HIGH TILT P+ & N+ MOLECULAR IMPLANTATION FOR 3-D STRUCTURES: RETAINED CHEMICAL DOSE VERSUS ELECTRICAL ACTIVATION LIMITED CONFORMAL DOPING

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We investigated using molecular dopants, $B_{18}H_{22}$ alternative for B & BF_2 between 400eV and 1keV and As_4 alternative for As between 3-6keV for high tilt angle implantation from 0^o to 60^o. To enhance and maximize dopant activation and minimize diffusion FLA (Flash lamp msec annealing) was employed. We observed that monomer B at 45^o tilt had the highest retained dose ($>1.1E15/cm^2$) but the lowest electrical activation level ($Bss=2.8E19/cm^3$) when using FLA only annealing. $B_{18}H_{22}$ at a tilt of 60^o had a retained dose of $5.5E14/cm^2$ but the highest dopant electrical activation level ($Bss=1.1E20/cm^3$). For As compared to As_4, at 60 degree tilt the retained dose for As went from $1.1E15/cm^2$ at 0^o tilt to $5.3E14/cm^2$ at 60^o tilt while for As_4 it went from $1.1E15/cm^2$ at 0^o tilt to $5.7E14/cm^2$ at 60^o tilt and the Rs values showed 7.5% improvement in dopant activation with As_4. Therefore we conclude that conformal and highest electrical dopant activation level is more important for 3-D structures when using msec annealing than does the conformal retained chemical dopant level and the best results were realized using $B_{18}H_{22}$ and As_4 molecular dopant at tilt angles up to 60 degrees.

INTRODUCTION

Both SOI and bulk FinFET device structures have been delayed until the sub-22nm node as reported at VLSI Sym 2008 (1) and IEDM 2008 (2) for SRAM devices. However, DRAM memory companies may introduce FinFET devices at sub-30nm node (3). This creates new challenges for extension doping of the vertical sidewall structure. Traditionally FinFET structures are doped using high tilt implantation as reported by J. Kedzierski et al. at IEDM-2001 (4). One of the concerns with high tilt implantation is retained dose which is effected by dose loss due to the cosine effect at higher tilt angles and sputter dose limit at lower implant energies and higher doses. Borland reported on the sputter dose limit with lower implant energies and showed that MSA (msec anneal) enhances dopant activation to higher solid solubility limit compared to spike/RTA annealing(5). Duffy et al., reported on the tilt angle effect at INSIGHTS-2007 comparing dopants of different atomic mass showing higher atomic mass leads to higher chemical retained dose at high tilt angles (6). At IEDM-2008 they reported on the effects of implant energy at high tilt on retained dose (7). An alternative to beam-line implantation doping is to use plasma implantation doping such as PIII or PLAD as first reported by Lenoble et al at VLSI Sym 2006 (8). The main concern with tilted beam-line implantation is the inability to achieve conformal chemical doping of the 3-D structures due to the top of the Fin getting 2x the chemical dopant dose compared to the vertical side-wall during a bi-mode tilted implant. Plasma implant doping has been studied as an alternative to improve conformal chemical doping but in fact recent results have shown plasma doping to be non-conformal as well and also results is severe FinFET sidewall silicon erosion as reported by Vandervorst et al., at IIT-2008 (9). Therefore in this study we applied the benefits of enhanced dopant activation using both FLA and beam-line molecular dopant implantation as reported by Mineji et al. at IWJT-2007 (10) and examine these effects for tilt angles from 0^o to 60^o and energies down to 400eV in order to compare conformal retained chemical dose versus conformal electrical dopant activation which should be limited to dopant solid solubility with MSA.

EXPERIMENTATION

A conformality study was done for the FinFET structure as shown in Figs. 1 and 2 below looking at the implant tilt angle effects from 0^{o} up to 80^{o} tilt angle on side wall to top dose ratio and also Fin spacing and height. A conformality factor of 1 can be realized for 60^{o} tilt which would be 30^{o} tilt angle for the vertical side wall and 60^{o} tilt for the top of the Fin structure. However, due to the FinFET shadowing effects 30^{o} is the realistic maximum for the tilt angle which would be 60^{o} on the side wall. In this study we used the Nissin Claris implanter which has a maximum tilt angle limit of 60^{o} for 300mm wafers and the Applied Quantum-X which is limited to 45^{o} for the various beam-line implantations.

