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LASER ANNEALED BORON IMPLANTED SILICON SOLAR CELLS*

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Summary

The use of high power laser pulses is being explored as a technique for annealing radiation damage in ion implanted silicon prior to the fabrication of solar cells. Extensive studies have been carried out to compare laser and conventional thermal annealing characteristics using $^{11}\text{B}^+$ (35 keV) implanted silicon (100) crystals. Our results show that laser annealing can completely restore electrical activity in the implanted layer with little or no degradation of the minority carrier lifetime in the substrate. Moreover, the residual disorder in the implanted layer is drastically reduced in comparison to that observed after conventional thermal annealing.

Solar cells have been fabricated using $^{11}\text{B}^+$ (35 keV) implanted, laser annealed, 80 $\Omega\text{-cm}$ (100) Si. A substantial improvement in cell parameters is observed in laser annealed cells compared to similar cells fabricated using conventional thermal annealing. Results will be presented to compare laser and thermally annealed ion implanted cells, and to compare these to cells fabricated using standard diffusion techniques. Possible reasons for the improvement in the laser annealed cells compared to the thermally annealed ion implanted cells will be discussed.

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1. INTRODUCTION

Ion implantation has been used extensively as a production technique for the fabrication of controlled p-n junction devices. However, the need for high temperature annealing to remove the lattice damage produced by the energetic dopant ions considerably reduces the use of this technique, and lowers its suitability for many applications. The reasons are: (1) As a result of the high temperature anneal there is usually a reduction of the minority carrier lifetime (MCL) in the underlying substrate material, and (2) the MCL in an implanted layer is shorter than that of a thermally diffused layer (1), due to the existence of unannealed secondary defects such as dislocations, dislocation loops or stacking faults. These secondary defects are very stable against high temperature annealing. These factors, plus the introduction of an undesired Gaussian concentration profile, have limited many applications of the ion implantation technique.

Recently, high power laser pulses were successfully used for annealing lattice damage in ion implanted layers (2-9). The effects of laser annealing can be confined to the damaged region by the proper choice of the wavelength, energy and pulse duration time. Our recent study (9) of laser annealed boron implanted Si indicates that laser annealing can restore the electrical activity with little or no degradation of the MCL in the substrate material, and leaves substantially less lattice damage than does conventional thermal annealing. In addition, the boron concentration profile is markedly changed to a broader, nearly flat top distribution. By combining the advantages of ion implantation with high power laser annealing, it is possible to fabricate high efficiency solar cells by totally eliminating the conventional high temperature thermal diffusion and/or annealing process.

2. EXPERIMENTAL

Silicon slices (1 cm x 1.5 cm x 0.1 cm) with (100) surfaces were cut from an 80 Ω -cm dislocation free float zone single crystal Si ingot. The wafers were chemically polished in CP6 ($\text{HF}:\text{CH}_3\text{COOH}:\text{HNO}_3=1:1:2$) and implanted under high vacuum (2×10^{-8} torr) with $^{11}\text{B}^+$ (35 keV) to $2 \times 10^{15} \text{ cm}^{-2}$. Laser annealing was accomplished by using a Q-switched ruby laser ($\lambda = 0.694 \mu\text{m}$, pulse duration time ~ 30 -50 ns) with beam diameter of ~ 1.0 cm and energy density of 1.5-1.7 Joules $\cdot\text{cm}^{-2}$ per pulse. This energy density is sufficient to anneal the lattice damage in the implanted region

without producing much surface damage. To cover the entire sample area, several pulses were used on each sample. Because of the inhomogeneous energy distribution of the pulse, some scattered surface damage was observed. The conventional thermal annealing was carried out in a quartz furnace at 900°C and 1000°C in a helium atmosphere. In making the photovoltaic cell, evaporated aluminum was used to establish a front contact through a mask which has a grid design with 9% shadow fraction in a standard comb pattern. An electroless nickel deposit was made on the back side of the cell and this side was then soldered to a sample holder to form the back contact. No antireflection coating or special texturized surfaces were used.

3. RESULTS AND DISCUSSION

1. Characteristics of laser annealing

For completeness, a review of our previous work (9) on a comparison of the annealing characteristics between laser and conventional thermal annealing is given as follows. The results of our electrical measurements indicate that laser annealing provides much higher recovery of electrical activity than 900°C thermal annealing, which implies that laser annealing results in a better recovery of the crystal structure. These results are confirmed by the observation of transmission electron microscopy (TEM) studies. Figure 1 shows a comparison between laser annealed (a-c) and thermally annealed samples of $^{11}\text{B}^+$ (35 keV, $3 \times 10^{15} \text{ cm}^{-2}$) implanted Si. Electron micrographs were taken under both bright (a) and dark field (b) imaging conditions for optimum visibility and contrast from defects. As shown in the figures, the implanted, laser annealed samples had no visible damage in the form of dislocations, stacking faults and dislocation loops down to a resolution of $\sim 10 \text{ \AA}$. A [001] electron diffraction pattern (c) had no irregularity, confirming further the perfection of the lattice of the implanted layer after laser annealing. On the other hand, the implanted thermally annealed specimen (d) had extensive damage remaining in the form of dislocation loops, with an average loop size of $\sim 250 \text{ \AA}$ and a dislocation loop density of $\sim 1.0 \times 10^{16} \text{ cm}^{-3}$.

