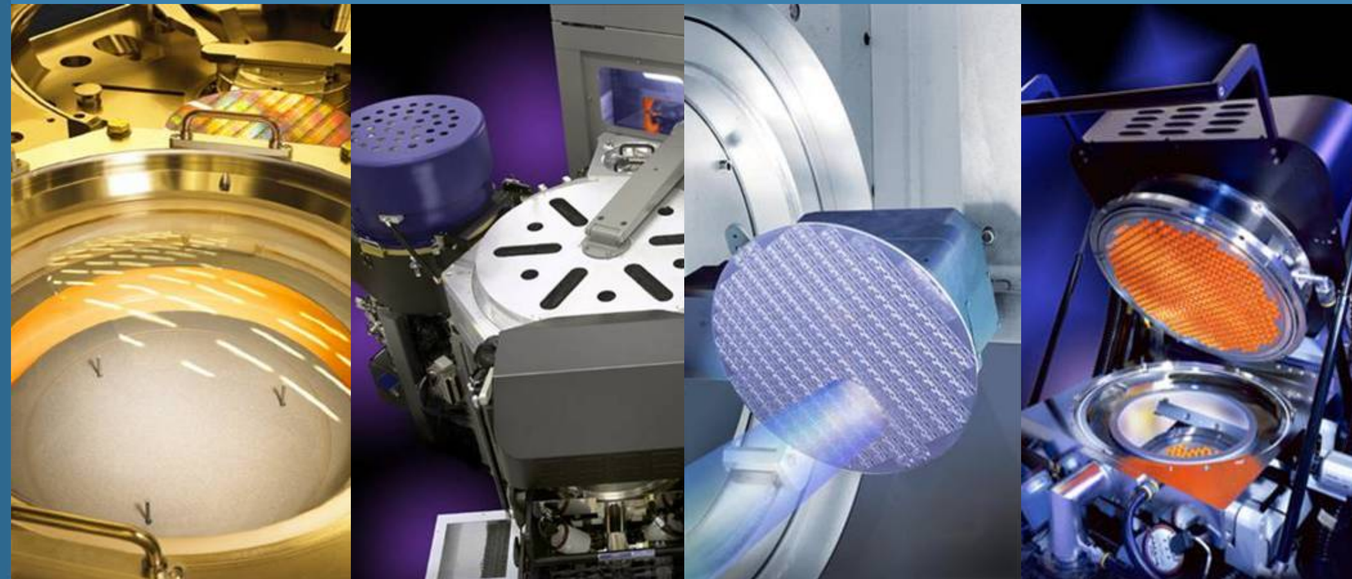
Front End Products Group



Use of Co-Implantation to Extend Spike RTP to the 65nm Node and Beyond

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Applied Materials, Inc., Santa Clara, CA

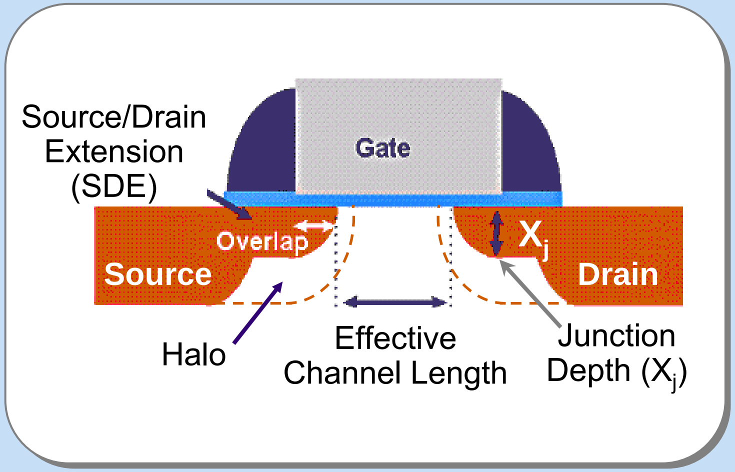
WCJTG Meeting, July 14, 2005

External Use

Outline

- Introduction – Roadmap
- Fluorine Co-Implantation for PMOS Junctions
- Carbon Co-Implantation for PMOS Junctions
- Carbon Co-Implantation for NMOS Junctions
- Summary and Conclusions

Ultra-Shallow Junction CMOS Device Scaling



ITRS 2002

Tech. Node	90nm	65nm	45nm	32nm
X_j	<250Å	<170Å	<120Å	<90Å
R_s	<660 Ω/sq	<760 Ω/sq	830 Ω/sq	940 Ω/sq
Abrupt-ness	4.1 nm/dec	2.8 nm/dec	2.0 nm/dec	1.4 nm/dec
Anneal	Spike	Transition		Advanced

Device Requirements: Increase transistor drive current ($I_{d,sat}$)
Reduce short channel effects (SCE)
Decrease power (dynamic and stand-by)

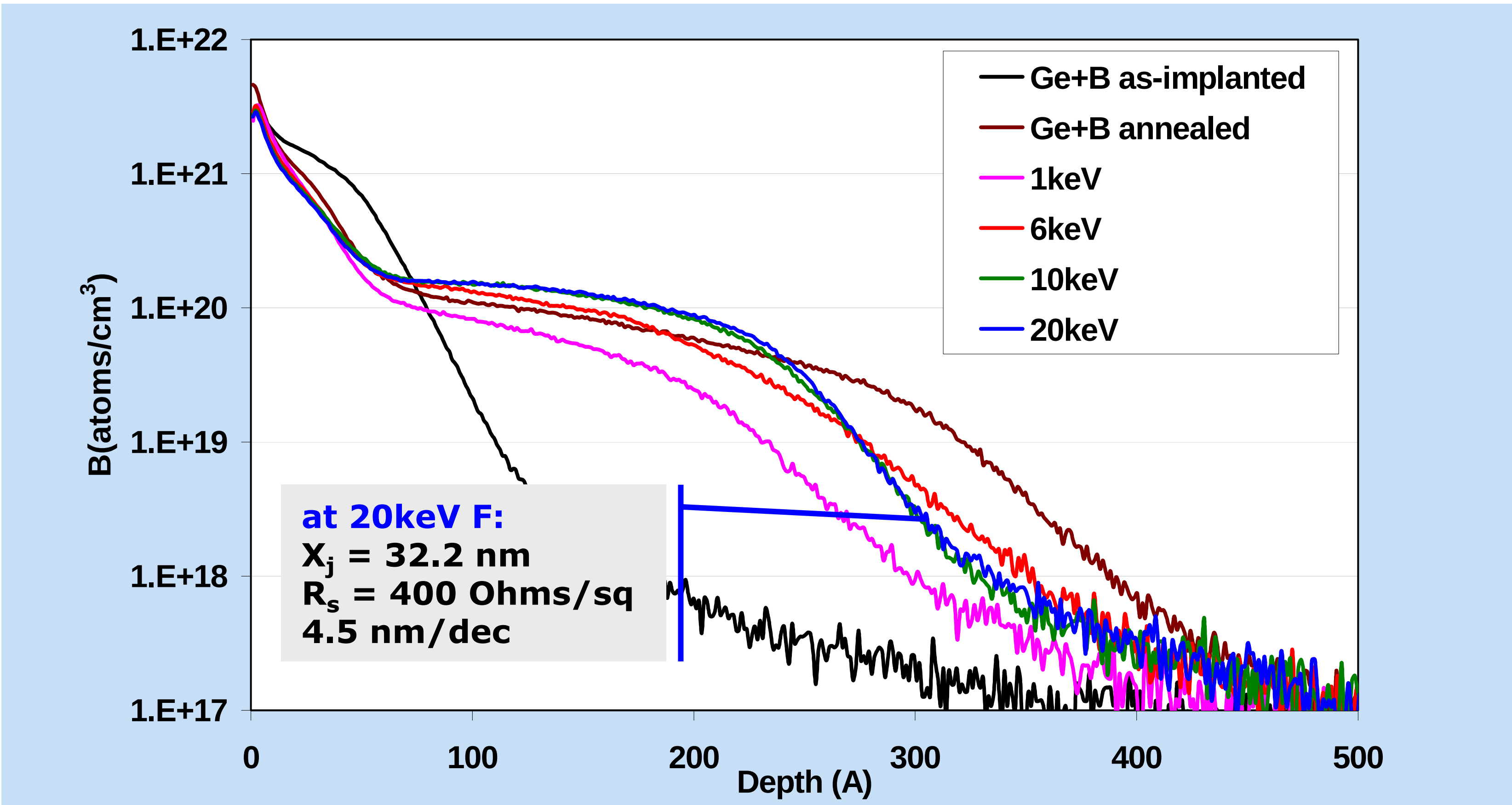
Process Requirements: Shallow junctions (X_j), Abrupt junctions,
Low sheet resistance, Optimum overlap,
Junction depth uniformity, Ease of integration

Fluorine Co-Implant for PMOS (Boron)