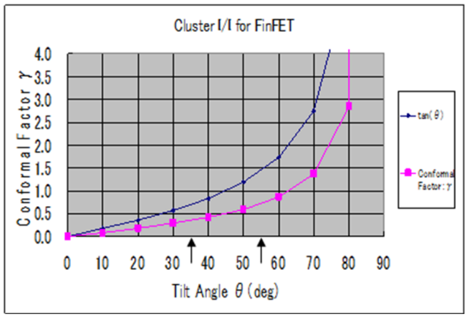

Fig.1: Tilt angle effects on conformal dose.

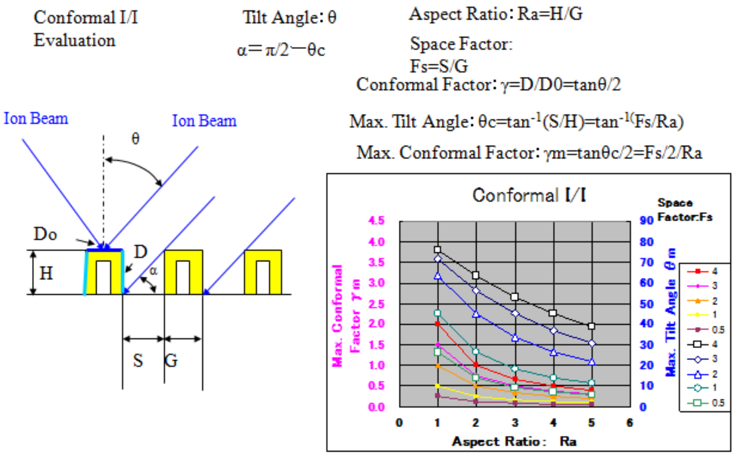

Fig.2: Fin struture aspect ratio on conformal dose.

BF$_2$, B$_{18}$H$_{22}$, As and As$_4$ implants were performed by Nissin on their Claris single wafer cluster ion implanter while monomer B was implanted by IMEC using their Applied Quantum-X ion implanter. The detailed implant matrix for both p-type and n-type dopants are shown in Tables I & II below. BF$_2$ implants were done at a dose of 1E15/cm^2 and at 2keV/0^{o} tilt (400eV equivalent), 2keV/15^{o} tilt, 2keV/30^{o} tilt, 3keV/45^{o} tilt and 4keV/60^{o} tilt. At 60^{o} tilt an energy split of 2keV, 4keV and 8keV was also done. B$_{18}$H$_{22}$ implants were done at a dose of 5.5E13/cm^2 (1E15/cm^2 equivalent) at 8keV/0^{o} tilt (400eV equivalent), 8keV/15^{o} tilt, 9keV/30^{o} tilt, 11keV/45^{o} tilt and 16keV/60^{o} tilt. An energy split at 60^{o} tilt was also done at 8keV, 16keV and 32keV. Monomer B implants at 1E15/cm^2 dose was done at 500eV/0^{o} tilt, 520eV/15^{o} tilt, 580eV/30^{o} tilt and 710eV/45^{o} tilt at IMEC. Arsenic (As) implant at 1E15/cm^2 dose was done at 3keV/0^{o} tilt, 3.1keV/15^{o} tilt, 3.5keV/30^{o} tilt, 4.2keV/45^{o} tilt and 6keV/60^{o} tilt. At 60^{o} tilt energy split of 3keV, 6keV and 12keV were done. As$_4$ implants at 2.5E14/cm^2 dose (1E15/cm^2 equivalent) were done at 12keV/0^{o} tilt, 12.4keV/15^{o} tilt, 13.9keV/30^{o} tilt, 17keV/45^{o} tilt and 24keV/60^{o} tilt. At 60^{o} tilt energy split at 12keV, 24keV and 48keV were done. All the wafers were MSA at Dai Nippon Screen using their FLA system with a 450^{o}C preheat temperature and 30J Flash power. 4PP was used to measure sheet resistance (Rs) and thermal-wave (TW) monitoring of the implant. PCOR-SIMS^{SM} analysis was used to determine junction depth and also dopant retained chemical dose for the various implant energies and tilt angles as reported below in Tables I & II. Dopant electrical activation level Bss (boron solid solubility) was determined by plotting 4PP sheet resistance (Rs) versus SIMS junction depth (Xj).

