Activation of low-dose Si^+ implant into $In_{0.53}Ga_{0.47}As$ with Al^+ and P^+ co-implants

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***Abstract*— To test if Si^+ activation could be improved through forced site selection, co-implantation of varying doses of Al^+ and P^+ with a fixed Si dose into $In_{0.53}Ga_{0.47}As$ has been studied. P^+ implants are shown to have limited effectiveness in raising overall n-type activation of Si^+ implants while Al-co-implantation is shown to dramatically lower overall n-type activation with increasing Al dose. Implant damage from the co-implant species is thought to be one possible reason for the limited effectiveness P co-implantation has on raising the maximum electrical activation of Si implants. The results suggest that co-implantation has a dramatic, but complicated, effect on activation.**

Keywords—Ion Implantation; Co-Implantation; InGaAs;

There is a renewed interest in using III-V materials such as $In_xGa_{1-x}As$ future CMOS generations due to their high electron mobility but one problem facing the adoption of III-V materials for n-channel devices is the low doping concentrations that can be achieved in source drain regions relative to Si [1]. N-type doping concentrations on the order of $0.8\text{-}1.2\times10^{19}$ cm^{-3} are regularly reported for Si implants into $In_{0.53}Ga_{0.47}As$, but epitaxial growth methods regularly report Si concentrations higher than what has been achieved from ion implantation [2-8]. Previous authors have hypothesized that the amphoteric nature of silicon leads to high levels of self-compensation from acceptor and donor creation as well as the formation of next nearest neighbor neutral pairs in III-V materials that are heavily doped [9,10]. In order to combat Si self compensation it has been further hypothesized that the introduction of excess group V species through ion implantation would help maintain stoichiometry of the implanted material by consuming group V vacancies which would further promote Si occupation of group III sites upon implant activation [11].

20 keV, 6×10^{13} cm^{-2} Si implants performed at 100°C into 300 nm of MOCVD $In_{0.53}Ga_{0.47}As$ on InP were used to study the effect of group III and V co-implants on Si activation. 20 keV Al and P co-implants with doses ranging from 3×10^{13} cm^{-2} to 6×10^{14} cm^{-2} were also implanted at 100°C. Al and P were chosen for this study since the chemical effect of a group III and group V could be compared directly and the low mass of Al and P relative to other group III and V species such as Ga and As should reduce implant damage that has been shown to be p-type [12]. The implanted samples were then coated with 15nm of ALD Al_2O_3 deposited at 250°C to protect against surface roughening during the subsequent 750°C 5s RTA used to activate the implanted dopants. The dielectric cap was removed with buffered oxide etch after activation annealing and van der Pauw Hall effect was used to measure the active sheet number, mobility and sheet resistance.

Cross-sectional TEM (XTEM) was performed on the samples receiving the highest 6×10^{14} cm^{-2} co-implant doses of Al^+ and P^+ in conjunction with the 6×10^{13} cm^{-2} Si^+ implant. No amorphous layer was observed for the highest co-implant dose samples indicating that all the implant conditions in this study are non-amorphizing. Fig. 1 show results of the electrical activation for the varying dose P^+ and Al^+ co-implants in conjunction with the 20 keV, 6×10^{13} cm^{-2} Si^+ implant after a 750°C 5s RTA. P is observed to have no significant effect on increasing activation of the Si implants for P^+ doses up to 1×10^{14} cm^{-2} but co-implant doses over 1×10^{14} cm^{-2} result in reduced activation with the highest dose P implant in this study showing a large reduction in activation relative to the lowest P co-implant dose.

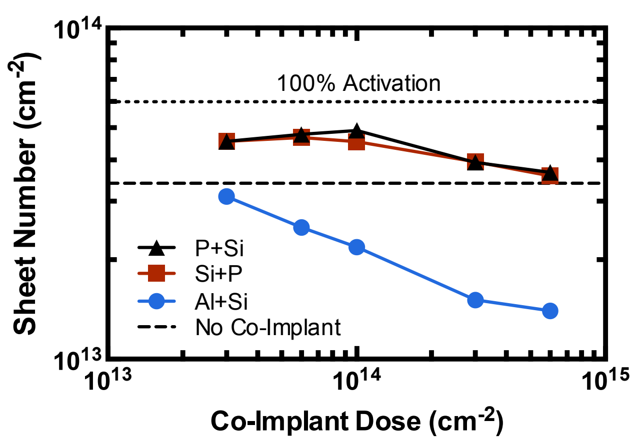

Fig. 1. Sheet number after 750°C 5s RTA for 20 keV, 6×10^{13} cm^{-2} Si and Al^+ and P^+ co-implant implanted at 100°C as function of Al^+ and P^+ co-implant dose.

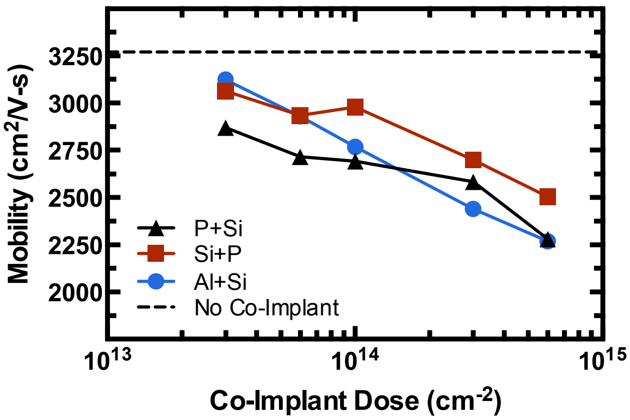

Fig. 2. Mobility after 750°C 5s RTA for a 20 keV, 6×10^{13} cm^{-2} Al^+ and P^+ or P co-implant implanted at 100°C as function of Al^+ and P^+ co-implant dose.

