USJ and strained-Si formation using infusion doping and deposition

OVERVIEW Infusion doping is a new technique for doping silicon with a gas-cluster ion beam source. The high total energy of the ionized gas cluster is concentrated into a region on the order of 100Å dia. The process produces momentary increases in surface temperatures and pressures significantly higher than those generated by conventional ion implantation processes, enabling ultrashallow, high-concentration doping and monolayer deposition control.

Infusion doping using gas-cluster ion beam technology is a new method of doping silicon that is distinctly different from ion implantation. In traditional ion implantation, the relationship observed between energy and junction depth is a linear fit due to nuclear-stopping power effects. In contrast, with infusion doping using gas-cluster ions, depth is related to the energy to the 1/3 power. This allows ultrashallow, high-concentration doping. Using B_2H_6 or BF_3 source gas, the resulting USJ boron-dopant profile measured by SIMS shows no evidence of channeling with extreme abruptness of <2.5nm/decade for a 12nm shallow junction. Results with B and Ge species have been achieved with doping up to low E22/cm^3 levels.

The germanium (Ge) infusion process also can be used to create a SiGe strain layer and relaxed layer structures for bulk wafers and SOI wafers. When the Ge infusion doping process saturates the surface at a high enough dose, Ge deposition is observed. Because this is a room-temperature process, localized/selective patterned-masked infusion doping and deposition using standard photoresist are possible, rather than having to use a hard mask as with selective epi. The Ge infusion process can deliver a throughput of 30wph on 300mm wafers, enabling low-cost manufacturing of SiGe with precise concentration control.

Infusion doping

Infusion doping utilizes a gas-cluster ion beam (GCIB) source to produce energetic clusters of atoms. Unlike ion implantation, which involves a single ionized atom or gas molecule, ionized clusters typically contain >5000 atoms/charge. Infusion doping of Si has been studied with a standard 300mm Epion *nFusion* GCIB system that produces clusters containing a few percent of Ge and B from Ar gas diluted with B_2H_6, BF_3, and/or GeH_4.

The gas-cluster ions used for surface processing are accelerated through potentials up to 30keV, and while they have high total energy, the energy is shared by the large number of atoms comprising the cluster, so that the energy/atom is <10eV. 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 (~100Å dia.) of the silicon surface. This results in momentary surface temperatures and pressures that are significantly higher than those produced by conventional ion processes.

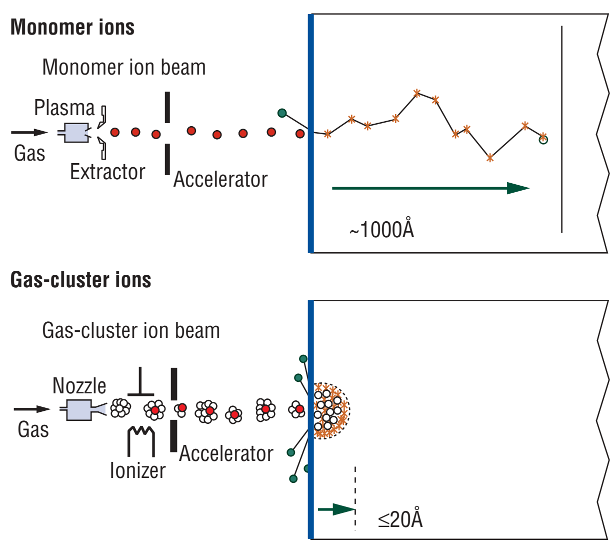

Figure 1. Comparison of monomer ion vs. cluster ion effects. Cluster ions have a high total energy, large mass, and low energy/atom.

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 millibar pressures that are generated over the few picoseconds of impact. The TTS propagates in three dimensions and is quickly quenched. This process is fundamentally different from ion implantation in which energy dissipates primarily along its trajectory (Fig. 1). Higher acceleration energies may be used to minimize space charge effects without dramatically affecting penetration depth.