Table I: p-type dopant implant matrix

P-Type	Substrate No.	Ion	Energy [keV]	Dose [/cm2]	Tilt [deg]	Twist [deg]	RS		TW		as I/I SIMS (Xj) A	after anneal SIMS (Xj) A
							(Ω/sq)	%STD	TW units	%STD		
B18-Tilt Depend	slot1	B18	8.0	5.50E+13	0	0	1007.00	2.759	205.23	2.170	110	100
	slot2		8.0		15		1027.40	2.652	203.97	2.210		
	slot3		9.0		30		1014.40	2.739	224.16	2.420		125
	slot4		11.0		45		1026.40	2.816	255.79	2.310		140
	slot5		16.0		60		1038.00	2.873	355.94	2.050	175	165
BF2-Tilt Depend	slot6	BF2	2.00	1.00E+15	0	0	2233.50	1.820	537.41	0.900	130	120
	slot7		2.00		15		2439.20	1.831	532.75	0.970		
	slot8		2.00		30		2535.40	1.719	530.15	1.020		
	slot9		3.00		45		1928.10	1.635	568.92	0.680		
	slot10		4.00		60		1766.80	1.460	581.78	0.480	175	165
(B-Tilt Depend)	slot11	B	0.50	1.00E+15	0	0	2035.00	2.515	597.82	1.200	175	205
	slot12		0.52		15		1983.00	3.104	594.29	1.110		
	slot13		0.58		30		2027.00	2.580	617.06	0.720		
	slot14		0.71		45		2007.00	2.468	629.77	0.420	235	255
	slot15		1.00		60							
B18 Energy Depend	slot16	B18	8.0	5.50E+13	60	0	1688.80	2.693	183.59	1.910		70
	slot17		16.0				1045.00	2.917	353.95	2.050		165
	slot18		32.0				658.33	4.105	582.90	0.390		285
BF2 Energy Depend	slot19	BF2	2.0	1.00E+15	60	0	3995.00	1.409	436.46	2.230		90
	slot20		4.0				1668.90	1.671	579.73	0.490		165
	slot21		8.0				750.80	0.948	582.16	0.410		250

Table II: n-type dopant implant matrix.

N-Type	Substrate No.	Ion	Energy [keV]	Dose [/cm2]	Tilt [deg]	Twist [deg]	RS		TW		as I/I SIMS (Xj) A	after anneal SIMS (Xj) A
							(Ω/sq)	%STD	TW units	%STD		
As4-Tilt Depend	slot1	As4	12.0	2.50E+14	0	0	460.12	0.830	463.03	1.010		145
	slot2		12.0		15		477.49	0.775	425.03	0.970		
	slot3		16.0		30		434.95	0.555	515.62	0.740		
	slot4		16.0		45		546.41	0.548	482.07	0.920		
	slot5		24.0		60		666.70	0.479	538.06	0.620		145
As-Ion Deference	slot6	As	3.0	1E15	0	0	511.06	0.582	500.54	0.940		145
	slot7		3.0		15		524.65	0.608	478.78	1.020		
	slot8		4.0		30		448.34	0.283	559.83	0.740		
	slot9		4.0		45		538.99	0.604	541.19	0.850		
	slot10		6.0		60		701.99	0.456	567.50	0.690		145
As4 Energy Depend	slot11	As4	12	2.50E+14	60	0	1014.00	0.877	364.83	0.680		
	slot12		24				660.90	0.437	542.38	0.620		145
	slot13		48				464.70	0.387	617.01	0.380		
As Energy Depend	slot14	As	3.0	1.00E+15	60	0	1102.30	0.957	453.34	1.260		
	slot15		6.0				711.22	0.410	569.29	0.590		145
	slot16		12.0				323.42	0.330	656.83	0.360		

