	Element	Dose,1/cm2	Energy, keV
PH	Phosphorus	1.00E+16	20
PL	Phosphorus	2.00E+15	20
C	Carbon	2.00E+15	40
F	Fluorine	2.00E+15	40
SB	Antimony	1.00E+16	20

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

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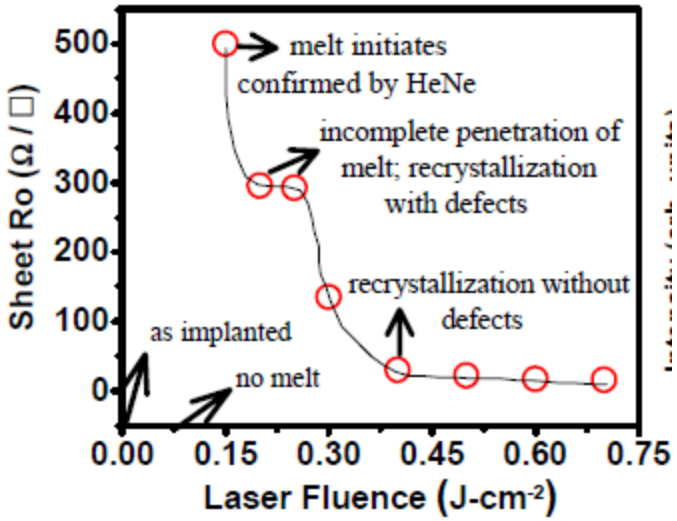
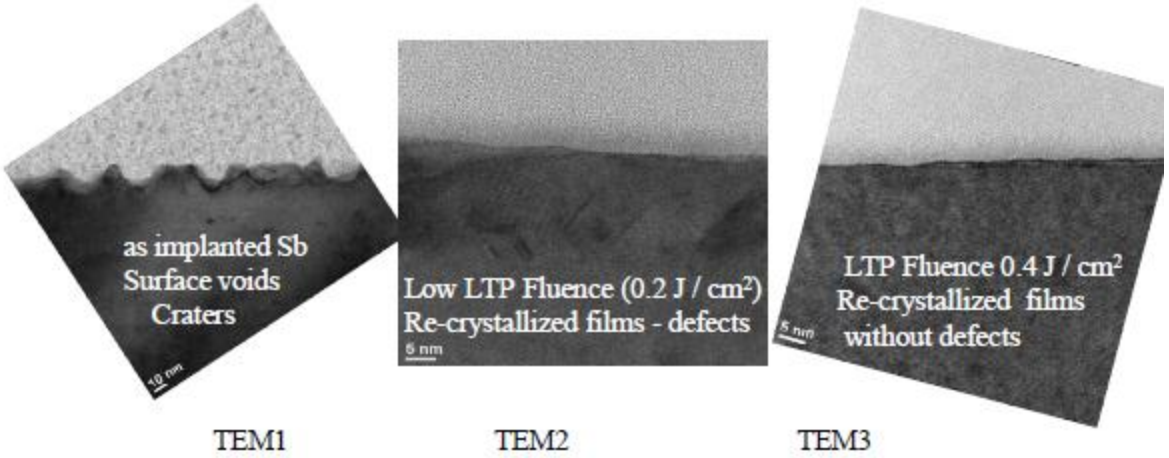
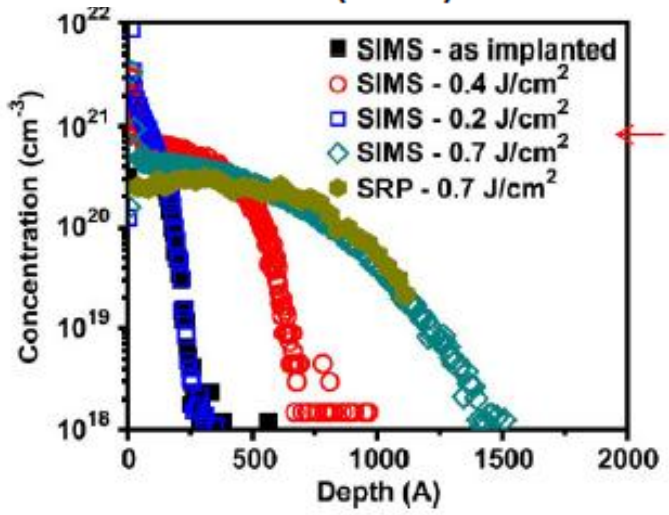




Thareja, 2010, P, As, and Sb implant with ~40 nm junction depth



Note very good SRP result

Sb Laser Anneal shows better activation than P or As

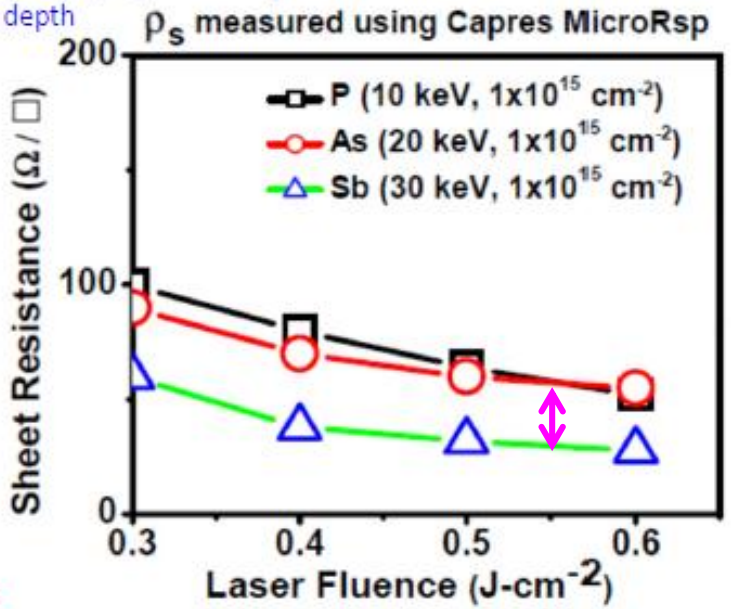
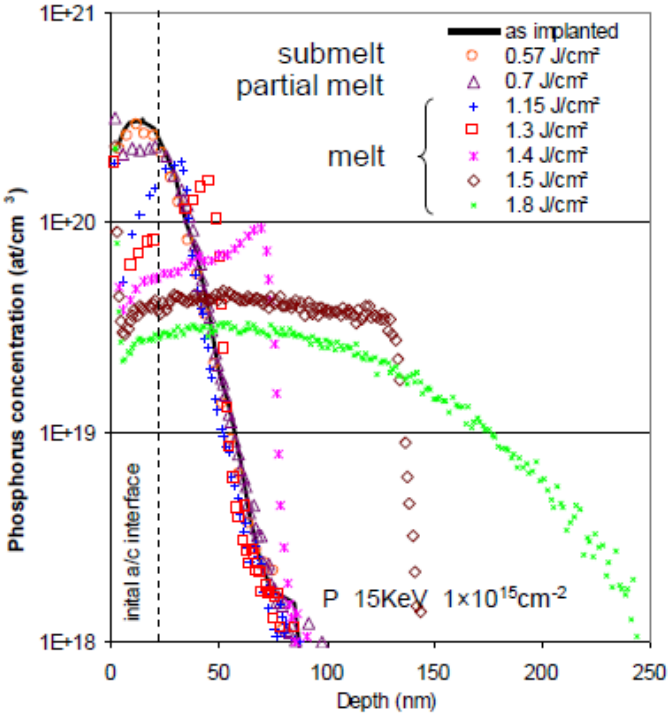
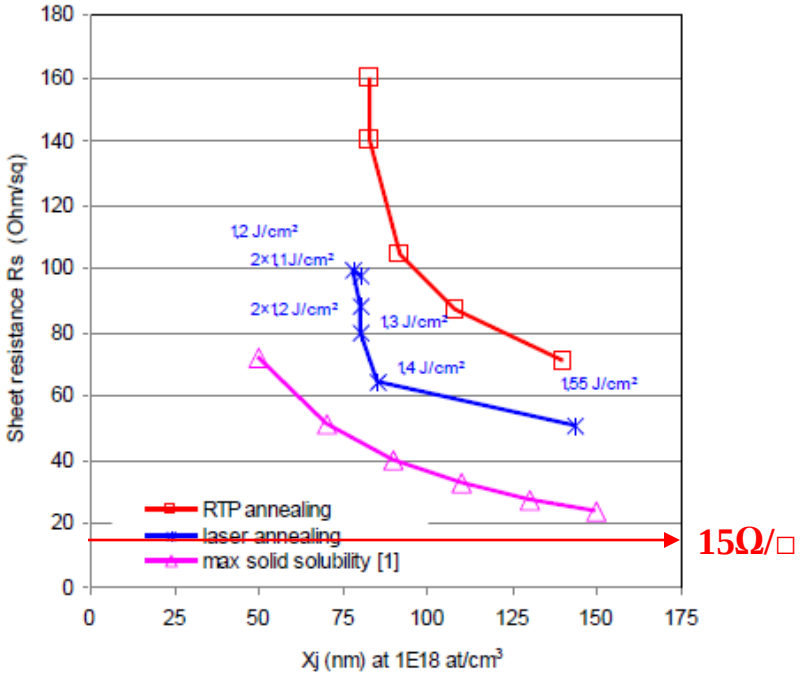


