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The Cluster Implant *Source*

Cluster Implant for 32nm

Wade Krull

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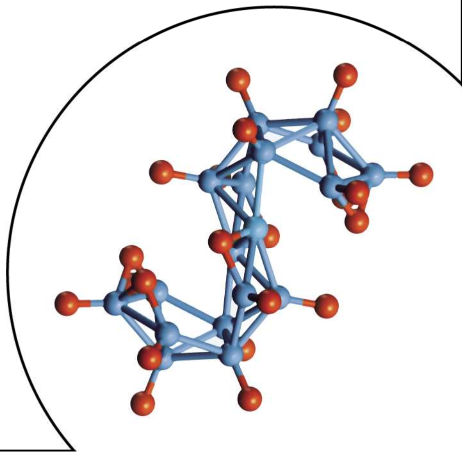

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General Features of Cluster Implant

- High productivity at low energy
- Self-amorphization due to high mass species
- High substitutional placement on anneal
- Elimination of EOR defects

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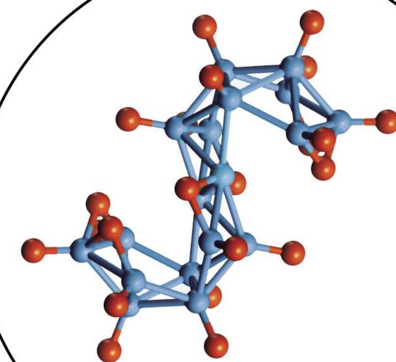
ClusterBoron Implant for 32nm PMOS SDE



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45nm & 32nm USJ Requirements

45 nm Node:

- $R_s \sim 1000\ \Omega/sq$, $X_j < 20nm$
- $R_s \cdot X_j < 20$ (kΩ-nm)

32 nm Node:

- $R_s < 1000\ \Omega/sq$, $X_j < 15nm$
- $R_s \cdot X_j < 15$ (kΩ-nm)

Implant Conditions

- $B_{18}H_{22}$ 500eV (equiv)

  1E15 atoms/cm^2
- BF_2 500eV (equiv)

  1E15 atoms/cm^2

Co-implants:

- $C_{16}H_{10}$ 3keV (equiv)

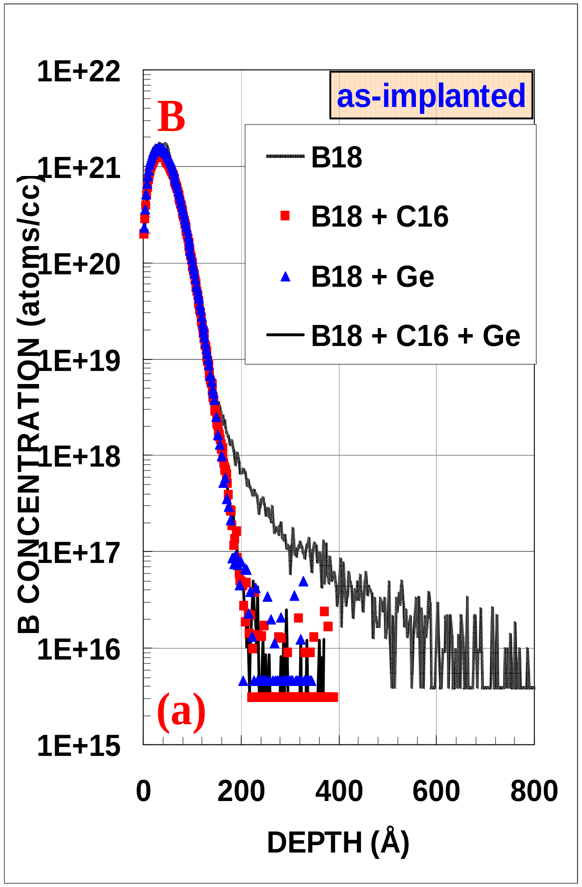
  1E15 atoms/cm^2
- Ge^+ 20keV

  5E14 atoms/cm^2

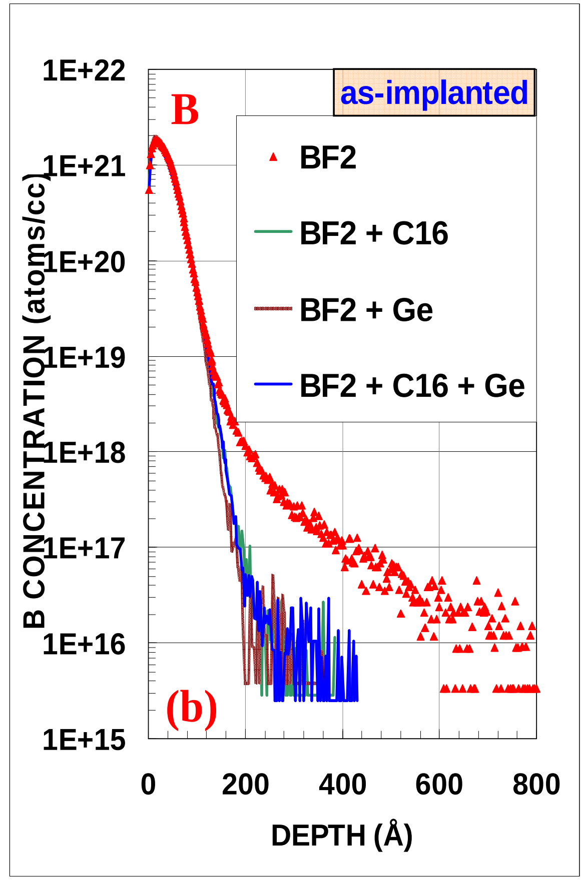
#	Implant
1	B_{18}
2	B_{18} + C_{16}
3	B_{18} + Ge
4	B_{18} + C_{16} + Ge
5	BF_2
6	BF_2 + C_{16}
7	BF_2 + Ge
8	BF_2 + C_{16} + Ge

$B_{18}H_{22}$ and BF_2 with Co-implants

$B_{18}H_{22}$ with co-implant



BF_2 with co-implant



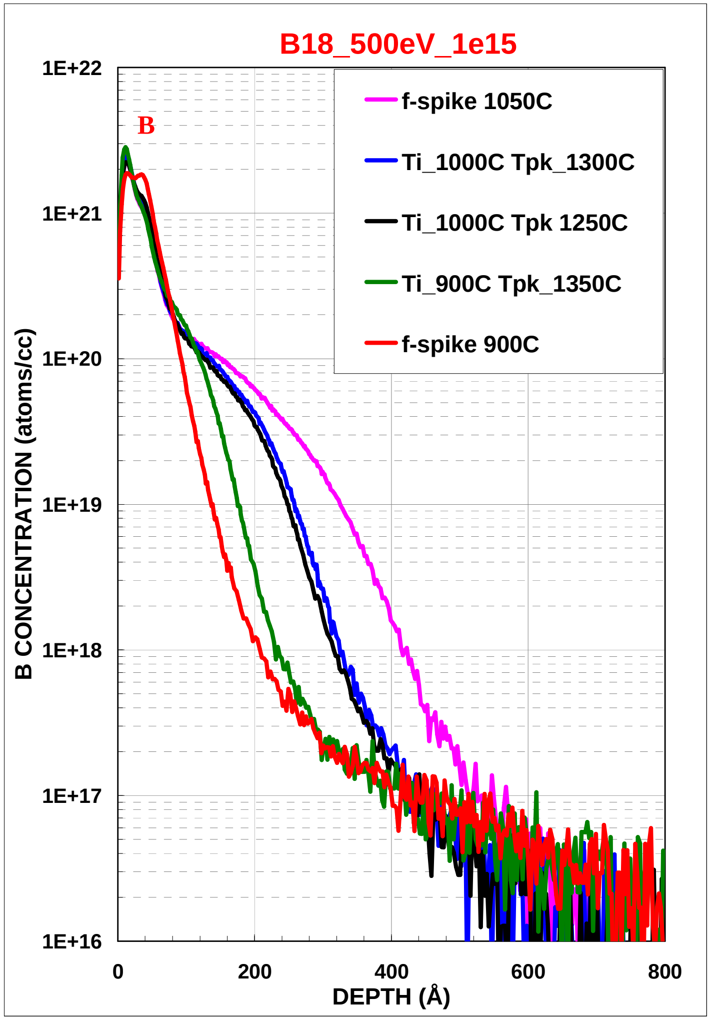
$B_{18}H_{22}$ & BF_2 implant - 500eV (equiv), 1e15

Flash Anneal Conditions

- f-spike 900°C, f-spike 1000°C
- f-spike1025°C, f-spike1050°C
- T_i-750°C T_{pk} - 1050°C & 1250°C
- T_i-900°C T_{pk} - 1250°C & 1350°C
- T_i-1000°C T_{pk} - 1250°C & 1300°C

B_{18} and BF_2 implants are 500eV per boron atom @ 1e15 atoms/cm^2

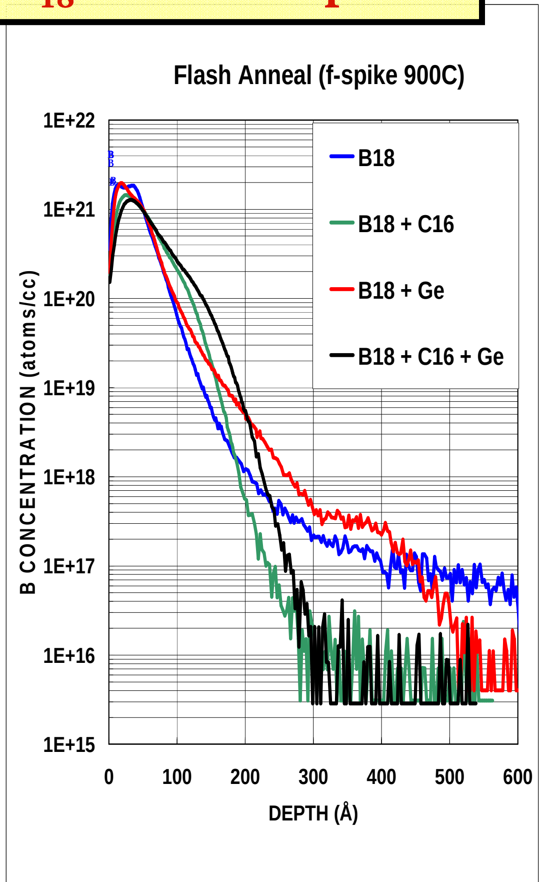
B_{18} – 500eV, 1e15 (SIMS PROFILE) - FLASH ANNEAL



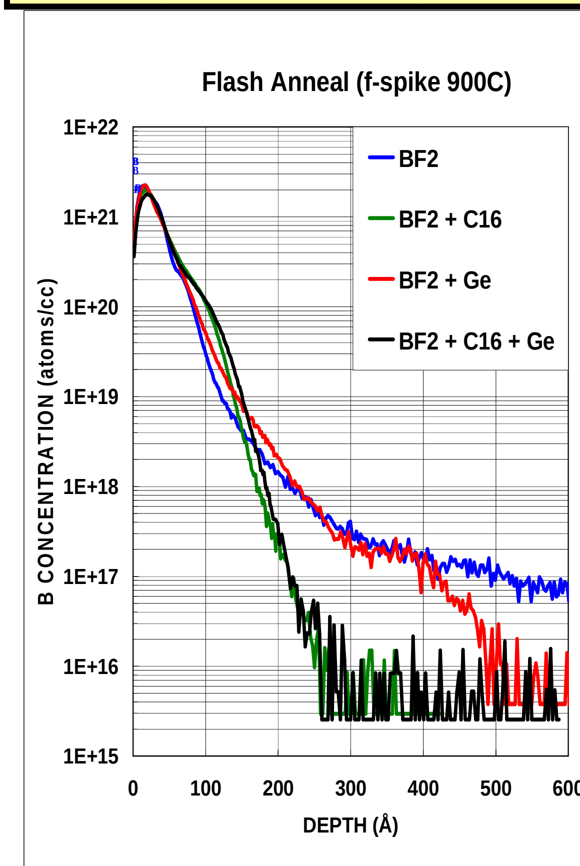
Sample ID	B_{18} 500eV, 1e15				
Anneal Recipe	Spike 900C	Spike 1050C	T_i_900C_ T_{pk}_1350C	T_i_1000C_ T_{pk}_1250C	T_i_1000C_ T_{pk}_1300C
Rs (Ω/sq)	1431	428	562	582	523
Xj (nm)	15.4	37.8	20.4	28.0	27.9
Rs. Xj / 1000	22.0	16.2	11.5	16.3	14.6

f-spike anneal (900°C)

