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Germanium Channels for CMOS ... Facts and Fantasies

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- **why go back to germanium !**
- **comparisons with silicon**
- **activation and doping ceiling**
- **implantation defects**

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Scaling silicon CMOS has made ICs cheaper faster and reduces power per function

Beyond 90nm scaling has given diminishing returns so new approaches ie novel device structures, SOI, new gate materials and possibly new channel materials

- oxide can't be scaled beyond 1.2nm because of tunnelling currents
- SiON probably inadequate beyond 45nm node so need hi k dielectrics to improve short channel effects and gate leakage
- mobility in thin channels compromised need higher μ materials
- strained Si, III-Vs. Ge?

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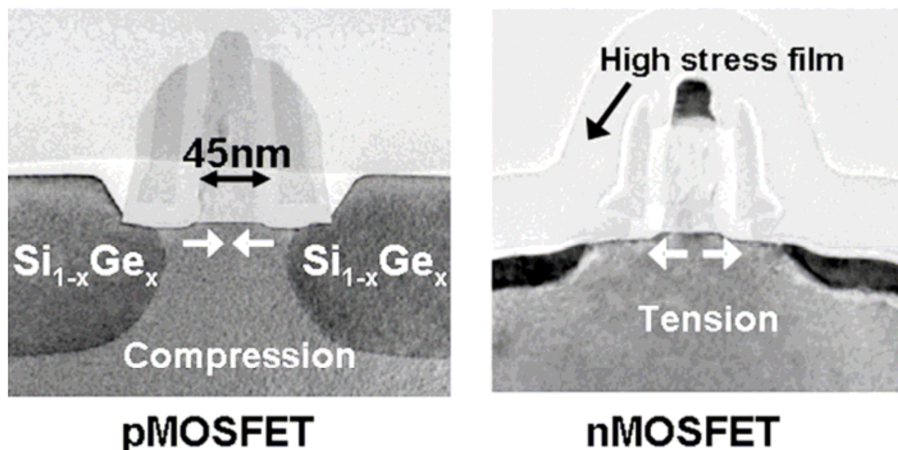
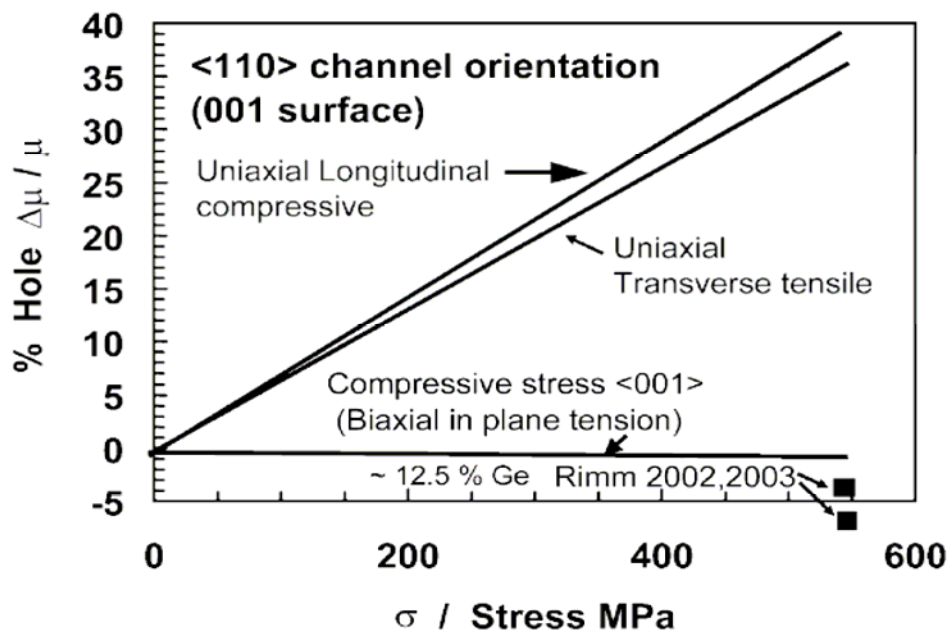
The mobility problem … use strain or throw away Si?





INTEL 90nm node process: tensile strain in NMOS via nitride cap & uniaxial compressive via local SiGe

10% drive current increase for NMOS 20% for PMOS ~50% increase in “bulk” hole mobility available in principle

Thompson et al (2004) IEEE ED Letters ***25*** *p191*

Thompson et al (2004) IEEE Trans ED ***51*** *p 1790*

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Is Ge a contender for ICs beyond the 45nm node?

	Si	Ge	GaAs
Electron mobility (cm^2/Vs)	1350	3900	8500
Hole mobility (cm^2/Vs)	450	1900	400
Band gap (eV)	1.12	0.67	1.42
Electron saturation velocity (x10^7 cm^2/s)	1	0.6	2
Thermal conductivity at 300K (W/cm/?C)	1.3	0.58	0.55

- 400% increase in hole mobility with Ge but … there are a few problems!
  - GOI or localised growth essential
  - interface state density high and uncontrollable
  - little fundamental data on implantation

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Interface states … conflicting reports in the literature and on the street

- Ge diffuses into HfO_2 and degrades it as a dielectric … hafnium aluminates better but rare earth oxides favoured by some ….
- nitrided germanium oxide good compromise as first stack layer
- interface state density >10^{12} cm^{-2} … not controllable
- forming gas anneal doesn't work for most people
- reasonable PMOS devices from Chui (Stamford now at INTEL)
- no interface states seen in EPR … why?

