22nm Node p+ USJ Formation Using PAI & HALO Implantation With Laser Annealing

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Abstract. Boron 200eV p+ USJ dopant activation and junction leakage was studied with various combinations of PAI (Ge, B_{36}, In & Xe) and HALO (As & Sb) implantation using msec laser annealing between 1220^{o}C and 1350^{o}C. For B only case without PAI or HALO, increasing laser anneal temperature from 1220^{o}C to 1350^{o}C improved dopant activation boron solid solubility (Bss) from 3E19/cm^3 to 1.2E20/cm^3 with excellent junction leakage below the lower detection limit of <1E-7A/cm^2. Deep Ge-PAI improved dopant activation Bss by 4x to 1.2E20/cm^3 at 1220^{o}C and degraded junction leakage by >10x due to residual implant damage (EOR defects) beyond the junction. Higher laser anneal temperatures up to 1350^{o}C improved junction leakage to below detection limit and Bss improved to 1.4E20/cm^3. With deep Xe-PAI junction leakage was severely degraded by 5 orders of magnitude to above the upper detection limit of >2.5E-2A/cm^2 but with annealing temperatures >1300^{o}C junction leakage improved, at 1350^{o}C junction leakage improved to 8E-5A/cm^2 and Bss to 1.5E20/cm^3. With shallower PAI junction leakage improved but at the expense of dopant activation at lower MSA temperatures <1300^{o}C but the 3keV Ge-PAI dopant activation and leakage was similar to molecular B. With the presence of either As or Sb HALO structure, >5 orders of magnitude degradation in junction leakage current was detected (>2.5E-2A/cm^2) and higher laser anneal temperatures of 1320^{o}C was needed to improve dopant activation and junction leakage. However, the combination of Sb-HALO with In-PAI gave the best optimized Bss >4E20/cm^3 and low leakage <1E-5A/cm^2.

Keywords: HALO, PAI, ultra shallow junction, sheet resistance, junction leakage, laser anneal.
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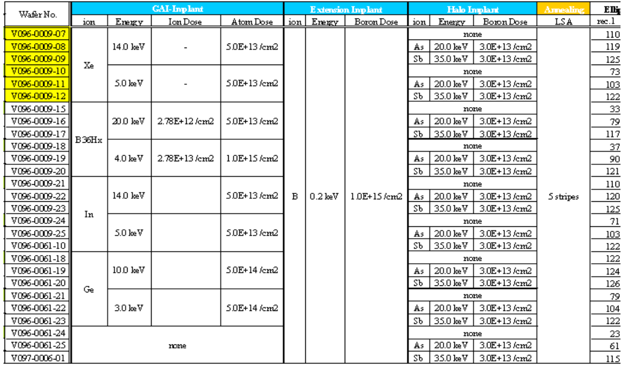
INTRODUCTION

For 22nm node p+ USJ requires high dopant activation with low junction leakage. With msec annealing (MSA) between 1200^{o}C to 1300^{o}C the best B only dopant activation Bss (boron solid solubility) is <8E19/cm^3 requiring a PAI (pre-amorphizing implant) to create a surface amorphous layer deeper than the junction enhancing Bss to >1E20/cm^3 or use B molecular dopant which is self-amorphizing. The deep PAI amorphous layer can lead to end-of-range (EOR) defects and junction leakage degradation (1). Switching PAI species to heavier ions such as In, Sb or Xe reduces the amorphizing dose to <5E13/cm^2 with minimal EOR defects (2-4). Shallower PAI reduces leakage and will also reduce dopant activation. MSA peak temperatures between 1300^{o}C and 1350^{o}C gives best dopant activation with or without a PAI layer with low leakage but this can be a process integration issue with some strain-Si and HK/MG material stability. The presence of an n-type doped HALO structure under the p+ USJ have been reported to grade junction leakage by 4 to 6 orders of magnitude due to BTBT (band to band tunneling) and therefore overwhelm any leakage degradation caused by PAI EOR damage (5). Therefore in this paper we study the effects of As versus Sb HALO for self-amorphization and with or without PAI for p+ USJ formation.

