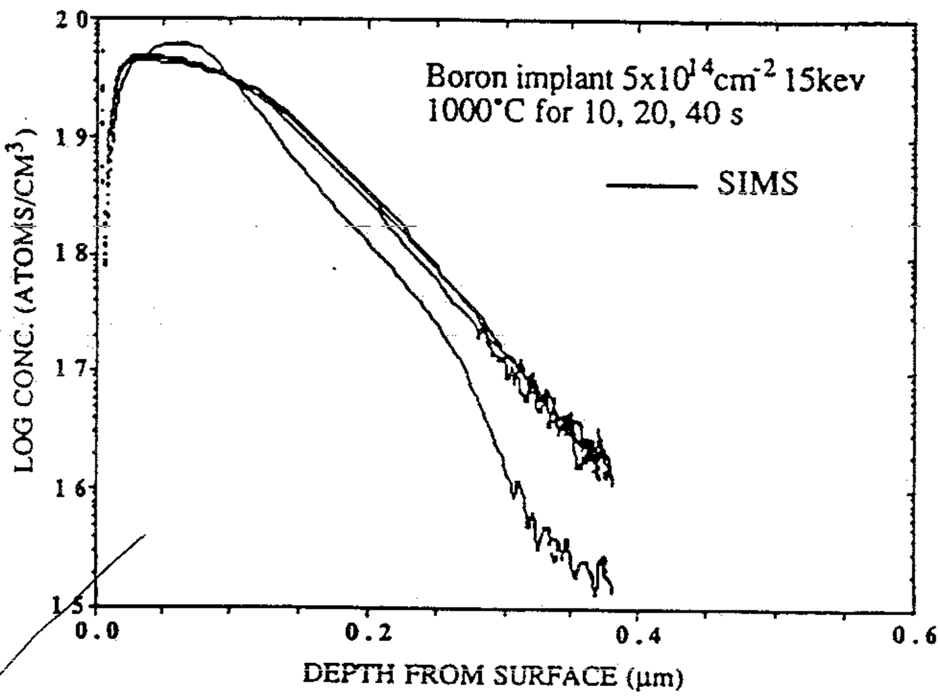
What is TED?

- During annealing following implantation, dopant diffusion is greatly enhanced.

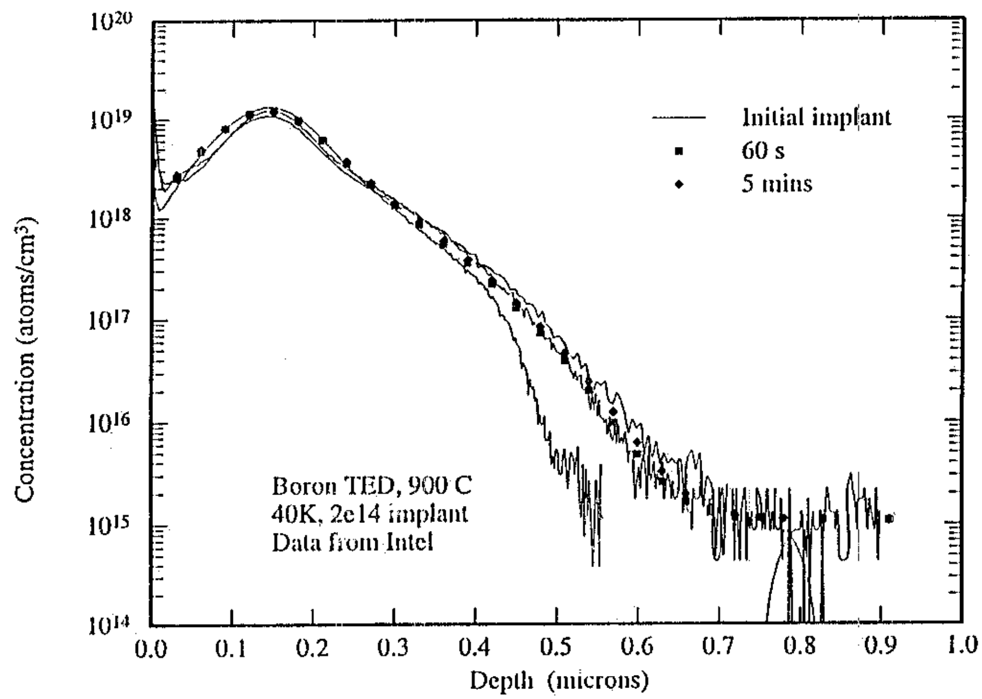


(Kinoshita *et al.*)

- The enhanced diffusion lasts only a short time (temperature dependent) leading to the term Transient Enhanced Diffusion.
- Effects are greatest for P and B, which have the largest interstitial diffusion component.
- TED is due to excess point defects (interstitials) generated by the implant.
- In modern VLSI processes, TED often dominates the total $(Dt)_{\mathrm{eff}}$ seen by dopants.

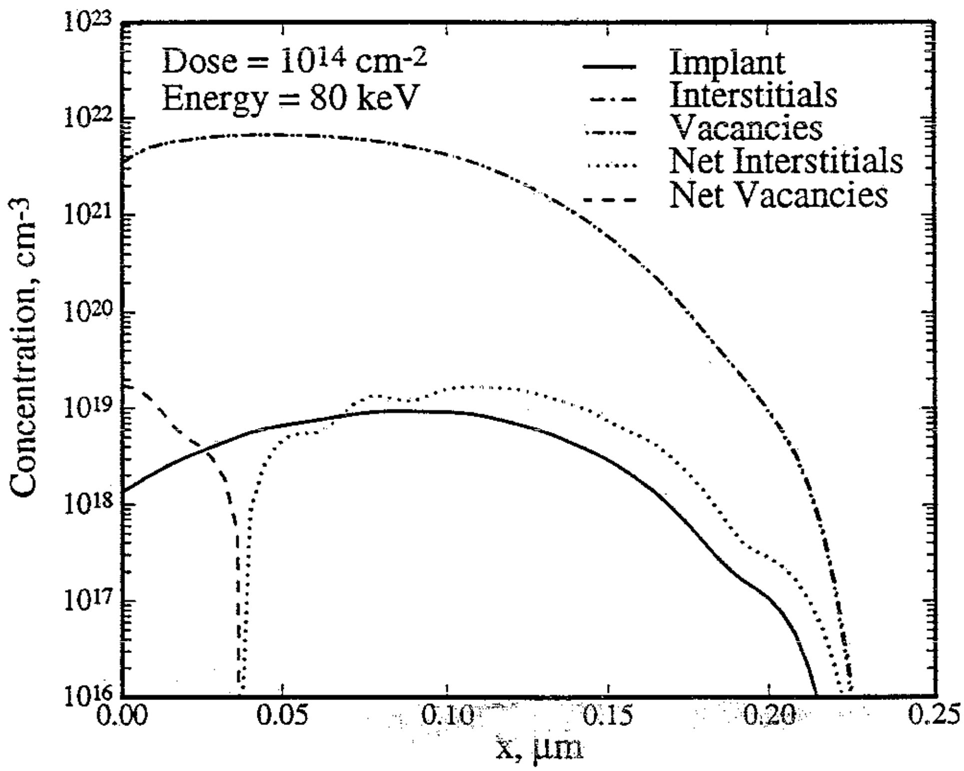
Transient Enhanced Diffusion

- Ion implantation damage greatly enhances dopant diffusion.
- For submicron processes, TED often dominates profile motion.