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until recently not much basic data on implantation into germanium had been determined

- implantation defects
- defect removal
- activation of dopants
- doping ceilings
- transient enhanced diffusion

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Is germanium fundamentally different to silicon in relation to implantation? …

- YES because the energy needed to create a vacancy in Ge is much less than in Si (neutral vacancy 1.9eV in Ge but 3.3eV in Si) and so:
  - diffusion of all technologically important dopants is thought to be vacancy mediated …
  - transient enhanced diffusion may result from meta-stable vacancy clusters (not interstitials)?
  - the doping limitation mechanisms in n-type may be more dramatic than in silicon (vacancy driven)

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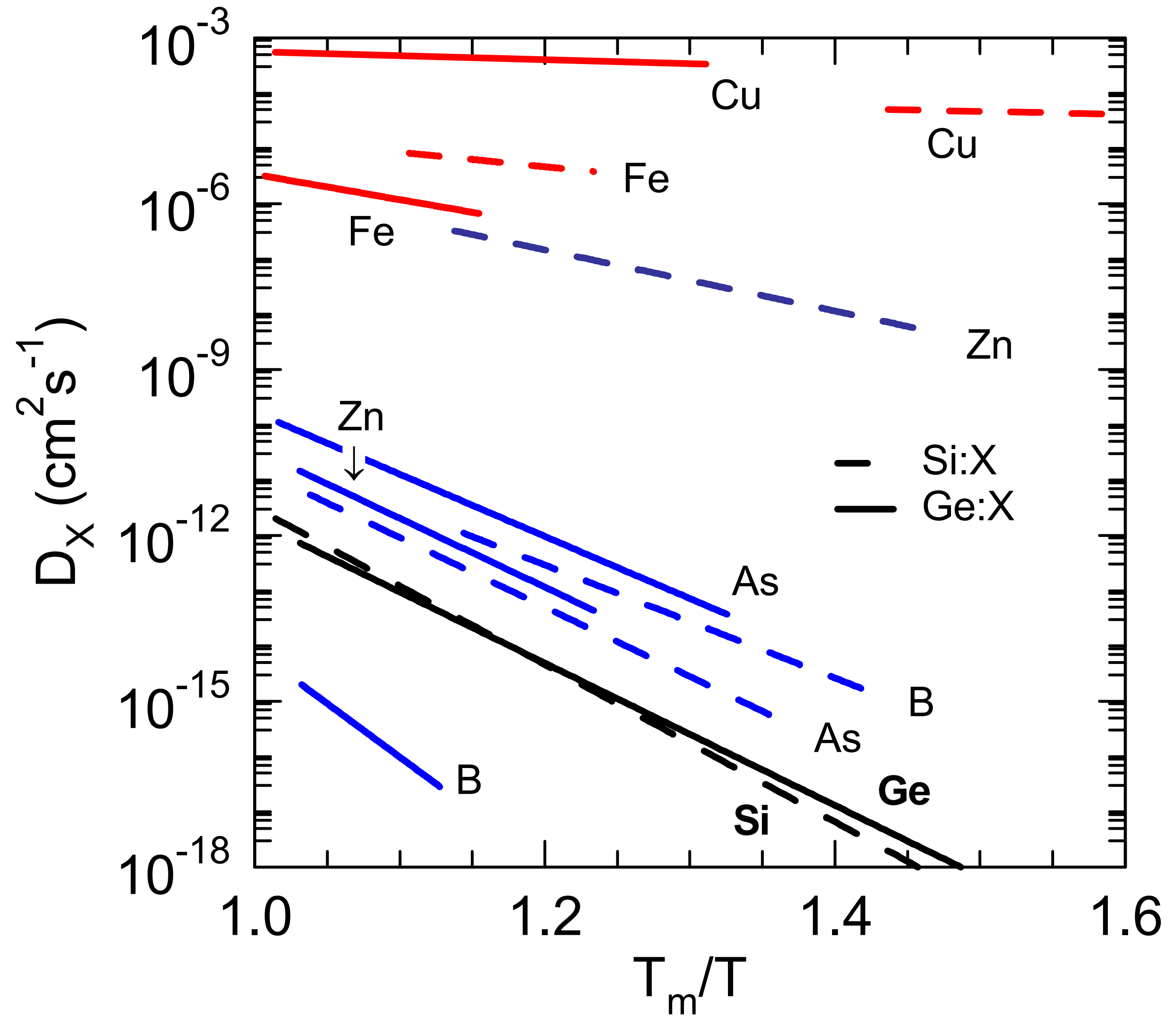
Diffusion in Ge compared to Si (normalised to melting point) $T_m(Ge) = 1210$ K, $T_m(Si) = 1685$ K



continuous lines Ge
broken lines Si

boron is a slow diffuser in Ge

from Harmut Bracht Münster EMRS 2006

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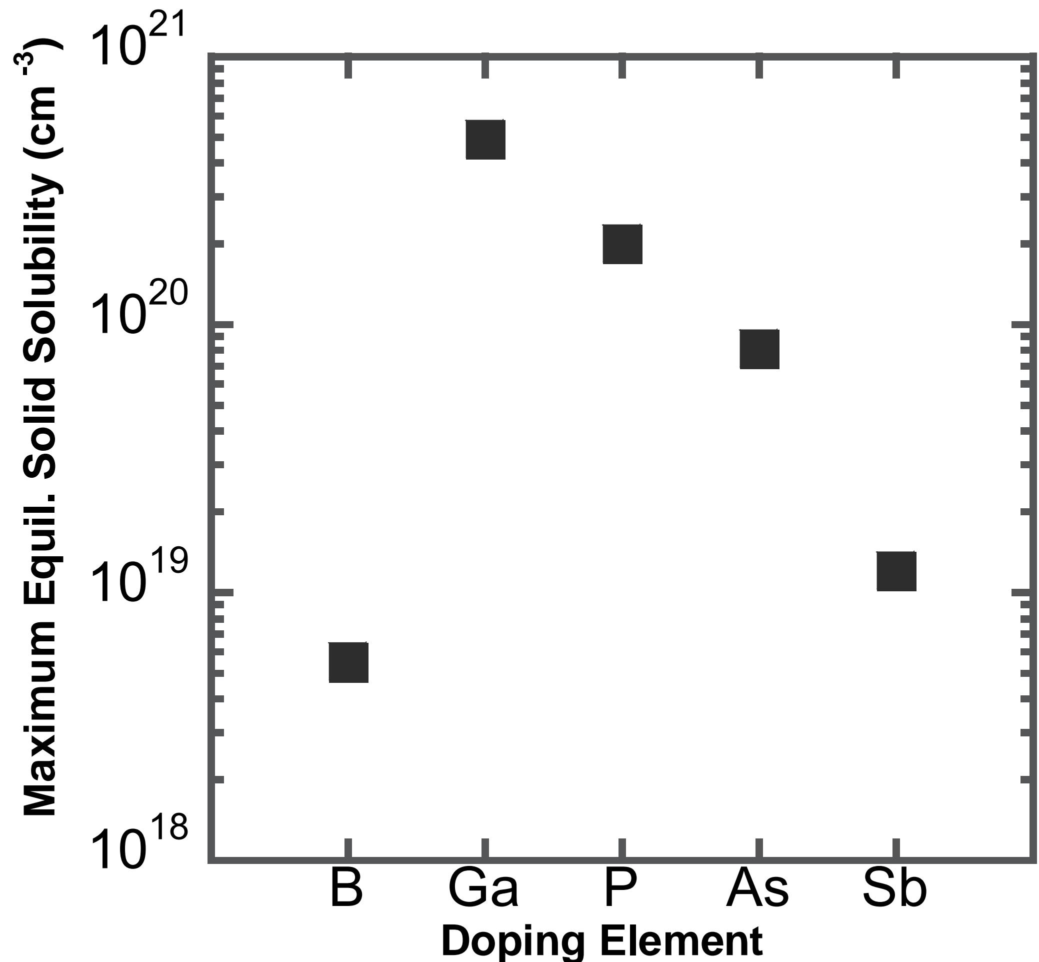
dopants in germanium