Fig. 2. Concentration profiles (SIMS and SRP) of as-implanted and laser-annealed samples.

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

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)

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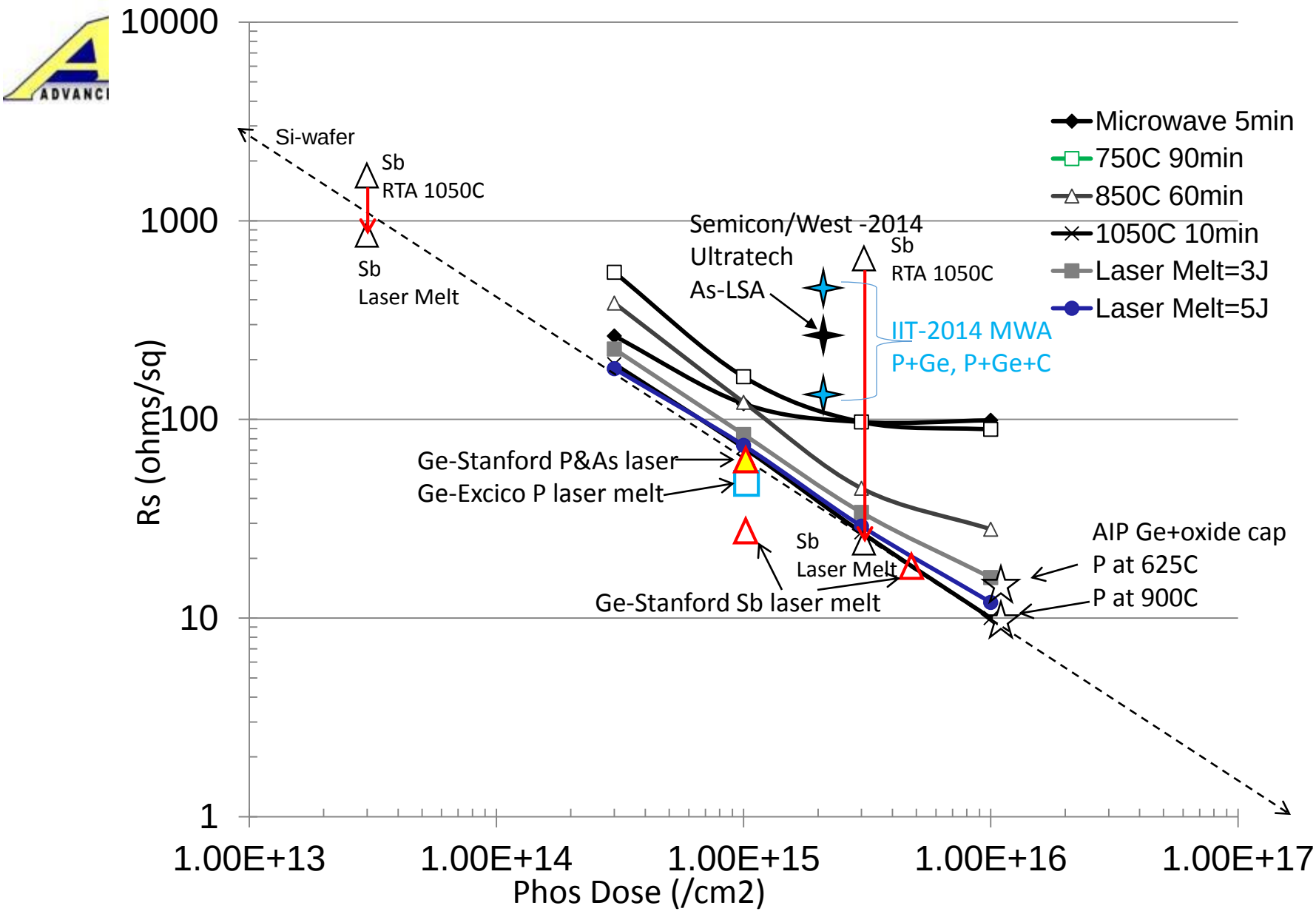
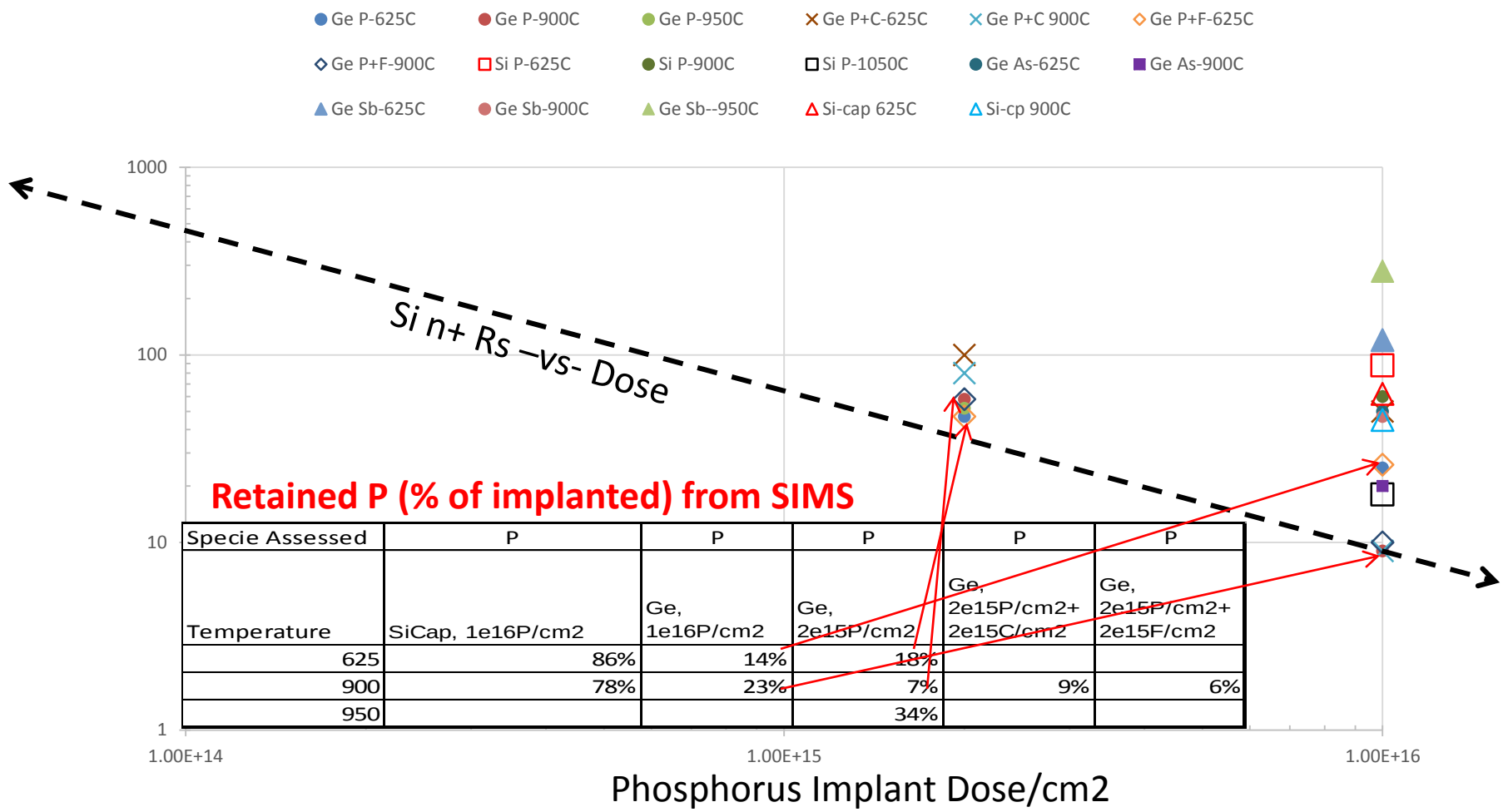
Mazzocchi et al., IEEE-RTP 2009