Initial Defect/Damage Profiles

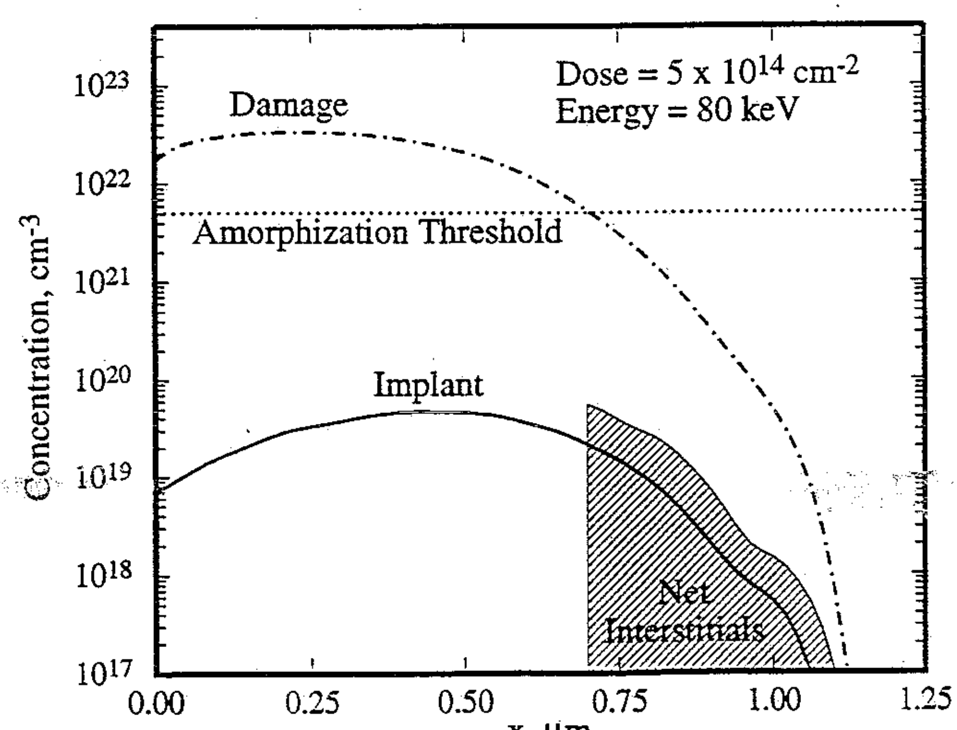
- Initial defect distribution much higher ($\sim$ 1000 times) than implant.
  - Vacancy and interstitial profiles nearly identical.
  - Interstitials displaced slightly towards bulk.
- If recombination is close to diffusion-limited, *total* defect distributions quickly ($\sim$ 0.1 sec at 800°C) reduce to *net* defect concentrations.
  - Surface vacancy-rich, bulk interstitial-rich



- Net interstitial excess often reasonably approximated by implant profile (1+ model).

Effects of Amorphization

- At high doses, surface regions become amorphized.
- Epitaxial regrowth occurs rapidly and nearly defect-free at moderate temperatures (~ 500°C)
- Amorphizing doses lower for heavier ions (As, Ge).
  - Boron generally doesn't cause amorphization even at very high doses.
- Amorphizing implants result in less TED, which is nearly independent of dose.
- Initial defect profiles in regrown region not known.
  - Often assumed to be near equilibrium values.

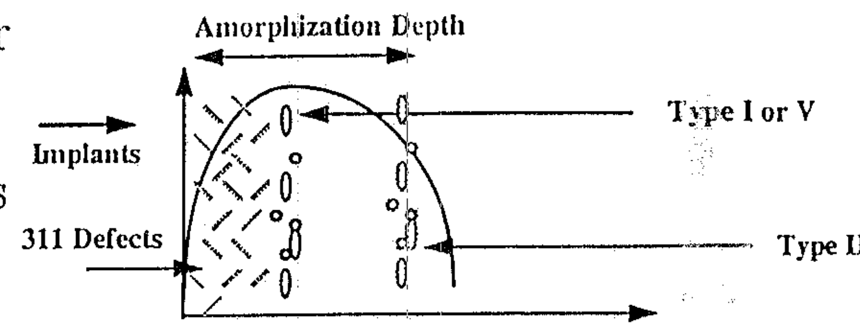


Extended Defects

- Ion implantation leads to the formation of extended defects.
- Interstitial clusters
  - Primarily {311} (or {113}) planar defects (also known as "rod-like" defects).
- Dislocation loops
  - For high implant doses ($> 10^{14}\text{cm}^{-2}$, Jones *et al.*) dislocation loops are observed.
  - Loops ripen (large ones grow, small shrink) during annealing.
  - Removing loops requires long, high-temperature annealing – potential negative device impact.
- Extended defect:
  - Are primarily extrinsic (extra partial planes).
  - Provide repository for excess interstitials
  - Reduce initial supersaturation (C_I/C_I^*), but extend TED period.