Maximum equilibrium solid solubility (600°C) of dopants in germanium is much lower than in silicon. For equilibrium B a 10nm implant will be expected to give 30,000 Ω-

ITRS (Si) requirement for the 30nm node is 300 Ω-sq for a 12nm implant

... a long way off (~2 orders) but Ga seems OK and P is near



Trumbore Bell Sys Tech J 39 (1960) 205

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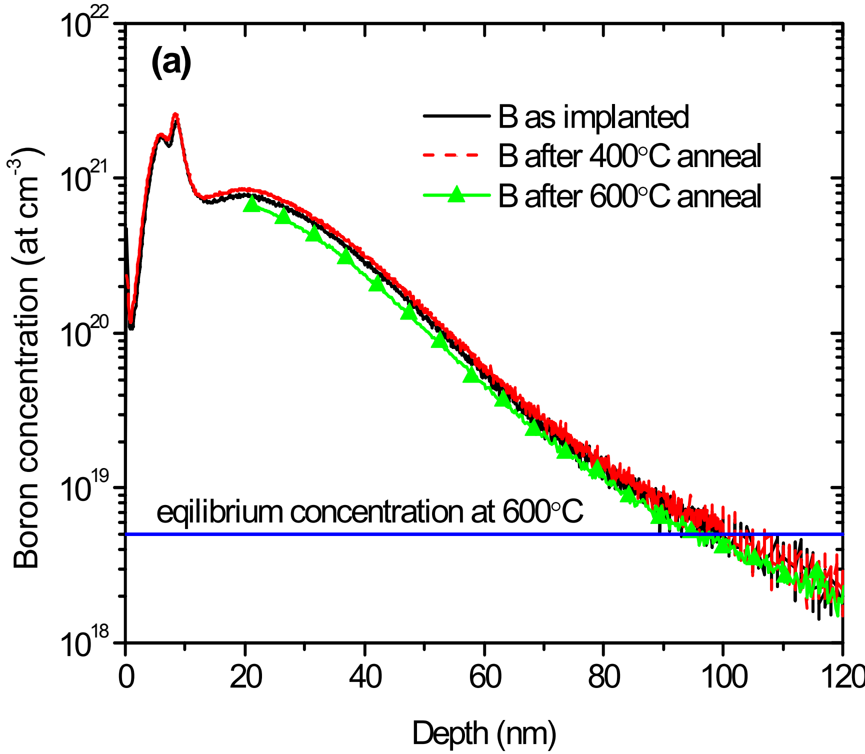
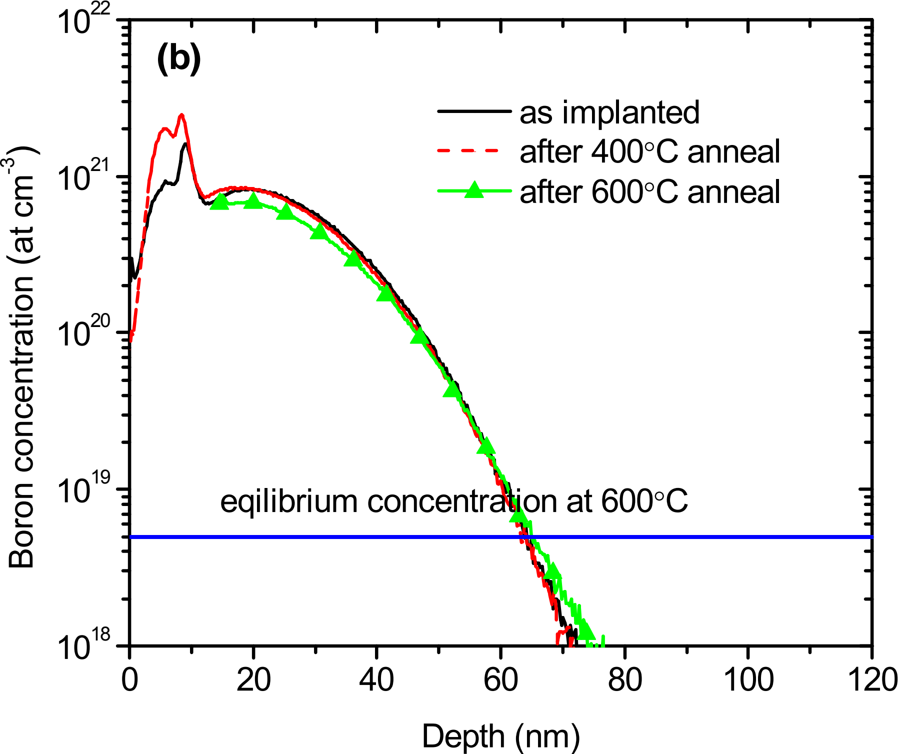
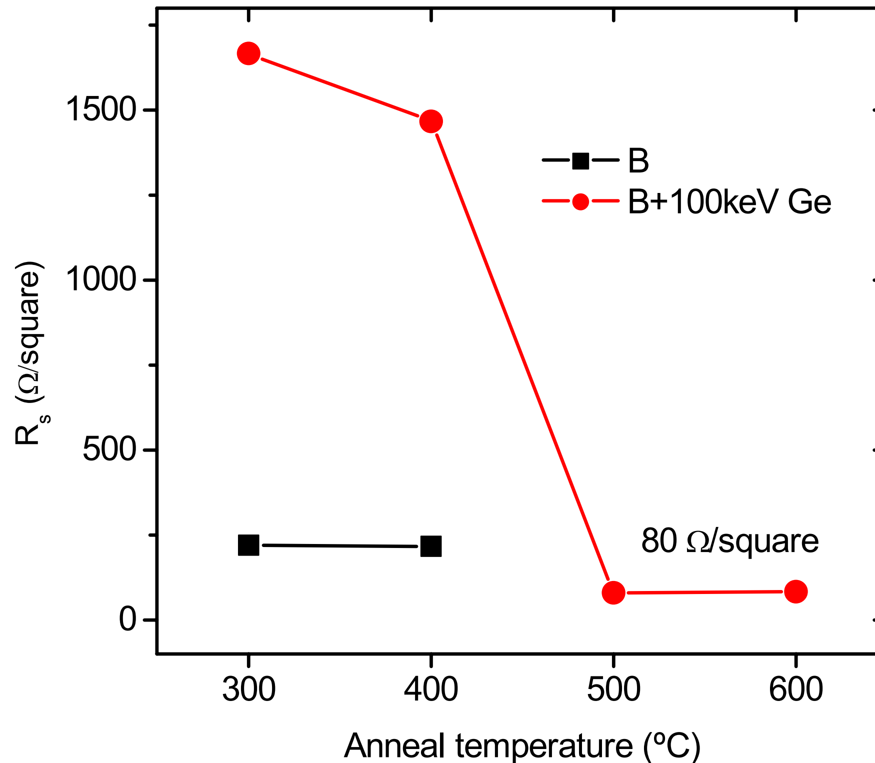
B implants in Ge with and without Ge pre-amorphisation