EXPERIMENTATION

All the implants and LSA anneals on these 27 n-type 200mm wafers were conducted by Renesas/Kita-Itami. In this study we investigated the baseline p+ USJ process of B=200eV, 1E15/cm^2 dose to target an Xj <10.0nm without B-channeling,. To this baseline process we compared various PAI conditions for their effects on amorphizing depth, reduction in B-channeling, impact on B diffusion (TED), enhancement in B-dopant activation at various MSA peak temperatures, impact on junction leakage and residual implant end-of-range (EOR) damage/defects. To quickly verify the as implanted amorphous layer depth we used ellipsometric measurements at Renesas as shown in Figure 1; 1) the B control no-PAI amorphous depth was 2.3nm which is the thickness of the surface native oxide (PCOR-SIMS verified this to be 2.4nm), 2) Ge-PAI 5E14/cm^2 dose at 3 & 10keV formed an amorphous layer 7.9 & 12.2nm deep, 3) Xe-PAI 5E13/cm^2 dose at 5 & 14keV formed an amorphous layer 7.3 & 11.0nm deep, 4) In-PAI 5E13/cm^2 dose at 5 & 14keV formed an amorphous layer 7.1 & 11.0nm deep, 5) B_{36}-PAI 1E15/cm^2 dose at 100eV B-equivalent formed an amorphous layer 3.7nm deep and 6) B_{36}-PAI 5E13/cm^2 dose at 500eV B-equivalent formed an amorphous layer 3.3nm deep. We also compared As-HALO (20keV/3E13) to Sb-HALO (35keV/3E13) amorphous layer 6.1nm and 11.5nm respectively. Each wafer received MSA annealing at 5 different LSA peak temperatures (1220°C, 1240°C, 1280°C, 1320°C & 1350°C) using the Ultratech LSA system with a linear scan pattern.



Wafer No.	GAI-Implant				Extension Implant			Halo Implant			Annealing	Elli
	ion	Energy	Ion Dose	Atom Dose	ion	Energy	Boron Dose	ion	Energy	Boron Dose	LSA	rec.1
V096-0009-07	Xe	14.0 keV	-	5.0E+13 /cm2	B	0.2 keV	1.0E+15 /cm2	none			5 stripes	110
V096-0009-08								As	20.0 keV	3.0E+13 /cm2		119
V096-0009-09								Sb	35.0 keV	3.0E+13 /cm2		125
V096-0009-10		5.0 keV	-	5.0E+13 /cm2				none				73
V096-0009-11								As	20.0 keV	3.0E+13 /cm2		103
V096-0009-12								Sb	35.0 keV	3.0E+13 /cm2		122
V096-0009-15	B36Hx	20.0 keV	2.78E+12 /cm2	5.0E+13 /cm2				none				33
V096-0009-16								As	20.0 keV	3.0E+13 /cm2		79
V096-0009-17								Sb	35.0 keV	3.0E+13 /cm2		117
V096-0009-18		4.0 keV	2.78E+13 /cm2	1.0E+15 /cm2				none				37
V096-0009-19								As	20.0 keV	3.0E+13 /cm2		90
V096-0009-20								Sb	35.0 keV	3.0E+13 /cm2		121
V096-0009-21	In	14.0 keV		5.0E+13 /cm2				none				110
V096-0009-22								As	20.0 keV	3.0E+13 /cm2		120
V096-0009-23								Sb	35.0 keV	3.0E+13 /cm2		125
V096-0009-24		5.0 keV		5.0E+13 /cm2				none				71
V096-0009-25								As	20.0 keV	3.0E+13 /cm2		103
V096-0061-10								Sb	35.0 keV	3.0E+13 /cm2		122
V096-0061-18	Ge	10.0 keV		5.0E+14 /cm2				none				122
V096-0061-19								As	20.0 keV	3.0E+13 /cm2		124
V096-0061-20								Sb	35.0 keV	3.0E+13 /cm2		126
V096-0061-21		3.0 keV		5.0E+14 /cm2				none				79
V096-0061-22								As	20.0 keV	3.0E+13 /cm2		104
V096-0061-23								Sb	35.0 keV	3.0E+13 /cm2		122
V096-0061-24	none							none				23
V096-0061-25								As	20.0 keV	3.0E+13 /cm2		61
V097-0006-01								Sb	35.0 keV	3.0E+13 /cm2		115

FIGURE 1. Experimental matrix split conditions.

