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Activation of Implanted Boron Atoms in Silicon Wafers by Infrared Semiconductor Laser Annealing Using Carbon Films as Optical Absorption Layers

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We report continuous wave (CW) IR semiconductor laser annealing for the activation of boron atoms implanted into an n-type Si wafer with diamond-like carbon (DLC) films as optical absorption layers. Boron atoms were implanted at 10 keV at doses of 5×10^{14}, 1×10^{15}, and 1.5×10^{15} cm^{-2}. The depth at the boron concentration of 10^{18} cm^{-2} was 50 nm. Samples were annealed by irradiation at 66.5–80.5 kW/cm^2 and 2.6 ms. The sheet resistance of the sample markedly decreased to 531 Ω/sq for implantation at 1.5×10^{15} cm^{-2} by laser annealing. Boron atoms were almost completely activated at a carrier density near the boron concentration for implantation at 10 keV. The largest diffusion length of boron atoms was 3 nm.

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The activation of impurity atoms implanted into Si wafers using a rapid annealing technology is expected to be increasingly significant for the formation of ultra-shallow junctions.[1–4] A high activation ratio and the absence of marked impurity diffusion are required to fabricate an extremely shallow source/drain extension (SDE) region with depth of 10 nm order in metal–oxide–semiconductor (MOS) transistor devices for a 45 nm node and beyond, which cannot be realized by conventional rapid thermal annealing (RTA). Flash lamp annealing (FLA) or laser spike annealing (LSA) for a duration in the order of milliseconds and excimer laser annealing for a very short time in the order of nanoseconds have been carried out for this purpose.[2–4] Furthermore, we have also proposed an annealing method on the order from 10^{-4} to 10^{-3} s using IR semiconductor laser diodes.[5–7] An IR semiconductor laser is an attractive light source because high-power (~10 kW), high-efficiency (~50%), and stable laser diode systems have already been developed and commercially available. We use a diamond-like carbon (DLC) film as an optical absorption layer in order to solve the problem of the low optical absorbance in the IR regions for Si. DLC layers can have a high optical absorbance at IR range because of a high extinction coefficient and a low refractive index giving a low reflection loss. A high thermal durability to a temperature around 5000 K enables the carbon layers to act as heat sources for the underlying Si substrates to be annealed at a high temperature.[8)]

In this paper, we report the annealing of Si implanted with boron atoms using an IR semiconductor laser. We demonstrate the effective activation of dopant atoms and low electrical resistance. We also report that initial boron concentration in-depth profiles were not significantly changed by laser annealing.

Thin silicon dioxide (SiO_2) layers with a thickness of 7.9 nm were grown over n-type Si(100) substrates with a resistivity of 5–15 Ω cm prior to an implant operation as screen oxide layers. The ion implantation of boron impurities using BF_2^+ ions was conducted for the Si substrates. The ion energy was 10 keV. The doses were 5×10^{14}, 1×10^{15}, and 1.5×10^{15} cm^{-2}. The pre-amorphization of junctions by Ge or Si implantation (PAI) was not carried out. DLC films with a thickness of 200 nm were formed on the Si surface by unbalanced magnetron sputtering (UBMS) with Ar gas.[9)] Optical measurement revealed that DLC/Si has an optical absorbance of 85% at 940 nm, which is the wavelength of our laser light. Samples were normally irradiated with a fiber-coupled continuous wave (CW) laser diode with a wavelength of 940 nm at a power of 19–23 W in air at room temperature. The diameter of the core and the numerical aperture (NA) of the fiber were 400 µm and 0.22, respectively. The diverged beam was concentrated on the sample surface by a combination of six aspherical lenses. The power distribution of the beam was Gaussian like. The size of the beam spot was 180 µm at the full width at half maximum (FWHM) of the laser power distribution. The peak power density was 66.5–80.5 kW/cm^2 on the sample surface. Samples were mounted on an X–Y stage driven by linear motors at a constant velocity of 7 cm/s in the Y direction. Thus, the dwell time of the laser beam, which is defined as (beam size)/(scanning velocity), was 2.6 ms. The stage was also moved with a 50 µm step in the X direction. After laser irradiation, the carbon layers were removed by oxygen plasma treatment. Then, the screen oxide layers were also removed using HF solutions.

