Reducing the Reverse-Bias Current in 450°C-Annealed n+p Junction by Hydrogen Radical Sintering

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Ultra–shallow n+p junctions featuring very low reverse–bias current densities (3.1x10^{-9} A/cm^2 at -5 V) have been successfully formed at a post–implantation annealing temperature as low as 450°C. Such a low reverse–bias current level has been achieved by eliminating residual point defects remaining after 450°C post–implantation annealing by a newly developed hydrogen radical sintering (H^-sintering).

1) INTRODUCTION

There is a strong interest in forming low reverse–bias current junctions at low temperatures (e.g., 450°C) because the establishment of total low temperature processing (below 500°C) is an essential requirement for implementing metal substrate CMOS devices, which are expected to operate at frequencies as high as 10 GHz.1 Previously we succeeded in reducing the reverse–bias current of ion–implanted n+p junctions by low temperature annealing. This was achieved by using a UHV ion implanter3 to eliminate residual gas contamination, and also by installing silicon protecting covers over metal internal components of the ion implanter (Fig.1) in order to eliminate metal contamination caused by high energy ion beam sputtering3. However, junctions formed at 450°C so far have presented reverse–bias current levels about two orders of magnitude higher than samples formed at 1000°C, so that sources of leakage current other than residual gas–molecule adsorption and metallic sputtering contamination must be investigated.

Sintering in forming gas ambient is widely accepted as a process to reduce the interface trap density4–5. It is proposed that hydrogen atoms can passivate electrically active traps existing at the interface between Si and SiO2. However, numerous papers have shown that annealing in molecular hydrogen ambient at temperatures below 600°C result in little H penetration into the bulk of Si. The classic H penetration measurement by Wieringa and Warmoltz7 showed a very low hydrogen solubility in Si (around 10^{-15} cm^{-3} at 1 atm at 1200°C), giving support to the observation. Consequently, there is no report about passivation of traps existing in the bulk of the Si by sintering in H–containing ambient.

However, the rather large value of the hydrogen diffusivity in Si (around 10^{-10} cm^2/s at room temperature)7 can provide a large number of hydrogen molecules penetrating through the bulk of Si, thus might give chance to terminate traps in Si. The fact that no trap passivation effect has been so far observed suggests that molecular hydrogen has a very low reactivity with traps located in the bulk of Si. It is proposed in this work that sintering in an ambient containing hydrogen radicals (H^*) instead of molecular hydrogen can reduce the density of traps in the midgap existing in the bulk of Si.

2) EXPERIMENTAL PROCEDURE

The n+p diodes were formed by implanting As at 25 keV with a dose of 2x10^{15} cm^{-2} to p-type, (100) Si substrates of 4.5–6.0 Ωcm resistivity. The annealing of ion–implanted layers was carried out in nitrogen ambient at varying temperatures ranging from 450°C to 1000°C. All diodes were subjected to sintering in a forming gas ambient at 400°C for 20 min. H^-sintering was carried out in a specially designed furnace, which is schematically presented in Fig.2. The furnace is made of 0.5 m long Hasteloy tube with an internal diameter of 30 mm. A gas mixture of 10%H_2/90%Ar was fed to the furnace through a 4 m long Ni tube with an...
3) RESULTS AND DISCUSSION

The reverse-bias current obtained by post-implantation annealing at 450°C, even without \( \text{H}^- \)-sintering, is three to four orders of magnitude lower than the previously reported data\(^8\), \(^9\), as shown in Fig.3. Therefore, our diodes are very sensitive to low-level defects, thus being suited to study the behavior of residual defects in low-temperature annealed junctions.

![Schematic of the furnace designed to carry out the hydrogen radical sintering.](image)

Fig.2) Schematic of the furnace designed to carry out the hydrogen radical sintering.

In Fig.4 the current densities are shown as a function of the applied bias for different annealing temperatures. It is observed that not only the reverse-bias current but also the forward-bias current increases as the post-implantation annealing temperature is decreased. The reverse-bias current of junctions annealed at low temperatures is governed by the carrier generation in the depletion region. Therefore, the increase in the current density is attributed to the residual defects generated by ion implantation, which increase as the annealing temperature is reduced. Thus, the behavior of the reverse-bias current is quite reasonable. On the other hand, however, the forward-bias current is governed by the diffusion of electrons (recombination current) in the neutral p-type region. Thus, it depends on the properties of the p-type substrate not in the vicinity of the implanted region. Therefore, it is hard to believe the forward-bias current increases depending on the annealing temperature.

![Current-voltage characteristics measured for \( n^+p \) junctions formed by 450°C, 500°C, 600°C and 1000°C post-implantation annealing.](image)

Fig.4] Current–voltage characteristics measured for \( n^+p \) junctions formed by 450°C, 500°C, 600°C and 1000°C post-implantation annealing.
It is expected that such point defects deep-distributed in the Si substrate can be terminated by H⁺-sintering. H⁺-sintering carried out at 450°C, however, did not show any improvement in the diode characteristic. Presumably, the H⁺-sintering temperature of 450°C is too high to stabilize the termination of point defects. Then, the H⁺-sintering was carried out at 420°C for 3 h. Reduction in the reverse-bias current by 20–30% was observed, as shown in Fig.6. The figure shows the current densities measured after the H⁺-sintering normalized to the values before the sintering process. The use of H⁺-sintering permitted us to lower the reverse-bias current level at −5 V down to 3.1×10⁻⁹ A/cm². It is noteworthy that samples sintered in forming gas at the same temperature did not present any improvement in the reverse-bias current level. Optimization of H⁺-sintering conditions is presently in progress and more significant improvements are yet expected.

5) CONCLUSION

It has been shown that H⁺-sintering at 420°C for 3 h is effective in reducing the reverse-bias current by 20 to 30% compared to the values before the sintering. This sintering has been proposed by the assumption that one source of excessive currents of the junction annealed at low temperature are point defects produced during the ion implantation, deep distributed into the bulk Si, which could not be completely annealed out by post implantation annealing at low temperature. The reverse-bias current at 5 V has been reduced to a value as low as 3.1×10⁻⁹ A/cm² by the present technology.

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REFERENCES