High & Low Dose USJ Implantation Into Ge-epi on Si Wafers: Dopant Activation, Damage Recovery and Mobility Effects

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***Abstract*—High dose (5E15/cm^2) and low dose (5E13/cm^2) Ultra-Shallow-Junction (<10nm) implantation into 100-200nm Ge-epi on Si wafers with 308nm laser sub-melt to melt annealing for dopant activation, damage recovery and mobility effects was investigated. Half wafer Ge-PAI was used for additional amorphization. Ge-epi implant damage recovery annealing shows a TW reverse trend from that typical in Si with implant damage recovery at energy density above 1.2J/cm^2. Ge electron mobility for high dose P and As implant was 25-50cm^2/Vs and low dose P or low dopant activation P mobility was >200cm^2/Vs while high dose B hole mobility was 44cm^2/Vs.**

Keywords—Ge-epi; mobility; Rs sheet resistance; therma-wave; Ge Ultra Shallow Junction

I. Introduction

High mobility Ge channel material is expected to be introduced at the 7nm node for PMOS and then for NMOS by 5nm node. The current use of embedded S/D-epi stressor to induce compressive p-channel strain with eSiGe-epi with up to 70%-Ge and tensile n-channel strain with eSiCP-epi with up to 1.5%-C has reached it's limit requiring direct high mobility channel material such as SiGe, Ge or III-V materials. USJ formation for source drain extension (SDE) in high mobility Ge material reports higher p+ B activation with cold implants due to improved amorphization and with RTA annealing while laser annealing results in lower B activation [1,2]. For n+ junctions using P, As or Sb dopants, RTA annealing results in rapid diffusion and very deep junctions while msec or nsec laser annealing results in shallow junctions with high dopant activation [3,4]. Therefore in this study we investigated the effects of Ge-PAI for improved amorphization and implant dose on nsec laser annealing for p+ and n+ dopant activation, implant damage recovery and mobility.

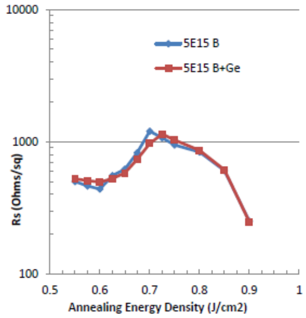
II. EXPERIMENTATION

100-200nm Ge-epi on P(100) and N(100) 300mm Si wafers were grown at CNSE-SUNY-Albany. Half of each wafer received Ge implants at 5keV and 5E13/cm^2 dose for amorphization (Ge-PAI) followed by full wafer B implant at 500eV with either 5E13/cm^2 or 5E15/cm^2 dose into the Ge-epi on N(100) Si wafer while the Ge-epi on P(100) Si wafers received As and P implants at 1keV, Sb implant at 3keV with either 5E13/cm^2 or 5E15/cm^2 dose targeting <10nm USJ. Prior to nsec laser annealing a 20nm SiN capping layer was deposited on the N(100) Si wafers and 10nm SiO_2 capping layer on the P(100) Si wafers by IMEC in Belgium. Using a 308nm laser the implanted Ge-epi wafers were laser annealed with varying energy density from 0.5 J/cm^2 up to 1.7 J/cm^2. Hx-4PP was used to measure sheet resistance (Rs) for dopant activation and therma-probe (TW) to measure laser anneal implant damage recovery. The ALPro system was used for differential Hall effect to measure Rs, active carrier density and mobility.