- Pre-amorphization affects the as-implanted B profile: (channeling suppression)
- No significant diffusion in c-Ge or a-Ge up to 600°C.

p-type dopants: B activation with & without pre-amorphization



- B highest activation (20%) takes place at low T in c-Ge (300ºC)
- However, 60% activation achieved from a-Ge phase.
- Increasing the B doping dose improves Rs (down to ~80 Ω-sq).

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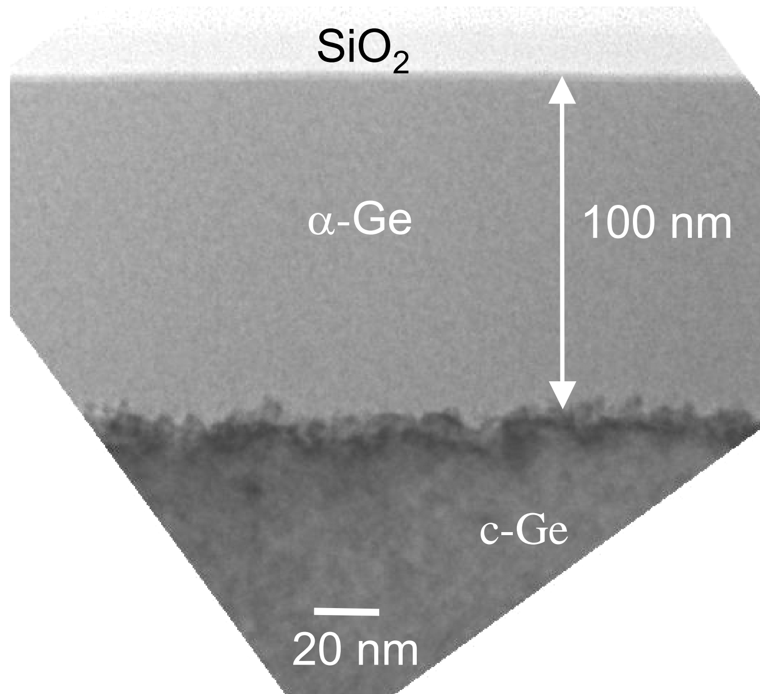
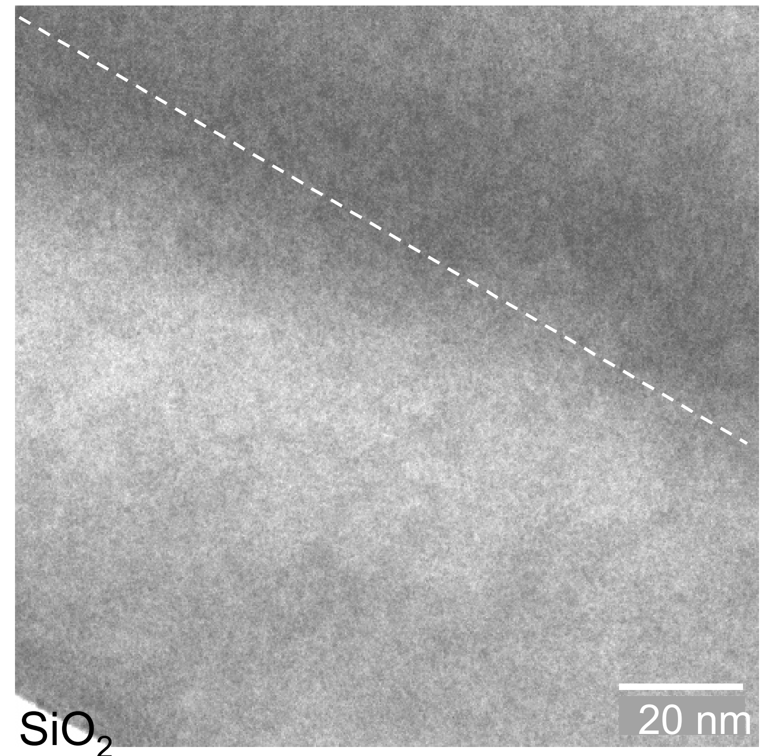
p-type dopants Re-crystallization of pre-amorphized and B-doped Ge



