ELECTRICAL ACTIVATION AND DOPANT DIFFUSION OF HEAVILY BORON IMPLANTED SILICON

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To investigate electrical activation and dopant diffusion behavior, heavily boron (B) implanted (^{11}B 2.0 keV 4.0 x 10^{15} cm^{-2}) silicon wafers were annealed using a novel millisecond flash anneal and/or a conventional tungsten halogen lamp-based rapid thermal anneal (RTA). Sheet resistance and B depth profiles were measured using a four point probe and secondary ion mass spectroscopy (SIMS) before and after annealing. Wafers which were "spike" annealed or "soak" annealed by the RTA system showed electrical activation as well as a significant B diffusion (15~40 nm) after annealing depending on the annealing conditions. In wafers annealed only by the flash annealing system, the electrical activation of B implanted silicon improves as flash power increases at a given preheat temperature without B diffusion. Previously "spike" annealed and "soak" annealed wafers showed additional electrical activation after additional flash annealing without additional B diffusion.

INTRODUCTION

For high performance, advanced dynamic random access memory (DRAM) devices with below 90 nm design rules, the higher conductivity of word and bit lines without additional dopant diffusion is required. The minimization of thermal exposure and its precise control are few examples of the key issues in thermal processing. With the shrinkage in device dimensions and allowable thermal budgets, lamp-based, single wafer rapid thermal processing (RTP) systems have replaced many thermal processing applications traditionally performed in large batch furnaces. Rapid thermal annealing (RTA) has become the preferred method for advanced implant annealing down at the 90 nm node [1]. The combination of "soak" and "spike" RTA are widely used for implant activation applications depending on ion species and implant conditions. The annealing time for typical "soak" anneal is in the range of 10~30 s at a target temperature. The "spike" annealing duration is often less than few seconds within +/- 50°C from the peak temperature [2-3]. To further improve the dopant activation rate with minimal dopant diffusion, faster implant annealing methods are desired.

Similar requirements exist for ultra-shallow junction (USJ) formation beyond the 90 nm node. In an effort to extend current technology (combining ion implantation and anneal), a very rapid anneal (<10 ms) at a very high temperature (>1100°C) is considered the most promising solution for USJ formation to electrically activate the dopant species without causing diffusion from heating the bulk Si wafer. For this application, excimer laser-based and non-filament based arc-lamp annealing techniques are being actively investigated due to their fast heating characteristics [4-11]. The optical energy for heating from the excimer laser and arc lamp are in the ns and ms ranges, respectively.

In this study, heavily boron (B) implanted silicon wafers were annealed to investigate the effect of a novel millisecond flash annealing or a conventional tungsten halogen lamp-based RTA on the electrical activation and dopant diffusion. The effect of multiple processing (combinations of annealing methods and processing sequences) on dopant activation and diffusion was also investigated. Sheet resistance and B depth profiles were measured using a four point probe and secondary ion mass spectroscopy (SIMS) before and after annealing.

EXPERIMENT

A conventional tungsten halogen lamp-based RTA system and a xenon (Xe) arc-lamp based flash annealing system were used in this study. The conventional RTA system employs arrays of tungsten halogen lamps and illuminates a Si wafer through a quartz tube from the top and bottom sides. Wafer temperatures are measured using a pyrometer through the quartz tube. A multiple zone power control method is used to adjust temperature uniformity on the Si wafer and wafer temperature ramp up rate, soak time and ramp down rate are programmable. The flash annealing system consists of arrays of Xe arc flash lamps and a hot plate for wafer pre-heating. The duration of the flash was controlled around 1 ms. The flash discharge energy was controlled in the range of 0.05 MJ ~ 0.5 MJ. Preheating of wafers was performed up to 500^{o}C using a hot plate to investigate the effect of wafer temperature prior to the flash on electrical activation and dopant diffusion.

