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ELECTRICAL CHARACTERISTICS OF ION-IMPLANTED LASER-ANNEALED SILICON

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ELECTRICAL CHARACTERISTICS OF ION-IMPLANTED LASER-ANNEALED SILICON^{*}

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In the past year, many experiments have been conducted to study the use of laser radiation for the removal of lattice damage produced in Si by ion implantation processes.¹⁻⁵ Detailed results concerning the use of a Q-switched ruby laser to remove lattice damage and an understanding of the associated annealing mechanism have been reported by us in previous publications^{1,5,6} for B (the most widely used p-type dopant) implanted Si. In this paper, we present the results of electrical measurements on Si implanted with n-type dopants such as P and As and laser annealed.

We have used van der Pauw measurements to determine the sheet resistivity and sheet carrier concentration of various implanted samples after thermal and laser annealing. The results have been correlated with transmission electron microscopy (TEM) studies. In order to examine the feasibility of the method for device fabrication, mesa diodes were fabricated and tested. Laser-induced defects were also studied by deep level transient spectroscopy (DLTS) to investigate any effect of laser-induced damage on device performance.

Laser annealing was performed in air with a Q-switched ruby laser (pulse duration ~ 50 ns) operating in a multimode condition. Implants (80 KeV

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and 100 KeV) were carried out at room temperature to doses in the range of 1×10^{14} to $2 \times 10^{16} \text{ cm}^{-2}$ on 5-10 ohm-cm B-doped (100) Si samples.

The threshold laser energy density for complete annealing of the implanted layer was found to be dependent on such parameters as the implant energy and species. Figure 1 shows the sheet resistivity as a function of the laser energy density for As and B implanted Si samples. The threshold energy density for the recovery of electrical activity for the As implanted Si is lower than for the B implanted Si. Since the damage profile of 100 KeV As implanted Si is shallower than that of 35 KeV B implanted Si,⁷ this result was anticipated because, as predicted by Wang *et al.*⁸ the annealing threshold is expected to be closely related to the depth of the disordered region. The results of the melt front profile calculations in ref. 8 suggest that the annealing mechanism is governed by liquid phase epitaxial regrowth. The regrowth of the damaged layer is dependent on the melting depth and duration and these are dependent on the incident photon energy density for a fixed pulse duration.

Figures 2a and 2b are plots of the measured free carrier concentrations in silicon samples implanted with various doses of ^{31}P (80 KeV) and ^{75}As (100 KeV) and subsequently subjected to thermal and laser annealing (1.5 J/cm^2). Since recrystallization of amorphous Si occurs at $\sim 600^\circ\text{C}$, the thermal annealing results indicate that all samples except the lowest dose P implanted one in Fig. 2a are amorphous after implantation. However, in the high dose samples, the recovery of the electrical activity at 600°C is rather poor. Transmission electron microscopy investigation of these samples indicated poor crystallinity. This fact may be related to the high degree of amorphousness after high-dose implantations. Ohdomari *et al.*,⁹ in examining Si implanted with Ar at various doses, reported that the higher the degree of amorphousness, the worse was the quality of the crystallinity after recrystallization. On the other hand, in the laser annealed samples, full recovery of the free carrier concentration was achieved irrespective of the initial state of the amorphousness.

The TEM results in Fig. 3 show that there is no damage in the laser annealed Si samples down to the resolution of the microscope $\sim 10 \text{ \AA}$. In contrast, lattice imperfections in the form of dislocations or dislocation

loops remain after thermal annealing at 900 and 1100°C. These results demonstrate that laser annealing is much more effective in removing lattice damage and restoring electrical activity than is conventional thermal annealing.

In order to investigate the feasibility of laser annealing techniques for device fabrication, mesa diodes (area $\sim 1.1 \times 10^{-3} \text{ cm}^2$) were formed on various samples. Figure 4 shows a typical forward-biased dark I-V curve of a diode fabricated from an As-implanted laser-annealed Si sample. The I-V characteristics may be fitted to the ideal diode equation $I = I_0 [\exp(\frac{qV}{A kT}) - 1]$ by using $A = 1.62$ in the voltage range 0.3 to 0.5 V; this indicates that recombination effects are reasonably reduced in the space charge region. Due to excess diode resistance the I-V curve bends away from an $A = 1.62$ line beyond 0.5 V. Reverse current measured at -0.5V indicates a low leakage current.

The effect of laser induced defects in Si was studied by the DLTS technique. Figure 5 shows the DLTS spectrum of an unimplanted, B doped Si control sample irradiated with three laser pulses ($E = 1.5 \text{ J cm}^{-2}$). There is a dominant peak with an energy level at $E_v + 0.24 \text{ eV}$. Depth profile measurements show that the defects are concentrated near the surface, extending into the sample about 10 μm . A similar though somewhat broader peak with an energy level at $E_v + 0.22 \text{ eV}$ was observed in samples irradiated with a single laser pulse under voltage bias and pulse conditions such that the measured region was from about 1.7 to 2 μm in depth. By selecting a deeper region in the Si (2 to 2.5 μm) an additional peak was observed with an energy level at $E_v + 0.37 \text{ eV}$. In both measurements the trap density was $\sim 1 \times 10^{14} \text{ cm}^{-3}$. Compared to the emitter doping density in a normal device, the density of these trapping centers is so low that their influence on junction characteristic can be neglected; this is confirmed by the good I-V curve shown in Fig. 4.

In conclusion, our results indicate that complete removal of lattice damage can be achieved by using those laser conditions which give rise to full recovery of electrical activity in the implanted layer, no matter what the degree of amorphousness. The annealing threshold of the laser energy

density varies with the implanted species and the implantation energy. Diodes with good junction characteristics can be fabricated, and the density of laser-induced defects is so low that they have no significant effect on diode performance.

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Fig. 1. The recovery of sheet resistivity as a function of laser energy density for As (Δ) and B ($\bullet$) implanted Si.

Fig. 2. Sheet carrier density of (a) ^{31}P and (b) ^{75}As implanted Si after laser and thermal annealing.

- A. Comparison of laser and thermal annealing in $^{31}\text{P}^+$ implanted (80 KV, dose $1.0 \times 10^{15} \text{ cm}^{-2}$) silicon: a) Laser annealed, bright field; b) Weak beam electron micrograph after annealing at 1100°C for 30 min. The arrows indicate the directions of diffraction vector $[2\bar{2}0]$ and their length is $0.3 \mu\text{m}$.

- B. Comparison of laser and thermal annealing in arsenic ($^{75}\text{As}^+$) implanted (100 KV, dose $= 1.0 \times 10^{16} \text{ cm}^{-2}$) silicon: a) Laser annealed, bright field; b) Weak beam electron micrograph after thermal annealing at 900°C for 30 min.

Fig. 3

Fig. 4. Junction Characteristics of an As implanted laser annealed mesa diode.

Fig. 5. DLTS spectrum for B doped Si irradiated with three laser pulses ($E = 1.5\text{ J cm}^{-2}$, $\tau \sim 50\text{ ns}$).