Raman scattering spectral measurement using a 514.5 nm Ar ion laser as an excitation light source was carried out in order to analyze crystalline states on the Si surface. Then, the sheet resistance measurements were carried out. The carrier density of the sample implanted with boron atoms at a dose of 1.5×10^{14} cm^{-2} and annealed at 23 W (80.5 kW/cm^2) was also estimated by Hall effect measurement. The boron concentration in-depth profile was measured by secondary ion mass spectroscopy (SIMS) analysis.

Figure 1 shows the Raman scattering measurement results for the sample implanted with boron atoms at a dose of 1.5×10^{15} cm^{-2}. The laser irradiation powers used were 0 (as-implanted), 19, 20, 22, and 23 W. An as-implanted sample had a higher intensity in the wave number range of 400–500 cm^{-1} than a laser-irradiated sample. The broad band around 480 cm^{-1} for the as-implanted sample indicates that the Si surface was partially amorphized by BF_2^+ ion

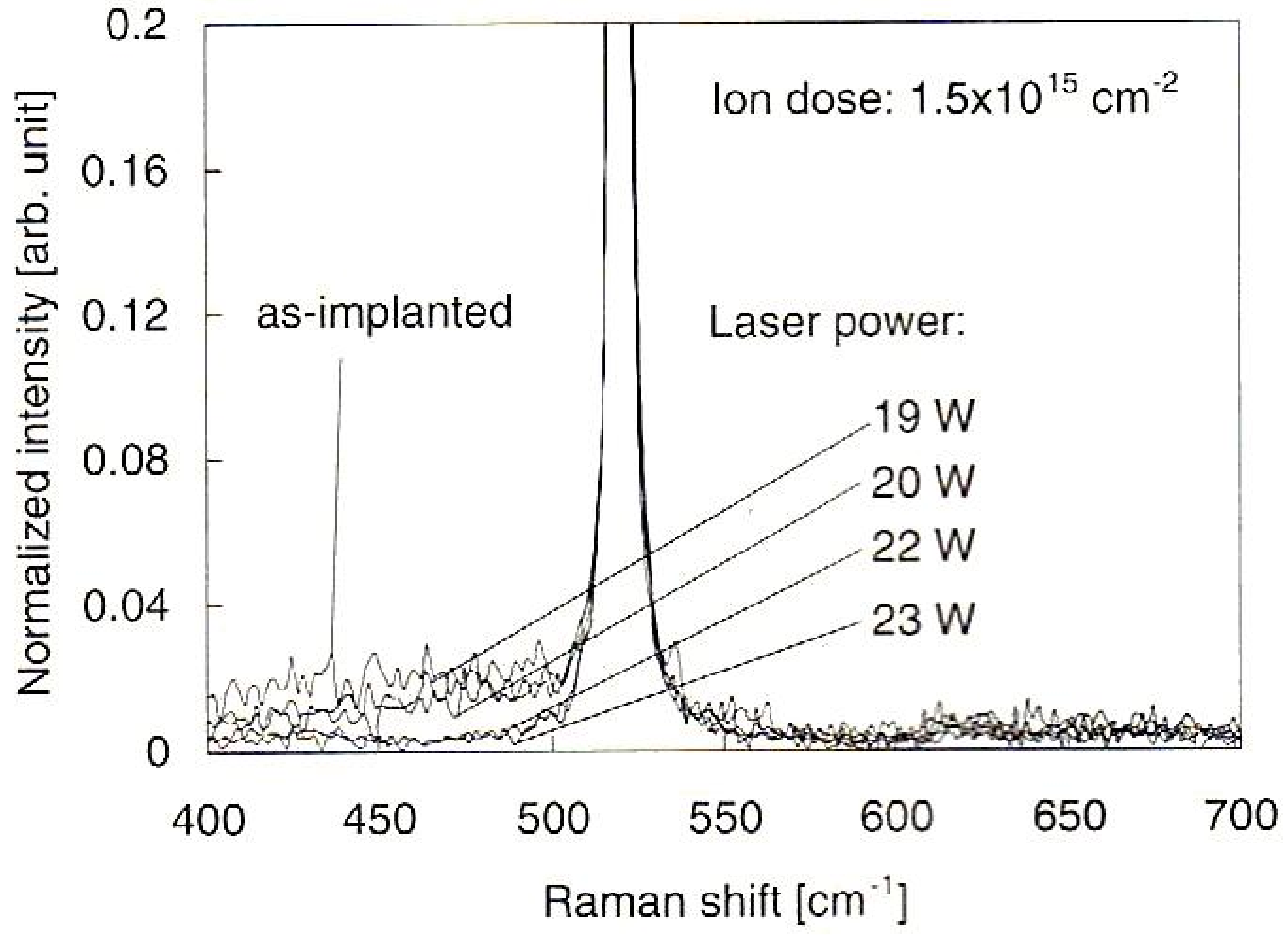

Fig. 1. Raman scattering spectra of surface regions of 1.5×10^{15}-cm^{-2}-as-implanted and laser-annealed samples for laser powers of 0 (as-implanted), 19, 20, 22, and 23 W.

