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LATTICE LOCATION OF IMPLANTED As AND Sb IN SILICON AFTER PULSED LASER ANNEALING

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ABSTRACT

The substitutional fractions for As and Sb implanted into silicon and subjected to pulsed laser annealing have been determined using ion channeling techniques. Substitutional fractions of 98-99% are achieved by laser annealing for both of these dopants at doses up to $\sim 1.4 \times 10^{16}/\text{cm}^2$. Channeling results are also presented showing the effect of different laser energy densities on the removal of lattice damage and the incorporation of As into substitutional lattice sites.

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Laser annealing of ion implanted silicon has been shown to lead to complete recovery of electrical activity in the implanted region with little or no degradation of minority carrier lifetime in the substrate.¹ One of the most important materials characteristics associated with the laser annealing process is the lattice location of the implanted species after the laser treatment. In this paper we report measurements using the ion channeling technique to determine the lattice location of implanted As and Sb in single crystal silicon [(100) orientation] after pulsed laser annealing using a Qswitched Ruby laser. Our results show that the substitutional fraction of these dopants is in the range of 98-99% for all doses up to $\sim 1.5 \times 10^{16}/\text{cm}^2$. This high degree of substitutionality is achieved even when the dopant concentration significantly exceeds the limit of solid solubility.

Implants (100 keV energy) were carried out at room temperature under high vacuum conditions (2×10^{-8} torr) to doses in the range 1×10^{15} to $\sim 3 \times 10^{16}/\text{cm}^2$. Laser annealing was carried out in air using the Qswitched output of a Ruby laser ($\sim 50 \times 10^{-9}$ sec pulse duration time) at energy densities that could be varied between 0.6 and ~ 3 Joules/ cm^2 . Ion channeling measurements (2.5 MeV He^+ ions) were used to investigate the damage distribution and the lattice location of the implanted species in the as implanted and laser annealing conditions.² Both aligned spectrum results and detailed angular scans across major axial directions were used in determining the substitutional fractions.³ Each aligned spectrum or angular scan was taken on a fresh spot of the crystal to minimize damage effects associated with the incident beam.

Figure 1 shows the backscattered energy spectrum obtained with the beam aligned along the [110] axial directions for crystals implanted by

^{121}Sb (100 keV, $1.6 \times 10^{16}/\text{cm}^2$) in the as implanted and laser annealed ($1.6 \text{ Joules}/\text{cm}^2$) conditions compared to results from a virgin crystal. The silicon part of the as-implanted spectrum reaches the random value showing that the crystal has been made amorphous down to a depth of $\sim 1400 \text{ \AA}$ by the implant. After laser annealing, the aligned spectrum changes such that the yield is only slightly greater than that for the virgin crystal, and little if any evidence remains of a damage distribution. This shows directly that long range single crystal order has been restored to the implanted region by the laser pulse. The low yield of particles scattered from Sb after laser annealing shows that most of the Sb atoms occupy substitutional sites in the silicon lattice.

Figure 2 shows detailed angular scans across two of the major axial directions in this crystal. These results were obtained by plotting the yield of ^4He ions scattered from Sb and Si atoms in the indicated depth intervals. Yields were normalized to the random value and plotted as a function of the tilt angle away from the axial direction. As shown in Figure 2, the widths of the yield curves from both Si and Sb are very nearly the same in both angular scans. In addition the values for $X_{\min}$ (at $\theta=0$) from Sb are only slightly greater than that for Si in both angular scans. This indicates that the Sb atoms are highly substitutional in the silicon lattice after laser annealing. Angular scan results from crystals implanted by ^{75}As (100 keV) up to doses of $1.4 \times 10^{16}/\text{cm}^2$ show a similar close agreement between the yield curves associated with scattering from As from Si. This confirms that As is also highly substitutional in the silicon lattice after laser annealing.