B_{18} with co-implant



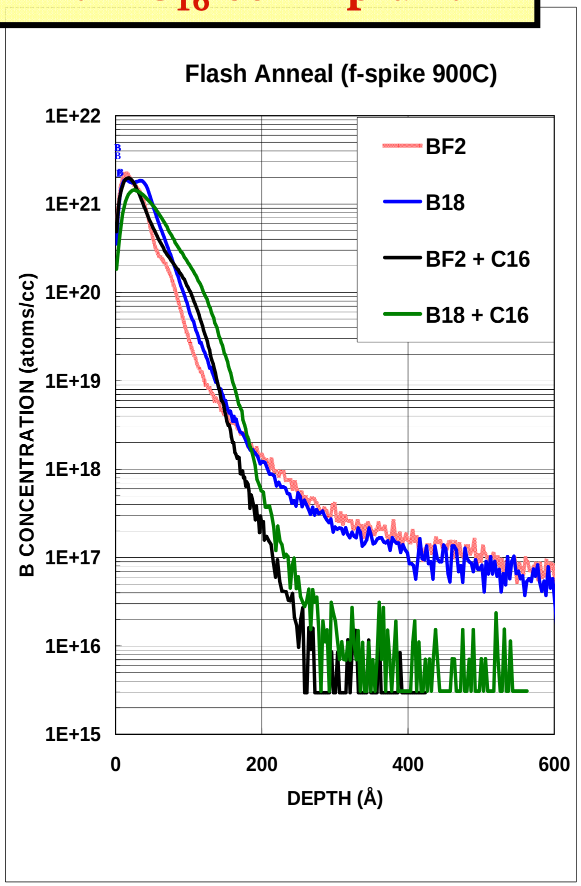
BF_2 with co-implant



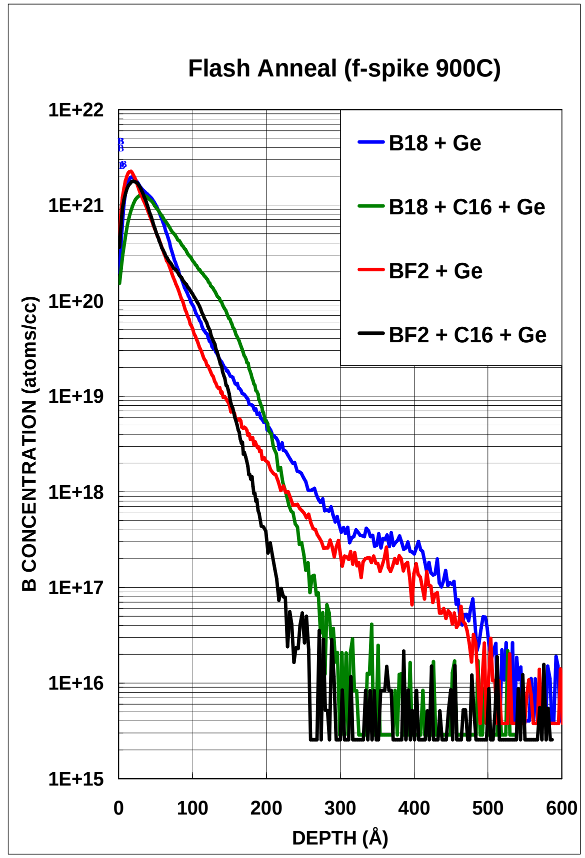
Abrupt junction with C_{16} with co-implants

f-spike anneal (900°C)

With C_{16} co-implant



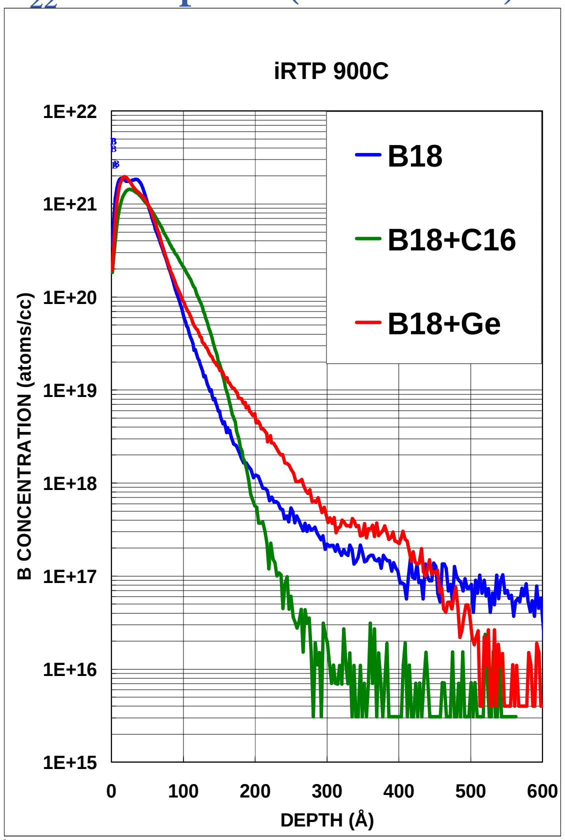
With C_{16} + Ge co-implants



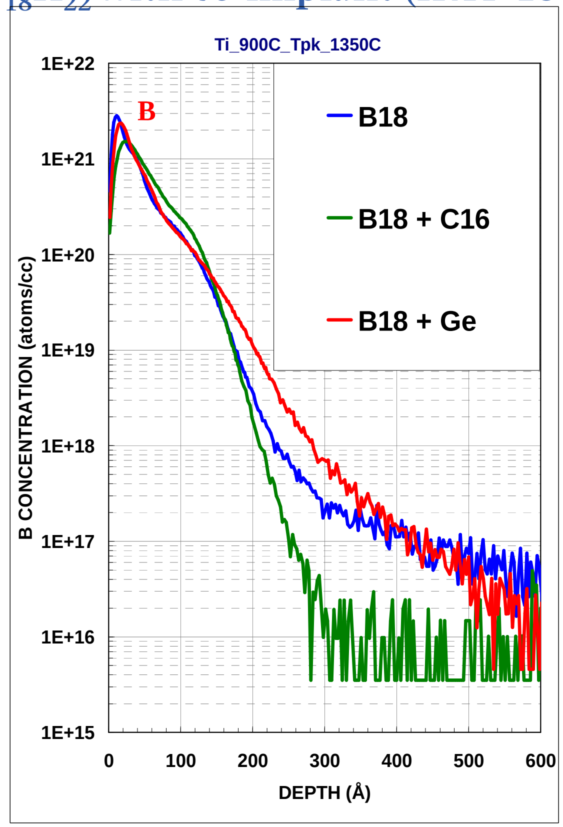
The pile up due to Ge implants is eliminated with C_{16} co-implant

iRTP 900°C, fRTP T_i 900°C - T_{pk} 1350°C

$B_{18}H_{22}$ co-implant (iRTP 900°C)



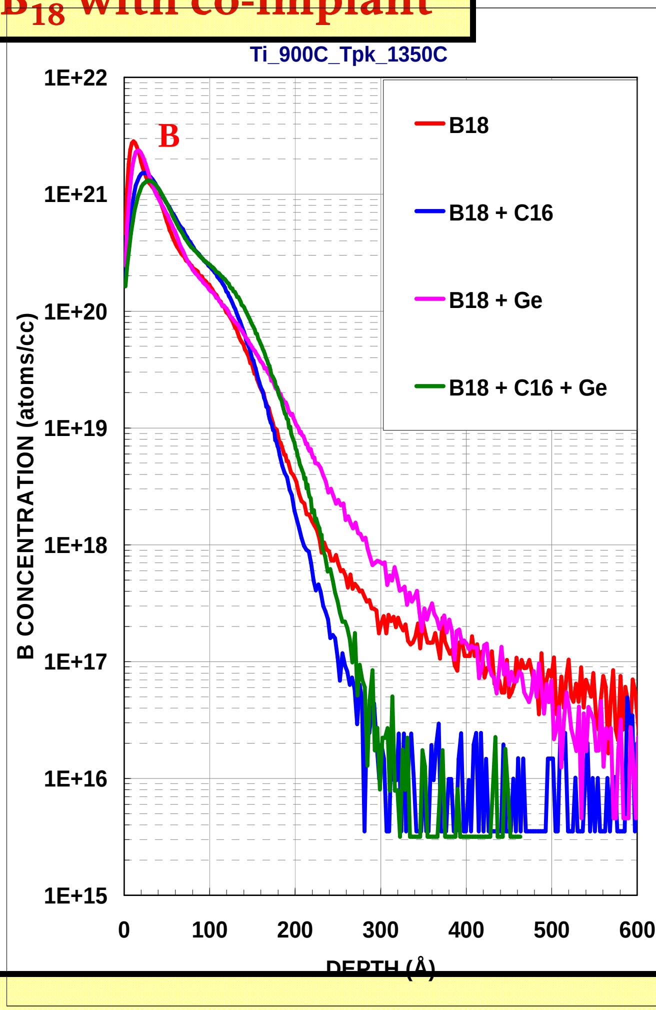
$B_{18}H_{22}$ with co-implant (fRTP 1350°C)



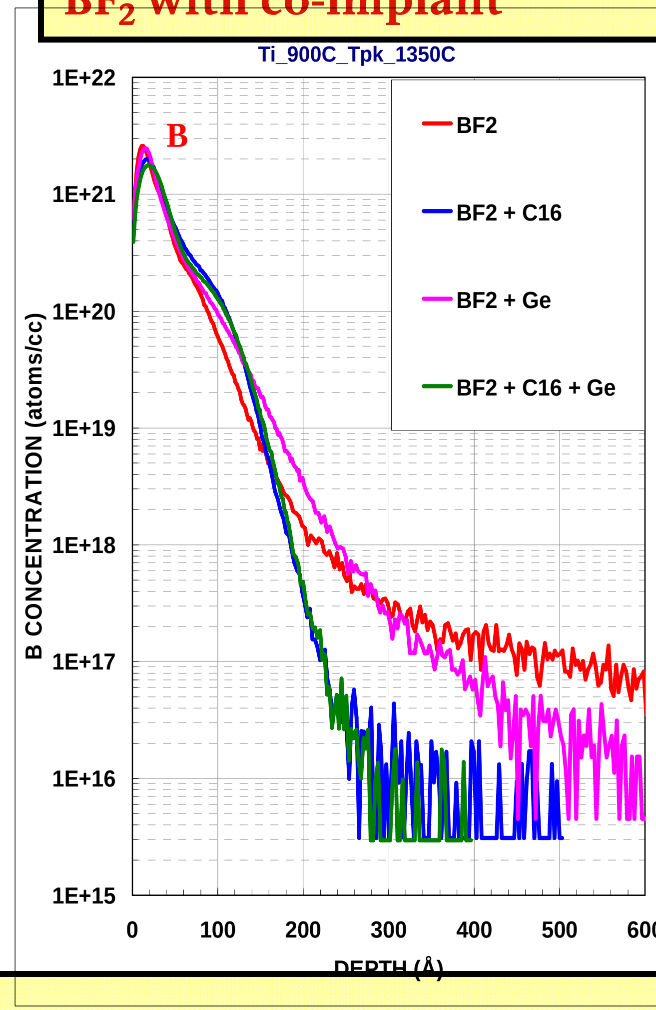
High boron concentration at Ge EOR defect region. Reduced concentration with $C_{16}H_{10}$ at iRTP 900°C. The concentration is removed at the higher flash temperature Tpk = 1350°C.

