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Efficient Activation of As in Ultrashallow Junction Induced by Thermal Plasma Jet Microsecond Annealing

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1. Introduction

The formation of ultra shallow junction (USJ) for source and drain extension is crucial for preventing short-channel effect in the miniaturization of Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs). Recently, millisecond rapid thermal annealing (RTA) such as flash lamp annealing (FLA) [1] and laser spike annealing (LSA) [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 noncontact temperature measurement technique applicable to the millisecond RTA of Si wafers. In addition, we applied thermal plasma jet (TPJ) annealing to the activation of As and B implanted to Si wafer surface [3]. We have reported that efficiency of As activation is very sensitive not only to annealing temperature, but to heating and cooling rates. When the maximum annealing temperature (T_{max}) is the same, faster heating and cooling improves the activation efficiency [4].

In this work, we applied micro TPJ (μ-TPJ) annealing to the activation of As in Si wafers to investigate the effectiveness of microsecond annealing. Activation of As in USJ was compared by applying TPJ induced millisecond and microsecond annealing.

2. Experimental Procedure

In the experiment, double-side-polished, 0.5-mm-thick p-type Si(100) wafers were used. As cluster ions (As_2^+) were implanted at 3 keV at a dose of 5×10^{13} ~ 5×10^{14} /cm^2. Here, junction depth (X_j) after ion implantation was 11.9 nm (@1.0×10^{18} /cm^3). The Si wafers were preheated at 670 K with a plate heater, and millisecond and microsecond RTA were carried out by TPJ irradiation. Details of the TPJ equipment used were reported previously [3]. Arc discharge was generated by supplying a DC power (p) of 0.93 to 2.6 kW, where the DC voltage was 13.3 to 17.6 V with a discharge current of 70 ~ 150 A, between the electrodes under an Ar gas flow rate (f) of 7.0 L/min. Electrode spacing (ES) was set at 2.0~3.0 mm. The TPJ was formed by blowing out arc plasma though an orifice of 0.8 ~ 2 mm diameter. The Si wafer was linearly moved by a motion stage in front of the TPJ with scanning speeds (v) ranging from 800 to 4000 mm/s. The distance between the plasma source and the substrate (d) was kept at 1.0 ~ 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 wafers with an infrared laser (λ = 1546 nm) from the back surface and detecting the reflected light intensity using an InGaAs photodiode. The optics and Si wafer were set on the motion stage and moved together.

3. Results and Discussion

Firstly, we carried out generation of high power density TPJ for microsecond RTA. We used a small orifice of 0.8 mm diameter instead of 2.0 mm to concentrate TPJ. Because we expected the concentration of TPJ induced by the thermal pinch effect due to the water-cooled small orifice. The open circles in Fig. 1(a) shows optical thickness variation during μ-TPJ irradiation extracted from the number of oscillation observed in transient reflectivity of Si wafer. We can reproduce transient optical thickness variations by simulation as shown by solid line. From the analysis results, we obtained the transient temperature variation during μ-TPJ irradiation as shown by Fig. 1(b). T_{max} is almost equal, but we can reduce the annealing duration (t_a) and increase the heating and cooling rates (R_h, R_c) significantly as understood by the comparison with the case of conventional TPJ. Figure 2 shows the maximum surface temperature (T_{max}) as a function of input current during μ-TPJ irradiation. T_{max} increased with increasing input current from 70 to 120 A, and a T_{max} of 535 K was achieved with v = 1000 mm/s. Figures 3 and 4 show t_a and R_h as a function of v. By applying μ-TPJ, we can perform 200 to 500 μs annealing which is much shorter than the case of TPJ. In addition, R_h increased from 2.0×10^5 K/s of conventional TPJ to as high as 8.7×10^5 K/s.

Figure 5 shows R_S as a function of T_{max} after TPJ and μ-TPJ irradiation. In the case of TPJ irradiation, smallest R_S of 1126 Ω/sq was obtained at T_{max} of 920 K and it slightly increased with increasing annealing temperature. On the other hand, R_S decreased with increasing T_{max} in the case of μ-TPJ irradiation and R_S of 1120 Ω/sq was obtained at 905 to 982 K. These results suggest that clustering of As at wafer surface is suppressed by microsecond annealing. In order to get better insight, we evaluated clustering of As by X-ray photoelectron spectroscopy (XPS). Figure 6 shows $As3d_{5/2}$ spectra measured after TPJ and μ-TPJ irradiation. The binding energy was calibrated with the $Si2p_{3/2}$ peak due to Si(100) at 99.3 eV and intensity was normalized by the $Si2p_{3/2}$ peak intensity of Si(100). Here, As^{0+} is reported

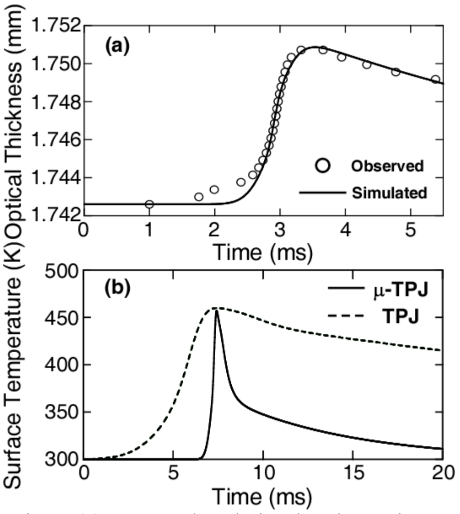

Fig.1. (a)Measured and simulated transient optical thickness variations. (b)Transient temperature variations.

