Ge & Ge+B INFUSION DOPING AND DEPOSITION FOR ULTRA-SHALLOW JUNCTION, BLANKET AND LOCALIZED SiGe OR Ge FORMATION ON Cz AND SOI WAFERS

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Abstract. Ge and Ge+B infusion doping and deposition using Gas Cluster Ion Beam (GCIB) technology is a new method for doping and deposition that offers many advantages over traditional ion implantation and chemical vapor deposition (CVD) techniques. Using B_2H_6, USJ boron dopant profile showed no evidence of channeling with extreme abruptness of <2.5nm/decade for a 12nm shallow junction and box-like profiles can also be realized. Adding GeH_4 to the B_2H_6 gas mixture for Ge+B co-doping resulted in self-amorphization and after SPE recrystalization no residual end-of-range defects remained. A 3x increase in boron solid solubility (Bss) was achieved and when the infusion dose was above 5E14/cm^2, dose controlled deposition (DCD) occurred. The DCD infusion process is insensitive to residual surface impurities (native oxide) due to the highly localized transient thermal spike (TTS) and no post deposition interfacial layer could be detected enabling complete single crystal epitaxial regrowth of the 100% Ge amorphous layer at temperatures down to 550^{o}C. Adding SiH_4 gas mixture for SiGe DCD or top layer Si-cap on 100% Ge both strained and strain relaxed SiGe and Ge structures could be formed. Because this is a room temperature process, localized/selective patterned masked infusion doping and deposition using standard photoresist is possible. This method of SiGe and Ge formation can be used for bulk and SOI CMOS applications and potentially reduce the processing steps for SGOI and GeOI formation by up to 75%.

INTRODUCTION

The SiGe material system has received much attention in the last few years as being critical to continued device scaling and extending the life of planar single gate CMOS technology. SiGe epitaxy provides 2 unique and independent benefits for CMOS device scaling. For USJ applications Ozturk et al. reported a significant increase in boron dopant electrical activation due to increased Bss (boron solid solubility) in the SiGe system by over an order of magnitude (1). In 100% silicon, Bss is limited to 5E20/cm3 at the melting point of silicon (1407^{o}C) while in 80% silicon and 20% Ge Ozturk achieved >2E21/cm3 boron electrical activation at <600^{o}C. Without Ge this value would be 1E19/cm^3. Lee et al. also showed an increase of 2x in boron activation levels in their SiGe USJ structures (2). To incorporate this into pMOS devices would require selective etching laterally under the gate edge followed by SiGeB selective epi growth (SEG) as reported by Ozturk et al. and Mansoori and shown in Fig. 1 (1,3). As with any SEG process, surface cleaning to eliminate epi/substrate interface contamination is very critical. The 2nd area for SiGe epitaxy is for device channel mobility enhancement using strain-Si epitaxy on relaxed SiGe epilayer. This is a very costly and complex process involving multiple thick and thin SiGe and Si epitaxial deposition steps, cleaning steps and even a polishing step. Misfit dislocation at the epi/substrate interface and 10^5 to 10^7 defects/cm^2 on the top epilayer surface are typical. There has been debate over what is the preferred strain method, global blanket biaxial strain-Si epi on relaxed SiGe epi or to have localized tensile and compressive strain. Localized uniaxial tensile strain in the channel for nMOS devices while localized uniaxial compressive strain in the channel for pMOS devices was reported by Ghani et al. of Intel using localized selective SiGeB SEG process for pMOS to induce uniaxial compressive strain in the channel (4). Therefore in this paper we will present Ge and GeB infusion doping and DCD as an alternative method to realize USJ and blanket or localized SiGe formation for both bulk and SOI CMOS technology without the manufacturing risks, process complexity and costs associated with SiGe CVD Epi processing.

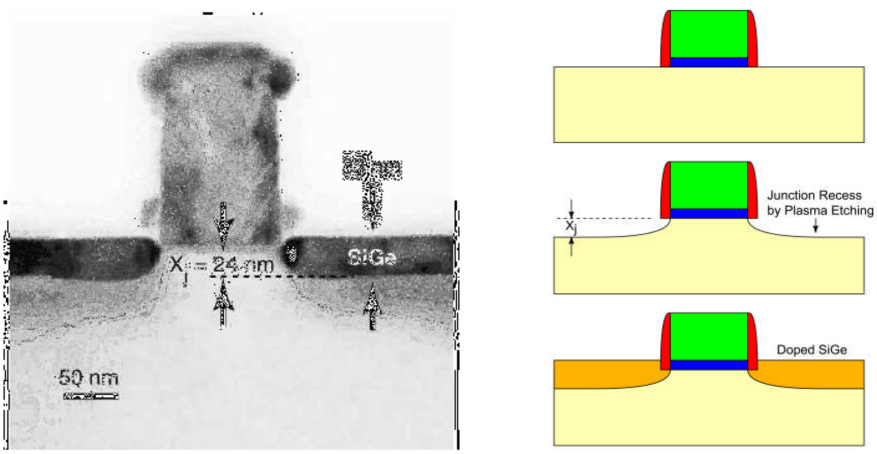


Fig. 1: SiGeB SEG for pMOS extension and raised source drain structure (1).

INFUSION DOPING TECHNIQUE

Infusion doping utilizes a GCIB source to produce energetic clusters of atoms. Unlike ion implantation which involves a single ionized atom or gas molecule, ionized clusters contain typically >5000 atoms per charge. Infusion doping of Si with GCIB has been studied with a standard 300mm Epion nFusion GCIB tool, by producing clusters made up of Ar and B, Ge or Si containing molecules such as B_2H_6 , GeH_4 or SiH_4 gases diluted in argon as shown schematically in Fig. 2. The gas cluster ions used for surface processing are accelerated through potentials up to 30keV. Although the gas cluster ions have high total energy, the energy is shared by the large number of atoms comprising the cluster, so that the energy per atom is <6eV. A single B ion with such low energy would not be able to penetrate the Si surface; however, with infusion the high total energy of the ionized gas cluster is concentrated into a very small region (~100A diameter) of the silicon surface resulting in momentary surface temperatures and pressures which are significantly higher than those produced by conventional ion processes. Upon impact with the substrate, the cluster locally heats a volume of Si generating a transient thermal spike (TTS) while the several thousand atoms in the cluster infuse into the surface with the Mbar pressures which are generated over the few pico-seconds of the impact. The TTS propagates in 3-dimensions and is quickly quenched. This is fundamentally different from ion implantation whose energy dissipates primarily along its trajectory as illustrated in Fig. 3. This enables higher acceleration energies may be used to minimize space charge effects without dramatically effecting penetration depth.