Ti_ 900ºC T_{pk} 1350ºC

B_{18} with co-implant



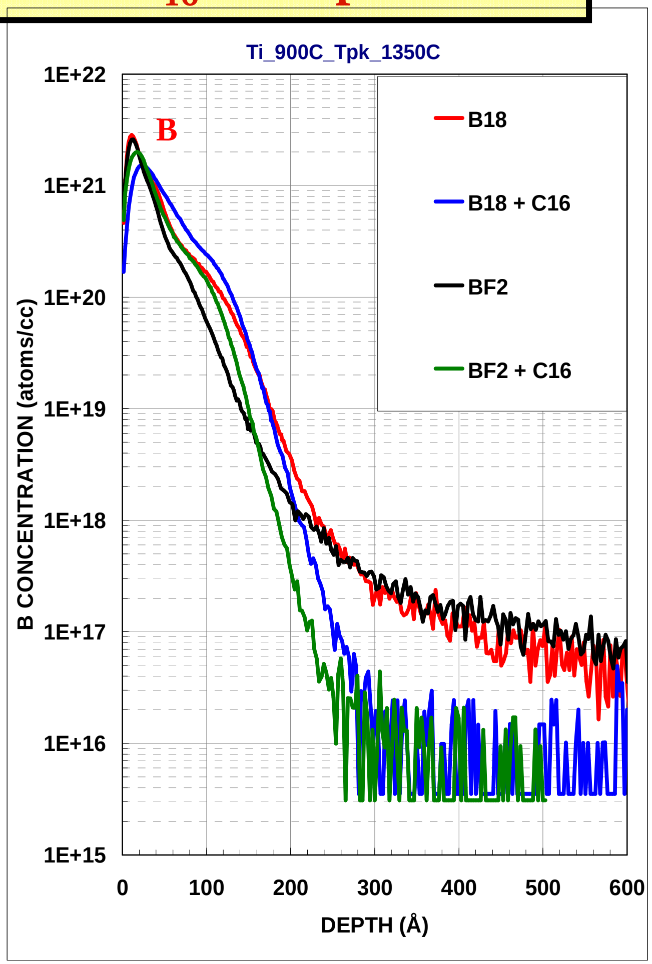
BF_2 with co-implant



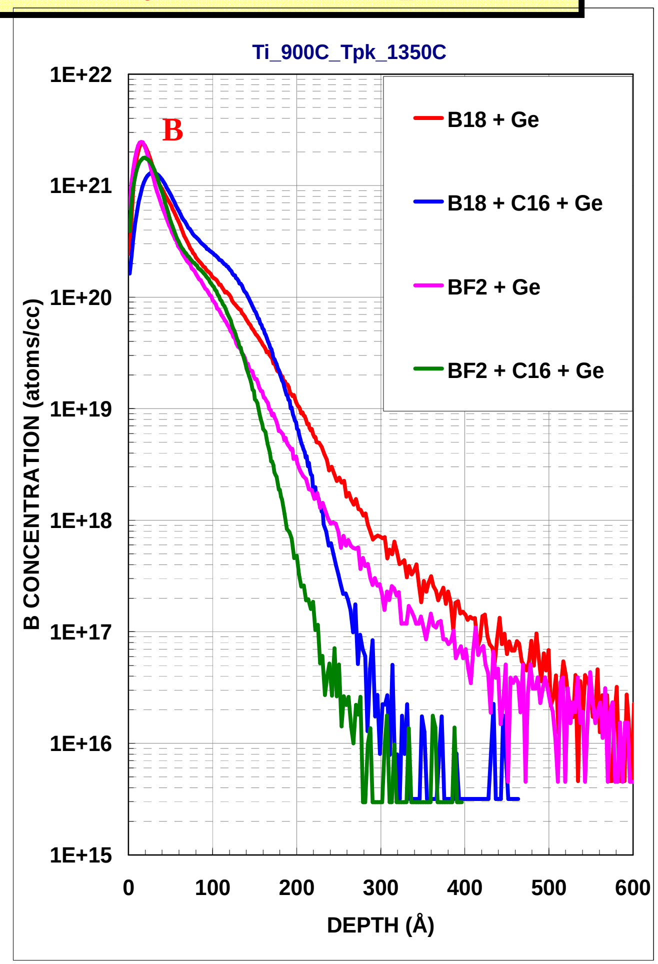
Abrupt junction with C_{16} with co-implants

Ti_900ºC T_{pk} 1350ºC

With C_{16} co-implant

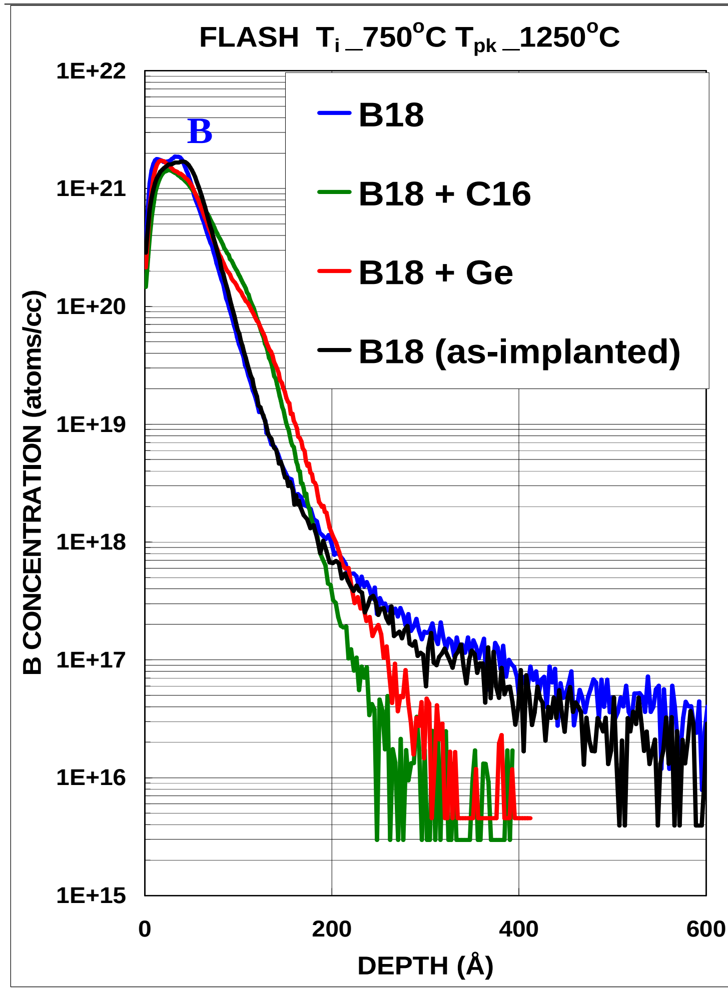


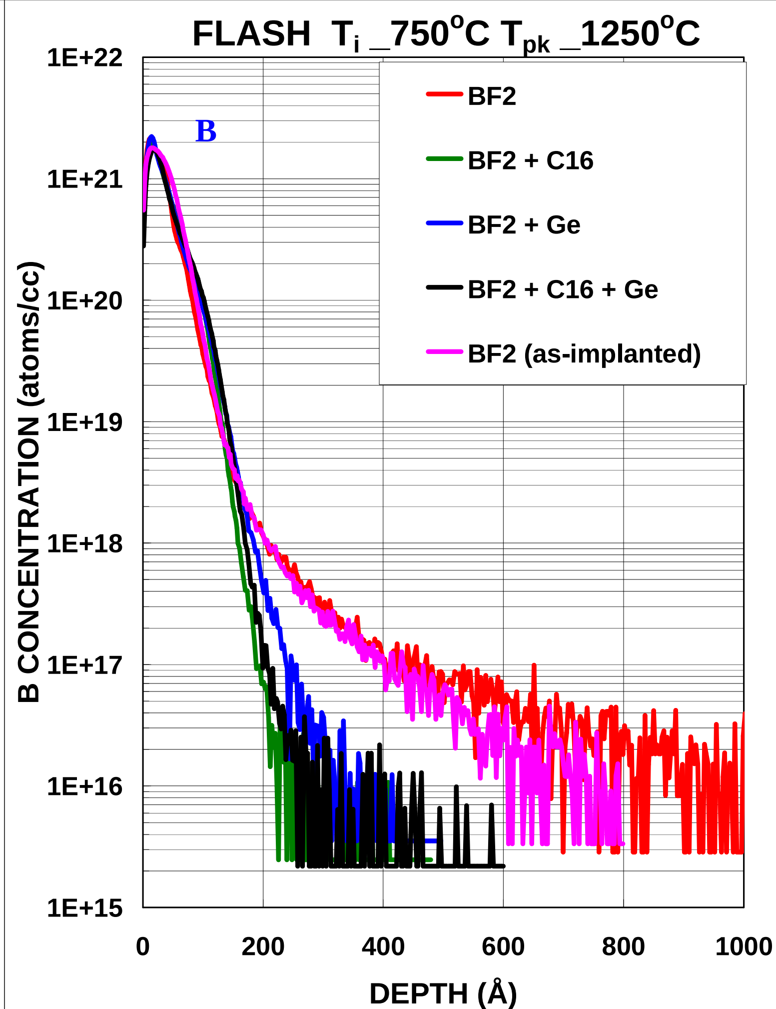
With C_{16} + Ge co-implants



Better activation with C_{16} co-implant

FLASH Ti _750ºC Tpk _1250ºC





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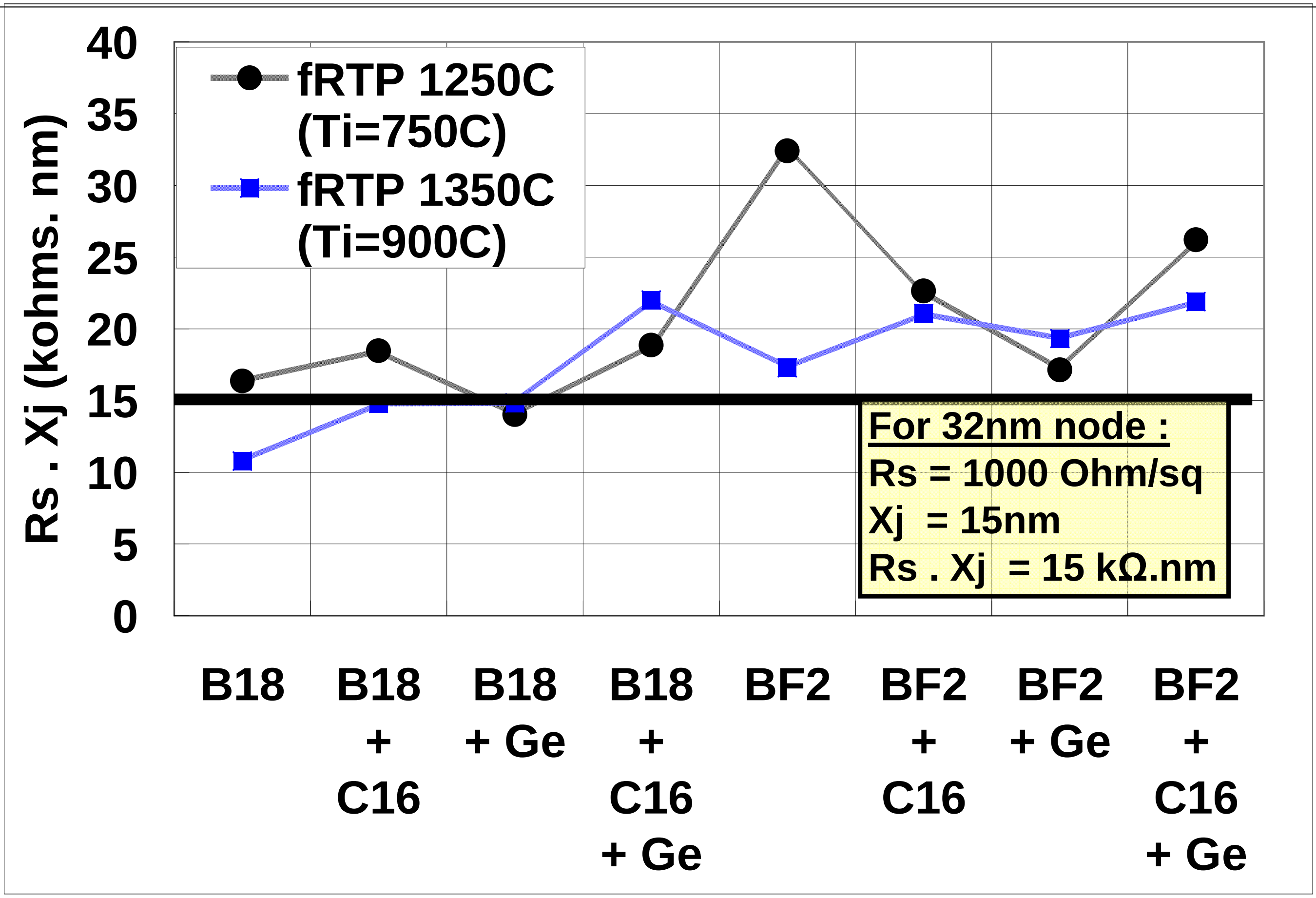
$R_s \cdot X_j$ Product: 32 nm Node

