

Shallow Junction Formation with Preamorphization and Rapid Thermal Annealing of Boron Implanted Silicon

M. A. Hayashi^{a,*}, J. E. C. de Queiroz^a, J. A. Diniz^a and J. W. Swart^{a,b}

a)Centro de Componentes Semicondutores, UNICAMP

C.P. 6061, 13083-970 Campinas-SP

b)Faculdade de Engenharia Elétrica e de Computação, UNICAMP

C.P. 6101, 13083-970 Campinas-SP

*marcelo@led.unicamp.br

Abstract

In this paper, we demonstrate that shallow junctions can be formed without ultra-low energy ion implantation machines. Preamorphization of silicon wafers with fluorine ions and rapid thermal annealing, can produce boron (10 keV implant) junctions of 50 nm. Fluorine ions played a major role in this scheme. Alongside channeling suppression by the amorphous layer, fluorine interaction with vacancy-type defects during annealing, leads to uphill boron diffusion effect, shrinking the junction depth. Also, electrical activation was higher with this procedure than with preamorphization with other species.

1. Introduction

Improvements in the performance of large scale integration circuit devices are achieved by scaling down its dimensions. To keep the appropriate electrical characteristics, both lateral and vertical dimensions must be reduced. Lateral dimension depends primarily on lithography and etching processes, and vertical dimension requires shallower doping profiles at source/drain regions. 0.15 μm CMOS technology demands junctions as shallow as 30 nm. The implant technologies needed for ultra-shallow junction fabrication are in research and development stage. Ultra-low energy (< 5 keV) boron implants have been intensively studied to produce shallow junctions. However, most commercial ion implanters currently in use were not designed to operate in this range of energy. An alternative approach is to combine substrate amorphization, prior to boron implant, to suppress channeling, and rapid thermal annealing (RTA) to reduce diffusion. With this scheme, shallow junctions could be produced with energies that are not so extreme, so that conventional implant machines can be used. Several species of ions were used to preamorphization, mainly Si, Ge and F [1-4]. Huang [3] et al. applied F pre-implant and RTA to produce 100 nm junction depth and a sheet resistance of 340 Ω/sq . Krasnobaev et al. [4] reported a reverse annealing of boron junction with F, where B atoms were activated "under-surface" and deactivated in the "amorphous/crystalline interface". In this case, 60 nm junction depth was fabricated. In the present work, the process of p-type

junction formation by using Si, Ar and F preamorphization, boron implantation and rapid thermal annealing are studied, in order to establish the optimal conditions to achieve shallower junctions, without ultra-low energy implantation.

2. Sample preparation

Single crystal, phosphorous doped (2-10 Ω cm) n-type 100 silicon wafers were used in this study. Wafers were cleaned by RCA process, and then preamorphized with Ar, F and Si ions according table 1. Due to its lower mass, fluorine dose was higher than Si and Ar to assure an homogeneous amorphous region.

Table 1- preamorphization conditions.

sample/ion	Energy (keV)	Dose (ions/cm ²)
#1/Ar	50	5×10^{14}
#2/F	50	2×10^{15}
#3/Si	50	5×10^{14}

Boron implants were performed at 10 keV and 5×10^{14} ions/cm², for the three samples and for a fourth, non preamorphized (direct B implant) control sample labeled #0. All implants were 7 degrees tilted away from the ion beam. Ion implants were performed in a medium current, medium energy Eaton GA 4204 machine. Rapid thermal annealing was done at 960°C for 10s and 30s in N₂ atmosphere.

3. Results and Discussion

X-ray diffraction characterization was performed at Laboratório de Difração de Raios-X/IFGW/UNICAMP to assess damage recovery, and so the optimal thermal annealing time. Boron depth profiles were obtained from secondary ions mass spectroscopy (SIMS) at Laboratório de Pesquisa em Dispositivos/ IFGW/UNICAMP. Electrical activation was measured by a four-probe setup.

