Solid Solubility Limited Dopant Activation of Group III Dopants (B, Ga & In) in Ge Targeting sub-7nm Node Low p+ Contact Resistance

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1. Introduction

Low contact resistance (Rc) is key to boost device performance for sub-10nm node. At VLSI Technology Symposium 2016 Samsung reported they reduced Rc by 10% from 14nm to 10nm bulk FinFET technology [1]. TSMC in their beyond 10nm node FinFET paper reported reducing S/D (source/drain) parasitic resistance and enhanced contact process [2] and at IEDM-2016 reported 7nm FinFET reduced S/D parasitic resistance and developed a novel contact process [3]. A complete session #7 was dedicated to "Contact Resistance Innovations for Sub 10nm Scaling" with 4 papers at the VLSI Technology Symposium 2016 [4-7]. To achieve Rc in the low E-9 Ωcm^2 requires active dopant carrier concentration >5E20/cm^3 to low E21/cm^3. For SiP n+ S/D contacts P >1E21/cm^3 active dopant carrier concentration is realized with laser melt annealing resulting in Rc <1E-9 Ωcm^2 [6]. For 70%-SiGe p+ S/D contacts IMEC reported using pre and post Ge amorphous implants to boost the B-implant activation with nsec laser melt annealing to reduce Rc from 1.2E-8 Ωcm^2 to 2.1E-9 Ωcm^2 [4]. IBM/GF on the other hand reported reducing SiGe p+ S/D Rc from 1.3E-8 Ωcm^2 to 1.9E-9 Ωcm^2 by using a thin 12nm 100%-Ge trench-epi and switching from a p+ Ge:B to a p+ Ge:B:group-III metastable alloy for surface interface doping [8]. The group-III Me-alloy in Ge boosted p+ dopant activation from ~1E19/cm^3 with B to ~8E20/cm^3 with Ge+Me-alloy. They mentioned no difference between msec non-melt and nsec melt laser annealing.

Solid solubility limits for various dopant elements in Ge were reported by Trumble back in 1959 [9]. No data for B in Ge only in Si which was 6E20/cm^3 at the melting point of 1407ºC however, he reported other group-III dopants in Ge, Al peaks at 4.2E20/cm^3 between 550ºC to 750ºC and drops to <4E19/cm^3 at the melting point of Ge while in Si it peaks at 2E19/cm^3 between 1075ºC to 1250ºC, Ga peaks at 5.0E20/cm^3 between 625ºC to 725ºC and drops to <4E19/cm^3 at the melting point of Ge while in Si it peaks at 4E19/cm^3 between 1175ºC to 1275ºC and In peaks at 4E18/cm^3 at 800ºC and drops to <4E17/cm^3 at the melting point of Ge. Nissin reported on p+ Al implant doping in Ge at IIT-2016 and achieved 4E20/cm^3 with RTA but commented the Ga implants resulted in high Rs (poor dopant activation) [10]. The group III element solid solubility dopant activation in Ge compared to Si is 0.017x less for B, 20x higher for Al, 13x higher for Ga and nuetral for In. Another issue with p+ implant doping in Ge is the defect acceptor formation. Borland and Konkola reported this can be as high as 3E19/cm^3 while Zaima et al reported post implant anneals >500ºC was required to eliminate these defect acceptor formation in Ge [11,12]. Therefore in this study we investigated the solid solubility dopant activation limit for various group-III p+ implants (BF_2, $B_{18}H_{22}$, In & Ga) in Ge-epi with non-melt and melt RTA and nsec laser annealing.

2. Experimentation

We grew 100nm undoped Ge epilayers on 200mm Si N(100) wafers at NDL and NTU in Taiwan. Nissin in Japan performed half wafer group III p+ dopant implants: 1) BF_2 (13keV/2 E15/cm^2), 2) $B_{18}H_{22}$ (56.7keV/1.1 E14/cm^2), 3) In (30keV/2 E15/cm^2) and 4) Ga (18keV/2 E15/cm^2). The wafers were then laser annealed using the LT-3000 a 308nm Excimer laser anneal system at LASSE in France with varying energy density levels from 0.4J/cm^2 (non-melt SPE) up to 1.8J/cm^2 (melt LPE). Also 10 sec RTA annealing at temperatures from 550°C (SPE) to 950°C (LPE) were performed at NDL on selected wafer pieces. Sheet resistance 4PP measurements were performed on as implanted unannealed regions to determine the defect generated acceptor level and on all the annealed regions. SIMS depth profiles were performed by EAG on selected samples as were SRP analysis.

