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Millisecond Rapid Thermal Annealing of Si Wafer Induced by High Density Thermal Plasma Jet Irradiation

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1. Introduction

With the scaling of MOSFETs, strict requirements for source and drain extension such as small junction depth and low sheet resistance have to be satisfied. Substitutional doping of impurities to Si lattice with a concentration beyond equilibrium soluble limit has to be achieved without significant diffusion of dopant atoms. For the formation of ultra-shallow junction, millisecond rapid thermal annealing (RTA) such as flash lamp annealing [1] has been studied intensively. Si wafer is preheated to ~ 1000 K and then the surface is heated about 600 K within a few milliseconds. Accordingly, 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 [2, 3]. During the RTA, a periodic oscillation is observed in transient reflectivity of Si wafer, which is originated from change in optical thickness due to heat diffusion. By analyzing the oscillation, temperature distribution in Si wafer is obtained precisely with millisecond time resolution. As a result, it was clarified that the maximum surface temperature during TPJ annealing reached ~ 510 K [2, 3], which is roughly 1300 K lower than compared to the case of quartz. This is because the thermal conductivity of Si (129.2 $W\bullet m^{-1}K^{-1}$) is two orders of magnitude higher than that of quartz (1.3 $W\bullet m^{-1}K^{-1}$). Practically, Si wafer surface have to be heated as high as 600 K.

In this work, we have investigated TPJ irradiation condition and Si wafer temperature. Especially, much effort has been carried out to generate high density TPJ, so that Si wafer surface can be heated more than 600 K within millisecond.

2. Experimental

In the experiment, a double-side polished, 0.7-mm-thick n-type Si (100) wafer was used. Millisecond RTA was performed by irradiating the wafer with TPJ. The thermal plasma source used in the experiment is schematically shown in Fig. 1. The W cathode and the water-cooled Cu anode separated 1.0 to 3.0 mm from each other were connected to a power supply. Arc discharge was generated by supplying DC power (p) of 2.0 to 2.4 kW, where the DC voltage was 13.3 to 15.6 V with a constant discharge current of 150A, between the electrodes under an Ar gas flow rate of (f) 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 300 to 1000 mm/s. The distance between the plasma source and the substrate (d) was changed from 0.6 to 2.5 mm. For the measurement of the temperature profile of a Si wafer during RTA, an optical probe was used, as shown in Fig. 1. 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.

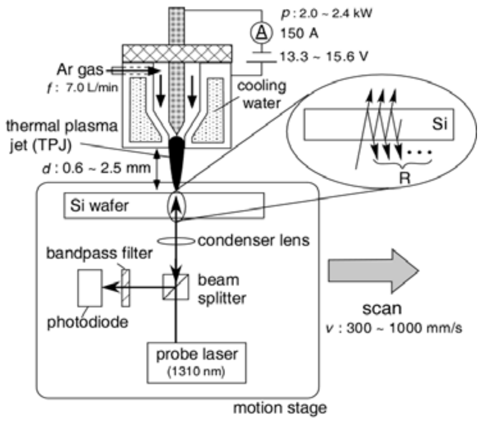

Fig.1. Schematic diagram of thermal plasma jet (TPJ) annealing of Si wafer.

3. Results and discussion

In this experiment, we used a small orifice of 2 mm in diameter instead of 4 mm to concentrate TPJ. Figure 2(a) shows an example of transient reflectivity obtained under an annealing condition of v = 300 mm/s and d = 0.6 mm. The oscillation in the transient reflectivity is due to the interference of the incident light multiply reflected between the top and bottom surface of the wafer as schematically shown in the inset of Fig. 1. Since the refractive index of Si (n_{Si}) changes with temperature, the optical thickness of Si wafer during the annealing changes in accordance with heat diffusion and this induces the oscillation. We extracted the optical thickness variation from the number of peaks and valleys as shown by the open diamonds in Fig. 2(b). By simulating the change in optical thickness on the basis of heat diffusion and optical interference, we can precisely reproduce transient optical thickness variations as shown by the solid line in Fig. 2(b). From the analysis, we obtained the transient temperature profile at different depth of the Si wafer with a millisecond time resolution as shown in Fig. 2(c). Consequently, Maximum surface temperature T_{max} of

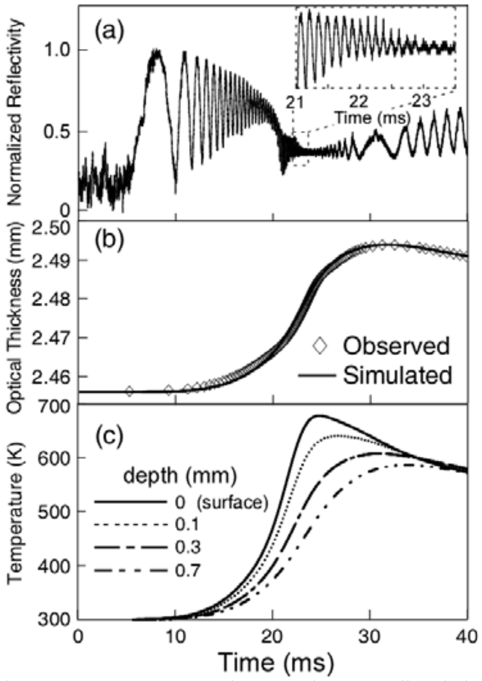

Fig. 2. (a)Measured transient reflectivity under v = 300 mm/s and d = 0.6 mm. (b)Measured and simulated optical thickness variation with time, and (c) transient temperature variations at different depth in Si wafer.