External Use

Fluorine Energy Optimization: SIMS Profiles

Ge/2keV/5E14 + F/2E15 + B/0.5keV/1E15 + 1050°C spike

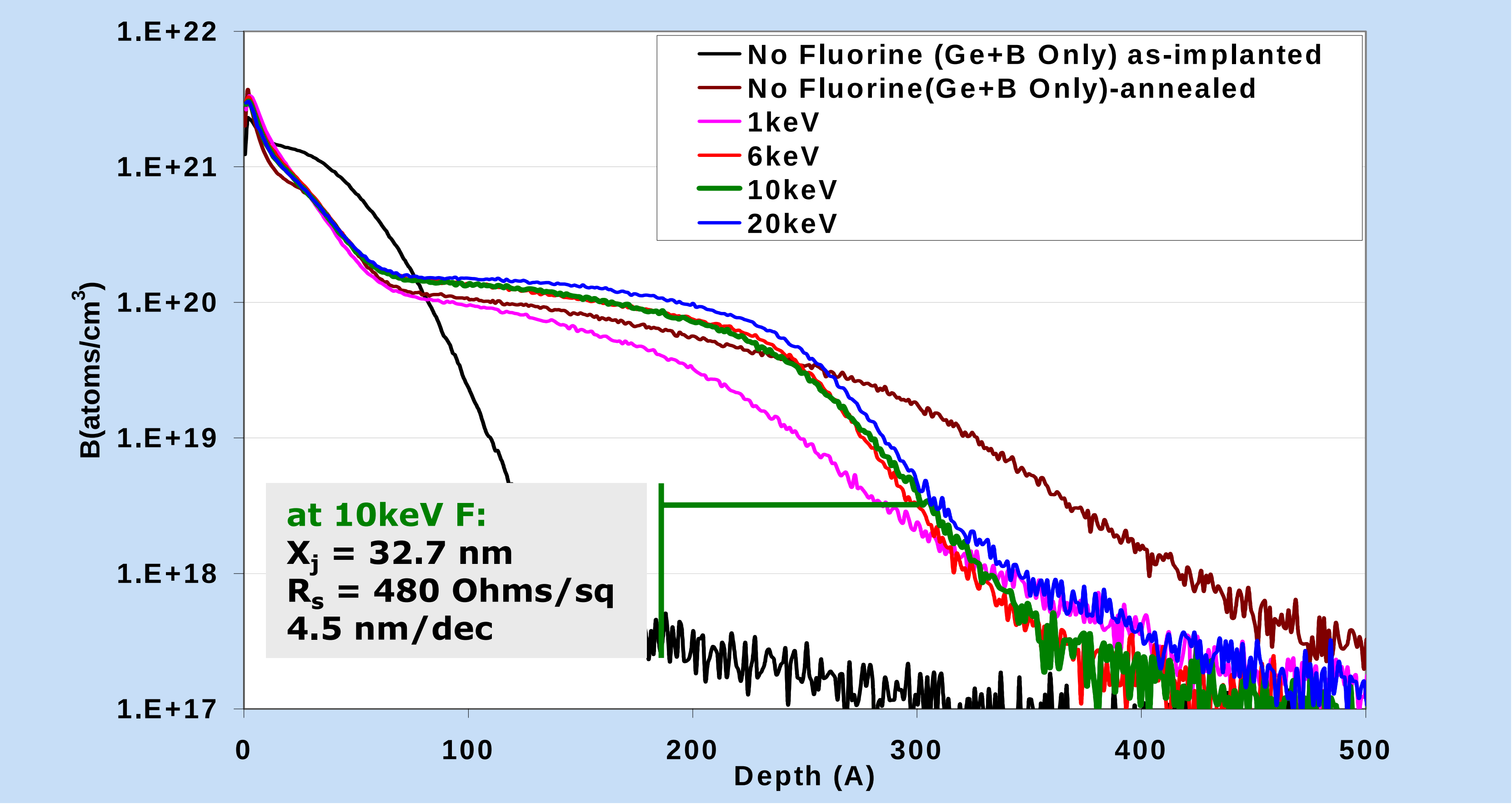


- **A steeper profile is formed with F energies from 10 to 20 keV**
- **18% decrease in both X_j and R_s and 36% in abruptness over the baseline (Ge+B only)**

H.Graoui et al., MRS 2004 proceedings.

Fluorine Energy Optimization: SIMS Profiles

Ge/20keV/1E15 + F/2E15 +B/0.5/1E15 + 1050°C spike

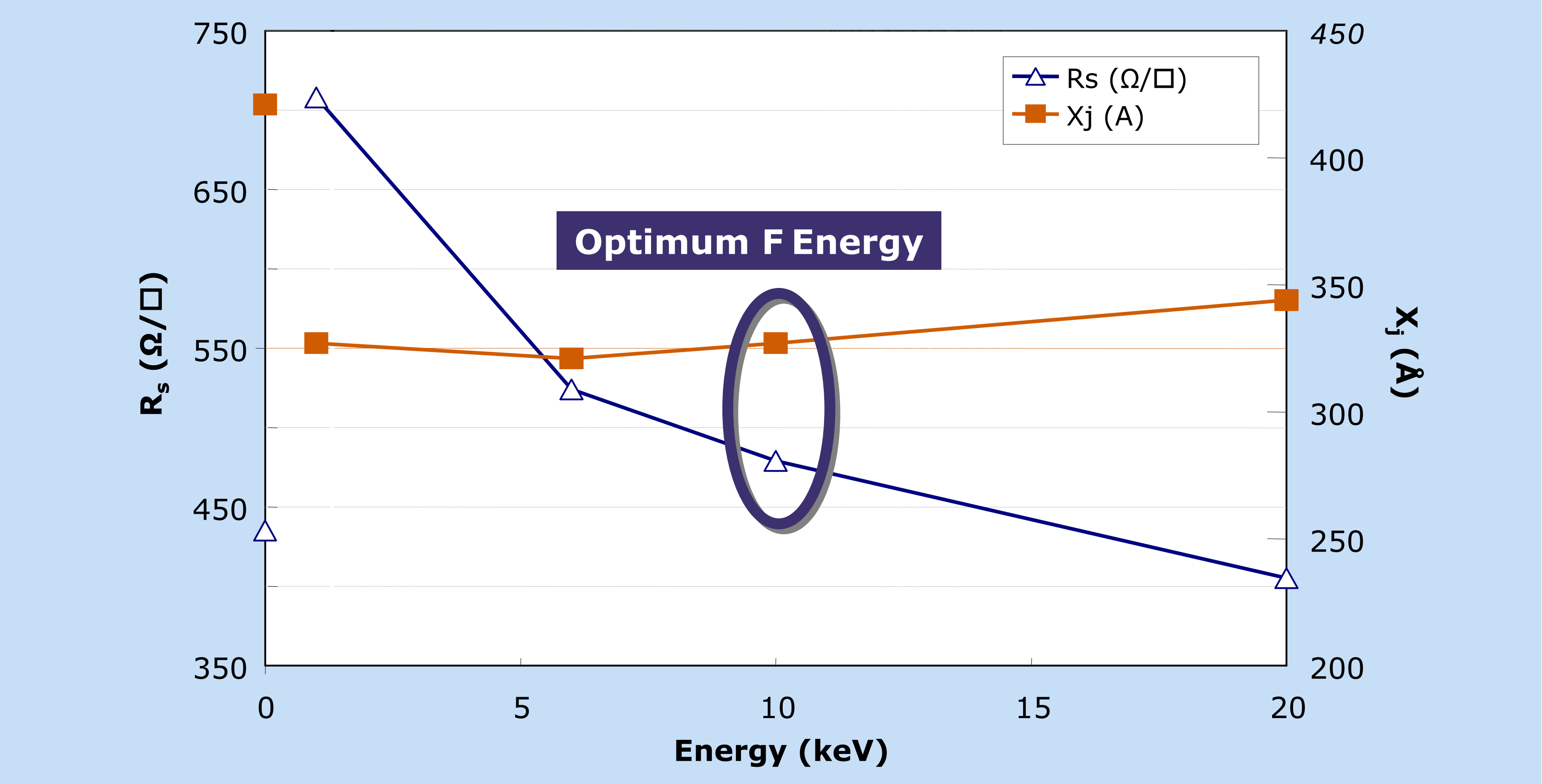


- **A steeper profile is formed with F^+ energies from 6 to 20 keV**
- **Reduction of 22% in X_j, 10% in R_s and 45% in abruptness over the baseline (Ge+B only)**

H.Graoui et al., MRS 2004 proceedings.