3. Results

As Implanted No Anneal Acceptor Defect Formation in Ge

The as implanted Rs 4PP measurements revealed differences in implant damage acceptor formation among the group-III dopants as shown in Fig.1. $B_{18}H_{22}$ implant had the lowest Rs at 308Ω/□ followed by BF_2 at 491Ω/□ then Ga at 1234Ω/□ and In at ~1603Ω/□. The elemental SIMS depth profiles for the as implanted no anneal cases are shown in Fig.2. From the Ge-SIMS profile using the 50%-Ge point as a marker for the Ge/Si metallurgical interface the wafer with half BF_2 and $B_{18}H_{22}$ implant Ge-epi thickness is 125nm while the wafer with half Ga and In implant is 145nm thick. Using 5E18/cm^3 dopant concentration to define the junction depth (Xj) and plotting Rs versus Xj as shown in Fig.3 we determined the as implanted defect generated acceptor level in the Ge-epilayer to be ~5E19/cm^3 for $B_{18}H_{22}$ which is above B solid solubility in Ge, ~3E19/cm^3 for BF_2 which is again above B solid solubility in Ge, ~1E19/cm^3 for Ga which is below Ga solid solubility in Ge and ~8E18/cm^3 for In which is above In solid solubility in Ge. Spreading Resistance Profile (SRP) using limited calibration samples for carrier depth profiles are shown in Fig.4. $B_{18}H_{22}$ shows the highest acceptor formation level of ~2E19/cm^3 followed by BF_2 and Ga both at ~2E18/cm^3 and then In at ~5E17/cm^3. Note that these SRP carrier concentration values are much lower than the Rs/Xj determined values which may be due to limited SRP calibration samples for Ge.

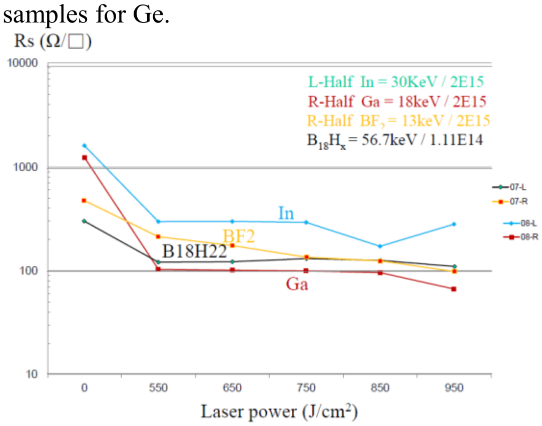

Fig.1: Rs 4PP results for as implanted no anneal and RTA/10sec at 550°C, 650°C, 750°C, 850°C and 950°C.

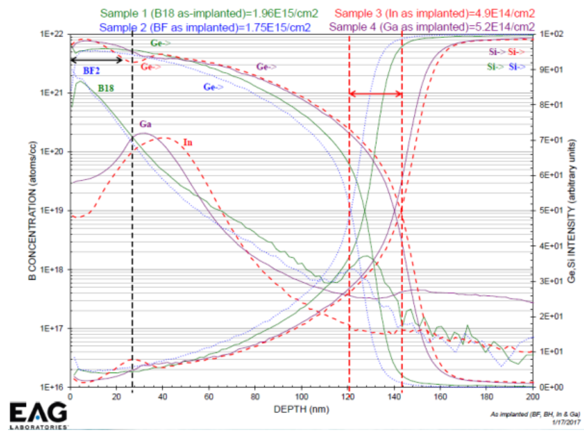

Fig.2: SIMS elemental concentration depth profile for as implanted no anneal cases.

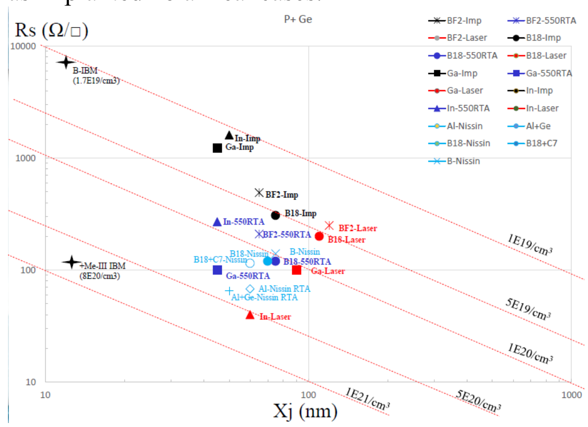

Fig.3: Rs versus Xj plot for p+ doping in Ge.