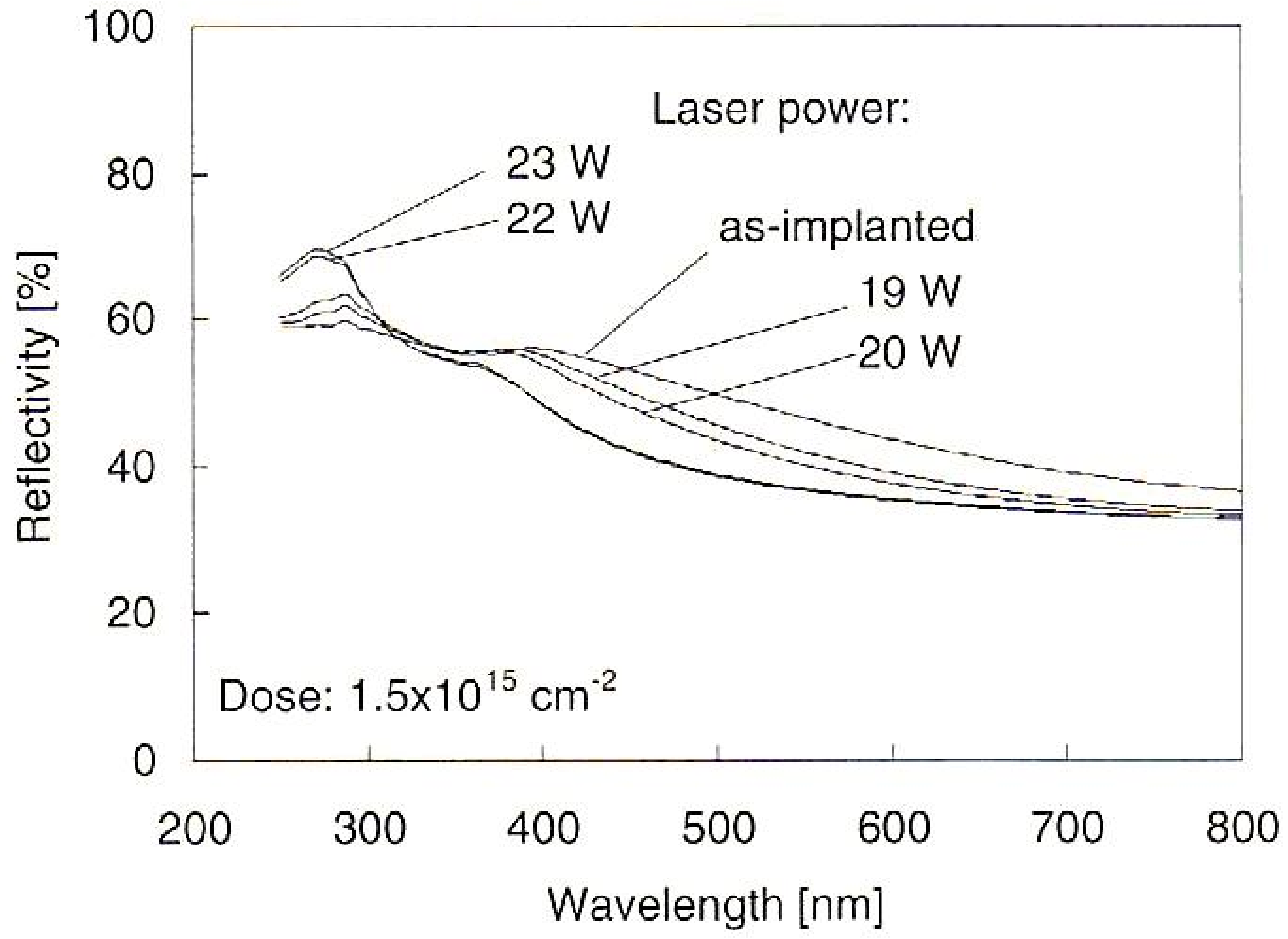

Fig. 3. Optical reflectivity spectra of 1.5×10^{15}-cm^{-2}-as-implanted and laser-annealed samples for laser powers of 0 (as-implanted), 19, 20, 22, and 23 W.