Tungsten-halogen lamps, used in conventional RTA systems, require a few seconds to reach maximum filament temperature, approximately 3000^{o}C, at a given power and provide their maximum light intensity at about 1.1 μm - 1.4 μm (1.13 eV - 0.88 eV). Since the optical energy output of tungsten-halogen lamps is much too slow, they are not suitable for implant annealing applications which require minimal dopant diffusion. In contrast, 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. Since the flash lamp emits substantially shorter wavelength photons compared to both tungsten-halogen lamps and the absorption edge of Si (0.96 μm or 1.1 eV), it is more effective to rapidly heat the surface of a Si wafer. The combination of high energy photon irradiation and short flash time (<20 ms) makes selective surface heating possible without significantly heating the bulk Si. A 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 very rapidly, as the thermal energy is absorbed by the bulk Si. Details of the flash anneal system and its characteristics are described elsewhere [10, 12].

To investigate electrical activation and dopant diffusion behavior, heavily B implanted p-type silicon wafers with a resistivity of ~20 Ω·cm (mainly ^{11}B 2.0 keV 4.0 x 10^{15} cm^{-2}) were annealed using a novel millisecond flash anneal and a conventional tungsten halogen lamp-based RTA. Sheet resistance of implanted wafers were measured using a four point probe before and after annealing. The B depth profile was measured using a four point probe and secondary ion mass spectroscopy (SIMS) before and after annealing. Junction depth movement and boron diffusion of implanted wafers after annealing were estimated from the B depth profiles as measured by SIMS.

RESULTS AND DISCUSSION

Typical SIMS boron depth profiles of as-implanted (^{11}B 2.0 keV 4.0 x 10^{15} cm^{-2}) wafers and wafers after "spike" anneal at 1050°C for 1.5 s and "soak" anneal at 995°C for 20 s using a conventional tungsten halogen lamp-based RTA system are shown in Fig. 1. The as-implanted sheet resistance (Rs) and junction depth x_j at a B concentration of 1.0 x 10^{18} cm^{-3} are in the range of 1100~1500 ohm/sq. and 70~75 nm, respectively. Typical sheet resistance and junction depth x_j after the "spike" anneal at 1050°C for 1.5 s are 70~75 ohm/sq. and 93 nm. The "soak" anneal at 995°C for 20s brings the sheet resistance down to ~64 ohm/sq. with a junction depth of 112~118 nm. To enhance the electrical activation of implanted dopants, annealing at higher temperature is desired. However, the high temperature annealing causes dopant diffusion resulting in an undesired dopant profile (or junction depth and abruptness). Both "spike" and "soak" annealing using a conventional RTA system resulted in significant boron diffusion from the as-implanted profile with the "spike" and "soak" anneal moving the junction depth by 18~23 nm and 37~48 nm, respectively. A shorter annealing time is desired to minimize dopant diffusion during dopant activation annealing.

SIMS depth profiles of B implanted wafers annealed by the novel millisecond flash annealing system are superimposed on the as-implanted profile in Fig. 2. Wafers were preheated at 470°C prior to the millisecond flash annealing and flash energy was varied from 60% to 100% of the rating of the system. As seen in the figure, no significant dopant movement was observed under various flash anneal conditions. All wafers showed junction depths of 70~75 nm. The sheet resistance and junction depth of flash annealed wafers are plotted in Fig. 3 as a function of flash energy used. The sheet resistance monotonically decreases from the as-implanted values of 1000~1500 ohm/sq. to ~60 ohm/sq. as the flash power was increased without moving the junction. The sheet resistance value of ~60 ohm/sq., achieved at 100% flash energy, was 12~20% lower than typical values achieved after "spike" or "soak" anneal. The junction depth is also 17~36% more shallow than for those wafers after "spike" or "soak" anneal. The millisecond flash anneal is seen to be very effective in activating dopant without changing the as-implanted dopant profile significantly.