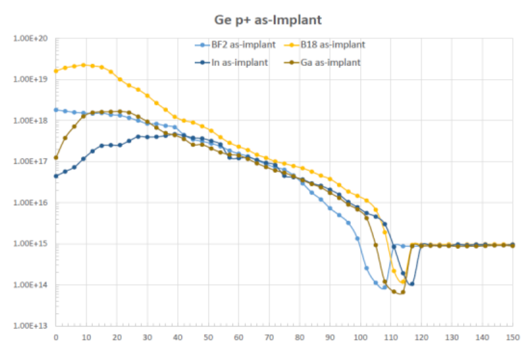

Fig.4: SRP electrically active carrier density depth profile for as implanted no anneal cases.

10 sec RTA Anneal

The 10 sec RTA anneal 4PP Rs results were also shown in Fig.1 for 550°C, 650°C, 750°C and 850°C non-melt solid phase epi (SPE) crystallization anneals as well as for the 950°C melt anneal liquid phase epi (LPE) crystallization. Based on the Rs response both $B_{18}H_{22}$ and Ga look to be fully activated after the 550°C RTA anneal with Rs saturating at ~100Ω/□ for Ga between 550°C to 850°C however, with melt annealing at 950°C Rs drops to 66Ω/□.

$B_{18}H_{22}$ saturates at ~120$\Omega/\square$ while BF_2 Rs continually drops from 210$\Omega/\square$ at 550ºC to 100$\Omega/\square$ at 950ºC. In on the other hand saturates at 290$\Omega/\square$ from 550ºC to 750ºC then drops at 850ºC to 172$\Omega/\square$ but reverses and increases back to 280$\Omega/\square$ for 950ºC melt anneal.

The group III SIMS depth profiles for the 550ºC anneal case are shown in Fig. 5. All the samples now show a surface layer of ~20nm in thickness resulting in the 50% Ge/Si marker to be at a depth on 145nm. The Rs/Xj dopant activation values are 3.0E20/cm^3 for Ga, 1.2E20/cm^3 for $B_{18}H_{22}$, 9E19/cm^3 for In and 8E19/cm^3 for BF_2 (see Fig.3). The $B_{18}H_{22}$ results reported here are similar to the B and $B_{18}H_{22}$ results reported by Nissin as shown in Fig.3 and their Al implant result of 4E20/cm^3 for RTA annealing [10].

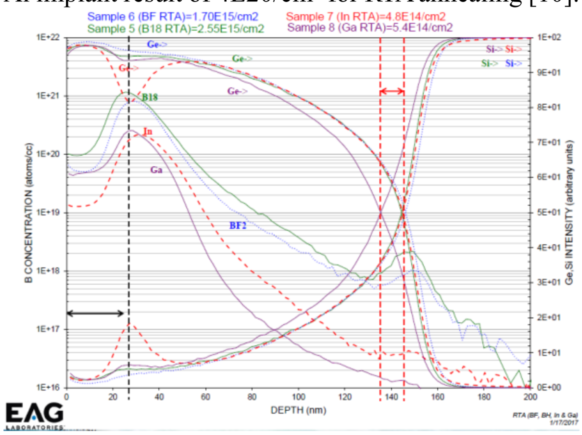

Fig.5: SIMS elemental concentration depth profile for 550ºC RTA anneal cases.

The SRP surface activation values are 3-5x lower as shown in Fig. 6 with Ga ~1E20/cm^3, $B_{18}H_{22}$ ~2.2E19/cm^3, BF_2 ~1.5E19/cm^3 and In ~1.2E19/cm^3.

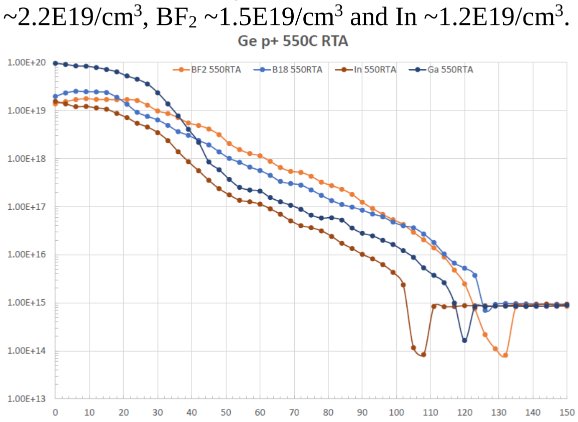

Fig.6: SRP electrically active carrier density depth profile for 550ºC RTA anneal cases.

