Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp326-327

Infrared Semiconductor Laser Annealing Used For Activation of Silicon Implanted With Boron and Phosphorus Atoms

N.Sano[1], K.Ukawa[2], T. Sameshima[2], M.Naito[3] and N. Hamamoto[3]
[1] Hightec Systems Corporation, Yokohama, 222-0033, Japan (sano@hightec-sys.com)
[2] Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan
[3] Nissin Ion Equipment Co., Ltd. Koka, Shiga 528-0068, Japan

I. Introduction

Rapid heating is important for activating silicon implanted with dopant atoms in order to fabricate semiconductor devices with a low thermal budget. A high activation ratio and no marked impurity diffusion are required to fabricate extremely shallow source/drain extension (SDE) region within a depth of 10 nm order in metal-oxide-semiconductor (MOS) transistor devices for 45 nm node and smaller, which cannot be realized by conventional rapid thermal annealing (RTA) [1]. Flash lamp annealing (FLA) or laser spike annealing (LSA) for several milliseconds and excimer laser annealing for the order of nanoseconds have been developed [2-4]. Moreover, activation of deep silicon region is also important for device fabrication, for example, insulated gate bipolar transistors (IGBT) [5]. We have developed continuous wave (CW) infrared semiconductor laser annealing using carbon layer as an optical absorption layer.[6.7] Infrared semiconductor lasers with a power of 10 kW and a high conversion efficiency of 50% are available are available and attractive for rapid laser annealing with a short tact time. In order to solve a problem of low optical absorbance of Si in the infrared region, we used carbon as a photo absorption layer. In this paper, <u>we report ten-microseconds rapid activation of silicon implanted with boron and phosphorus atoms using CW infrared semiconductor laser.</u> We demonstrate activation of dopant atoms distributed 2 μm deep from the surface as well as located at the just surface region within 10 nm from the surface with no significant dopant diffusion. We also report analysis of free carrier optical absorption to investigate carrier concentration and its in-depth distribution.

II. Laser annealing, sample preparation and evaluation

Fig. 1 shows a schematic image of laser irradiation. A CW semiconductor laser diode with a wavelength of 976 nm and a power of 40 W was used. Optics was developed in order to shape a narrow and uniform line laser beam. The laser beam length along to beam movement is 15 μm. The beam width was 500 μm. A laser intensity of 500 kW/cm^2 was achieved at the sample surface. The laser intensity along to width uniformly distributed within plus or minus 4% of the average intensity. Samples were mounted on an X-Y stage driven by linear motors When a sample was moved at 1 m/s, 15 μs rapid laser irradiation was achieved.

Boron clusters with a boron concentration of 1×10^{15} cm^{-2} were implanted with an acceleration energy of 6 keV into n-type silicon substrates with a resistivity of 10 Ωcm. Phosphorus ions with a concentration of 1×10^{15} cm^{-2} were also implanted at 100, 300 and 500 keV into p-type silicon substrates of 13 Ωcm. Carbon films with a thickness of 200 nm were subsequently formed on the silicon surface as a photo absorption layer by the sputtering method. The optical absorbance was 75 % at 976 nm. The CW infrared semiconductor laser at 40 W was irradiated to the carbon surface during sample moving. After laser irradiation, carbon layers were removed by oxygen plasma treatment. Secondary ion mass spectroscopy (SIMS) analysis was conducted to measure the in-depth profiles of boron and phosphorus concentrations. The sheet resistance was estimated by electrical current measurement. The free carrier optical absorption effect was analyzed in order to investigate the carrier concentration, its in-depth profile as well as the sheet resistance. Optical transmissivity spectra were measured by conventional Fourier transform infrared (FTIR) spectrometry after polishing of the rear surface of the samples. The optical transmissivity spectra were analyzed using a numerical calculation program, which was constructed with free carrier absorption effect and the optical interference effect using a model of air/60-layered doped Si/Si substrate structures [8]. The free carrier in Si causes changes in the real refractive index and extinction coefficient. These changes depend on the carrier density and carrier mobility. The most possible in-depth distributions of the electron carrier density and carrier mobility were obtained by fitting the calculated transmissivity spectra to the experimental transmissivity spectra.