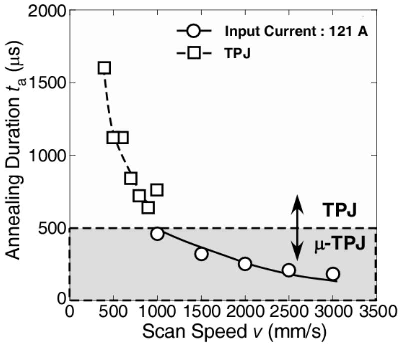

Fig.3. t_a as a function of different v during μ-TPJ irradiation.

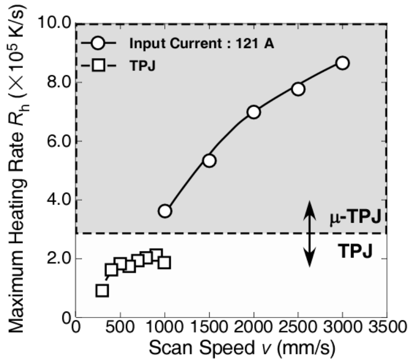

Fig.4. R_h as a function of different v during μ-TPJ irradiation.

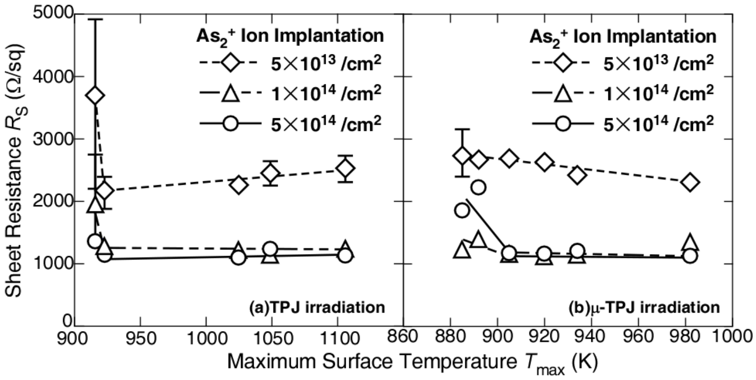

Fig.5. R_S values as functions of T_{max} during (a)TPJ or (b)μ-TPJ irradiation.

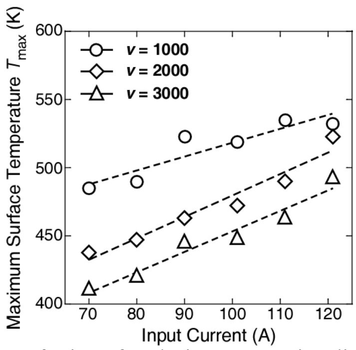

Fig.2. T_{max} of Si wafer during μ-TPJ irradiation with different input current.

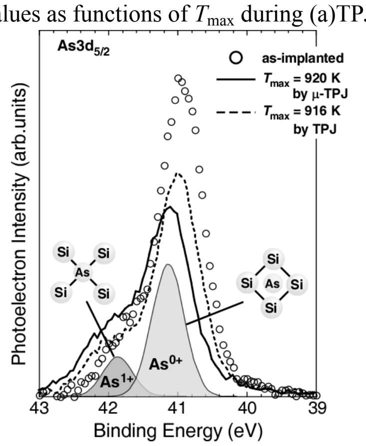

Fig.6. As3d$_{5/2}$ spectra measured after TPJ and μ-TPJ irradiation. The binding energy was calibrated with the Si2p$_{3/2}$ peak due to Si(100) at 99.3 eV and intensity was normalized by the Si2p$_{3/2}$ peak intensity of Si(100).

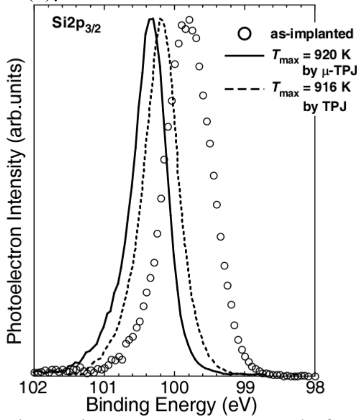

Fig.7. Si2p$_{3/2}$ spectra measured after TPJ and μ-TPJ irradiation. Intensity was normalized by the Si2p$_{3/2}$ peak intensity of as-implanted sample.

as non-activated component and a component (As^{1+}) which is chemical shift of 0.9 eV is activated component of As [5]. Regardless of almost equal T_{max} during TPJ and μ-TPJ irradiation, the relative amount of activated As after μ-TPJ irradiation is larger compared to TPJ case. This result indicated that microsecond annealing can be effective to activate As with suppressing clustering and interstitials. Figure 7 shows Si2p$_{3/2}$ spectra measured after TPJ and μ-TPJ irradiation. Intensity was normalized by the Si2p$_{3/2}$ peak intensity of as-implanted sample. Si2p$_{3/2}$ signal shift after μ-TPJ irradiation is lager than TPJ irradiation. Here, this shift is attributed to shallowing of fermi level which means larger electron density. This result indicated that activation of As by μ-TPJ irradiation is useful for efficient activation of As in USJ.

3. Conclusion

We carried out generation of high power density TPJ for microsecond RTA by using a small orifice of 0.8 mm diameter instead of 2.0 mm to concentrate TPJ and could be annealing a range of microsecond annealing. We activated As into Si wafers by this annealing technique using μ-TPJ and could be efficient activation of As in comparison to TPJ irradiation.

4. Acknowledgements

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