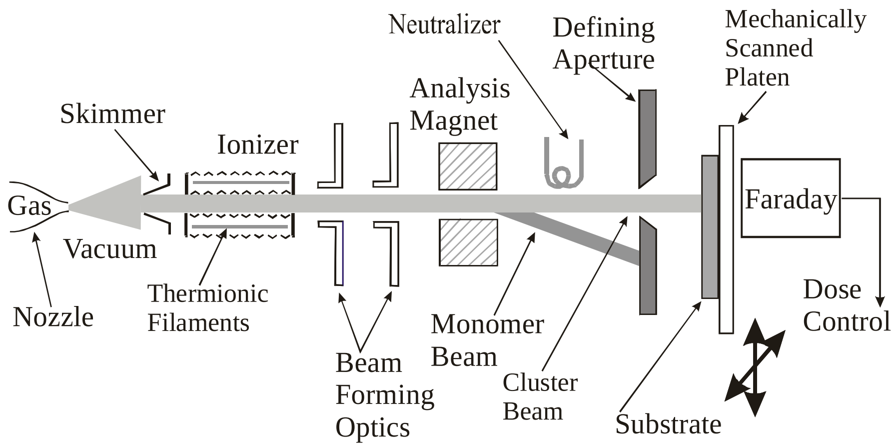


Fig. 2: Schematic of Epion's infusion doping equipment.

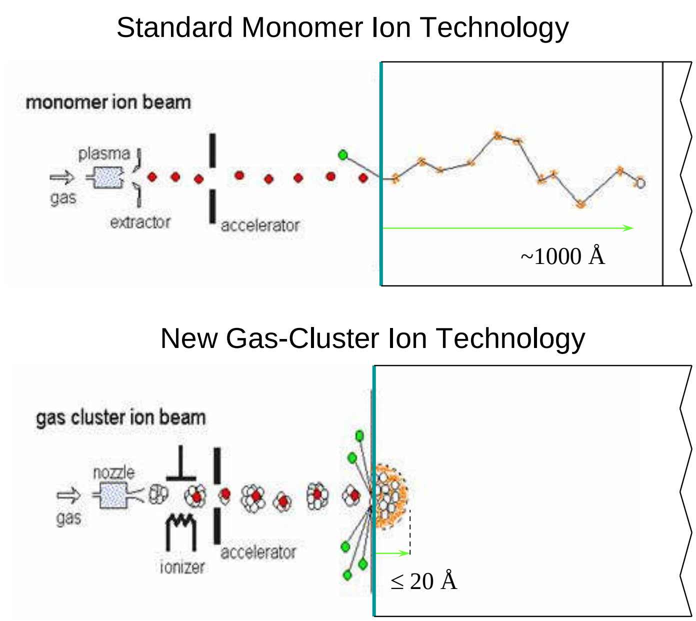


Fig. 3: Illustration comparison of monomer ion implantation versus cluster ion infusion effects.

Nearly all gases and mixtures of gases can be nucleated into clusters (5-7). Rare gases such as Ar and Xe readily form clusters as do most diatomics (ie. O_2, N_2) and molecules (ie. B_2H_6, BF_3, CH_4, NF_3, CF_4). The kinetic removal rates are low for GCIB processing with non-reactive gases (such as Ar and Xe) is <0.4nm/minute however, significant localized chemical effects can take place when reactive gas molecules such as

CF_4, NF_3, O_2, H_2, etc. are included in the clusters and under these processing conditions infusion surface etching will occur at rates up to 10nm/minute. As a consequence of the locally high temperatures in the impact infusion volume, such gas cluster beams can be used to perform well-controlled non-damaging directional chemistry on the substrate surface. This characteristic of GCIB has been successfully used in corrective etching of SOI wafers to attain uniform very thin silicon layers down to 5.2nm +/-0.2nm as shown in Fig. 4 (8).

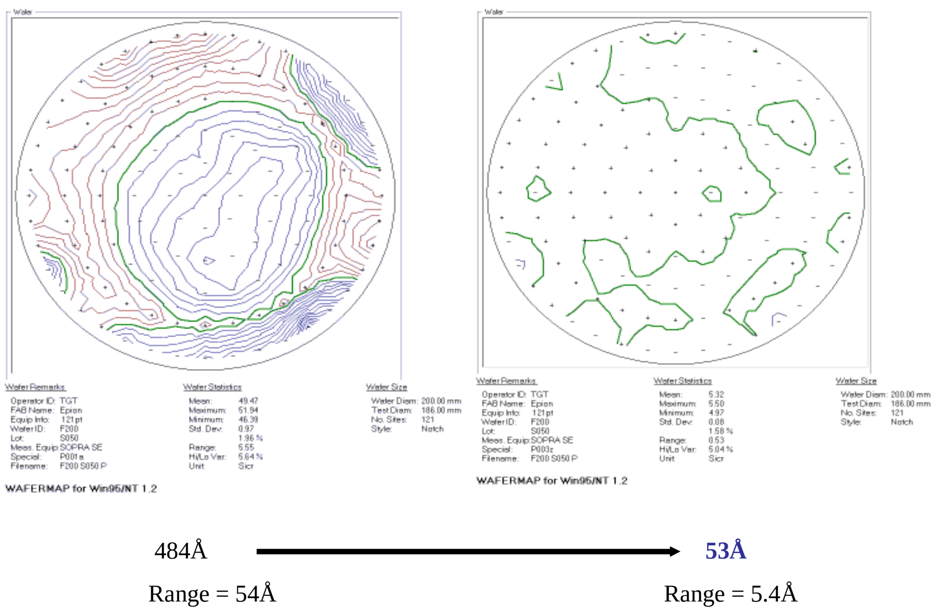


Fig. 4: Localized GCIB corrective etching of silicon to realize uniform very thin SOI wafers.

A comparison between traditional ion implantation doping using 500eV B_{11} monomer and infusion doping by 5keV gas clusters made up of a mixture of B_2H_6 and Ar gases is shown in Fig. 5. No channeling is observed using the infusion doping technique and a 1E18/cm^3 junction depth (Xj) at 12nm is achieved with an abruptness of <2.5nm/decade. Significant channeling can be seen with the ion implantation process resulting in an Xj at 37nm. A Ge pre-amorphizing implant (PAI) would be required to reduce Xj to 15nm and a 300eV implant would be needed to realize an Xj at 12nm (9). Fig. 6 shows the effects of infusion doping energy on junction depth for a 2E15/cm^2 B GCIB dose at 20keV resulting in a realized surface boron level of 2E22/cm^3 and retained dose of 2E16/cm^2. Fig. 7 shows the relationship of junction depth measured at 5E19/cm^3 versus infusion doping energy over the energy range of 2.5keV to 30keV. Unlike ion implantation, the stopping distance for infusion doping follows the energy of acceleration to the 1/3 power. This is because the volume of the silicon the cluster locally heats is linearly related to the energy of the cluster and thus the depth of this hemispherical volume will follow an energy to the 1/3 power law. The effects of this pressurized TTS can also be seen in Fig. 8 where a wafer that had a 5keV/2E15/cm^2 B infusion doping process followed by a post Ar GCIB process at 5keV and 0.3 or 1E15/cm^2 dose (B=3 or 2

E21/cm^3 respectively). Note the ability to flatten the B profile and making it more box-like in shape while maintaining an Xj at 12nm since the GCIB energy was kept at 5keV. The doping process is linear and also controllable by the gas mixture ratio. A one-to-one correlation between the gas cluster dose and the SIMS measured retained boron dose in silicon was observed. A 1E14ions/cm^2 GCIB boron dose corresponded to a 1E15 atoms/cm^2 SIMS retained dose in silicon and a 1E15ions/cm^2 GCIB dose corresponded to a 1E16 atoms/cm^2 SIMS retained dose as shown in Fig. 9a. Increasing the energy by 6x from 5keV to 30keV also increased the amount of boron atoms incorporated into the silicon per charge from 10 up to 65 as shown in Fig. 9b. For higher gas mixtures of boron up to 200 boron atoms per charge have been incorporated into the silicon.