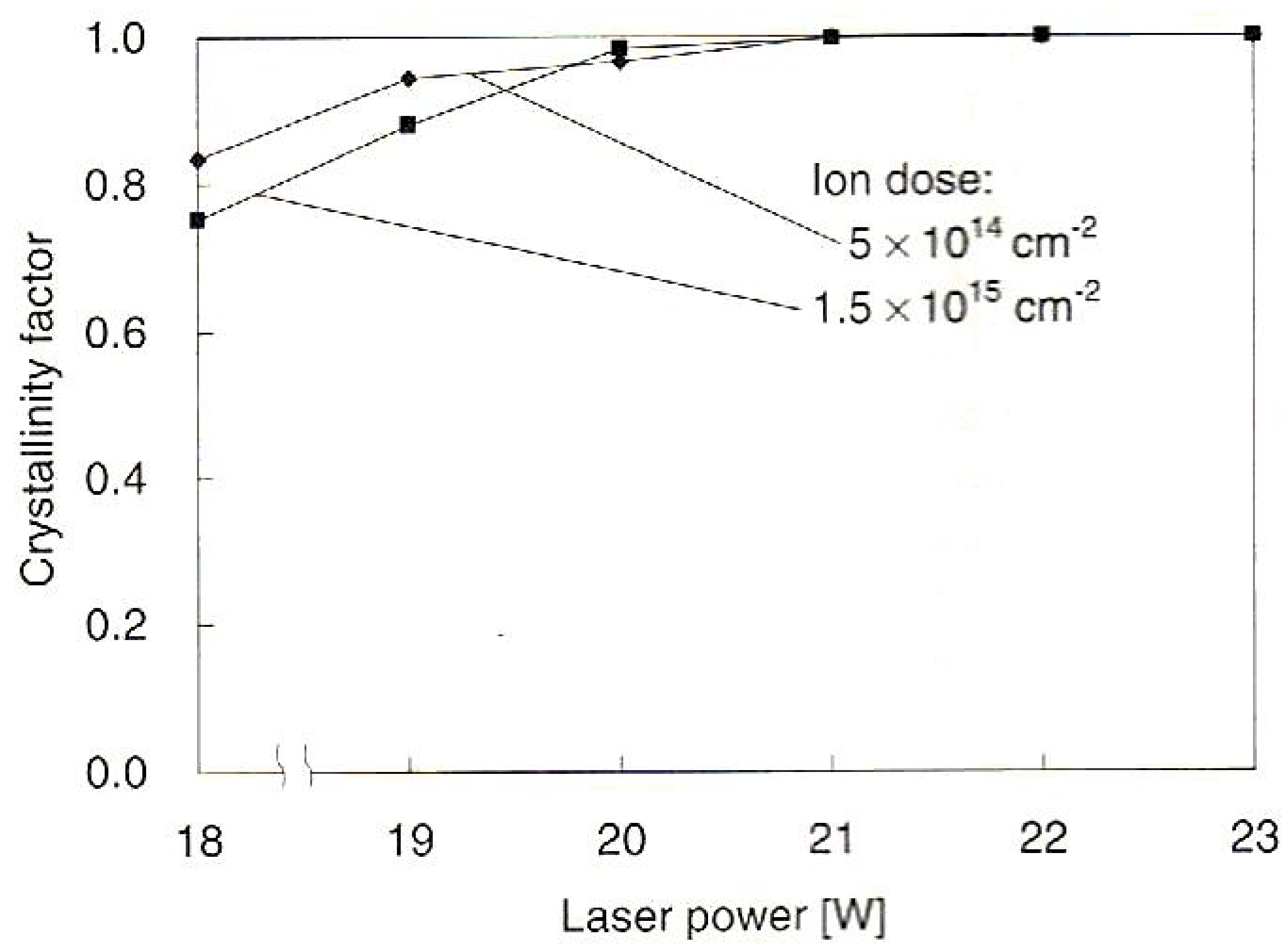

Fig. 2. Crystallinity factor as function of laser power estimated by peak analyses of Raman spectra. The boron doses used were 5×10^{14} and 1.5×10^{15} cm^{-2}.