RESULTS

P-TYPE DOPANT RESULTS

Results from the SIMS analysis are shown in Figs. 3-10 below. Fig. 3 shows the as implanted SIMS B profiles before Flash annealing for B, BF_2 and $B_{18}H_{22}$ at 0^o, 45^o and 60^o tilt angle. Significant channeling can be seen with monomer B at both 0^o and 45^o tilt. At 0^o tilt BF_2 shows less channeling and $B_{18}H_{22}$ shows the least amount but at 60^o tilt both BF_2 and $B_{18}H_{22}$ profiles are identical. Fig. 4 shows the SIMS profiles after Flash annealing , monomer B shows about +2.5nm of diffusion while both BF_2 and $B_{18}H_{22}$ shows about -1.0nm of diffusion (surface out diffusion). Also of note is the double hump peak for the BF_2 and monomer B dopant species. Usually this hump in the B profile is caused by B pile-up at the implant end-of-range damage (EOR). The double hump peak can be seen more clearly in Fig. 5 showing SIMS B profiles for BF_2 dopant species at 60^o tilt from 2keV to 8keV implant energies after Flash anneal. Fig. 6 shows SIMS B profile for $B_{18}H_{22}$ at 0^o, 30^o, 45^o & 60^o tilt after Flash anneal and Fig. 7 shows SIMS B profiles for $B_{18}H_{22}$ dopant species at 60^o tilt from 8keV to 32keV implant energies after Flash anneal. The plot of Rs versus Xj is shown in Fig.8 for monomer B at 45^o tilt angle and for BF_2 & $B_{18}H_{22}$ at 60^o tilt angle. Note that the electrical dopant activation level due to boron solid solubility (Bss) limit in silicon for monomer B is $3E19/cm^3$ at 45^o tilt and $3.2E19/cm^3$ at 0^o tilt. For BF_2 Bss at 60^o tilt varies from 4-$7E19/cm^3$ dependent on junction depth and $4E19/cm^3$ at 0^o tilt. For $B_{18}H_{22}$ Bss at 60^o tilt varies from $1.1E20/cm^3$ at 7nm to $7E19/cm^3$ at 26nm and at 0^o tilt is up to $1.3E20/cm^3$. Fig.9 shows the SIMS retained dose comparison for BF_2 & $B_{18}H_{22}$ at 60^o tilt and for monomer B at 45^o tilt. The calculated Bss versus junction depth is shown in Fig.10. Fig.11 shows the retained dose for tilt angle variation from 0^o up to 60^o tilt. The calculated Bss versus tilt angle is shown in Fig.12. The 60^o tilt 8keV $B_{18}H_{22}$ SIMS profile in Fig. 7 is what can be expected on the vertical side wall of the Fin structure with an Xj=7.0nm, retained dose of $5.3E14/cm^2$ (Fig.8), Rs=1688 and Bss=$1.1E20/cm^3$ (Fig.9) while the 30^o tilt 9keV $B_{18}H_{22}$ SIMS profile in Fig.6 would be the expected profile for the Fin top with an Xj=12.5nm, retained dose of $8.5E14/cm^2$ (Fig.10), Rs=1014 and Bss=$1.0E20/cm^3$ (Fig.11). Fig. 12 shows the Rs versus Xj data comparing B at 45^o tilt to BF_2 and $B_{18}H_{22}$ at 60^o tilt showing the advantage of using $B_{18}H_{22}$ to achieve highest dopant activation. The enhanced dopant activation effect of using $B_{18}H_{22}$ for p+ USJ, Bss>$1E20/cm^3$ without end of range damage and defects is shown in Figs. 9 & 11. A shallower implant at 30^o and 60^o tilt angle would further increase Bss from $7E19/cm^3$ to >$1E20/cm^3$.