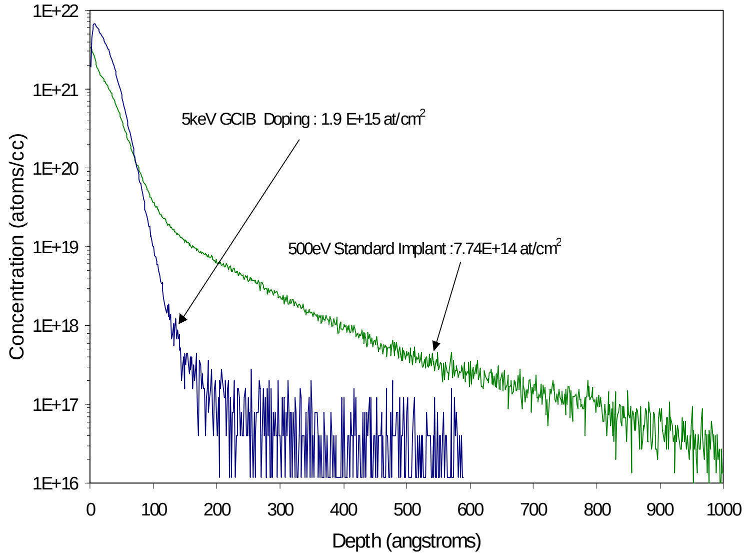


Fig. 5: SIMS comparison of implantation (channeling) and infusion (non-channeling) doping profiles of boron.

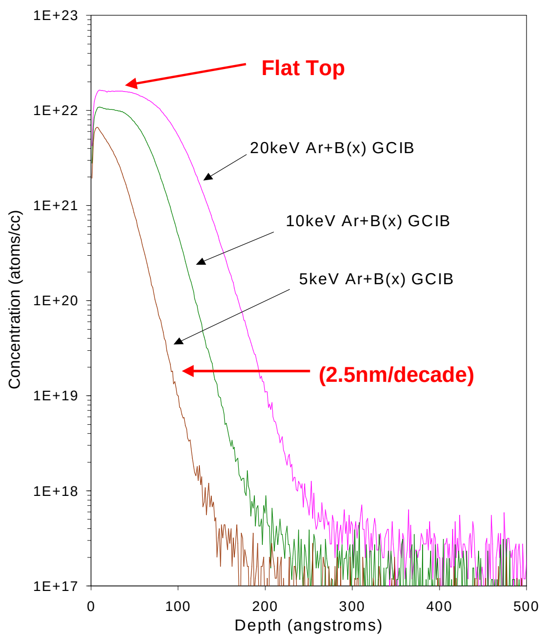


Fig.6: SIMS dopant profiles for 5-20keV infusion doping energies.

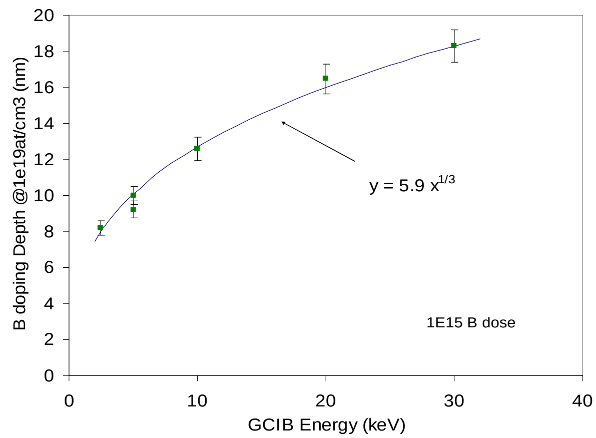


Fig. 7: Junction depth to the 1/3 power for infusion B doping.

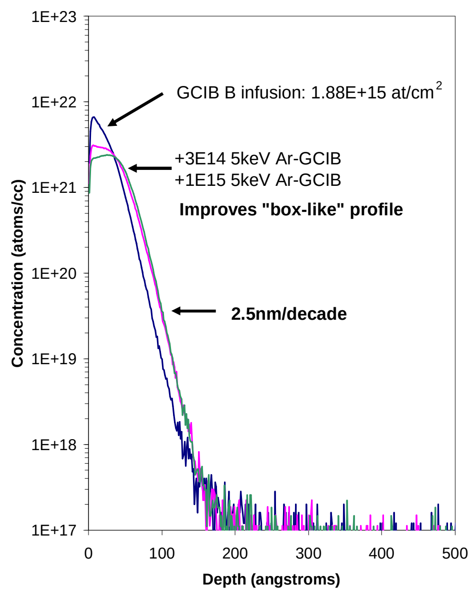
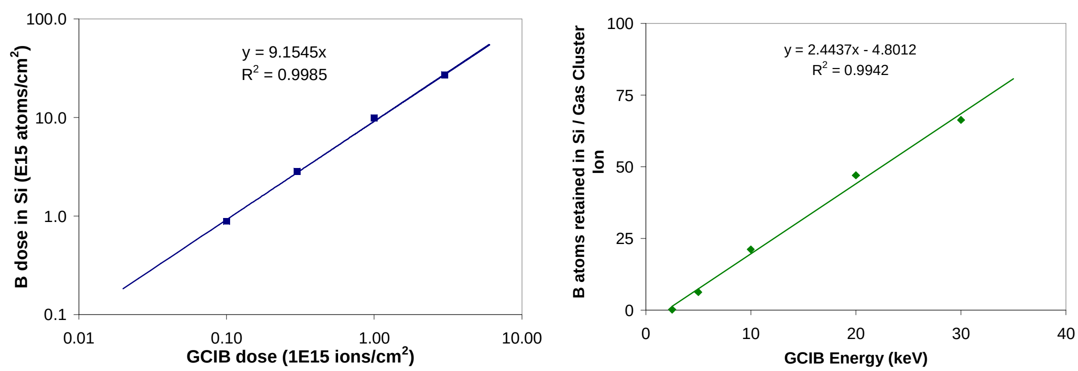


Fig. 8: Transient thermal spike localized heating effects creating a more box-like shaped boron profile.



a) b)

Fig. 9: Comparison between a) GCIB B dose versus silicon B retained dose and b) B doping efficiency versus energy.

