Carbon Heating Tube Used for Rapid Heating System for Semiconductor Annealing

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We report a new heating system with a carbon heating tube (CHT) which was made by a quartz tube filled with carbon particles and Ar gas. A 60-mm long and 4-mm diameter CHT was set in a cavity in which 2.45-GHz microwave was introduced. Via complete absorption of the input microwave power by carbon in the CHT during multi-reflection of microwave in the cavity, the CHT was effectively heated to 1279°C at a microwave power of 200 W for 33 s. Crystallization of a 50-nm-thick amorphous silicon thin film formed on glass substrate was demonstrated by mechanically moving the silicon sample just below the heated CHT. A high crystalline volume ratio of 0.9 was achieved.

1. Introduction

Thermal annealing is important to fabricate semiconductor devices such as thin film transistors (TFTs) and solar cells.[1-4] Activation and crystallization are achieved by heat treatment to form the pn junction and crystalline state.[5] Many heating technologies have been developed such as rapid thermal annealing, laser annealing[6-9], plasma jet annealing[10], and rapid thermal annealing.[11] We have recently proposed a combination of the carbon powder absorber with 2.45 GHz microwave irradiation as a simple rapid thermal annealing method.[12,13] Conductive carbon is heated via free carrier absorption of the electromagnetic energy of microwave generated from vibration of electrons in the cavity resonator of the magnetron. Carbon powders with a packing density of 0.08 achieved heating at the temperature of 1163°C by 1000 W microwave irradiation for 28 s. The activation and recrystallization of silicon implanted with boron and phosphorus atoms were also demonstrated.

In this paper, we propose a new heating systems with a lamp of carbon heating tube (CHT) for rapid thermal annealing for semiconductor device fabrication. We first present the heating system in detail. We then demonstrate 1279°C heating properties of the CHT by 2.45 GHz microwave irradiation. We also demonstrate crystallization of amorphous silicon films by the present heating system.

Experimental

Figure 1 shows (a) a schematic image of CHT and (b) a heating system with the CHT. Quartz tubes with 60-mm long and 4-mm inter diameter and 6-mm outer diameter were made. 2-μm-diameter-carbon powders with a 0.1-g weight were put in the quartz tubes: the packing density was controlled as 0.08, which was determined by the previous work as the best value for heating.[12] After carefully evacuating air gas inside the quartz tubes by a vacuum pump under keeping carbon powders stay in the quartz tubes, Ar inert gas was filled in the quartz tube at 10.5 Torr. The edges of the quartz tubes were closed by thermal welding. Two quartz rods were jointed at the edges of the CHT by thermal welding to hold the CHT. The CHTs is consequently heated by microwave irradiation with no loss of carbon powers via oxidation. Moreover, CHTs have no electrode wires, which gives a capability of highly thermal proof structure because the junction between lamp materials and the electrode metals has always a serious problem of thermally stress-induced damage. A CHT was placed

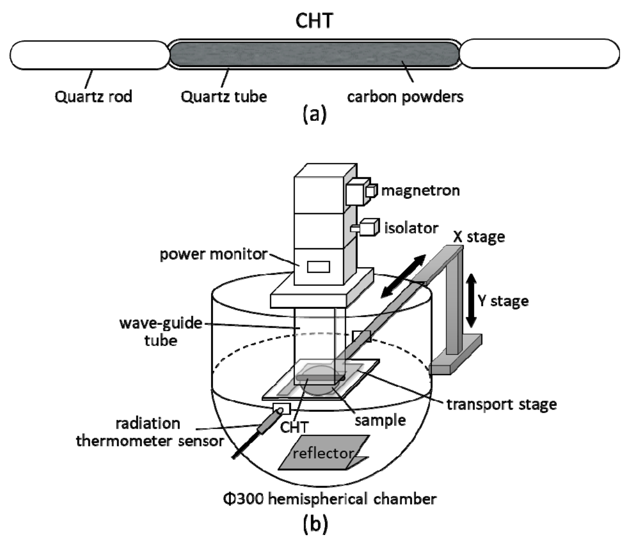

Fig. 1 (a) Schematic image of CHT and (b) a heating system with the CHT.