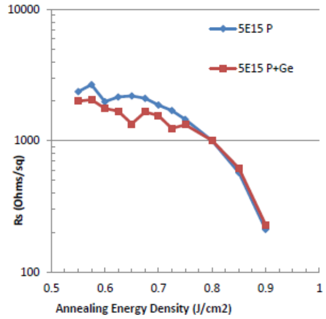
III. Results

A. *Dopant activation for sub-melt to melt laser anneals (0.5-0.9J/cm^2)*

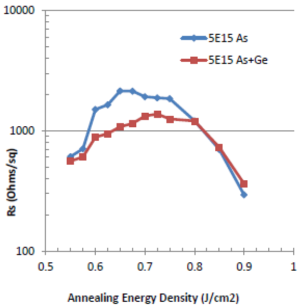
Fig.1 a-d shows the Hx-4PP Rs results for the high dose 5E15/cm^2 implant dopants with and without Ge-PAI for the sub-melt to melt laser annealing energy density from 0.55 to 0.90J/cm^2. The melt threshold was observed to be between 0.60-0.75J/cm^2 depending on the specific implant conditions and usually cause a change in the Rs trends. No difference in Rs dopant activation could be seen for B and Sb dopant implants w or w/o Ge-PAI in Fig.1 a & d while for both P and As, Ge-PAI resulted in lower Rs for laser energy density up to 0.8J/cm^2 (Fig.1 b & c). For B and As implants, Rs increased with increasing laser energy density from 0.55 to 0.75J/cm^2 then reverse trend, decreasing Rs with increasing laser energy density from 0.75 to 0.95J/cm^2 as shown in Fig. 1 a & c suggesting dopant deactivation or acceptor defect effects [4]. The inflection point at 0.70J/cm^2 may be due to transition from surface sub-melt to melt and this is more drastic for the lower dose implants.



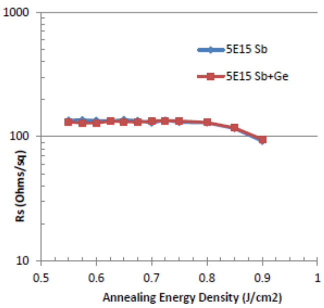
a) B implant



b) P implant



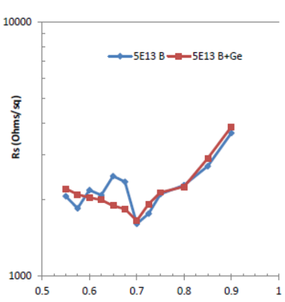
c) As implant



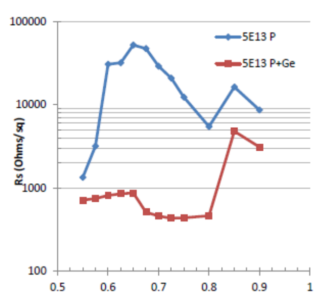
d) Sb implant

Fig.1. Hx-4PP Rs results for 5E15/cm^2 dose w & w/o Ge-PAI.

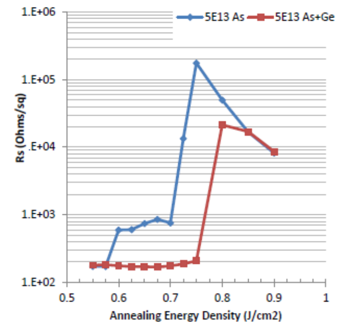
Lower dose 5E13/cm^2 implants with and without Ge-PAI for the sub-melt to melt laser annealing energy density from 0.55 to 0.90J/cm^2 Rs results are shown in Fig.2 a-d. For B dopant no significant difference with or without Ge-PAI was observed (Fig.2a) and a reverse trend inflection point in Rs occurs for energy density above 0.725J/cm^2 (sub-melt to melt transition) with increasing Rs due to B deactivation or acceptor defect annihilation. For P dopant Rs was 50x lower with Ge-PAI as shown in Fig.2b, dropping at 0.675J/cm^2 from 87Ω/□ to 46Ω/□ and then increases 10x to 4790Ω/□ at 0.85J/cm^2 converging closer to the non Ge-PAI Rs results. As dopant Rs results in Fig.2c starts out at 175Ω/□ w and w/o Ge-PAI but then jumps up to 600Ω/□ w/o Ge-PAI at 0.6J/cm^2 and then jumps again 30x at 0.75J/cm^2 (melt transition) to 177KΩ/□ then decreases and converge with the Ge-PAI value of 17KΩ/□ at 0.85J/cm^2. The As Ge-PAI case Rs jumps 100x from 209Ω/□ to 21.4KΩ/□ at 0.8J/cm^2 (melt transition). Sb dopant Rs trend was the opposite, Ge-PAI Rs starts off 10x higher (1260Ω/□) at 0.55J/cm^2 than w/o Ge-PAI (160Ω/□) and drops at 0.70J/cm^2 (melt transition) to 185Ω/□ remaining flat saturating at 120Ω/□.