Unlike ion implantation, which uses a plasma to generate ions, or plasma immersion ion implantation which generates a plasma over the wafer, no plasma's are used in the GCIB beamline. This enables infusion doping to have a cleaner process without concern for heavy metals. VPD-ICPMS measurements of 200mm wafers that have been doped with boron show no heavy metal contamination above 5E10/cm^2 (Fig. 10). Initial results for an infusion doping process realizing an Xj=10nm has demonstrated a 1E15/cm^2 dose (GCIB dose of 1E14/cm^2) throughput of >20wph for 300mm wafers. Electrical characterization of the 5keV B infusion doping process showed the SIMS chemical junction depth to be 25nm while the SRP electrical junction depth was 6nm and an electrically active surface dopant level of 1.5E20/cm^3. This value was in agreement with non-penetrating 4PP Rs values using elastic material or Hg probes which measured 2,800 ohms/square (1.0E20/cm^3) as shown in Fig. 11 (10,11).

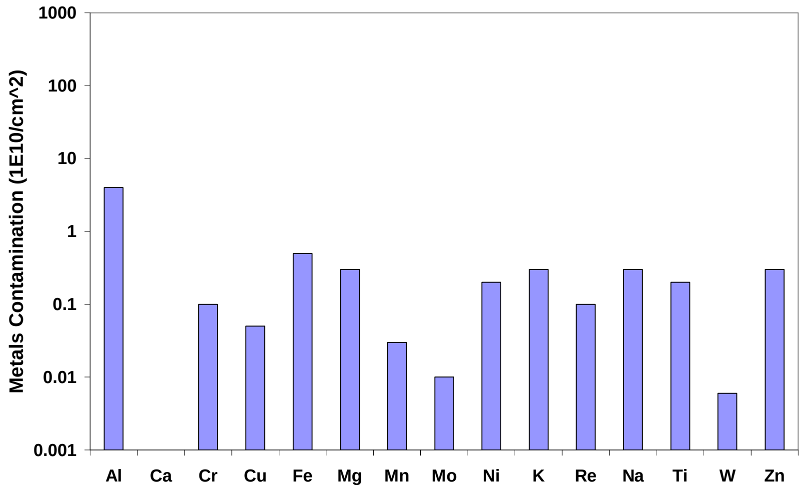


Fig. 10: Metallic analysis results.

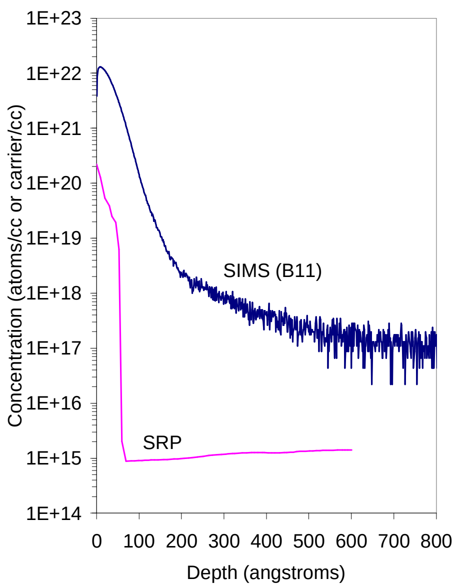


Fig. 11: Comparison of SIMS to SRP boron dopant profile (chemical –vs- electrical).

Mixing Ge with the B and Ar cluster resulted in self-amorphization of the USJ structure without having to add an additional Ge pre-amorphizing implantation (Ge-PAI) step usually used in traditional implantation for USJ formation. The self-amorph0rus SiGeB structure is shown in Fig. 12 & 13. After either a 550^{o}C or 950^{o}C 1 hour anneal complete SPE recrystalization is observed. No residual defects were observed by planar or cross-sectional TEM including no end-of-range (EOR) damage as usually observed with implanted Ge due to excess interstitials beyond the amorphous interface as reported by Matsuda et al. and shown in Fig. 14 (12).

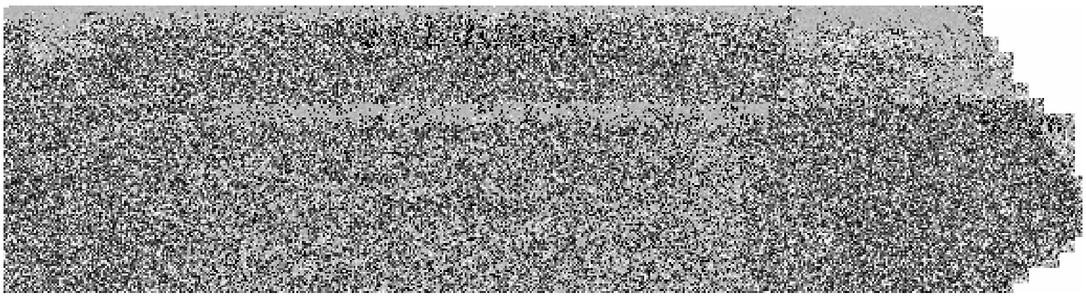


Fig. 12: X-TEM Ge infusion doping of 12nm.

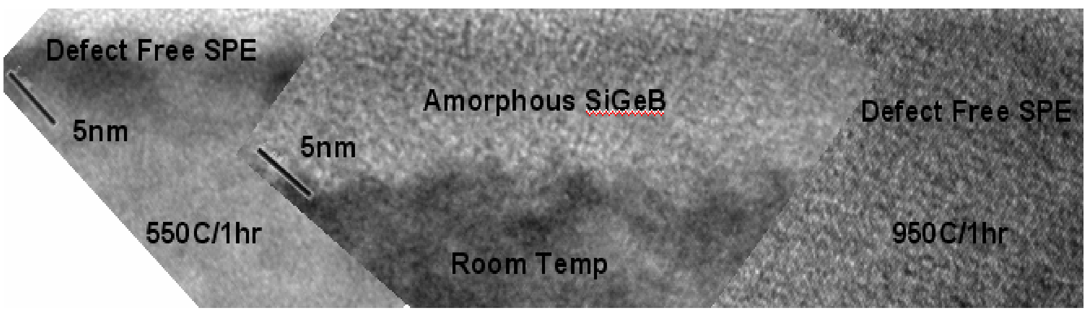


Fig. 13: Atomic resolution imaging of Fig. 8 showing defect free SPE Ge infusion layer.