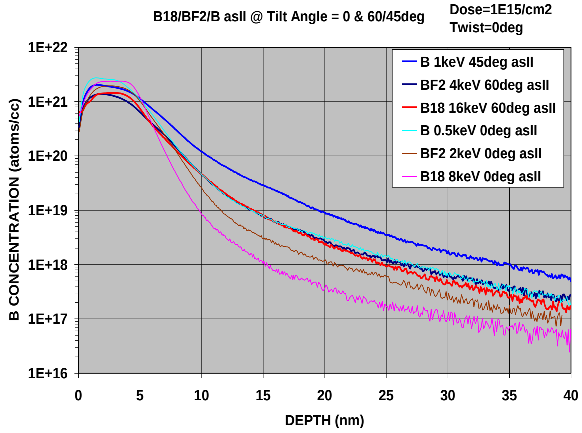

Fig.3: 0^o to 60^o B implant profiles before anneal.

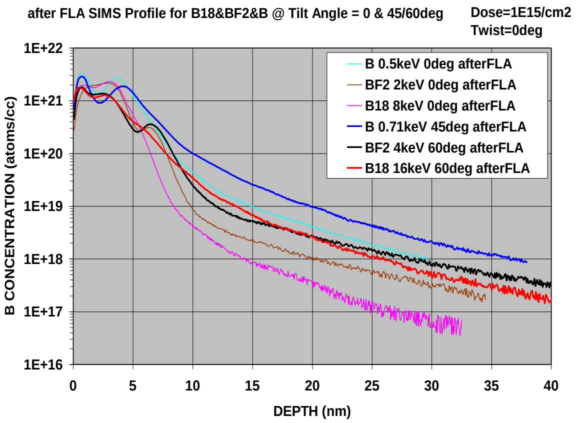

Fig.4: 0^o to 60^o B profiles after Flash anneal.

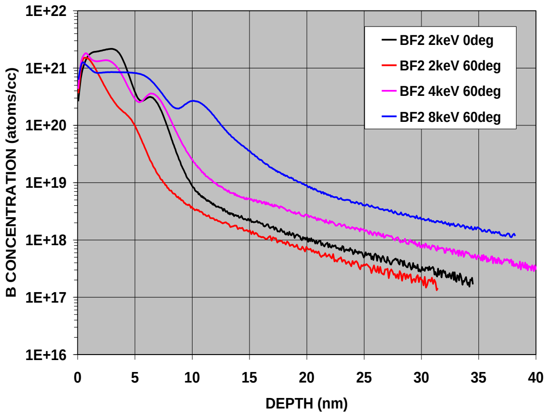

Fig.5: BF_2 0^o & 60^o tilt after Flash anneal.

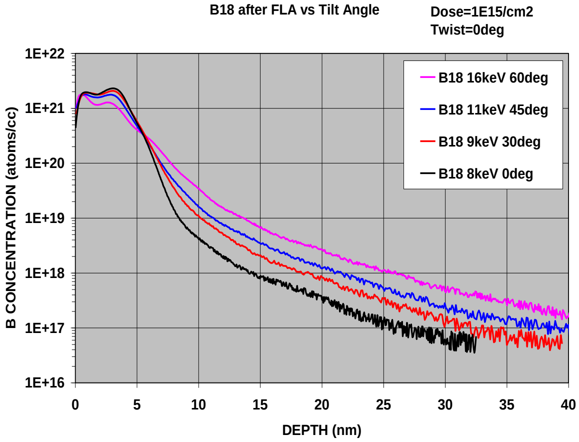

Fig.6: $B_{18}H_{22}$ at 0^o, 30^o, 45^o & 60^o tilt angle.