TED and Extended Defects

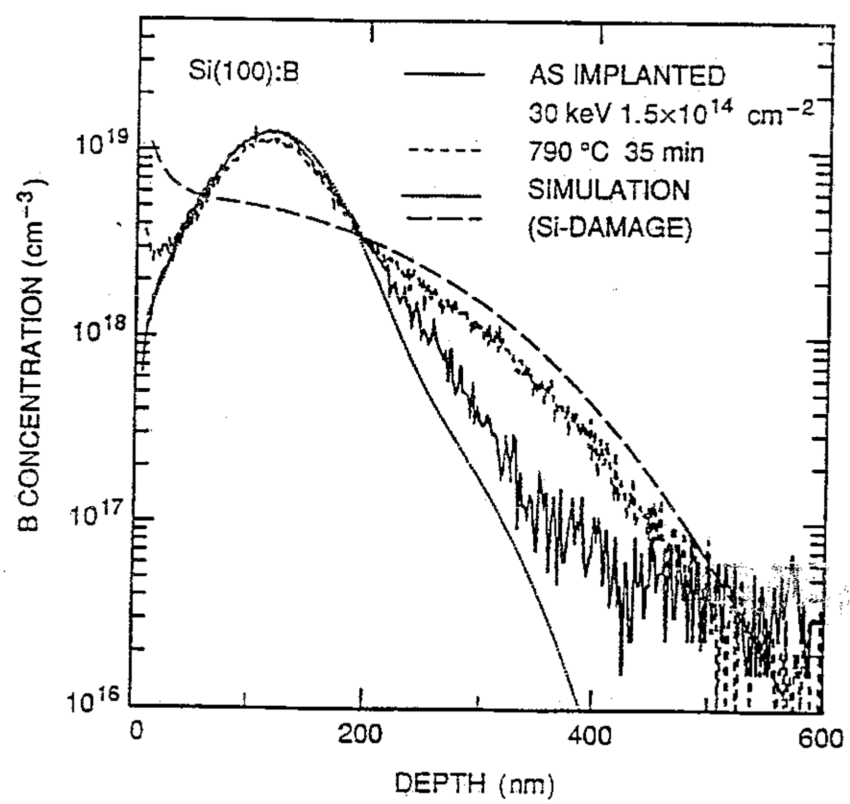
- During annealing of ion implantation extended defects form:
  - Primarily {311} defects for sub-amorphizing doses.
  - Primarily dislocation loops for amorphizing doses.



- Ostwald ripening: Size of extended defects increases and their density decreases with time.
- TED period matches {311} defects dissolution time.
- Defects store interstitials, reducing initial supersaturation, but greatly extending period.
- Modeling extended defects is key to TED modeling.

Dopant Activation/Deactivation

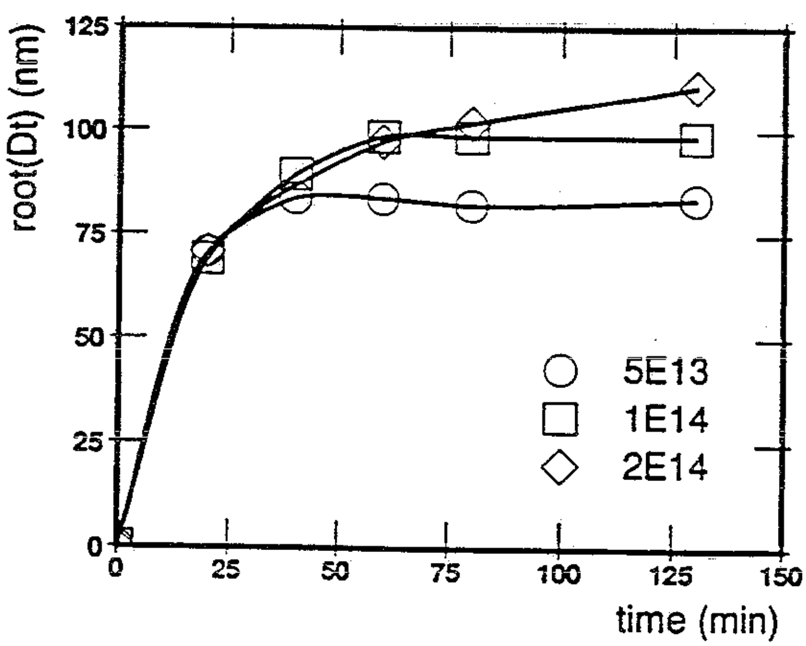
- Peak of high dose implants exceed solid solubility.
- Deactivation due to clustering/precipitation.
- Dopant activation affected by point defect concentrations.
  - $C_{\mathrm{I}} > C_{\mathrm{I}}^{*}$ speeds up precipitation (faster D_{A}).
  - Interstitial supersaturation increases As solubility (fewer I), reduces B solubility (more I)
- Effect of TED on activation sometimes called transient activation.



(Stolk *et al.*)

Other Experimental Observations

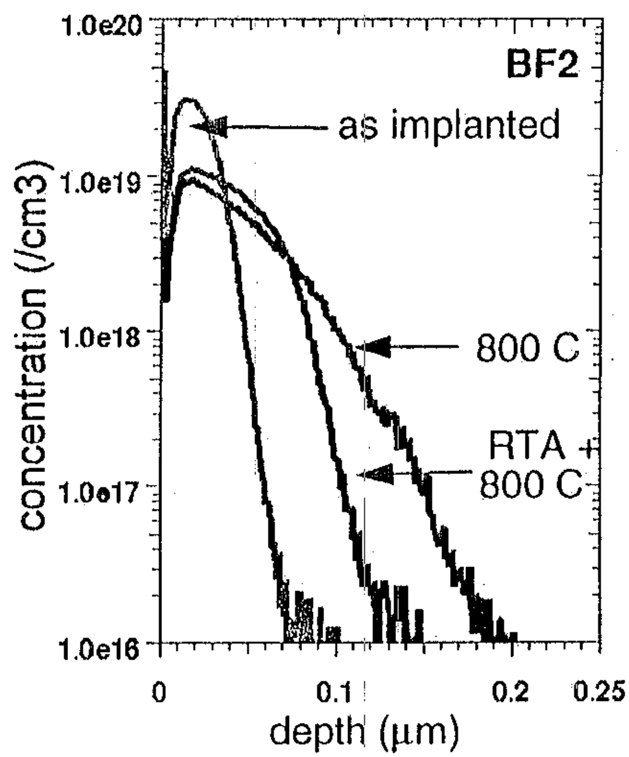
- Enhanced diffusion increases with increased energy.
  - Damage further from surface anneals slower
- Sublinear dependence of enhanced diffusion on dose.
- Higher dose gives longer transient, but not higher peak diffusion (Packan).



  - Interstitial clusters also disappear at about the same time (Cowern)
  - Transient period much longer at low T ($T\Uparrow$ $TED\Downarrow$)
- Dependence of marker layer TED on marker layer dose (Griffin)
  - Non-dilute concentration of dopant/defect pairs.