Fluorine Energy Optimization: R_s vs. X_j

Ge/20keV/1E15 + F/2E15 + B/0.5/1E15 + 1050°C Spike Anneal

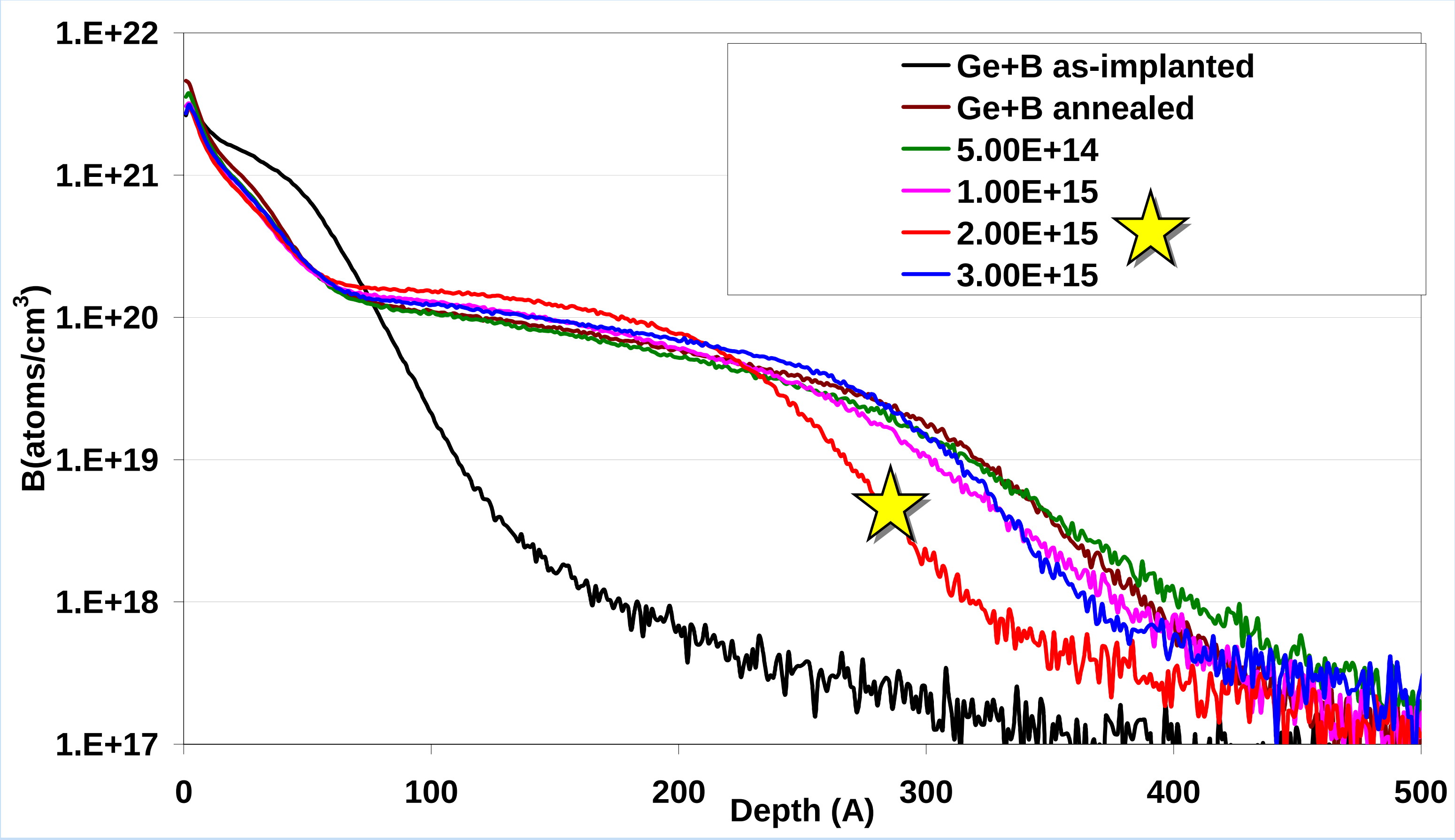


Optimum F energy is 10 keV ➔
An energy ratio of 1-to-20 between the F and B

H.Graoui et al., MRS 2004 proceedings.

Fluorine Dose Optimization: SIMS Profiles

Ge/2keV/5E14 + F/10keV+B/0.5keV/1E15 + 1050°C spike



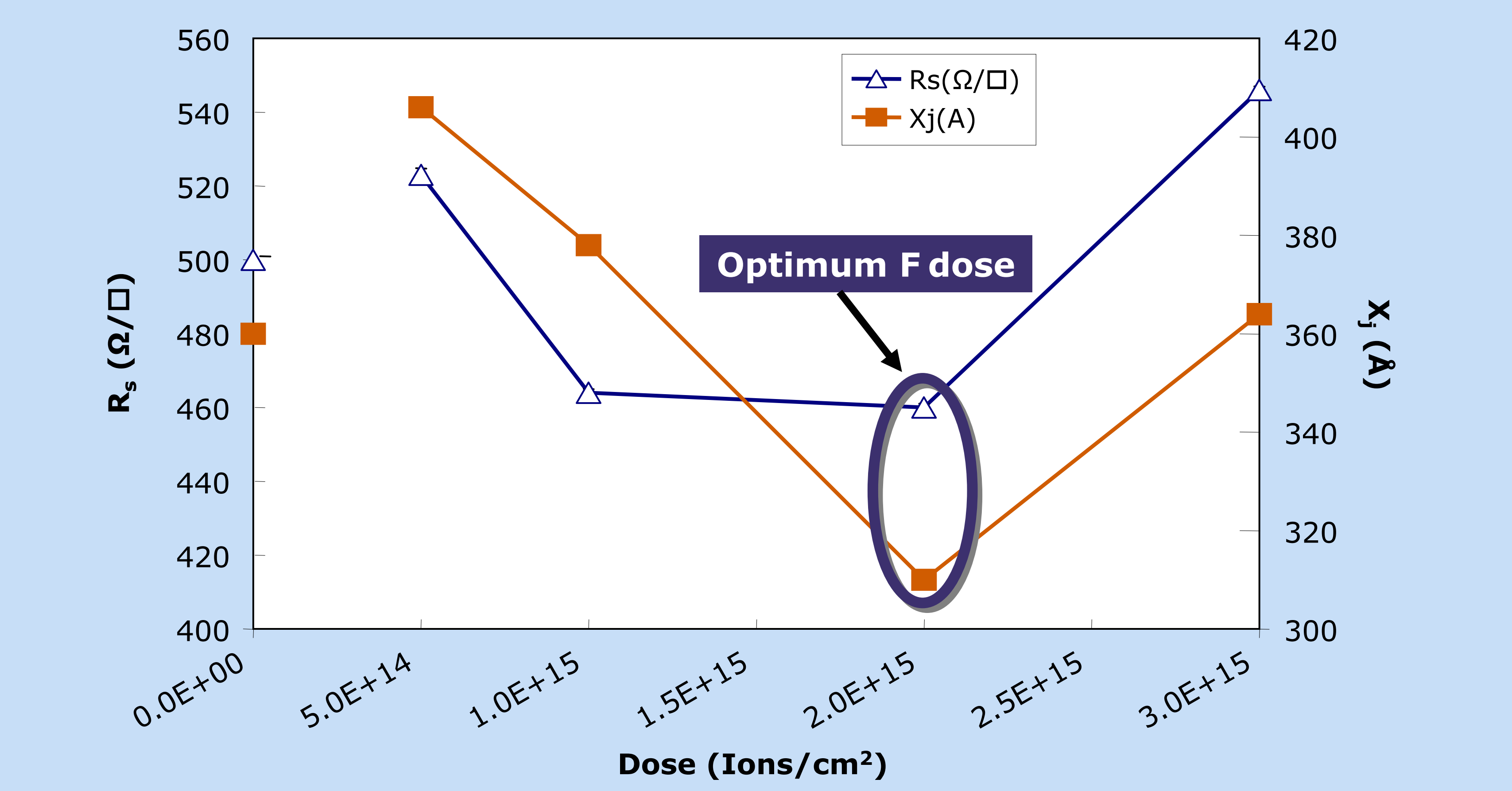
Optimum F dose is 2E15/cm^2; at higher dose the junction diffuses more

H.Graoui et al., MRS 2004 proceedings.