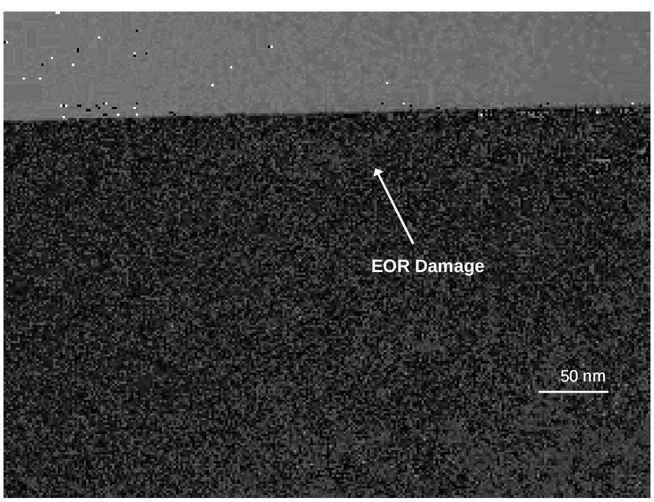


Fig. 14: 550^{o}C annealed SPE recrystalized Ge-PAI structure with residual EOR damage (12).

INFUSION DOSE CONTROLLED DEPOSITION (DCD)

Infusion doping of Ge at 5keV and low infusion doses of <1E14/cm^2 resulted in shallow Ge doping profiles of <12nm as shown in Fig. 15a. At higher infusion doses of Ge >1E15/cm^2 dose controlled deposition was realized of a 40nm thick deposited amorphous Ge surface layer (Fig. 15a). The calculated deposition rate on 300mm wafers was 5nm/min and up to 900 Ge atoms were infused into silicon for each cluster for a 30keV infusion process. At 5keV, 150 Ge atoms were infused into silicon for each cluster. Fig. 15b shows the effects of infusion energy and dose on Ge DCD film thickness. Increasing the energy by 6x to 30keV increased the Ge atoms incorporated into silicon per charge to 895 (Fig. 15b).

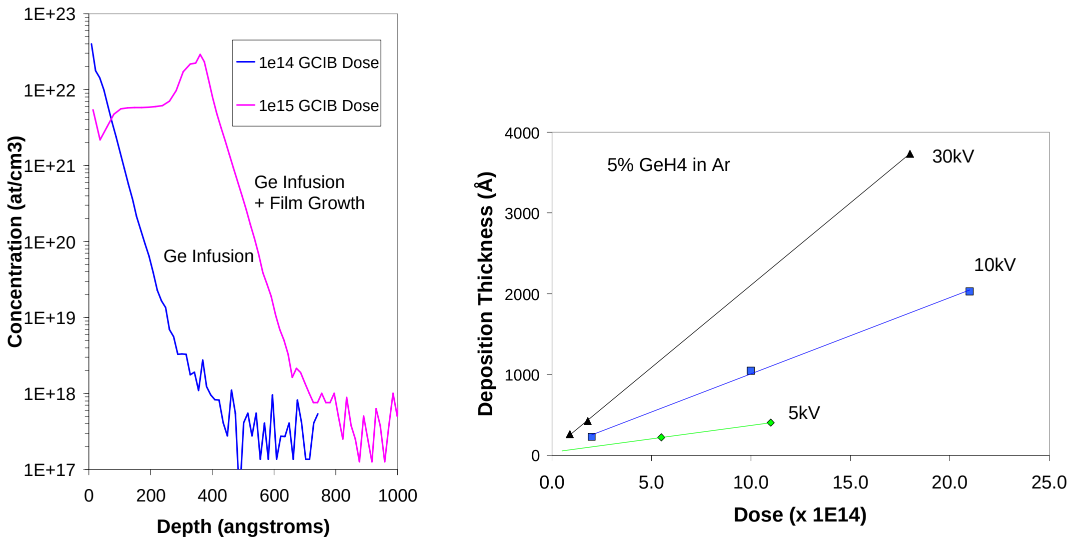


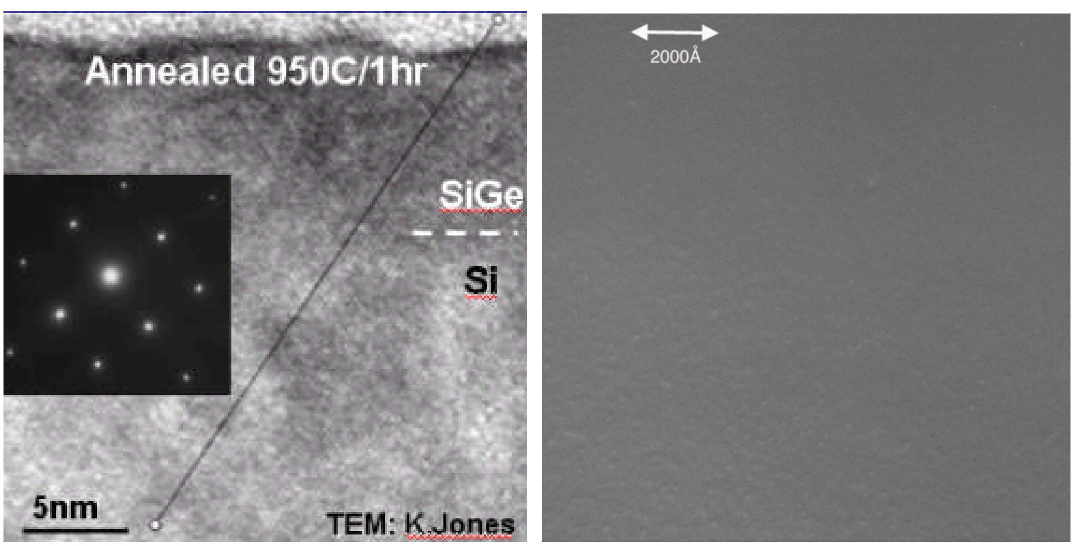
Fig. 15: Ge infusion processing; a) Ge infusion doping (1E14/cm2) and dose controlled deposition (1E15/cm2), b) comparison of 5keV, 10keV and 30keV DCD.

As an alternative to using SiGe epitaxial growth or high dose Ge ion implantation, we investigated using infusion doping of Ge to form localized or blanket SiGe and Ge structures. This technique can eliminate the graded and relaxed SiGe epitaxial layer process and post polishing step for blanket SiGe formation for bulk CMOS. For PD/SOI CMOS applications this technique can be used with either SIMOX or bonded SOI wafers and can potentially significantly reduce the processing steps by up to 75% as shown in Table 1 below. Because the infusion process is at room temperature, photoresist masking material can be used to achieve patterned localized Ge infusion and the formation of localized SiGe & Ge strain-Si structures. Also, this technique can be used with the Ge condensation SGOI formation technique and layer transfer FD/sSOI technique. Substituting a C-containing gas such as CH_4 for the GeH_4 similarly results in infusing C into the surface of Si. This will result in a controllable method of compressive strain layers for enhanced pMOS channel mobilities.