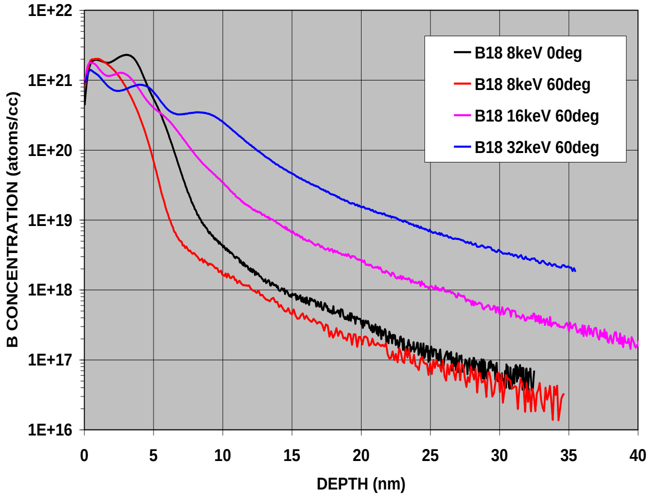

Fig.7: $B_{18}H_{22}$ at 0^{o} & 60^{o} tilt after Flash anneal.

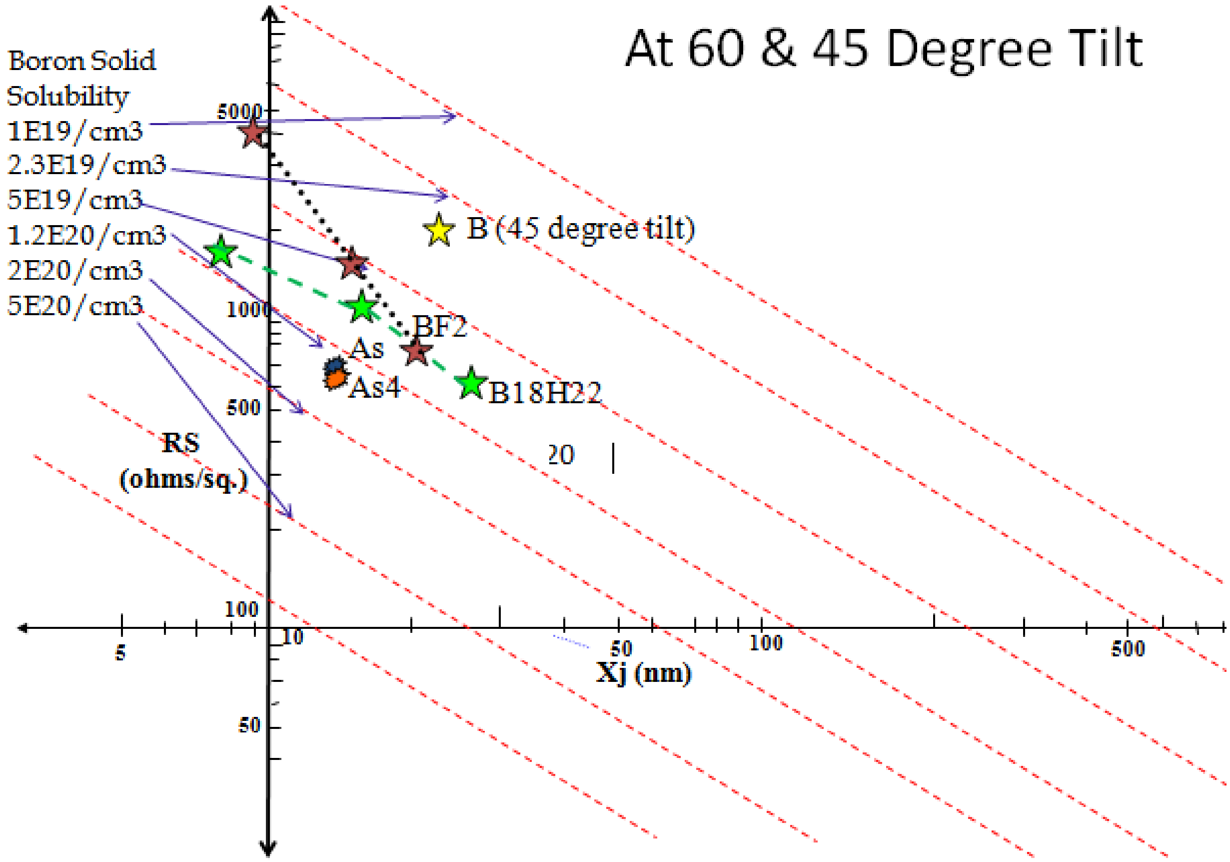

Fig.8: Rs versus Xj plot showing estimated dopant activation Bss values.