RESULTS

Our expected amorphous layer depths for the shallow PAI was 6.0nm and 16.0nm for the deep PAI so based on ellipsometry the shallow PAI was slightly deeper and the deep PAI was slightly shallower than expected. The 3E13/cm^2 dose for both the As and Sb HALO implants were not high enough to form an amorphous layer as shown in the X-TEM of Figure 2 even though ellipsometry measured 6.1nm amorphous layer for As-HALO and 11.5nm for Sb-HALO. The critical HALO dose for amorphization is somewhere between 3-5E13/cm^2.

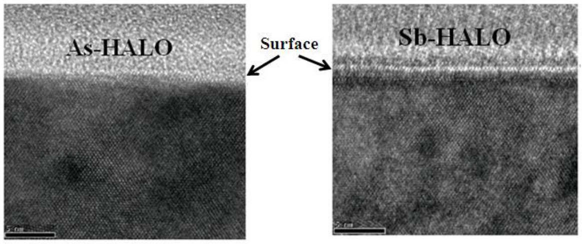


FIGURE 2. X-TEM of As & Sb HALO no anneal regions.

PCOR-SIMS analysis was used to determine the surface native oxide thickness, implant species retained dose, junction depth and dopant diffusion as shown in: 1) Figure 3 for no PAI (B, As & Sb HALO) samples unannealed and 1350°C annealed regions, 2) Figure 4 for Ge-PAI (B, As & Sb HALO) and 3) Figure 5 for In-PAI (B, As & Sb HALO). The surface native oxide for B only as shown in Figure 3 measured by SIMS is 2.4nm compared to 2.3nm by ellipsometry with an Xj=8.7nm, after anneal TED was 3.0nm and the B-channeling tail starts at about 4E19/cm^3. With the As or Sb HALO structure a slightly deeper B-channeling tail is detected starting at about 6E19/cm^3 resulting in deeper Xj of 10.0nm for As-HALO and 9.8nm for Sb-HALO. B diffusion without PAI is 2.4-3.5nm but the B diffusion profile for the As-HALO is different, lowest for above 1E19/cm^3 and highest for below 1E19/cm^3. With Ge-PAI all the junction depths are slightly shallower by 0.5-1.5nm with the B-channeling tail starting at about 1E19/cm^3 as shown in Figure 4. However, Ge-PAI resulted in B diffusion to increase by about 2x varying from 5.0-6.1nm and the B profiles were all similar. The B-channeling tail was reduced to about 5E18/cm3 with In-PAI as shown in Figure 5 resulting in similar Xj for B, As and Sb HALOs. Amount of B diffusion was least for B at 4.0nm and greatest for As-HALO at 6.5nm. Note that in all the profiles Sb-HALO has a steeper retrograde surface compared to As-HALO even after the 1350°C anneal and In-pile up at the surface.

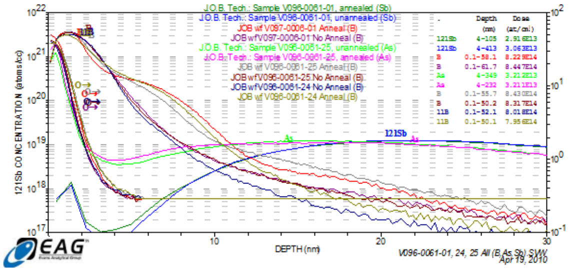


FIGURE 3. PCOR-SIMS analysis for no-PAI samples.

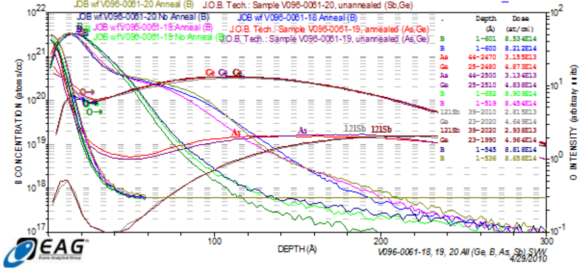


FIGURE 4. PCOR-SIMS analysis for deep Ge-PAI samples.