Quantitative measurements of the substitutional fractions have been obtained using both the aligned spectrum results and the detailed angular scan results. Table I summarizes the aligned spectrum results from a crystal implanted by ^{75}As (100 keV, $1.4 \times 10^{16}/\text{cm}^2$) after laser annealing. These results are tabulated in terms of the $x_{\min}$ values associated with scattering from As atoms and from Si atoms with the incident beam aligned along three principal axial directions. ($[110]$ and $[\bar{1}\bar{1}0]$ are equivalent axial directions but the depth resolution is different due to the scattering geometry.) $x_{\min}$ values for both As and Si were determined from the ratio of the yield of scattered particles with the beam in the aligned direction to the yield in a random direction over a fixed depth interval. The depth interval used in the results of Table I for both As and Si extends from 500 Å to ~3500 Å in the crystal. Measurements of dopant profiles after laser annealing⁴ have shown that all of the implanted dopant is localized to within 3500 Å of the surface.

The substitutional fractions for As as measured along a given axial direction were calculated in the usual way

$$\text{Fraction Substitutional} = \frac{1 \times x_{\min}(\text{As})}{1 \times x_{\min}(\text{Sb})} \times 100$$

As shown in Table I, the substitutional fractions along either of the three principal axial directions is in the range 98-99%. This value is significantly higher than has been reported after thermal annealing of As implanted silicon (80-90%)³ although results comparable to these for both As and Sb have been recently reported in implanted crystals with have been subjected subsequently to high temperature diffusion.⁵

Table II summarizes similar aligned spectrum results for a crystal implanted by ^{121}Sb (100 keV, $7.47 \times 10^{15}/\text{cm}^2$) after laser annealing. The $\chi_{\min}$ results for Si and Sb are low along each of the principal directions and the corresponding substitutional fractions are as high as those for As in Table I. Conventional thermal annealing studies have shown Sb to be ~90% substitutional.³

Table III shows the $\chi_{\min}$ results for Sb and Si obtained with the beam oriented along one of the principal directions $[1\bar{1}0]$ as a function of dose for Sb implanted crystals. Results obtained from a virgin crystal are also included. For doses below $1 \times 10^{16}/\text{cm}^2$ the $\chi_{\min}$ results for Si and Sb are both low and the substitutional fractions are 98-99%. For the two highest dose cases, the $\chi_{\min}$ results are significantly higher but the substitutional fraction in the depth range 500-3000 Å is still very high (98 and 87%). The increased $\chi_{\min}$ value for both Si and Sb in the two crystals is directly related to a damaged layer as observed by transmission electron microscopy² extending from the surface to a depth of ~300 Å. This layer contains precipitates at dislocation loops and dislocation tangles. This thin damaged layer at the surface gives rise to significant dechanneling of the incident beam, which in turn leads to an increase of particles scattered from greater depths in the crystal.

The very high substitutional fractions for Sb (98-99%) for implant doses up to $\sim 1 \times 10^{16}/\text{cm}^2$ are achieved even though the Sb concentration far exceeds its limit of solid solubility in silicon. Profile measurements^{2,4} on these crystals have shown that the Sb concentration extends up to $1 \times 10^{21}/\text{cm}^3$ after laser annealing whereas the limit of solid solubility at the melting point is $\sim 3 \times 10^{19}/\text{cm}^3$. Therefore laser annealing is capable of incorporating dopants into substitutional lattice sites at concentrations

which are much greater than the limit of solubility. The pulsed laser annealing mechanism⁶ is pictured as one in which the incident laser light causes the first few thousand angstroms of the crystal to be melted. The melted region then recrystallizes epitaxially from the underlying substrate by means of liquid phase epitaxial regrowth. During epitaxial regrowth dopants are incorporated into the solid at concentrations that are determined by the dopant concentration in the liquid at the moving liquid-solid interface. This regrowth results in damage free single crystal material with dopants in substitutional lattice sites. The time required for recrystallization is of the order of a few hundred nanoseconds and the surface region then cools rapidly toward ambient temperature in a few microseconds. Presumably this time scale is too short for the formation of precipitates in the solid phase. Dopant concentration in excess of solubility limit is a metastable condition and precipitation will occur if the laser annealed crystals are subsequently thermally annealed (900°C - 30 min).⁷

