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Strain compensation in boron-indium coimplanted laser thermal processed silicon

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Strain in B-implanted laser thermal processed (LTP) silicon is reduced by coimplantation of In. Strain in the codoped layer is calculated using lattice constants measured by high-resolution x-ray diffraction. Compensation of the strain with increasing In dose corresponds to suppression of the carrier deactivation during post-LTP annealing. © *2005 American Institute of Physics*.
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I. INTRODUCTION

Since the invention of light amplification by stimulated emission of radiation or LASER in 1960, lasers have been used in a variety of ways to process semiconductors. As early as 1968, lasers were used to modify the electrical resistivity of semiconductors.[1] By 1976 lasers were being used to remove lattice damage caused by ion implantation and to electrically activate dopants in a process termed laser annealing.[2] In 1978, recrystallization of an amorphous silicon film was achieved by irradiation with a single laser pulse.[3,4] More recently lasers have been used to melt doped amorphous layers to define the depth of electrically active junctions.[5] The process of laser irradiating a doped amorphous layer to achieve full melt and subsequent epitaxial regrowth resulting in the depth of the electrical junction being defined by the original amorphous layer thickness is termed laser thermal processing (LTP). LTP offers the ability to achieve junctions that are ultrashallow, hyperabrupt, and highly activated.[6,7] LTP can activate dopant species, such as boron (B), to concentrations in excess of equilibrium solid solubility.[5] However, the supersaturated solid solution is metastable and can deactivate during post-LTP annealing.[8,9] One factor affecting the deactivation kinetics may be the lattice contraction associated with the incorporation of B, which introduces a biaxial tensile strain in the doped layer.[10] Reduction of the net strain may be achieved by the incorporation of a dopant species that causes the lattice to expand, producing a compressive strain that is opposite to that introduced by B. A candidate for introducing a compressive strain to the Si lattice is In, which based upon covalent bond radius produces a lattice expansion comparable in magnitude to that of the lattice contraction introduced by B.[11] Hence, coimplantation of B and In may produce compensating strains that reduce the deactivation occurring during post-LTP annealing. In this letter the effect of In coimplantation on B ultrashallow junction formation following post-LTP annealing is investigated.

II. EXPERIMENTAL SETUP

Czochralski grown Si (100) wafers of *n* type are implanted with 15-keV Si^+ ions to a dose of 1×10^{15} ions/cm^2 to form an amorphous Si surface layer approximately 35 nm in depth. The amorphous layer is implanted with 1-keV B^+ ions to a dose of 3×10^{15} ions/cm^2. In addition, In^+ ions are coimplanted at 5 keV to doses of 0×10^0(control), 1×10^{14}, and 5×10^{14} ions/cm^2. Doses of In coimplants are purposely low to reduce dose effects on the laser interaction with the sample.[9,12] LTP is performed using a 308-nm wavelength XeCl excimer irradiation source with a pulse duration of 18 ns and an exposure area of 5×5 mm^2. Laser energy densities are varied from 0.66 to 0.74 J/cm^2, in increments of 0.04 J/cm^2. The exposed area is cropped to 4×4 mm^2 by dicing off the exposure edges. Cropping reduces the measurement error associated with nonuniformity of laser at the exposure edges. After LTP, samples are subjected to conventional rapid thermal anneals (RTAs) at a temperature of 900 °C for durations ranging from 1 to 600 s in an ambient of nitrogen.

III. RESULTS AND DISCUSSION

The dose of the In coimplant does not significantly alter the sheet resistance measured after LTP. Values are reported for samples irradiated with a laser energy density of 0.74 J/cm^2. The sheet resistance for each sample is measured by four-point probe. The sheet resistance values are plotted in Fig. 1 as filled circles. For all doses of coimplanted In, including the control, the measured sheet resistance values are approximately 120 Ω/sq.

