Activation and defect dissolution of non-amorphizing, elevated temperature Si^+ implants into $In_{0.53}Ga_{0.47}As$

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***Abstract*— A range of implant temperatures from 20 to 300C are studied for fixed 20 keV implant energy and 6E14 cm^{-2} dose Si implants into $In_{0.53}Ga_{0.47}As$. Hall effect measurements performed on the samples after rapid thermal annealing reveal that Si implant activation is actually maximized for intermediate implant temperatures from 50-110C that are shown to be non-amorphizing. While these results echo the conclusion of previous studies that elevated temperature Si implants into $In_{0.53}Ga_{0.47}As$ show increased activation over implants that are likely amorphizing, it is clear that there is a temperature window from 50-110C where activation is improved with increasing thermal budget for the dose and energy studied. Calculated Si solubilities of up to 1.3E19 cm^{-3} and sheet resistances as low as 26 ohm/sq are achieved for a 10 keV 5E14 cm^{-2} Si implant performed at 80C after 750C 5s annealing.**

Keywords—Ion-Implantation; InGaAs; Defects; Diffusion;

The high mobility of III-V materials makes them attractive for future device generations, the low dopant solubility of III-V's compared to Si has proven to be problematic for achieving the low resistance source/drain regions required for scaling [1]. Most previous reports of Si implants in $In_{0.53}Ga_{0.47}As$ and GaAs indicate that elevated implant temperatures can effectively increase the dopant activation but these studies generally compare only a room temperature implant that is likely amorphizing with elevated temperature implants that are non-amorphizing and lack significant microstructure characterization [2-4]. Recent reports on intermediate temperature implants into $In_{0.53}Ga_{047}As$ have shown improved activation after a single annealing treatment for implants performed at 80°C such that amorphization is avoided but non-amorphous damage as measured by RBS/C was maximized [5].

In order to observe a larger range of intermediate temperature implants from 50-110°C as well as the onset of the enhanced activation for implants in this range, 300 nm of MOCVD grown $In_{0.53}Ga_{0.47}As$ on InP was implanted with a 20 keV, 6×10^{14} cm^{-2} Si^+ dose at a range of temperatures from 20-300°C. After implantation, the samples were coated with 15 nm of ALD Al_2O_3 encapsulant before the subsequent anneal treatments. The samples were then repeatedly annealed in 50°C increments for 5s from 450°C to 750°C with van der Pauw Hall effect measurements being performed after each 50°C increment. Ohmic contacts on the Hall effect samples were formed with indium metal placed on un-encapsulated corners of the samples. A second set of $In_{0.53}Ga_{0.47}As$ samples used to study the effect of annealing time on non-amorphizing intermediate temperature implants were implanted at 10 keV, 5×10^{14} cm^{-2} Si^+ dose at 80°C. Hall effect measurements and encapsulation for the second set of samples was performed in an identical manner to the first.

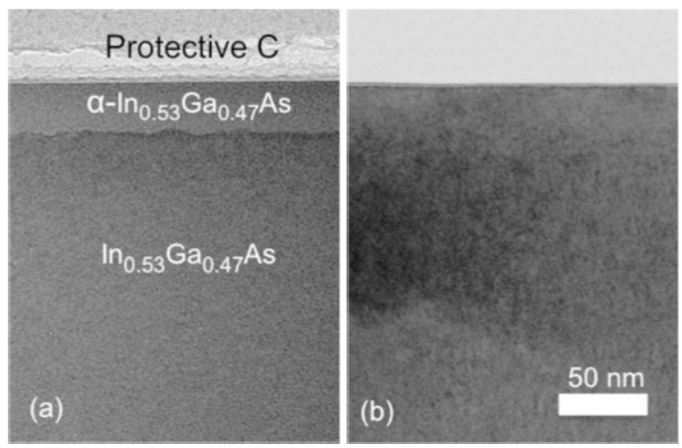

Fig. 1. Post implant XTEM of a) 20 keV, 6×10^{14} cm^{-2} Si^+ implant performed at 20°C and b) 20 keV, 6×10^{14} cm^{-2} Si^+ implant performed at 50°C into $In_{0.53}Ga_{0.47}As$.

Fig. 1 shows cross-sectional TEM of the post-implant microstructure of the 20 keV, 6×10^{14} cm^{-2} Si^+ after implantation at 20°C and 50°C. It is apparent that an implantation temperature of 50°C is sufficient to avoid the formation of an amorphous layer in the $In_{0.53}Ga_{0.47}As$ for the Si dose and energy used indicating that all implants performed above 50°C will be non-amorphizing for the 20 keV, 6×10^{14} cm^{-2} Si^+ implant.