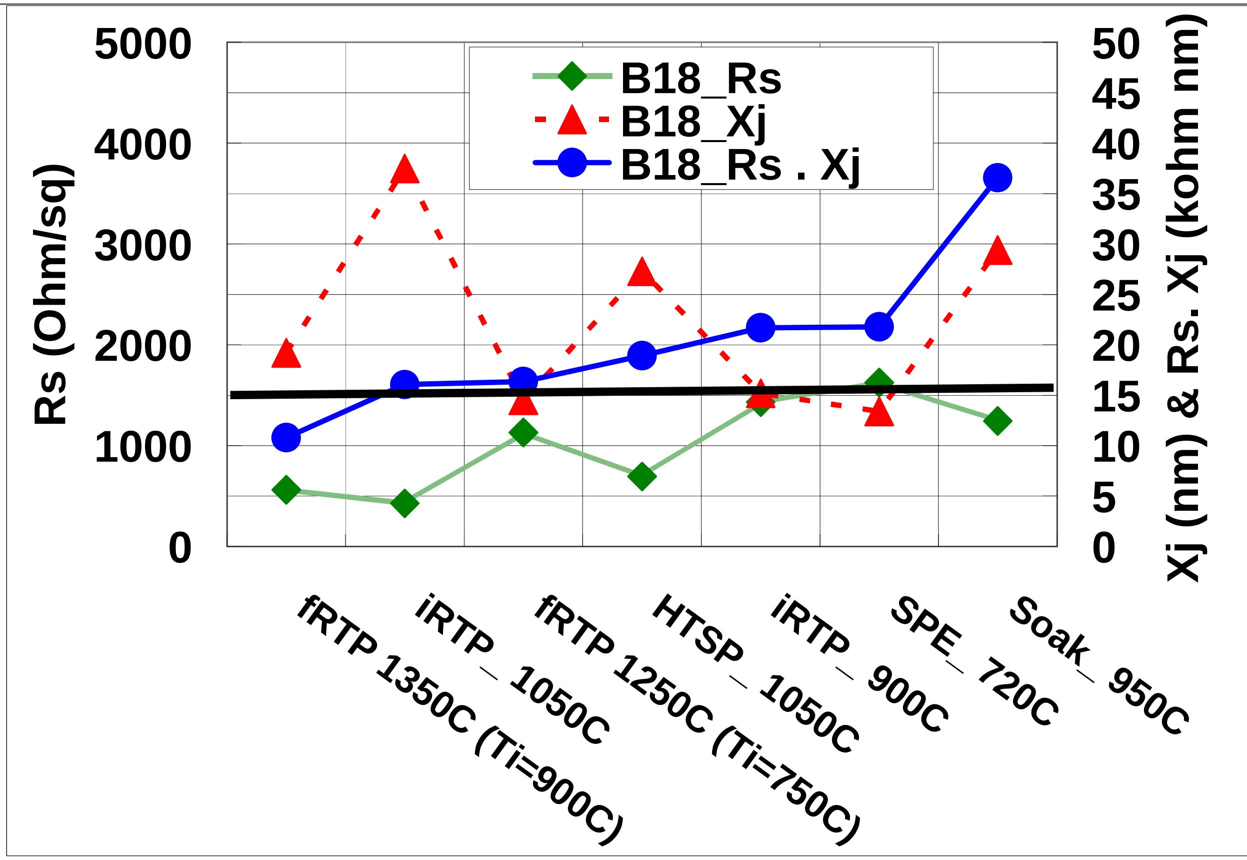
A Measure of Active Carrier Concentration



$R_s \cdot X_j$ product is lowest for the $B_{18}H_{22}$ implant, satisfying the 32nm requirement.

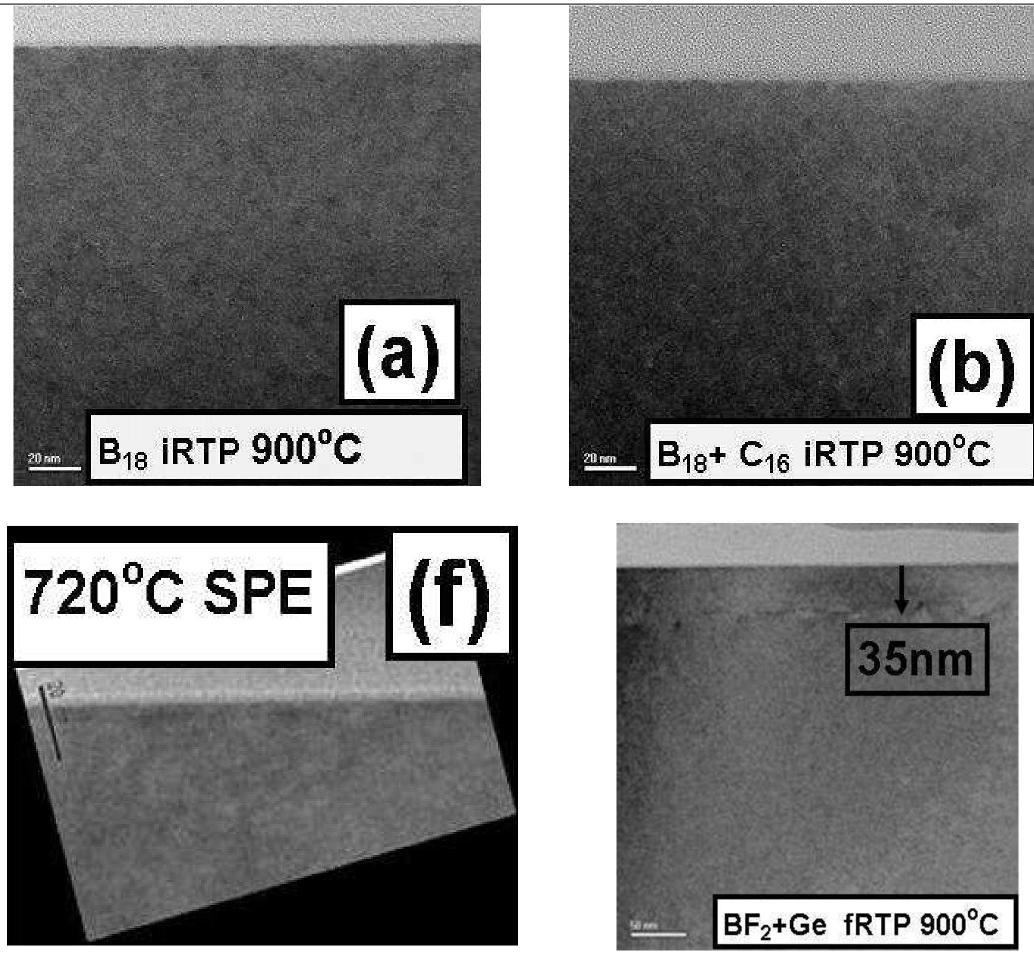
$R_s \cdot X_j$: 32 nm Node

Anneal Conditions for $B_{18}H_{22}$



$R_s \cdot X_j$ shows that the flash anneal satisfies the 32nm requirement.

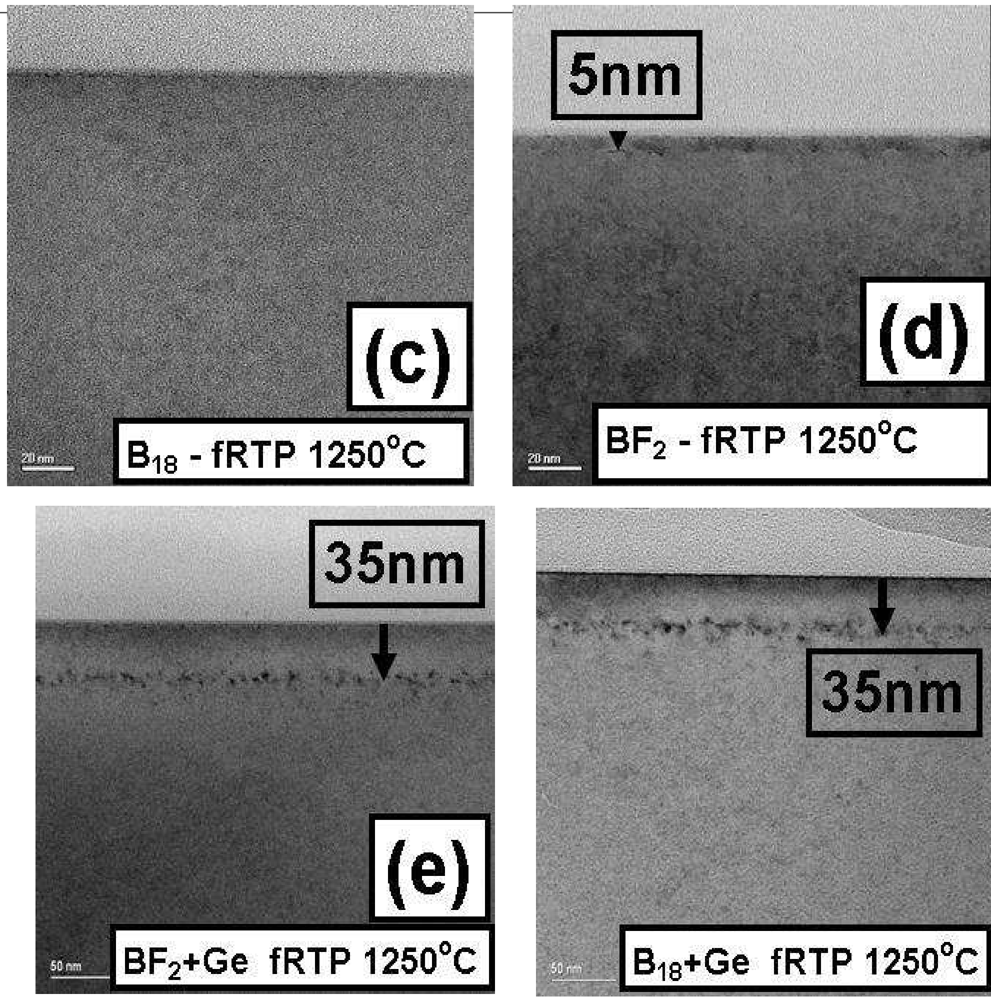
XTEM: iRTP 900^{o}C Anneal



With diffusionless anneal, no EOR defects with $B_{18}H_{22}$ and $B_{18}H_{22}$ + $C_{16}H_{10}$.