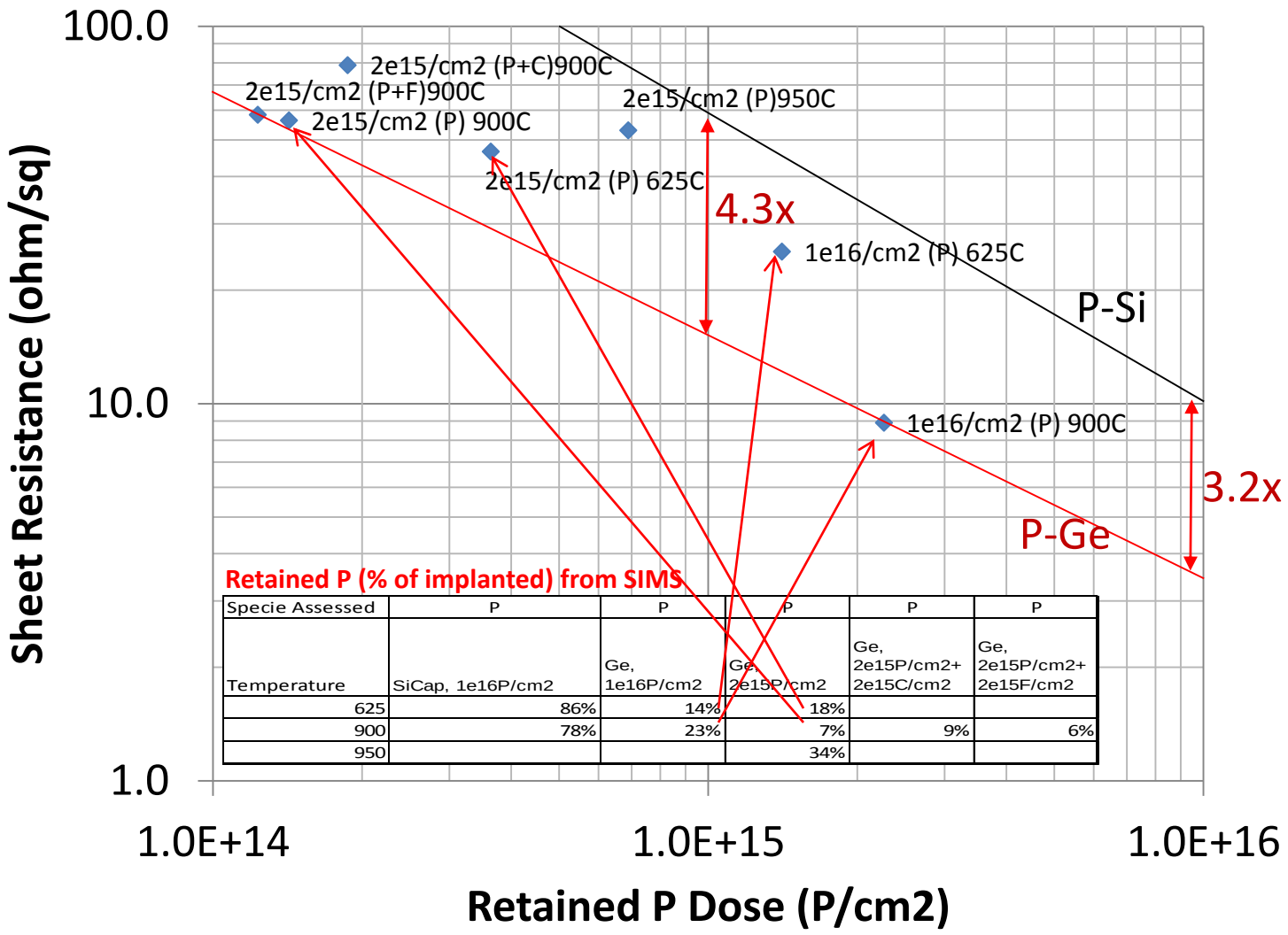

10000
1000
100
10
1
Rs (ohms/sq)
1.00E+13
1.00E+14
1.00E+15
1.00E+16
1.00E+17
Phos Dose (/cm2)
Si-wafer
Sb
RTA 1050C
Sb
Laser Melt
Semicon/West -2014
Ultratech
As-LSA
Sb
RTA 1050C
IIT-2014 MWA
P+Ge, P+Ge+C
Ge-Stanford P&As laser
Ge-Excico P laser melt
Sb
Laser Melt
Ge-Stanford Sb laser melt
AIP Ge+oxide cap
P at 625C
P at 900C
Microwave 5min
750C 90min
850C 60min
1050C 10min
Laser Melt=3J
Laser Melt=5J

n+ Rs versus Dose and Anneals



Retained P (% of implanted) from SIMS

Specie Assessed	P	P	P	P	P
Temperature	SiCap, 1e16P/cm2	Ge, 1e16P/cm2	Ge, 2e15P/cm2	Ge, 2e15P/cm2+ 2e15C/cm2	Ge, 2e15P/cm2+ 2e15F/cm2
625	86%	14%	18%		
900	78%	23%	7%	9%	6%
950			34%		