APPLIED MATERIALS®

Fluorine Dose Optimization: R_s vs. X_j

Ge/2keV/5E14 + F/10keV + B/0.5keV/1E15 +1050°C Spike Anneal

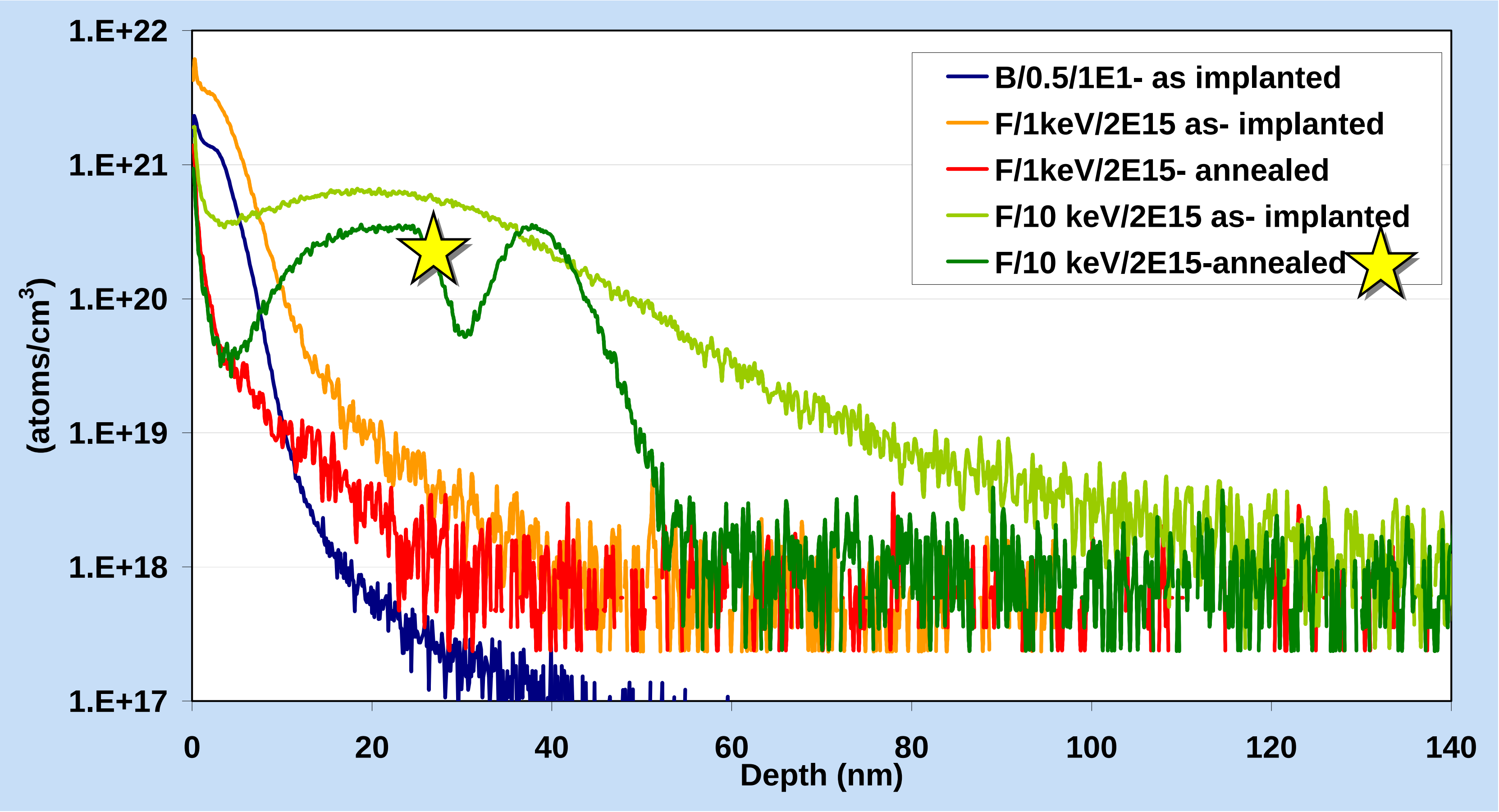


The optimum fluorine dose is 2E15 ions/cm²

H.Graoui et al., MRS 2004 proceedings.

Fluorine SIMS Profiles Before & After Anneal

Ge/2keV/5E14 + F/2E15 + B/0.5keV/1E15 + Spike



- **First 10 keV F peak located at B end-of-range and halts B diffusion**
- **Second F peak located at amorphous/crystalline interface**

H.Graoui et al., MRS 2004 proceedings.

Carbon Co-Implant for PMOS (Boron)

External Use

Experimental Details

Implants:

- Pre-amorphization (PAI)
  - Ge for B implants
  - Si for P and As implants
- Carbon
  - $1\times10^{15}/cm^2$ @2, 4 and 6 keV
- Boron
  - $7\times10^{14}/cm^2$ @ 500 eV
  - $1\times10^{15}/cm^2$ @ 500 eV
- Phosphorous
  - $7\times10^{14}/cm^2$ @ 500 eV and 1 keV
- Arsenic
  - $7\times10^{14}/cm^2$ @ 700 eV and 1 keV

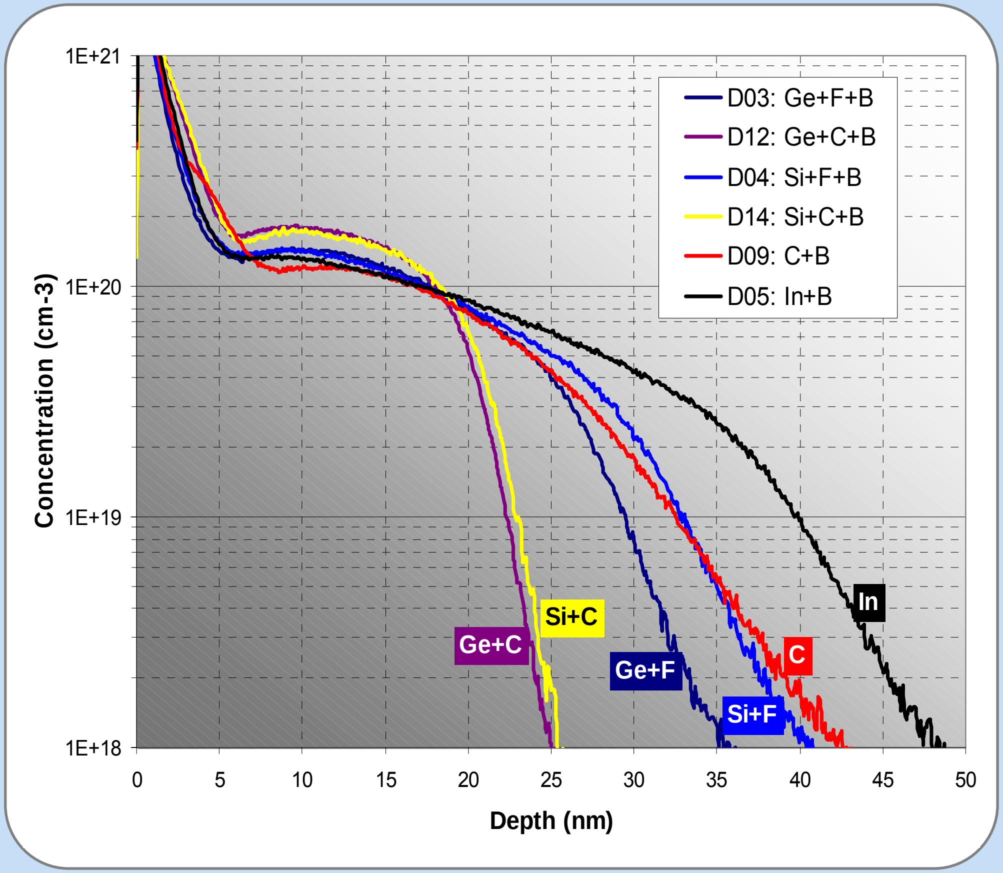
RTP spike anneals:

- Spike anneals
  - 1050°C (P, As) and 1070°C (B)
  - Ramp-up 250°C/s, ramp-down 90°C/s
  - 100% N_2 ambient for B and P
  - 10% O_2 ambient for As

65nm Ultra-Shallow Junction Solution:

Quantum® X Carbon Co-Implant + Radiance*Plus*™ Spike RTP

- Ge/C/B co-implants of optimal energies and doses with spike anneal meet 65 nm R_s and abruptness requirements
- Junction depth shortfall can be accommodated with offset spacer and halo optimization



IMEC/Philips Research Leuven. Data shown with permission.

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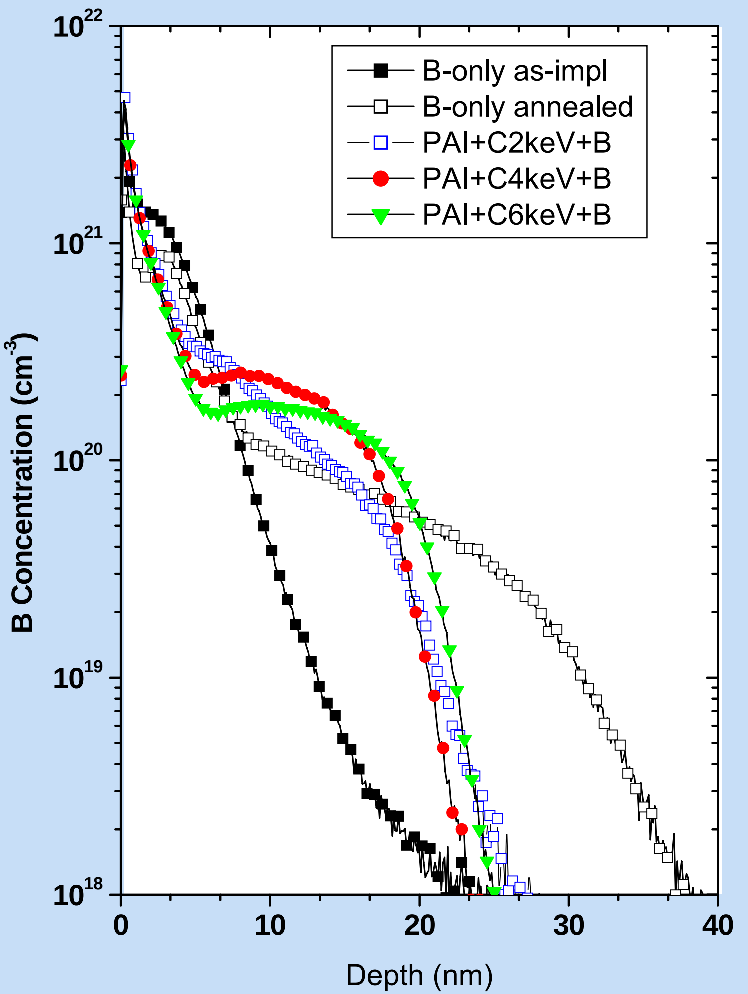
PMOS: 0.5keV B in Ge PAI+C Implanted Si