As-implanted

Depth of amorphous layer: 100 nm



Annealed at 400°C, 60s, N_2

Fully re-grown

No detectable EOR defects

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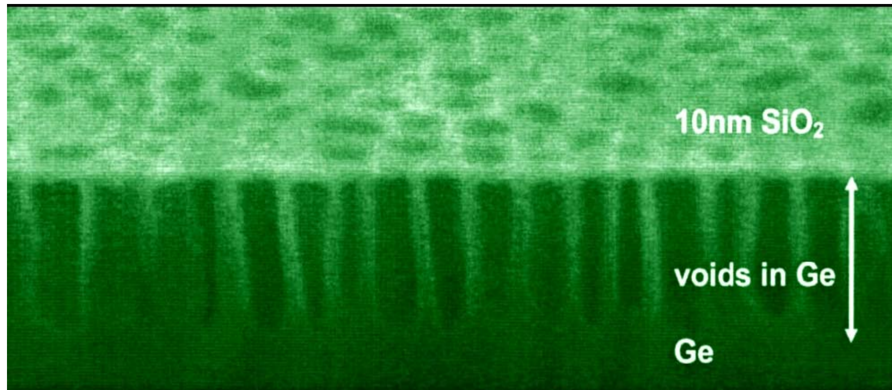
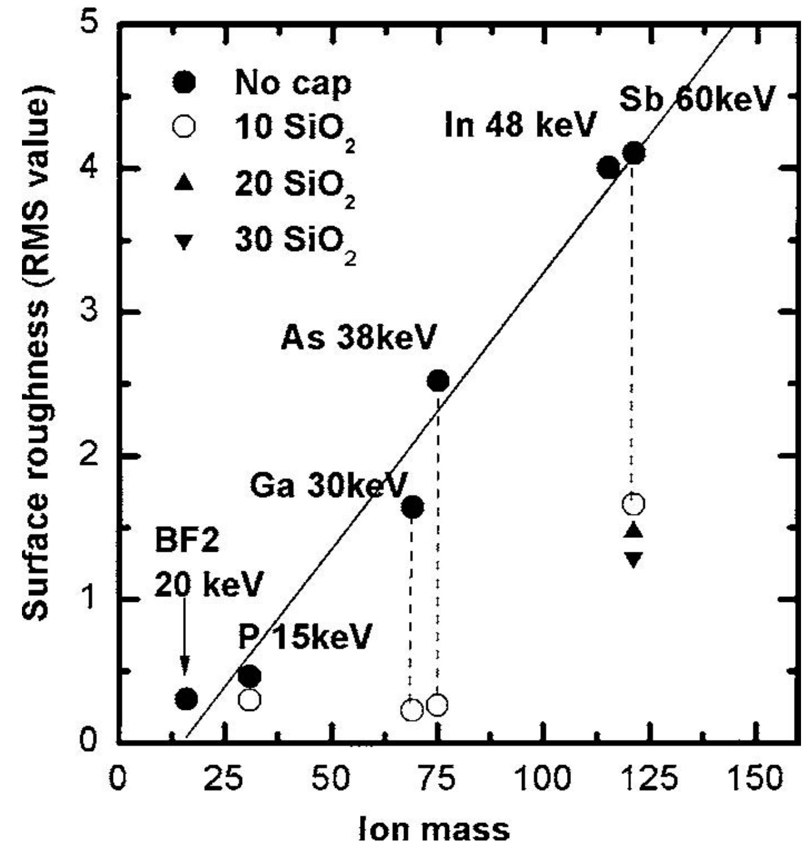
but beware of sputtering and vacancy clustering which cause surface roughness and form voids with heavy ions



voids are 100nm deep after 10^{15} Sb^+ at 70keV

surface roughness increases with ion mass … SiO_2 capping reduces sputtering

Janssens et al J. Vac Sci & Tech B 24 p510 (2006)



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n-type dopants … a very different story
P activation and diffusion

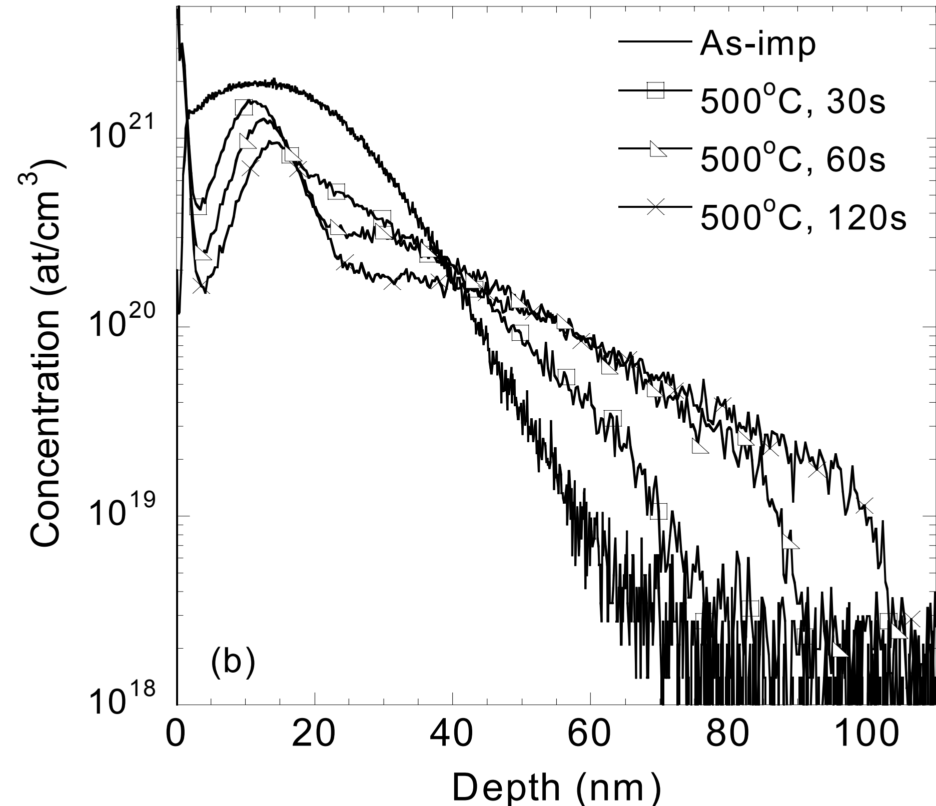
P-implantations suffer from:

