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22nm Node p+ USJ Defect Analysis with Various PAI and HALO Structures Using Laser Annealing

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***Abstract*- Boron 200eV 1E15/cm^2 p+ Ultra Shallow Junctions with various PAI (Ge, Xe & In) and HALO (As & Sb) implantation activated by msec laser annealing (1220^{o}C to 1350^{o}C) were studied using Junction Photo Voltage (JPV) and Modulated Photo Reflectance (MPR). JPV and MPR provided information about junction quality; dopant activation, junction capacitance, residual implant damage and junction leakage. Highest p+ junction quality and best p+ dopant activation was achieved with laser annealing temperatures >1300^{o}C. The results with Sb-HALO were worse than with As-HALO. For HALO implants junction leakage was controlled by direct band to band tunneling while for no HALO it was controlled by end of range residual PAI defects. The high junction leakage (exceeding E-5 A/cm^2) could lead to unreliable Rs and junction capacitance determination.**

INTRODUCTION

22nm node p+ USJ (ultra-shallow junction) <10nm requires high quality junctions (high dopant activation with low junction leakage). A PAI (pre-amorphizing implant) is used to create a surface amorphous layer usually deeper than the p+ shallow junction to eliminate boron dopant channeling and enhance dopant activation with MSA (msec annealing) however, this deep PAI amorphous layer can lead to end-of-range (EOR) damage beyond the junction degrading junction leakage by several orders of magnitude. Shallower PAI depth reduces junction leakage but will also reduce dopant activation unless the msec anneal (MSA) peak temperature is >1300^{o}C causing process integration issues with some strain-Si and HK/MG materials [1, 2]. MSA peak temperatures above 1300^{o}C also significantly reduces EOR damage and improves dopant activation with or without a PAI layer [3, 4, 5]. Switching PAI species from Ge to heavier ions such as Xe or In reduces the amorphizing dose by 10x to <5E13/cm^2 with minimal EOR defects however other point defects such as vacancy clusters or nano-bubbles were reported for Xe-PAI [3, 4]. The presence of an n-type doped HALO structure under the p+ USJ have been reported to degrade junction leakage by 4 to 6 orders of magnitude due to BTBT (band to band tunneling) and therefore overwhelm any leakage degradation caused by residual implant damage such as PAI EOR damage [1, 6].

Using sheet resistance (Rs) only as a reference metric for USJ "quality/goodness" can be very misleading resulting in very leaky junctions and in the wrong optimization of USJ processing [1].

In this work we will report on the quality of p+ USJ with and without As and Sb HALO, with and without PAI and with implants activated by MSA non-melt laser annealing with peak temperatures ranging from 1220^{o}C to 1350^{o}C.

EXPERIMENTATION

All the n-type 200mm wafers, implants and LSA anneals were provided 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. To this baseline process we compared various PAI conditions for their effects on amorphizing depth, reduction in B-channeling, enhancement in B-dopant activation, impact on junction leakage and residual implant (EOR) damage/defects. The wafer experimental matrix split is shown in Fig.1. Since in actual devices an n-type HALO dopant structure is present underneath the p+ SDE and the HALO dopant profile can dominate the p+/n junction leakage degradation we compared As-HALO at 20keV 3E13/cm^2 dose to Sb-HALO at 35keV 3E13/cm^2 dose. Each wafer received MSA annealing at 5 different LSA peak temperatures (1220^{o}C, 1240^{o}C, 1280^{o}C, 1320^{o}C & 1350^{o}C) using the Ultratech LSA system in a line scan pattern shown in Fig.2.

	No HALO	20keV/3E13 As-HALO	35keV/3E13 Sb-HALO
•B (200eV/1E15)	X	X	X
•With Ge-PAI (3keV/5E14)	X	X	X
•With Ge-PAI (10keV/5E14)	X	X	X
•With Xe-PAI (5keV/5E13)	X	X	X
•With Xe-PAI (14keV/5E13)	X	X	X
•With In-PAI (5keV/5E13)	X	X	X
•With In-PAI (14keV/5E13)	X	X	X

Fig.1: Experimental matrix split conditions.

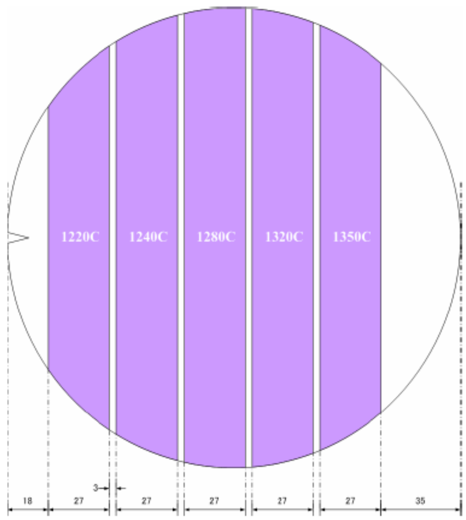

Fig.2: LSA laser anneal pattern.

Junction Photo Voltage (JPV) metrology at Semilab was used to determine sheet resistance (Rs), junction leakage (J_L) and junction capacitance (Jc) [7-12]. JPV measures an AC SPV signal on two electrodes located different distance from illuminated area as a function of AC light modulation frequency. The magnitude of the JPV signal depends on the lateral signal spreading, which has characteristic frequency dependence for given Rs, leakage and capacitance. These parameters can be obtained by fitting theoretical JPV frequency curves into measured ones. Typically Rs, leakage and capacitance can be reliably determined and separated as long as one parameter does not have overwhelming influence on JPV signal such as e.g. leakage when exceeding few E-5A/cm^2. If J_L exceeds 1E-5 to 1E-4A/cm^2 range then its influence on measured JPV at all frequencies becomes overwhelming and it is not possible to determine reliably Rs.

