Comparison of BF_2, In, Ga, C+Ga & In+BF_2 Dopant for 22nm Node Bulk & PD-SOI HALO Implantation or Ground Plane Back-Gate Doping for FD-SOI CMOS Technologies

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Abstract

We compared BF_2, In, Ga, C+Ga and In+BF_2 dopant species for nMOS HALO at 22nm node for planar bulk & PD-SOI or for FD-SOI ground plane back-gate doping which require steep retrograde dopant profile and good dopant activation using a 1200°C Flash + 900°C 10 sec RTA anneal sequence. The best results were with the C+Ga co-implant realizing a steep surface dopant profile and dopant activation in the 2-3E18/cm^3 level. In dopant activation was limited to 3-7E13/cm^3 due to low solid solubility limit from the 900°C RTA anneal. The BF_2, In+BF_2 and Ga implant conditions all showed flat to increasing dopant profile pile-up at the surface which is not desirable.

1. Introduction

With continued scaling of planar bulk and PD-SOI CMOS to 20/22nm node the channel doping level increases to high E18/cm^3 or low E19/cm^3. A flat HALO surface dopant profile degrades surface mobility so a steep retrograde profile is preferred for high surface channel mobility and good SCE (short channel effect). Vt variation for pMOS is less than nMOS and maintaining a steep retrograde HALO profile is difficult with boron (B) dopant due to B TED (transient enhanced diffusion) [1]. Switching to a heavier mass dopant like indium (In) for In-HALO an improved retrograde HALO surface profile is possible but is limited by lower dopant activation due to low In solid solubility in silicon and surface out-diffusion pile-up as reported by Sawada et al. of Toshiba [2]. By adding a C co-implant at 1E14/cm^2 dose they reported less In surface pile-up. Planar FD-SOI also known as UTBB-SOI (Ultra Thin Body and Box SOI) will also require a similar implant to HALO for ground plane back-gate doping with a peak in the E18/cm^3 level below the buried oxide with the thin silicon surface doping level at <E16/cm^3 as reported by Hold of ARM [3]. Using B implant for back gate doping Ban et al. of Intel reported excessive B diffusion resulting in too high a level of B in the thin surface silicon channel region of >E17/cm^3 [4]. An alternative to B is to use In for the p-type ground plane implant as reported by Skotnicki of ST and shown in Fig.1 [5]. Therefore we also investigated Gallium (Ga) dopant to achieve high dopant activation and steep retrograde surface profile since good Ga-implant dopant activation between 900°C to 1050°C was reported by Hoshi et al of Toshiba [6].

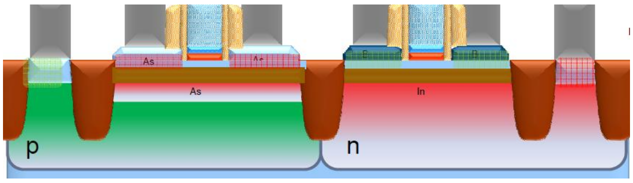

Fig.1: UTBB-SOI structure showing As for n-type ground plane and In for p-type ground plane back-gate doping [5].

2. Experimentation

The various p-type implants were done by Nissin using their Exceed medium current implanter. BF_2 implants were performed at 26keV, In implants at 60keV and Ga implants at 36keV all at doses of 1.5, 3.0 and 4.5E13/cm^2 and tilt angle of 30 degrees. Additionally, a combination of C+Ga (C_7=10keV/1E15 + Ga=36keV/3E13) and In+BF_2 (In=60keV/3E13 + BF_2=26keV/1.5E13, In=60keV/3E13 + BF_2=26keV/3E13 and In=60keV/4.5E13 + BF_2=26keV/1.5E13) implantations were studied. The ellipsometry amorphous layer thickness and TW (therma-wave) values after implant before annealing are shown in Fig.2 for these various single and multi combinational implants. Note that an amorphous layer 33-37nm thick was induced by the In implant when the dose was 3E13/cm^2 or 4.5E13/cm^2 as well as by the C_7 co-implant. The wafers were then sent to Dai Nippon Screen for annealing using their LA-3000-F system for the 1200°C Flash anneal followed by a 900°C 10sec RTA anneal on their LA-830 system. Sheet resistance (Rs) and junction leakage was measured by JPV (Junction Photo Voltage) method at Semilab in Hungary as well as SRP (Spreading Resistance Profile) measurements.