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625	86%	14%	18%		
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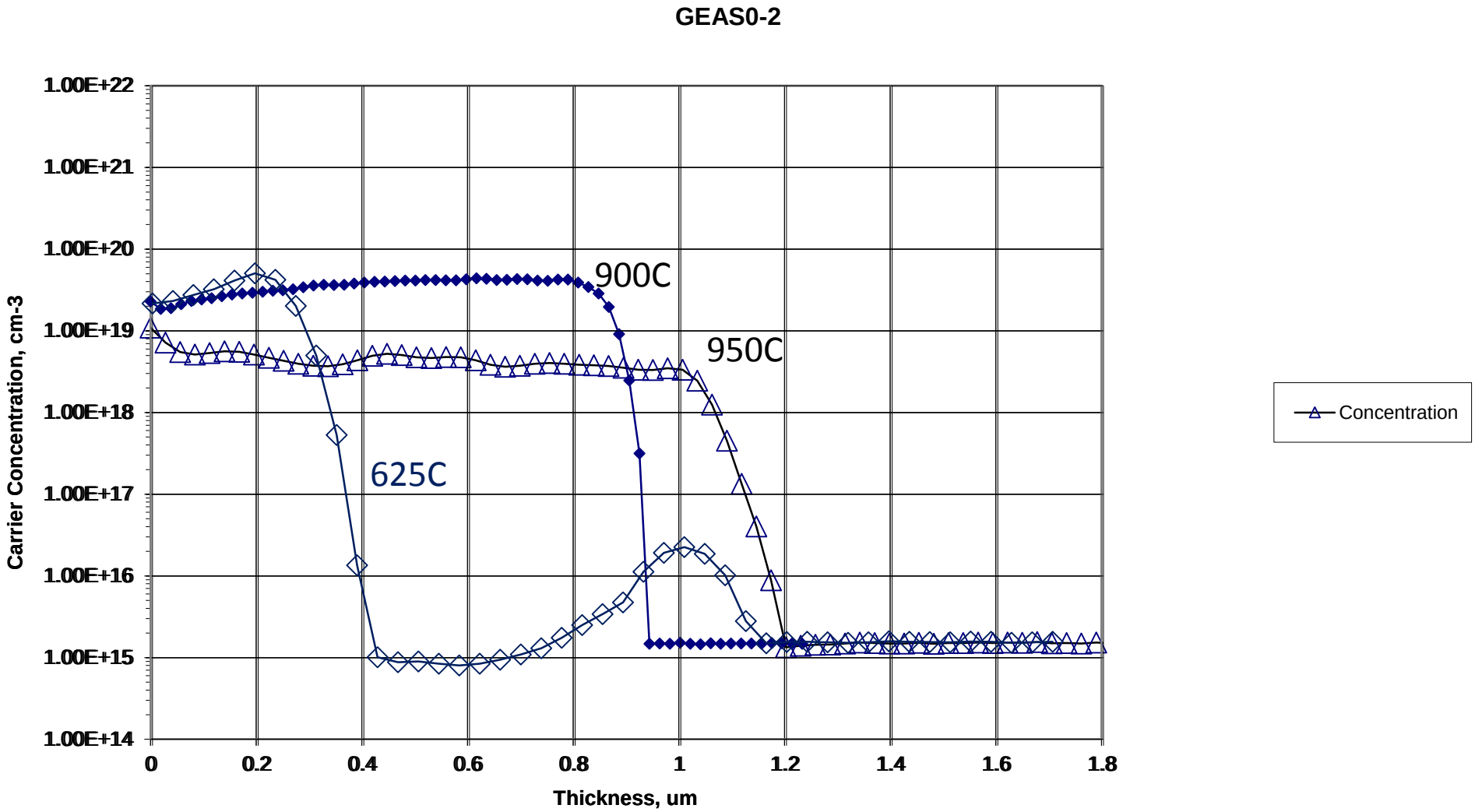
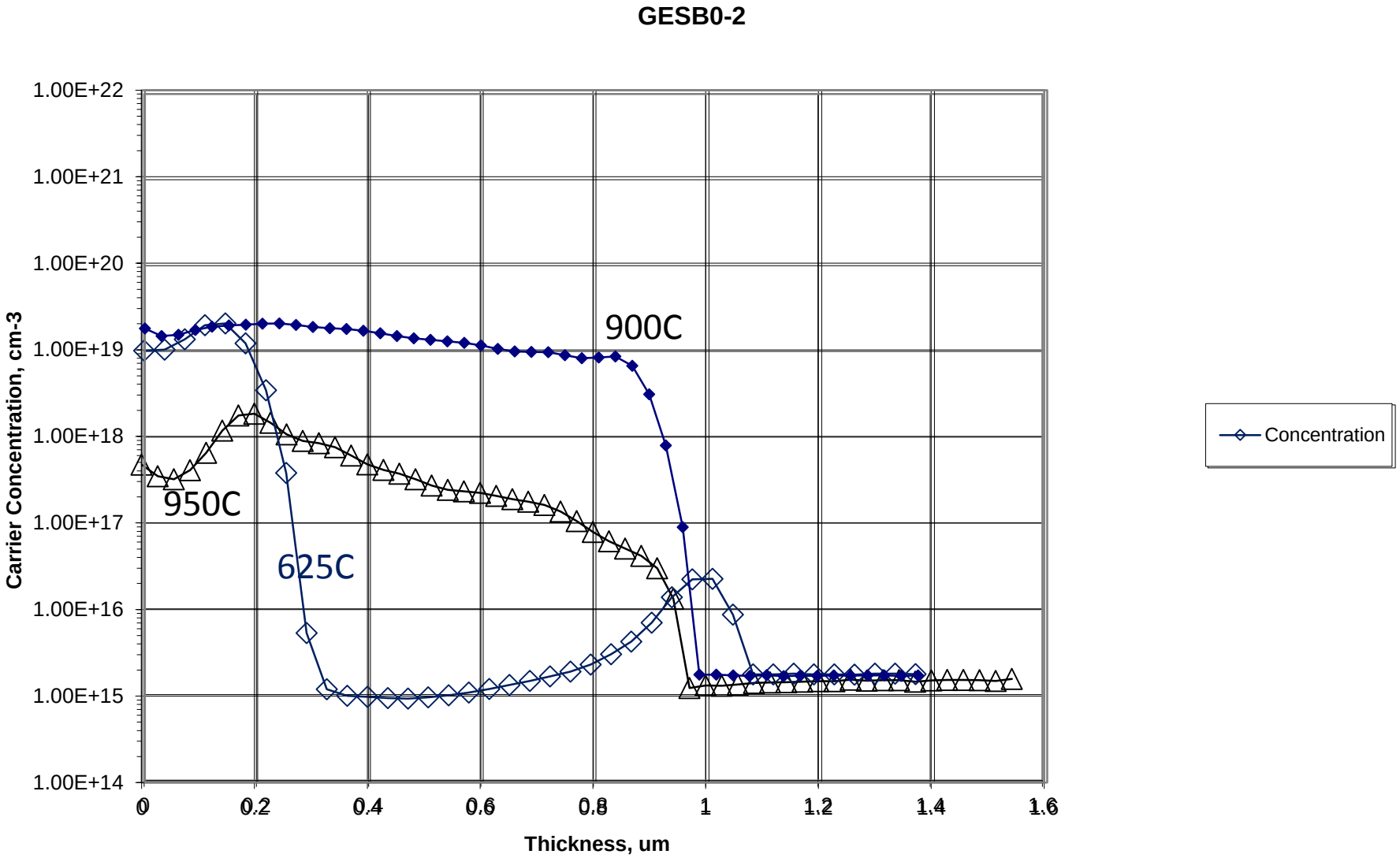
950			34%		