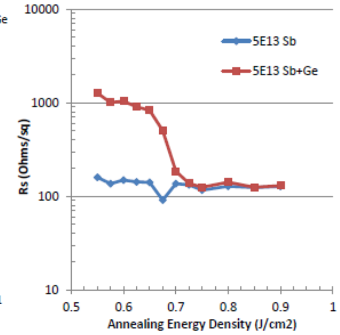
a) B implant



b) P implant



c) As implant



d) Sb implant

Fig.2. Hx-4PP Rs results for 5E13/cm^2 dose w & w/o Ge-PAI.

B. Dopant activation and implant damage recovery for deep melt laser anneals up to 1.7J/cm^2

Fig.3 shows the Hx-4PP Rs results for high dose (5E15/cm^2) B, P, As and Sb implants with and with/out Ge-PAI for the deeper melt depth laser annealing energy density up to 1.7J/cm^2. The non-anneal B region (0.0J/cm^2) Rs value was 450Ω/□ and with Ge-PAI was 550Ω/□. Lowest Rs (maximum activation) of 71Ω/□ occurs at 1.2J/cm^2 when the Ge melt depth exceeds the p+ USJ junction depth then gradually increases to 180Ω/□ by 1.70J/cm^2. Sb dopant looks to be fully activated with Rs of 131Ω/□ at 0.55J/cm2 and drops to 95Ω/□ at 0.90J/cm^2. Similar to B, As dopant Rs starts low at 350Ω/□ for 0.55J/cm^2 then increases peaking at 1400Ω/□ at 0.75J/cm^2 then decrease to low Rs of 79Ω/□ at 1.0J/cm^2 before increasing again with a peak at 94Ω/□ at 1.3J/cm^2 and then dropping to 67Ω/□ at 1.7J/cm^2. P dopant w or w/o Ge-PAI Rs starts off high at 2100Ω/□ at 0.55J/cm^2 and then responds in Rs values similarly to As above 0.80J/cm^2 with Rs lows at 1.0J/cm^2 and 1.7J/cm^2 and peak at 1.40J/cm^2.

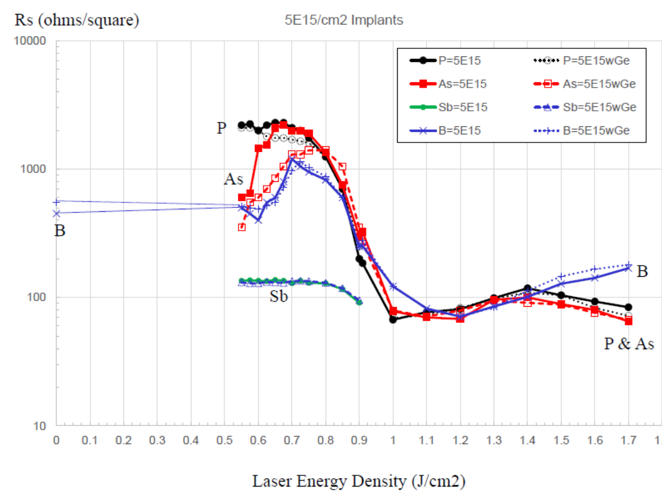


Fig.3. Hx-4PP Rs results for high and low dose B w & w/o Ge-PAI.

Fig.4 shows the Hx-4PP Rs results for low dose B, P, As and Sb implants with and without Ge-PAI for the melt laser annealing energy density up to 1.7J/cm^2. As shown in Fig.2 for the low dose P and As implants the transition to melt has a significant effect on Rs by first increasing in value, peaking between 0.75 and 1.0J/cm^2 and then decreasing to lowest Rs value at 1.7 J/cm^2. B response was very different with Rs constantly increasing to 10.9KΩ/□ at 1.10J/cm^2 and then to 16KΩ/□ by 1.70J/cm^2 so clearly an opposite raising trend or dopant deactivation with deeper melt depth. Sb stayed constant and flat with Rs around 130Ω/□ from 0.725 to 1.7J/cm^2.