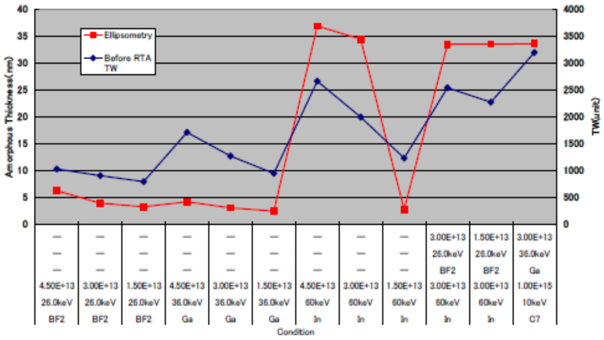

Fig.2: Correlation of amorphous layer depth by ellipsometry measurement to implant damage by TW measurement.

3. Results

A. *Crystal Trim simulation and SIMS results:*

First we did 30 degree tilt implant Crystal Trim profile simulations and the results are shown in Fig.3 for BF_2=26keV/3E13 in yellow, Ga=36keV/3E13 in pink and In=60keV/3E13 in blue [7, 8]. Ga dopant has a steeper surface profile than BF_2 and In is steepest (most retrograded). At a depth of ~3.0nm the surface dopant level for B is <3E18/cm^3, for Ga <8E16/cm^3 and for In <1E15/cm^3. Fig.4 shows the SIMS analysis after the Flash + RTA anneal and the surface dopant level at a depth of ~5.0nm for B is >6E18/cm^3 and piles-up at the surface to >5E19/cm^3, In drops to 3E18/cm^3 with a peak of 6E18/cm^3 at 20nm and also piles-up at the surface to >1E19/cm^3 while Ga is ~4E18/cm^3 with a surface pile-up of 6E18/cm^3. Most interesting is the C+Ga co-implant profile which shows only slight diffusion remaining retrograde in shape with a peak at 22nm of 2E19/cm^3 and a surface level of <2E18/cm^3 for an ideal nMOS HALO or p-type ground plane profile. Figs. 5& 6 shows the detailed SIMS dopant profiles after anneal for In, Ga and Ga+C for the various dose levels showing the near surface dopant levels. In Fig.5 the after anneal In steep retrograde surface profile is significantly degraded to only a 2x drop in the surface doping level from the peak doping. The combined In+BF_2 co-implants reduced the B-diffusion compared to BF2 alone by 10nm increasing the surface B flat level to >7E18/cm^3 and also reduced the position of the In retrograde peak by 2nm but the In Xj for all cases remained the same. Fig.6 shows the Ga & C SIMS profile results, note that only the Ga+C co-implant shows a steep retrograde profile of one order of magnitude for Ga with the high level of C >1E20/cm^3 at the surface with multiple peaks.

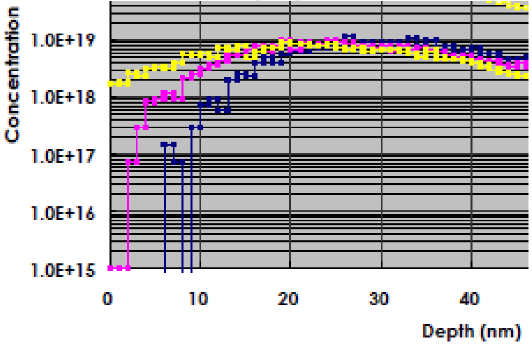

Fig.3: Crystal Trim simulation profiles for 3E13/cm^2 BF_2=26keV, In=60keV & Ga=36keV implants at 30 degree tilt.

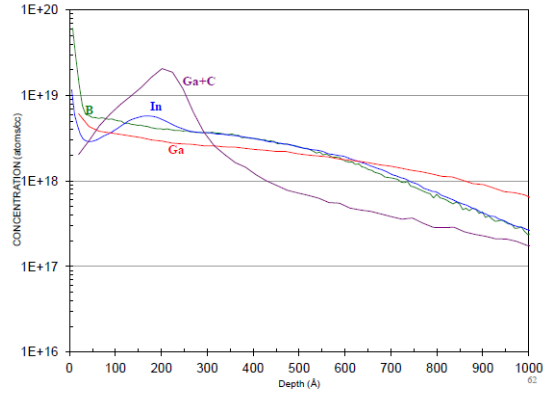

Fig.4: After anneal SIMS profile for 3E13/cm^3 BF_2, In, Ga & Ga+C.

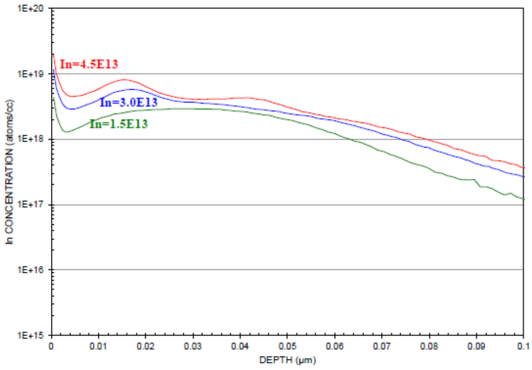

Fig.5: After anneal In SIMS profiles for 1.5, 3.0 and 4.5E13/cm^2 dose conditions.

