Nonmelt Laser Annealing of 5-KeV and 1-KeV Boron-Implanted Silicon

Susan Earles, Mark Law, *Fellow, IEEE*, Richard Brindos, Kevin Jones, Somit Talwar, and Sean Corcoran

***Abstract*—Nonmelt laser annealing has been investigated for the formation of ultrashallow, heavily doped regions. With the correct lasing and implant conditions, the process can be used to form ultrashallow, heavily doped junctions in boron-implanted silicon. Laser energy in the nonmelt regime has been supplied to the silicon surface at a ramp rate greater than 10^{10} °C/s. This rapid ramp rate will help decrease dopant diffusion while supplying enough energy to the surface to produce dopant activation. High-dose, nonamorphizing boron implants at a dose of 10^{15} ions/cm^2 and energies of 5 KeV and 1 KeV are annealed with a 308-nm excimer laser. Subsequent rapid thermal anneals are used to study the effect of laser annealing as a pretreatment. SIMS, sheet resistance and mobility data have been measured for all annealing and implant conditions. For the 5-KeV implants, the 308-nm nonmelt laser preanneal results in increased diffusion. However, for the 1-KeV implant processed with ten laser pulses, the SIMS profile shows that no measurable diffusion has occurred, yet a sheet resistance of 420 Ω/sq was produced.**

***Index Terms*—Boron, heavily doped, laser annealing, mobility, silicon.**

I. Introduction

One of the key issues involved in scaling PMOS transistors is reducing the depth of the p-type source/drain extensions [1]. The simplest method of producing p-type junctions is to implant boron, a p-type dopant. After the implant, the wafer is rapid thermally annealed (RTA) in an effort to activate the boron and remove damage created by the implant.

Upon annealing, the heating of the lattice and the damage from the implant results in boron diffusion, boron clustering, and defect evolution [2]–[4]. This produces deeper junctions, lower boron activation, and reduced mobility. Variations in the implant energy and thermal annealing techniques are thus required to produce shallower junctions.

Previous studies have investigated the use of high power pulsed lasers to melt the implanted layers to achieve high activation and abrupt junctions [5], [6]. Complications arising from melting and regrowth can limit the use of this technique [6]–[8].

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Experiments show increasing the ramp rate during thermal processing has been shown to decrease the TED of boron in silicon [9]–[11]. Plots of the ramp up rate versus diffusion length show that the ramp up rate would need to be around 10^{10} °C/s to result in a diffusion length of zero, and hence no TED [12]. Unfortunately, conventional RTA systems have peak ramp up rates of 200–400 °C/s. However, using a laser for thermal processing results in a ramp-up ramp that approaches the 10^{10} °C/s that current data suggests is needed for zero TED. The ramp-down or cooling rate is also dramatically higher for the laser annealed sample since only a small surface region of the wafer is heated during the NLA. Therefore, in an effort to reduce TED while achieving high dopant activation, the following study investigates the effects of nonmelt laser annealing on silicon heavily doped with boron.

II. 5-KeV Boron Experiment

A 5-KeV, 10^{15} ions/cm^2 B+ implant into a CZ grown ⟨100⟩ silicon wafer was processed with a 308-nm XeCl excimer laser using a 15-ns pulse at energy densities ranging from 0.4 to 0.6 J/cm^2. Control samples received an RTA step for 5 s at 1000 °C instead of the laser annealing. To help determine the amount of remaining damage, some samples processed with the NLA also received an RTA for 5 s at 1000 °C or a furnace anneal for 15 min at 750 °C. Al–Si contacts were then evaporated onto square samples that were then annealed at 450 °C in nitrogen for 30 min to produce ohmic contacts for Hall measurements. These samples were then analyzed using SIMS, Hall Effect, and Plan-view TEM.

For the 308-nm laser, the absorption depth into crystalline silicon is around 70 Å. During a 15-ns pulse at 0.6 J/cm^2, the temperature reaches approximately 1300–1400 °C 70 Å deep into the sample while the bulk of the sample remains unheated. After the 15-ns pulse, the heat rapidly dissipates by diffusion into the bulk, and cool down is expected in less than 1 ms. SIMS of the 5-KeV samples as-implanted and following the NLA show no movement in the boron profile, as was expected based on the ramp rate estimations.