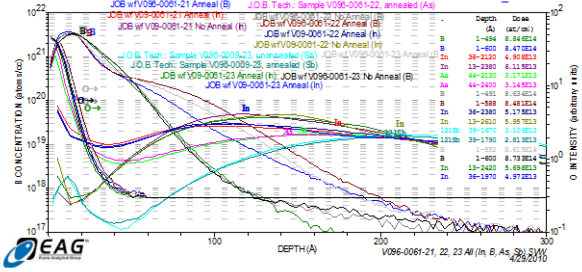


FIGURE 5. PCOR-SIMS analysis for deep In-PAI samples.

Dopant activation was first measured by 4PP sheet resistance (Rs) which was OK for the no HALO wafers but with As or Sb HALOs due to probe penetration we measured the substrate low Rs value of <100 ohms/sq. Figure 6 shows the 4PP Rs results on no HALO wafers. B only Rs at 1220°C was 4000 ohms/sq and improved by 4x to 1200 ohms/sq at 1350°C corresponding to Bss of 3E19/cm^3 at 1220°C and 1.2E20/cm^3 at 1350°C. The deep Ge-PAI (10keV) improved Rs by 4x at 1220°C to 1300 ohms/sq (Bss=1.2E20/cm^3) and improved to 800ohms/sq at 1350°C (Bss=1.4E20/cm^3). Reducing the Ge-PAI energy to 3keV had no effect on Rs at 1350°C but at the lower 1220°C Rs was higher at 1700 ohms/sq. Deep 14keV Xe-PAI Rs could not be measured at 1220°C and 1240°C due to very leaky junction but at 1280°C and above Rs of 750-800 ohms/sq could be measured for a Bss=1.5E20/cm^3. Reducing the Xe-PAI energy to 5keV gave an unexpectedly high Rs value of 3200 ohms/sq at 1220°C. To measure junction leakage current we used the Frontier RsL instrument and the leakage results are shown in Figure 7. For 10keV Ge-PAI, the leakage at 1220°C was 8E-5A/cm^2 and dropped to below detection at 1350°C and as expected the shallower 3keV Ge-PAI leakage was all below the lower detection limit of <1E-7A/cm^2 (Figure 9). 14keV Xe-PAI junction was very leaky above the upper detection limit of >2.5E-2A/cm2 until the LSA temperature was above 1320°C dropping to <1E-4A/cm^2 (Figure 10) and the 5keV Xe-PAI leakage response was similar to 10keV Ge-PAI (Figure 11). Note that LSA temperatures >1300°C is critical for lowest leakage and sheet resistance.

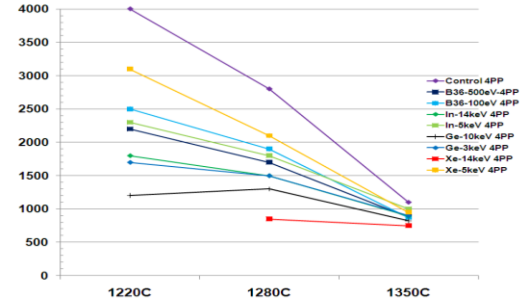


FIGURE 6. No HALO 4PP Rs results.

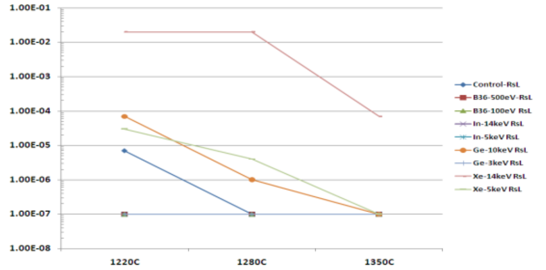


FIGURE 7. No HALO RsL junction leakage results.