The residual damage in the junction region was measured with Modulated Photo Reflectance (MPR) method known in the IC industry by acronym of TW (therma-wave) or Boxer Cross (BX) [9, 11, 12]. MPR measures changes of reflection of light from the wafer surface caused by presence of damage.

RESULTS

P+ Junction with Various PAI and no HALO

The JPV full wafer image of leakage is shown in Fig.3 for p+ USJ with no PAI and no HALO. The lateral variation in laser heating effects can be seen clearly along each strip. The J_L values for the various MSA temperatures and PAI implants are summarized in Fig. 4. The amorphous layer depth for Ge-PAI, Xe-PAI and In-PAI were reported elsewhere to be about 8nm deep for the shallow PAI (3keV Ge-PAI, 5keV Xe-PAI and 5keV In-PAI) and about 17nm deep for the deeper PAI (10keV Ge-PAI, 14keV Xe-PAI and 14keV In-PAI) [3-5]. For the lower MSA temperature anneals both the B-control and In-PAI all show very low leakage of <1E-7A/cm^2. Ge-PAI at 3keV with EOR damage at 8nm increased leakage by 10x to 9E-7A/cm^2 (same for all temperatures) while the deeper Ge-PAI at 10keV with EOR damage at 17nm at the lowest temperature increased leakage 100x to 1E-5A/cm^2. Increasing the annealing temperature had no effect on the 3keV Ge-PAI junction leakage but for the 10keV Ge-PAI leakage did improve by 5x to <2E-6A/cm^2 at 1350^{o}C. For Xe-PAI at 5keV, leakage showed very week dependence on annealing temperature. For Xe-PAI at 14 keV the leakage decreased from a very high level of 3.5E-4A/cm^2 at 1220^{o}C to 6E-6A/cm^2 at 1350^{o}C, a 60x improvement. It has been reported previously [3, 4] that the Xe-PAI creates 0.5nm bubbles/vacancies that are very stable and cannot be annealed out as detected by therma-wave analysis. The MPR measurements of residual damages are shown in Fig. 5. The MPR showed that the Xe-PAI defects are very stable (BX:<-4000) not changing much with increasing temperature and that the complete implant damage recovery for the Ge-PAI occurs for MSA annealing temperatures > 1300^{o}C (BX:>+3000).These results are in agreement with TW results for Xe-PAI and Ge-PAI reported earlier [3, 4].

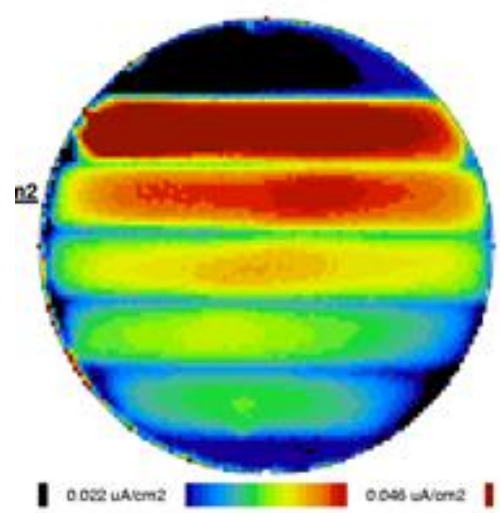

Fig.3: JPV full wafer junction leakage image of p+ USJ only case without PAI and HALO.

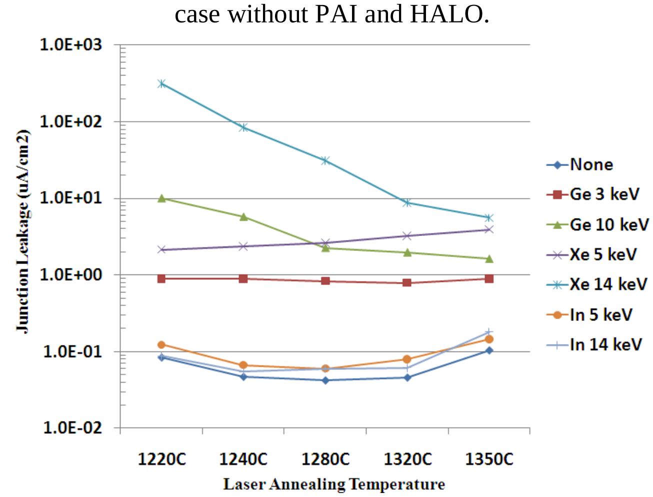

Fig.4: JPV junction leakage results for p+ USJ with Ge, Xe & In-PAI without HALO.

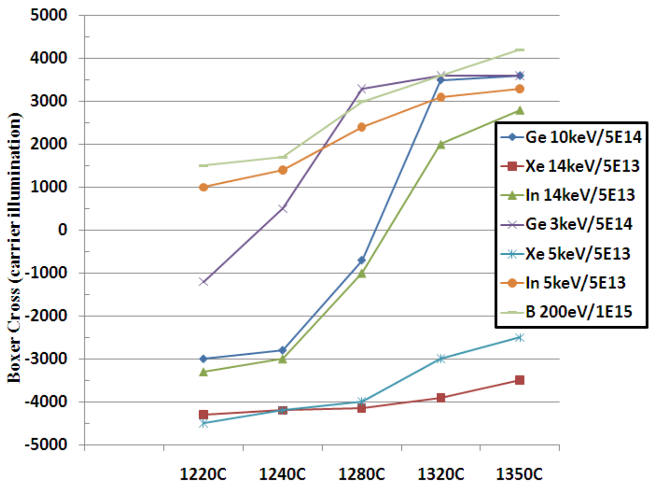

Fig.5. Measurements of residual damage with MPR for p+ USJ with various PAI and no HALO.