Fig. 1 shows the SIMS profiles as-implanted, following the RTA, and after the NLA with the RTA. A comparison of the SIMS between the samples receiving just the RTA and the samples receiving the NLA with the RTA shows the junction depth increases from 0.16 to 0.20 μm with very little difference in diffusion for the NLA from 0.4 J to 0.6 J/cm^2 (Fig. 1). The junction depth was measured at a boron concentration of 10^{18}/cm^3.

Fig. 2 shows the change in sheet resistance as the laser energy is increased. The point at Energy Density equal to 0 J/cm^2 corresponds to the sample that received an RTA and no NLA. Sheet

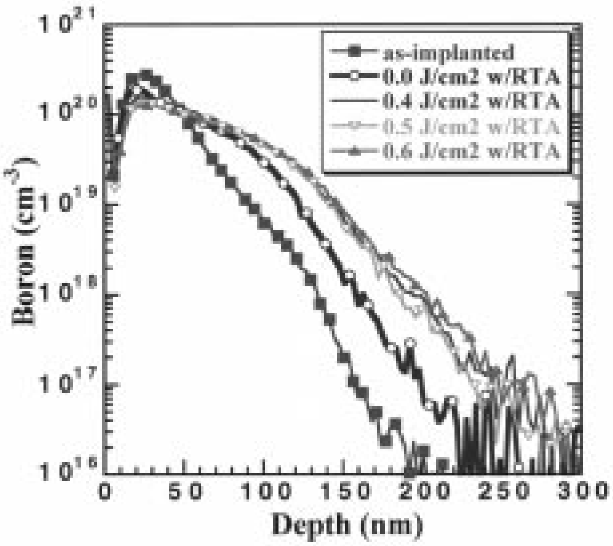

Fig. 1. SIMS of 5-KeV boron following NLA and 1000 °C, 5 s RTA.

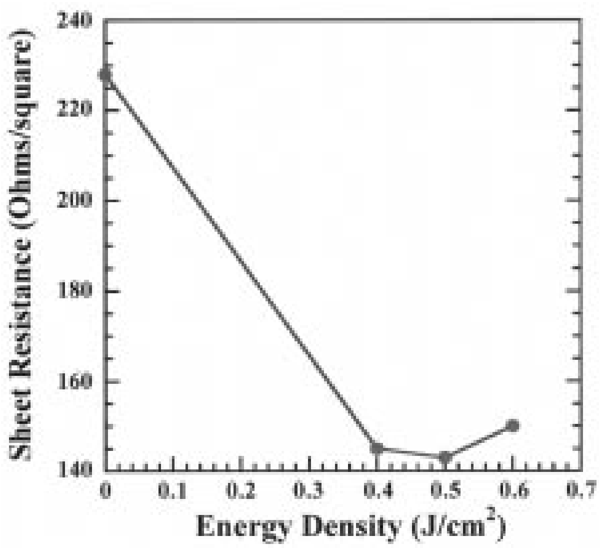

Fig. 2. Sheet resistance versus laser energy density following 1000 °C, 5 s RTA.

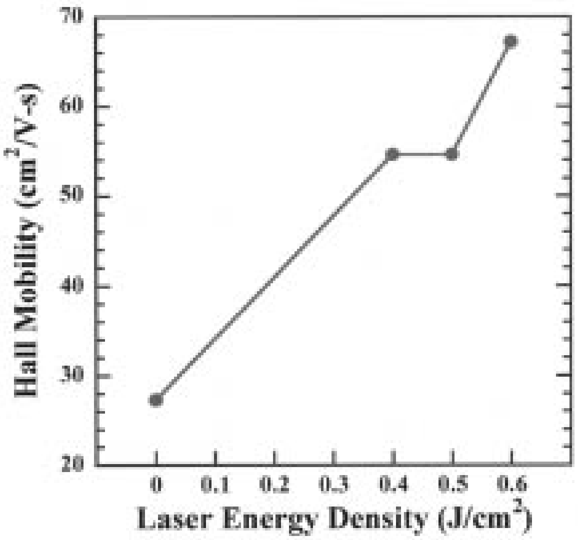

Fig. 3. Hall mobility versus laser energy density following RTA for 5-KeV boron.