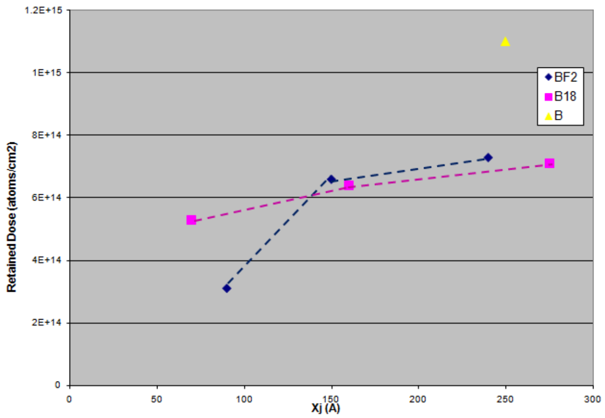

Fig.9: SIMS retained dose for 60° tilt implant.

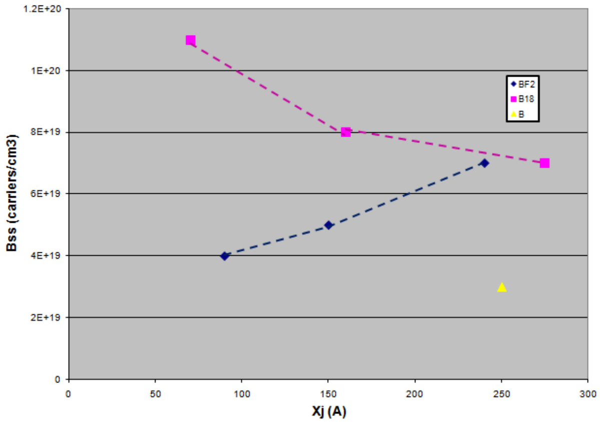

Fig.10: Bss at 60° tilt versus Xj.

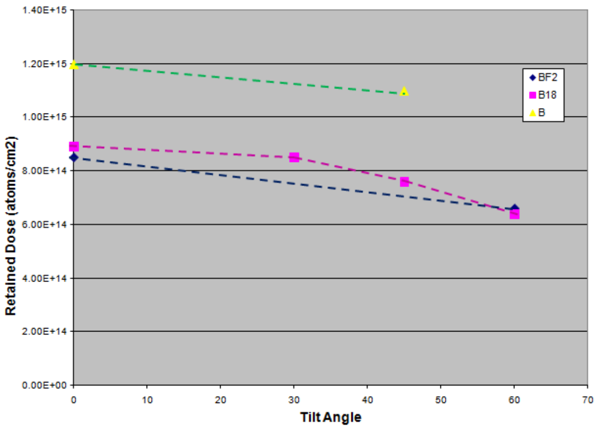

Fig. 11: SIMS retained dose from Figs. 4 & 6 and Table I

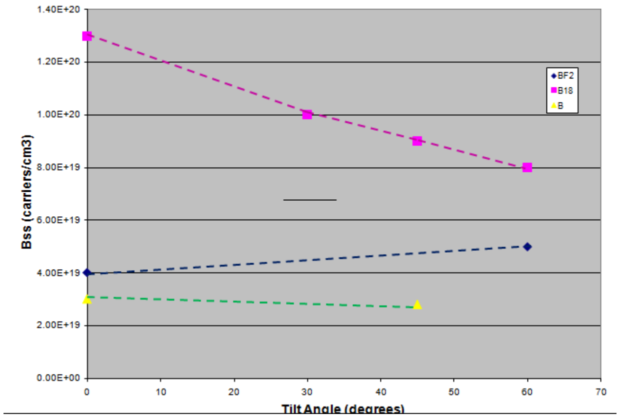

Fig.12: Bss from Fig. 8 and Table I.

