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ULTRA-SHALLOW IMPLANT ANNEAL USING SHORT WAVELENGTH FLASH LIGHT SOURCE

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$^{11}B^+$ and $^{49}BF_2^+$ implanted Si wafers with various implant energies and doses were annealed using a short wavelength flash light source. A xenon (Xe) arc lamp was used as a light source. The duration of the flash illumination is controlled between 1 ms and 10 s. Effects of wafer preheating using a hot plate prior to the flash were also investigated. Annealing characteristics of ultra-shallow $^{11}B^+$ and $^{49}BF_2^+$ implanted Si wafers were investigated in terms of electrical activation and dopant redistribution after annealing. Sheet resistance of implanted wafers was measured. Changes in depth profile of implant species and junction depth were determined using secondary ion mass spectroscopy (SIMS).

INTRODUCTION

Rapid thermal annealing (RTA) has become a preferred method for shallow junction implant anneal [1]. Very rapid annealing with very fast ramp rates ("spike anneal") at higher temperatures has been introduced as an effective method for shallow junction implant anneal to electrically activate implanted species with a minimum of diffusion for ultra-shallow junction (USJ) formation and excimer laser-based annealing and non-filament based arc lamp RTA techniques are being actively investigated [2-6]. The response time for the excimer laser and arc lamp is in the range of ns and ms, respectively.

In advanced Si devices, all the active device regions are located at the top surface (usually <1.0 μm from the surface) of 600~800 μm thick Si wafers. Selective surface heat treatment without heating the bulk of the Si wafer is ideal from the viewpoint of reducing dopant diffusion and prevention of defect generation during subsequent thermal cycles. Feasibility of laser thermal processing (LTP) for ultra shallow junction implant anneal using a short-wavelength (308 nm), pulsed XeCl laser with surface melting and sub-melt modes of LTP have been reported [4]. The surface melting mode gives high electrical activation efficiency, but it poses process integration problems. The sub-melt mode was developed to avoid the complication of process integration in the melting mode and gives reasonable electrical activation of implanted species. The annealing region of both LTP modes is limited by the spot size of the laser beam. It requires a significant number of pulses as well as a scanning mode using a stepper to activate the full wafer surface. In an effort to establish a practical USJ implant anneal method, flash-lamp annealing using various types of arc lamps (Ar and Xe filled arc lamps) has been actively investigated in

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recent years. Initial test results from various research groups [2-4], including the authors' [7, 8], have been very promising.

In this study, $^{11}B^+$ and $^{49}BF_2^+$ implanted Si wafers with various implant energies were annealed using a short-wavelength flash light source. Annealing characteristics of implanted wafers were investigated in terms of electrical activation, dopant diffusion and junction depth (x_j).

EXPERIMENTAL

Since the size of the boron (B) atom is small and diffuses faster in Si compared to other n-type dopants (such as P and As atoms) ultra-shallow implantation without channeling and with proper boron implant anneal are critical for proper USJ formation. A very short anneal in the millisecond range is desirable to form an effective USJ annealing strategy for maximum electrical activation with the least amount of dopant diffusion. It is necessary to understand the fundamentals of damage recovery, solid solubility of dopants, electrical activation and dopant diffusion during implant anneal thermal cycling.

A xenon (Xe) arc lamp was used as a flash light source. The duration of the flash was controlled between 1 ms and 10 s. The flash discharge energy was also controlled in the range of 0.05 MJ ~ 0.5 MJ. Preheating of samples was performed up to 800°C using a hot plate to investigate the effect of sample temperature prior to the flash on electrical activation and dopant diffusion. The emission spectrum of the flash lamp shows a maximum intensity at a wavelength between 0.3 μm and 0.4 μm (4.13 eV ~ 3.10 eV) depending on the discharge power. Tungsten-halogen lamps, used in conventional RTA systems, show their maximum light intensity at about 1.1 μm ~1.4 μm (1.13 eV ~ 0.88 eV), when the filament temperature reaches approximately 3000°C. Since the flash lamp emits substantially shorter wavelength photons compared to both tungsten-halogen lamps and the absorption edge (0.96 μm or 1.1 eV) of Si, it is more effective in rapidly heating the surface of a Si wafer. Figure 1 shows the light absorption spectrum of Si and the optical emission spectra from both a Xe-arc lamp and a tungsten-halogen lamp under different power conditions. The combination of high energy photon irradiation and short flash time (<100 ms) makes possible selective surface heating, without heating the bulk Si. Very fast temperature rise of the surface layer of interest (implanted layer) can be achieved with a short flash of high energy photons at high intensity. Following the flash, the temperature of the surface layer falls nearly as rapidly, as the thermal energy is absorbed by the bulk Si, but with relatively moderate temperature change of the bulk wafer. Schematic illustrations of time-resolved surface and bulk temperature after Xe arc lamp flash are summarized in Fig. 2.