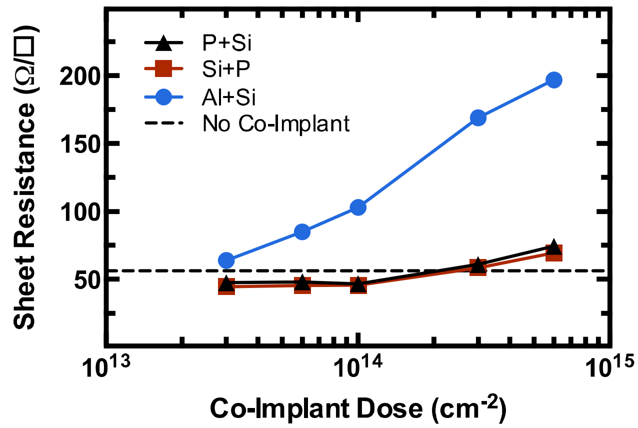

Fig. 3. Sheet resistance after a 750°C 5s RTA for a 20 keV, 6×10^{13} cm^{-2} Si and Al^+ and P^+ co-implant implanted at 100°C as a function of Al^+ and P^+ co-implant dose.

The effect of implant order was also studied and shown in Fig. 1 to have no effect on the overall activation of Si implants in $In_{0.53}Ga_{0.47}As$ for a given P dose. The results of the aluminum co-implant are also shown in Fig. 1 and the activation of Al co-implanted samples is observed to continually decrease with increasing Al dose. Reduced electrical activation in the case of Al co-implants is consistent with a reduction of electron donors formed by Si atoms on group III sites as a result of implanted Al occupying group III vacancies, but the results from the high dose P co-implants in this work and others suggest that implant damage is compensating as well indicating that the reduction in electrical activation may be due in part to a damage effect and not from a chemical effect alone [12]. For both the Al and P co-implants the mobility shown in Fig. 2 was observed to decrease with increasing co-implant dose and the sheet resistance shown in Fig. 3 show the expected inverse relationship to sheet number.

The results of co-implantation of Si with a group III or V species have not been previously reported in InGaAs but previous studies of co-implants of P and As with Si in GaAs have showed conflicting results with some authors reporting observed increases in activation while others reported no increase in activation [13,14]. Maximum doping that is limited below 100% activation by either self-compensation from Si-Si next nearest neighbor pairs or Si_{III} donor and Si_V acceptor compensation seems unlikely to be the reason for the observed activation limit of Si as co-implantation of P and Al should greatly reduce the probability of these compensation mechanisms given the co-implant doses are up to an order of magnitude greater than those of the implanted Si dose. The results of this work indicate that n-type doping with Si and a group V co-implant tends to saturate to a maximum sheet number below 100 percent activation of $\approx 4.5\times10^{13}$cm^{-2} for the conditions studied until the co-implant dose exceeds the implanted Si dose. The reduction in activation from large P co-implant doses is hypothesized to be a consequence of implant damage occurring from the large P co-implant dose relative to the implanted Si dose.

In conclusion, the results presented herein do not rule out the possibility of a co-implant effect due to a lack of any direct evidence of modification Si site location with co-implant species, but the results do indicate that co-implantation of group III and V species is not likely to be a successful route to achieving 100 percent activation of low dose Si implants in $In_{0.53}Ga_{0.47}As$. There is a dramatic effect of the co-implant species on Si activation but the reason for this difference is not well understood but the introduction of implant damage that has previously been reported to be compensating in III-V materials is likely one limit to the effectiveness of co-implantation for enhanced n-type doping.

References

[1] J.A. del Alamo, Nature **479**, 317 (2011)

[2] A. Alian, G. Brammertz, N. Waldron, C. Merckling, G. Hellings, H.C. Lin, W.E. Wang, M. Meuris, E. Simoen, K. De Meyer, and M. Heyns, Microelectronic Engineering **88**, 155 (2011

[3] T. Penna, B. Tell, A.S.H. Liao, T.J. Bridges, and G. Burkhardt, J. Appl. Phys. **57**, 351 (1985).

[4] M.V. Rao, S.M. Gulwadi, P.E. Thompson, A. Fathimulla, and O.A. Aina, Journal of Electronic Materials **18**, 131 (1989).

[5] A.N.M.M. Choudhury, Appl. Phys. Lett. **40**, 607 (1982).

[6] Y. Fedoryshyn, M. Beck, P. Kaspar, and H. Jaeckel, J. Appl. Phys. **107**, 093710 (2010)

[7] T. Fujii, T. Inata, K. Ishii, and S. Hiyamizu, Electronics Letters **22**, 191 (1986).

[8] R.A. Kubiak, J.J. Harris, and P. Dawson, J. Appl. Phys. **55**, 598 (1984).

[9] R.S. Bhattacharya, Appl. Phys. Lett. **40**, 890 (1982).

[10] J. Wagner, H. Seelewind, and W. Jantz, J. Appl. Phys. **67**, 1779 (1990).

[11] R. Heckingbottom and T. Ambridge, Radiation Effects **17**, 31 (1973).

[12] A.J. Moll, K.M. Yu, W. Walukiewicz, W.L. Hansen, and E.E. Haller, Appl. Phys. Lett. **60**, 2383 (1992).

[13] E.B. Stoneham, G.A. Patterson, and J.M. Gladstone, Journal of Electronic Materials **9**, 371 (1980).

[14] T.C. Banwell, M. Mäenpää, M.A. Nicolet, and J.L. Tandon, Journal of Physics and Chemistry of Solids **44**, 507 (1983)