Table 1: SGOI Process Flow

Standard bonded PD/SOI Wafer	Infusion PD/SOI Wafer
1) >3um graded SiGe Epi	1) Ge Infusion doping into SOI wafer Bonded SOI or SIMOX SOI wafer
2) Relaxed SiGe Epi	2) In-situ annealing for SiGe strain relaxation + thin strain-Si Epi
3) Wafer polishing	
4) Oxidation	
5) Hydrogen implant for layer spliting	
6) Bonding anneal and layer transfer	
7) Thinning and polishing	
8) Thin strain-Si Epi	

Results for a 12nm amorphous Ge infusion doping process after a 950°C 1 hour anneal is shown in Fig. 16. The atomic resolution X-TEM in Fig. 16a shows no defects as does the planar TEM in Fig. 16b. Results for a 300mm SOI wafer map for 51nm Ge DCD showed uniformity typical to implantation of <1% and not like CVD which would be a few percent (Fig. 17). The typical SiGe epi misfit dislocation cross hatching pattern is not visible in any of the Ge infusion samples because there is no defined epi/substrate interface for the misfits to form and glide. SIMS analysis of the room temperature and 550°C annealed Ge infusion deposition samples is shown in Fig. 18a for no surface cleaning and Fig. 18b for HF last surface cleaning. For the no surface cleaning samples the native oxide is dissolved by the transient thermal spike of the infusion process to a depth of about 10nm from the initial silicon wafer surface. The integrated oxygen dose is 1.9E15/cm2. This diffused oxygen level had no impact in preventing SPE single crystal regrowth in this infusion technique while it would prevent epitaxial regrowth in typical amorphous SiGe CVD deposition technique. Results from a 5keV 200nm Ge infusion deposition process on photoresist patterned wafers is shown in Fig. 19. No evidence of photoresist material degradation could be seen and some sidewall deposition occurred with a step coverage of about 20-30% in Fig. 19b.



a) X-TEM b) Planar TEM

Fig. 16: 12nm Ge infusion doping/deposition after 950°C anneal showing defect free single crystal SiGe layer after 950°C 1 hour anneal a) X-TEM free of defects and b) defect free planar TEM.

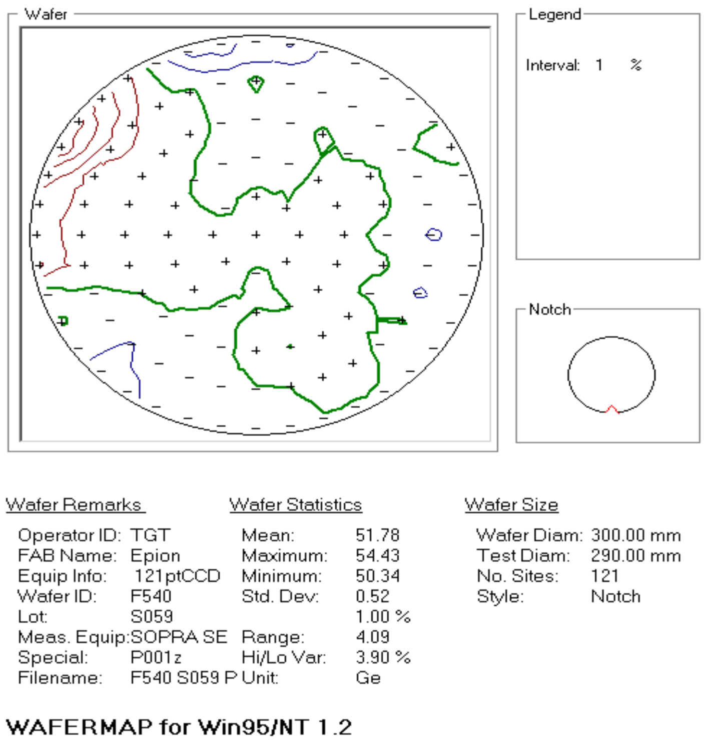
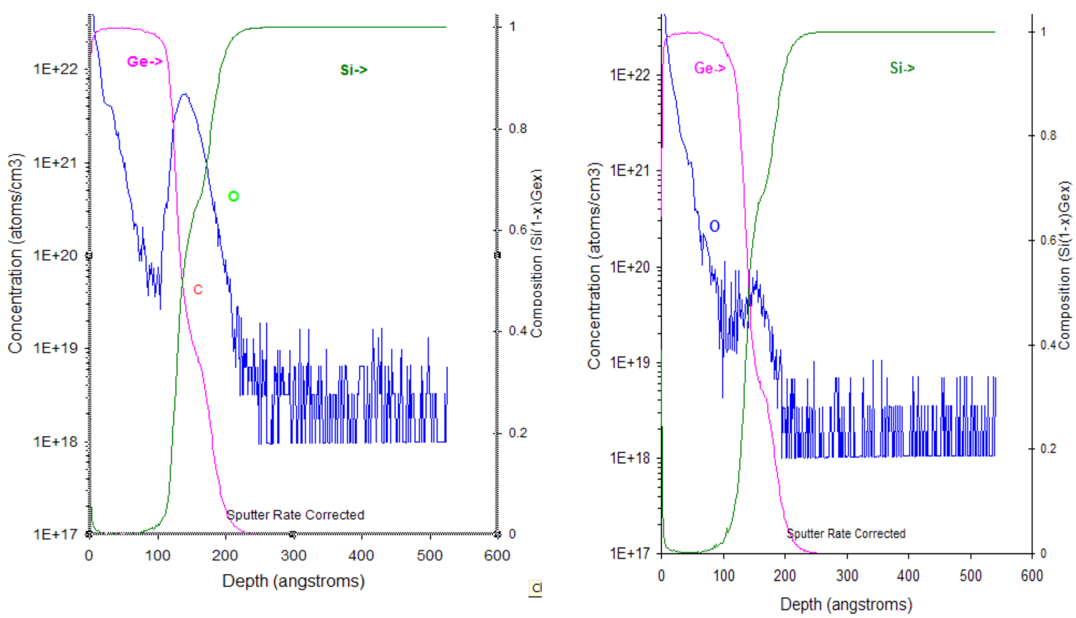
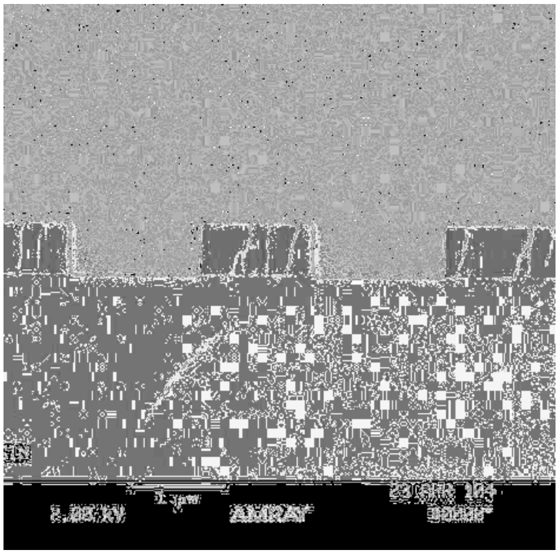


Fig. 17: 51nm Ge infusion deposition uniformity results on 300mm SOI wafer.