Figure 1 shows the SIMS results from all samples, as-implanted and after 30 seconds annealing. In figure 1-a, the sample without preamorphization shows a channeling tail, in the as-implanted profile, even with the 7° tilt. After annealing, boron diffused deeply into silicon even with the rapid thermal annealing. In ion implantation, light elements like boron transfer energy to

the target mainly by electron collisions, causing less damage to the crystalline lattice. In this process, point defect clusters are generated along the collision cascade. Thermal annealing dissolute these clusters, producing a supersaturation of self-interstitials. The excess interstitials kick dopants out of substitutional locations to form mobile dopant-interstitial complexes that broaden the doping profile, the so-called transient enhanced diffusion. So, rapid thermal annealing alone, couldn't avoid boron diffusion.

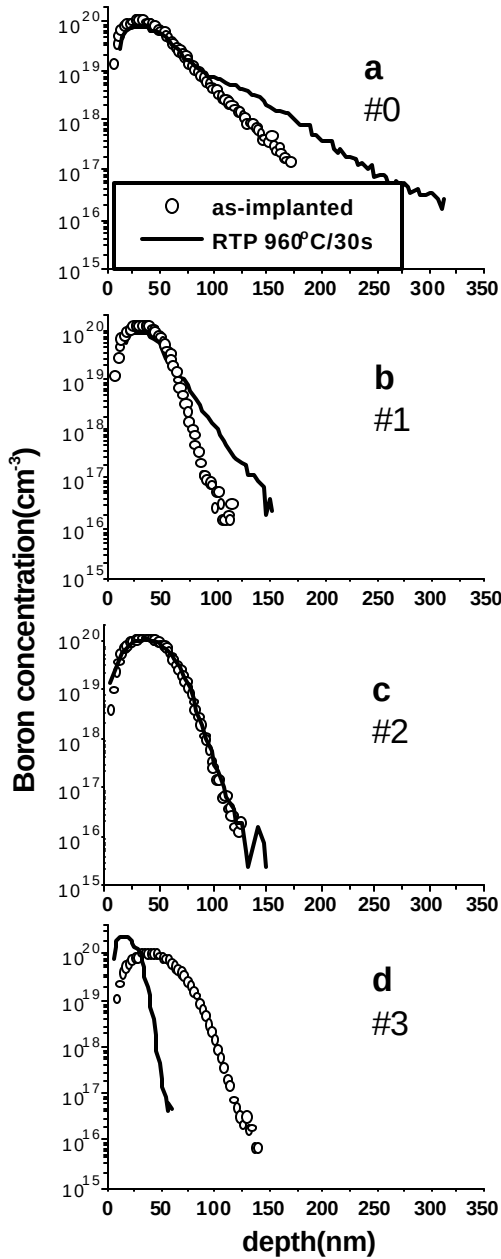


Fig. 1: SIMS profiles of B, as-implanted and after rapid thermal annealing 960°C/30s. a)no preamorphization, b)preamorphization with argon, c)preamorphization with Si, d)preamorphization with F. All boron implants were done at 10 keV.

Figure 1-b shows the profiles for Ar preamorphized sample. Compared to fig. 1-a, as-implanted profile shows that preamorphization reduced the channeling effect, but after annealing, diffusion shows up, and the previous advantage was lost. Previous work with gettering mechanisms [5] showed that high dose Ar implants produce Si-interstitials that enhances boron diffusion. Fig. 1-c shows that preamorphization with Si was slightly less effective to avoid channeling than Ar, due to its lower mass, but the annealed profile shows that diffusion was suppressed with rapid thermal annealing. Fluorine preamorphization (fig. 1-d) had a more noticeable effect. In addition to channeling suppression in the as-implanted profile, the annealed sample produced a very shallow (50 nm) boron profile, smaller than the as-implanted one. The expected result was a depth profile at least the same as before annealing, as we observed in Si preamorphization. Boron diffusion suppression was explained [3] by the interaction of excess F ions with interstitial Si, that otherwise are responsible for the enhanced diffusion. Probably, the formation of thermodynamically stable SiF_x complexes, would immobilize this interstitials. However, we don't have a conclusive answer to the boron profile shrinkage. It is thought that a high vacancy-type defects concentration at the under-surface would be responsible for this effect, capturing boron ions. One experimental evidence [6] of a vacancy-rich region is that F and Cl ions implanted in Si, increase the oxidation rate and suppress the formation of stacking fault defects, increasing vacancy-type defects. Although unexpected, junction shrinkage after thermal annealing already was observed in Mg-implanted GaAs [7]. This “uphill diffusion”, was explained by the substitutional-interstitial diffusion mechanism. In the region of uphill diffusion, the dopants diffuse from areas of excess interstitials toward areas of excess vacancies. So, this model could be a reasonable explanation of the observed junction shrinkage.