III. Results and discussion

Figure 2 shows the sheet resistance as a function of laser dwell time for samples implanted with boron cluster at 6 keV. The sheet resistance decreased to 1000 Ω/sq and leveled off above 40 μs. This result shows that activation of boron atoms was achieved well by laser heating longer 40 μs. Figure 3 shows boron atoms in-depth profiles of the samples as-implanted and laser-annealed for 40 μs. Boron atoms concentrated at the surface region within a depth of 10 nm for the both cases. There was no substantial diffusion of boron into the deep region during laser annealing. The results of Figs 2 and 3 indicate that boron atoms were activated well in solid phase by rapid laser annealing for 40 μs. SIMS measurement revealed that total amount of boron atoms in silicon was 6.0×10^{14} cm^{-2} for sample as-implanted and 3.3×10^{14} cm^{-2} for sample after laser annealing. Figure 4 shows FTIR transmissivity spectra for sample as-implanted and laser annealed for 40 μs. Figure 4 also shows a spectrum calculated by a numerical program of free carrier optical absorption using hole and electron carrier in-depth concentrations under the assumption of complete activation of boron atoms whose profile was given in Fig.3. The transmissivity of laser-annealed sample decreased because of free carrier optical absorption effect. The analysis of free carrier photo absorption revealed a total carrier concentration of 3.1×10^{14} cm^{-2}, which was close to the total boron atom concentration measured by SIMS. This means that boron atoms were well activated by laser annealing. The analysis also resulted in a sheet resistance of 1400 Ω/sq, which was close to that obtained by electrical current measurement.

Figure 5 shows phosphorus concentration in-depth profiles for samples as implanted and laser annealed with a dwell time of 43 μs in the cases of implantations at 100, 300 and 500 keV. The depths of the peak phosphorus concentration were 125, 370 and 620 nm for ion implantation at 100, 300, and 500 keV, respectively. Phosphorus atoms reached into 2 μm deep in the case of 500 keV. There was no substantial change in the phosphorus concentration profiles caused by 43 μs laser annealing for each implantation case. The heating duration was short enough to keep initial phosphorus in-depth profiles. The total phosphorus concentration incorporated in silicon was 1.0×10^{15} cm^{-2} for all samples as implanted and laser annealed. Figure 6 shows FTIR transmissivity spectra of the samples as implanted and laser annealed for a dwell time of 43 μs for phosphorus implantations at 100, 300 and 500 keV. Figure 6 also shows spectra calculated by a numerical program of free carrier optical absorption using electron and hole carrier in-depth concentrations under the assumption of complete activation of phosphorus atoms whose profiles were given in Fig.5. The spectra significantly changed after laser annealing because of free carrier optical absorption. A valley appeared in the spectrum between 1000 and 3000 cm^{-1} for implantation at 300 keV. Moreover, a small oscillation was observed between 1000 and 4000 cm^{-1} for implantation at 500 keV after laser annealing. These result from an optical interference effect between air and activated doped layers. Precise analysis of FTIR spectra gave the carrier concentration and sheet resistance as shown in Fig. 7. The carrier concentration was almost $1.0\text{x}10^{15}$ cm^{-2}. This indicates that phosphorus atoms were completely activated. The sheet resistance slightly decreased from 104 and 66 Ω/sq as the implantation energy increased to 500 keV because of increase in the carrier mobility caused by low impurity scattering..

IV. Conclusions

We investigated semiconductor laser annealing for activation of silicon implanted with boron and phosphorus atoms. Implantations of 1.0×10^{15} cm^{-2} boron clusters at 6 keV and 1×10^{15} cm^{-2} phosphorus ions at 100, 300 and 500 keV were conducted. 200 nm thick carbon films were formed on the silicon surface as a photo absorption layer using sputtering method. The line laser beam with a beam length of 15 μm was irradiated to samples at 40 W. SIMS measurement revealed that there was no substantial change in the boron and phosphorus concentration profiles in the case of laser annealing for 40 and 43 μs. The sheet resistivity decreased to 1000 Ω/sq in the case of boron implantation. FTIR transmissivity spectra and free carrier analysis resulted in almost complete activation of boron atoms. Phosphorus atoms were also completely activated by laser annealing. The sheet resistance decreased to 66 Ω/sq for sample implanted at 500 keV, whose phosphorus distributed into 2 μm in-deep. These results show that the present laser irradiation method has a capability of activation of boron and phosphorus atoms distributed from the surface to 2 μm deep.

References

[1] M. Mehrotra, et. Al, IEDM Tech. Dig. 419, 1999.
[2] T. Ito, et al, Ext. Abstr. 3rd Int. Workshop on Junction Technol., 23, 2002.
[3] A. Shima and A. Hiraiwa, Jpn. J. Appl. Phys. 45 5708, 2006).
[4] K. Goto, et. al, IEDM. Tech. Dig. 931, 1999..
[5] A. R. Hefner, Industry Applications, IEEE Trans. 30, 405, 1994.
[6] N. Sano, et al., Jpn. J.Appl. Phys. 46, L620,   2007.
[7] T. Sameshima, et al., Jpn. J.Appl. Phys. 46, 6474, 2007.
[8] T. Sameshima, et. al, Jpn. J. Appl. Phys. 38, 1892, 1999.