resistance values measured using the Hall Effect system drop by nearly 30% when laser preannealed to around 150 Ω/sq. This 30% decrease in sheet resistance occurs with a 25% increase in junction depth. Fig. 3 shows a plot of the Hall mobility versus laser energy. The Hall Effect results for the samples receiving the NLA followed by the RTA show a large increase in the Hall mobility as the laser energy increases. The increase in the mobility accounts for the drop in sheet resistance beyond that due to the increase in junction depth.

In order to determine the cause of the mobility increase, the samples receiving either the RTA or furnace anneal are analyzed using plan-view TEM. Results show the NLA strongly affects the extended defect density by producing a high density of smaller defects (Figs. 4 and 5). Fig. 4 shows plan-view TEM following the 0.4 and 0.6 J/cm^2 NLA. The formation of numerous small defects (represented by the black dots) following the 0.6 J/cm^2 NLA shows the dramatic effect of the laser preanneal on the defect nucleation (Fig. 4 top-center).

The top right picture of Fig. 4 is for the sample receiving just the RTA and no NLA. It shows the formation of numerous loops that extend to the surface (half loops). The bottom pictures from left to right are for the samples receiving the 0.4 J/cm^2 NLA followed by the RTA, 0.5 J/cm^2 NLA followed by the RTA and the 0.6 J/cm^2 NLA followed by the RTA. These pictures show the number of the loops extending to the surface (the half loops) decreases as the laser energy increases. Also, Fig. 4 shows that as the laser energy increases, the density of the defects increases while the size of the defects decreases.

To further illustrate the effect of the NLA on the defect evolution, the left picture in Fig. 5 shows the typical formation of 311 s (rod-like defects) and loops after a 15 min anneal at 750 °C. The right picture in Fig. 5 shows the formation of a high density of very small loops for a sample receiving a 0.6 J/cm^2, 15-ns NLA followed by a 15 min anneal at 750 °C. It is interesting to note that following the NLA, no 311 s, which are expected to be the main cause of transient enhanced diffusion of boron [13], exist.

In summary, for 5-KeV implants we see that a laser preanneal does not anneal all of the damage from the implant. It significantly alters the defects present after subsequent anneals, however, and produces a consistent increase in mobility of the layers.

III. 1-KeV Boron Multipulse Laser Annealing

A 1-KeV, 10^{15} ions/cm^2 B+ implant into a CZ grown ⟨100⟩ silicon wafer was also processed with the 308-nm XeCl excimer laser. The 1-KeV implants received one or ten 15-ns pulses at a constant energy density of 0.55 J/cm^2. Following the NLA some samples received an RTA for 5 s at 1040 °C. Control samples received the RTA and no NLA. These samples were then analyzed using SIMS, Hall Effect, and plan-view TEM. Indium contacts were used for the Hall Effect measurements.

Fig. 6 shows the SIMS of the 1-KeV samples as-implanted, after ten laser shots, after the 1040 °C, 5 s RTA, and after ten laser shots followed by the RTA. SIMS for the sample receiving one laser shot was nearly identical to the as-implanted profile,