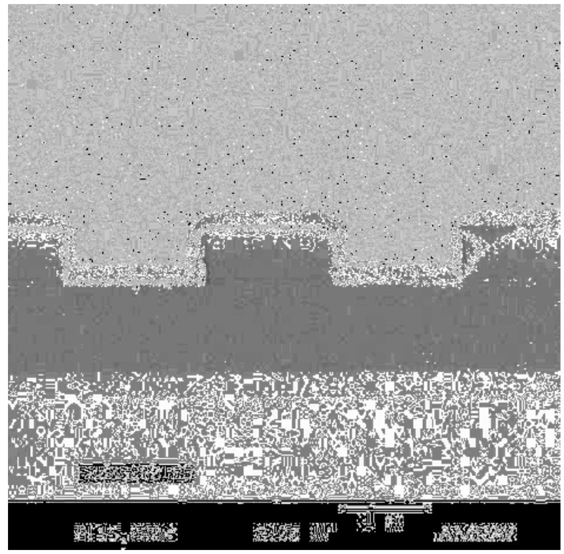


a) Ox=1.97E15/cm^2 b) Ox=3.8E13/cm^2

Fig. 18: Ge infusion deposition; a) no HF surface cleaning of native oxide and b) HF-dip for native oxide removal.



a) Photoresist



b) Photoresist post Ge infusion deposition

Fig. 19: Patterned photoresist SEM cross section of: a) before Ge infusion process and b) after 200nm of Ge infusion deposition.

Infusion DCD co-doping with Ge+B was studied and the controllable ranges of the Ge/B/Si ratios are easily managed by the gas mix, beam conditions and GCIB dose. X-TEM results for a 90nm deposited amorphous Ge+B layer is shown in Fig. 20. Threading dislocations are now visible after the 950^{o}C anneal for this thick recrystalized Ge+B layer and electron diffraction pattern results are shown in Fig. 21. Atomic resolution X-TEM is shown in Fig. 22 showing the 950^{o}C annealed dislocation. SIMS analysis in Fig. 23 shows the increase in Bss by 3x to 9E19/cm^2 in the Ge rich region for the 950^{o}C annealed sample.

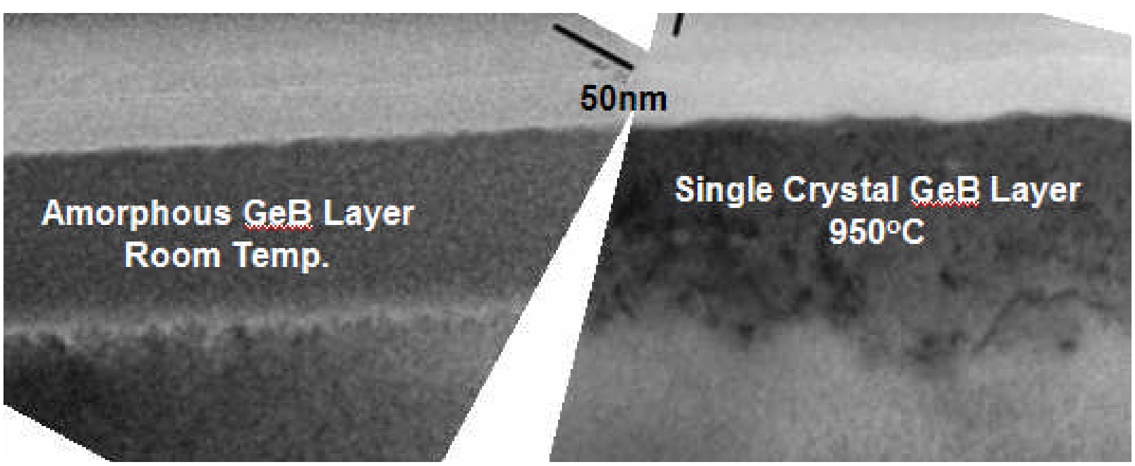


Fig. 20: X-TEM Ge infusion deposition of 90nm.

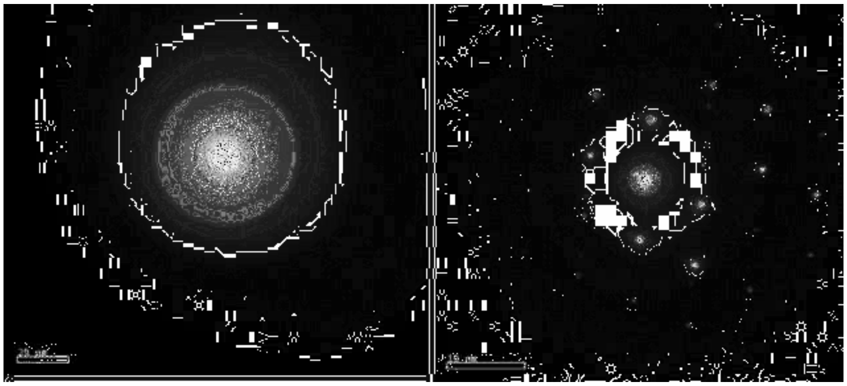


Fig. 21: Electron diffraction pattern showing room temp. amorphous Ge layer and 950°C SPE threading dislocation single crystal Ge layer.

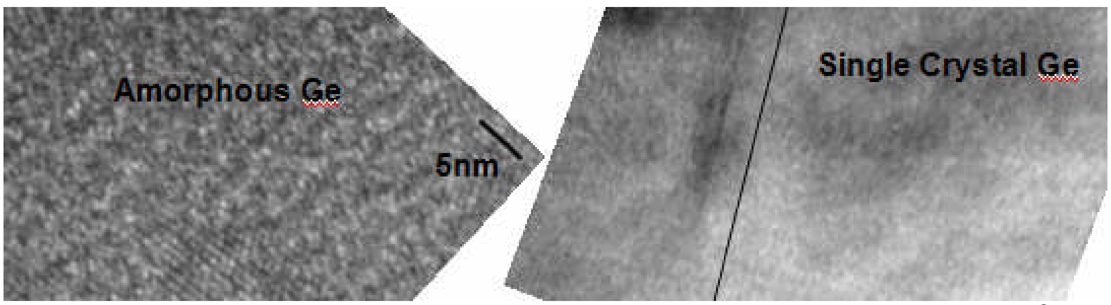


Fig. 22: Atomic resolution X-TEM showing room temp. amorphous Ge and 950°C single crystal Ge layers.