Table 2: Measured sheet resistance

sample	$R_s (\Omega/\text{sq})$ RTP 960°C/10s	$R_s (\Omega/\text{sq})$ RTP 960°C/30s
#0 (B)	589	335
#1 (Ar+B)	426	335
#2 (Si+B)	303	303
#3 (F+B)	272	253

Sheet resistance for all samples, table 2, were measured in a four-probe setup. 10 seconds treatment was not enough to complete activation on sample #0(direct B implant), but as shown before, increasing the time causes excess diffusion. The same occurs with the argon implanted sample #1. Sample #2, with Si pre-implant, had the same sheet resistance for both treatments, indicating that it needs less time to get higher electrical activation. This result is in agreement with X-ray diffraction measurements that showed a complete recrystallization after 10 seconds annealing. Unfortunately, due to a lack of time, we don't have the

junction depth profile for the 10 second annealed samples. Sample #3, with fluorine, had the best activation value after 30 seconds annealing, and from X-ray diffraction, it only had total damage recovery after that treatment time. The measured electrical activation value of 253 Ω/sq for this sample is very close to the theoretical estimated value of 250 Ω/sq . This theoretical value was calculated assuming complete boron activation, with equation 1:

$$R_s = \frac{1}{mq\Phi} \quad (1)$$

where the mobility μ was assumed 50 $\text{cm}^2/\text{V.s}$ for a dopant concentration of 10^{20} cm^{-3} (from SIMS measurements), q is the electron charge and Φ is the boron implantation dose, $5 \times 10^{14} \text{ cm}^{-2}$.

The higher electrical activation of B near the surface is also in accordance to the above mentioned model of sub-surface vacancy-rich region formation due to the deeper Si-interstitial-F complex formation.

4. Conclusion

From the results obtained so far, we can conclude that low energy boron implantation, without previous amorphization of the silicon substrate is not suitable for shallow junction fabrication, due to its severe channeling and diffusion effects. The preamorphization scheme, along reducing channeling, in Si and F cases suppressed the boron thermal diffusion. Fluorine has a remarkable effect, showing junction shrinkage after rapid thermal annealing, and the best values of electrical activation. Although some authors previously reported shallow junctions obtained from fluorine pre-implants, as far as we know, it is the first time that a uphill diffusion mechanism was observed in boron implanted silicon. Also, it was demonstrated that available commercial ion implantation machines are still useful to shallow junctions production.

The authors thank J. Godoy Filho and R. M. A. G. Floriano for technical support, and M. A. A. Pudenzi for SIMS measurements. We also thank FAPESP for financial support.

References

- [1] S. Saito, K. Kumagai and T. Kondo, Appl. Phys. Lett. 63 (2), pp.197-199, jul. 1993.
- [2] S. Aronovitz, H. Puchner and J. Kimball, J. Appl. Phys. 85 (7), pp.3494-3498, apr. 1999.
- [3] T. Huang, H. Kinoshita and D. L. Kwong, Appl. Phys. Lett. 65 (14), pp. 1829-1831, oct. 1994.
- [4] L. Y. Krasnobaev, J. J. Cuomo and O. I. Vyletalina, J. Appl. Phys. 82 (10), pp. 5185-5190, nov. 1997.
- [5] G. B. Bonner and J. D. Plummer, Appl. Phys. Lett. 46 (5), pp. 510-513, mar. 1985.
- [6] G. Greeuw and J. F. Verwey, Solid-State Electron. 26, pp. 241-246, 1983.
- [7] H. G. Robinson, M. D. Deal and D. A. Stevenson, Appl. Phys. Lett. 56 (6), pp.554-557, feb. 1990.