Annealing characteristics of ultra-shallow $^{11}B^+$ and $^{49}BF_2^+$ implanted Si wafers were also investigated in terms of electrical activation and dopant redistribution after annealing. Sheet resistance of implanted wafers was measured after annealing under various flash conditions. Change in depth profiles of implant species was investigated using secondary ion mass spectroscopy (SIMS).

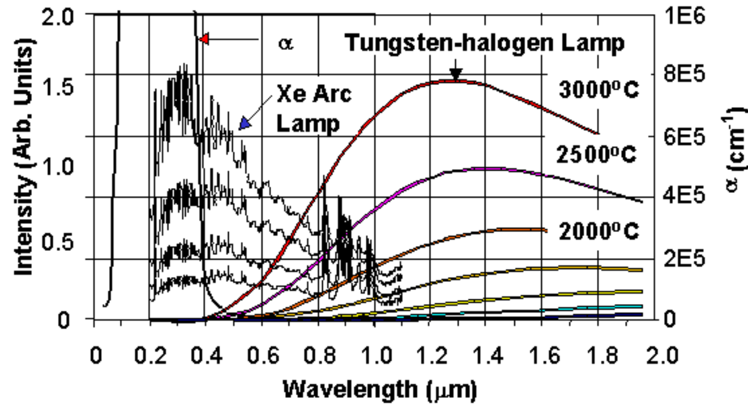

Figure 1. Light absorption spectrum of Si and optical emission spectra from Xe-arc lamp and tungsten-halogen lamp under different power conditions.

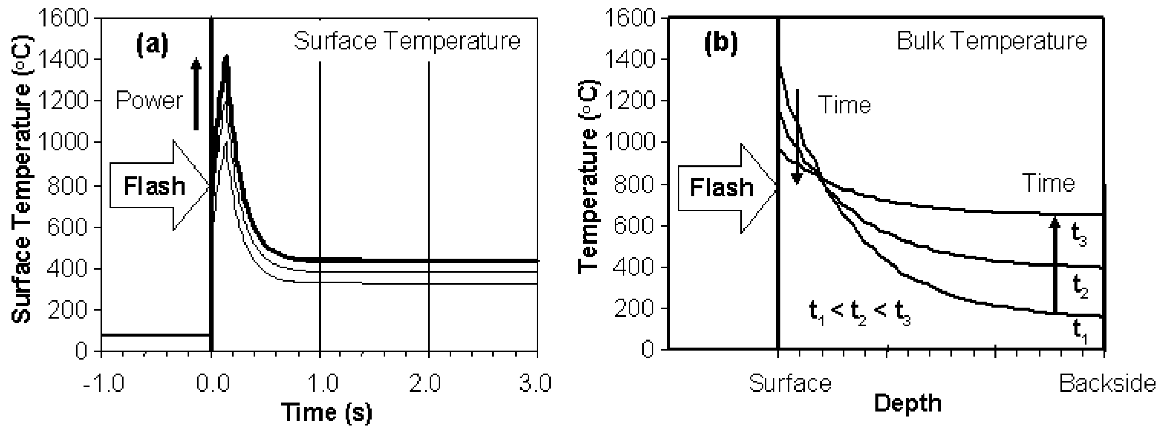

Figure 2. Temperature profile following flash exposure: (a) Surface temperature vs. time for 3 exposures, (b) Temperature vs. depth at 3 different times.

RESULTS AND DISCUSSION

To investigate the electrical activation by continuous ultraviolet (UV) illumination of implanted wafers at thermal equilibrium, $^{11}B^{+}$ (1 keV, 1.0 x 10^{15} cm^{-2}) implanted wafers were annealed for 0~10 s using a Xe-arc lamp operated at 10 kW. The junction depth (x_j) has been traditionally defined as the depth at which dopant concentration equals 1.0 x 10^{18} cm^{-3}. The as-implanted junction depth was 37.5 nm. As annealing time increases, sheet resistance of implanted wafers decreases due to electrical activation while the junction depth (x_j) becomes deeper due to dopant diffusion (Fig. 3 (a)). The sheet resistance of implanted wafers annealed at sufficiently high temperature is inversely proportional to the junction depth. Wafers annealed for 7 s showed significant diffusion without sheet resistance reduction compared to the wafer annealed for 6 s. This can be explained by resistivity increase due to the reduced average B concentration.