in the heating system as shown in Fig. 1(b), which consists of a magnetron for generating 2.45-GHz microwave with an electrical circuit for controlling a microwave power ranging from 100 to 1500 W, an isolator for blocking the reflectance of microwave backward the magnetron, a power monitor, a wave-guide tube, and a microwave cavity made by Al metals. The switching circuit controlled the intensity of microwave gradually increasing to a setting power by 3 s after the initiation. The Microwave generated in the magnetron was introduced to the cavity by the wave guide tube via the isolator and power monitor. The cavity was fabricated with a sophisticated structure to promote multiple reflection in the cavity, in which there were a wave-guide tube extended by 153 mm in the upper cylindrical part of the cavity and a reflection metal plate slant placed at the bottom spherical part of the cavity. That designed cavity achieved to effectively close microwave power in the cavity: the power monitor revealed a forward power of 500 W with a reverse power less than 10 W (detection limit). The CHT effectively absorbed the microwave power during the multiple reflection of microwave in the cavity. The cavity had a window port for observing light emission from CHT heated by microwave. A thermometer detecting 900-nm wavelength radiation light CHINO IR-FAS was used to monitor change in the temperature of the CHT in real time. The detection lower limit of the thermometer was about 550ºC. An infrared digital camera was also used to observe CHT heating. The Microwave was irradiated into the cavity for 33 s, in which the microwave intensity increased during initial 3 s and kept constant for 30 s. A mechanically moving stage was also installed in the cavity, as shown in Fig. 1(b) to move a sample just below the CHT for demonstration of heating by the CHT. 50-nm-thick amorphous silicon films formed on glass substrates were prepared by plasma enhanced chemical vapor deposition at 300ºC. The silicon film was annealed by CHT heated with continuous microwave irradiation at 200 W. The silicon film sample was moved at 0.12 mm/s in the normal direction just below the CHT. Uniform change in color of the silicon film was observed in 40 x40 mm^2 region by CHT heating. Raman scattering and optical reflectivity spectra measurements were used to estimate crystallization properties with the crystalline volume ratio.

Results and discussion

Figure 2 shows (a) a photograph of light emission from the CHT heated by 200-W microwave irradiation at 5, 33, and 38 s detected by the infrared camera and (b) changes in the temperature of the CHT with different powers ranging from 100 to 200 W during and after the microwave irradiation measured by the thermometer. Several spots emitting light was observed at 5 s of 200-W microwave irradiation, as shown in Fig. 2(a). Locally spontaneous heating in the CHT probably occurred in the initial stage. Subsequently, uniformly strong blight light emission was observed at 33 s in about 40-mm long region. This indicate that heat diffusion simultaneously occurred inside the CHT to make the temperature uniform in the CHT during microwave irradiation. The CHT effectively absorbed the microwave power and spatial-uniformly heated to a temperature high enough to emit blight light. The intensity of light emission was decreased uniformly after the termination of microwave as shown by the photograph at 38 s. This means that the CHT was cooled down uniformly. The temperature increased with time in the initial stage for every power case as shown in Fig. 2(b). This means that increase in the temperature was governed by heat capacity of the CHT. On the other hand, the increasing rate of temperature became low especially in the high microwave power case in the final stage of microwave irradiation. A radiation power loss caused by black-body radiation became important when the CHT was heated to high temperature. A high temperature of 1279ºC was observed at 33 s for 200 W. The maximum rate of temperature increase was obtained as 56 K/s in the case of a microwave power of 200 W. When the microwave irradiation was terminated, the temperature

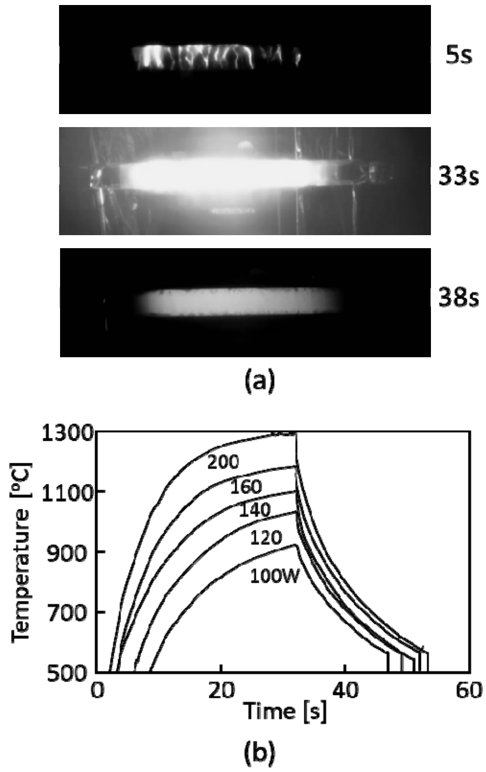

Fig. 2 (a) Photographs of light emission from the CHT heated by 200-W microwave irradiation at 5, 33, and 38 s and (b) changes in the temperature of the CHT with different powers ranging from 100 to 200 W for 33 s.

of CHT is rapidly decreased because of the radiation loss.