N-TYPE DOPANT RESULTS

Results from SIMS profiles are shown in Fig. 13 for monomer arsenic (As) and As_4 at 0° and 60° tilt. The dopant profile comparison between As and As_4 are very similar as shown in Fig.13 so the self-amorphization effects of using As is very good and no signification benefit in using As4 in reducing channeling though at the high tilt the tail of As is slightly deeper than As_4. Fig. 14 shows Rs versus tilt angle while Fig. 15 shows Rs versus implant energy at 60° tilt as well as retained dose at 6keV. We observed that the Rs value of using As_4 was about 7.5% better.

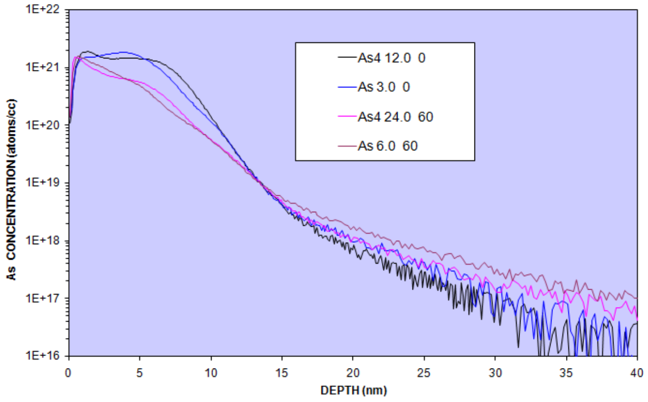

Fig.13: As SIMS profiles for As and As_4.

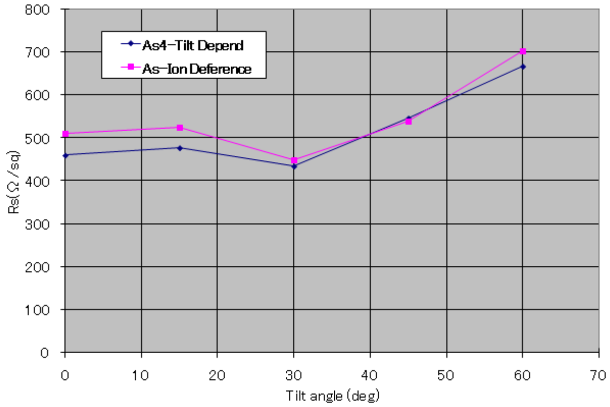

Fig.14: Rs versus tilt angle from Table II.

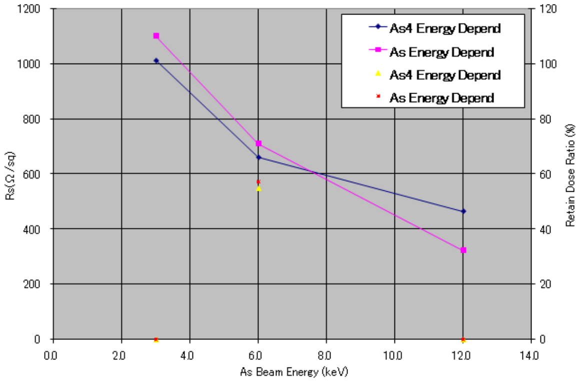

Fig. 15: From Table II at 60^o tilt implant.

SUMMARY

Using $B_{18}H_{22}$ molecular dopant is attractive to extend beam-line implantation to FinFET devices at high tilt angle. We observed enhanced dopant activation effects with $B_{18}H_{22}$ when using msec annealing by 3x up to >1E20/cm^3 compared to <4E19/cm^3 for B and BF_2 for improved activated conformal doping at both 30^o and 60^o tilt angle for Fin top and side wall. With As_4 we observed a 7.5% improvement in Rs. Therefore retained chemical dose is not as critical as enhanced dopant activation due to dopant solid solubility limit with msec annealing.

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