Junction capacitance (Jc) expressed in arbitrary units is shown in Fig.6. For abrupt p+/n junction capacitance is controlled by the doping concentration on the lightly doped side of the junction [10], which is formed by n-type substrates with a background doping level of 1E15/cm^3. The junctions for 14keV Xe-PAI and low annealing temperatures 1220^{o}C, 1240^{o}C and 1280^{o}C are very leaky and the capacitance cannot be reliably determined. For the highest annealing temperature of 1350^{o}C leakage drops sufficiently below 1E-5A/cm^2 and Jc values could be measured reliably.

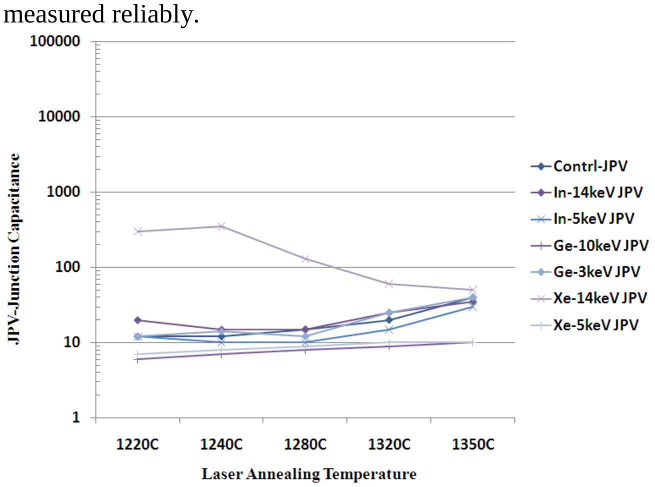

Fig.6: JPV junction capacitance for p+ USJ with PAI and no HALO (capacitance in arbitrary units).

JPV sheet resistance (Rs) results without HALO are shown in Fig.7. For B only case (without PAI or HALO), increasing laser anneal temperature from 1220^{o}C to 1350^{o}C improved Rs by 3x from 6700 ohms/sq to 2600 ohms/sq corresponding to a dopant activation boron solid solubility (Bss) of 2.3E19/cm^3 and 4.0E19/cm^3 respectively. The p+ USJ dopant activation level Bss was determined by plotting Rs versus junction depth (Xj) as shown in Fig.8. Evans Analytical Group (EAG) measured the B, Ge-PAI, In-PAI, As-HALO and Sb-HALO dopant profiles using their special high depth resolution PCOR-SIMS technique allowing the determination of both the physical and the electrical junction depth (Xj) profiles including surface oxide thickness as shown in Figs. 9-11 below. Boron Xj without PAI and no HALO varied from 6.3nm no anneal to 9.3nm for 1350^{o}C anneal, with As-HALO Xj varied from 7.8nm no anneal to 11.3nm for 1350^{o}C anneal and with Sb-HALO Xj varied from 7.8nm no anneal to 10.2nm for 1350^{o}C anneal. With 10keV Ge-PAI no HALO Xj varied from 6.4nm no anneal to 12.5nm for 1350^{o}C anneal, As-HALO Xj varied from 6.8 no anneal to 11.8nm for 1350^{o}C anneal and Sb-HALO Xj varied from 6.4nm no anneal to 11.9nm for 1350^{o}C anneal. With 14keV In-PAI no HALO Xj varied from 7.1nm no anneal to 11.1nm for 1350^{o}C anneal, As-HALO Xj varied from 6.4nm no anneal to 12.9nm for 1350^{o}C anneal and Sb-HALO Xj varied from 6.6nm no anneal to 12.0nm for 1350^{o}C anneal.

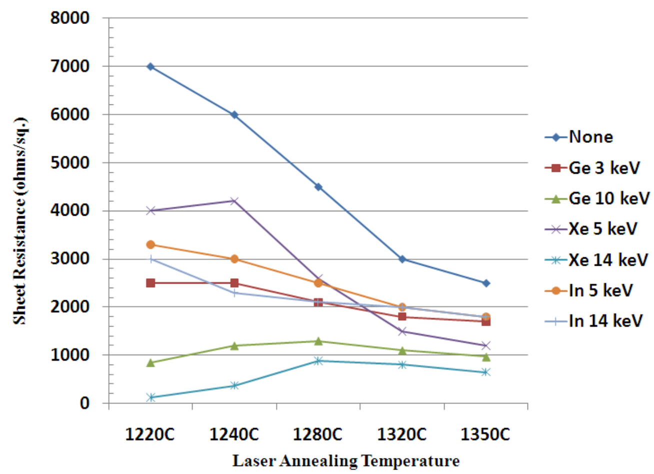

Fig.7: JPV Rs results for p+ USJ with Ge, Xe & In-PAI without HALO.

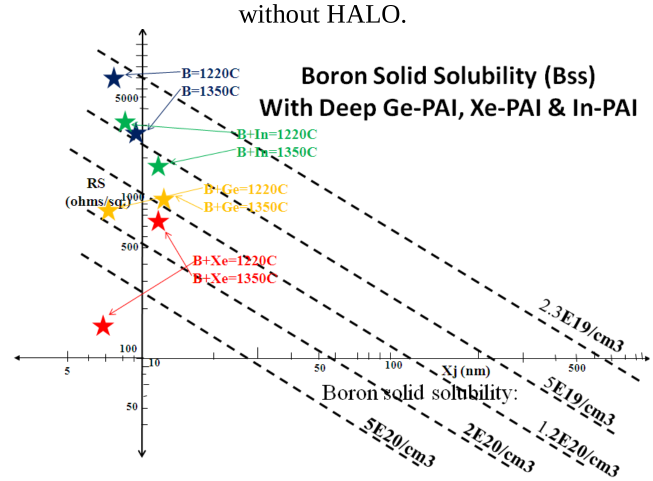

Fig.8: Rs versus Xj plot for B dopant activation Bss values with various PAI and no HALO.