XTEM: fRTP (T_i 750ºC & T_{pk} – 1250ºC)

Diffusionless Anneal



With diffusionless anneal, no EOR defects with $B_{18}H_{22}$.

XTEM: iRTP 900°C & Flash Anneal

Table I

Implant	Anneal (iRTP)	EOR defect	Depth (nm)
B_{18}	iRTP @ 900°C	NO	x
B_{18} + C_{16}	iRTP @ 900°C	NO	x
B_{18} + Ge	iRTP @ 900°C	YES	35
B_{18} + C_{16} + Ge	iRTP @ 900°C	YES	35
BF_2	iRTP @ 900°C	NO	x
BF_2 + C_{16}	iRTP @ 900°C	NO	x
BF_2 + Ge	iRTP @ 900°C	YES	35
BF_2 + C_{16} + Ge	iRTP @ 900°C	YES	35

Table II

Implant	Anneal (iRTP)	EOR defect	Depth (nm)
B_{18}	T_i 750°C T_{peak} – 1250°C	NO	x
B_{18} + Ge	T_i 750°C T_{peak} – 1250°C	YES	35
BF_2	T_i 750°C T_{peak} – 1250°C	YES	5
BF_2 + Ge	T_i 750°C T_{peak} – 1250°C	YES	32

- $B_{18}H_{22}$ is the only implant technology with no EOR defects following flash anneal.
- With diffusionless anneal, Ge co-implants are left with EOR defects whereas they are absent with $C_{16}H_{10}$ co-implants.

Summary

- **32nm targets are achievable with 500eV equivalent B18 implant and flash anneal**
- **Boron diffusion observed with 900C spike**
  - Amorphous state diffusion
  - Profile tail diffusion driven by EOR damage
- **EOR damage not observed for B18 implant even with diffusionless anneal process**

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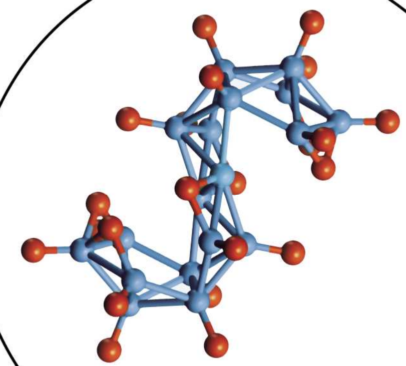
The Cluster Implant *Source*

ClusterCarbon Implant for NMOS Stressor



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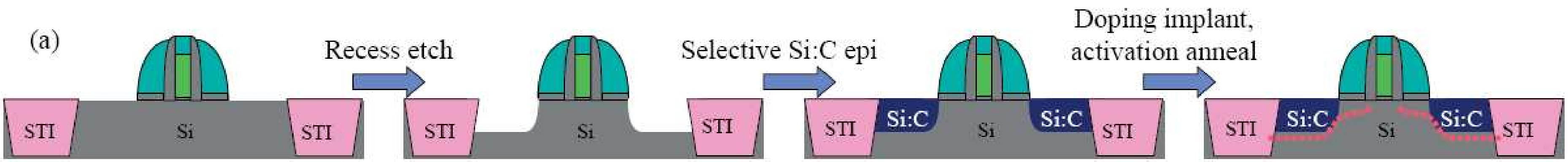
NMOS Stressor Requirements

- **Emulate success of PMOS e-SiGe for NMOS**
  - Provide performance boost independent of scaling and gate stack formation
    - *Goal of 10-30% drive enhancemen*
- **Si:C materials science very different from SiGe**
  - Epi process chemistry very difficult
  - 1.5-2% limit to carbon fraction in silicon lattice
- **Substitutional carbon required**
  - Interstitial carbon degrades stress
- **Compatible with CMOS integration**

Si:C Stressor Formation :
Selective epi Growth approach

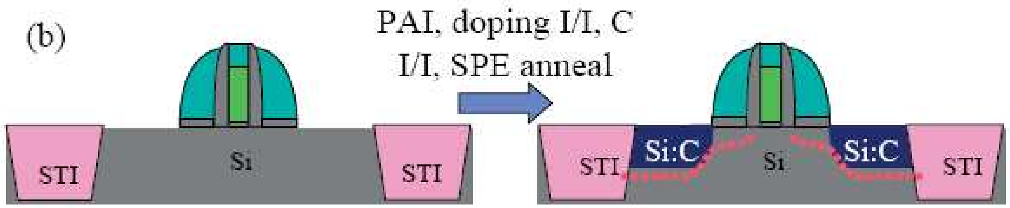
Conventional recess etch and SiC selective epi growth



Challenges :

- Expensive tool
- Narrow process window
- Faceting issue
- Extra etch and cleaning steps
- Difficult to get repeatable carbon incorporation
- Low throughput

Si:C Layer Formation :
ClusterCarbon™ implant approach



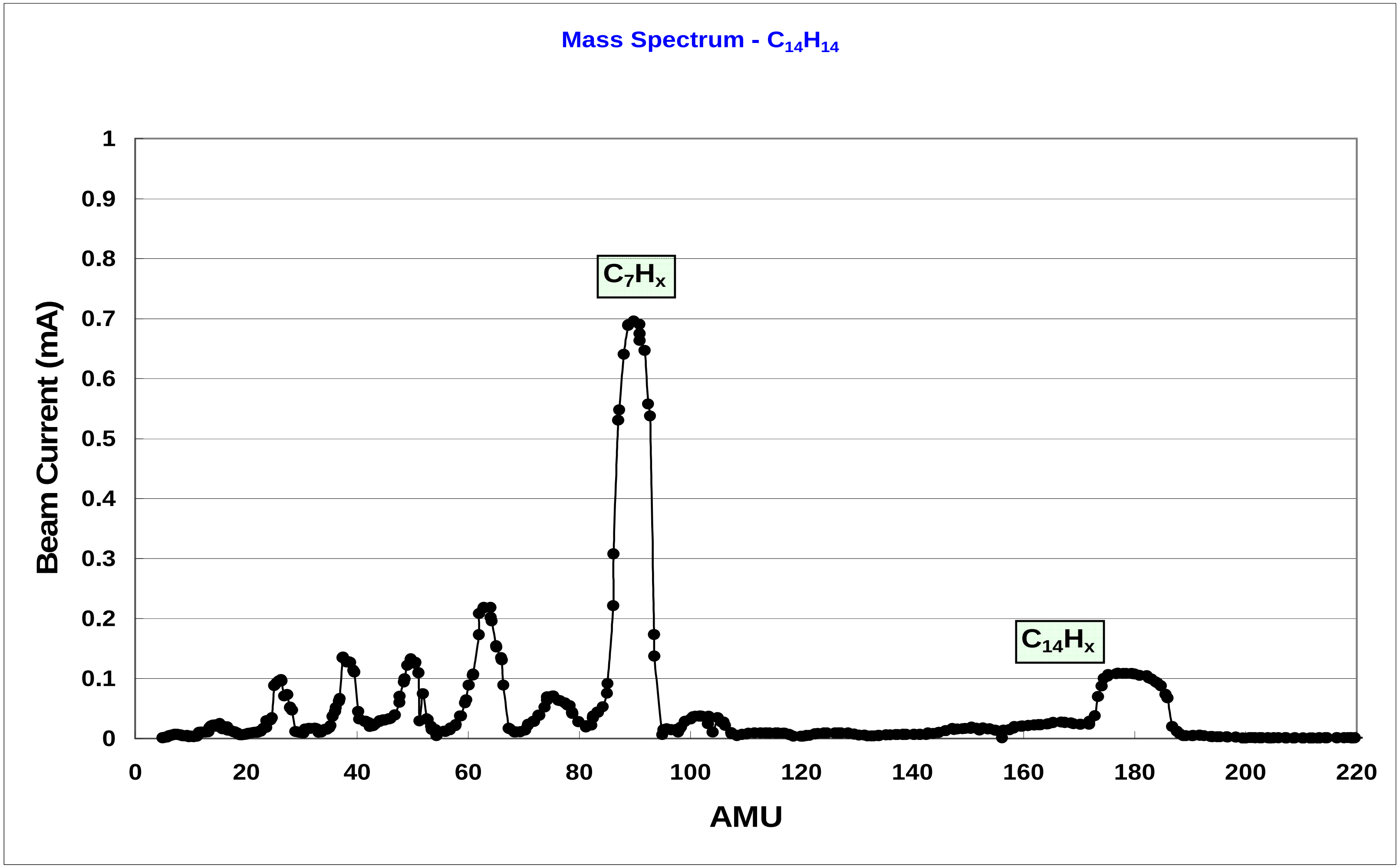
Advantages :

- **Self-amorphization with cluster implants**
- **Elimination of extra PAI-implant**
- **By suitable process sequence, elimination of end of range damage and better recrystallization**
- **Higher $[C]_{subs}$ with millisecond anneal**
- **Better leakage current performance**
- **Higher throughput**

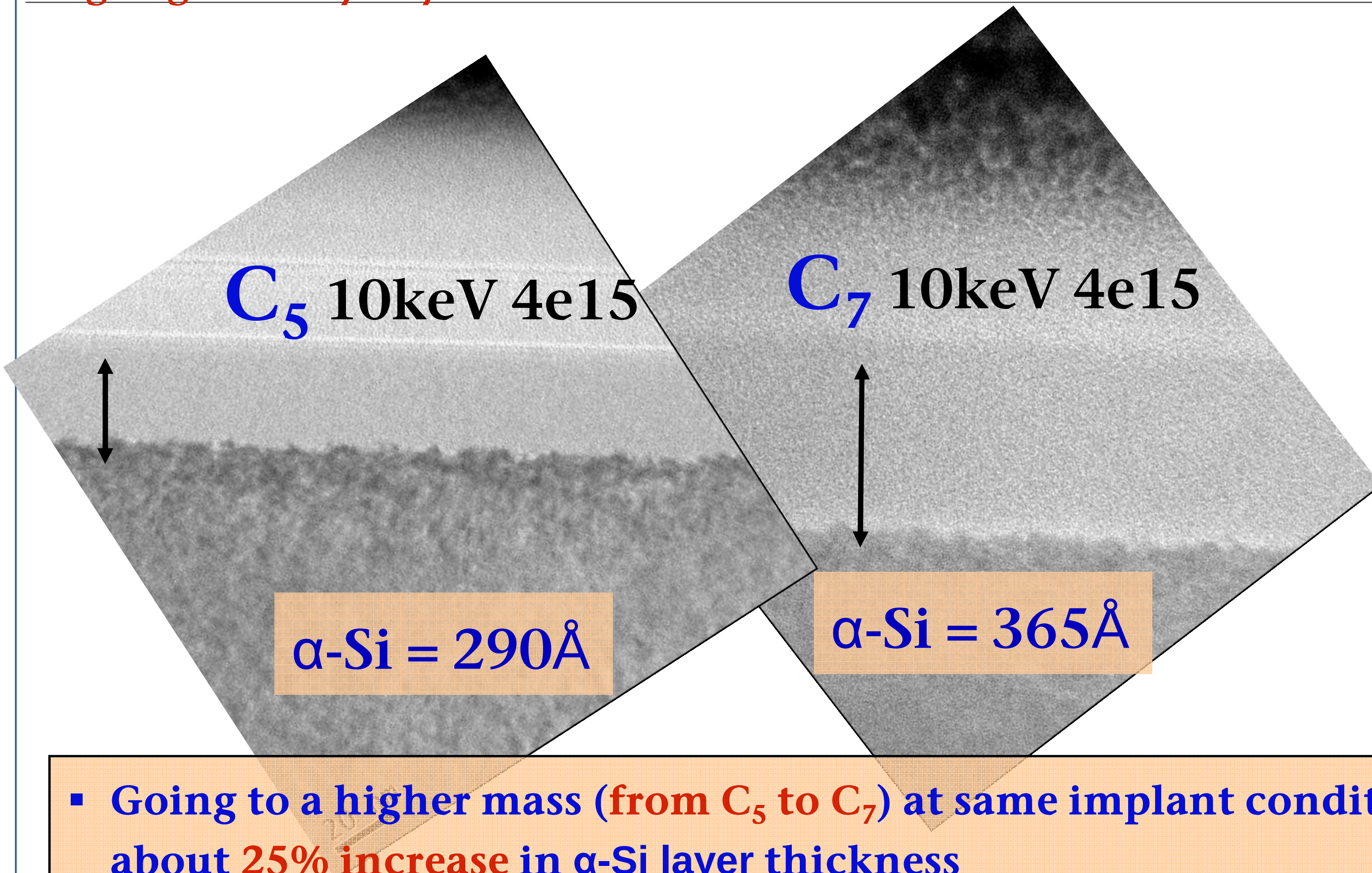
ClusterCarbon Implant Advantages for Si:C Stressor