- low activation ≤6x10¹⁹ cm⁻³

- **P-precipitation at high implantation doses ≥5x10¹⁵ at/cm²**

- **Concentration-enhanced diffusion above 2x10¹⁹ carriers/cm³**

Arsenic also has major problems



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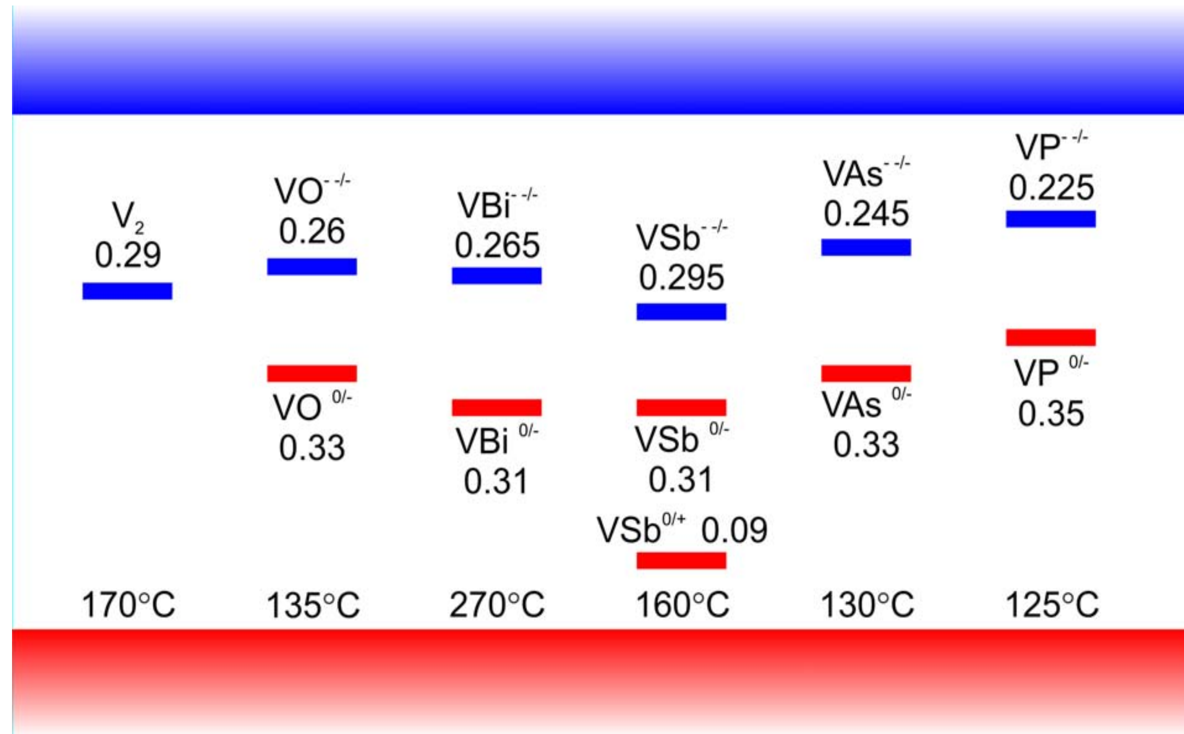
What about defects and junction leakage?

summary of recombination-generation states characterized in germanium



after annealing for 30mins at the temperatures indicated the concentration of the defect has reduced to half its original value

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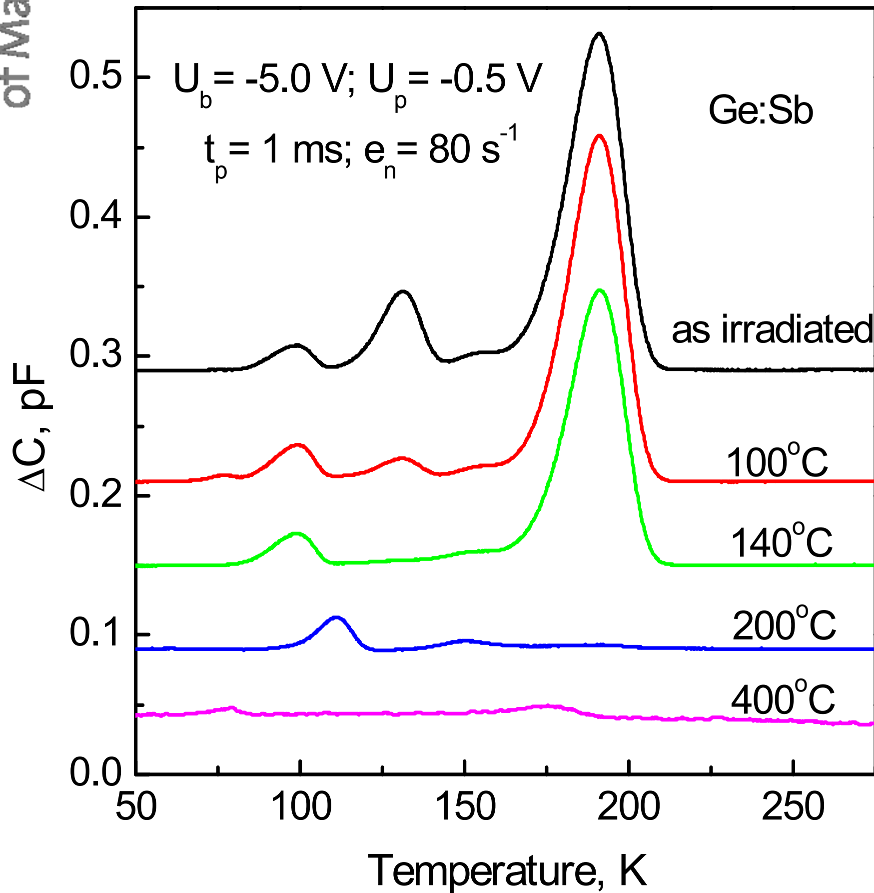
Irradiation damage removal