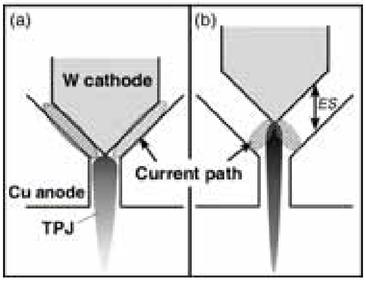

Fig. 3. Schematic illustration of TPJ concentration with large electrodes separation (*ES*).

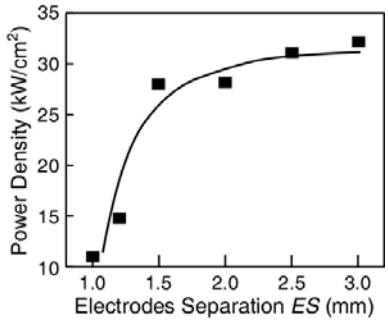

Fig. 4. Variation of power density as a function of cathode and anode separation.

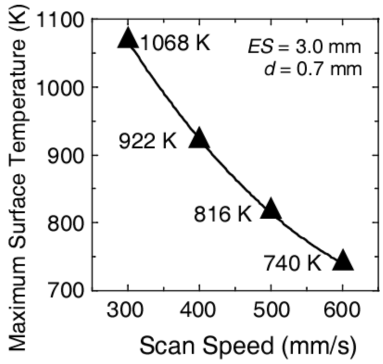

Fig. 5. Maximum surface temperature T_{max} of Si wafer with scan speed v.

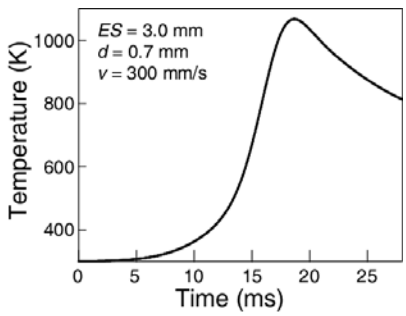

Fig. 6. Transient temperature variation of Si wafer surface annealed with high density TPJ.

Si wafer reached to 678 K, which is ~ 170 K higher than case of 4 mm orifice. This increase in temperature is attributed to the concentration of TPJ induced by thermal pinch effect due to water cooled small orifice. Still, further increase in TPJ density is required. Therefore, we pay attention to the distance between the cathode and the anode. When the electrodes separation (*ES)* is short, current path is relatively broad as illustrated in Fig. 3(a), while it is concentrated near the tip of W cathode with large *ES* as illustrated in Fig. 3(b). Higher plasma resistance and improved anode cooling by Ar gas flow also increases plasma density, accordingly high density TPJ could be generated. TPJ irradiation with different *ES* was conducted and the power density of TPJ was analyzed from transient reflectivity of Si wafer. It increased from 11.0 to 32.2 kW/cm^2 with increasing *ES* from 1.0 to 3.0 mm as shown in Fig. 4.

With the high density TPJ, we performed millisecond RTA under v of 300 to 600 mm/s and the maximum surface temperature during the anneal (T_{max}) is plotted in Fig. 5. Si wafer surface was heated to 1068 K under v of 300 mm/s. Figure 6 shows transient temperature variation inside the wafer observed under this annealing condition. The wafer surface was heated ~ 768 K within 10 ms. Which is sufficiently high temperature for impurity activation. Table I summarizes the T_{max}, annealing duration (t_a), heating rate (R_h), and cooling rate (R_c) as functions of scan speed v. These results indicate that we can control temperature, heating, and cooling rates in the order of $10^4 \sim 10^5$ K/s very accurately by changing TPJ irradiation conditions. Experiments for the application of TPJ annealing to ultra-shallow junction formation is now under investigation.

Table. 1. Characteristic values of the TPJ annealing.

v (mm/s)	300	400	600
T_{max} (K)	1068	922	740
t_a (ms)	4.0	3.0	2.0
R_h ($\times 10^5$ K/s)	1.60	1.72	1.81
R_c ($\times 10^5$ K/s)	0.40	0.42	0.46

4. Conclusions

High density TPJ is successfully generated by shrinking the orifice and by increasing the distance between anode and cathode. With 2 mm orifice and 3 mm electrodes separation, a power density as high as 32.2 kW/cm^2 is achieved. By irradiating the high density TPJ to Si wafer, its surface is heated to 1068 K within 10 ms under fast heating and cooling rates of 1.60 × 10^5 and 0.40 × 10^5, respectively. Present newly developed high density TPJ is a very powerful method for the further development of millisecond and even shorter RTA process.

Acknowledgements

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