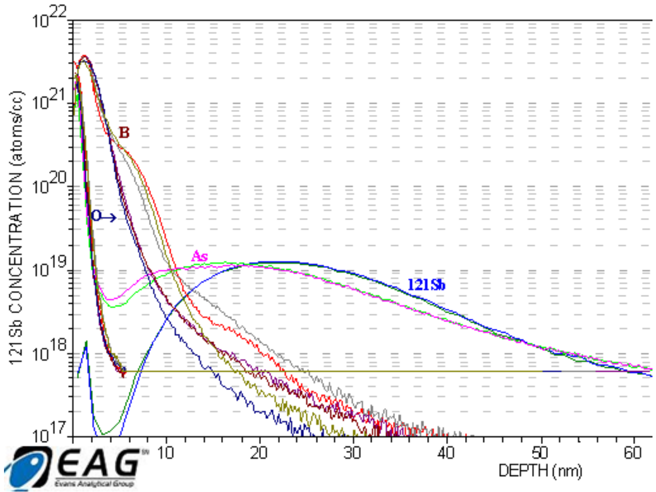

Fig.9: SIMS analysis of B, As & Sb without PAI.

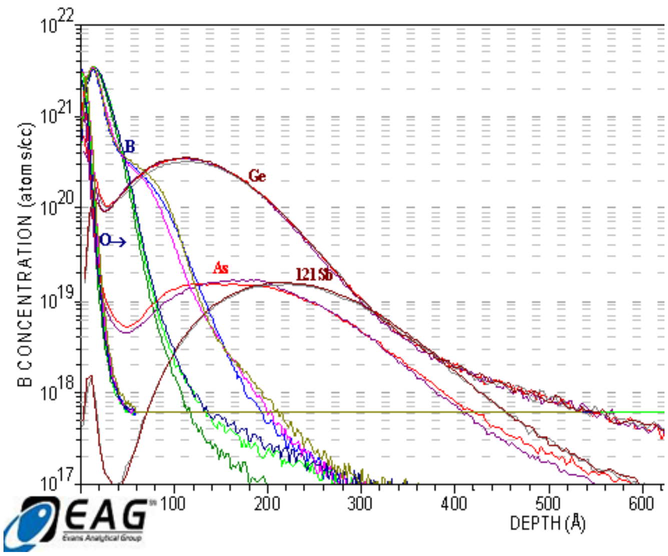

Fig.10: SIMS analysis of B, As & Sb with 10keV Ge-PAI.

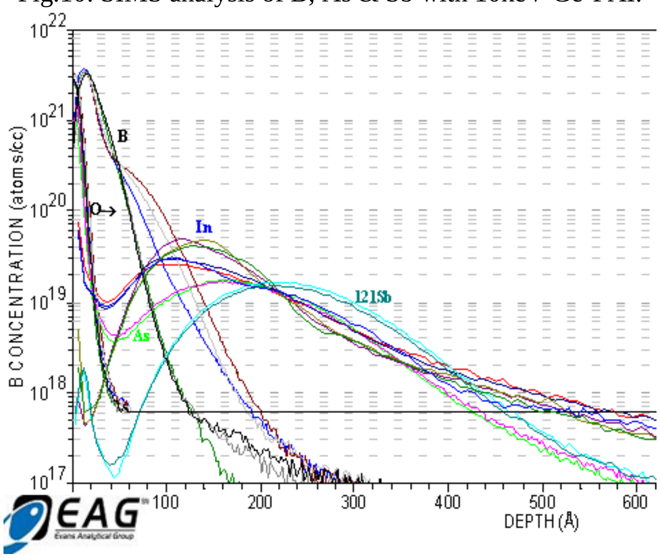

Fig.11: SIMS analysis of B, As & Sb with 14keV In-PAI.

The 14keV Xe-PAI annealed at 1220°C gives junction with very high leakage 3E-4A/cm^2. Due to high leakage Rs cannot be reliably determined. The direct measurements give an unbelievable low Rs value of 150 ohms/sq which corresponds to a dopant activation Bss=7E20/cm^3 as shown in Fig.8 which is above the silicon melt Bss value of 5E20/cm^3. For the highest annealing temperature of 1350°C leakage is reduced to 6E-6A/cm^2 and more realistic value of 700 ohms/sq is measured which corresponds to doping activation of Bss=1.5E20/cm^3. These results showed clearly that too high junction leakage would lead to incorrect Rs values and junction capacitance ; e.g. the 14keV Xe-PAI annealed at 1220°C gives junction with very high leakage 3E-4A/cm^2 and Jc of 350 (Fig.6) which is reduce to Jc<55 at 1350°C when leakage becomes low (<E-5 A/cm^2). The creditable Rs determination for implants without HALO could be done for junction leakage <5E-5A/cm^2. For the leakages exceeding this critical level the measured Rs values would be less than the actual Rs. This effect explains the unusual changes of the Rs values for the 14keV Xe-PAI with increasing annealing temperature. The measured Rs for temperature 1220°C to 1240°C is not credible because of the high leakage. It seems that the best B activation was achieved with Xe 14 keV PAI at the highest annealing temperatures. Also the 10keV Ge-PAI gave the low Rs of about 1000 ohm/sq for a Bss=1.1-1.8E20/cm^3 (Fig.8) and independent of the annealing temperature. These results show the importance of measuring junction leakage and capacitance, not just Rs only to determine junction quality.