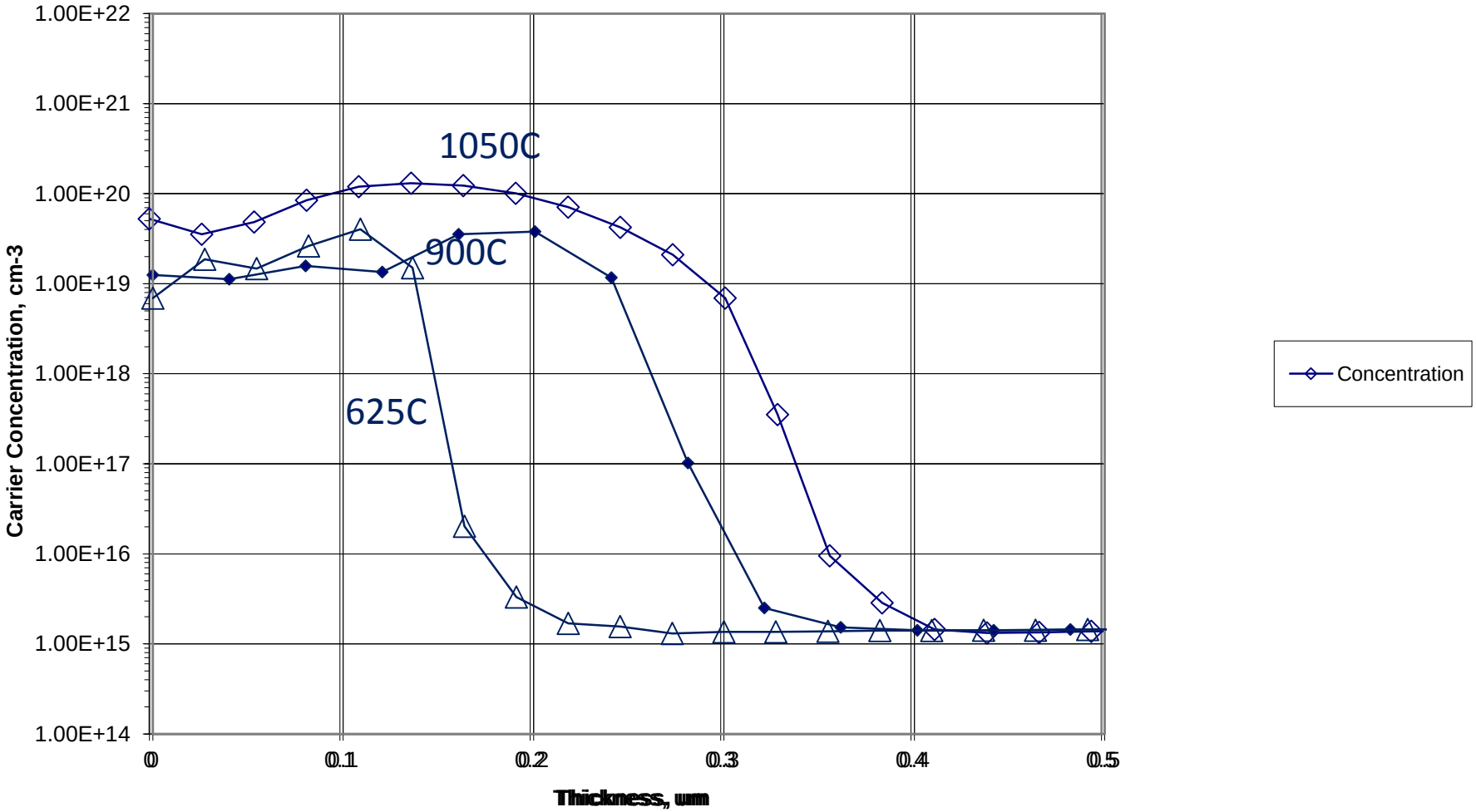
As=1E16 Implant RTA



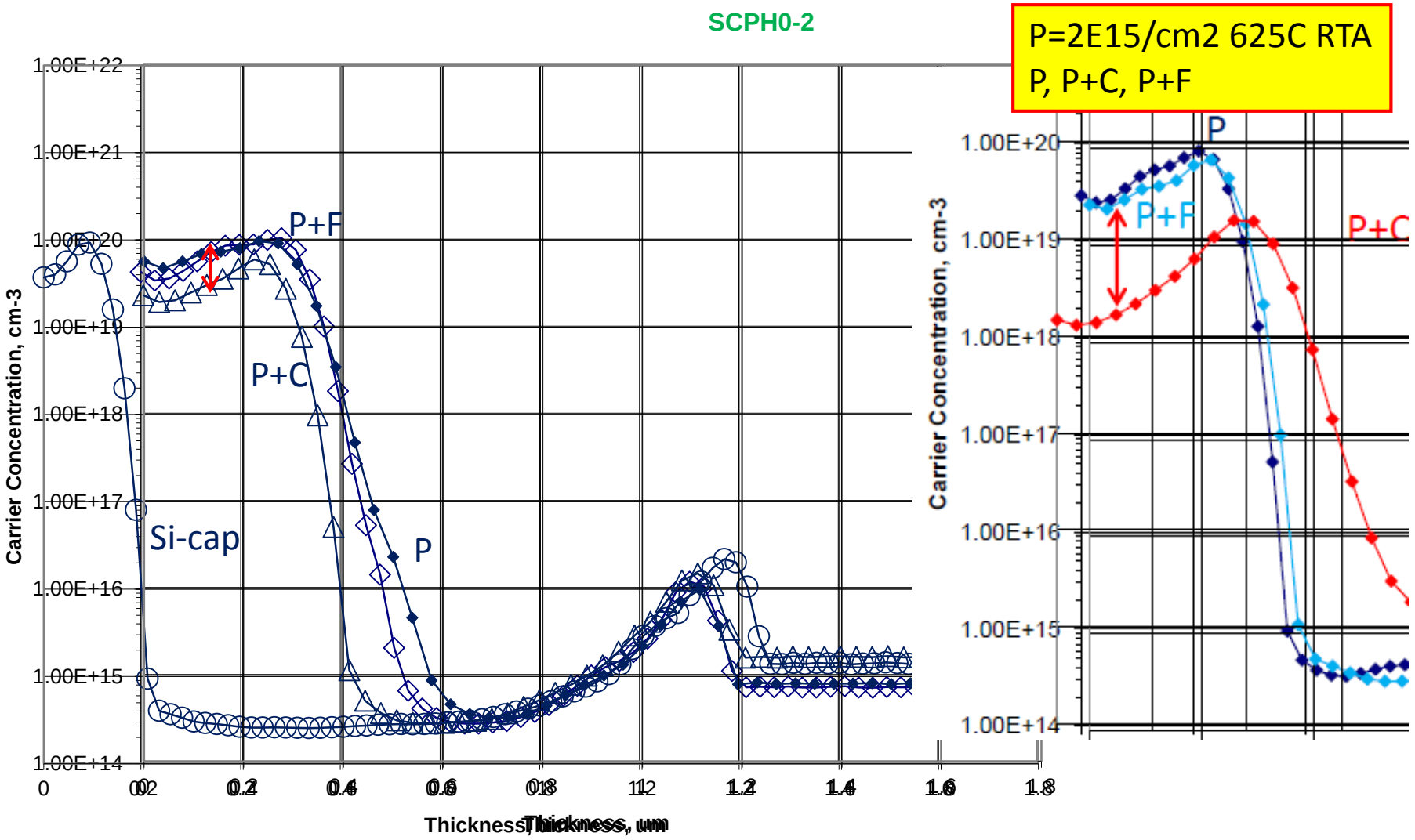
Sb=1E16 Implant RTA



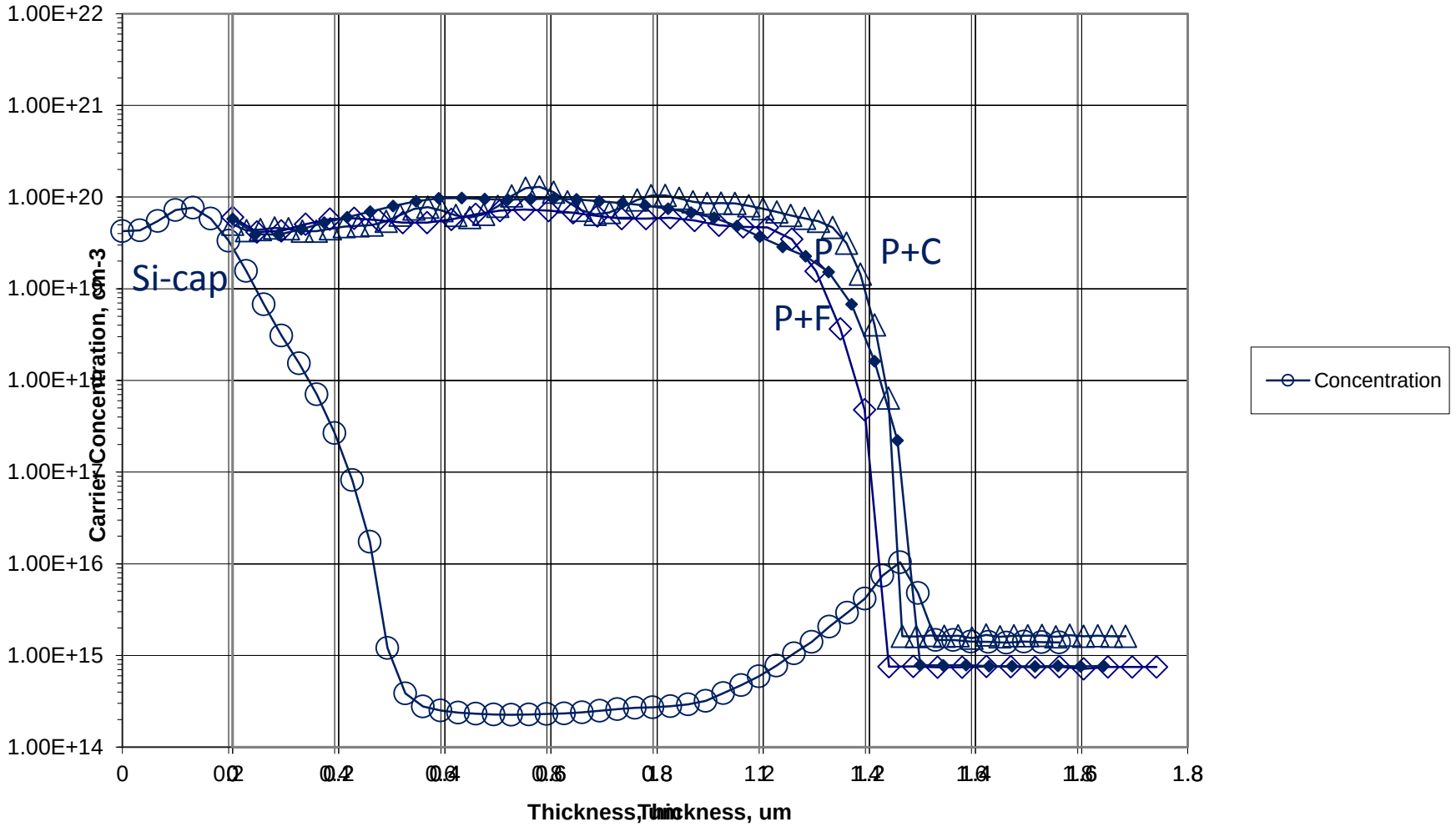
