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Activation of Dopant Atoms in Silicon by Microwave-Induced Rapid Heating with Wireless Carbon Heating Tubes

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Abstract

We report 2.45-GHz-microwave-induced heating system with carbon heating tubes (CHTs) which consists of 330-mm-long quartz tube filled with carbon powders and Ar gas. A metal cavity was developed to effectively introduce microwave to CHTs. Heating CHTs above 1000°C was experimentally demonstrated. 1.0×10^{15} cm^{-2} phosphorus implanted surface regions in crystalline silicon were activated and the sheet resistivity was decreased to 78 Ω/sq with an activation ratio of 80%. The photo-induced effective minority carrier lifetime increased to 120 μs because of reduction of defect induced by ion implantation.

1. Introduction

Thermal annealing is important to fabricate semiconductor devices. Many heating technologies have been developed and applied for fabrication processing [1,2]. We have proposed a wireless lamp of carbon heating tube (CHT), in which carbon powders were filled with inert gas in a quartz tube [3-6]. Conductive carbon is effectively heated via free carrier absorption of the microwave electromagnetic energy with excellent thermal properties of low specific heat and high heat proof. In this paper, we report application of the present CHT heating system to activation of ion-implanted dopant atoms. Decrease in the sheet resistivity (R_s) and increase in the effective minority carrier lifetime (τ_{eff}) are reported.

2. Experimental

Figure 1 shows a schematic image of the CHT heating system. A box-type cavity with open box top was made of stainless steel with a width, length, and height of 360, 360, and 200 mm. Its base had two microwave waveguides to introduce 2.45 GHz microwave up to an intensity of 6 kW. Metal inner cylinder with a diameter of 330 mm was installed in the cavity to concentrate the microwave intensity. The CHT was fabricated with a quartz tube with 330-mm long and 6-mm diameter containing 50-μm-diameter-carbon powders at a packing density of 0.45, which gave an average electrical conductivity of 200 S/m. Ar inert gas was filled in the quartz tube at 1400 Pa. The edges of the quartz tube were closed by thermal welding. Two quartz rods were jointed at the edges of a CHT by thermal welding to hold the CHT. 55 CHT rods were closely placed in parallel on the top of the cavity to cover the box top of the cavity. The box-type sample room was made of stainless steel conformally with a height of 60 mm placed on the CHTs. A radiation thermometer was used to monitor the temperature of the CHTs in real time from a small hole of the top wall of the sample room. The temperature of CHTs is controlled by a PID feedback circuit which sent a signal to the power source of the magnetron [7].

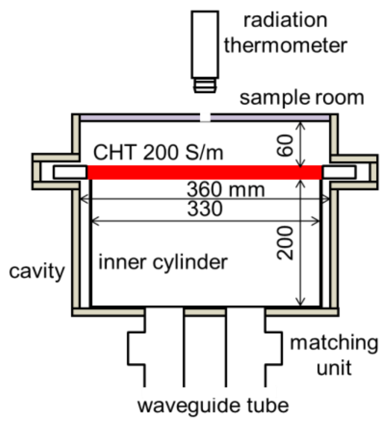

Fig. 1 Schematic image of the CHT heating system.

To investigate thermal activation of ion-implanted dopant atoms, 4-inch-diameter 17-Ωcm p-type silicon substrate with a thickness of 500 μm was prepared. The ion implantation of phosphorus and boron atoms with doses of 1.0×10^{15} cm^{-2} were conducted at 70 and 20 keV for the top and rear surfaces, respectively. The sample was placed on the CHTs and heated at 807°C for 5 min, which was the limit of the present equipment given by the maximum microwave power, the heat capacity, and the radiation power loss of 55 CHTs. Heating with 15 CHTs was also investigated to look for the possibility of rapid heating with high temperature by reducing the radiation power loss and heat capacity. We also prepared 80-Ωcm p-type silicon substrates. The ion implantation of phosphorus atoms was conducted with a dose of 1.0×10^{15} cm^{-2} at 70 keV for the top surface of the substrates. The samples were placed on the closely placed 15 CHT rods and heated at 770, 880, 1010, and 1090°C for 5 min. To estimate R_s and τ_{eff}, we measured the 9.35 GHz microwave transmittance of the samples in dark field and under 635-nm-light illumination [8].

3. Results and Discussion

Figure 2 shows the distribution of R_s in the 4-inch-diameter CHT-heated silicon substrate. The R_s of as-phosphorus and boron implanted sample was high of 572 Ω/sq, which was determined by free carrier density of silicon bulk. The R_s uniformly decreased ranging from 49 to 58 Ω/sq. This result indicates that the sample was uniformly heated and dopant atoms were effectively activated.

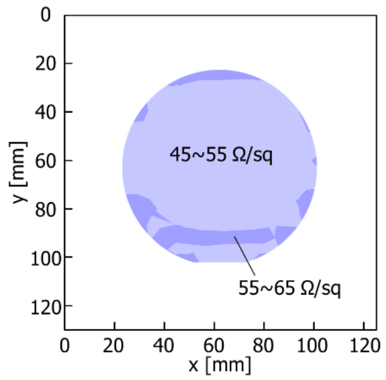

Fig. 2 Distribution of R_s in the CHT-heated silicon substrate.