Figure 3 shows the maximum temperature of the CHT as a function of microwave power ranging from 100 to 200 W for 33 s irradiation. The CHT was heated to 932ºC at 100 W. The maximum temperature increased to 1279ºC as the microwave power increased to 200 W. The maximum temperature was approximately determined by balance between the input microwave power and blackbody radiation loss as shown by solid curve calculated by the blackbody radiation theory. The temperature approximately increased to the microwave power to the power of 0.25, (microwave power)$^{0.25}$. Those results of Figs. 2 and 3 show rapid and clean heating system with a low power consumption was realized.

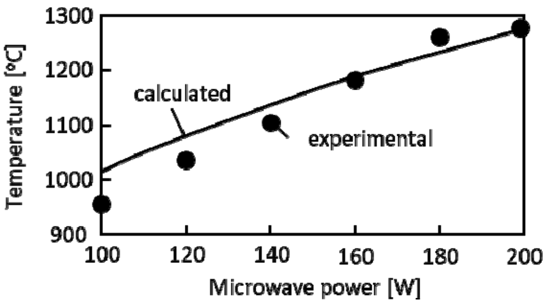

Fig. 3 Maximum temperature of the CHT as a function of microwave power

Figure 4 shows the optical reflectivity spectra of the silicon film sample heated by the CHT measured at the central 8x8 mm^2 region at (a) the top and (b) rear surfaces. Large E_1 and E_2 peaks owing to the optical transition in the tetrahedral crystalline band appeared at 370 and 275 nm in the optical reflectivity spectra measured at the top and rear surfaces of the silicon film sample. Marked changes in the optical reflectivity caused by the optical interference effect between silicon top surface and bottom interface were also observed for wavelength between 400 and 1000 nm. These characteristics indicate that the silicon films were crystallized in the whole thickness region. The experimental optical spectra were analyzed by numerical calculation program.[14] The dashed curves shown in Fig. 4 (a) and (b) were calculated spectra with a crystalline volume ratio of 0.9, which well fitted to experimental spectra. The silicon film was well crystallized and disordered region was almost eliminated.

Figure 5 shows the normalized Raman scattering spectra of the silicon film sample crystallized by the CHT measured at 19 points over the crystallized region and the as-deposited amorphous silicon film sample. The crystallized silicon film had a sharp peak associated with the phonon mode of the crystalline lattice, while

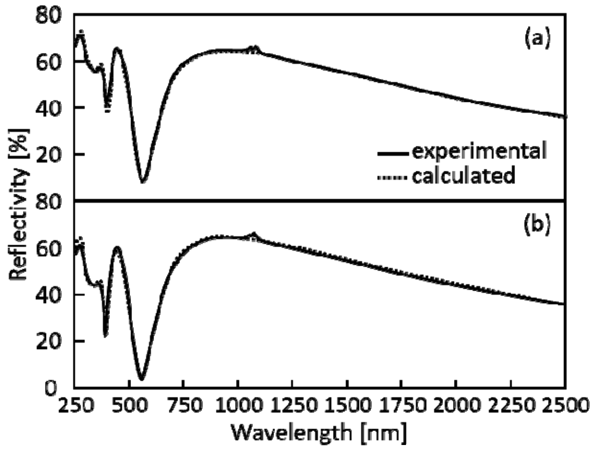

Fig. 4 Optical reflectivity spectra of the silicon film sample heated by the CHT at 200 W measured at (a) the top and (b) rear surfaces.

the as-deposited amorphous silicon film had a broad peak associated with phonon of disordered bonding structure. The 19 shapes of the sharp peak were similar. The peak wavenumber ranged from 514 to 516 cm^{-1}, which was lower than that of thermally relaxed crystalline silicon. This indicates the tensile stress existence between the silicon film and quartz substrate. The full width at half maximum ranged from 7.0 to 9.5 cm^{-1}. Broad tail associated with the phonon mode of nano-crystalline and amorphous structures at around 500 and 440 cm^{-1} were very small. Those results mean that the homogeneous crystalline state was realized.