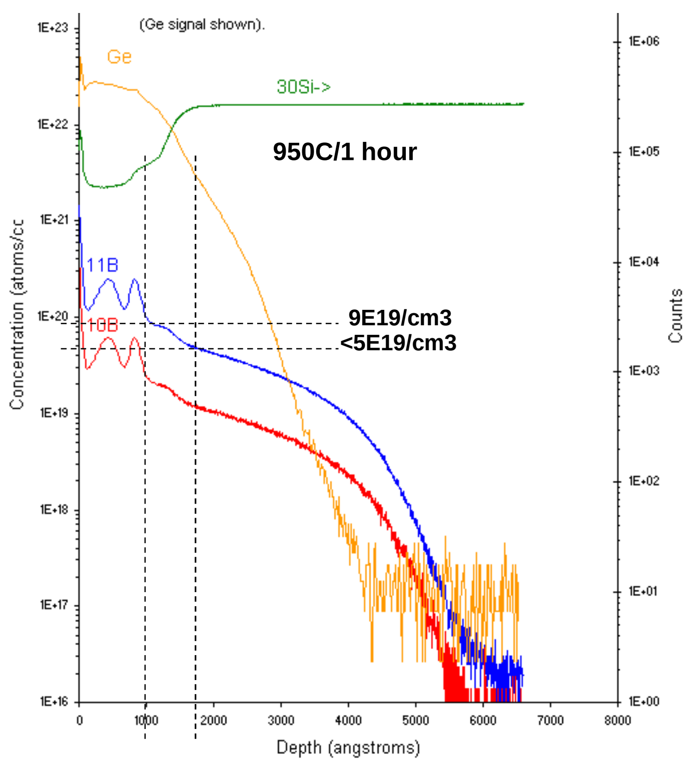
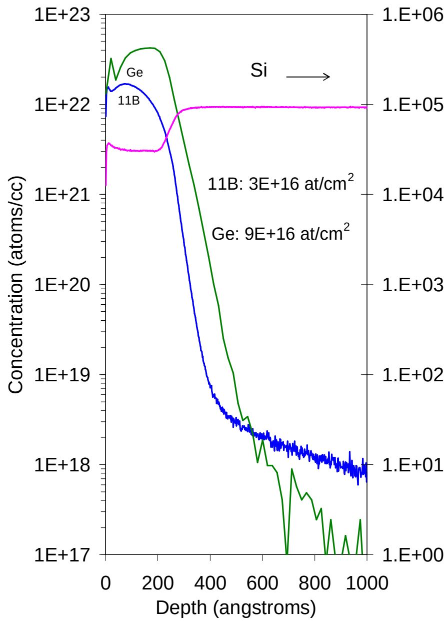
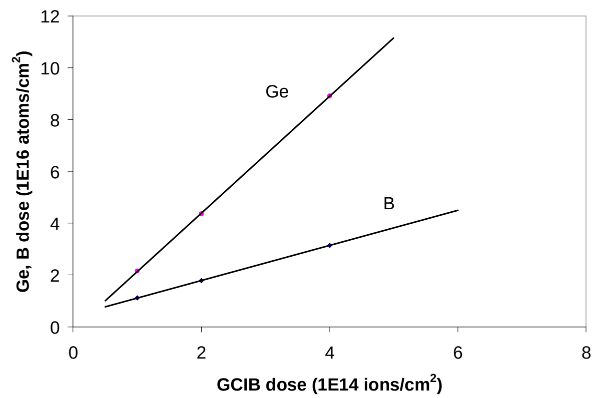


Fig. 23: SIMS analysis for 950°C annealing showing Bss increase to $9E19/cm^2$.

SIMS analysis for a 30keV Ge+B infusion doping process is shown in Fig. 24a were the Ge content is about 75%. Note the drop in silicon count near the surface by about 75% to a level of 25%. The GCIB dose efficiency versus energy is shown in Fig. 24b for the 30keV process. About 233 Ge atoms and 67 boron atoms are incorporated into the silicon per charge for the given gas mixture and flow.





a) Ge+B infusion doping b) Ge+B dose efficiency versus energy

Fig. 24: Ge+B infusion doping a) SIMS analysis and b) dose efficiency.

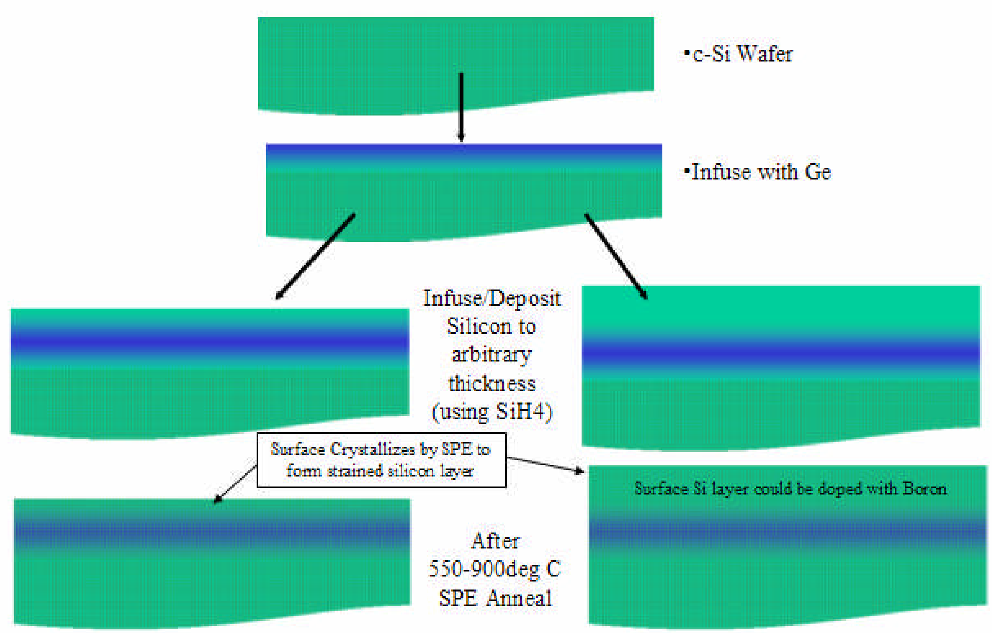


Fig. 25: DCD of 100% Ge with a Si-capping layer.

SUMMARY

USJ formation using infusion doping with boron achieved <12nm junctions determined by SIMS with a 1/3 power log relationship with no evidence of channeling and abruptness of <2.5nm/decade. Surface boron chemical doping levels as high as 2E22/cm^3 were achieved and box-like dopant profiles can be engineered. Infusion doping or deposition with Ge+B resulted in self-amorphization without the typical EOR damage after SPE recrystalization and an increase of Bss by 3x up to 9E19/cm^3 was measured. At doses above 1E15/cm^2 dose controlled deposition was achieved. This process is insensitive to surface native oxide enabling SPE single crystal regrowth at temperatures down to 550^{o}C without the typical misfit dislocation and high density of threading dislocation. By optimizing the process both strain and strain relaxed SiGe and Ge structures were achieved and both blanket and localized deposition on Cz and SOI wafers were demonstrated. 20-30% step coverage of patterned photoresist wafers was observed. With DCD using SiH_4 and GeH_4, 100% Ge with a Si-cap layer as shown in Fig. 25 is also possible. This method of SiGe formation can potentially reduce the processing steps for SGOI and GeOI by up to 75%.

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