Si-wafer P=1E16 Implant RTA



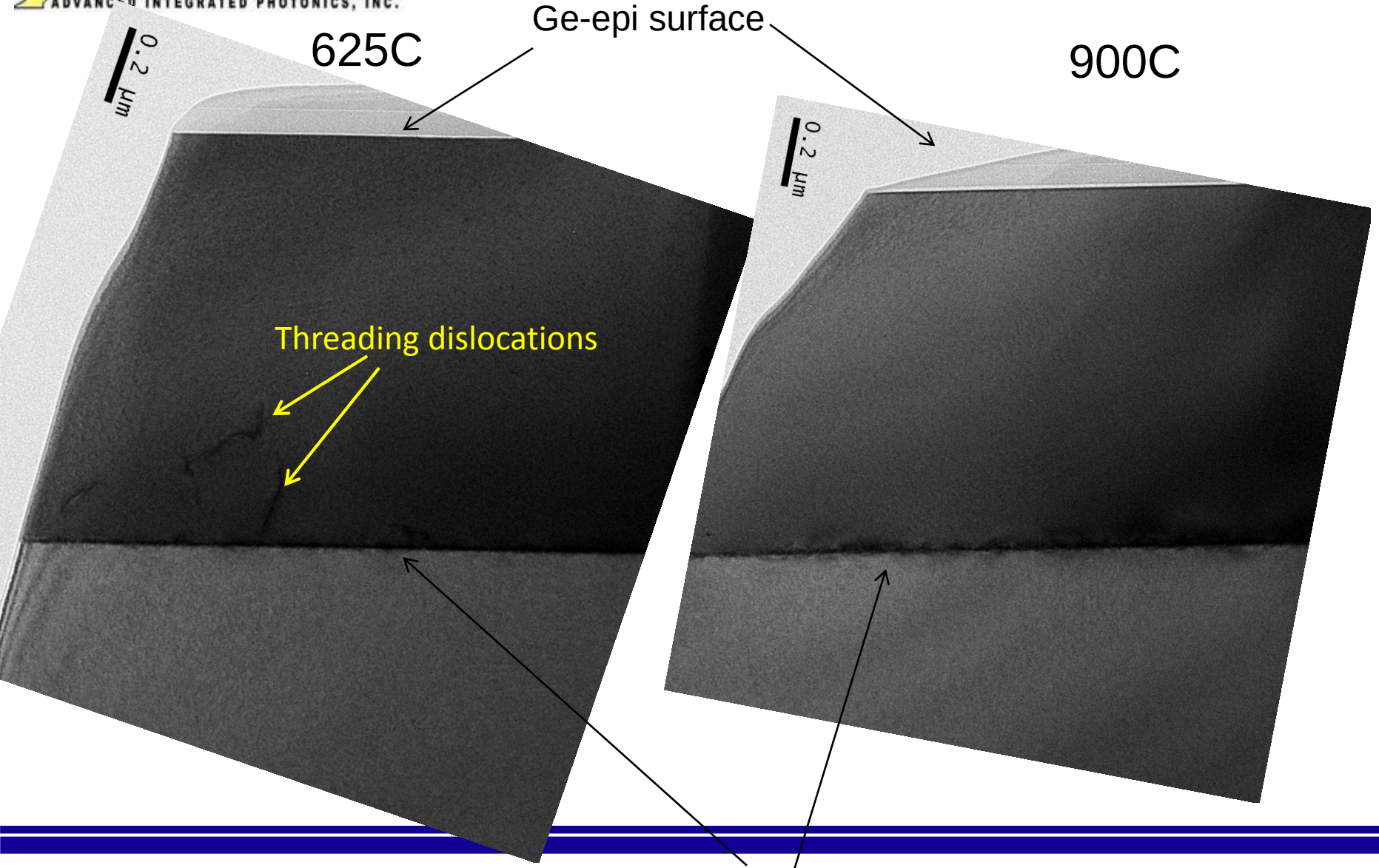
P=1E16,+C,+F,+Si-cap-implant 625C RTA



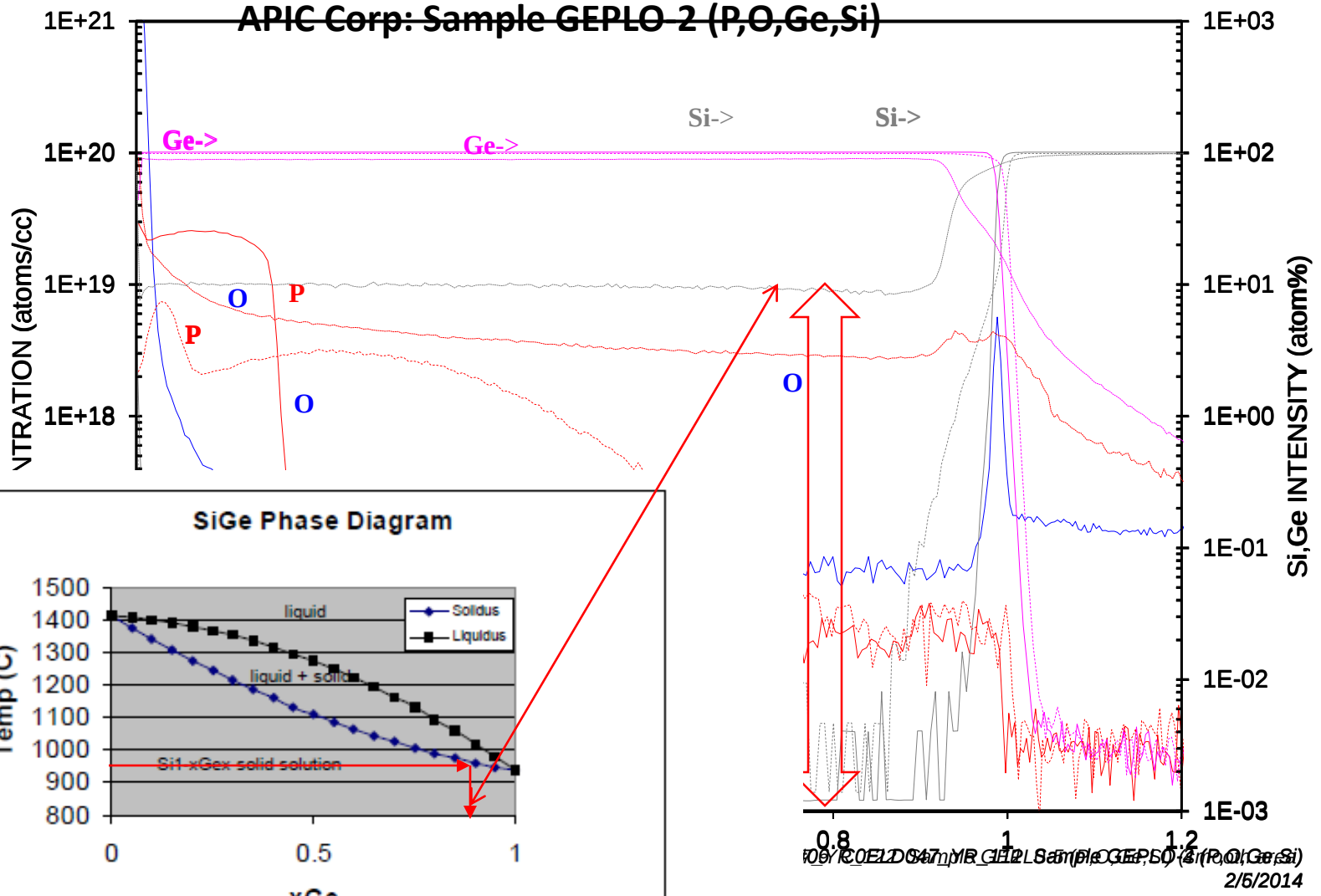