The effects of laser and thermal annealing on the dopant profiles for samples implanted to a dose of $1 \times 10^{16} \text{ cm}^{-2}$ are shown in Fig. 2; the profiles were obtained by secondary ion mass analysis using an ion microprobe. It is evident that pronounced changes occurred in the implanted profile distribution as a consequence of laser annealing. The concentration in

the near surface region was substantially increased and the profile broadened to greater depth in the crystal. Following laser annealing, the nearly Gaussian as-implanted boron profile became almost uniform from the surface down to a depth of $\sim 2000 \text{ \AA}$ in the crystal. The boron profile results we have obtained are in qualitative agreement with the carrier profile measured by electrical conductivity in the course of layer-by-layer etching (3).

11. Solar cell performance

Table I shows the data on cell parameters of $^{11}\text{B}^+$ (35 keV , $2 \times 10^{15} \text{ cm}^{-2}$) implanted cells subjected to laser annealing and to thermal annealing at 900 and 1100°C . For comparison a cell fabricated by standard diffusion technique is also included. All cells were fabricated from $80 \text{ }\Omega\text{-cm}$ n-type floating zone Si and evaluated without AR coating or drift field back contact. As can be seen from the table, there is a substantial improvement in the open circuit voltage (V_{oc}) and short circuit current (J_{sc}) in the laser annealed cells compared to cells fabricated using conventional thermal annealing. The improvement of the V_{oc} in the laser annealed cells can be understood by the complete annealing of the lattice damage in the implanted layer. The better J_{sc} can be partially explained by the longer MCL in the substrate layer as well as in the implanted layer. Moreover, the redistribution of the Gaussian profile into a much broader, nearly flat distribution from the surface to a depth of $\sim 0.2 \text{ }\mu\text{m}$ can substantially increase the collection efficiency by eliminating the undesired drift field toward the surface produced by the Gaussian profile. The fill factors are low in all the implanted cells, as well as in the diffused cells; we believe this to be due to our somewhat primitive metallization techniques. As we mentioned before, because of the nonuniform energy distribution in the laser pulse, scattered surface damage visible to the naked eye was produced. The damage, as observed with an optical microscope, indicated that some evaporation of material was produced by the hot spot of the laser pulse. This surface damage may cause some leakage current, as may be indicated by the relatively low value of shunt resistance in the laser annealed cells compared to that in the thermally annealed or diffused cells (see Table I). The elimination of the laser hot spot by further defocussing of the beam should greatly reduce the problem of surface damage. We would like to point out that throughout this study the implanted cell structures have not been designed for optimum solar cell performance.

However, comparable performance with cells fabricated by standard diffusion techniques has been obtained. These results strongly suggest that an effective automated processing capability with high yield of high efficiency cells can be developed.

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Table 1. Comparative data on cell parameters of $^{11}\text{B}^+$ (35 keV , $2 \times 10^{15}\text{ cm}^{-2}$) implanted cells subjected to laser and thermal annealing and cell fabricated with standard diffusion technique

Cell No.	Junction Formation	Minority Carrier Lifetime in base material* $\tau(\mu\text{s})$	Shunt Resistance $R_{sh}(\Omega)$	AM 1 Parameters**			
				$J_{sc}(\text{mA}/\text{cm}^2)$	$V_{oc}(\text{mV})$	FF	$\eta(\%)$
IL 1	$^{11}\text{B}^+$ implant laser anneal ($1.5\text{ J}/\text{cm}^2$)	81	3000	24.0	530	.61	7.8
IL 2	$^{11}\text{B}^+$ implant laser anneal ($1.7\text{ J}/\text{cm}^2$)	90	2000	23.0	520	.66	8.0
IT 1	$^{11}\text{B}^+$ implant thermal anneal $900^\circ\text{C}/30\text{ min}$	5	$>10^5$	13.7	465	.65	4.2
IT 2	$^{11}\text{B}^+$ implant thermal anneal $1000^\circ\text{C}/30\text{ min}$	2.6	$>10^5$	15.6	445	.61	4.4
D 1	Boron diffusion $950^\circ\text{C}/30\text{ min}$	7	$>10^5$	21.7	525	.66	7.5

*Measured by surface photovoltage measurement

**Tungsten lamp calibrated at $\sim 100\text{ mW}/\text{cm}^2$

FIGURE CAPTIONS

Fig. 1. TEM micrographs of $^{11}\text{B}^+$ (35 keV , $3 \times 10^{15}\text{ cm}^{-2}$) implanted silicon after laser treatment, a) bright field, b) dark field, c) (001) diffraction pattern; and d) thermal annealing weak beam dark field. The length of the arrows in Figs. (b) and (d) are $0.20\text{ }\mu\text{m}$.

Fig. 2. Depth profiles for $^{11}\text{B}^+$ (35 keV , $1 \times 10^{16}\text{ cm}^{-2}$) implanted silicon. Profiles were obtained for the as-implanted, thermally annealed (900°C - 30 min) and laser annealed conditions. Flattening of the profiles at counting rates $\leq 500/10\text{ sec}$ is believed related to insufficient aperturing and crater wall effects.

Fig. 1

Fig. 2