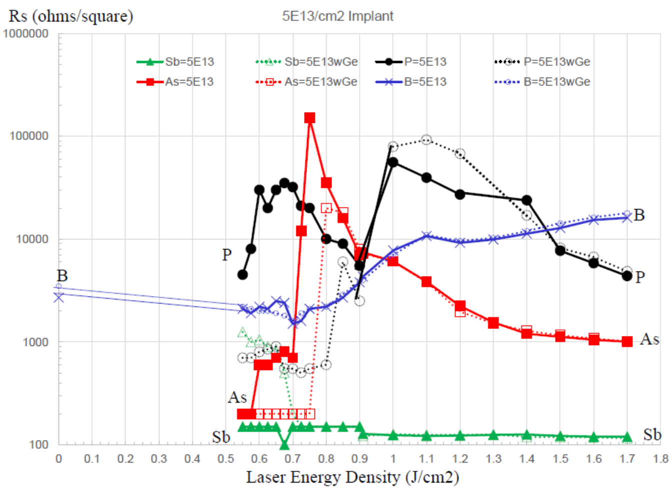


Fig.4. Hx-4PP Rs results for high and low dose P, As and Sb w & w/o Ge-PAI.

These maximum dopant activation values for Rs are ploted in Fig.5 for Rs versus implant dose showing a clustering for the high 5E15/cm^2 dose for P, As, B and Sb between 67-82Ω/□ while at 5E13/cm^2 dose a large variation from 116-17KΩ/□.

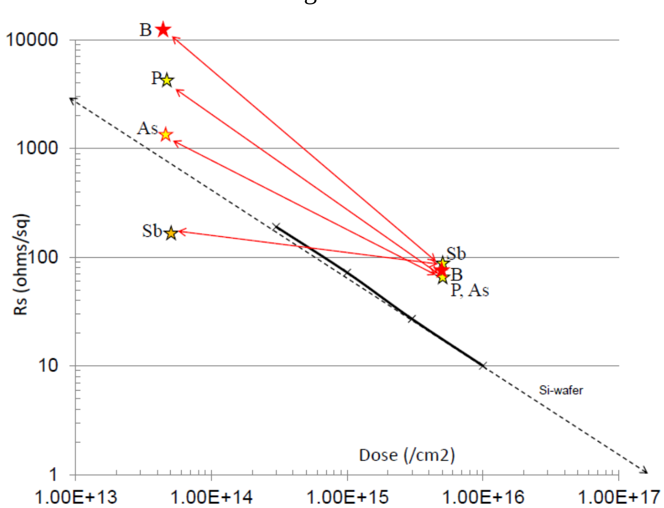


Fig.5. Rs versus implant dopnat dose.

Ge-epi wafers with USJ implant and laser anneal for implant damage recovery was monitored using therma-probe (TW) analysis as shown in Fig.6. The TW response with Ge material is opposite to that usually observed with Si. TW unit incrreases with implant damage recovery in Ge. Low dose and high dose B implant annealing TW response are similar in trends and TW values rapidly increasing until 1.3J/cm^2 at >200K TW units. This corresponds to when the melt depth exceeds the p+ junction with lowest Rs of 71Ω/□. Low dose Sb and As implant annealing TW response are also very similar saturating at ~90K TW units at >1.2J/cm^2 when in melt depth exceeds the n-USJ. As high dose TW response is similar to the P implant anneal response and does not reach saturation even after 1.7J/cm^2 showing continuous increase in TW unit above 100K suggesting there still remains some residual implant damage in Ge requiring high laser energy density and deeper melt to reach the levels seem for B with TW >200K.

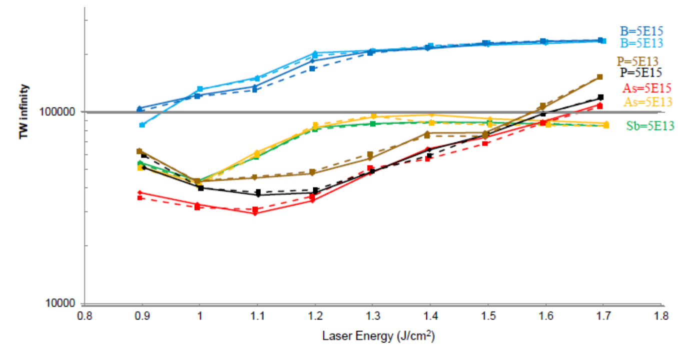


Fig.6. Ge-epi USJ implant and laser anneal damage recovery analysis by therma-probe (TW) measurement.