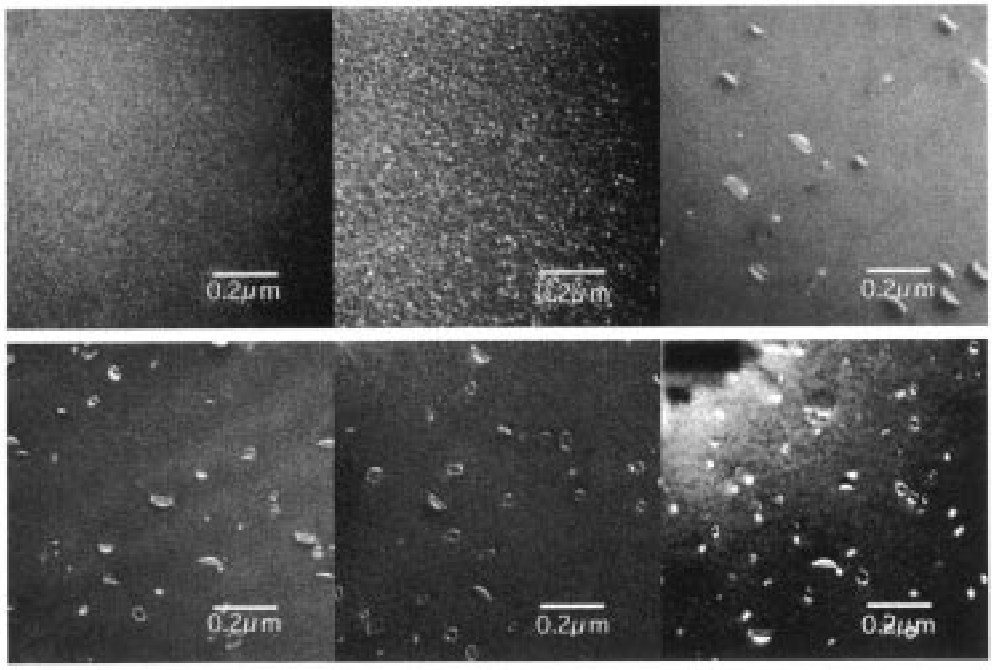

Fig. 4. TEM following 0.4 J/cm^2 NLA and 0.6 J/cm^2 NLA and RTA (top from left to right). TEM of samples receiving 0.4, 0.5, or 0.6 J/cm^2 NLA followed by RTA (bottom pictures from left to right).

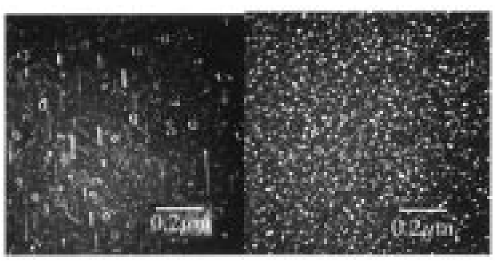

Fig. 5. TEM following 750 °C furnace anneal (left) and sample receiving NLA plus 750 °C furnace anneal (right).

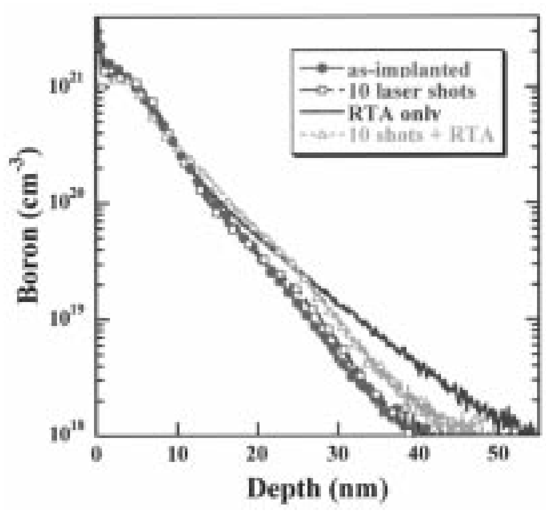

Fig. 6. SIMS of 1 KeV, 10^{15} ions/cm^2 B following ten laser pulses, with 1040 °C, 5 s RTA, and ten-pulse plus 1040 °C, 5 s RTA.