308nm Laser Anneal

Results for the 308nm laser anneal from 0.4J/cm^2 to 1.8J/cm^2 power density are shown in Fig.7 for Rs 4PP. Most interesting is In which starts out at a high Rs value of 1603$\Omega/\square$, first drops to ~1000$\Omega/\square$ from 0.6-0.9J/cm^2 then drops again as the melt depth exceeds the implant depth then saturates at ~40$\Omega/\square$ at 1.7-1.8J/cm^2. The In-SIMS profile in Fig. 8 shows that the 1.7J/cm^2 melt depth is ~125nm with the In melt LPE crystallized surface region solid solubility chemical limit of ~4E19/cm^3 but the effective Rs/Xj activation level >10x higher at ~5.5E20/cm^3 as shown in Fig.3. After LPE crystallization In segregates and piles up at the surface forming a rich InSiGe surface layer ~20nm thick with 17%-Si and In=4E20/cm^3. This could be a metal group-III alloy as reported by IBM [8] resulting in the very low Rs value of ~40$\Omega/\square$. Ga on the other hand saturates at ~100$\Omega/\square$ for 1.7J/cm^2 laser power with no change in the surface layer for an Rs/Xj activation level of ~1E20/cm^3. For B dopant species both BF_2 and $B_{18}H_{22}$ dopant source seems to show no Rs effects with laser melt annealing but the B-SIMS profiles show a melt depth of 125nm with B pile-up at the liquid/solid interface and a flat level of 2.5E19/cm^3 for BF_2 and 4.0E19/cm^3 for $B_{18}H_{22}$ suggesting this is the melt solid solubility level of B in Ge and this supports the Rs/Xj value of 3.5E19/cm^3 for BF_2 and 5.0E19/cm^3 for $B_{18}H_{22}$ which is the same values for the as implanted defect acceptor formation.

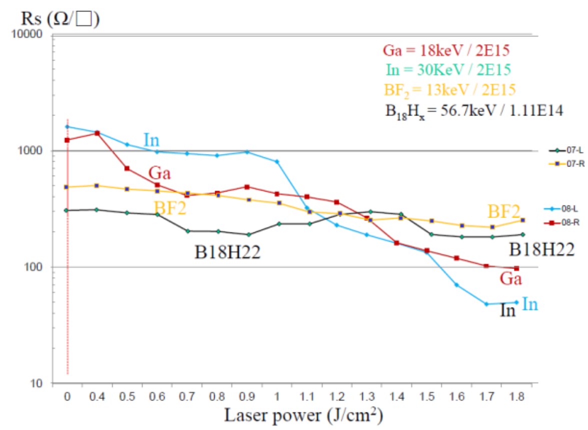

Fig.7: Rs 4PP results for 308nm laser anneal.

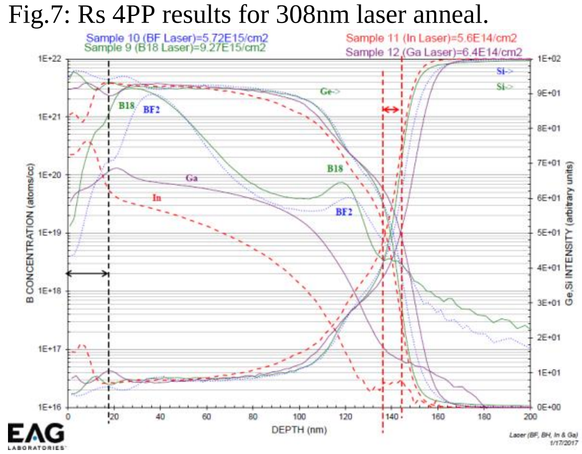

Fig.8: SIMS elemental concentration depth profile for laser annealed cases.

4. Conclusions

$B_{18}H_{22}$ implant had the highest as implanted defect acceptor level formation in Ge at ~5E19/cm^3 while In implant had the lowest at ~1.2E19/cm^3. With RTA SPE crystallization annealing Ga had the highest dopant solid solubility level in Ge at ~3E20/cm^3 over the temperature range of 550ºC to 950ºC followed by $B_{18}H_{22}$ at ~1.2E20/cm^3 then In at 9E19/cm^3 and BF_2 at 8E19/cm^3. With laser melt annealing and LPE-crystallization In formed a surface layer Ge+Si+In alloy with 83% GeSi and In surface concentration pile-up of 4E20/cm^3 resulting in an Rs/Xj activation level of 5.5E20/cm^3 which is >10x higher than the solid solubility limit of 4E19/cm^3 in Ge. Ga dropped to 1.2E20/cm^3 and B was ~5E19/cm^3. Therefore if low temperature 550ºC RTA annealing is to be used for Ge p+ S/D contacts Ga group-III dopant is best while if laser melt annealing is to be used In dopant is best for highest solid solubility dopant activation and therefore lowest possible contact resistance (Rc).

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