The electrical activation of implanted wafers using hot-plate assisted heating was investigated (Fig. 3 (b)). The hot-plate temperature and annealing time were fixed at 800°C and 25 s, respectively. The hot-plate annealed wafer showed sheet resistance of 22.9 kΩ/sq. and junction depth of 47.5 nm. The hot plate anneal at 800°C for 25 s moved the junction depth by 10nm (from 37.5 nm to 47.5 nm), but without sufficient electrical activation. When a strong ultraviolet (UV) pulse (flash) from a Xe arc lamp was introduced at the end of the hot plate anneal, the sheet resistance was decreased to 1.7 kΩ/sq. without dopant diffusion. The flash power and duration were 5 kJ and 10 ms. Extended UV radiation after hot plate anneal, up to 1 s, also decreased sheet resistance significantly without increasing the junction depth. However, additional UV irradiation for 2 s reduced the sheet resistance to 402.2 Ω/sq. at the expense of junction movement, to 60 nm.

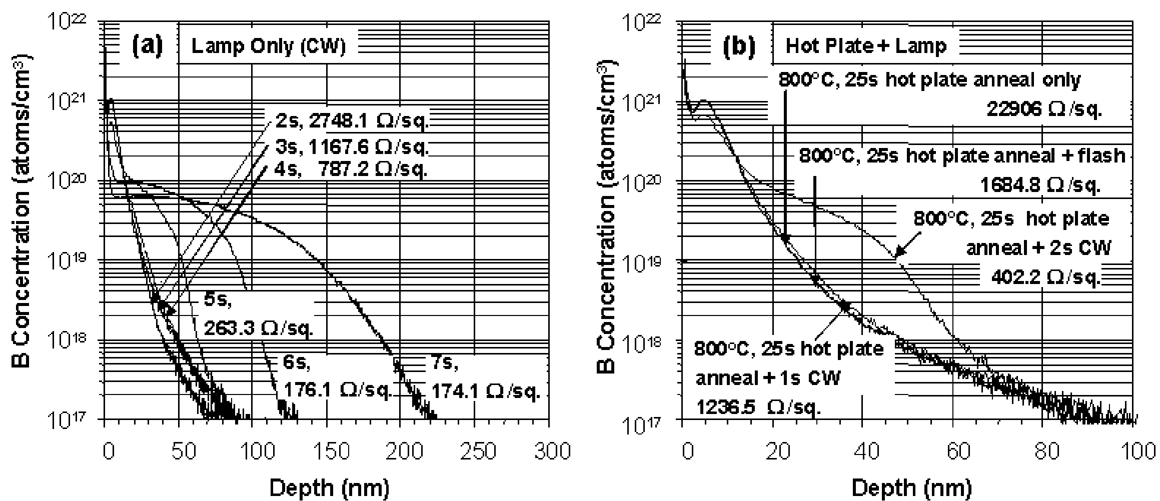

Figure 3. SIMS depth profile and sheet resistance of $^{11}B^+$ (1keV, 2.0 x 10^{15} cm^{-2} without pre-amorphization) implanted wafers before and after annealing.

A combination of very strong UV flash (but, substantially shorter than 1 s) with preheating of the wafer (below 700°C, so that dopant difusion is negligible), gives ideal USJ implant annealing results (i.e. effective electrical activation without significant dopant diffusion). SIMS depth profiles and sheet resistance values of $^{11}B^+$ (1keV, 2.0 x 10^{15} cm^{-2}) with Ge pre-amorphization (5 keV, 1.0 x 10^{15} cm^{-2}) implanted wafers before and after flash annealing at different preheating temperatures are shown in Fig. 4. As implanted junction depth, x_j, was 26.0 nm. By Ge pre-amorphization, ion channeling during ion implantation was suppressed significantly. As a result, the implanted junction depth was significantly reduced compared to the $^{11}B^+$ (1 keV, 1.0 x 10^{15} cm^{-2}) implanted wafers without Ge pre-amorphization. The flash energy and duration were fixed at approximately 25 kJ and 5 ms. Actual flash power density at the surface of the wafer was not measured in this experiment. As the preheating temperature is increased, sheet resistance decreases for the same flash annealing condition. No B diffusion was observed from flash annealed wafers at room temperature and 400°C. The wafers flashed at 700°C and 800°C showed lower sheet resistance values due to efficient electrical activation, but significant B diffusion was also observed even for very short exposures (a few ms). The

junction depth, x_j, of wafers flashed at 700°C and 800°C were 34.0 nm and 56.0 nm, respectively. While the wafer flashed at 800°C showed 60% increase in junction depth, it exhibited only 40% of sheet resistance of the wafer flashed at 700°C. In the wafer flashed at 700°C, a change in B SIMS depth profile corresponding to B solid solubility (1.5 x 10^{20} cm^{-3}) was observed at 13.0 nm. A higher solid solubility (2.5 x 10^{20} cm^{-3} at 11.0 nm) of B was observed in wafers flashed at 800°C. Under the same flash condition, the preheating temperature plays an important role in electrical activation.