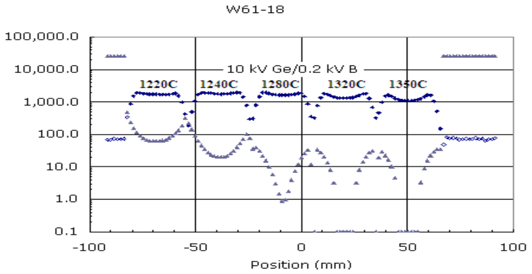


FIGURE 8. No HALO 10keV Ge-PAI RsL results.

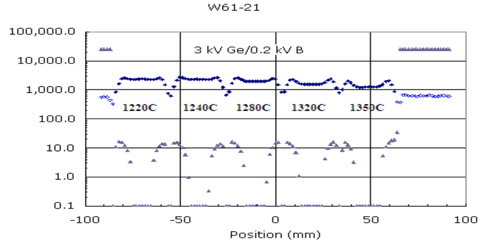


FIGURE 9. No HALO 3keV Ge-PAI RsL results.

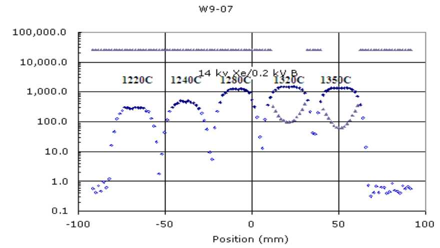


FIGURE 10. No HALO 14keV Xe-PAI RsL results.

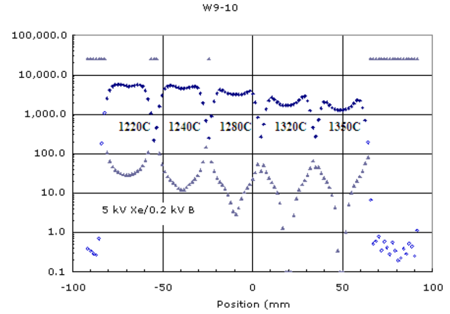


FIGURE 11. No HALO 5keV Xe-PAI RsL results.

When the As or Sb HALO structures were added the p+ junctions became very leaky above the upper detection limit of >2.5A/cm^2. As-HALO no PAI is shown in Figure 12 and note that for the 1220°C and 1240°C anneal temperatures the Rs value is <20 ohms/sq which is the substrate sheet resistance but at 1280°C the Rs value jumps up to 3000 ohms/sq though leakage is still above detection limit. Not until the 1320°C anneal did the leakage value drop to a detectable level of 7E-4A/cm^2 and Rs improve to 1500 ohms/sq and with the 1350°C anneal Rs drops to 1100 ohms/sq (Bss=1.3E20/cm^3) and leakage to 1E-3A/cm^2. The Sb-HALO results are shown in Figure 13 and the junction remained very leaky for all the temperatures so no Rs value could be determined. The As-HALO with the deep 10keV Ge-PAI results are shown in

Figure 14 and now the leakage is above detection limit for all annealing temperatures and the p+ Rs values are now lower than before for >1300°C anneal. Even with the shallow 3keV Ge-PAI the junctions are still very leaky as shown in Figure 15 and the >1300°C anneal Rs values are lower than before for a Bss >3E20/cm^3. As-HALO with the 14keV In-PAI showed complete recovery of junction leakage to <1E-6A/cm^2 as shown in Figure 16 for the full temperature range and Rs also varied from 700-1100 ohms/sq. In-PAI had a similar recovery effect with Sb-HALO as shown in Figure 17 with junction leakage in the 1E-5A/cm^2 range but for anneals at 1280°C and above Rs improved from 900 ohms/sq to 150 ohms/sq for a very high dopant activation (Bss=5E20/cm^3).

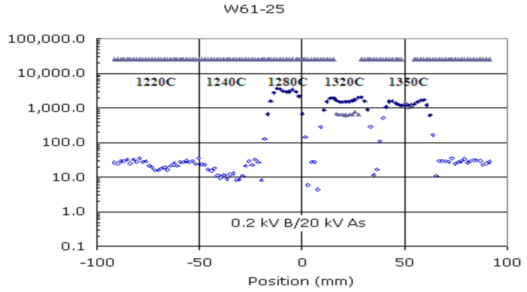


FIGURE 12. As-HALO no PAI RsL results.