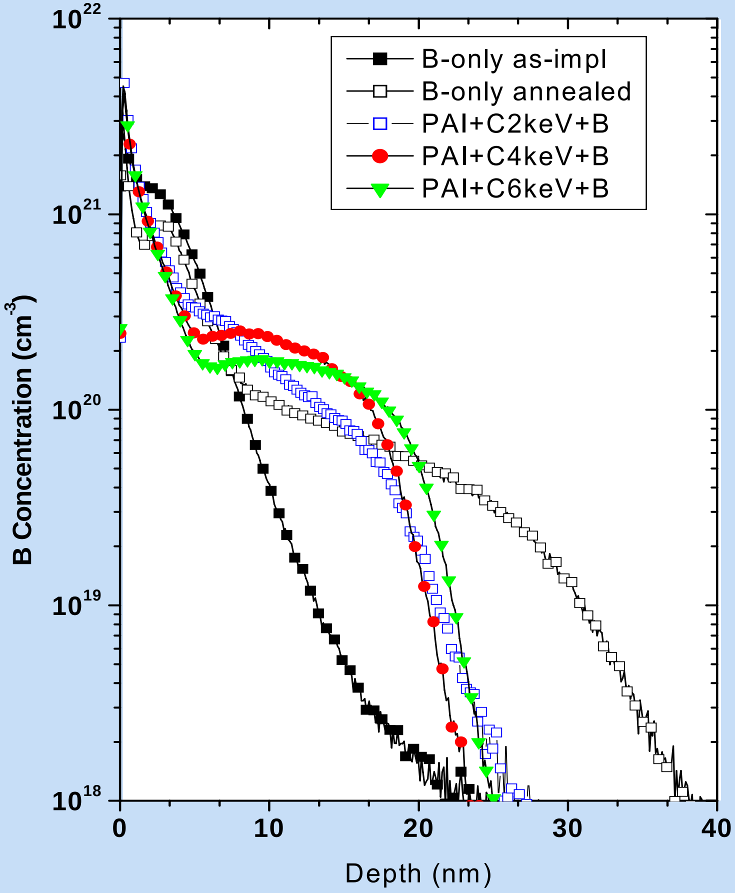
Condition	X_j (nm) at 1E19	R_s (Ohm/sq)	Abruptness (nm/dec)
B-only	30.8	490	7.2
B + PAI + C (2keV)	21.2	644	4.5
B + PAI + C (4keV)	20.6	526	2.7
B + PAI + C (6keV)	22.3	468	2.3

- Shallow, abrupt junctions produced by co-implants of Ge PAI, C, and B
- PAI: Ge 20keV 5×10^{14} cm^{-2} (35 nm α-layer)
- SPE of α-layer will result in substitutional C and improved B activation
- Substitutional C:
  - Suppresses Si interstitial-mediated B diffusion
  - Suppresses defect formation and EOR-damage-driven diffusion
  - Strain-related effects?

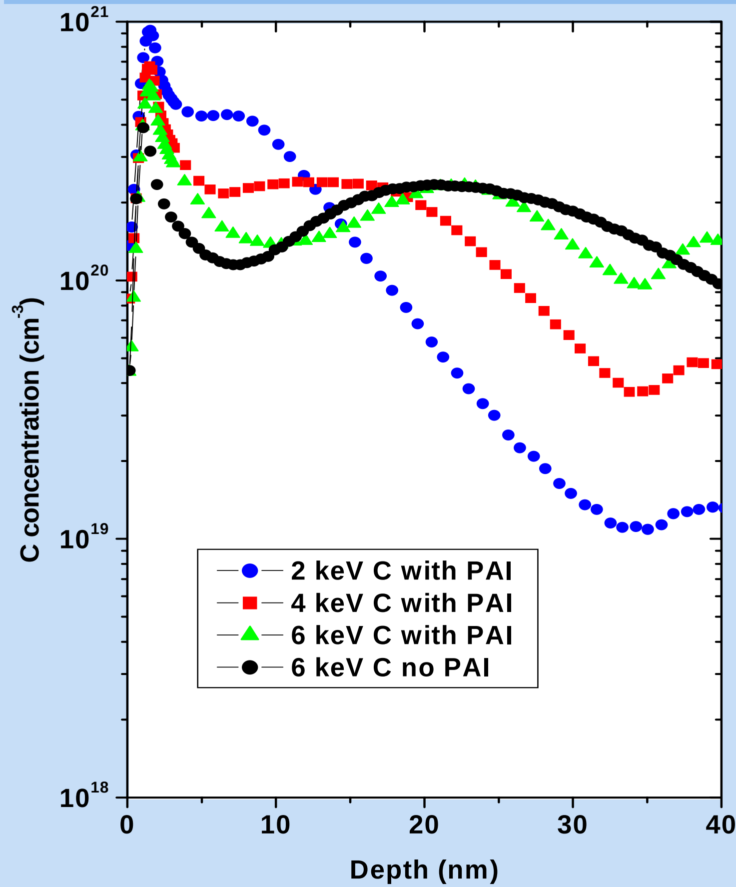
E. Collart et al., Applied Materials, IMEC, Philips Research Leuven, AVS USJ Workshop 2005.

PMOS: Annealed Boron/Carbon SIMS Profiles

Boron SIMS



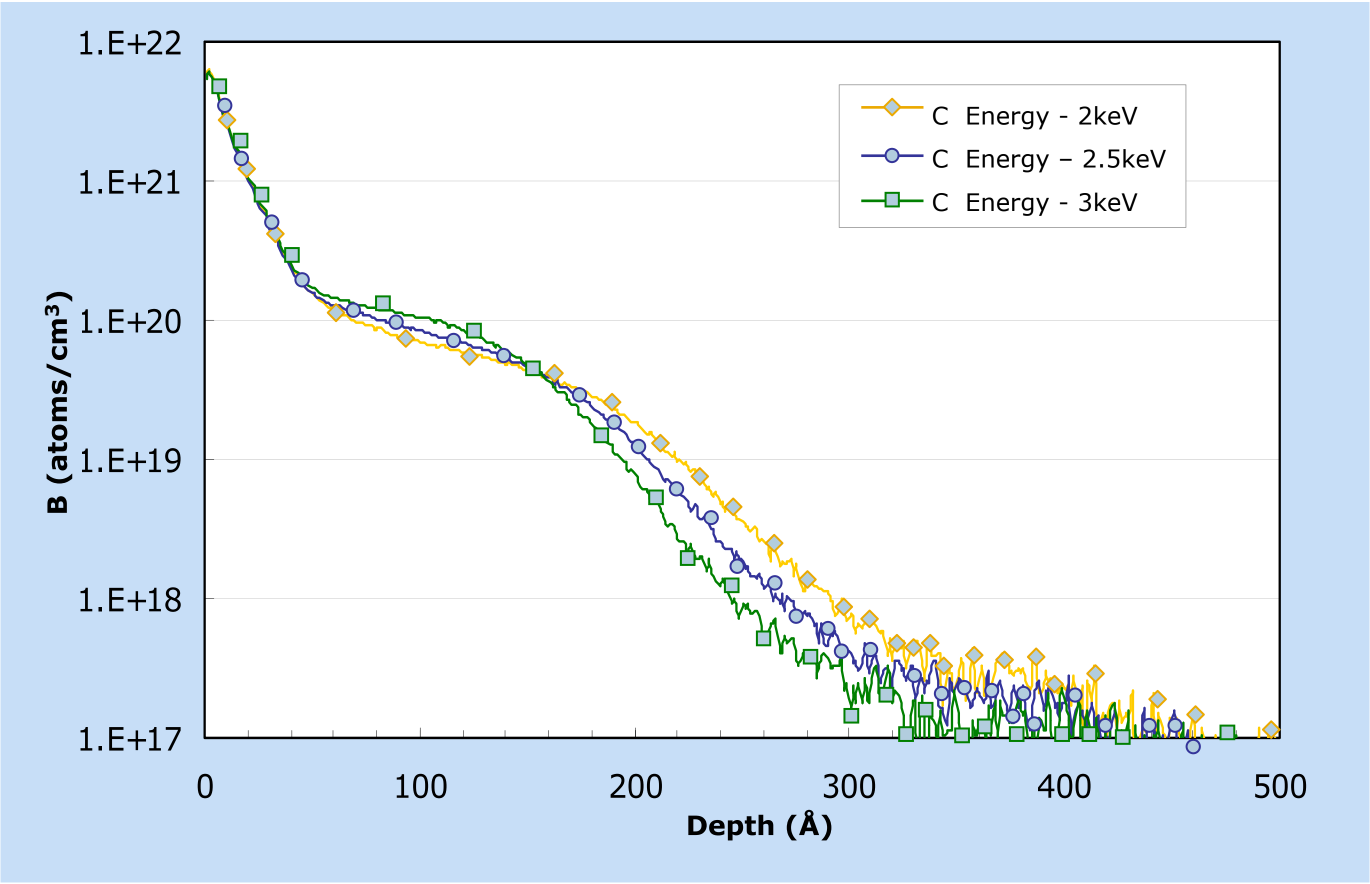
Carbon SIMS



- **First carbon peak coincides with the carbon projected range and at the end-of-range of the B profile**