Subsequent annealing of the LTP samples increases the sheet resistance of the doped layers. Figure 2 is a plot of the sheet resistance measured by four-point probe as a function of the post-LTP annealing time at 900 °C. For all doses of coimplanted In the sheet resistance increases as a function of annealing time. The rise in the sheet resistance during the post-LTP anneal is suppressed with increasing dose of coimplanted In. At the final annealing time of 600 s, the sheet resistance for the sample coimplanted with a 5×10^{14} ions/cm^2 dose of In results in a sheet resistance of approximately 365 Ω/sq. In contrast, the sheet resistance for the control that is not coimplanted with In is approximately 477 Ω/sq. Hence, coimplantation of In suppresses the rise in sheet resistance by approximately 23%.

The suppression of the sheet resistance correlates to a reduction in the deactivation of the carrier population and

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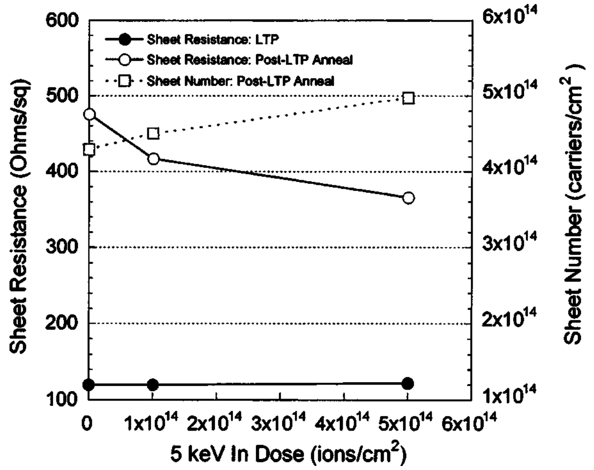

FIG. 1. Sheet resistance values measured by four-point probe and sheet number values measured by Hall effect as a function of In coimplant dose. The filled data points are measured after LTP at 0.76 J/cm^2 while the open data points are measured subsequent to the post-LTP anneal at 900 °C for 600 s.

improved mobility. Figure 1 is a plot of the sheet number measured by Hall effect (right ordinate) and sheet resistance measured by four-point probe (left ordinate) at the final post-LTP annealing time of 600 s as a function of In coimplant dose. The coimplantation of a 5×10^{14} ions/cm^2 dose of In results in a sheet number of approximately 5×10^{14} carriers/cm^2, which is 14% larger than value of 4.3×10^{14} carriers/cm^2 measured for the control without In. The mobility also increases with increasing In dose. Of the suppression in the sheet resistance, approximately 44% is accounted for by an improvement in the carrier mobility, the remaining 56% is due to a reduction in the carrier deactivation.

The reduction in the deactivation is not due to differences in B depth distributions. Figure 3 contains secondary-ion-mass spectroscopy (SIMS) depth profiles of the B implants (3×10^{15} ions/cm^2) measured after annealing at 900 °C for 600 s. The post-LTP anneal results in the diffusion of the implanted B. Diffusion is most significant below concentrations of approximately $5\times10^{19}/cm^3$. However, the

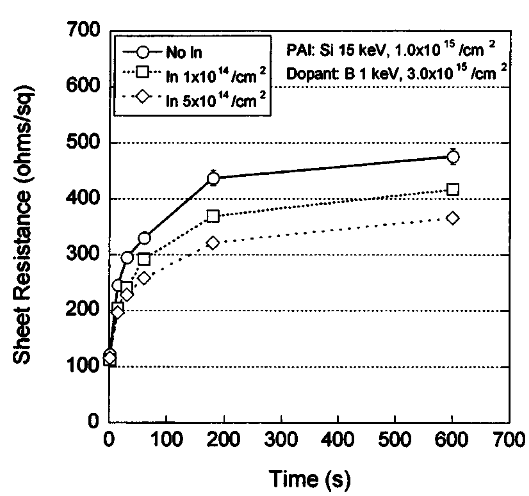

FIG. 2. Sheet resistance measured by four-point probe as a function of annealing time at 900 °C.