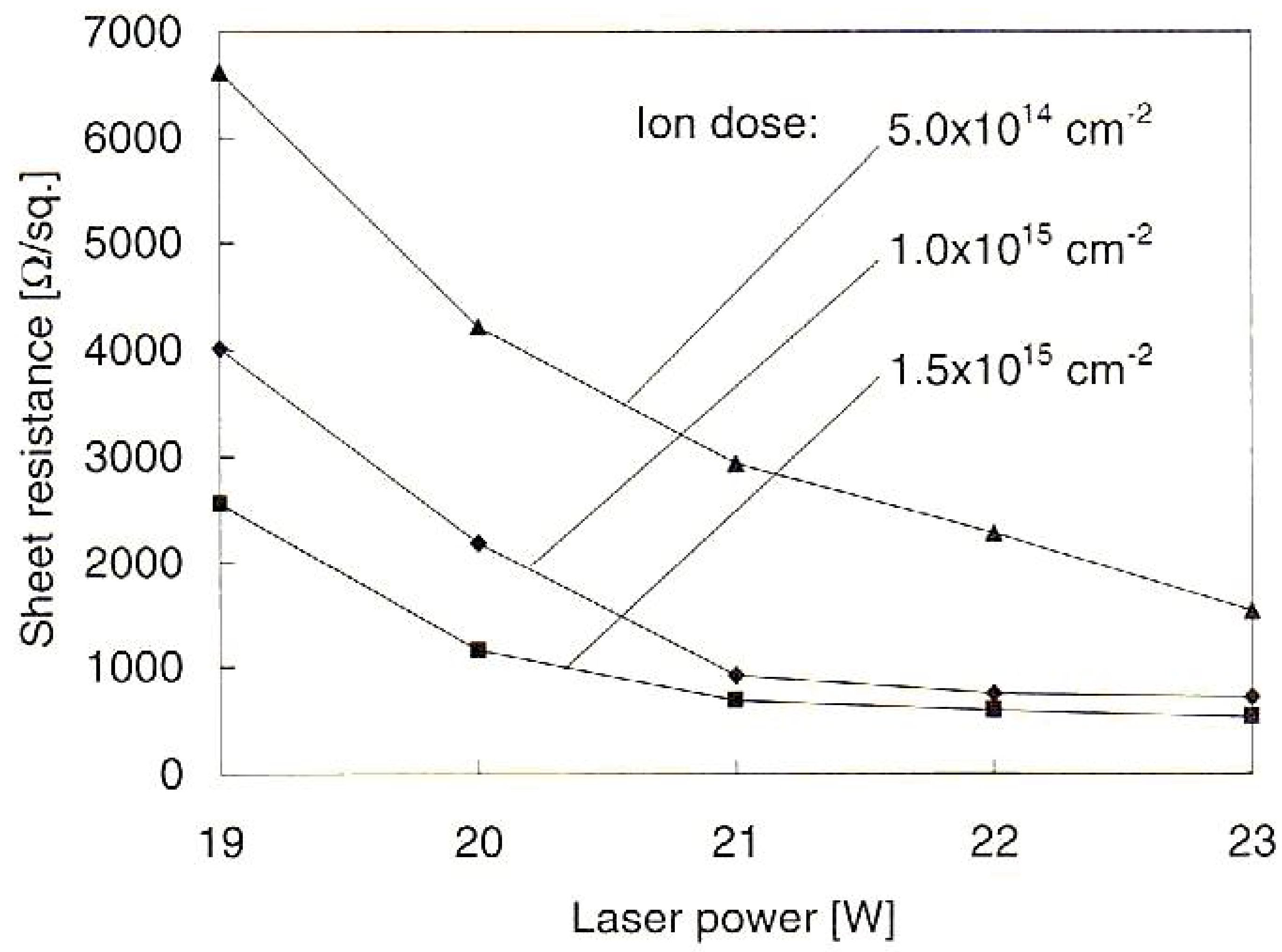

Fig. 4. Sheet resistance changes with laser powers of 19–23 W for 1.5×10^{15} cm^{-2} boron implantation at 10 keV.

implantation. As the laser irradiation power increased, the tail state at a wave number smaller than 520 cm^{-1} decreased. This indicates that recrystallization was enhanced by increasing the laser irradiation power. By peak analysis, Raman spectra can be separated into a sharp phonon peak of crystalline silicon and a broad band of amorphous silicon components at wave numbers of 520 and 480 cm^{-1}, respectively. We defined the crystallinity factor as a ratio of the crystalline peak component to the totally integrated intensity of the Raman spectra of Si. Figure 2 shows the crystallinity factor as a function of the laser irradiation power for the samples implanted with boron atoms at doses of 5×10^{14} and 1.5×10^{15} cm^{-2}. The crystallinity factors of the samples implanted at doses of 5×10^{14} and 1.5×10^{15} cm^{-2} increased to 0.83 and 0.75, respectively. As the laser irradiation power increased, the crystallinity factor also increased and was 1 at a laser irradiation power above 21 W for both cases. This indicates that the boron-implanted and amorphized surface regions were recrystallized almost completely for laser annealing at 73.5 kW/cm^2.

Figure 3 shows the optical reflectivity spectra of the sample implanted with boron atoms at a dose of 1.5×10^{15} cm^{-2} for various laser irradiation powers. The reflectivity of the sample at the E_2 peak at around 270 nm was suppressed by the amorphization of the surface region of Si wafers by ion implantation. On the other hand, it was found that as the laser irradiation power increases, the intensity of the E_2 peak also increases because of recrystallization, as observed in the above Raman spectral results. However, the decreased intensity of the E_1 peak by ion implantation, which is another critical point of crystalline silicon at a wavelength of 364 nm, was not recovered by laser irradiation. We supposed that it is caused by the weakened excitonic interaction at the E_1 peak in heavily doped silicon with boron atoms, as discussed by Viña and Cardona.[10)]

