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Activation of B and As in Ultra Shallow Junction with Heating and Cooling Rates Controlled Millisecond Annealing Induced by Thermal Plasma Jet

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1. Introduction

Formation of ultra shallow junction (USJ) for source and drain extension is a crucial issue to prevent short channel effect in scaled MOSFETs. Recently, millisecond rapid thermal annealing (RTA) such as flash lamp annealing [1] and laser spike annealing [2] have been studied intensively to activate implanted dopants without significant diffusion. In order to improve the efficiency of dopant activation even beyond soluble limit in Si lattice, precise control of heating and cooling rates in millisecond or even shorter RTA is indispensable. In our previous work, we have developed a non-contact temperature measurement technique applicable to millisecond RTA of Si wafer induced by thermal plasma jet (TPJ) irradiation [3].

In this work, we applied high power density TPJ to activate B in Si wafer. The annealing condition for efficient doping is investigated including a comparable study with As doping case. It will be discussed that not only the peak annealing temperature, but the annealing duration plays an important role for efficient doping.

2. Experimental

In the experiment, a double-side polished, 0.5-mm-thick n-type Si (100) wafers were used. B cluster ions ($B_{10}H_x$) were implanted at 5 keV with a dose of 5×10^{14} ions/cm^2 into the Si wafers. In the case of As, As^+ ions were implanted at 10 keV with 1×10^{15} ions/cm^2 dosage. Si wafers were preheated at 570 to 770 K with a plate heater and millisecond RTA was carried out by TPJ irradiation. The details of TPJ equipment have been reported previously [4]. Arc discharge was generated by supplying DC power (p) of 2.0 to 2.5 kW, where the DC voltage was 14.0 to 16.3 V with a constant discharge current of 150 A, between the electrodes under Ar gas flow rate (f) of 7.0 L/min. The TPJ was formed by blowing out the arc plasma through an orifice of 2 mm in diameter. The Si wafer was linearly moved by a motion stage in front of the TPJ with scanning speed (v) ranging from 400 to 1400 mm/s. The distance between the plasma source and the substrate (d) was held at 1.5 mm. For the measurement of the temperature profile of a Si wafer during RTA, an optical probe was used. Transient reflectivity was measured by irradiating the Si wafer with an infrared laser (λ = 1310 nm, 15 mW) from the back surface. The optics and the Si wafer was set on a motion stage and moved together.

3. Results and Discussion

By analyzing UV reflectivity peak (E_2 peak) height associated with direct transition in Si bandgap (Fig. 1), thickness of surface amorphization layer was estimated. It was ~ 6 nm in B implanted samples and larger than ~ 15 nm in As implanted samples. In the case of B implanted samples, the amorphous layer thickness remain unchanged even after preheating at 770 K. On the other hand, we confirmed crystallization of surface amorphous layer by preheating As implanted sample as high as 770 K. Therefore, we decided the preheating temperature below 670 K. Figure 2 shows Raman scattering spectra of B implanted Si wafer before and after TPJ irradiation. A small peak at ~ 618 cm^{-1}, which is associated with Si-B bond, was observed after TPJ irradiation. This suggests crystallization of surface amorphous layer and activation of B. Figure 3 shows sheet resistance of B implanted samples (R_S) as a function of maximum surface temperature (T_{max}) during TPJ irradiation. R_S of As implanted samples is also plotted for comparison. R_S decreased from around 9000 to 392 Ω/sq with increasing T_{max} from 729 to 1392 K. These results imply that B in the Si wafer are efficiently activated by TPJ irradiation with crystallization of amorphous layer. In the case of B, R_S monotonically decreases with T_{max}, while it saturates around 262 Ω/sq at a T_{max} higher than 1000 K in the case of As (Fig. 3). Surface morphology of B implanted samples were investigated by atomic force microscopy (AFM) as shown in Fig. 4. No significant change in surface roughness was observed even after TPJ irradiation, and the root mean square (RMS) roughness values are 0.21 nm in all samples. Figure 5 shows carrier concentration and mobility as a function of T_{max} after TPJ irradiation. Hole concentration increased with increasing T_{max} and it reached 1.8×10^{20} cm^{-3}, while mobility slightly decreased from 60 to 30 cm^2/Vs. Figure 6 shows activation efficiency (η) as a function of T_{max}. It gradually increased from 1200 K sharply and we obtained a maximum value of 13 %. In the case of As implanted samples, η rapidly increases with a temperature around 900 K. Roughly speaking, B activation requires 300 ~ 400 K higher temperature. Figure 7 shows SIMS profile before and after TPJ irradiation. No significant enhanced diffusion of the B implantation profile can be observed. In the case of T_{max} = 1392 K, junction depth (X_j) increased from 21.8 to 23.5 nm. On the other hand, X_j was 21.8 nm without detectable diffusion of dopant in the case of T_{max} = 1330 K. Figure 8 compares R_S-X_j relationship between TPJ and FLA [5]. TPJ irradiation achieves almost equivalent USJ. In order to get better understanding on the effect of annealing temperature and duration on the R_S of USJ, TPJ annealing was performed under various condition. Figure 10 shows R_S of B and As implanted samples after TPJ irradiation as functions of T_{max} and annealing duration (t_a). We realize that R_S is lower in shorter t_a if T_{max} is same. For example, heating and cooling characteristics of (a) to (d) indicated in Fig.9. are listed in Table. I . The T_{max} of (a) to (d) is almost the same, but R_S is largely different. It should be noted that R_S decreases with decreasing t_a or increasing heating and cooling rates (R_h, R_c). This result indicates that not only the peak annealing temperature, but the heating or cooling periods play important role for efficient activation of dopant atoms.