Nearly all gases and mixtures of gases can be nucleated into clusters [1–3]. Rare gases such as Ar and Xe readily form clusters, as do most diatomics (i.e., O_2, N_2) and molecules (i.e., B_2H_6, BF_3, CH_4, NF_3, CF_4). The kinetic removal rates are low for GCIB processing with nonreactive gases (such as Ar and B_2H_6); however, significant

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localized chemical effects can take place when reactive gas molecules such as CF_4, NF_3, O_2, and H_2 are included in the clusters. Under these processing conditions, infusion surface etching will occur. As a consequence of the locally high temperatures in the impact infusion volume, such gas-cluster beams can be used to perform well-controlled, nondamaging directional chemistry on the substrate surface. This characteristic of GCIB has been used in corrective etching of SOI substrates to attain a uniform, fully depleted SOI thickness down to 5.2nm ±0.2nm [4].

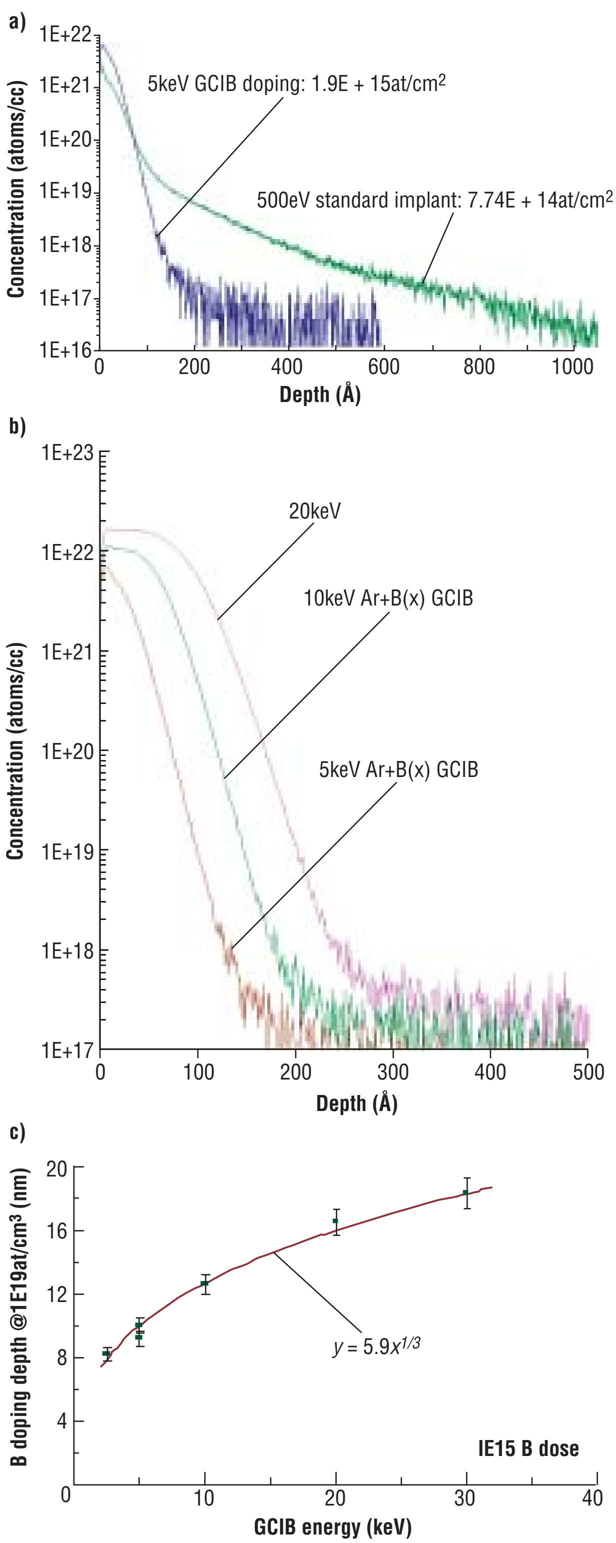

Figure 2. Doping profiles: **a)** SIMS comparison of implantation (channeling) and infusion (nonchanneling) doping profiles, **b)** SIMS dopant profiles for 5–20keV infusion doping energies, and **c)** infusion doping with $E^{1/3}$ depth dependence.