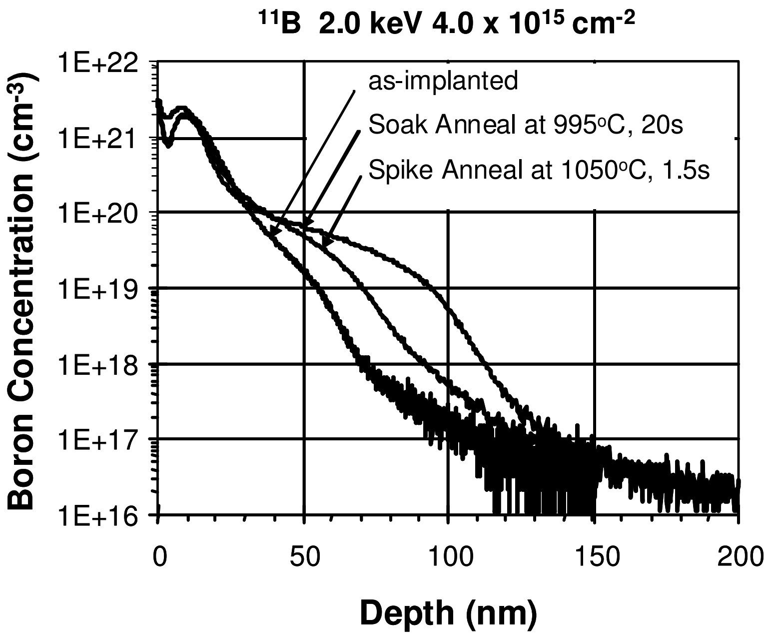

Figure 1. Boron depth profiles measured by SIMS before and after RTA using a conventional tungsten halogen lamp-based RTA system.

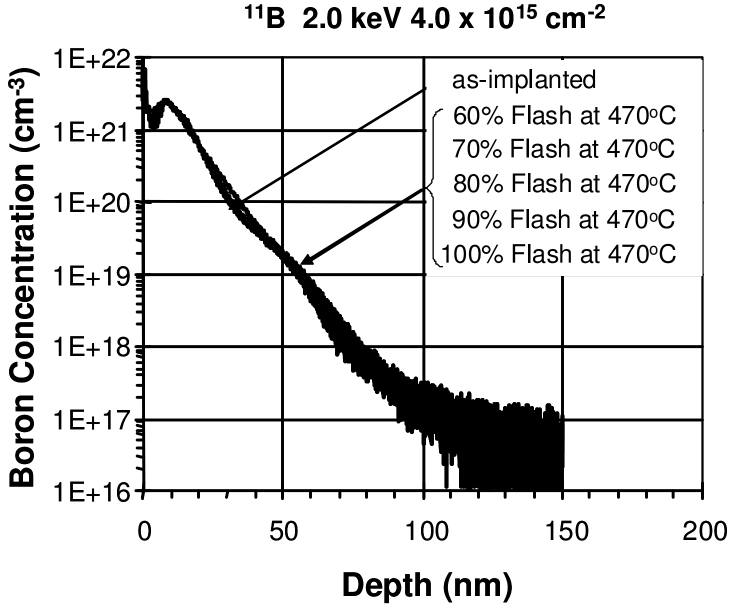

Figure 2. Boron depth profiles measured by SIMS before and after millisecond flash annealing under various flash power conditions at wafer preheating temperature of 470°C using Xe arc flash lamp-based RTA system.