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3. Conclusions

By irradiating the high density TPJ to B–implanted Si wafer , an USJ with a R_S value of 392 Ω/sq and a Xj of 23.5 nm has been successfully formed. By comparing the annealing temperature dependence of activation efficiency between B and As implanted samples, B activation requires 300 ~ 400 K higher temperature. It has been clearly shown that the R_S is not only a function of annealing temperature, but heating and cooling characteristics plays an important role in millisecond annealing for USJ formation.

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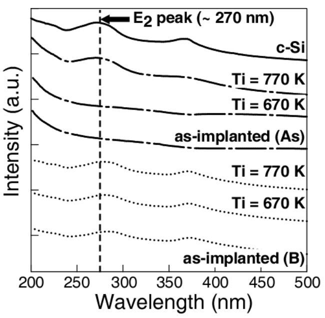

Fig.1. UV reflectivity spectra of B and As implanted and preheated samples.

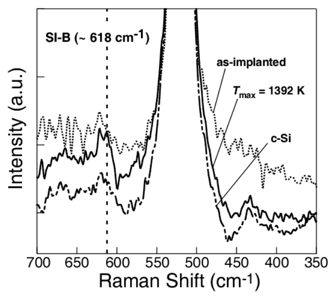

Fig.2. Raman scattering spectra before and after TPJ irradiation with preheating of 770 K.

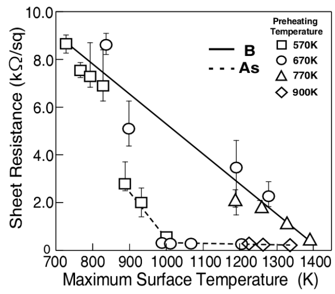

Fig.3. R_S of B and As implanted samples as a function of T_{max} during TPJ irradiation.

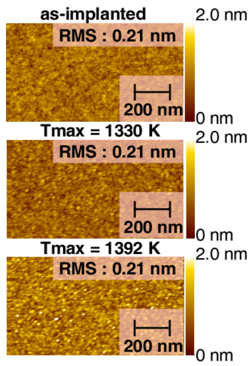

Fig.4. Surface morphology before and after TPJ irradiation observed by AFM.

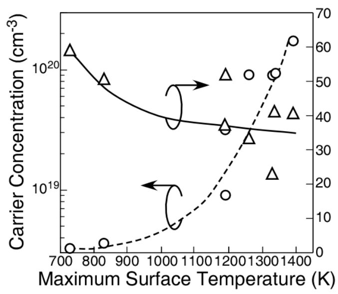

Fig.5. Carrier (hole) concentration and mobility as a function of T_{max} .

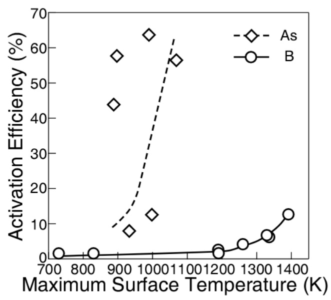

Fig.6. Activation efficiency of B and As implanted samples as a functions of T_{max}.

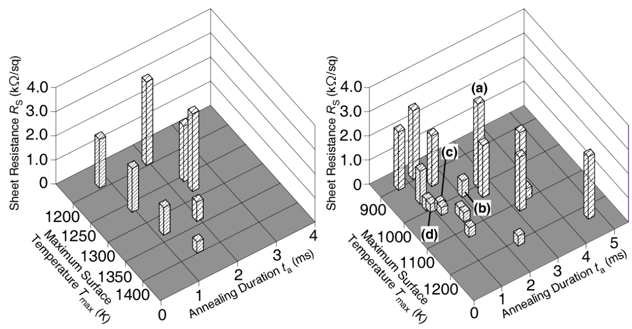

Fig.9. R_S after TPJ irradiation as functions of T_{max} and t_a.

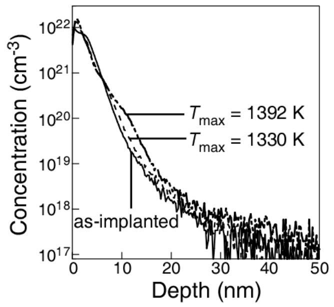

Fig.7. SIMS profile of B before and after TPJ irradiation.

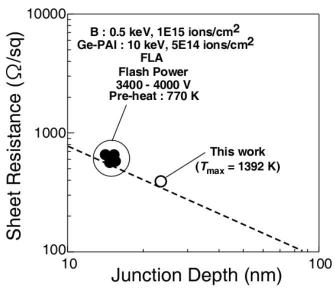

Fig.8. R_S-X_j relationship between TPJ and FLA.

Table. I . Characteristics values of TPJ annealing performed.

	(a)	(b)	(c)	(d)
T_{max} (K)	998	1002	1012	999
t_a (ms)	2.7	2.1	1.2	1.0
R_h (×10^5 K/s)	0.92	1.69	2.08	2.79
R_c (×10^5 K/s)	0.27	0.47	0.63	1.04
R_S (Ω/sq)	3403	584	274	247