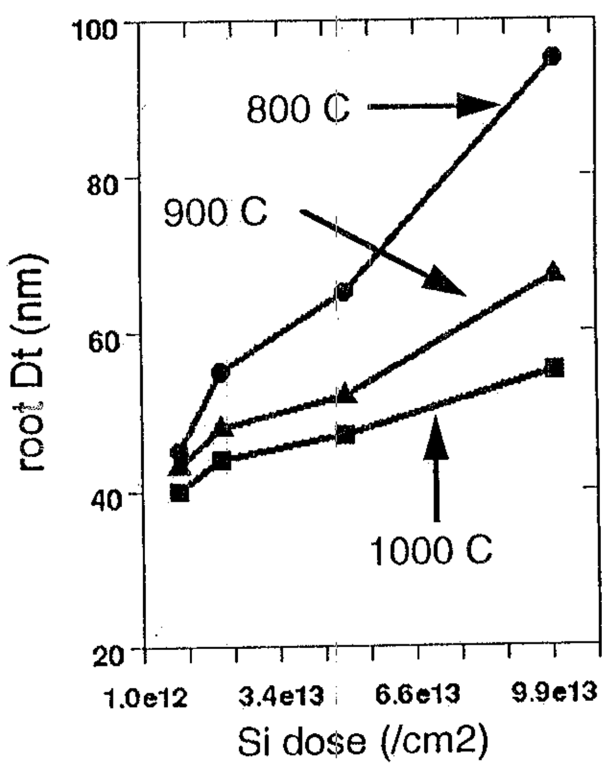
More is Less ....

- Adding thermal steps can decrease junction depths
- Point defects recombine more quickly at high temperatures reducing transient diffusion
- Less diffusion results in steeper profiles which translates into higher performance devices

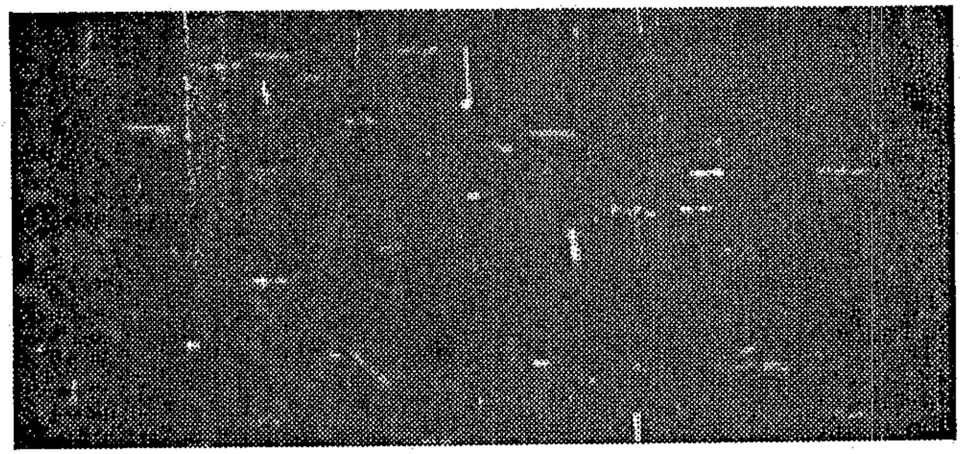


Effects of Implant Dose and Anneal Temperature on TED

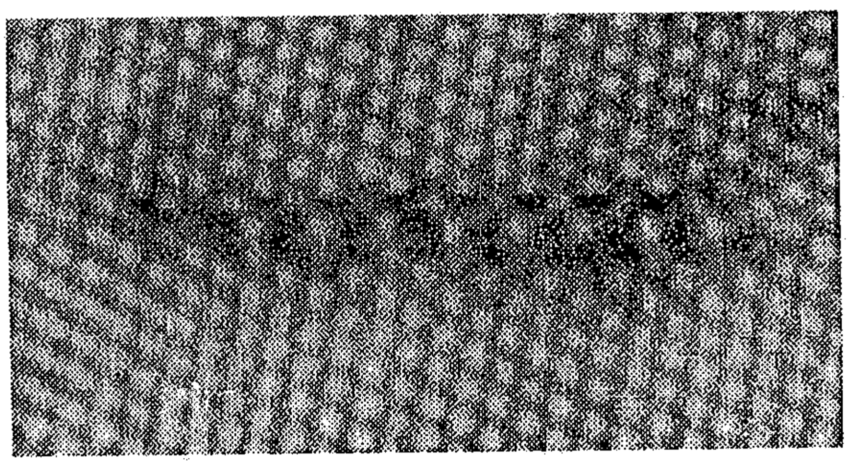
- as expected, higher Si doses lead to more TED
- surprisingly, higher anneal temperatures can lead to shallower junctions
- even relatively low dose implants can result in large TED effects



{311}s: Interstitial defects post-anneal



Weak-beam dark-field plan view,
e.g. 145keV Si, 1e14cm-2, 740°C, 15 mins



<110> cross-section HREM
e.g. 350keV Si 1e14cm-2, 740°C 15mins

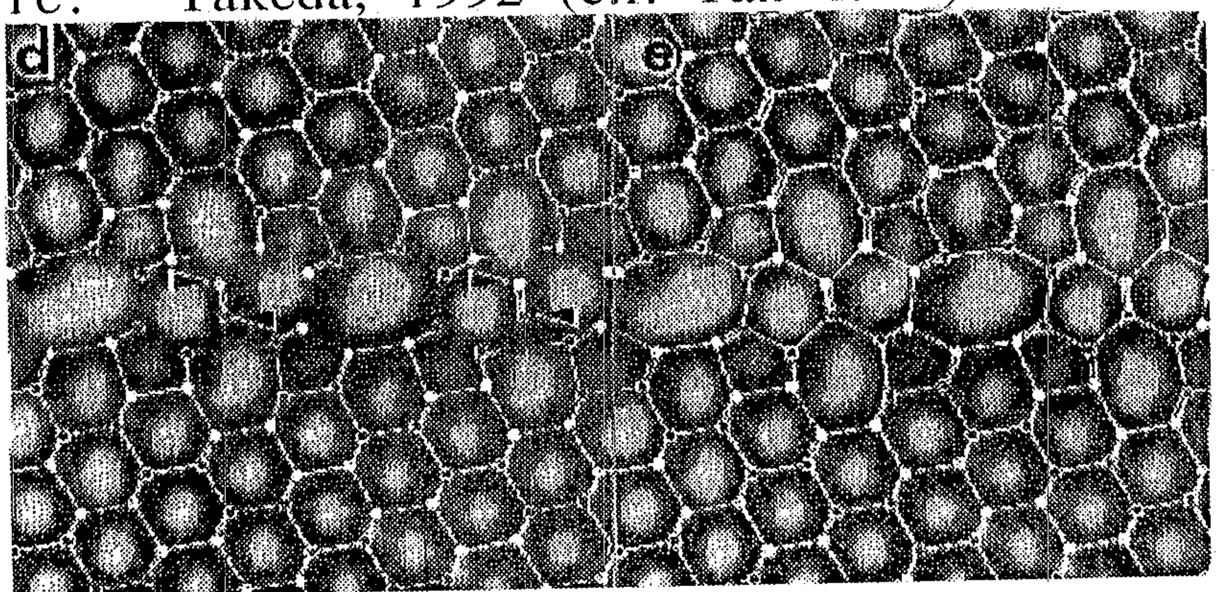
{311} defects

a.k.a. "B precipitates", a.k.a. "coesite" a.k.a. "rod-like defects"