A comparison between traditional ion-implantation doping using a 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. 2a. No channeling is observed using the infusion doping technique and a 1E18/cm^3 junction depth (X_j) at 12nm is achieved. Significant channeling can be seen with the ion-implantation process, resulting in an X_j at 37nm. Pre-amorphizing implantation would be required to reduce X_j to 15nm, and a 300eV implant would be needed to realize an X_j at 12nm [5]. Figure 2b shows the effects of infusion doping energy on junction depth and a realized surface boron level of 2E22/cm^3 could be achieved with a retained dose of 2E16/cm^2. Figure 2c shows the relationship of junction depth measured at 1E19/cm^3 vs. infusion doping energy over the acceleration range of 2.5–30keV.

Unlike ion implantation, the stopping distance for infusion doping follows the energy of acceleration to the 1/3 power because the volume of the substrate that the cluster locally heats is linearly related to the cluster's energy. The depth of this hemispherical volume will therefore follow an energy to the 1/3 power law. The effects of this pressurized TTS can also be seen in Fig. 3 for the case of a wafer that had a 5keV B infusion-doping process followed by a 5keV Ar GCIB process. Note the ability to flatten the B profiles, making it more box-like in shape.

The infusion doping process appears to be linear and easily controllable (the composition of the clusters is determined exclusively by the gas mix in the cylinder and MFC). The correlation between the gas-cluster dose and the SIMS-measured retained boron dose in silicon was 1:1. A 1E14 ions/cm^2 GCIB boron dose corresponded to a 1E15 atoms/cm^2 SIMS retained dose in silicon,

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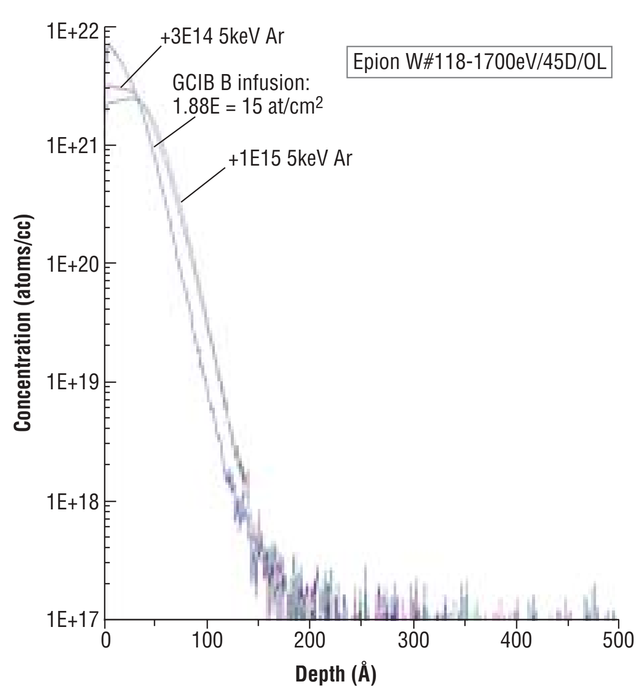

Figure 3. Transient thermal-spike localized heating effects create a more box-like profile in shaped boron.

and a 1E15 ions/cm^2 GCIB dose corresponded to a 1E16 atoms/cm^2 SIMS retained dose.

Unlike ion implantation, which uses plasma to generate ions, or plasma-immersion ion implantation that generates a plasma over the wafer, no plasmas 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 infusion doped with boron show no heavy metal contamination above 5E10/cm^2.

More than 200 B atoms can be infused into the Si for every cluster ion of a given gas mixture. It has been demonstrated that infusion doping can easily deliver the equivalent of >20mA of B atoms and keep the B atoms to <20nm from the surface. Initial results for an infusion doping process realizing an X_j = 10nm have shown a 1E15/cm^2 dose throughput of >30wph for 300mm wafers.

sSOI process flow

Standard bonded PD/SOI wafer	Infusion PD/SOI wafer
>3µm graded SiGe epi	Ge infusion doping into SOI wafer
Relaxed SiGe epi	• Bonded SOI wafer or SIMOX SOI wafer
Wafer polishing	In situ annealing for SiGe strain relaxation + thin strained-Si epi
Oxidation	
Hydrogen implant for layer splitting	
Bonding anneal and layer transfer	
Thinning and polishing	
Thin strained-Si epi	

Infusion doping USJ characterization

Various dopant activation annealing techniques were investigated, including flash/RTA up to 1250°C, and furnace annealing between 550°C and 950°C. With diffusionless activation annealing, the electrical X_j was <6nm as measured by SRP, while SIMS measured 20nm as shown in Fig. 4.