Figure 3 shows (a) R_s of the ion-implanted regions and (b) τ_{eff} in the case of 635-nm light illumination to the phosphorus implanted surfaces as a function of CHT heating temperature. The R_s of as-implanted sample was high of 1550 Ω/sq because of the low electron carrier density in the silicon bulk, as shown by an arrow in Fig. 3(a). It decreased to 87, 77, 75, and 81 Ω/sq, as the CHT heating temperature increased to 770, 880, 1010, and 1090°C. Those experimental data resulted in that the implanted regions were activated with R_s of 92, 80, 78, and 85 Ω/sq, respectively. If the carrier mobility is assumed as 100 cm^2/Vs for doped silicon region, the activation ratio was estimated as 67, 78, 80, and 74%, respectively. The carrier generation were successfully achieved by the CHT heating. Although τ_{eff} was low of 9.6×10^{-7} s in the cases of as-phosphorus implanted surfaces, as shown by an arrow in Fig. 3(b), it increased to 1.2×10^{-4}, 1.2×10^{-4}, and 9.3×10^{-5} s as the CHT heating temperature increased to 770, 880, and 1010°C. These experimental τ_{eff} indicate that defect states caused by ion implantation were effectively reduced. However, τ_{eff} was markedly decreased to 2.5×10^{-6} s in the case of 1090°C heating. It has probably caused thermal stress in silicon and generated a high density of recombination defect states [9].

4. Conclusions

We demonstrated CHT heating equipment which consisted of 2.45-GHz microwave irradiation at 6 kW, a metal cavity with a 330-mm-diametered cylinder, 55 CHTs with a 6-mm-diameter and 330-mm-long quartz tube filled with conductive carbon powders at an average electrical conductivity of 200 S/m in Ar gas at 1400 Pa. The 55 CHTs were heated to 807°C by microwave irradiation at 5.7 kW. The 15 CHTs were heated above 1000°C because of lower heat capacity and lower irradiation power loss. The p-type silicon surface regions with 1.0×10^{15} cm^{-2} phosphorus ion implanted were heated at 770, 880, 1010, and 1090°C by CHT heating. The R_s of implanted regions decreased to 92, 80, 78, and 85 Ω/sq, respectively. The τ_{eff} increased to 1.2×10^{-4} s in the case of 635 nm light illumination to the phosphorus implanted surfaces for the 880°C-CHT-heated sample. Increase in the τ_{eff} indicates that defect states caused by ion implantation were effectively reduced.

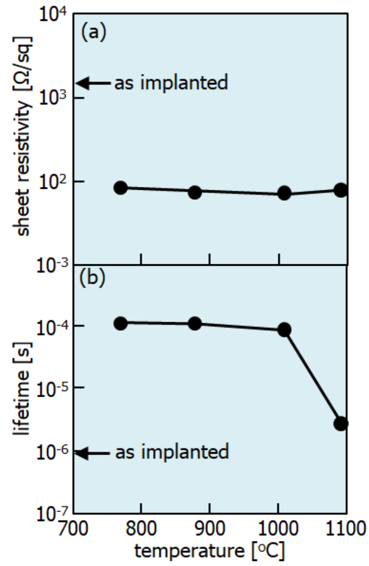

Fig. 3 (a) R_s of the ion-implanted regions and (b) τ_{eff} in the case of 635-nm light illumination to the phosphorus implanted surfaces as a function of CHT heating temperature. Arrows show the values of the as-implanted samples.

Acknowledgements

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References

[1] S. M. Sze, *Semiconductor Devices*, Wiley, New York (1985)

[2] Y. Taur and T, Ning, *Fundamental of Modern VLSI Physics*, Cambridge University Press, Cambridge, U. K. (1998) Chap. 2.

[3] T. Sameshima, T. Miyazaki, G. Kobayashi, T. Arima, T. Kikuchi, T. Uehara, T. Sugawara, M. Hasumi, I. Serizawa, IEEE Access **7** (2019) 23798.

[4] S. Kimura, K. Ota, M. Hasumi, A. Suzuki, M. Ushijima, T. Sameshima, Appl. Phys. A **122** (2016) 695.

[5] M. Yoshikawa, N. Nagai, M. Matsuki, H. Fukada, G. Katagiri, H. Ishida, A. Ishitani, I. Nagai, Phys. Rev. B **46** (1992) 7169.

[6] T. Sameshima and N. Andoh, Jpn. J. Appl. Phys. **44** (2005) 7305.

[7] Aidan O'Dwyer, *Handbook of PI and PID Controller Tuning Rules, 3rd ed.*, London, Imperial College Press (2009) p. 4-17.

[8] T. Sameshima, H. Hayasaka, T. Haba, Jpn. J. Appl. Phys. **48** (2009) 021204.

[9] T. Sameshima and S. Shibata, Jpn. J. Appl. Phys. **53** (2014) 061301.