Long history, Davidson, 1970......Aseev

- electron irradiation,
- oxide precipitation,
- high-T ion irrad,
- metal implantation

Structure: Takeda, 1992 (c.f. Tan 1981)



1ml hexagonal Si or <110> rows of self-interstitials

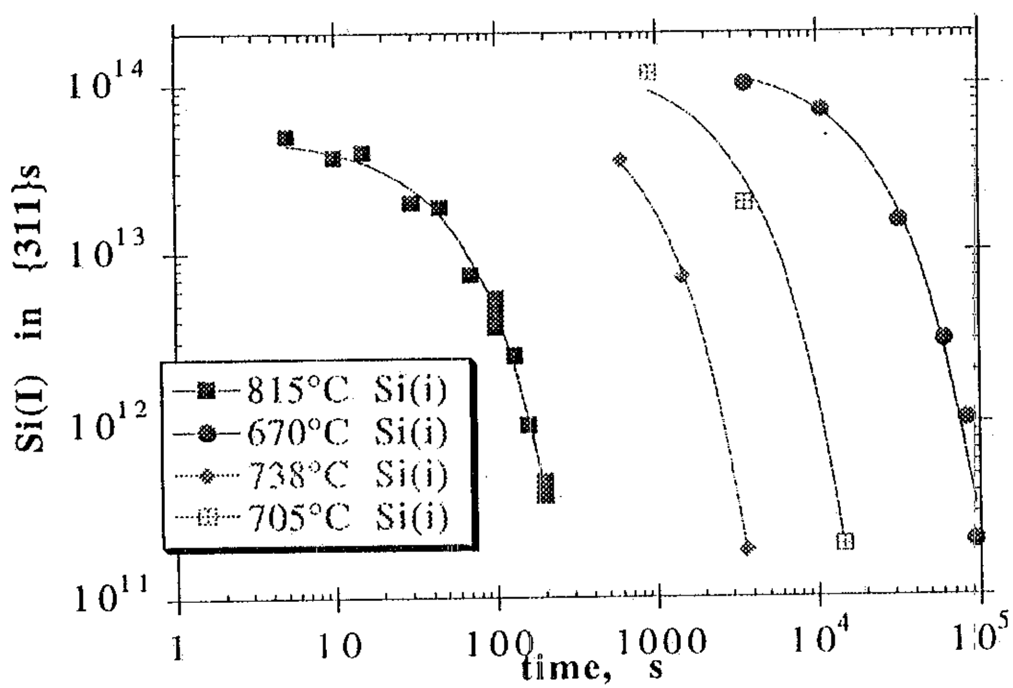
{311}s: source of the interstitials

{311} density, length (PV WB DF)