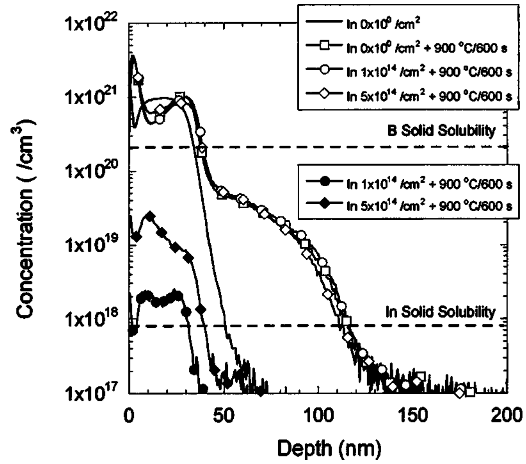

FIG. 3. SIMS depth profiles of B and In. The open markers indicate the boron depth profiles, while the filled markers indicate In.

B depth profiles are similar in both depth and shape for all samples, measured after the post-LTP anneal. Based on the similarity in the B depth profiles, the reduction in the deactivation associated with In does not appear to be the result of increased diffusion or subsequent junction depth.

Like B, In is a *p*-type dopant and when substitutional in the Si lattice may be ionized to become electrically active. Figure 3 contains SIMS depth profiles of In after the post-LTP anneal. Assuming that the In is completely substitutional and active, its contribution to the sheet number is estimated by integrating the depth profile. For the implant dose of 5×10^{14} ions/cm^2 the estimated sheet number is approximately 5.1×10^{13} carriers/cm^2, which accounts for only 76% of the difference in the sheet number measured for the equivalent In dose. Hence, assuming that all the In is electrically active does not completely account for the reduction in the deactivation. Furthermore, the assumption that In is completely substitutional is a gross overestimation considering that the maximum equilibrium solid solubility of In in Si is approximately $8\times10^{17}/cm^3$,[13] which is approximately two orders of magnitude lower than SIMS concentrations used to estimate the sheet number. Based on the equilibrium solid solubility of In in Si the actual contribution to the sheet number is considerably lower than that previously estimated. Hence, a contribution from electrically active In cannot entirely account for the reduced deactivation with increasing In coimplant dose.

Incorporation of dopants into a Si layer can contract or expand the lattice of the layer relative to the undoped Si substrate depending on the tetrahedral covalent bonding radius of the impurity. Figure 4 is a plot of the high-resolution x-ray diffraction (HR-XRD) rocking curves measured after LTP for layers coimplanted with B and In. Each rocking curve is measured with Cu $K\alpha1$ radiation around the (400) diffraction plane. The high intensity peak is (400) diffraction from the Si substrate. For all doses of coimplanted In, a satellite peak resulting from the doped layer is present at a higher differential diffraction angles. The higher angle indicates that the lattice constant of the doped layer is smaller than that of the substrate, and is therefore in tensile strain. With increasing dose of coimplanted In the satellite peak

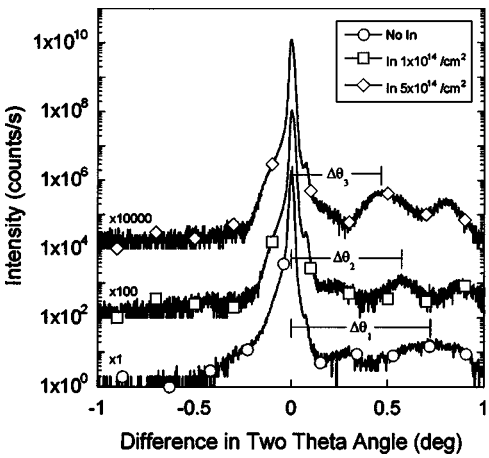

FIG. 4. HR-XRD rocking curve data measured after LTP as a function of In coimplant dose.