P+USJ With As & Sb HALO

The leakage for junctions with an As-HALO or an Sb-HALO under the surface p+ USJ are shown in Fig.12. Presence of the HALO implants degrades leakage orders of magnitude. Note that at the low MSA temperatures the leakage is degraded by 4-5 orders of magnitude (>5E-3A/cm^2) which is in agreement with previous reports [1, 5, 6]. For the higher MSA temperatures >1300°C for As-HALO, leakage is reduced by two orders of magnitude. For the Sb-HALO the leakage remain unchanged for the lower annealing temperatures and then increases slightly with increasing temperature possibly due to improved Sb-HALO dopant activation.

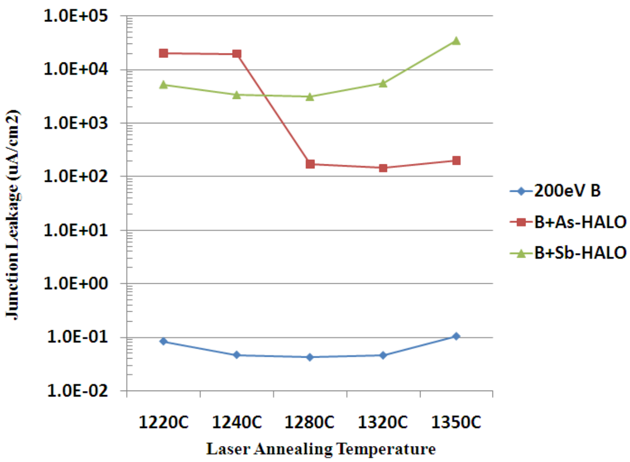

Fig.12: HALO dominates junction leakage degradation, no PAI.

The As-HALO p+ USJ JPV leakage image is shown in Fig. 13. Only three annealing strips for the three highest annealing temperatures are visible. In the other regions the leakage is so high that it could not be distinguished from leakage in non annealed regions. Notice non homogeneity of leakage along the annealing stripes which point out to various processing problems. It seems that leakage maps are an excellent indicator of process uniformity. The rest of the J_L results for the As-HALO and Sb-HALO with the PAI are shown in Figs. 14 & 15. The 14keV In-PAI As HALO for all annealing temperatures has very low leakage in the mid-E-6A/cm^2 level as if no HALO or a very low HALO dopant level was present. This trend was also seen with the Sb-HALO; J_L is in the upper E-6A/cm^2 range for 1220^{o}C and 1240^{o}C MSA anneals but increases by 100x at 1320^{o}C and above possibly due to improved Sb-HALO dopant activation. Figs. 16 & 17 shows JPV leakage full wafer map images for the As and Sb HALO with 14keV In-PAI respectively clearly showing the improved leakage at the lower MSA temperatures. For the Sb-HALO with Ge-PAI leakage improved dramatically at 1280^{o}C and above from E-2 to E-4A/cm2 similar to the no PAI case. Note that the Xe-PAI shows no temperature dependence on leakage due to the stable point defects (bubbles/vacancy clusters) [3, 4].

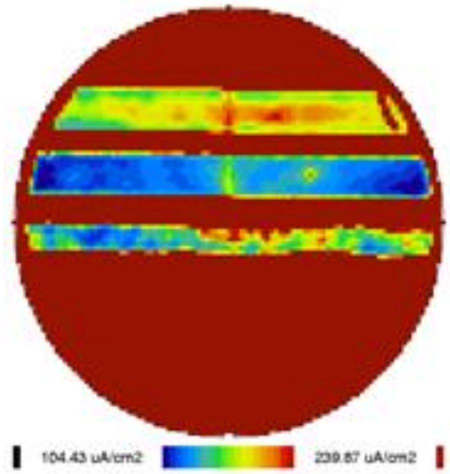

Fig.13: JPV full wafer junction leakage image for p+ USJ with As-HALO and no PAI, note no detection for 1220^{o}C and 1240^{o}C laser anneal regions.

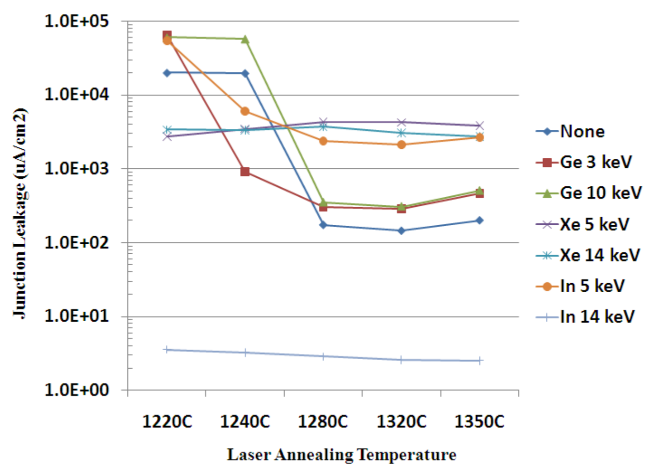

Fig.14: As-HALO JPV junction leakage results.

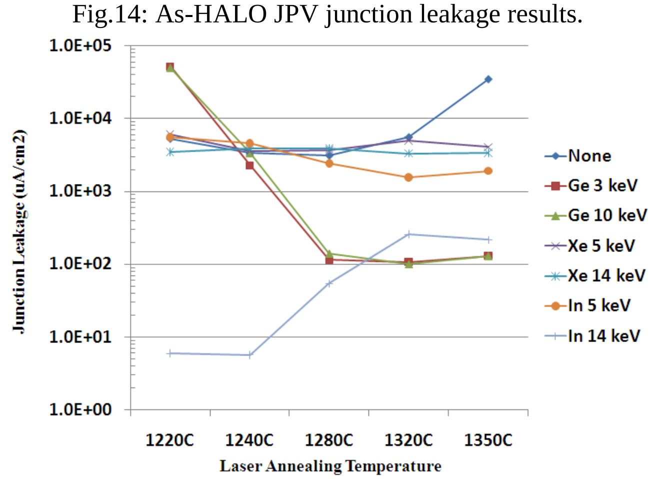

Fig. 15: Sb-HALO JPV junction leakage results.