- **Implant approach provides simple and direct process for stressor formation**
- **Implant provides very accurate control (1%) of carbon concentration**
  - Multiple implants at different energies can be used to tailor carbon depth profile
- **ClusterCarbon implant - self-amorphization with low crystalline damage below a-Si layer**
  - Amorphous layer thickness determines stressor thickness
- **Highest substitutional carbon achieved by recrystallation of amorphous layer by millisecond anneal process**

ClusterCarbon: C_7H_7 from $C_{14}H_{14}$



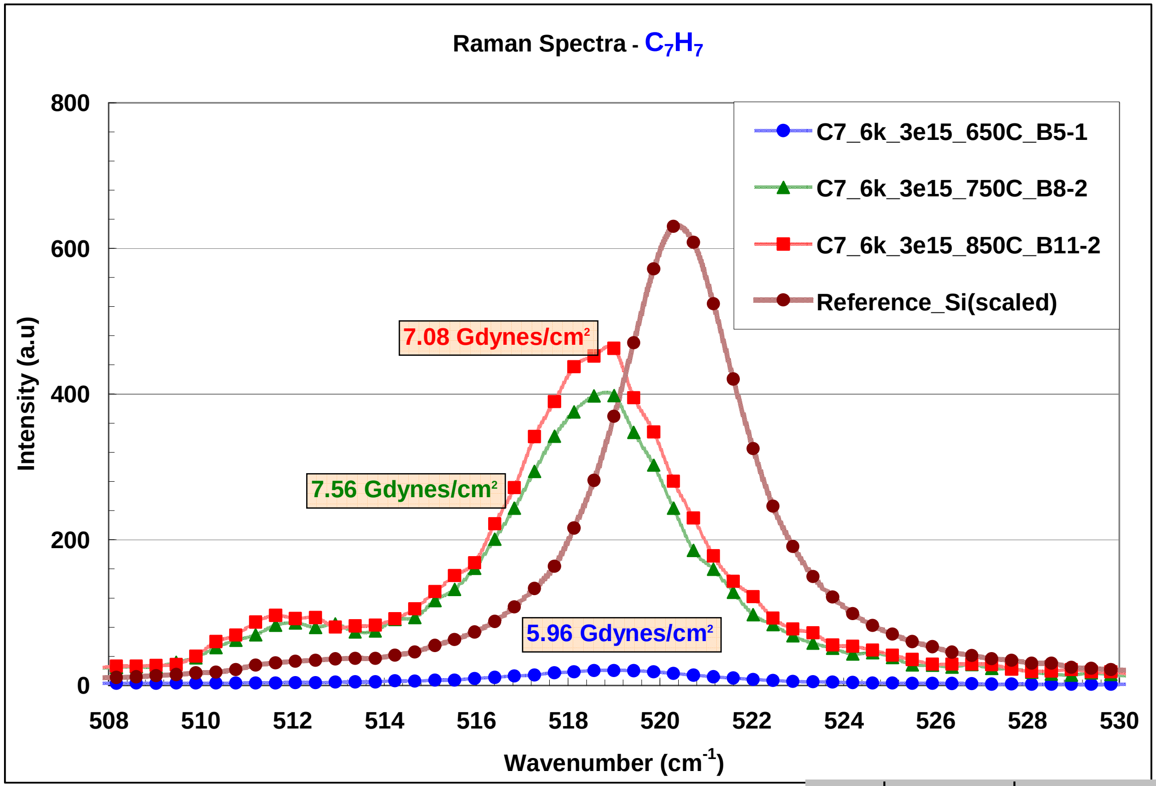
ClusterCarbon Self-amorphization - C_5H_5 vs C_7H_7



- Going to a higher mass (from C_5 to C_7) at same implant condition yields about 25% increase in α-Si layer thickness

UV Raman (363.8nm) Results

C_7H_7 @3e15



Strained layer thickness equal to the amorphous layer thickness for 750°C sample

#	Species	Carbon Implant & Anneal	Strained layer thickness from Wafer bow (Å)	Amorphous layer thickness (TEM) (@6keV)	UV Raman Stess (MPa)
1	C_7H_7	6k_3e15_750C	232	220	760

Substitutional Carbon Percentage from HRXRD

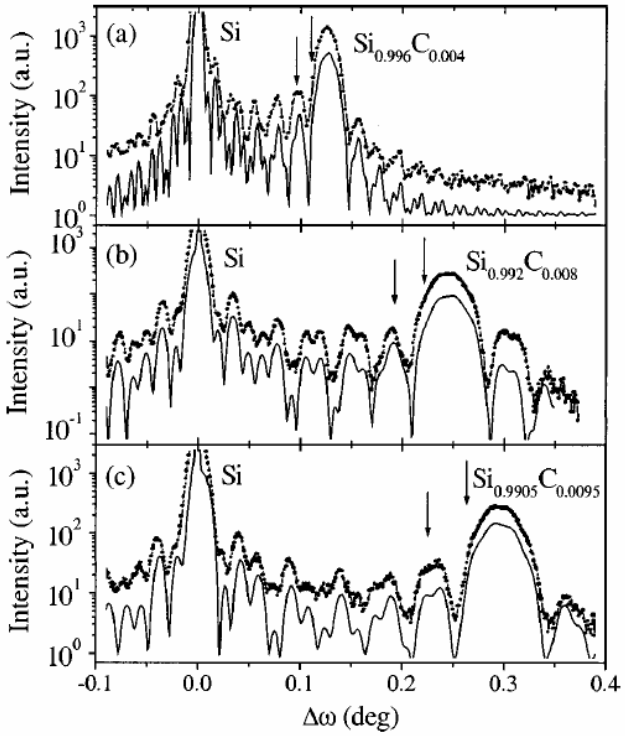
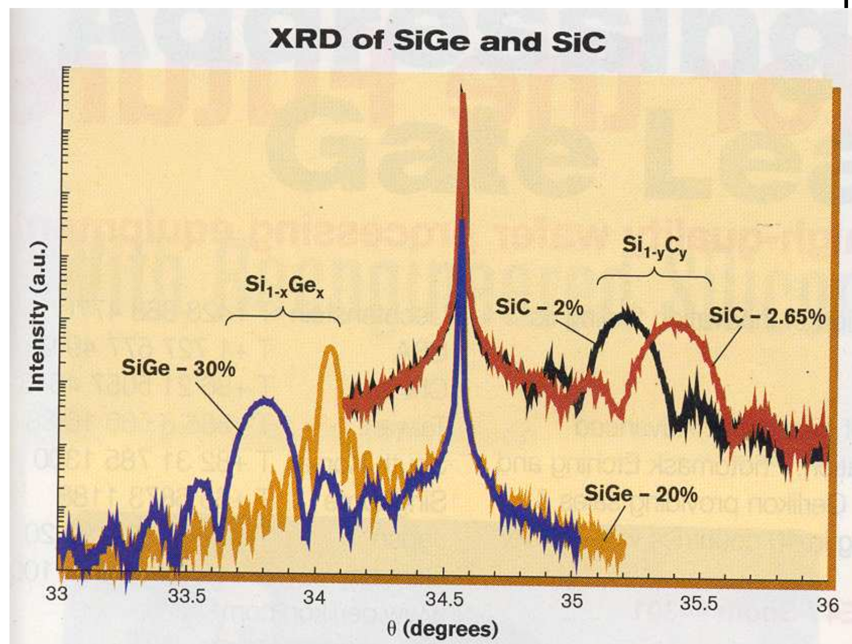


FIG. 2. XRD rocking scans around the (004) Bragg reflection of three epilayers (dots: measurements, solid lines: simulations). Arrows indicate peak positions corresponding to epilayers with the same C concentrations as given, but assuming a variation of the relaxed lattice constant according to Vegard's rule between Si and C, and between Si and β-SiC.

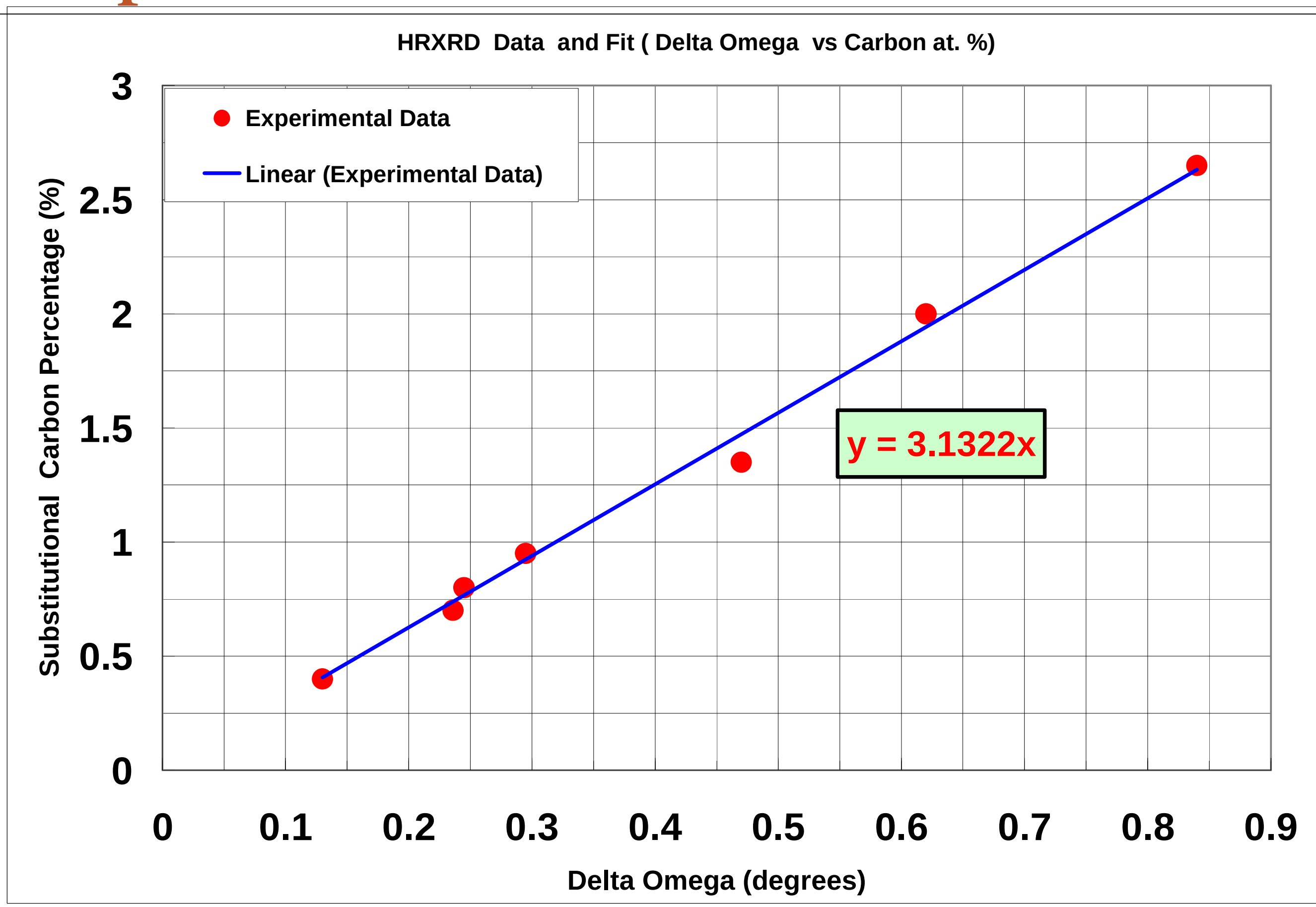
Semi. Int. Mar. 2007 issue



6. Different concentrations of $Si_{1-x}Ge_x$ and $Si_{1-y}C_y$ epi films used as pMOS and nMOS S/D stressors, respectively. Interference fringes indicate high crystalline quality.
(Source: ASM)