C. ALPro Differential Hall Effect Analysis for Bulk Rs, Dose and Mobility

ALPro differential Hall effect analysis for the high dose B, As, P and low dose P implants into Ge-epi results are shown in Table I. Good agreement between Hx-4PP Rs values in Figs. 2 & 3 and ALPro Rs values except for the P high dose 1.0J/cm^2 anneal. The high ALPro Rs value of 1157Ω/□ at 1.0J/cm^2 corresponds to the 0.8J/cm^2 value from Hx-4PP in Fig.2. Also ALPro measures the electrical carrier density and the average electrically active dose of the implant in Table I so the dopant activation level can be determined. For the 5E15/cm^2 high dose B the activated dose is ~1E15/cm^2 so only 20% activation. High dose As was 1.8E15/cm^2 at 1.0J/cm^2 for 36% activation and 2.9E15/cm^2 at 1.6J/cm^2 for 58% activation. High dose P was 2.5E13/cm^2 at 1.0J/cm2 so 0.5% activation and 2.8E15/cm^2 at 1.6J/cm^2 for 56% activation. Low dose P was 5.1E12/cm^2 at 1.6J/cm^2 for 10% activation. Average bulk drift mobility is also listed in the Table I and plotted against the Ge and Si electron and hole mobility reference chart in Fig.7 for comparison. The high dose implant mobility values are below the reference electron and hole mobility values on the chart by about 50% to 75% (25-45cm^2/Vs versus 90cm^2/Vs) and the low dose P electron mobility is about 80% lower (200cm^2/Vs versus 900cm^2/Vs). These lower Ge mobility values maybe due to the high TDD in Ge epilayers.

TABLE I. ALPro DHE results for B, As and P implants

DHE Analysis	B=5E15 (1.0J/cm^2)	B=5E15 (1.6J/cm^2)	As=5E15 (1.0J/cm^2)	As=5E15 (1.6J/cm^2)	P=5E15 (1.0J/cm^2)	P=5E15 (1.6J/cm^2)	P=5E13 (1.6J/cm^2)
Bulk Rs (Ω/□)	129.8	148.7	72.1	80.9	1157	88.4	6161
Average Dose (#/cm^2)	1.0E15	9.8E14	1.8E15	2.9E15	2.5E13	2.8E15	5.1E12
Average Bulk Drift Mobility (cm^2/Vs)	47.1	42.5	48.3	26.5	216.7	25.3	200.9

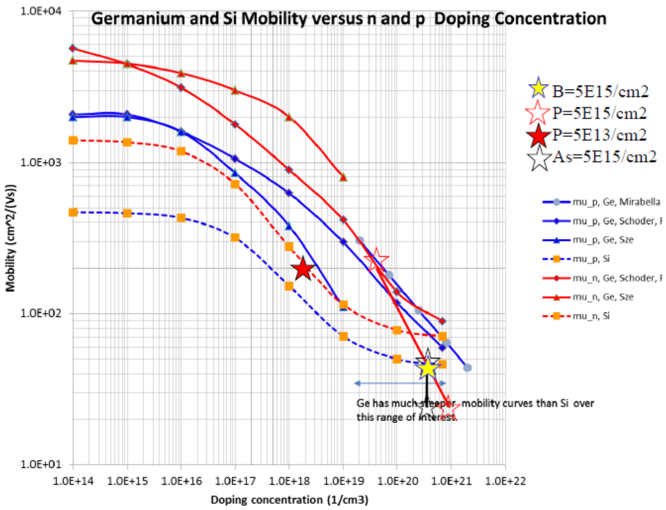


Fig.7. Comparison of Ge-epi USJ ALPro bulk drift mobility to Si and Ge reference electron and hole mobility.

IV. SUMMARY

Ge-epi USJ formation by B, P, As and Sb implantation at high dose (5E15/cm^2) and low dose (5E13/cm^2) with and without Ge-PAI was investigated using sub-melt to melt 308nm laser annealing. Amorphization by Ge-PAI improved dopant activation with sub-melt annealing for low dose P and As implant with opposite effect for Sb implant. With melt annealing dopant activation for high dose implants were similar but for low dose significant differences were observed. Different degrees of implant damage recovery after laser annealing was also observed using therma-probe TW analysis. Highest mobility >200cm^2/Vs was measured for low dose P and low dopant activation (0.5%) high dose P implants.

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