E. Collart et al., Applied Materials, IMEC,
Philips Research Leuven, AVS USJ Workshop 2005.

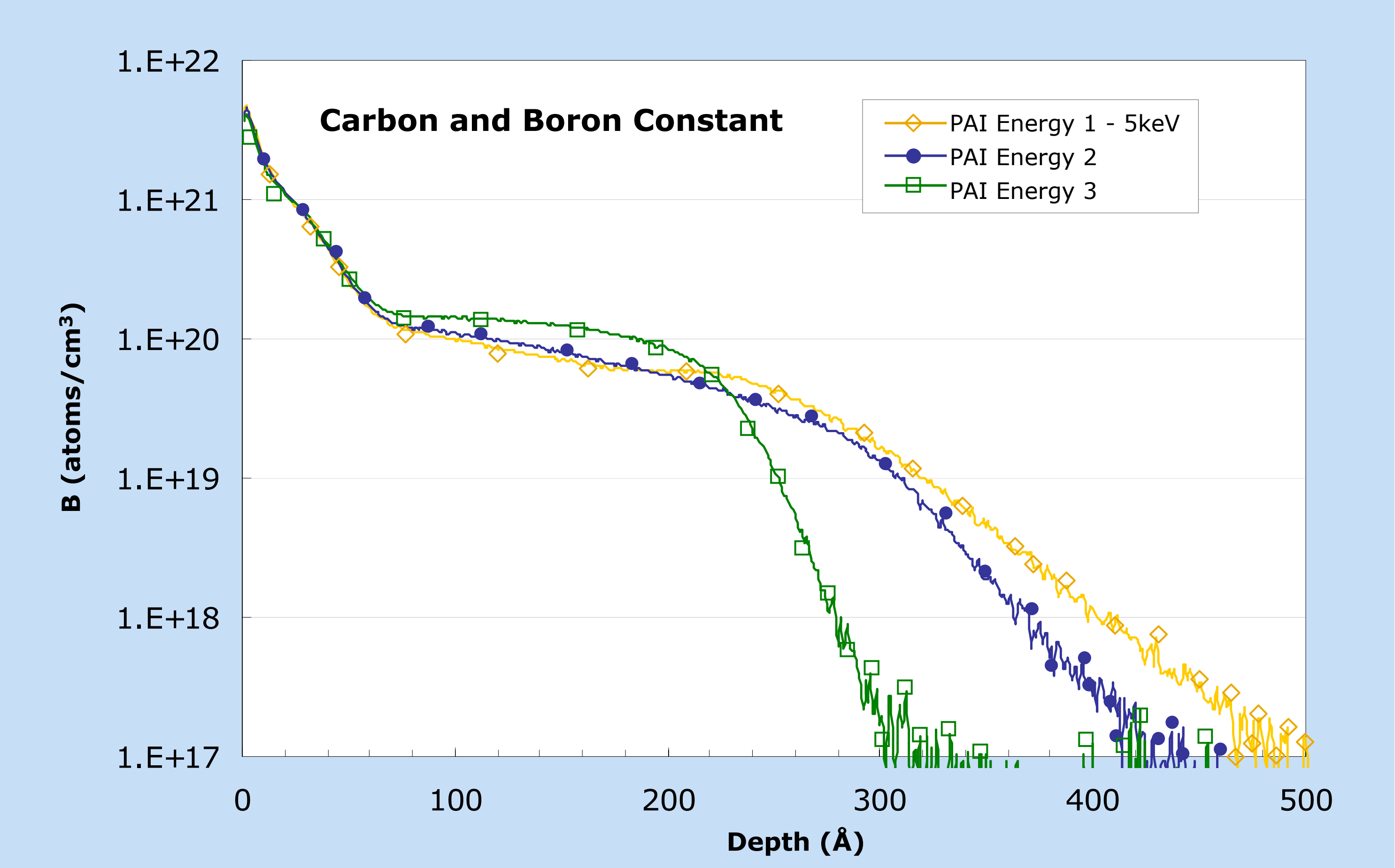
Carbon Co-Implantation Optimization with 0.2keV B^+



A variation of 0.5 keV in carbon energy can result in junctions with different junction depths and abruptnesses

H.Graoui et al., European MRS 2005.

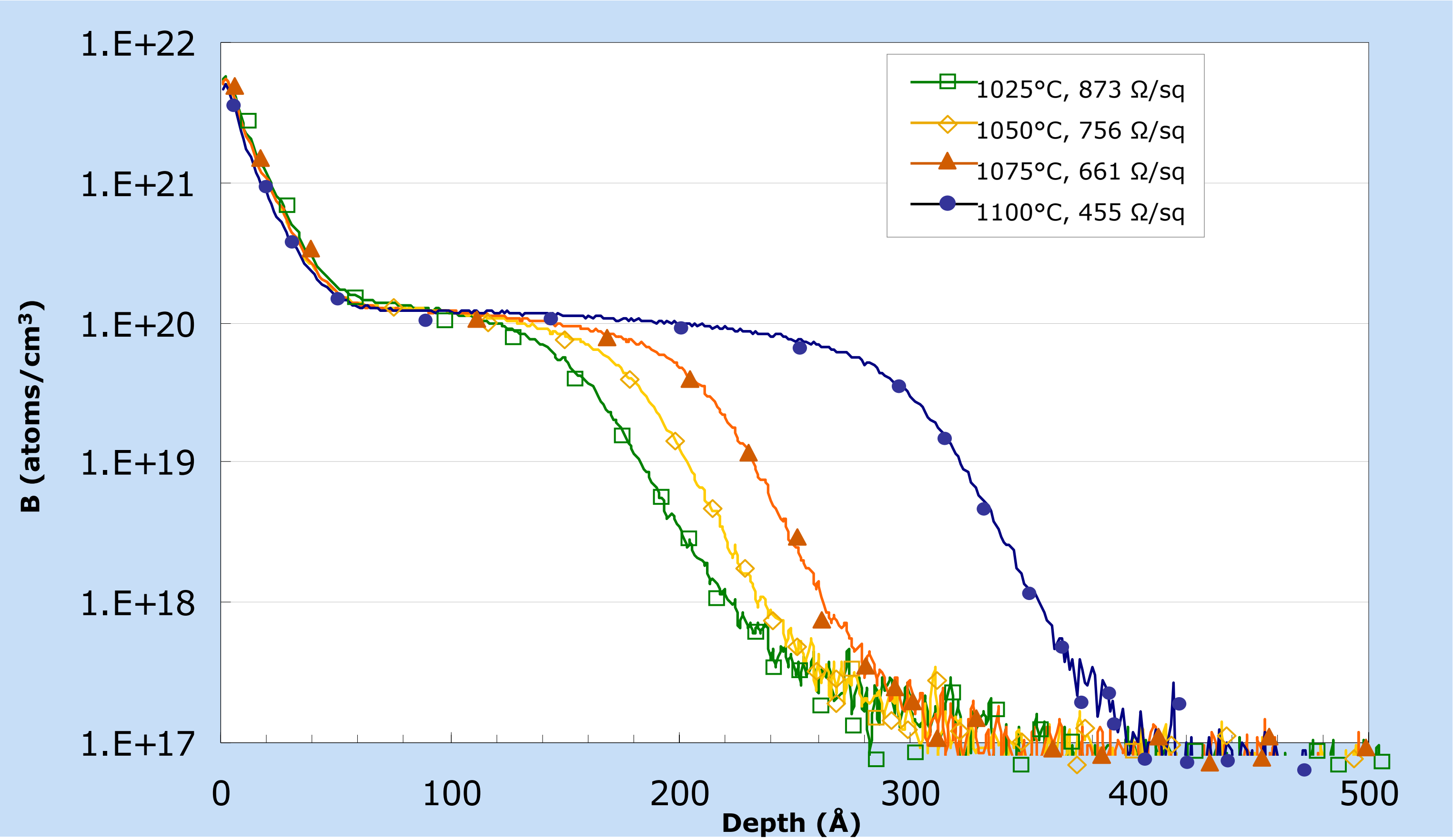
Change in Junction Formation by Varying the PAI Depth



Ge PAI energy also has to be optimized

H.Graoui et al., European MRS 2005.

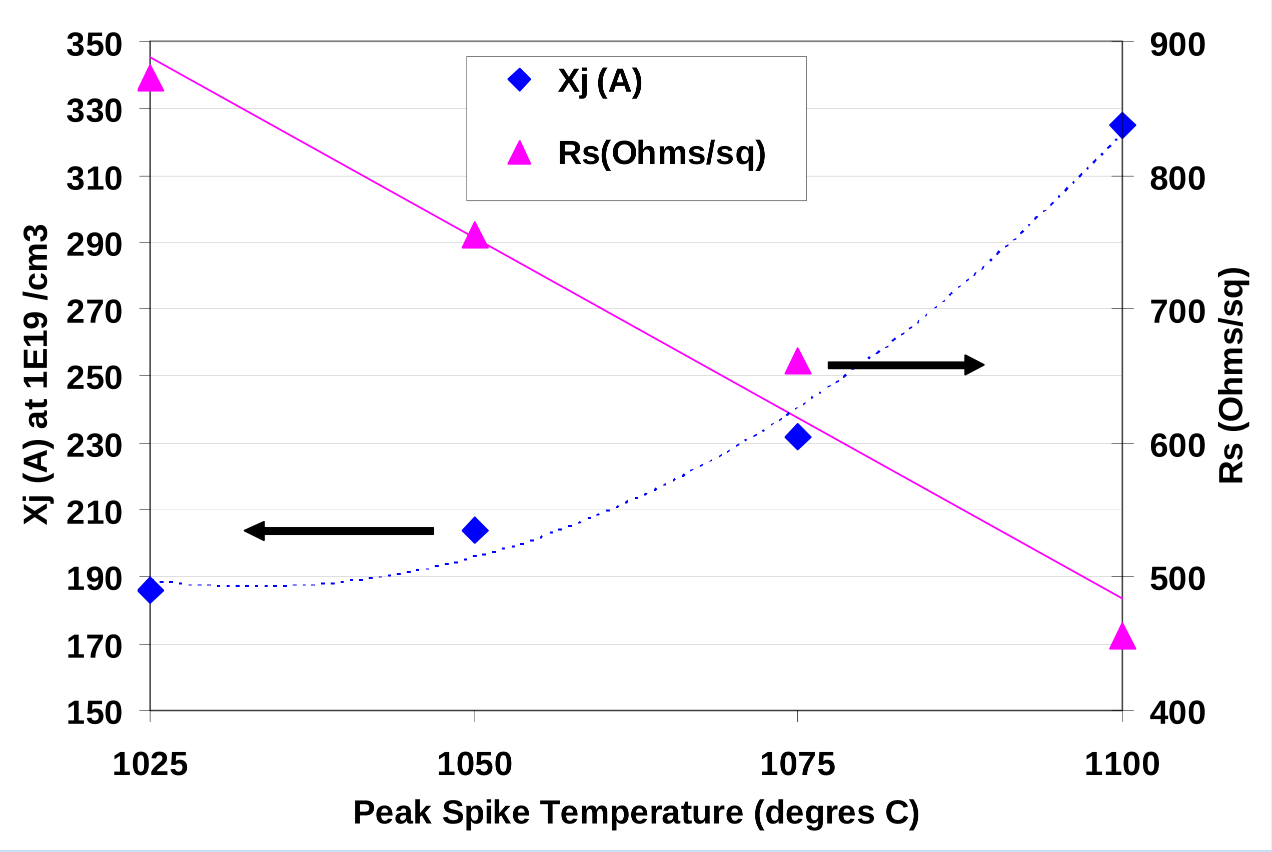
Effect of Different Spike Temperature on Junction Formation



Junction abruptness is constant at 2.5 nm/dec even up to 1100°C, while the junction diffuses and sheet resistance decreases

H.Graoui et al., European MRS 2005.