Δω vs substitutional carbon percentage

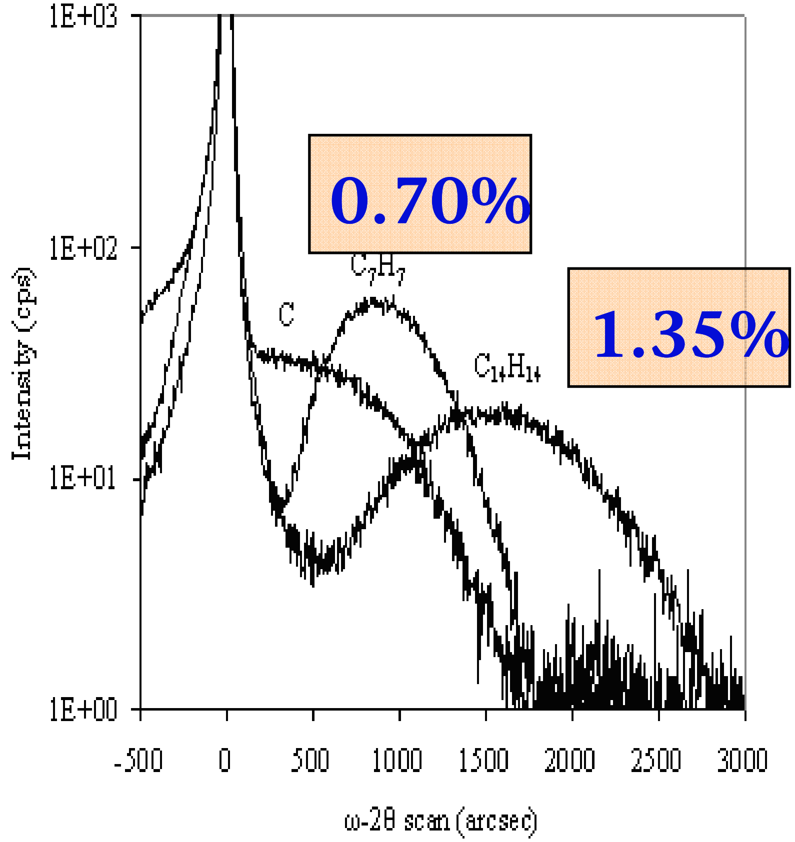
Substitutional Carbon Percentage from HRXRD Fit for Experimental data



From $\Delta\omega$ we can estimate substitutional carbon percentage

Substitutional Carbon Percentage determined with HRXRD

ECS 2007 – TI, Axcelis, SemEquip



VLSI 2007 – pg 44

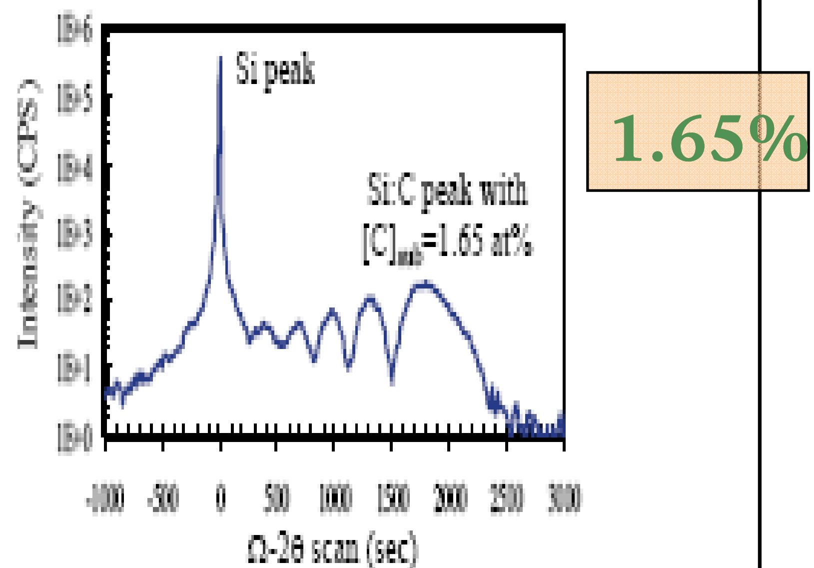
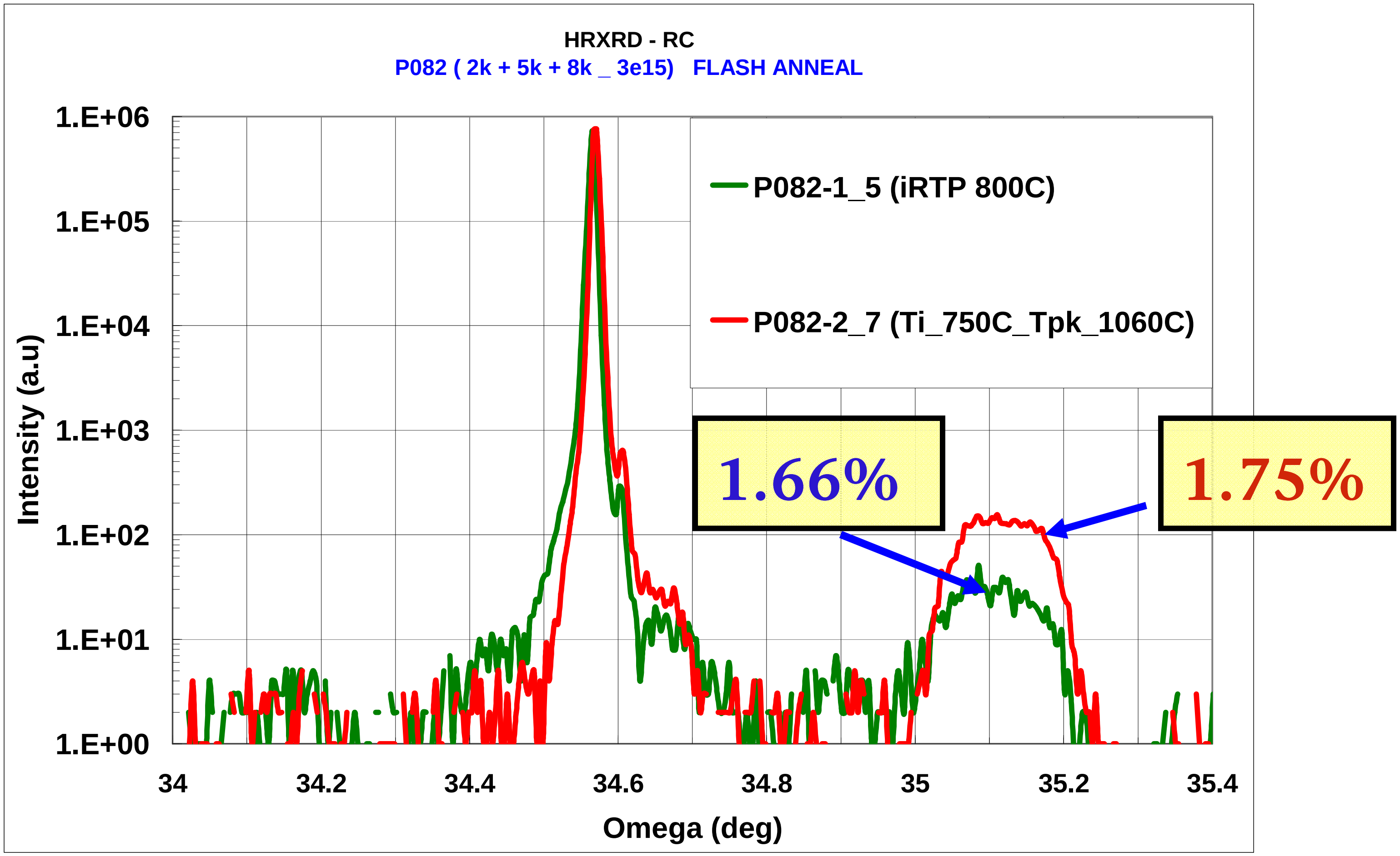
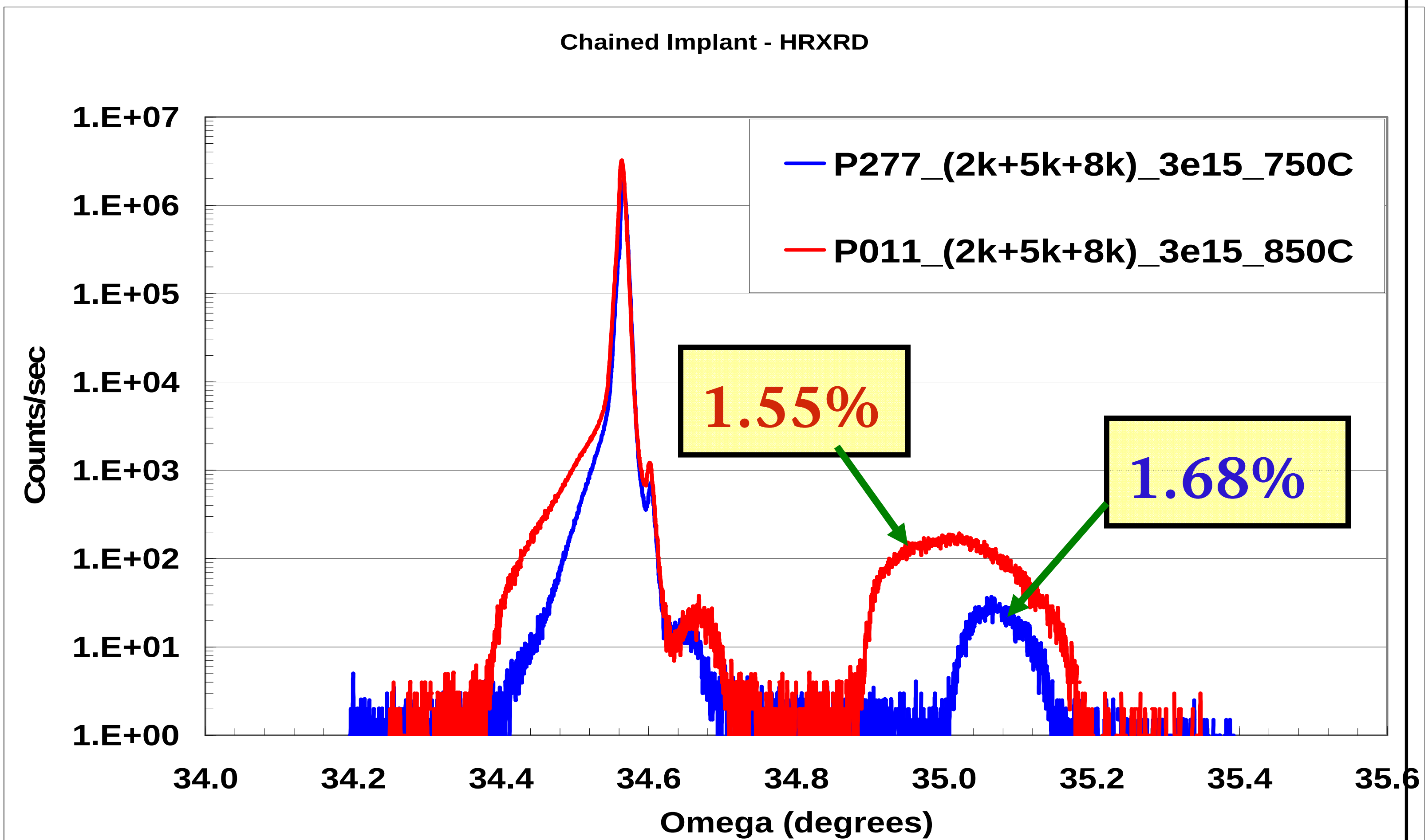


Fig. 2 HRXRD rocking curve of the SPE Si:C film ($[C]_{sub}$=1.65 at.%) grown on (100) Si substrate. The well defined Si:C peak and fringes indicate that the Si:C film is high-quality single crystal.