Figure 4 shows the sheet resistance changes of the samples at doses of 5×10^{14}, 1×10^{15}, and 1.5×10^{15} cm^{-2} at 10 keV in the laser irradiation power range of 19–23 W. The sheet resistance decreased to 722 and 531 Ω/sq for doses of 5×10^{14} and 1.5×10^{15} cm^{-2}, respectively, as the laser

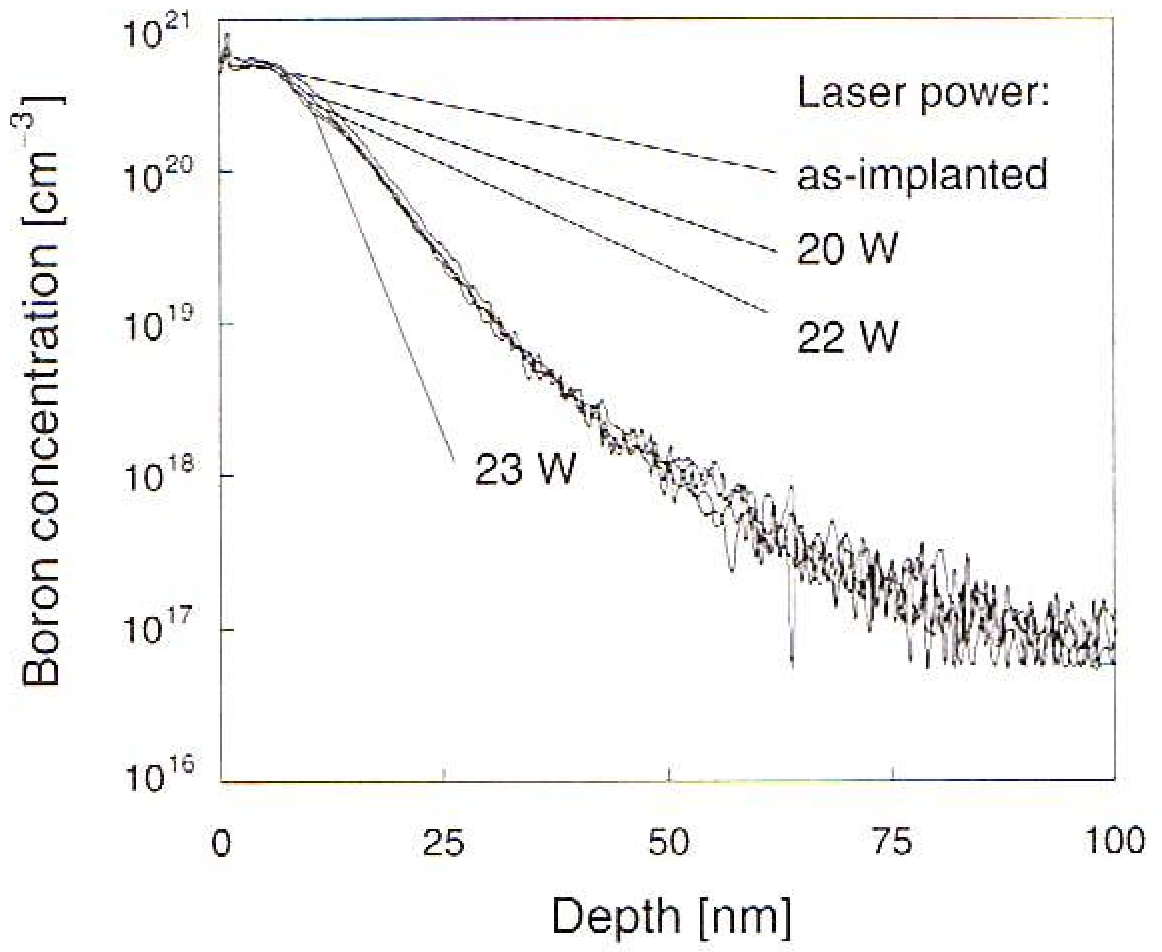

Fig. 5. SIMS profiles of boron atoms implanted into Si at dose of 1.5×10^{15} cm^{-2} at ion energy of 10 keV. Laser annealing was carried out at laser power of 0 (as-implanted) and 20–23 W (70–80.5 kW/cm^2).

irradiation power increased. It almost leveled off for laser irradiation powers between 21 and 23 W for both cases of 1×10^{15} and 1.5×10^{15} cm^{-2}. These results made us believe that boron impurities were well activated at a laser power above 22 W.