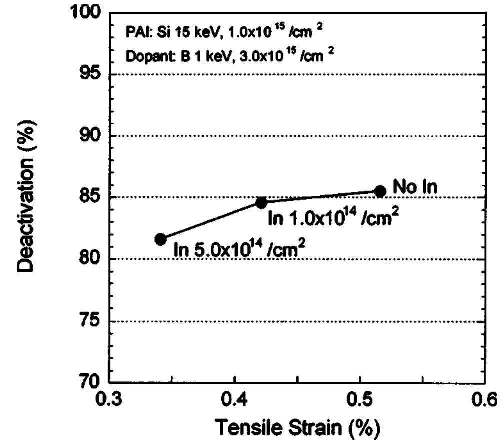

FIG. 5. Percent change in deactivation and strain as a function of In coimplant dose.

shifts back towards the substrate peak demonstrating that the strain associated with substitutional boron is compensated by coimplantation of In.

The magnitude of the strain is calculated using Bragg's law in conjunction with the pseudomorphic lattice growth mismatch formula. Bragg's law relates the interplanar spacing d_{hkl} for Miller indices h, k, and l, to θ, which is the angle between the incident beam and the lattice plane of interest,

$$n\lambda = 2d_{hkl}\sin(\theta), \tag{1}$$

where λ is the wavelength of the Cu $K\alpha 1$ radiation (1.5405 Å) and n is an integer associated with the order of the Bragg reflection. Assuming that the in-plane lattice parameter is constrained by the substrate,[10] the strain for each coimplant dose can be estimated using the pseudomorphic lattice growth mismatch formula,

$$\frac{\Delta a}{a} = \left[\frac{C_{11}}{(C_{11}+2)(C_{12})}\right]\left(\frac{\Delta d}{d}\right), \tag{2}$$

where $\Delta a/a$ is the derivative of the alloy lattice constant, $\Delta d/d$ is the derivative of the lattice expansion in the direction normal to the surface, and C_{11} and C_{12} are the second-order elastic moduli of Si. The values of second-order moduli for silicon are reported as 16.577×10^{11} dyn/cm^2 for C_{11} and 6.39×10^{11} dyn/cm^2 for C_{12}.[14] The satellite peaks are located at 0.728, 0.572, and 0.472 deg above the Si substrate peak, corresponding to lattice contractions of 1.239%, 1.010%, and 0.818% for In coimplant doses of 0×10^0, 1×10^{14}, and 5×10^{14}/cm^2, respectively. Applying the pseudomorphic lattice mismatch formula, the strains associated with the lattice contractions are 0.516%, 0.420%, and 0.340 %, which decrease with increasing dose of coimplanted In.

Reduction in strain with increasing In dose corresponds to a reduction in the deactivation. Prior to the post-LTP anneal, the sheet number values measured for all doses of coimplanted In are approximately equal to the B implant dose of 3×10^{15}/cm^2. In contrast, the strain calculated for the same samples decreases with increasing dose of In. The compensation of the strain corresponds to a reduction in the deactivation during the subsequent post-LTP anneal at 900 °C for 600 s. Figure 5 is a plot of the percent deactivation occurring during the post-LTP anneal against the tensile strain calculated after LTP. There is a correlation between the reduction in strain and the reduced deactivation. At zero strain the curve still predicts significant deactivation. However, studies with increased In dose to further reduce the deactivation result in difficulties both from limited In solubility and from modification of the LTP process window.

IV. CONCLUSIONS

In conclusion, coimplantation of B with In is investigated as a means to reduce the deactivation by strain compensation. Doped layers are activated by LTP at an energy density of 0.74 J/cm^2 and then subjected to a post-LTP anneal at 900 °C for 600 s. The sheet resistance values measured prior to the post-LTP anneal are independent of the In dose, but after the post-LTP anneal decrease with increasing dose of In. As confirmed by HR-XRD rocking curves, coimplantation of In reduces the strain introduced by the incorporation of B into the lattice. Hence, compensation of the strain corresponds to a reduction in the deactivation during post-LTP anneals.

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