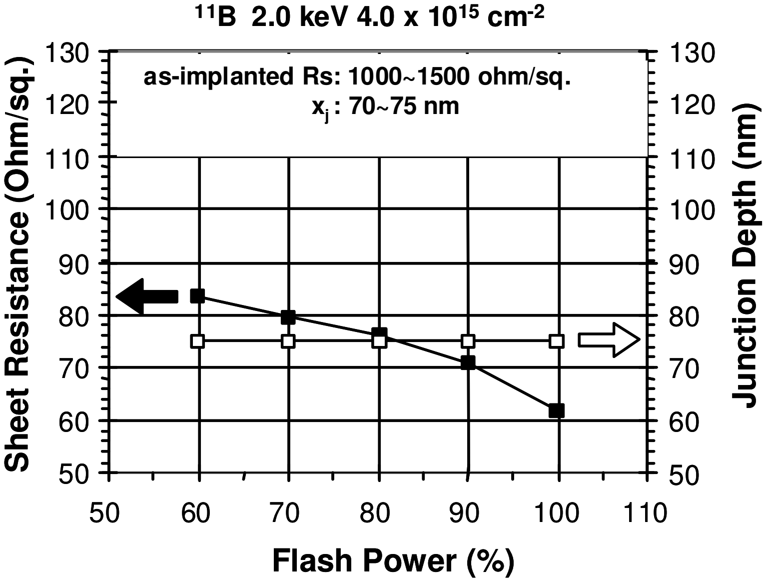

Figure 3. Sheet resistance and junction depth after millisecond flash annealing under various flash power conditions at wafer preheating temperature of 470°C using Xe arc flash lamp-based RTA system.

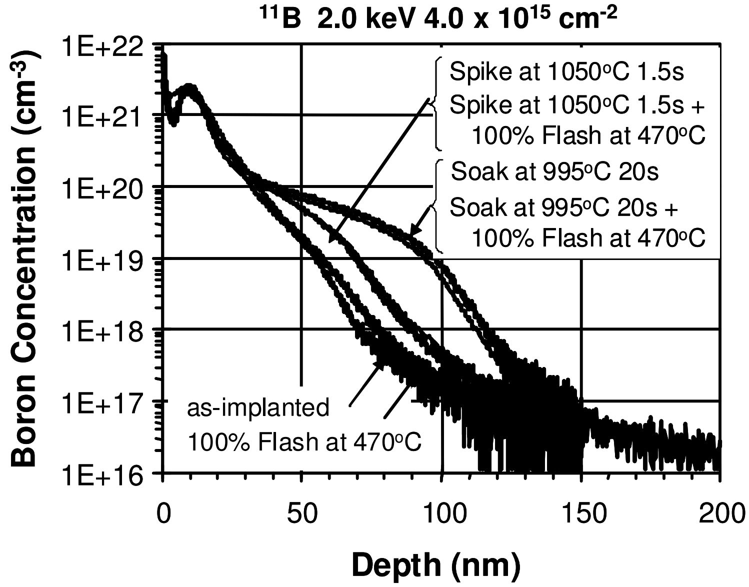

Figure 4. Boron depth profiles measured by SIMS before and after various combinations of annealing methods.

To investigate the effectiveness of the flash anneal, some of the "spike" annealed and "soak" annealed wafers were reprocessed by the flash annealing system. The flash energy was varied to see whether a subsequent flash anneal can provide additional dopant activation of previously annealed wafers using the conventional RTA system. Figure 4 summarizes B depth profiles measured by SIMS before and after various combinations of annealing methods. The subsequent flash anneal did not result in additional dopant diffusion. The wafers reprocessed by the flash annealing system showed additional electrical activation without additional B diffusion due to higher electrical activation efficiency of the millisecond flash annealing. The sheet resistance and junction depth x_j (at B concentration of 1.0 x 10^{18} cm^{-3}) under various combinations of flash anneal and conventional lamp-based RTA conditions are summarized in Fig. 5.