P=1E16, Si-cap,+C,+F, P-implant 900C RTA

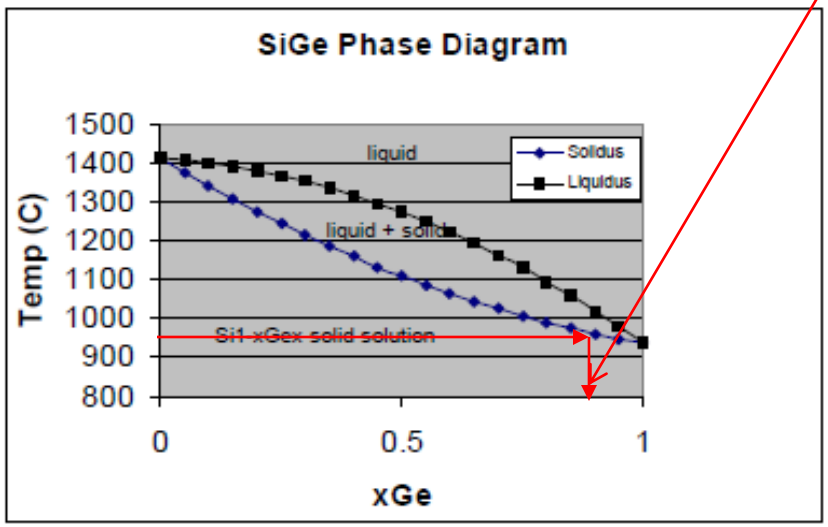


625C & 900C RTA Annealing



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.