Figure 3 presents aligned backscattering results showing the effects of different laser energy densities on the damage distribution and the degree of dopant substitutionality on the lattice for As (100 keV, $1.4 \times 10^{16}/\text{cm}^2$) implanted crystals. Transmission electron microscope studies⁸ and dopant profile measurements⁹ (obtained from the random backscattering spectrum) on these same crystals are reported in companion papers. The silicon part of the as-implanted aligned spectrum goes to the random value showing that the crystal has been made amorphous by the implant down to a depth of $\sim 1600 \text{ \AA}$. After laser annealing with 0.63 Joules/cm^2 there is no change in the silicon part of the aligned spectrum but a significant redistribution takes place in the part of the spectrum corresponding

to scattering from As. TEM results⁸ and profile measurements⁹ show that redistribution of As takes place over a depth of 1000 Å and the crystal structure in this depth interval is fine grained polycrystalline which cannot be distinguished from the amorphous state by channeling. This behavior is interpreted to mean that the melt front penetrated ~1000 Å at this laser energy density (0.63 J/cm^2) and recrystallization was not epitaxial since the melt front did not penetrate to the underlying single crystal substrate. After laser annealing at 0.82 J/cm^2 the damage distribution in the silicon has decreased but the width is equivalent to the as-implanted damage distribution. TEM⁸ and profile measurements show more redistribution of the As and the resulting crystal structure is large grained polycrystalline indicating that the melt front may not have penetrated into the underlying single crystal substrate. After annealing at 1.07 J/cm^2 the yield in the aligned direction is considerably reduced but the surface peaks from Si and As as well as the aligned yield is greater than that obtained after annealing at 1.41 Joules/cm^2 . These observations correlate well with TEM⁸ results which show that a thin damaged layer ~200 Å thick exists on the surface of the crystal annealed at 1.07 J/cm^2 . Behind this damaged layer is single crystal material. This indicates that regrowth is epitaxial to within 200 Å of the surface. Profile measurements⁹ show redistribution of As which is to be expected from diffusion in the liquid. This layer gives rise to an enhanced surface peak and to dechanneling of the incident beam accounting for the increased aligned yield from deeper depths. At 1.41 Joules TEM shows damage free single crystal material starting at the surface. Substitutional fractions for As are 98% in the depth interval 300-2500 Å at either 1.07 or 1.41 Joules/cm^2 .

In conclusion we have shown that As and Sb can be incorporated very efficiently into substitutional sites in the silicon lattice as a result of pulsed laser annealing. Substitutional fractions are measured to be 98-99% even when the dopant greatly exceeds the limit of solid solubility. Incorporation of dopants into substitutional lattice correlates well with the onset of liquid phase epitaxial regrowth as inferred from channeling measurements, transmission electron microscopy,⁸ and profile measurements.⁹

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FIGURE CAPTIONS

Figure 1a [110] Aligned Backscattered Energy Spectrum from ^{121}Sb (100 keV, $1.6 \times 10^{16}/\text{cm}^2$) Implanted Silicon.

Figure 1b Angular Scans Across the [110] and [111] Axial Directions for ^{121}Sb (100 keV, $1.6 \times 10^{16}/\text{cm}^2$) Implanted, Laser Annealed Silicon.

Figure 2 Laser Annealing of ^{75}As (100 keV, $1.4 \times 10^{16}/\text{cm}^2$) Implanted Silicon with Different Energy Densities.

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^{121}Sb -100 keV, $1.6 \times 10^{16}/\text{cm}^2$ in $\langle 100 \rangle$ Si
[110] Aligned Spectrum

Antimony Implanted Silicon;
100 keV, $1.6 \times 10^{16} \text{ cm}^{-2}$, One Pulse Laser Annealed

Fig. 1

^{75}As (100 keV, $1.4 \times 10^{16}/\text{cm}^2$) in $\langle 100 \rangle$ Si [100] Aligned Spectrum.

Fig. 2