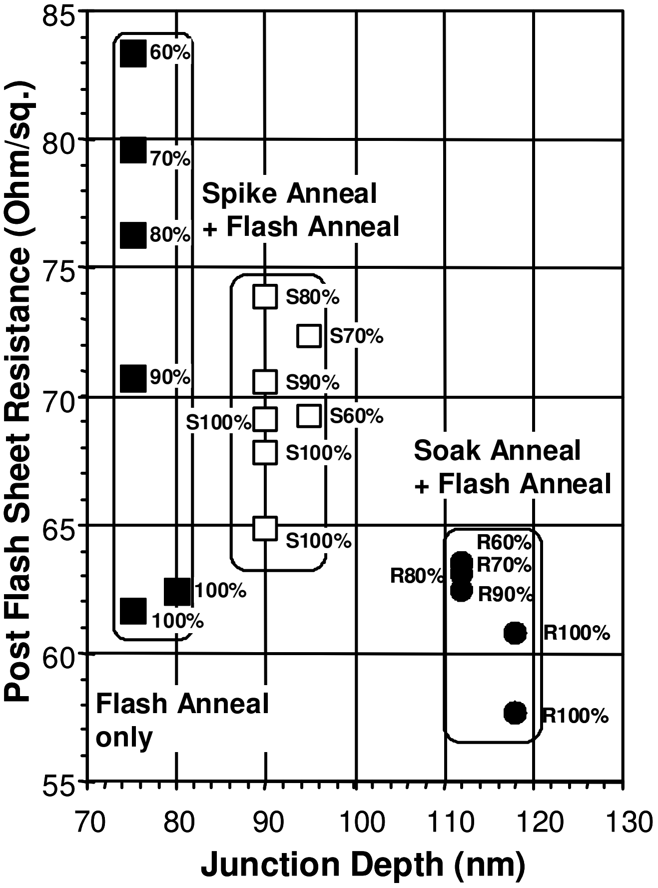

Figure 5. Sheet resistance and junction depth x_j (at B concentration of 1.0 x 10^{18} cm^{-3}) plot under various combinations of flash anneal and conventional lamp-based RTA conditions.

For high performance device manufacturing, precise dopant profile control including junction depth control are extremely important for achieving high device performance. A small increase in dopant activation for a given dopant profile would potentially enhance device performance significantly. Boron solid solubility and diffusivity in Si is strongly affected by the Si temperature [12], so to achieve higher electrical activation, very fast, very high temperature activation is required. However, the high annealing temperature may also cause B diffusion, thus a fast temperature rise and rapid cooling methods of annealing are required.

In wafers annealed by the flash annealing system only, the electrical activation of B implanted silicon improves as flash power increases at a given preheating temperature, however without B diffusion. Flash anneal and the combination of flash anneal and conventional RTA are demonstrated to be very effective in controlling both electrical activation and dopant diffusion. A high power, short wavelength flash anneal is confirmed to be very effective in electrical activation of fast diffusing dopants such as B without significant diffusion. Flash anneal is promising as a shallow junction implant anneal technique for advanced DRAM with 90 nm node and beyond.

SUMMARY

Heavily boron (B) implanted (^{11}B 2.0 keV 4.0 x 10^{15} cm^{-2}) silicon wafers were annealed to investigate electrical activation and dopant diffusion behavior using a novel millisecond flash anneal and a conventional tungsten halogen lamp-based rapid thermal anneal (RTA). The effect of flash anneal on already annealed wafers by the conventional RTA system was also investigated. Sheet resistance and B depth profile were measured using a four point probe and secondary ion mass spectroscopy (SIMS) before and after annealing. Wafers “spike” annealed or “soak” annealed by the RTA system showed good electrical activation. However, a significant B diffusion (15~40 nm) was observed after annealing depending on the annealing conditions. In wafers only annealed by the flash annealing system, the electrical activation of B implanted silicon improves as flash power increases at a given preheating temperature without B diffusion. The sheet resistance and junction depth achieved at 100% flash energy were 12~20% lower and 17~36% more shallow than typical values achieved after “spike” or “soak” anneal. Additional flash anneal to previously “spike” annealed and “soak” annealed wafers also showed additional electrical activation without additional B diffusion.

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keywords

1. electrical activation
2. implant anneal
3. xenon arc lamp
4. flash anneal
5. dopant diffusion
6. junction depth (x_j)

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