Summary: Dopant Activation in Si-vs-Ge

- P-Type Dopant (B & BF2)
  - Room temperature activation (acceptor formation)
    - Higher dose 5E15 vs 5E14 (acceptor level ~1E14/cm2 or 1E19/cm3)
    - Amorphization by BF2 reduces EOR damage and acceptor formation level
    - C implant also produces 1E19/cm3 acceptor level
  - B Fully active in Ge at 500C
  - 5x lower Rs may be related to solid solubility differences of B in Ge versus Si as well as 3x higher hole mobility in Ge
  - B deactivation observed with Ge-melt laser annealing
- N-type Dopant (P, As & Sb)
  - We observed 3x lower Rs with a surface oxide cap when annealing Ge implanted with P above 625C!
  - Contrary to others we observed lower Rs for all n-dopants in Ge compared to Si! P best then As followed by Sb. Could Sb implant damage create more acceptor levels therefore higher Rs due to dopant compensation?
  - Lower P-dose (2E15) fully active at 550C, 1E16 P-dose requires >900C.
  - Examined C, F and Sb co-implant effects,
    - C-defects creates p-type acceptor compensating dopants around 1E19/cm3 and no C-diffusion
    - No difference with F, after RTA SIMS shows F all gone with a peak at the Ge/Si interface.
    - Sb degrades high dose P activation but improves low dose P activation at the higher RTA temperatures.
  - Si-cap improves P activation in Si at 625C and 900C anneal shows minimal P diffusion into Ge and no Ge-epi threading dislocations! This is BEST solution for nMOS as proposed in SST July 2005 for planar HK/MG-last and for FinFET in March 2012

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

John Borland[1,2], Michiro Sugitani[3], Peter Oesterlin[4], Walt Johnson[5], Temel Buyuklimanli[6], Robert Hengstebeck[6], Eron K[7], Kevin Jones[7], Ajeet A[8]

[1]JOB Technologies, Aiea, Hawaii
[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]Prussin Tek, LA, CA

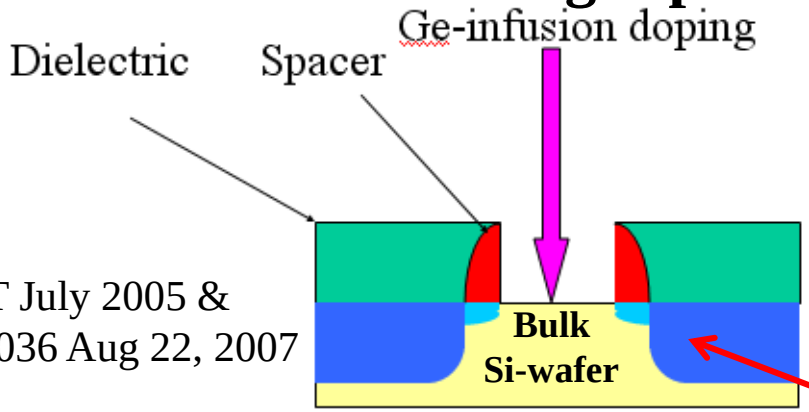
J.O.B. Technologies (Strategic Marketing, Sales & Technology)

1

Ge-channel Formation by Ge implant, plasma or infusion doping (n+Si-cap S/D doping)

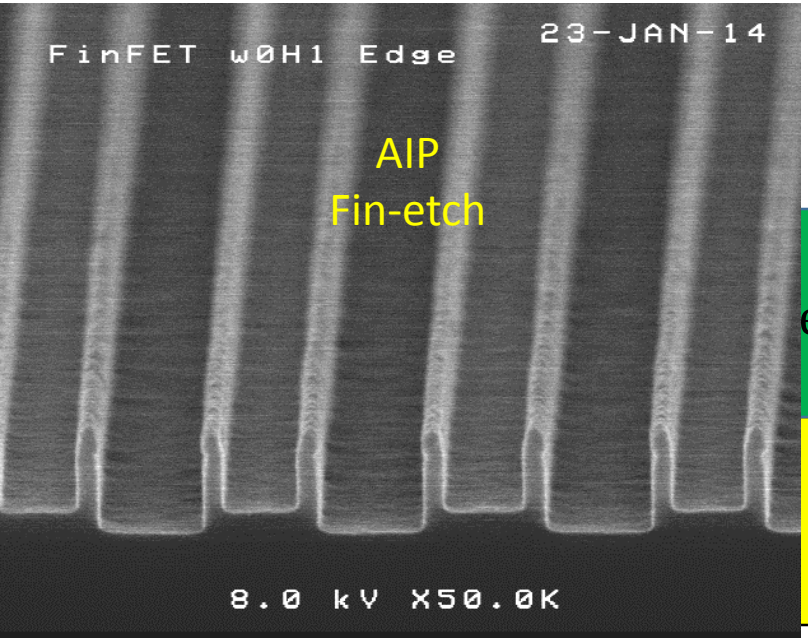
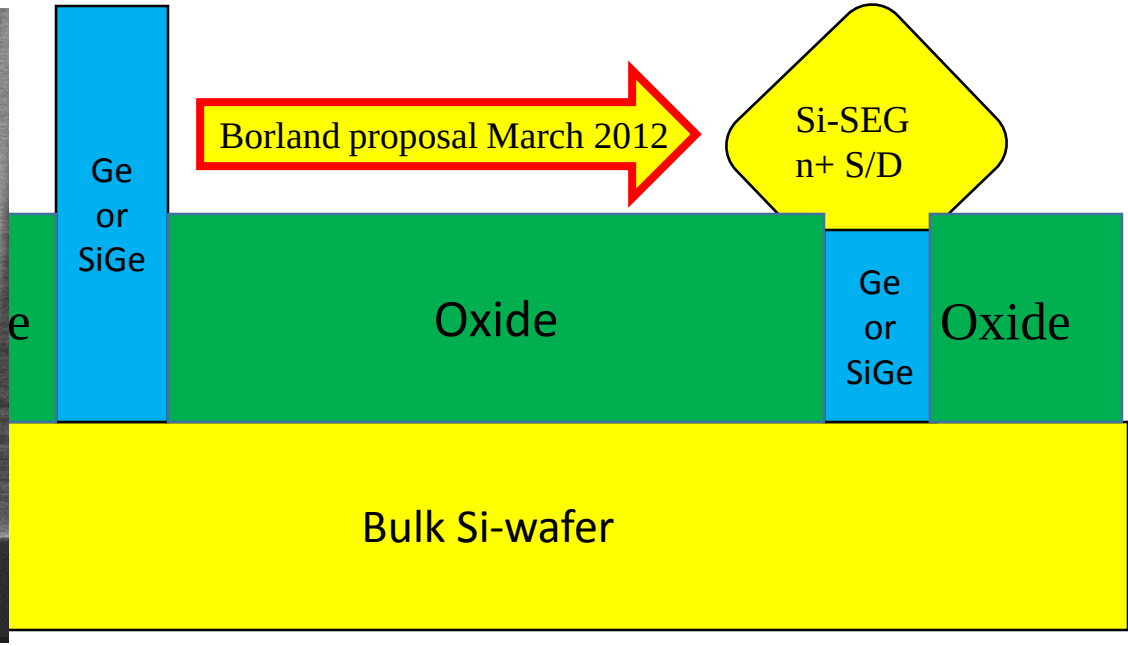
ADVANCED INTEGRATED PHOTONICS, INC.

nMOS Ge-channel formation using replacement gate process flow



Borland et al., SST July 2005 &
US Patent #7,259,036 Aug 22, 2007

nMOS Fin/channel



nMOS n+ Si-S/D