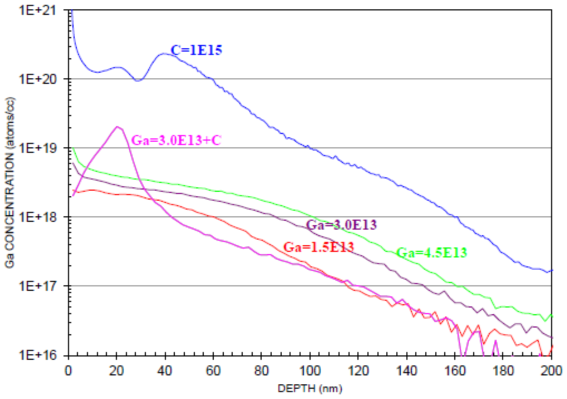

Fig.6: After anneal Ga and Ga+C SIMS profiles for 1.5, 3.0, and 4.5E13/cm^2 dose conditions.

B. Rs & SRP dopant activation results:

The JPV-Rs results are shown in Fig.7 as a function of implant dose. Note that the In Rs values are much higher than the other dopant conditions by about 4-6x (>25,000Ω/□) suggesting the 900°C RTA activation anneal was at In dopant solid solubility limit (activation anneal temperature limited) while the BF$_2$ and Ga Rs values were similar (4,000-8,000Ω/□) so implant dose limited. The Ga+C implant Rs value was also high at 12,000 Ω/□ possibly due to the high C co-implant dose of 1E15/cm^2. The In+BF$_2$ co-implans dopant activation Rs values were mainly determined by the BF$_2$ implant dose and not the In implant dose.

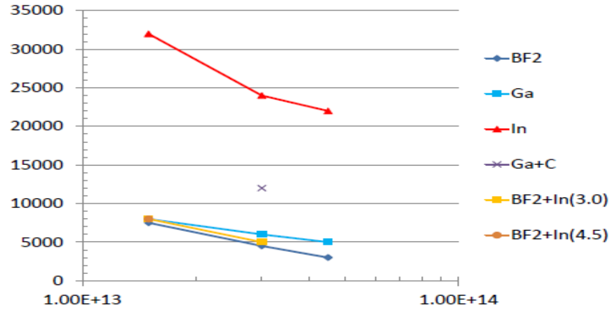

Fig.7: JPV-Rs results for the various implant dose and dopant species.

The SRP results for the 3E13/cm^2 dose for In, Ga and BF$_2$ implants are shown in Fig.8. From the carrier density measurements we can determine the implant dopant electrical activation levels and rough estimate of the implant junction depth. For the In dopant case the measured activated dopant surface level was a very low 3E17/cm^3 while for Ga ~4E18/cm^3 and for BF$_2$ ~7E18/cm^3 even though the B-SIMS chemical level in Fig. 4 is <6E18/cm^3. We observed both some good and poor agreement between SRP-Xj and SIMS-Xj as seen when comparing Figs. 4 & 8 so the Rs versus Xj chart in Fig.9 is for SIMS-Xj and not SRP-Xj which was usually much shallower. The Ga 1.5E13/cm^2 dose Rs results at 900°C is dose limited and not temperature limited however, as the dose increases going from 3.0E13/cm^2 to 4.5E13/cm^2 the Rs values are slightly higher than the equivalent BF$_2$ dose (see Figs.7&9) so a higher 950°C RTA anneal would be better for higher Ga activation levels.

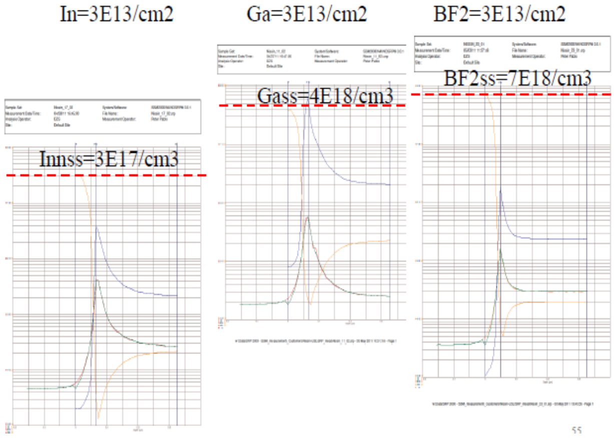

Fig.8: SRP carrier depth profile measurements for the 3E13/cm^2 implant dose conditions for In, Ga and BF$_2$.