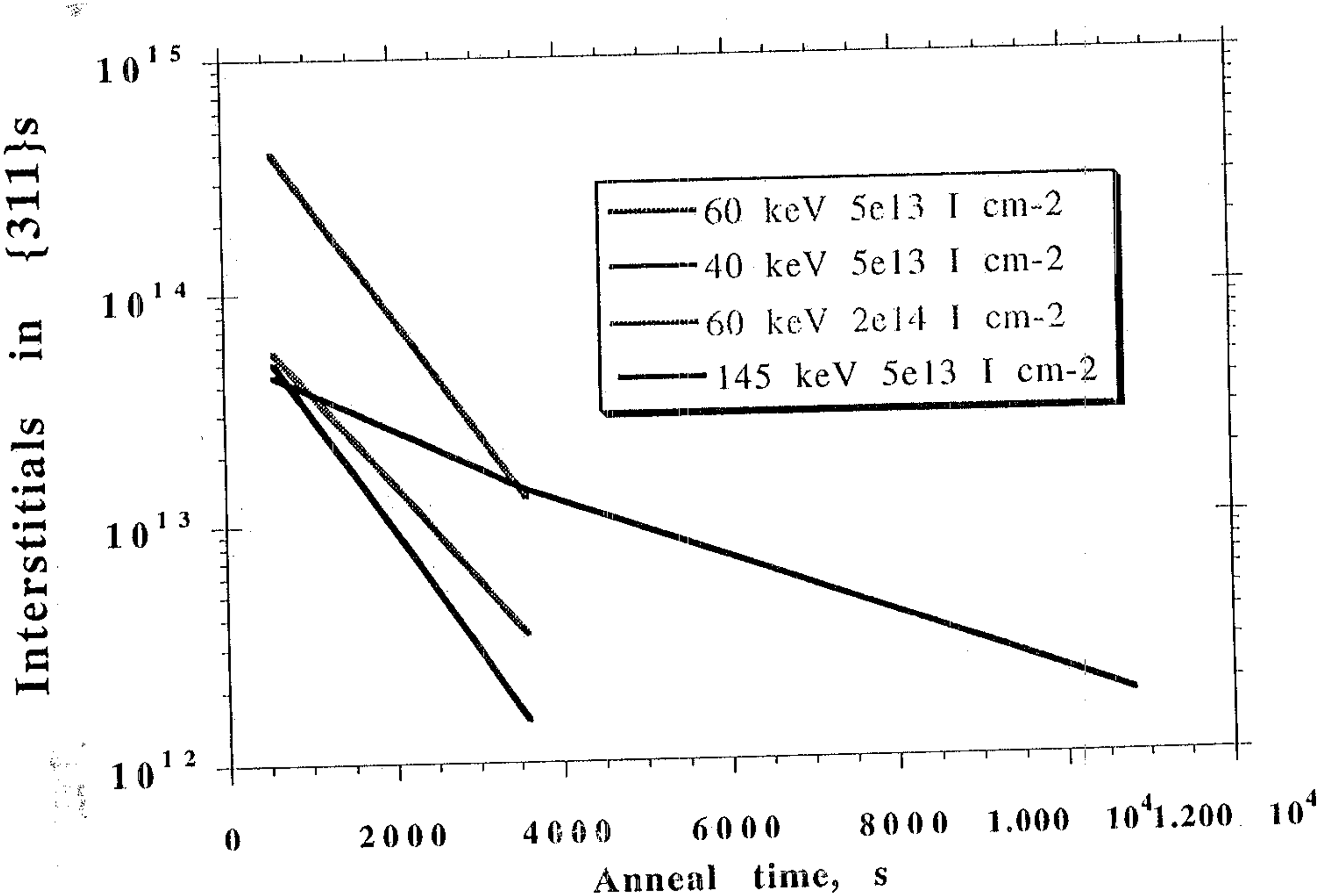
{311} width (HREM) ⇒ ≈4nm,

no observable dependence on energy, dose, time, T

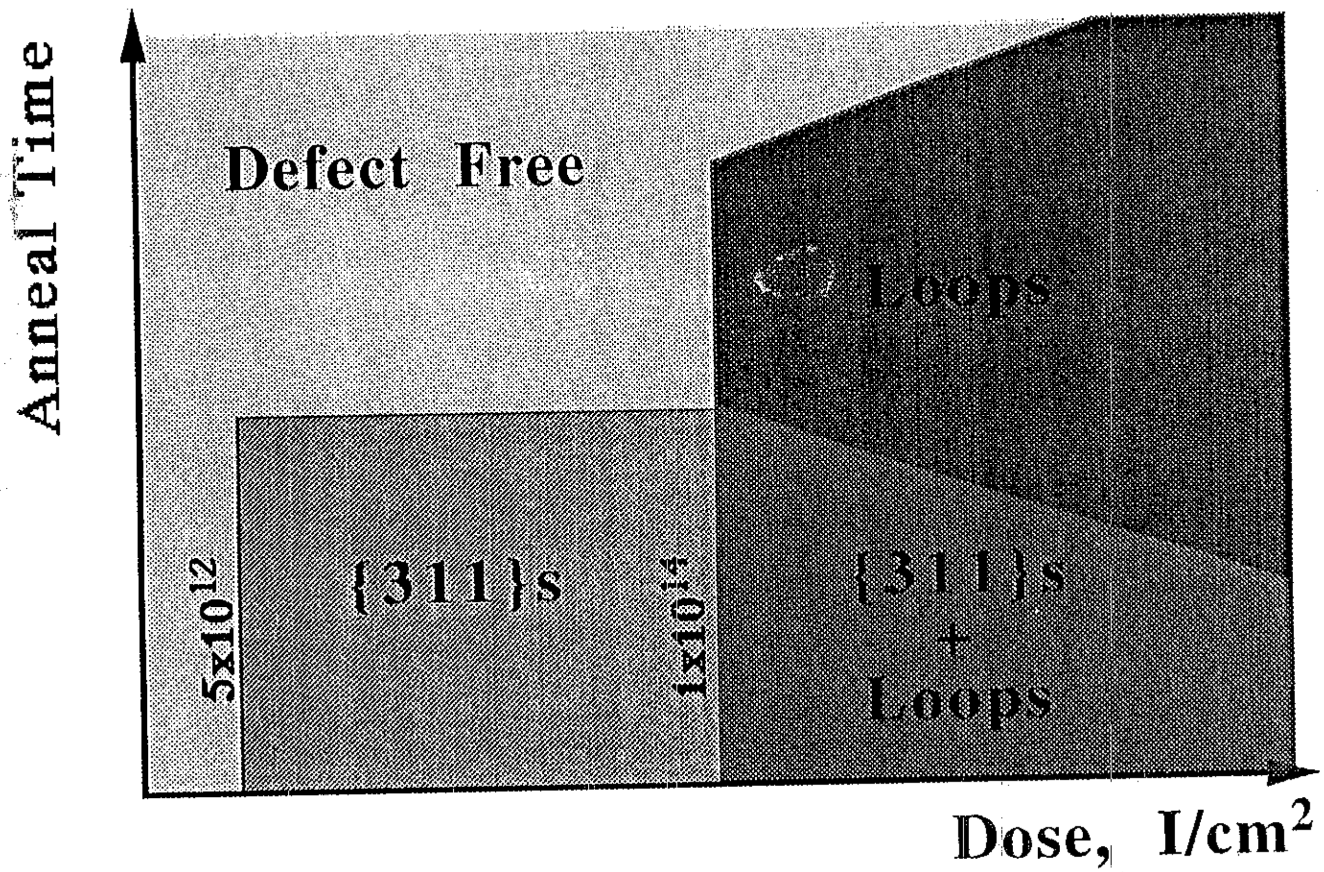
Evaporation of {311}s matches TED time



Effect of Implant energy:
Decrease in {311} evaporation rate @ high E



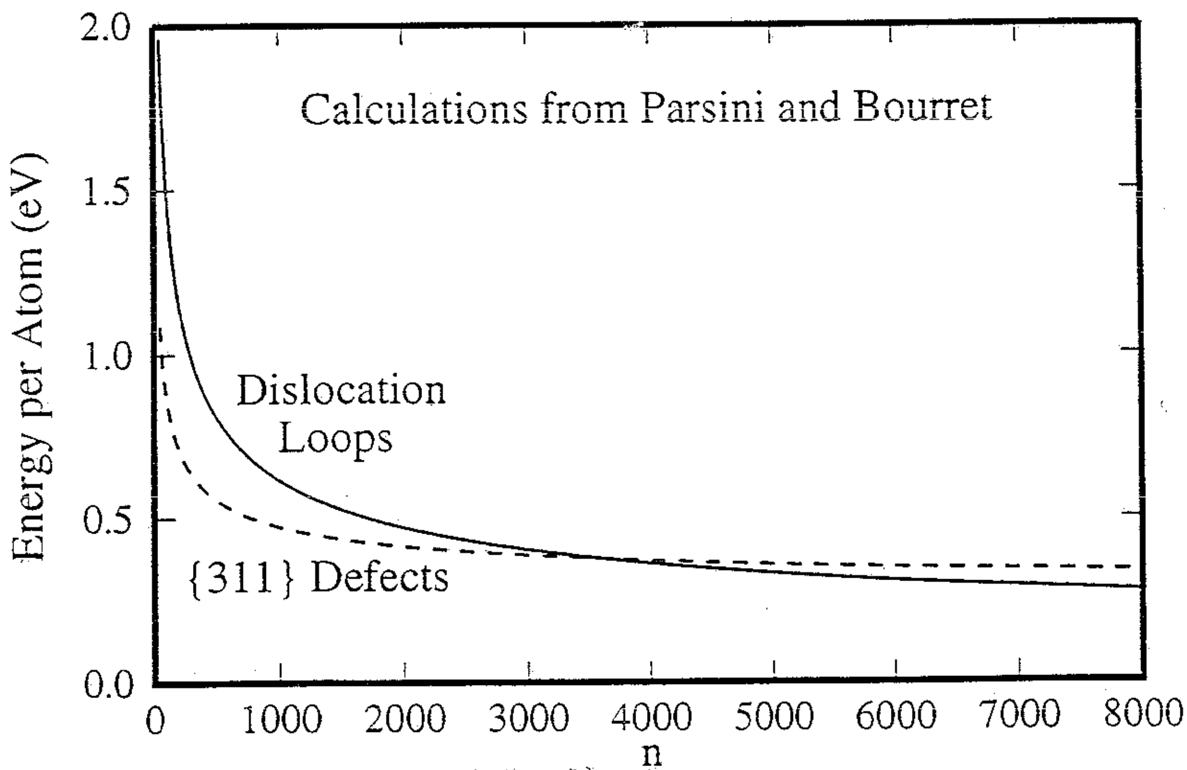
Phase Diagram for interstitials



Notes: TED @ <5x10^{12} (Cowern): Si(I) clusters
>2x10^{14}, double TED: fast & slow (e.g. Solmi)

Extension to Dislocation Loops

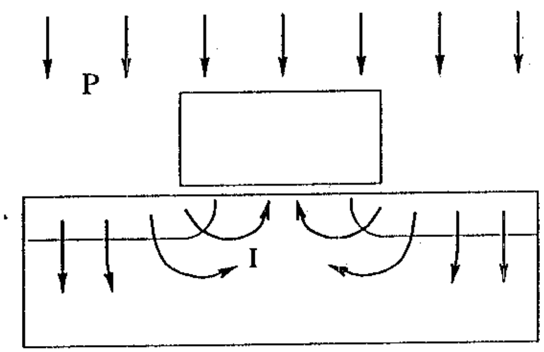
- For high implant doses dislocation loops are observed.
- Posssible nucleation path for loops is transformation from {311} defects.