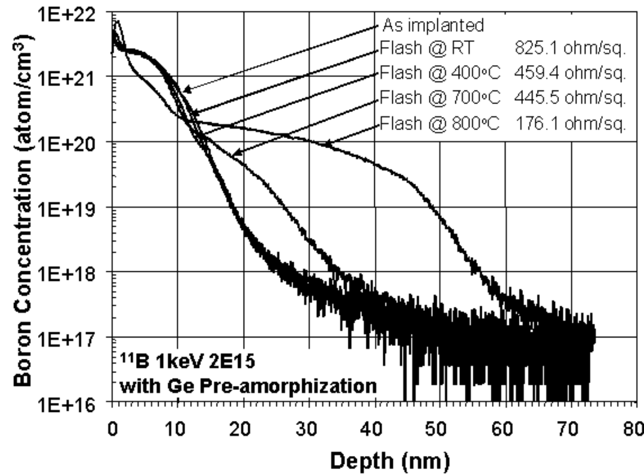

Figure 4. SIMS depth profile and sheet resistance of $^{11}B^{+}$ (1 keV, 2.0 x 10^{15} cm^{-2} with Ge pre-amorphization) implanted wafers before and after flash annealing at different preheating temperatures.

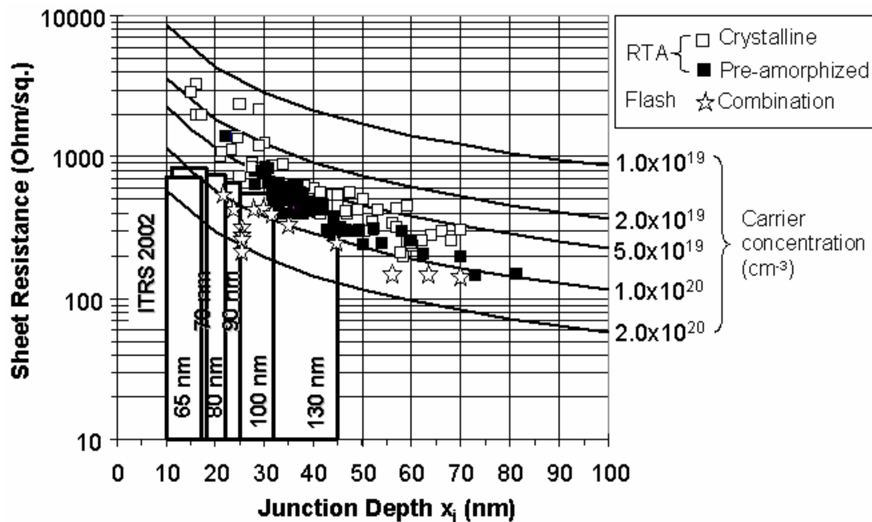

Figure 5. Sheet resistance of $^{11}B^{+}$ and $^{49}BF_2^{+}$ implanted wafers as a function of junction depth x_j after annealing.

Figure 5 shows the sheet resistance of $^{11}B^{+}$ and $^{49}BF_2^{+}$ implanted wafers as a function of junction depth (x_j) after annealing under various conditions using several annealing techniques [6]. In the case of the Xe-arc-lamp flash anneal performed in this

study, the sheet resistance of 250~350 Ω/sq. was achieved with a junction depth of 24.0 nm. The flash annealed wafers exhibited lower sheet resistance for a given junction depth due to efficient electrical activation with less diffusion. No significant dopant diffusion was observed after Xe-arc-lamp flash annealing at room temperature with low preheating temperatures.

To achieve higher electrical activation, increased B solid solubility is required. For higher B solid solubility, a high annealing temperature is a requirement. However, elevated annealing temperature also enhances B diffusion and makes the shallow junction ion implant anneal more difficult. The high power, short wavelength flash annealing is found to be very effective in electrically activating fast diffusing dopants such as B without significant diffusion and is promising as a USJ implant anneal technique for 65 nm node and beyond.

SUMMARY

$^{11}B^+$ and $^{49}BF_2^+$ implanted Si wafers with various implant energies and doses were annealed using a short-wavelength, xenon (Xe)-arc-lamp. The duration of flash light is controlled between 1 ms and 10 s. Annealing characteristics of ultra-shallow $^{11}B^+$ and $^{49}BF_2^+$ implanted Si wafers were investigated in terms of electrical activation and dopant redistribution after annealing. Sheet resistance and depth profile of implanted wafers were measured using a four point probe and secondary ion mass spectroscopy (SIMS). USJ implant anneal (higher electrical activation without dopant diffusion) was successfully demonstrated by the short-wavelength Xe-arc-lamp flash annealing technique with a combination of wafer preheating using a hot-plate. For 65 nm node and beyond, the short-wavelength, high-power flash annealing is very effective in electrically activating fast diffusing dopants such as B without significant diffusion and is promising as a USJ implant anneal technique.

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