Figure 5 shows the boron atom in-depth profiles of the samples implanted with boron atoms at a dose of 1.5×10^{15} cm^{-2} at 10 keV and laser annealed at 0 (as-implanted), 20, 22, and 23 W. With the screen oxide, the depth at the boron concentration of 10^{18} cm^{-2}, which is called junction depth, was 50 nm for the as-implanted sample. SIMS results revealed that the effective dose of boron atoms is 7.6×10^{14} cm^{-2} for the as-implanted sample. About one-half of the implanted boron atoms were recoiled or trapped in the screen oxide. With the laser irradiation power of 23 W, the effective dose decreased to 6.3×10^{14} cm^{-2}. About 17% of the implanted boron atoms in Si were lost. This might mainly be caused by diffusion into the screen oxide. The boron concentration in the depth range of 0–30 nm was decreased by laser irradiation at 80.5 kW/cm^2. The peak boron concentration at the depth of 0.8 nm was decreased from 8.2×10^{20} to 5.8×10^{20} cm^{-3}. However, the junction depth was 53 nm for the sample annealed at 23 W. Only 3 nm diffusion was observed. In other words, there were no marked changes in boron profiles except for a decrease in peak concentration. The diffusion coefficient of boron atoms in solid silicon was about 1×10^{-10} cm^2/s at a high temperature of around 1300 °C.[11] The heat duration of 2.6 ms can allow a diffusion length of 10.2 nm [$\sim 2 \times (1 \times 10^{-10} \times 2.6 \times 10^{-3})^{0.5}$]. This is higher than our maximum diffusion length of 3 nm observed from the SIMS results. The duration at which the temperature of the DLC/Si interface is above 1300 °C might be shorter than the dwell time of 2.6 ms.

The carrier density of the sample annealed at 23 W was measured by Hall effect measurement and confirmed to be about 6.3×10^{14} cm^{-2}. In other words, it was found that the activation efficiency is almost 100% by comparison with the effective dose obtained by SIMS measurement and that millisecond heat treatment is important for activating the implanted impurities with a high efficiency while keeping initial dopant concentration profiles. These results show that the present laser annealing technique is expected to be useful for the formation of ultra-shallow junctions.

In summary, a 940 nm CW laser annealing method with a DLC optical absorption layer was applied to the activation annealing of a Si wafer ion-implanted with boron atoms. Boron atoms were implanted to n-type Si substrates at 10 keV with doses of 5×10^{14} and 1.5×10^{15} cm^{-2} via screen oxide films with a thickness of 7.9 nm. The initial junction depth was 50 nm. DLC films with a thickness of 200 nm were formed on the oxide surface by UBMS. The boron-implanted Si wafers were annealed by laser irradiation in the power density range of 66.5–80.5 kW/cm^2 at a dwell time of 2.6 ms. The amorphized region by ion implantation was almost completely recrystallized at a laser power above 22 W. SIMS measurements revealed that the present laser annealing for a laser dwell time of 2.6 ms hardly changes boron concentration in-depth profiles. After laser annealing at 23 W, sheet resistances markedly decreased to 722 and 531 Ω/sq for doses of 5×10^{14} and 1.5×10^{15} cm^{-2}, respectively. Boron atoms were almost completely activated. The diffusion length of boron atoms was lower than 3 nm. No marked diffusion of carbon atoms from the DLC layer into the Si wafer was also observed. The present annealing method is expected to be useful for the formation of ultra-shallow junctions for future MOS devices.

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