Junction Depth and Sheet Resistance Trends as Spike Temperature Increases

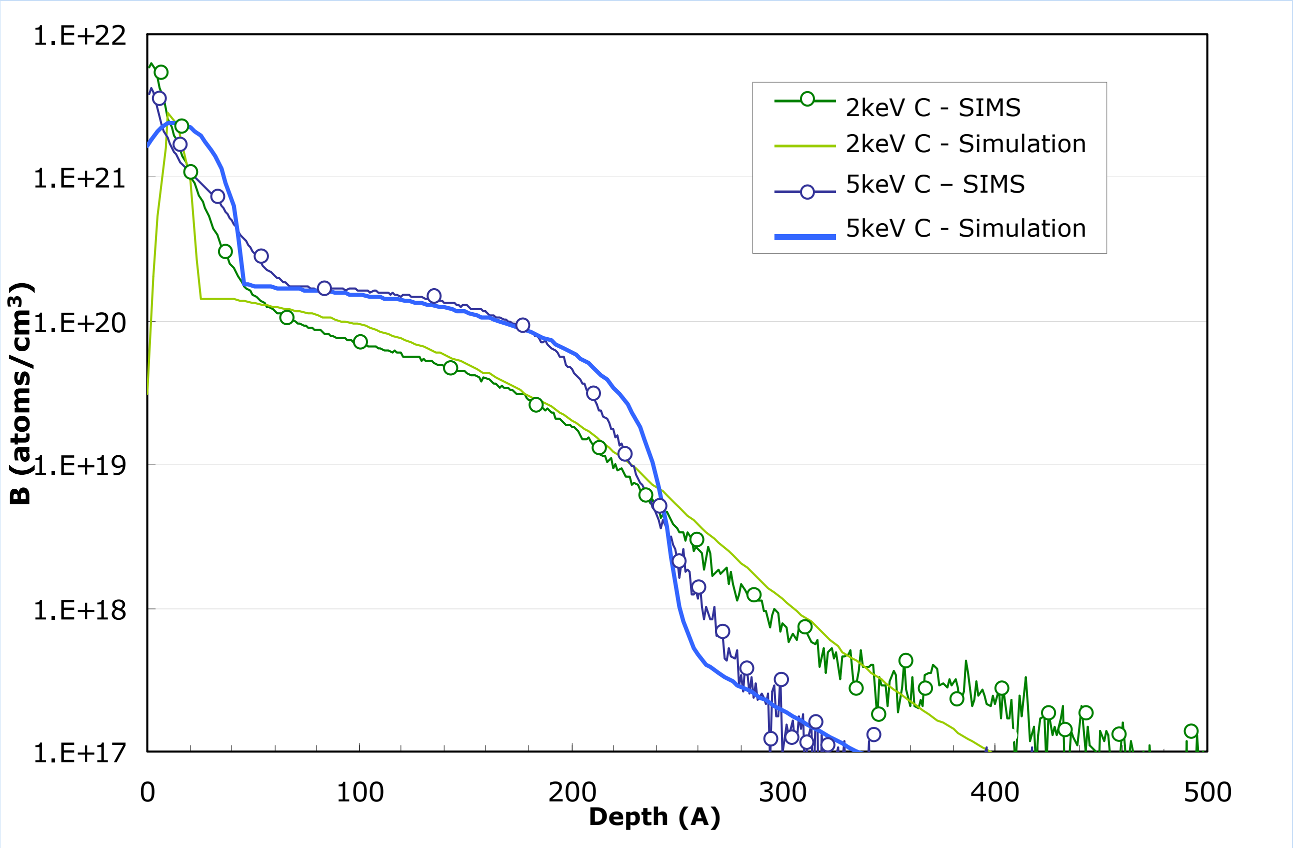


Junction depth increases exponentially especially above 1050°C, while sheet resistance shows a linear decrease

H.Graoui et al., European MRS 2005.

Simulation of Carbon Co-Implanted Junctions

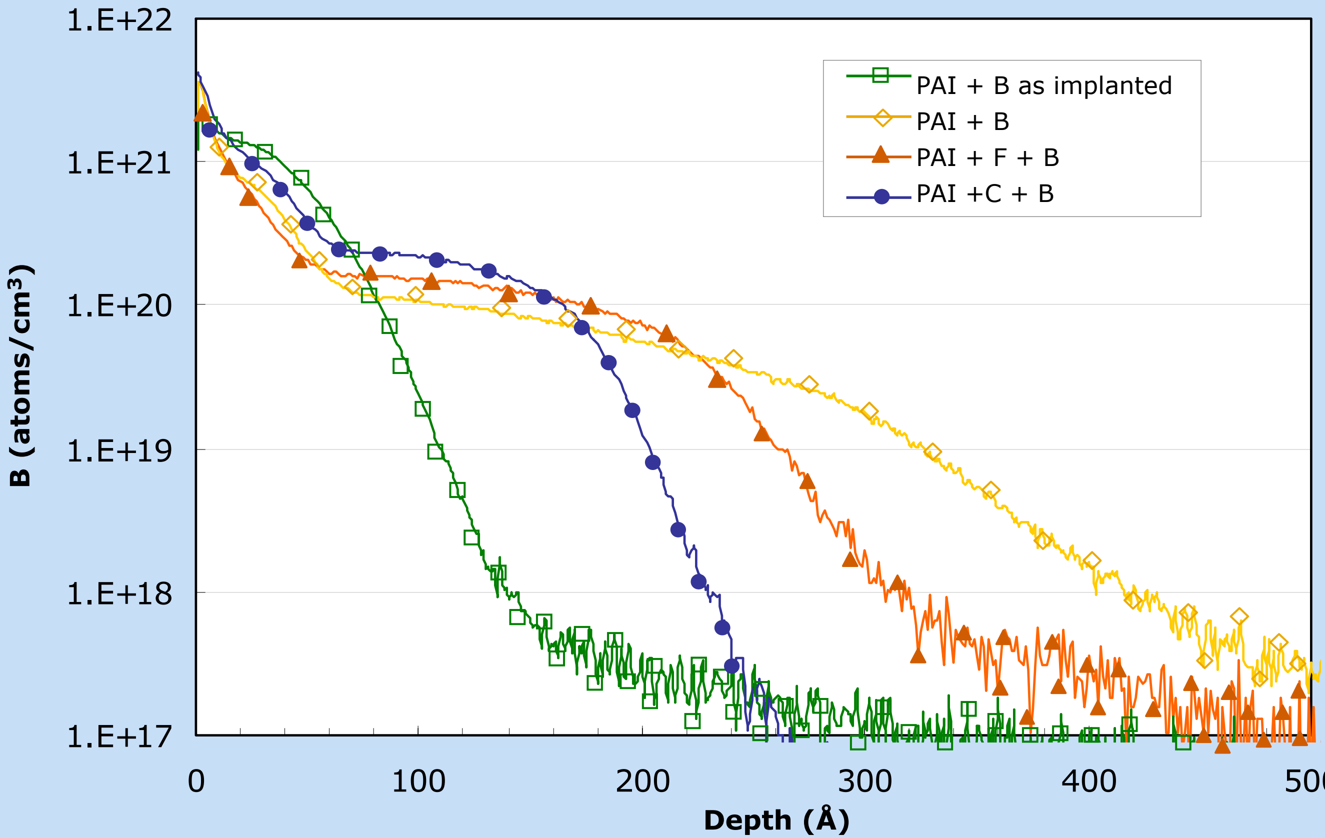
Synopsys TSuprem-4 Model



Physics-based model shows that at 5keV all implant damage appears to be captured by carbon

H.Graoui et al., European MRS 2005.