Measurements of the activation as a function of annealing temperature for implants performed at 20°C, 80°C and 300°C are shown in Fig. 2. Implants performed at 80°C exhibit slightly higher activation than implants performed at 20°C or 300°C over the beginning of the annealing range from 450-550°C however, once the annealing temperature has risen to 600°C there is little variation in the overall activation of each sample until annealing at 700°C-750°C where the activation of the 80°C implant temperature over the 20°C and 300°C implant is apparent. The measured sheet number after the final 5s annealing step at 750°C as a function of implant temperature for the 20 keV, 6×10^{14} cm^{-2} Si^{+} implant is shown in Fig. 3. It is observed that elevated implant temperatures from 50-110°C result in significantly higher activation than implants performed above or outside this window. The variable annealing and implant temperature results in Fig. 2 and Fig. 3 respectively indicate that annealing temperatures of 700°C or higher are necessary for Si implants into $In_{0.53}Ga_{0.47}As$ performed in the 50-110°C range to show the significant enhancement in activation relative to implants performed outside the 50-110°C Si implantation range.

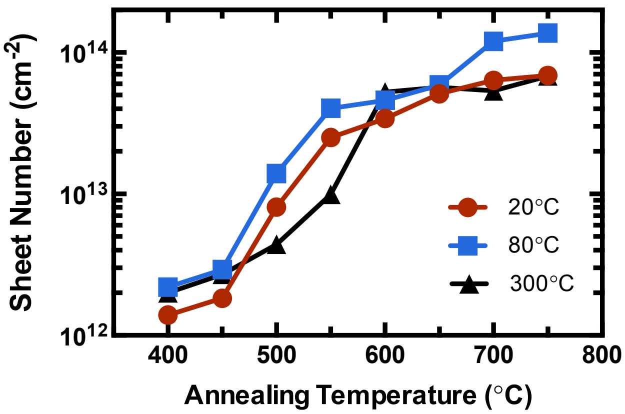

Fig. 2. Sheet number for 20 keV, 6×10^{14} cm^{-2} Si^{+} implant into $In_{0.53}Ga_{0.47}As$ performed at 20°C, 80°C, and 300°C as a function of annealing temperature for a 5s RTA

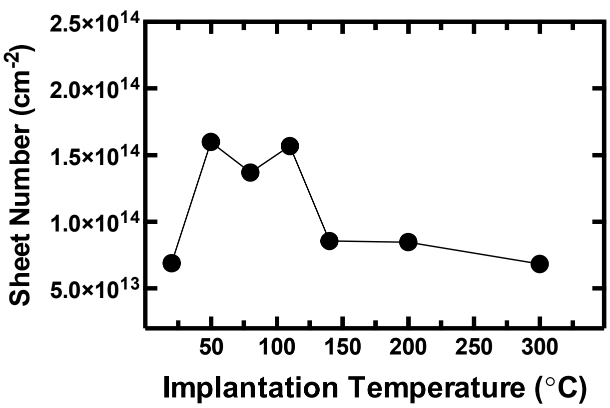

Fig. 3. Sheet number for 20 keV, 6×10^{14} cm^{-2} Si^{+} implant into $In_{0.53}Ga_{0.47}As$ as a function of implantation temperature and after 5s RTA from 450 to 750°C in 50°C increments.

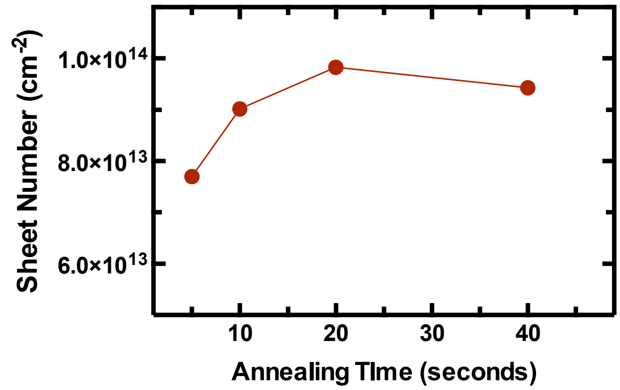

Fig. 4. Sheet number for 10 keV, 5×10^{14} cm^{-2} Si^{+} implant into $In_{0.53}Ga_{0.47}As$ perfomed at 80°C as a function of annealing time for a 750°C RTA

A second experiment was performed using a 10 keV, 5×10^{14} cm^{-2} Si^{+} implant performed at 80°C to determine if longer annealing times at 750°C would further maximize Si activation in $In_{0.53}Ga_{0.47}As$. Anneals ranging from 5 to 40s were performed at 750°C. Electrical activation results shown in Fig. 4 indicate that active sheet number is maximized for anneals of 20s or more. Fig. 5 shows XTEM of the post-anneal microstructure after a 5, 10, 20 and 40s RTA. A band of sub 5 nm loop-type defects observed to be ≈30 nm below the surface are readily apparent for the 5s anneal, consistent with previous reports, but anneals of 10s or more shows no evidence of loops after annealing indicating that the sub threshold loops are not stable for extended annealing times at 750°C for the implant conditions studied [5-6].