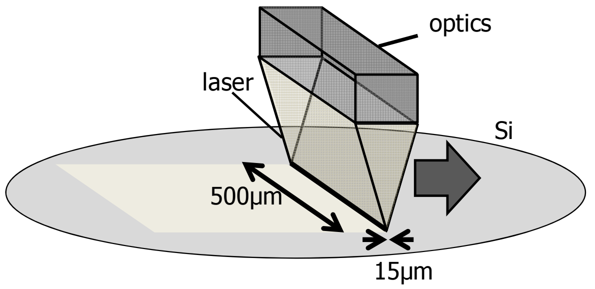

Fig.1 Schematic image of laser irradiation

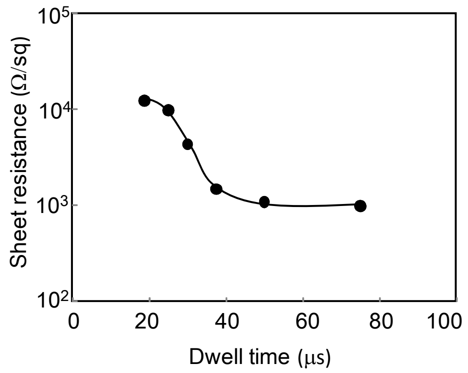

Fig.2 Sheet resistance as a function of laser dwell time for samples implanted with boron clusters at 6 keV.

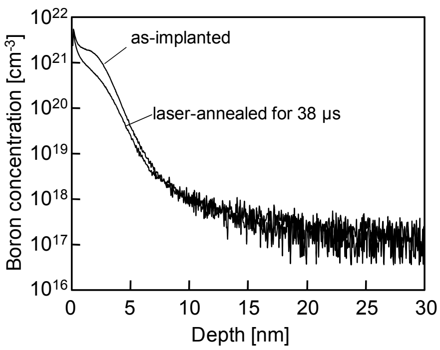

Fig.3 Boron atoms in-depth profiles for samples as implanted and laser annealed for 40 μs.

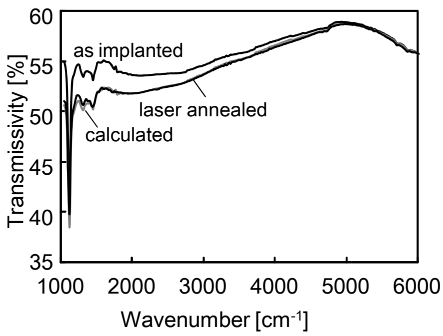

Fig.4 FTIR transmissivity spectra for samples boron as implanted and laser annealed for 40 μs. A spectrum calculated by a numerical program of free carrier optical absorption was also presented.

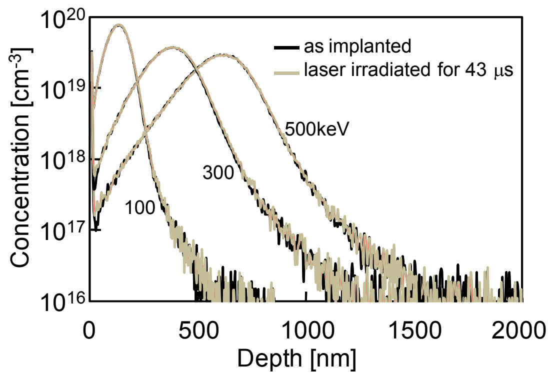

Fig.5 Phosphorus concentration in-depth profiles for samples as implanted and laser annealed with a dwell time of 43 μs in the cases of implantation at 100, 300 and 500 keV.

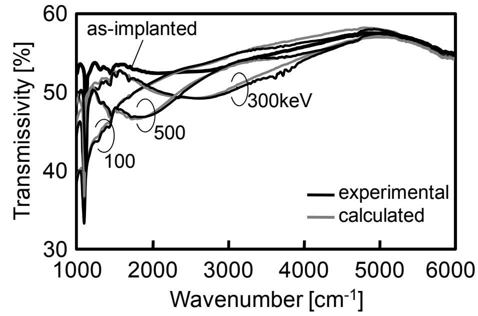

Fig.6 FTIR transmissivity spectra of the samples as implanted and laser annealed for a dwell time of 43 μs for phosphorus implantation at 100, 300 and 500 keV. Spectra calculated by a numerical program of free carrier optical absorption were also presented.

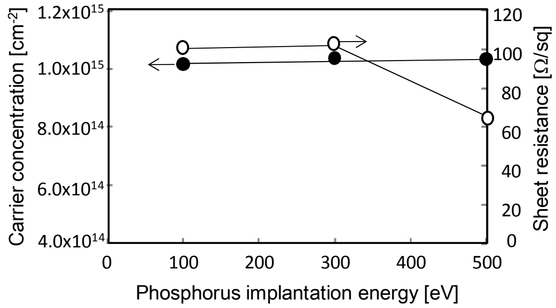

Fig.7 Carrier concentration and sheet resistance as a function of phosphorus implantation energy for samples implanted with $1x10^{15}$ cm^{-2} phosphorus atoms and annealed by laser for 43 μs.