Carbon Co-implantation Enables PMOS USJ Formation Down to X_j = 20 nm



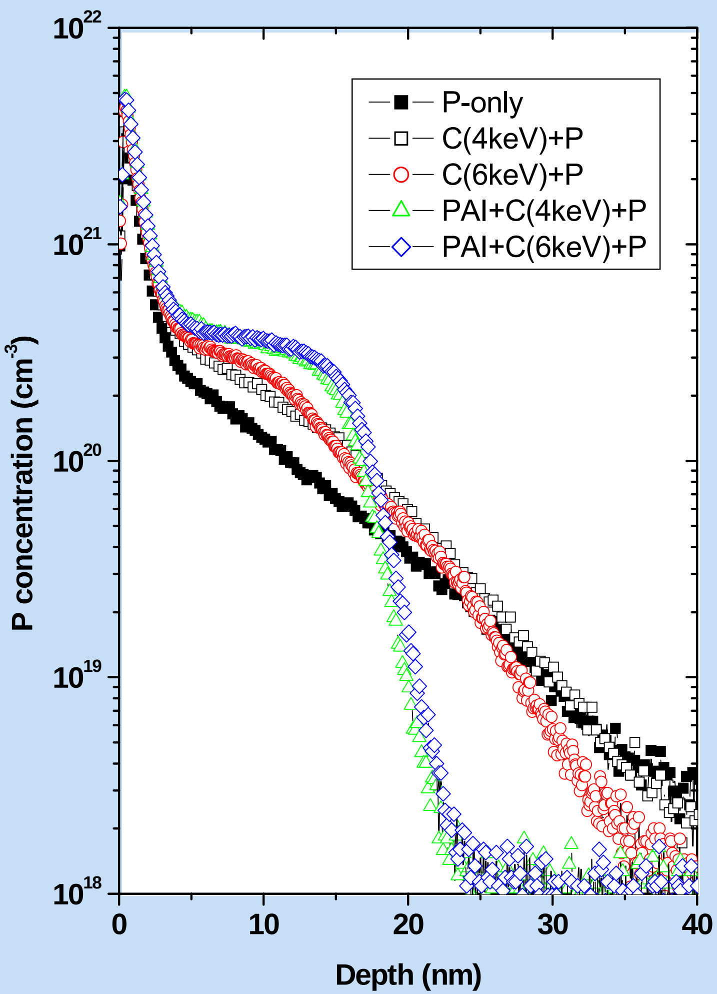
Junctions as shallow as 20 nm, 573 Ohms/sq and 2.5 nm/decade can be obtained, offering potential solutions for high performance 65 nm transistors

H.Graoui et al., European MRS 2005.

Carbon Co-Implant for NMOS (Phosphorous & Arsenic)

External Use

NMOS: 1 keV P in c-Si, c-Si+C, and PAI+C

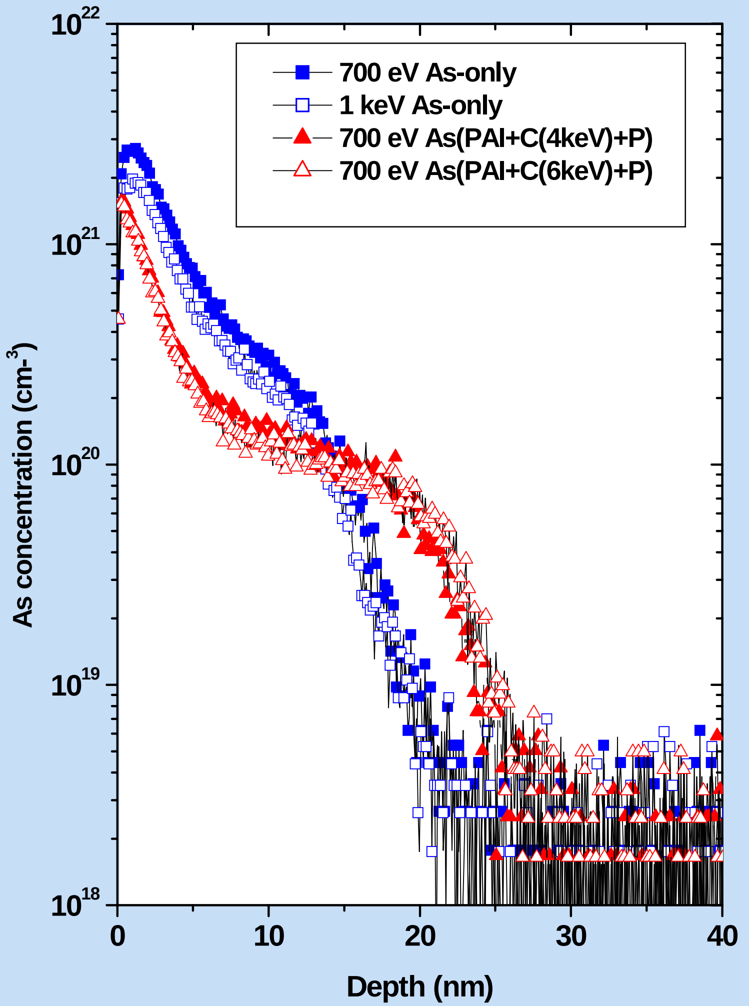


Condition	X_j (nm) at 1E19	R_s (Ohm/sq)	Abruptness (nm/dec)
P-only	30	411	18.0
P + C (4keV)	30	392	13.2
P + C (6keV)	28	349	12.0
P + PAI + C (4keV)	20	357	3.2
P + PAI + C (6keV)	20.5	318	3.0

- Shallow, abrupt junctions produced by co-implants of Si PAI, C, and P
- PAI: Si 25 keV 1×10^{15} cm^{-2} (60 nm α-Si)
- SPE of α-layer will result in substitutional C and improved P activation
- Substitutional C
  - Suppresses Si interstitial-mediated P diffusion at low [P]
  - Enhanced PV^- diffusion at high [P]?
  - Strain-related effects?

E. Collart et al., Applied Materials, IMEC, Philips Research Leuven, AVS USJ Workshop 2005.

NMOS: As in c-Si and in PAI+C+P Implanted Si

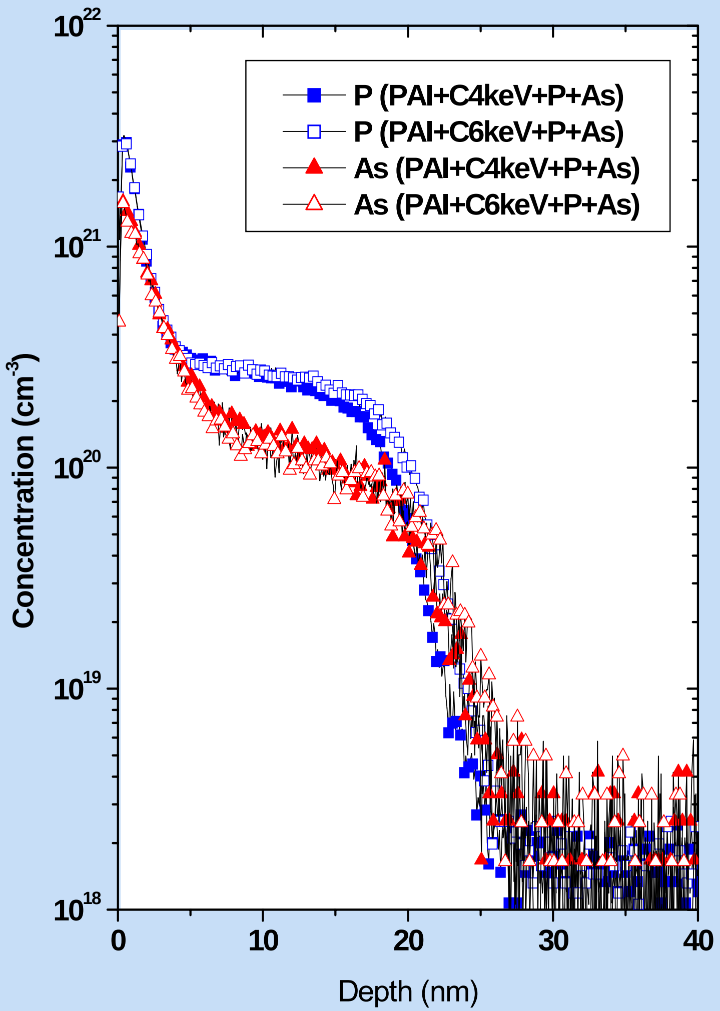


Condition	X_j (nm) at 1E19	R_s (Ohm/sq)	Abruptness (nm/dec)
As-only (0.7keV)	18.3	480	4.8
As-only (1keV)	18.3	497	4.3
As (0.7keV) + P + PAI + C (4keV)	23.4	307	3.8
As (0.7keV) + P + PAI + C (6keV)	23.4	280	3.8

- Good junction characteristics for single-specie As implant
- Co-implantation drives As deeper
- Reduced As concentration probably due to 100% N_2 anneal conditions

E. Collart et al., Applied Materials, IMEC, Philips Research Leuven, AVS USJ Workshop 2005.

NMOS: Comparison of P and As profiles



Condition	X_j (nm) at 1E19	R_s (Ohm/sq)	Abruptness (nm/dec)
P: P + As + PAI + C(4keV)	23	307	4.0
P: P + As + PAI + C(6keV)	23	280	3.6
As: P + As + PAI + C(4keV)	23.4	307	3.8
As: P + As + PAI + C(6keV)	23.4	280	3.8

- P and As profiles taken from same wafer
- Under single-specie implant conditions P and As have different diffusion mechanisms
- In this experiment junction depth and trailing slope are virtually identical for both species
- P diffused deeper than in PAI+C+P case
- Activated P concentration higher than As due to its higher solid solubility

E. Collart et al., Applied Materials, IMEC, Philips Research Leuven, AVS USJ Workshop 2005.

Summary and Conclusions

- Combination of PAI (Si or Ge) and F or C implant dramatically improves ultra-shallow junction characteristics for both PMOS and NMOS dopants
- SPE of amorphous layer crucial to provide C on substitutional lattice sites and improve activation of dopants
- Substitutional C is believed to:
  - Suppress B and P diffusion
  - Suppress EOR damage formation and EOR damage-driven diffusion
- Very similar B, P and As profiles under PAI+C conditions
- Co-implantation with conventional spike anneal is a very promising candidate for ≤65 nm USJ formation