  - {311} defects have a smaller energy per perimeter, but larger energy per area.
  - {311} defects have lower energy for small defects, loops for large defects.

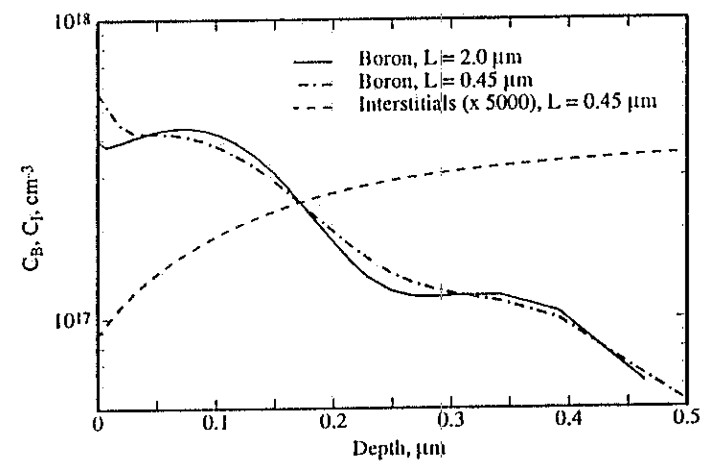


- Can extend model by assuming defect energy is $\min\left(\Delta G_n^{311}, \Delta G_n^{\text{loop}}\right)$.

Application to RSCE

- Reverse short channel effects due to lateral diffusion of point defects from S/D implant.





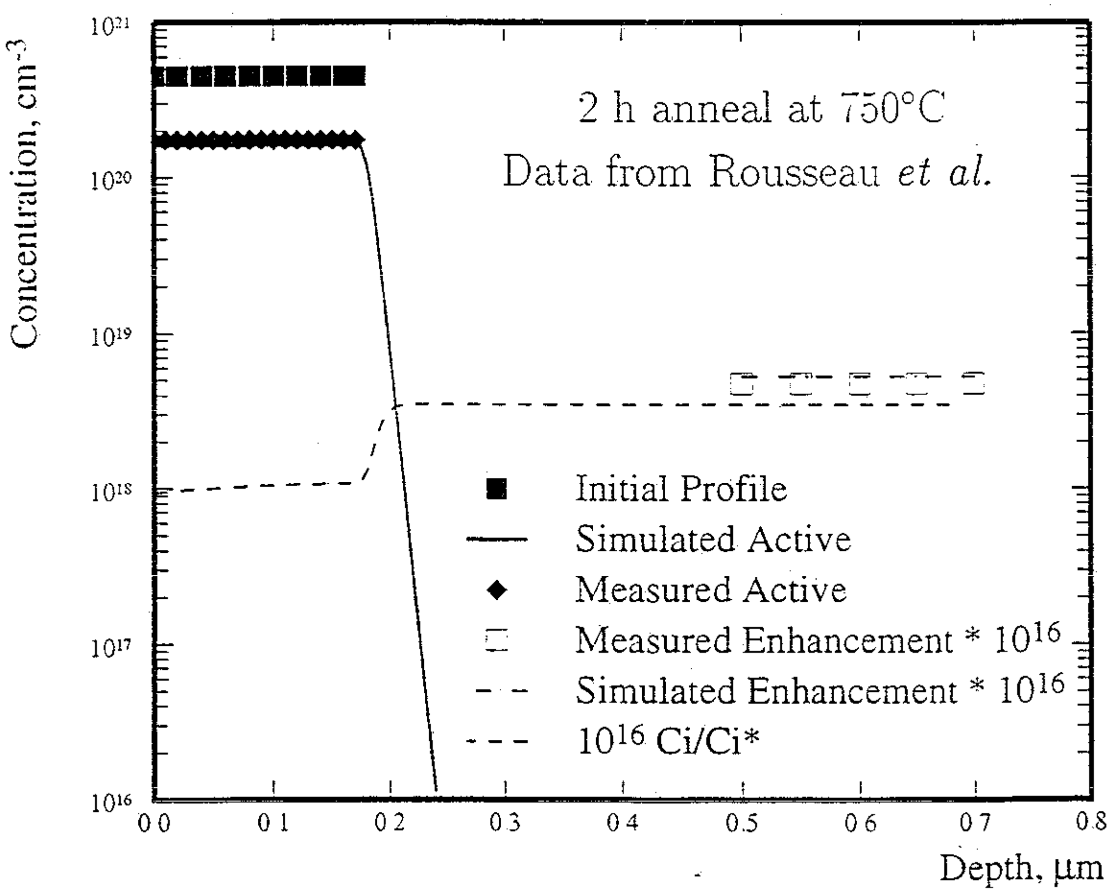
- Simulation gives accurate estimate of reverse short channel effect due to TED ($\sim 0.2\,\text{V}$, Rafferty *et al.*).
- Needs interface recombination rate much faster than high thermal budget experiments (segregation model).