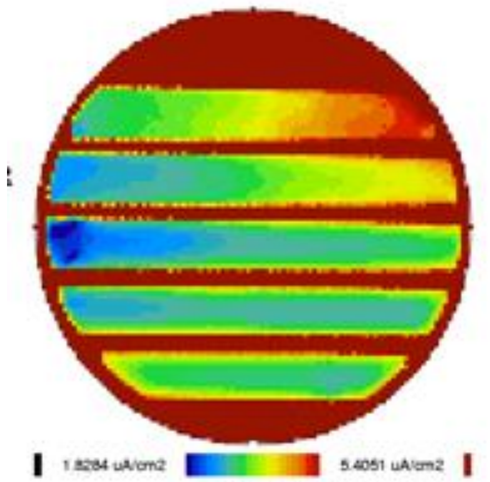

Fig.16: JPV wafer image of As-HALO with 14keV In-PAI showing all 5 annealing regions on the wafer.

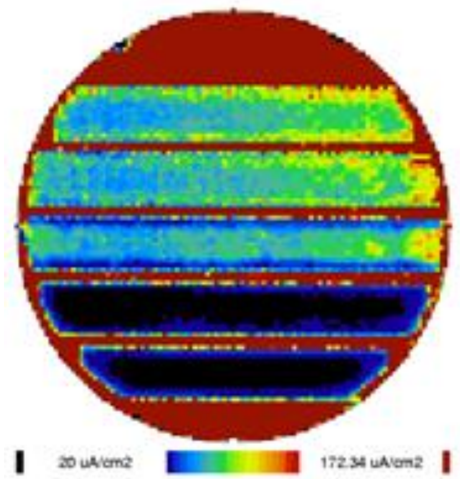

Fig.17: JPV wafer image of p+ USJ with Sb-HALO and 14keV In-PAI.

The junction capacitance for the As-HALO is shown in Fig.18 and for the Sb-HALO in Fig.19. For all cases with exception of the 14keV In-PAI, the capacitance of the HALO junctions is 100x higher than the capacitance for no HALO junctions; increase from about Jc=10 to Jc=1000. This result is expected since with the HALO implant dopant level on the lightly doped side of the junction increased from E15/cm^3 level for no HALO to 1E19/cm^3 (Figs. 9-11). The junction capacitance increases as a square root of lightly doped side of the junction doping concentration [10]. The 14keV In-PAI Jc values for the As-HALO are similar to the no HALO values (Jc=10) verifying complete As-HALO dopant compensation by the deeper In-PAI. The increase in Jc values at higher MSA temperature for all the As-HALO conditions suggests improved As-HALO dopant activation. The very high Jc values of >70,000 for the Xe-PAI with the As-HALO are not credible due to the very high leakage. This demonstrates that the excessive leakage above 1E-3A/cm^2 increases the measured value of junction capacitance above the actual value. Also note that the Sb-HALO case with 14keV In-PAI shows Jc value increase at MSA >1300^{o}C suggesting improved Sb-HALO dopant activation in Fig.19.

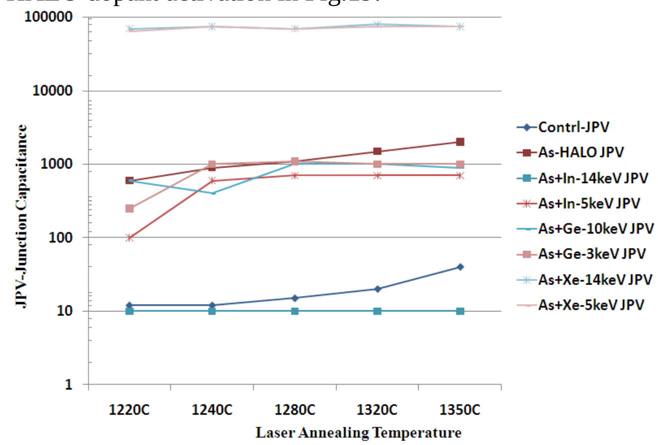

Fig.18: JPV junction capacitance for p+ USJ with As-HALO and PAI (capacitance in arbitrary units).

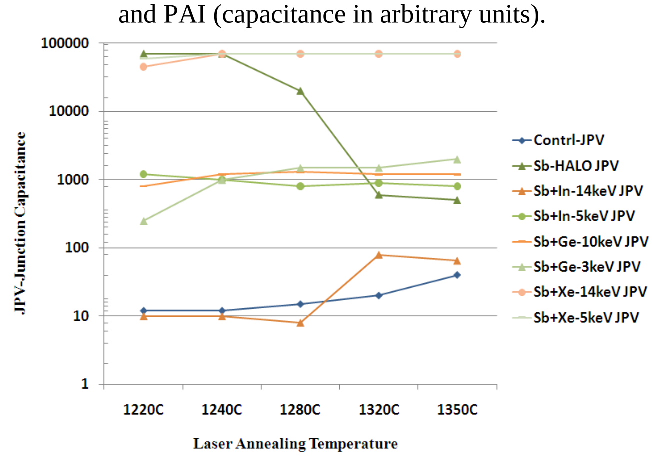

Fig.19: JPV junction capacitance results for Sb-HALO (capacitance in arbitrary units).