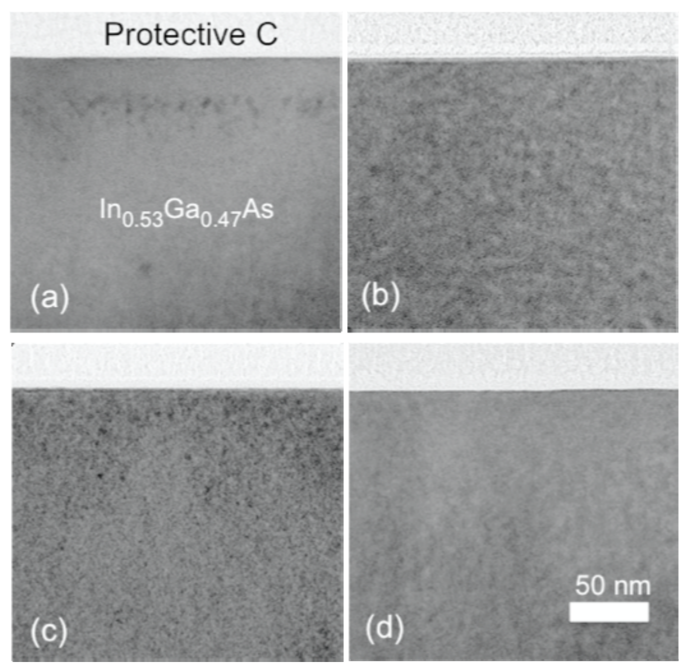

Fig. 5. XTEM micrograph of a 10 keV, 5×10^{14} cm^{-2} Si^{+} implant into $In_{0.53}Ga_{0.47}As$ perfomed at 80°C after a) 5s, b) 10s, c) 20s and d) 40s RTA performed at 750°C

SIMS measurements of the post anneal Si implants shown in Fig. 6 were used to estimate the Si solubility based on the measured sheet number using the method described in previous reports [7]. The Si solubility for was calculated to be $1.2\times10^{19}cm^{-3}$ and $1.3\times10^{19}cm^{-3}$ for the 5s and 40s anneals respectively. While previous reports have generally concluded that Si diffusion in $In_{0.53}Ga_{0.47}As$ is minimal, the results presented in this work indicate significant Si diffusion is occurring for the implant and annealing conditions studied [6,8].

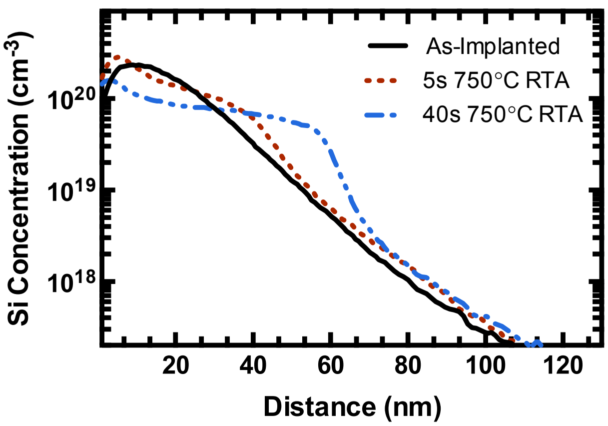

Fig. 6. SIMS of Si concentration profiles for 10 keV, $5\times10^{14}\,cm^{-2}\,Si^{+}$ implant into $In_{0.53}Ga_{0.47}As$ after implantation, and post-anneal for a 5 and 40s RTA at 750°C.

In conclusion, it has been shown that non-amorphizing, intermediate temperature implants show higher activation relative to implants performed outside the window of 50-110°C but annealing temperatures of at least 700°C are required for this effect to be seen. Loop-type defects formed during annealing after a non-amorphizing implants are shown to be unstable for anneals of 10s or more and post anneal SIMS indicate that Si diffusion is occurring for the implant and annealing conditions studied in contrast to previous reports which generally show limited Si diffusion in $In_{0.53}Ga_{0.47}As$.

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