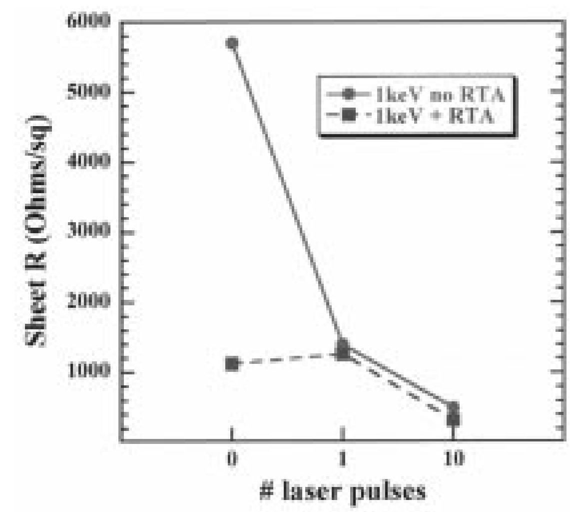

Fig. 7. Sheet resistance versus laser pulses for 1 KeV, 10^{15}/cm^2 B for samples receiving just NLA (1KeV no RTA), and those processed with 1040 °C, 5 s RTA (1 KeV + RTA).

while SIMS for the one laser shot plus the RTA was nearly identical to the RTA alone. Fig. 6 shows that the NLA of ten laser shots prior to the RTA decreases the boron diffusion while one laser shot shows no noticeable effects. This case is different than that for the 5-KeV implant discussed in the prior sample. The laser preanneal does not produce a deeper junction. For the 1-KeV implant, the bulk of the damage and boron is now contained within the absorption depth (70 Å), and we believe that this means a greater amount of the damage gets annealed during the NLA.

Fig. 7 shows the change in sheet resistance as the number of laser pulses is increased for samples receiving just the NLA and for those receiving the NLA followed by the RTA. The results show that the NLA alone results in a decrease in sheet resis-

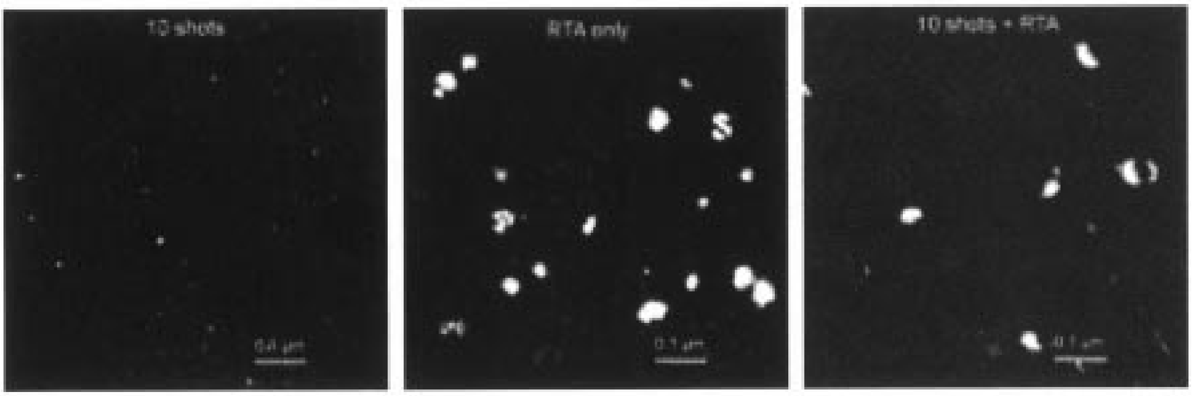

Fig. 8. Plan-view TEM of 1-KeV, $10^{15}/cm^2$ boron-implanted silicon following (from left to right) ten shots, RTA only, ten shots plus RTA.

tance equivalent to the drop seen for the samples receiving the RTA. The decrease in sheet resistance following the NLA occurs with little change in the junction depth (Fig. 6). For these samples, NLA alone is sufficient for activation of the layer. Ohmic contacts could not be made to the sample receiving one laser shot therefore no Hall measurements were made. The sample receiving ten laser shots has a Hall mobility of 15 cm^2/V-s, while those receiving the RTA had a nearly constant mobility around 30 cm^2/V-s.