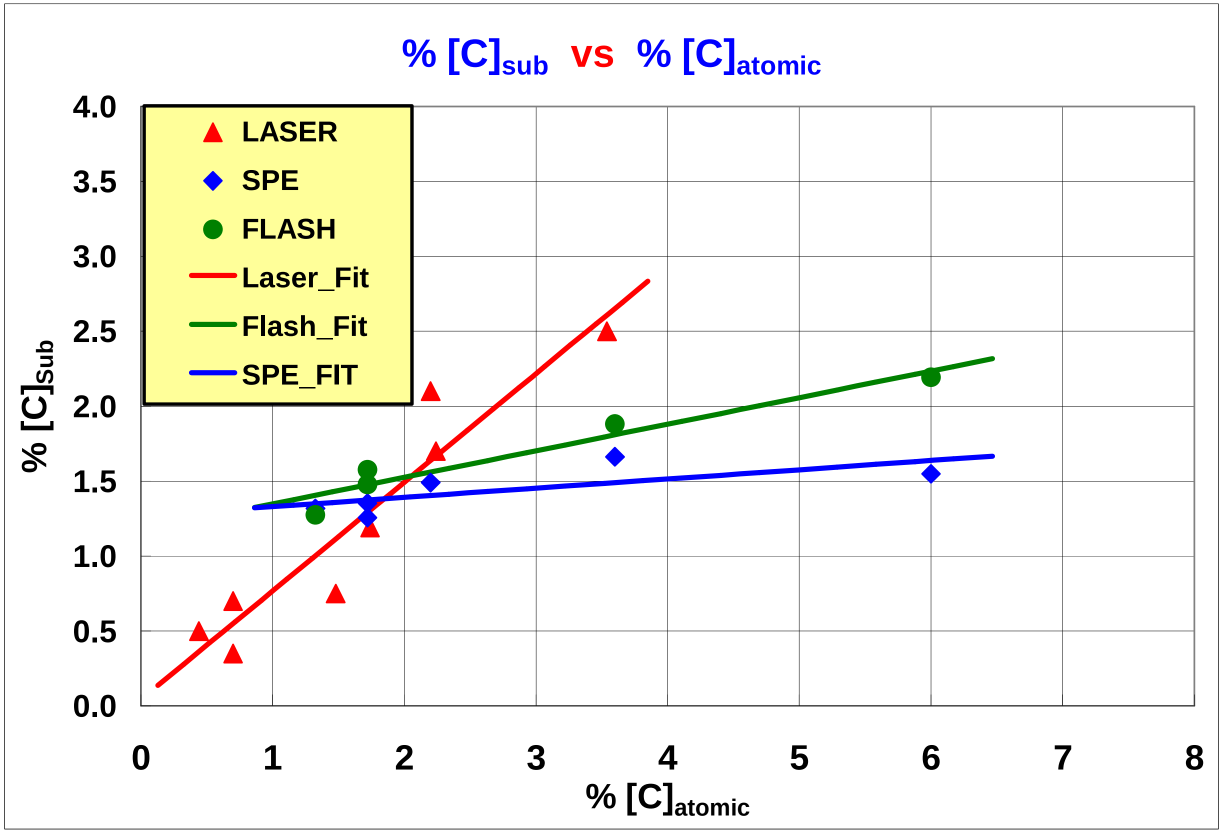
Chained or Multiple implant – HRXRD Flash Anneal (2k + 5k + 8k) @ 3e15



Chained or Multiple Implant – HRXRD
SPE Anneal @ 750ºC and 850ºC (2k + 5k + 8k) @ 3e15

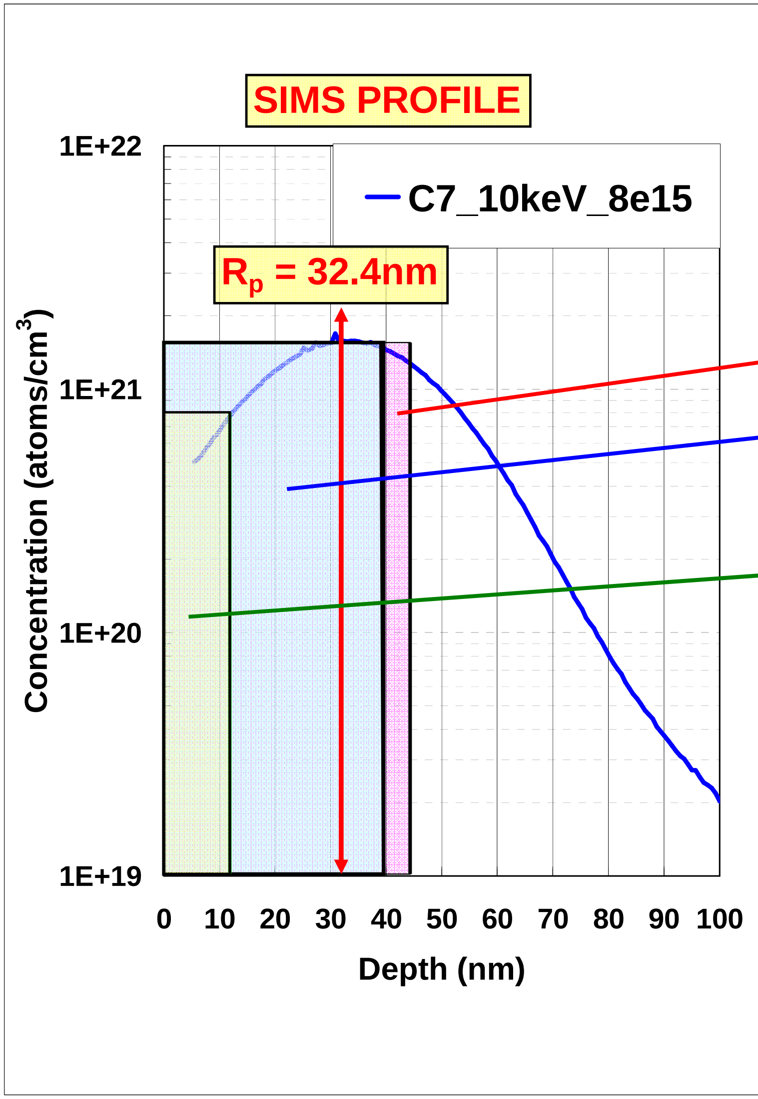


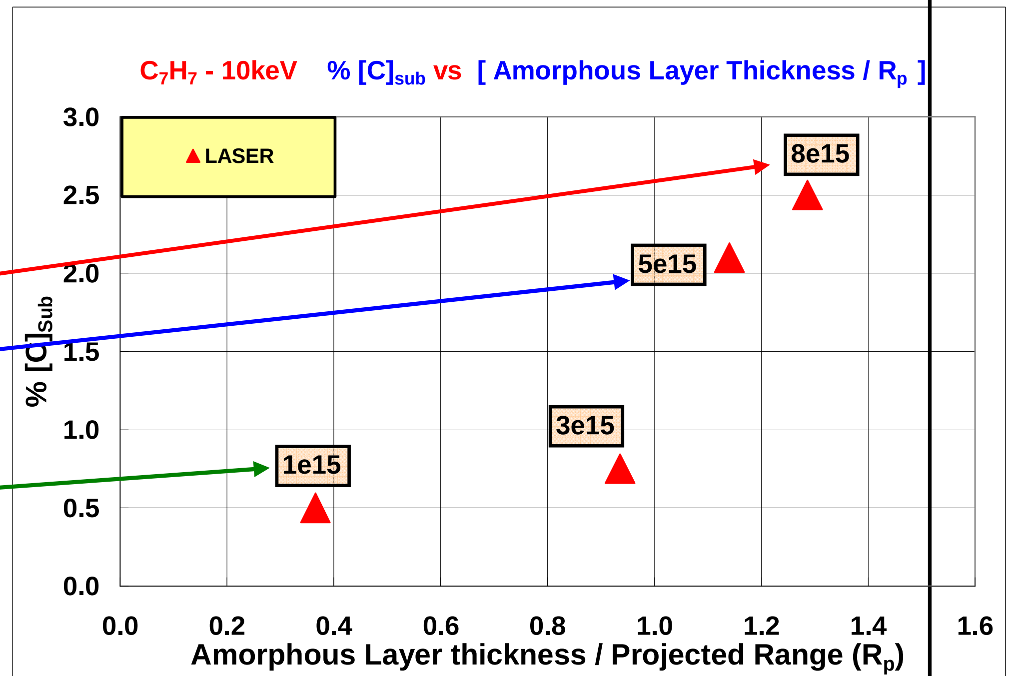
ClusterCarbon - % $[C]_{sub}$ vs % $[C]_{atomic}$



- LASER: $[C]_{sub}$ increases with dose
- SPE: $[C]_{sub}$ reaches its solid solubility limit (~1.5%)

% $[C]_{sub}$ Dependence on α-Si Thickness





HRXRD Results - Substitutional Carbon

#	Implant Energy	SIMS plateau depth at 5e20 (atoms/cm^3) (nm)	% of Substitutional Carbon for various anneals					
			SPE 750°C - 5sec	SPE 850°C - 5sec	iRTP 800°C	iRTP 850°C	Flash T_i 750°C T^{peak} 1059°C	Flash T_i 750°C T^{peak} 1272°C
1	2k + 5k + 8k 3e15 + 3e15 + 3e15	41	1.55	1.68	1.66	1.35	1.75	2.19
2	3k + 6k + 9k 1.5e15 + 3e15 + 3e15	48	1.66	1.50	1.66	1.22	1.82	1.88

- Percent of substitutional carbon is highest with MSA anneal
- For SPE, going beyond 850°C reduces the amount of substitutional carbon, confirming the results that carbon is kicked out of its substitutionality beyond 800°C

Summary

- ClusterCarbon provide an approach to NMOS stressor which is simple, direct and inexpensive
- ClusterCarbon approach demonstrates incorporation of greater than 2% substitutional carbon with millisecond anneals
- 1.5% substitutional carbon could be achieved just with SPE alone
- The ClusterCarbon approach eliminates the need for PAI implant that is otherwise required for monomer carbon implants
- % $[C]_{sub}$ scales with percent of atomic carbon concentration
- Amorphous layer depth is critical in obtaining higher $[C]_{sub}$
- The heavier the mass of the ClusterCarbon, the better is the $[C]_{sub}$ incorporation