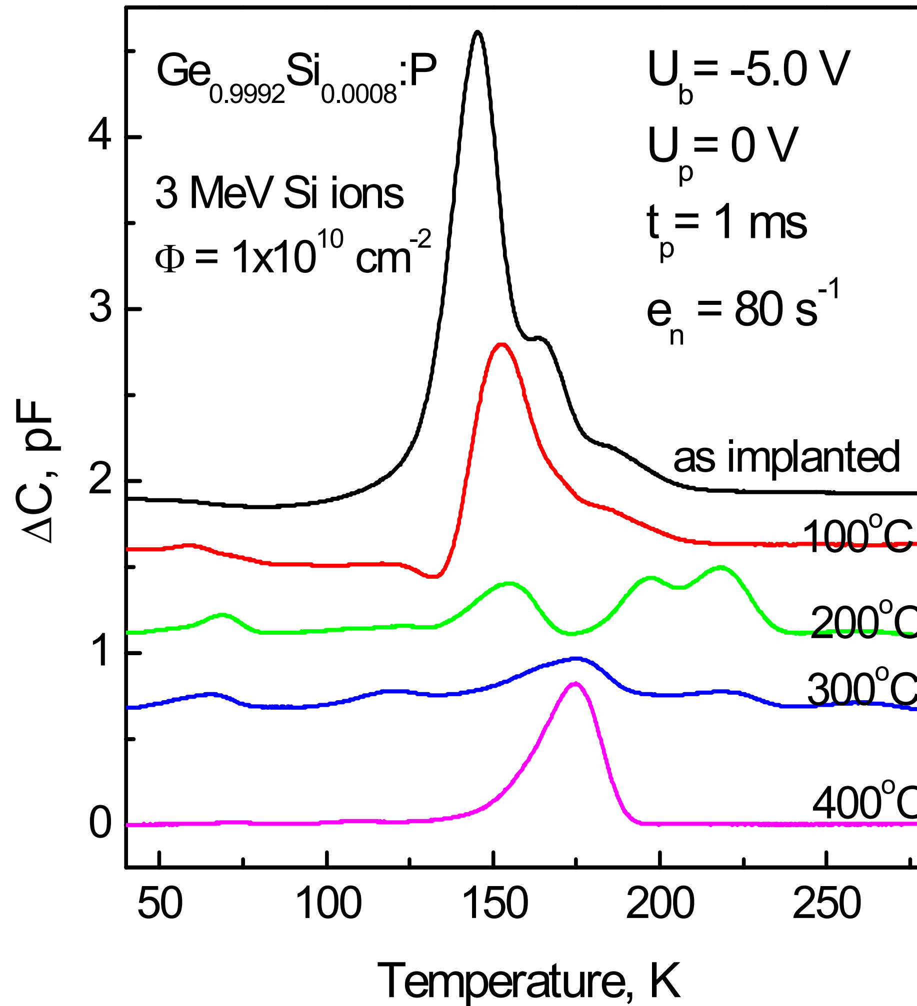


DLTS of Ge:Sb as irradiated and annealed for 30mins at the indicated temperature. Similar measurements have been done on P, As and Bi doped material.

MESSAGE:

All irradiation induced generation-recombination centres can be removed with a very low thermal budget

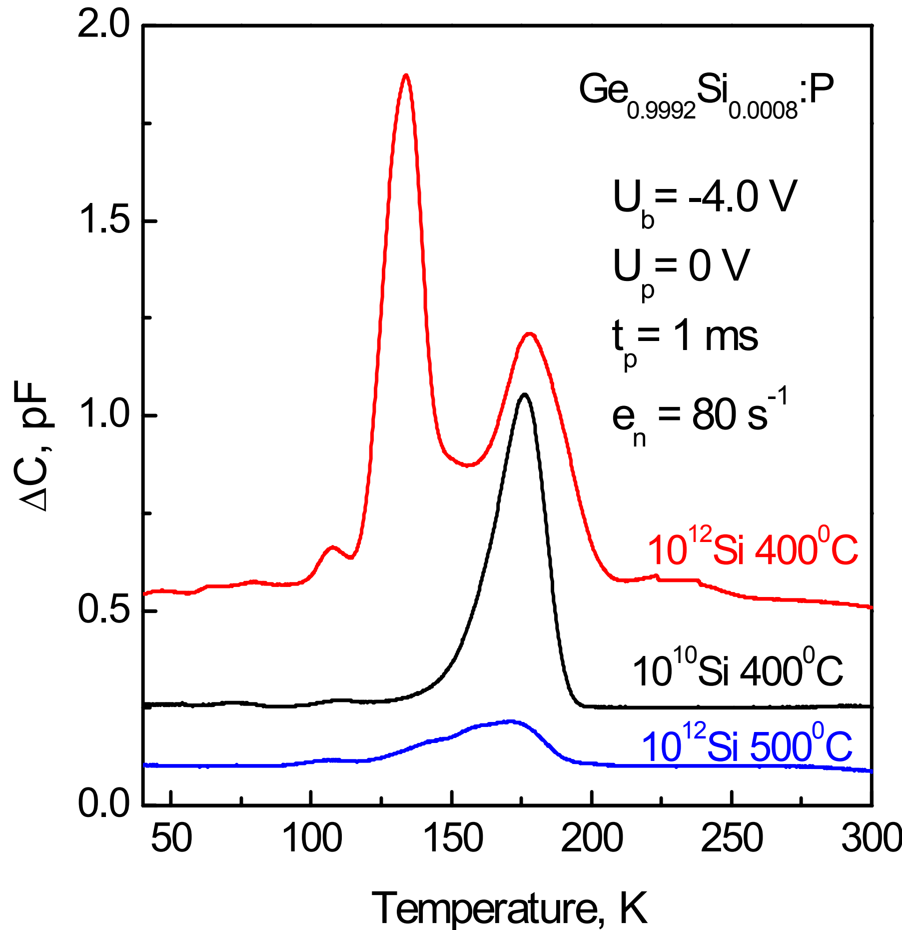
DLTS of Ge with low dose Si implant and anneal