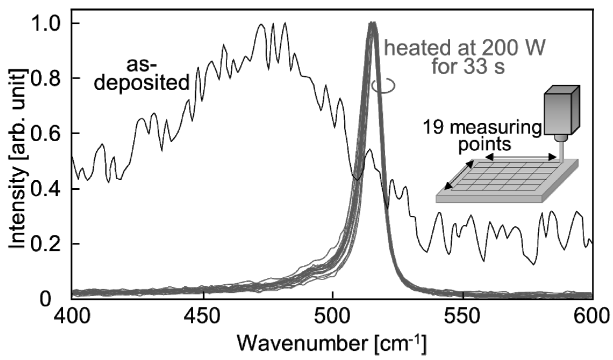

Fig. 5 Normalized Raman scattering spectra of the silicon film sample crystallized by the CHT measured at 19 points over the crystallized region and the as-deposited amorphous silicon film sample.

The present heating system with the CHT will be applied for various heat treatment. High temperature heating of the CHT by low microwave power was demonstrated. Moreover, the CHT with no electrode has an advantage for its application to heat treatment in severe environment for example high humidity atmosphere. The CHT with no electrode will also make it possible to realize simple heating system because no complicated wiring is necessary.

4. Conclusions

A new heating system with a carbon heating tube (CHT) was proposed. The CHT was made with a quartz tube filled with carbon particles and Ar gas. A 60-mm long and 4-mm inner diameter CHT was set in a cavity in which 2.45-GHz microwave was introduced. The sophisticated designed cavity completely closed microwave with negligible small of microwave reflectance loss. The CHT effectively absorbed microwave during multi-reflection of microwave in the cavity and heated to a high temperature. The temperature and heating rate were obtained as 1279ºC and 56 K/s for 33-s microwave irradiation at a power of 200 W. Crystallization of a 50-nm-thick amorphous silicon thin film formed on glass substrate was demonstrated by mechanically moving the silicon sample just below the heated CHT with a microwave power of 200 W. Optical reflectivity spectra measurements revealed that crystallization in the whole film thickness was achieved. A high crystalline volume ratio of 0.9 was obtained. Raman scattering spectra measurement resulted in sharp peak of crystalline phonon mode. The peak shape was similar among 19 measurement points. Homogeneous crystalline state was realized.

Acknowledgments

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References

1) S. Uchikoga amd N. Ibaraki: Thin Solid Films, 383, (2001) 19.
2) S. Inoue, K. Sadao, T. Ozawa, Y. Kobashi, H. Kwai, T. Kitagawa and T. Shimoda: Tech. Dig. IEDM, 2000, p. 197.
3) K.Shibata and H. Takahashi: Workshop on Active Matrix Liquid Crystal Displays'01, 2001, p. 219.
4) S. M. Sze: Semiconductor Devices, Wiley, New York, 1985.
5) Y. Taur and T, Ning: Fundamental of Modern VLSI Physics, Cambridge University Press, Cambridge ,U. K., Chap. 2, 1998.
6) R. F. Wood and C. E. Giles: Rhys. Rev. B23 (1981) 2923.
7) T. Sameshima, S. Usui and M .Sekiya: IEEE Electron Device Lett. 7 (1986) 276.
8) K. Sera, F. Okumura, H. Uchida, S. Itoh, S. Kaneko and K. Hotta: IEEE Trans. Electron Devices 36 (1989) 2868.
9) T. Serikawa, S. Shirai, A. Okamoto and S. Suyama: Jpn. J. Appl. Phys. 28 (1989) L1871.
10) S. HIGASHI, H. KAKU, H. MURAKAMI, S. MIYAZAKI, H. WATAKABE, N.ANDO and T.SAMESHIMA: Jpn. J. Appl. Phys. 44 (1989) 108.
11) G Mannino: Appl. Phys. Lett. 78 (2001) 889.
12) T. Nakamura, S. Yoshidomi, M. Hasumi, T. Sameshima and T. Mizuno: Mater. Res. Soc. Symp. 1666 (2014) A13-09.
13) S. Kimura, K. Ota, M. Hasumi, A. Suzuki, M. Ushijima and T. Sameshima: Appl. Phys. A. 122 (2016) 695.
14) K. Ukawa, Y. Kanda, T. Sameshima, N. Sano, M. Naito and N. Hamamoto: Jpn. J. Appl. Phys. 49 (2010) 076503.