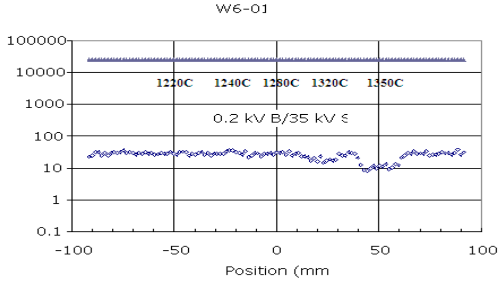


FIGURE 13. Sb-HALO no PAI RsL results.

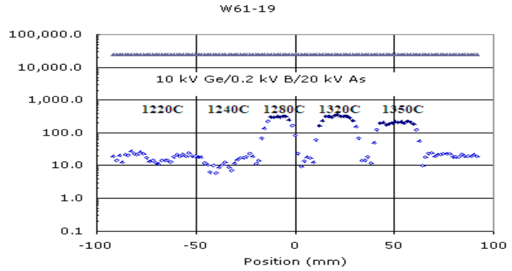


FIGURE 14. As-HALO 10keV Ge-PAI RsL results.

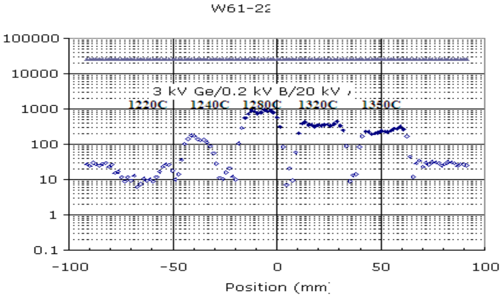


FIGURE 15. As-HALO 3keV Ge-PAI RsL results.

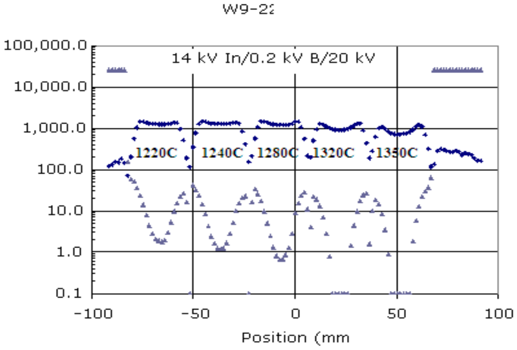


FIGURE 16. As-HALO 14keV In-PAI RsL results.

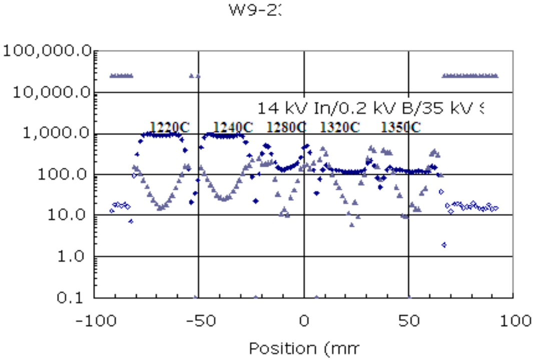


FIGURE 17. Sb-HALO 14keV In-PAI RsL results.

SUMMARY

Both deep and shallow PAI layers in combination with the HALO dopant structure must be optimized together to maximize p+ USJ dopant activation and minimize junction leakage. We found that laser annealing peak temperature >1300°C was critical to achieve best junction quality.

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REFERENCES

1. J. Borland, Y. Kawasaki, J. Halim and B. Chung, Solid State Technology, July 2008, p.38.
2. H. Yoshimura et al., SSDM 2008, paper 8-B-4, Sept 2008.
3. J. Borland et al., IEEE/RTP 2009, p.49.
4. J. Borland et al., IEEE/RTP 2009, p.59.
5. R. Duffy et al., ECS Transaction, vol.3, no.2, p.19, 2006.