MESSAGE:

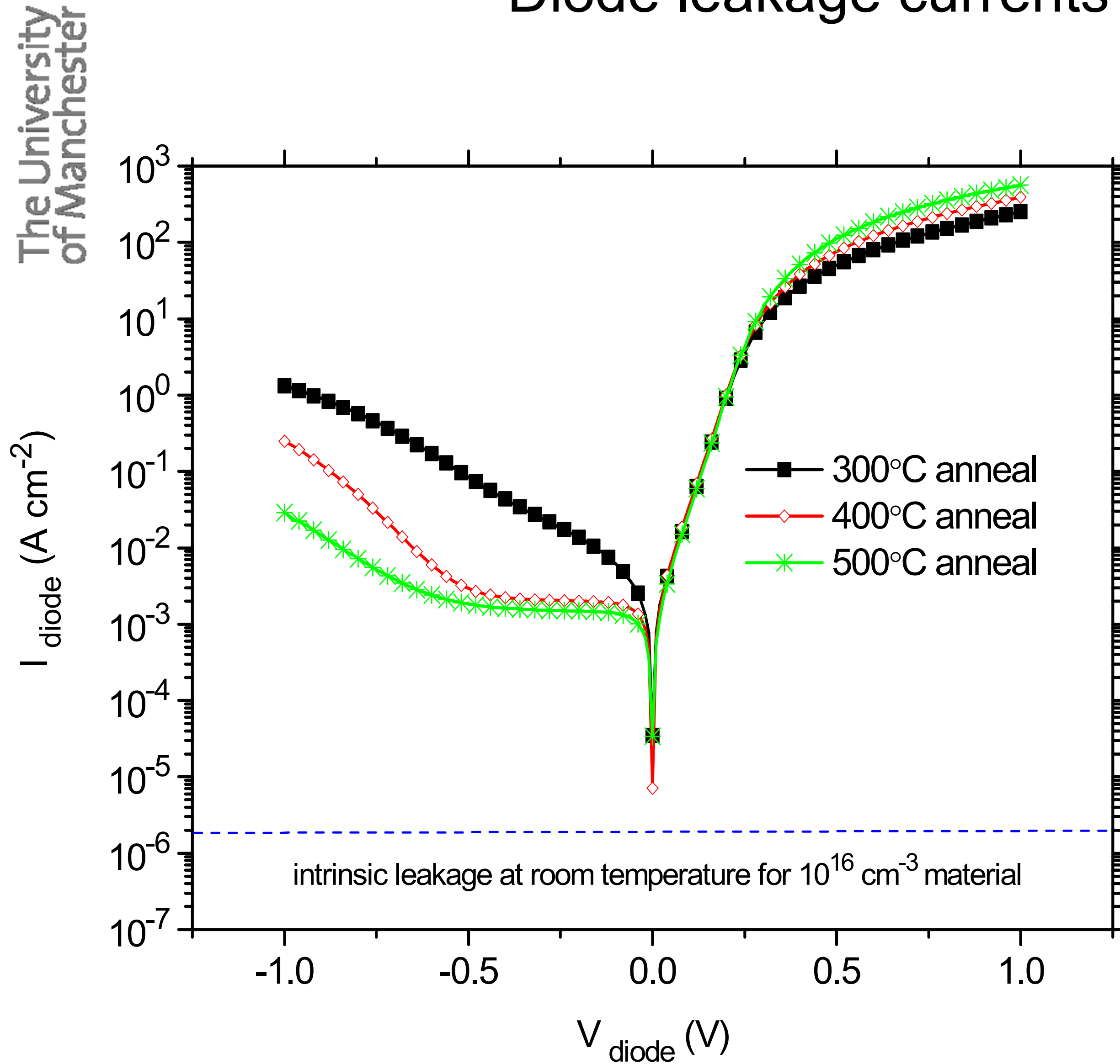
much more complex spectrum and evolution during annealing than irradiation case. Very substantial concentration of generation centres remaining after 400°C anneal

DLTS of Si implanted Ge after annealing



increased dose results in more persistent generation centres (substantial leakage current after 500^0C anneal)

Diode leakage currents



p^+n diode after annealing for 5 minutes The diode was made by implanting 13keV B^+ ions into n-type germanium

after 500ºC anneal the dominant current is due to surface leakage

residual deep states contribute 8×10^{-5} A cm^{-2} (calculated from DLTS data)

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Overview

- major interface state problem still to be resolved
- boron seems a well behaved dopant in Ge … good activation no significant diffusion with adequate activation thermal budgets.
- n-type dopants do not appear to provide adequate activation with simple techniques.
- surface leakage two orders more significant than in Si
- Implant damage difficult to remove … a 500^{0}C anneal of a 10^{12} cm^{-2} 3MeV Si leaves a substantial concentration of generation centres and junction leakage.

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