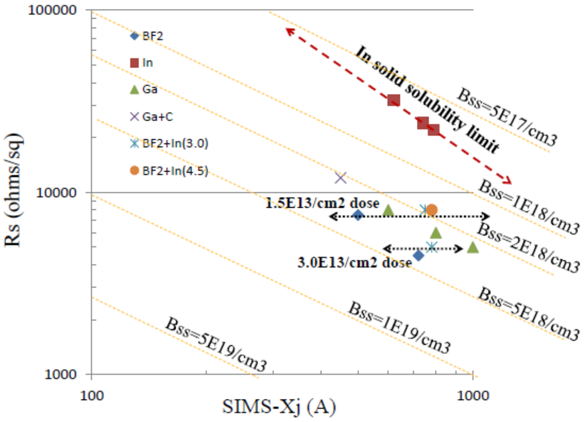

Fig.9: Rs versus SIMS-Xj for the various implant conditions.

C. Residual implant damage by JPV junction leakage and PMR analysis:

Measurements of JPV junction leakage are shown in Fig. 10. In dopant had the lowest junction leakage level even though it induced a 33nm deep amorphous layer followed by Ga and then BF$_2$. The Ga+C case had the highest leakage due to the high dose and deep C profile which resulted in an amorphous depth of 33nm with higher levels of residual implant damage after anneal as revealed by the C-SIMS profile in Fig. 6. A lower C dose should be considered down to 1E14/cm^2 as reported by Toshiba [2] to achieve higher Ga activation levels and lower junction leakage. As shown by the TW results in Fig.2 the Ga implants show more implant damage compared to BF$_2$ with In showing the most and was amorphizing. However, after anneal In shows the lowest level of residual implant damage followed by Ga and then BF_2 based on the PMR (Photo Modulated Reflectance) results in Fig.11 and consistent with the JPV leakage trend results in Fig.10. This is also consistent to In-PAI defect analysis reported by Borland et al. where annealed In-amorphous re-crystallized regions show very low residual damage [9, 10].

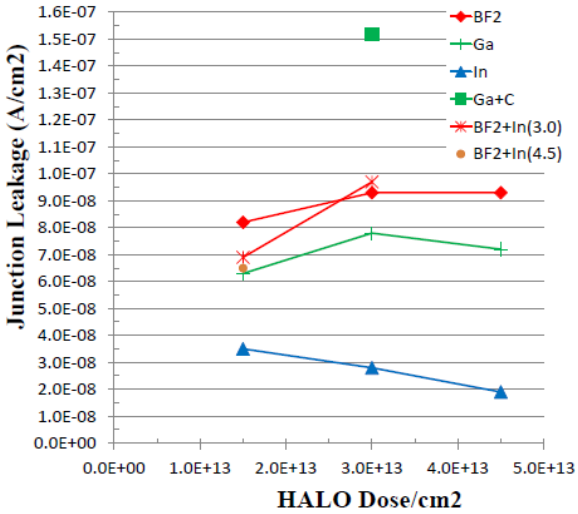

Fig.10: JPV junction leakage measurements for the various implant conditions.

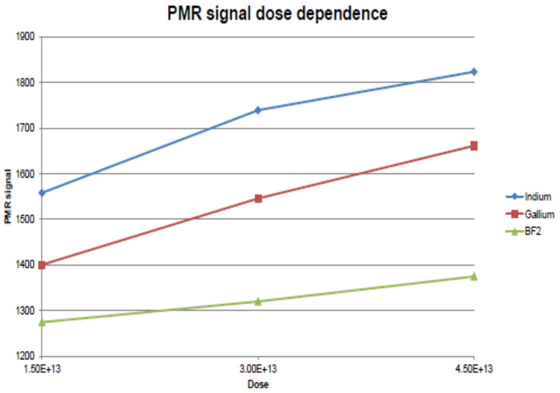

Fig.11: After anneal PMR analysis of the residual implant damage.

4. Summary

BF_2 dopant diffusion resulted in a flat B surface level while In dopant remained retrograded but due to In low solid solubility limit at 900°C, dopant activation level was a very low 3-6E17/cm^3. Only the Ga+C co-implant realized a steep retrograde surface profile with dopant activation level of 2-3E18/cm^3. Lower C-implant dose between 1-5E14/cm^2 should improve junction leakage and higher RTA annealing temperature should improve activation to >5E18/cm^3.

Acknowledgments

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