The JPV Rs results for the As-HALO are shown in Fig. 20. The laser anneal temperature of 1280^{o}C or higher was required to get an expected Rs value >1000 ohms/sq (Bss=1.1E20/cm^3) for the no PAI case as shown in Fig.21 for Rs versus Xj. For these annealing conditions J_L was less than 2E-4A/cm^2. For the lower annealing temperatures the junctions were very leaky >1E-2A/cm^2 (Figs. 12 & 14) and the unreliably low Rs value of <200 ohms/sq (Bss=7E20/cm^3) were measured. The 14keV In-PAI case showed Rs value of 1800 ohms/sq at 1220^{o}C and Rs=1000 ohms/sq at 1350^{o}C. This will result in Bss=1.1E20/cm^3 at 1220^{o}C and 1350^{o}C. For the deep In-PAI J_L junction leakage was low at 3.5E-6A/cm^2. It seems that for reliable determination of Rs for the As-HALO the critical leakage has to be below 2E-4A/cm^2. The Sb-HALO Rs results are worse than the As-HALO as shown in Fig.22. For most of the wafers the leakages for Sb-HALO are higher than for As-HALO and they exceed the critical threshold of 2E-4 A/cm^2. In these cases no credible Rs values could be measured. The 14keV In-PAI with Sb HALO at the lower

MSA temperatures of 1220°C, 1240°C and 1280°C all have low leakage below the critical value of 2E-4 A/cm^2 and the credible Rs of 1300 ohms/sq at 1240°C (Bss=1.4E20/cm^3) and 580 ohms/sq at 1280°C (Bss=2E20/cm^3) were measured as shown in Fig.23. In the regions annealed at 1320°C and 1350°C the leakage exceeded 2E-4 A/cm^2 and unbelievably low Rs value of <150 ohms/sq (Bss=7E20/cm^3) were measured. The leakage in the case of Ge-PAI at 3keV and 10keV annealed at temperature of 1280°C or higher is below the critical value. The Rs in these samples change from 500 ohm/sq at 1280°C to 300 ohm/sq at 1350°C (Bss increasing from 2.2 to 4E20/cm^3) indicating the enhanced activation of B in presence of Ge-PAI. Theses values are somewhat higher than expected.

During determination of the absolute Rs values for the junctions with the HALO implants we used the JPV Rs calibration which was developed for the junctions with much lower (100 times) capacitance. At this stage it is not clear if higher by factor of 2 to 3 than expected the Bss values for the Sb HALO with the Ge PAI are caused by extension of this low capacitance calibration to the high capacitance HALO junctions or to some other factors. Further work is required to establish if the JPV calibration for low capacitance junctions could be extended to junctions with 100 times higher capacitance.

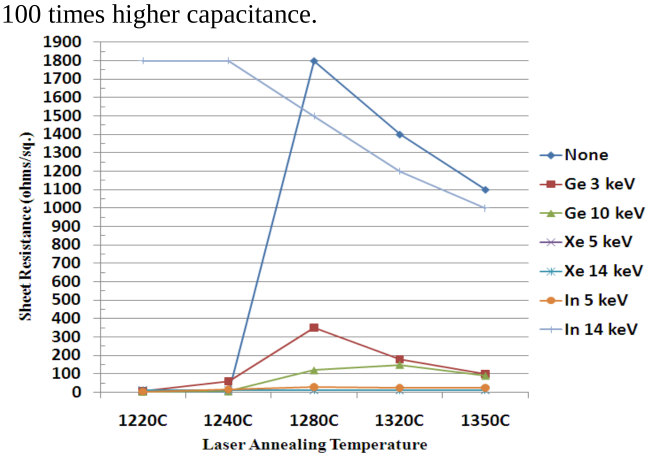

Fig.20: JPV sheet resistance results for p+ USJ with As-HALO.

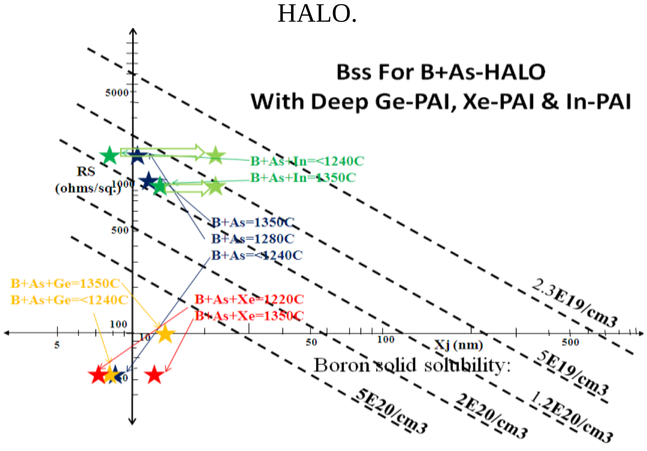

Fig.21: Rs versus Xj plot for B dopant activation Bss values for As-HALO with various PAI.

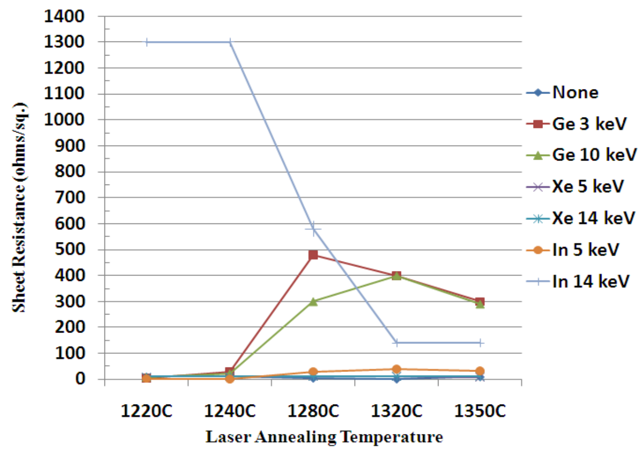

Fig. 22: JPV Rs results for p+ USJ with Sb-HALO and PAI.