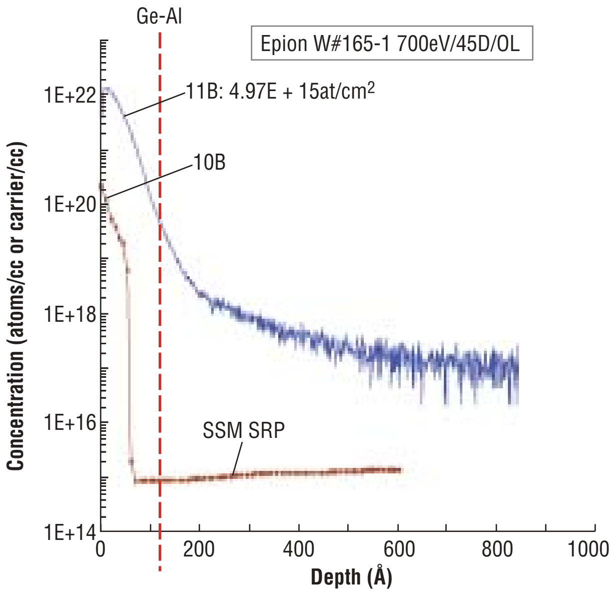

Figure 4. SIMS boron dopant profiles for 550°C SPE annealed comparing SIMS to SRP boron dopant profile.

After the 550°C, 1 hr furnace anneal for solid-phase epitaxial regrowth (SPE) of the amorphous layer, sheet resistance (R_S) measurements were made using different techniques for comparison. The standard 4PP measured 755Ω/sq. due to probe penetration of this shallow 6nm junction. Solid State Measurements' Elastic Material 4PP system measured 2795Ω/sq., agreeing with the top surface resistance value of 3321Ω measured by its SRP method. Four Dimension's Hg-4PP system measured 2872Ω /sq., agreeing well with both EM-4PP and SRP. These results clearly show the issues with 4PP R_S measurements and SIMS junction depth measurements on electrical junctions <30nm [6].

Infusion Ge and Ge+B doping: monolayer deposition results

As an alternative to using SiGe epitaxial growth or high-dose Ge ion implantation, infusion doping of Ge and Ge+B to form localized or blanket strained-Si structures was investigated. 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, significantly reducing the processing steps by up to 75% (see table). 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 strained-Si structures. This technique also can be used with the Ge condensation sSOI formation and layer-transfer FD/sSOI techniques.

Infusion doping of Ge at low GCIB doses of <1E14/cm^2 resulted in shallow Ge doping profiles of <34nm (Fig. 5a). At higher GCIB doses of Ge >1E15/cm^2, monolayer controlled deposition was realized, as shown in Fig. 5b for a 90nm-thick deposited amorphous Ge surface layer. For some process conditions, >1000 Ge atoms are infused into the surface for every ion. In this manner, a deposition rate >10nm/min on 300mm wafers is possible.

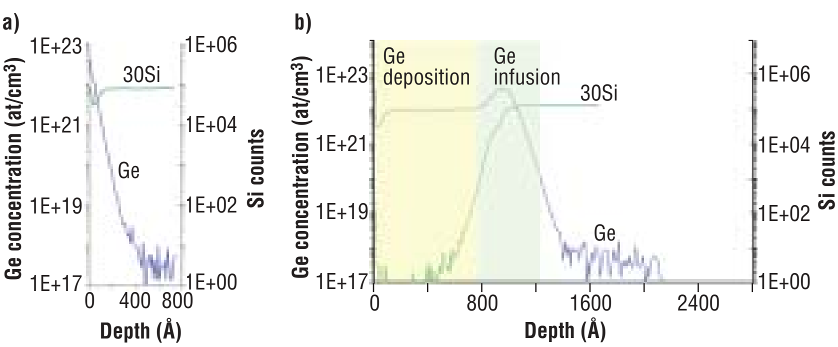

Figure 5. Infusion processing with **a)** Ge infusion doping to a depth of 34nm and **b)** Ge infusion deposition to a thickness of 90nm.