Point Defects and Precipitation

- Due to size differences, precipitates can be expected to incorporate point defects.
  - Vacancies for arsenic, interstitials for boron.
- Point defect concentrations change effective solubility.
  - $C_I > C_I^*$ increases solubility of arsenic (Subramanian *et al.*).
  - $C_I > C_I^*$ decreases solubility of boron (TED).
- Precipitation processes inject/extract point defects.
  - Arsenic precipitation injects interstitials and/or extracts vacancies (Rousseau *et al.*).

Interactions of Point Defects with Dopant Precipitation

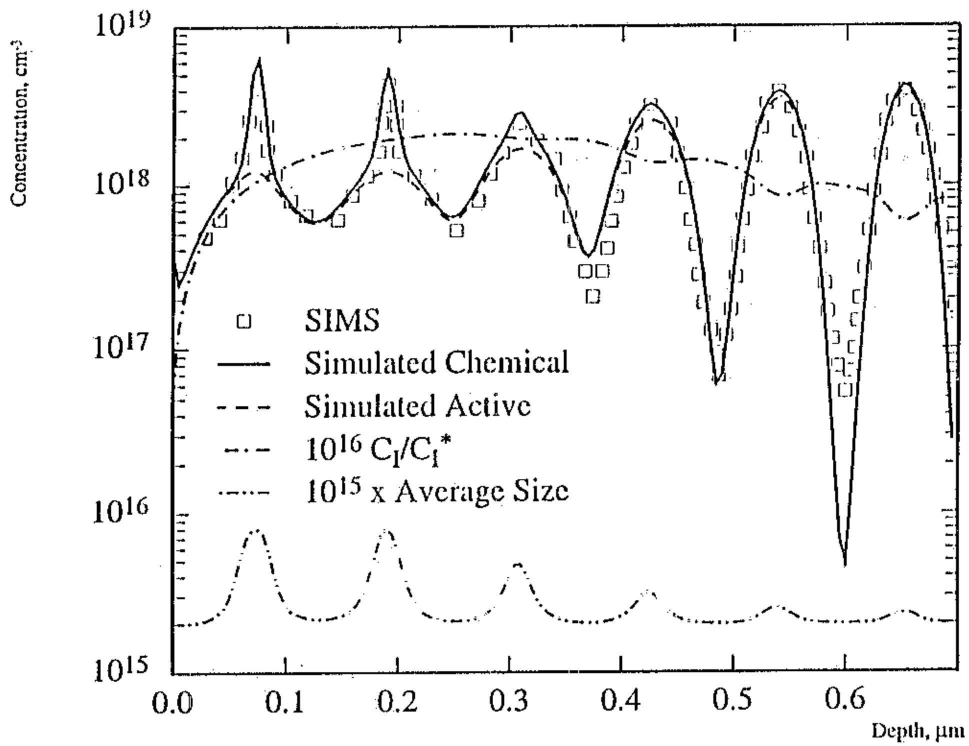
- Arsenic (boron) precipitates can be expected to incorporate vacancies (interstitials).
  - Effective solid solubility depends on point defect concentrations (Subrahmanyan *et al.*).
  - Precipitation injects interstitials (Rousseau *et al.*).
- Included vacancy incorporation in RPM applied to arsenic precipitation



- During TED interstitial supersaturation reduces (increases) solubility of boron (arsenic).

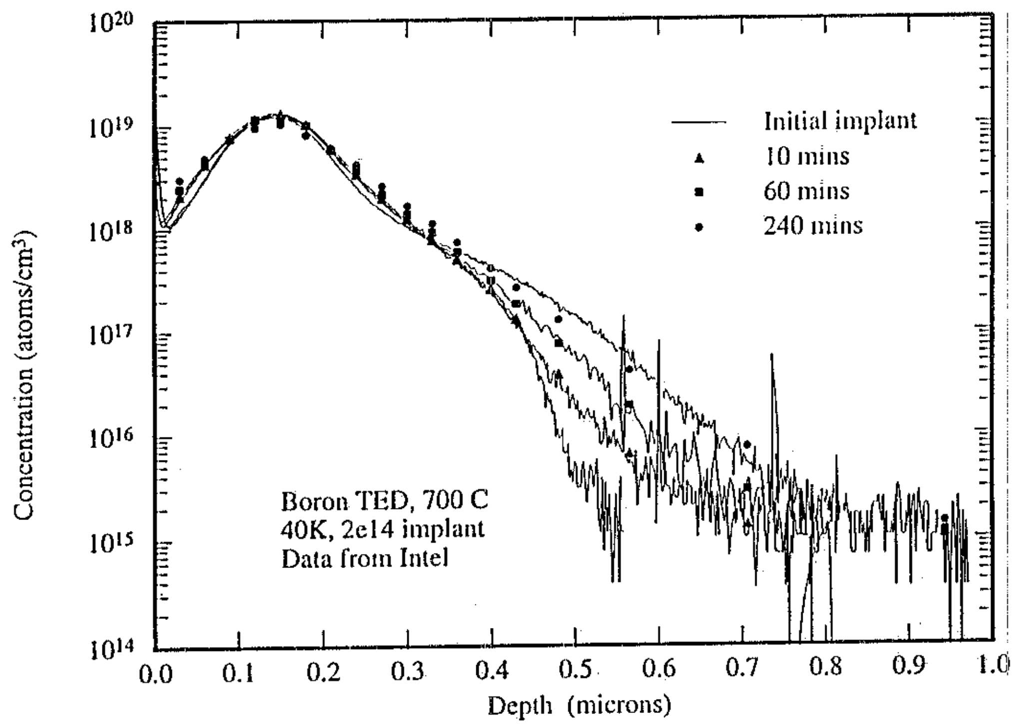
TED in B Delta-Doped Superlattice

- $5 \times 10^{13} \text{cm}^{-2}$ 40 keV Si, annealed 10 min at 790°C (Stolk).



- Model correctly describes transient activation and diffusion.

Boron TED/TA



- Effective solubility increases with time.