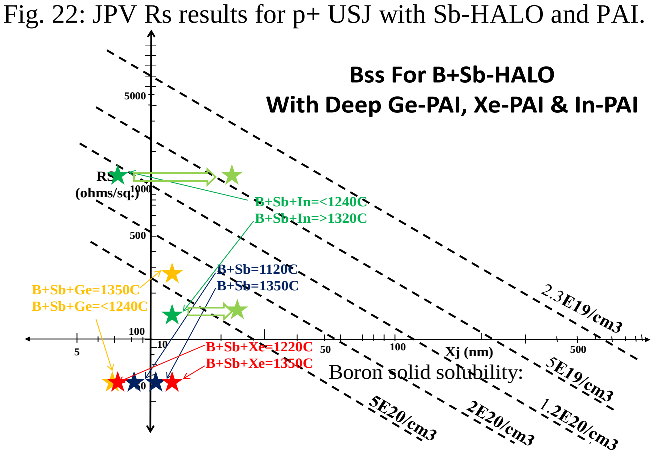

Fig.23: Rs versus Xj plot for B dopant activation Bss values for Sb-HALO with various PAI.

The MPR results are shown in Fig.24 for the As-HALO and Fig.25 for the Sb-HALO. There is no significant difference in the residual damage level seen with the HALO as compared to the no HALO case which is understandable since the HALO/pocket dose is low 3E13/cm^2 compared to the p+ 1E15/cm^2 dose and the PAI dose of 5E13/cm^2 or 5E14/cm^2.

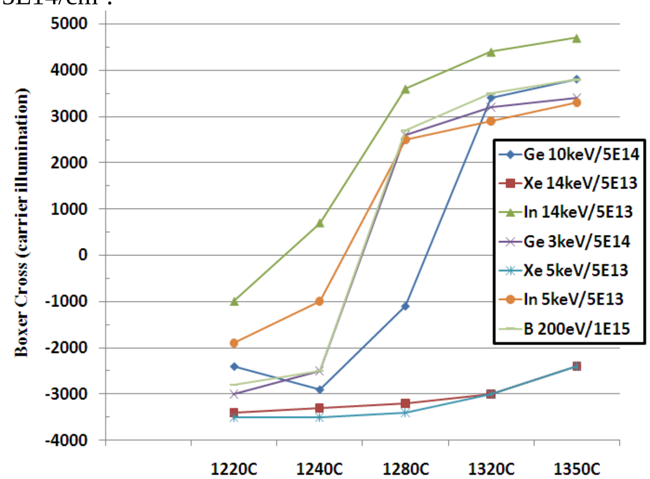

Fig.24: MPR results for As-HALO and various PAI.

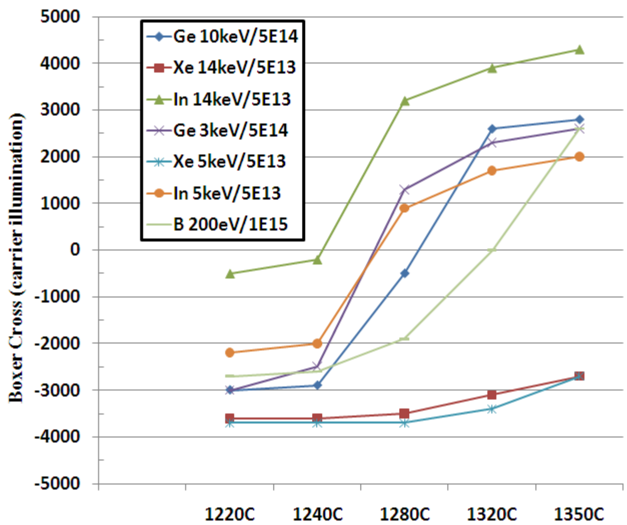

Fig.25: MPR results for Sb-HALO and various PAI.

SUMMARY

Boron 200eV 1E15/cm^2 p+ USJ junctions with various PAI (Ge, Xe & In) and HALO (As & Sb) implantations annealed between 1220^{o}C and 1350^{o}C with msec laser annealing were studied using JPV (junction photo voltage) and MPR (modulated photo reflectance). These measurements provided information about junction quality; dopant activation as measured by Rs, junction capacitance, residual implant damage and junction leakage. The highest p+ junction quality; the lowest leakage and the lowest Rs was achieved with annealing temperatures >1300^{o}C. The p+ USJ with Sb-HALO were for most of the PAI implants worse than with the As-HALO. The exception is the case of 3 keV and 10 keV Ge PAI and annealing temperature of 1280 C or higher. For these implants the leakage for the Sb HALO is lower as compare to the As HALO. The 14keV Xe-PAI resulted in the best dopant activation but showed the highest residual implant damage and junction leakage. The 14keV In-PAI with the As or Sb HALO showed good junction quality even at the lowest annealing temperatures with the lowest residual implant damage by MPR, the lowest junction leakage current and junction capacitance possibly due to complete dopant compensation of the HALO implant by the deep In dopant.

The leakage for p+ USJ without HALO correlated well to expected EOR damage depth. When the HALOs are present under the p+ USJ junction, leakage increases by a few orders of magnitude indicating that direct band to band tunneling is responsible for leakage. Junction capacitance (Jc) was found to give interesting information in aiding the interpretation of the results of the junction leakage and HALO dopant compensation effects. The reliable Rs measurements for HALO could be done with JPV only when junction leakage is below 2E-4 A/cm^2. It seems that maps of leakage could be useful in assessment of non uniformity of doping activation and damage removal during MSA.

Our results of Rs measurements of JPV for p+ USJ junctions over HALO with lower leakage indicate that the further improvement in determination of absolute values of Rs could be achieved when separate calibration of JPV will be developed for junctions with higher capacitance.

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