Plan-view TEM pictures of the 1-KeV boron after 10 laser shots, after the RTA, and after ten laser shots plus the RTA are shown in Fig. 8. Fig. 8 shows the NLA of ten laser shots alone nucleates numerous small loops (left-most picture). Fig. 8 also shows that this NLA prior to the RTA reduces the final loop density (right-most picture) compared with the RTA alone (center picture). This change in defect density is qualitatively similar to that for the 5-KeV samples.

IV. Discussion

Contrary to the 5-KeV SIMS results, which show that the boron profile diffuses more when given an NLA prior to the RTA, SIMS results of the 1-KeV boron show that the NLA prior to the RTA actually decreases the boron diffusion. Also, the NLA prior to the RTA results in an increase in the loop density for the 5-KeV samples and a decrease in the loop density for the 1-KeV samples. This variation is due to the fact the 1-KeV implant damage is contained primarily within the absorption depth of the laser and is therefore more likely to be annealed.

The variations in loop densities and diffusion can be attributed to the interaction of the laser beam with the damage and boron following the implant. The laser used has an absorption depth around 70 Å. The peak of the boron as-implanted profile is around 260 Å for the 5-KeV implant and 50 Å for the 1-KeV implant. For the 1-KeV implant, the effect of the laser is distributed across the bulk of the damage and dopant profile. While for the 5-KeV implant, the laser interacts with less than a fifth of the damage and dopant profile. During the NLA, the surface is heated to 1200–1400 °C for a few nanoseconds. This allows time for the silicon interstitials to move around, but not the boron. Thus during one laser shot interstitials diffuse to the surface where they recombine while some remain behind in clusters.

For the 5-KeV implant, during one laser shot a region around 70 Å thick rich in interstitials is heated resulting in the nucleation of numerous small interstitial clusters. When followed with an RTA, these interstitial clusters grow and act as traps for interstitials which would normally recombine at the surface. This concentration of loops between the surface and the peak of the dopant/interstitial profile results in more interstitials diffusing into the bulk instead of toward the surface. This increases the number of interstitials available to contribute to TED and defect formation during post-annealing. As shown in Fig. 1 similar diffusion occurs for all laser energies followed with the RTA. Also, although the number of loops increases as the laser energy is increased, the number of interstitials contained in the loops after the RTA is roughly the same for each sample (Fig. 4). Since the bulk of the damage is not annealed during the NLA, post-processing of the samples receiving the NLA results in similar boron diffusion.

For the 1 KeV, the bulk of the interstitials and boron are within 70 Å of the surface. This high concentration of impurity ions decreases the absorption length of the silicon reducing the depth of the heated layer. During the first laser shot, numerous small defects are nucleated in this thin region with the size of the defect being no larger than the width of the heated region. During subsequent laser shots the width of this heated region increases along with the size of the defects. After ten laser shots the defects are large enough to be detected in the TEM. Meanwhile, during each pulse interstitials have been making it to the surface where they recombine resulting in fewer interstitials available to form loops and contribute to TED during post-annealing.

For both the 5-KeV and 1-KeV implants, results show that the mobility is greater in the samples that have more loops. Logically, more defects should mean more scattering sites so the mobility should go down as the number of loops increases. What we believe is occurring is that the loops are trapping boron as well as silicon interstitials resulting in a decrease in the carrier activation. This decrease in carrier activation results in the increase in mobility measured. The plan-view TEM following the NLA alone and the sample receiving the NLA plus the RTA both show fewer interstitials remaining compared to the sample receiving just the RTA. The defects are also smaller in the sample receiving the NLA. For these nonamorphizing implants, smaller defects are unlikely to be in the depletion region of the device as they exist around the peak region of the implanted ion. Both cases lead to less leakage current.

V. Conclusions

Heavily doped, ultrashallow regions in boron-implanted silicon using pulsed laser annealing have been created. It has been shown that NLA consistently decreases the sheet resistance. For deeper profiles, damage remains unannealed and subsequent RTA still shows increases in junction depth. For a shallower implant, the NLA shows reduced junction depth and sheet resistance. The NLA also repairs crystalline damage from the implant resulting in improved mobilities and most likely lower leakage currents. Thus, NLA alone can be used to make satisfactory layers for shallower implants.

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