A co-doping Ge+B process is achieved when B_2H_6 gas is added to the clusters. Controllable ranges of the Ge/B/Si ratios are easily managed by the gas mix, beam conditions, and GCIB

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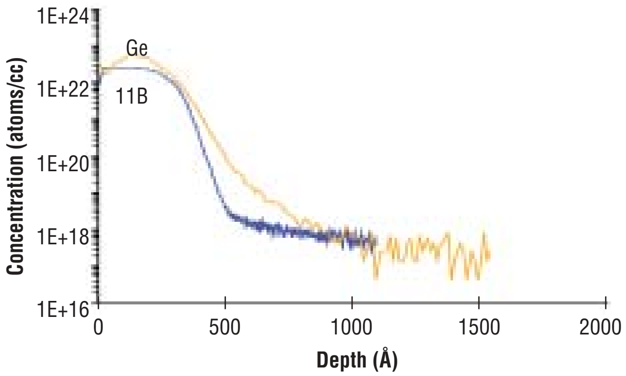

Figure 6. Ge+B infusion doping resulting in $Si_{0.1}Ge_{0.55}B_{0.35}$.

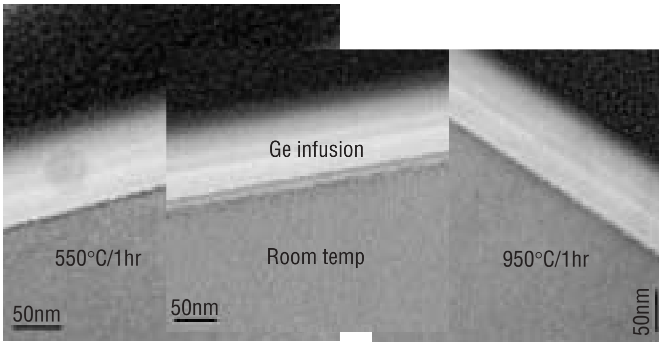

Figure 7. X-TEM of a Ge infusion doping structure to a depth of 12nm.

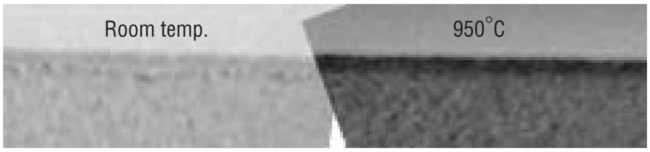

Figure 8. X-TEM of an 11-monolayer (1.4E16/cm^2 Ge infusion deposition structure with thickness = 3.3nm.

dose. An example is shown in Fig. 6, where this particular condition and dose resulted in a Ge+B infusion process of Si (<10%), Ge (<55%), and B (<35%) determined by XPS analysis. Various Ge+B co-doping structures were subjected to a variety of anneals including a 1 hr furnace annealing at 550°C and 950°C. The boron solid solubility limit (B_{ss}) for the 950°C annealed sample with a 70% Ge content was 3× higher than in 100% Si, as determined by SIMS analysis (9E19/cm^3 vs. 3E19/cm^3). X-TEM results for a 12nm Ge+B infusion doping process are shown in Fig. 7 for an as-infused amorphous structure, 550°C/1 hr anneal recrystallized single crystal, and a 950°C recrystallized single crystal. Similar results for a pure 3.3nm deposited amorphous Ge layer (11 monolayers, 1.4E16/cm^2) are shown in Fig. 8. Infusion co-doping of Ge with B also results in self-amorphization, so no additional pre- or post-amorphizing implantation step is necessary when using diffusionless activation such as high-temperature flash, laser, or low-temperature SPE annealing.

Conclusion

USJ formation using infusion doping with boron achieved <12nm junctions determined by SIMS, with a relationship to acceleration energy to the 1/3 power, no evidence of channeling, and abruptness of <2.5nm/decade. Surface boron chemical-doping levels as high as 2E22/cm^3 were achieved. Using SRP, the electrical junction depth was 6nm with an R_S of 2837Ω/sq. measured by both EM-4PP and Hg-4PP for a 550°C SPE diffusionless activation anneal. Infusion doping or deposition with Ge or Ge+B also looks promising for blanket and localized strained-Si formation for bulk strained-Si CMOS and sSOI CMOS applications. Adding Ge to the B infusion doping process realized self-amorphization, and a 3× increase in B_{ss} was measured. ■

Acknowledgments

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