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# Boron segregation in As-implanted Si caused by electric field and transient enhanced diffusion

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Boron segregation in an implanted arsenic profile in Si during annealing was investigated under various annealing conditions. It was found that both the implant damage created by arsenic implantation and arsenic deactivation enhance the diffusion of the embedded boron layer toward the shallow As implanted profile. The segregation phenomenon was observed in both 650 °C furnace annealed (FA) and 1000 °C rapid thermally annealed (RTA) samples. For the 650 °C FA sample, the boron segregation peak was located at the junction formed by implanted As, where residual dislocation loops at the original amorphous/crystalline (*a*/*c*) interface were also observed. However, no *a*/*c* interface dislocation loops were found to be present for the RTA samples. Additional anomalous boron segregation was observed for the 1000 °C RTA+750 °C FA samples. The additional boron segregation is not correlated with defect layers. It is, therefore, concluded that the anomalous boron segregation is caused by the electric field resulting from the formation of a *p*-*n* junction. © *1998 American Institute of Physics.* [S0003-6951(98)00214-9]

Profile engineering becomes more important as metal–oxide–semiconductor field effect transistors (MOSFETs) shrink toward smaller geometry. For submicron devices, the channel length is scaled down, thus the channel profile redistribution near the source/drain (S/D) region during annealing is very critical for device performance. Damage created by As implants for S/D formation creates excess point defects which not only cause arsenic transient enhanced diffusion (TED) but also affect the nearby channel boron profiles.[1] The boron segregation in an As profile has been reported to cause the depletion of boron near the S/D, which, in turn, enhances the short channel effects on *n*-channel MOSFETs. Dislocation loops created by As implants have been proposed as the mechanism driving this behavior because similar segregation and dislocation layers have been observed in Si or Ge implanted samples after annealing.[2–4] In the work of Sadana *et al.*,[2] the possible contribution from the electric field has been neglected because of the absence of segregation in an As-doped epilayer structure after annealing. Uwasawa *et al.*[3] also ignored the electric field effects due to the drift reduced by high carrier concentration at high temperature. In this letter, we examine the mechanism of boron segregation by monitoring the dopant redistribution of As and B during postimplant annealing. The experimental results show that the contribution of the electric field resulting from junction formation to boron segregation is very significant with combined effects of TED.

To approach a real device fabrication process, ⟨100⟩, 5–15 Ω cm, *p*-type silicon wafers were implanted by B at 100 KeV with a dose of $1\times10^{13}$ cm$^{-2}$ to form an embedded boron layer. A 20 nm screen oxide was grown during a 45 min annealing at 850 °C in an oxygen ambient. After oxidation, a 900 °C 20 min nitrogen anneal was used to eliminate damage from the B implant. Arsenic was then implanted into the wafers at 60 keV to a dose of $5\times10^{15}$ cm$^{-2}$. Annealing after the As implant was performed at various temperatures and times by using either furnace annealing or the rapid thermal annealing (RTA) technique. Arsenic deactivation was done by performing a low temperature anneal at 750 °C for 160 min after a 1000 °C 1 min RTA activation. Secondary ion mass spectrometry (SIMS) was used to analyze the profiles of both As and B. The distribution of dislocation loops was analyzed by cross sectional transmission electron microscopy (XTEM). The sheet resistance of the annealed samples was measured by a four-point-probe to monitor the activation and deactivation of arsenic in the samples after annealing.

Figure 1 shows the XTEM and SIMS profiles from the sample annealed at 650 °C for 160 min after the As implant. The XTEM picture shows two discrete layers of dislocation loops. The defect layer near the projected range of the As-implanted profiles is related to the arsenic clustering where the arsenic concentration is over solid solubility.[5] The second layer of dislocation loops is at the original *a*/*c* interface created by the As implant.[6] Since the dislocation loops behaved like strong sinks of point defects and damage created by implantation was eliminated by solid phase epitaxial growth in the amorphized region,[7] the SIMS profiles show that the dopant redistribution due to TED is confined beyond the *a*/*c* interface during the postimplant annealing. The arsenic profile has minimum tail diffusion, but significant segregation under the arsenic profile has led to the boron depletion out-

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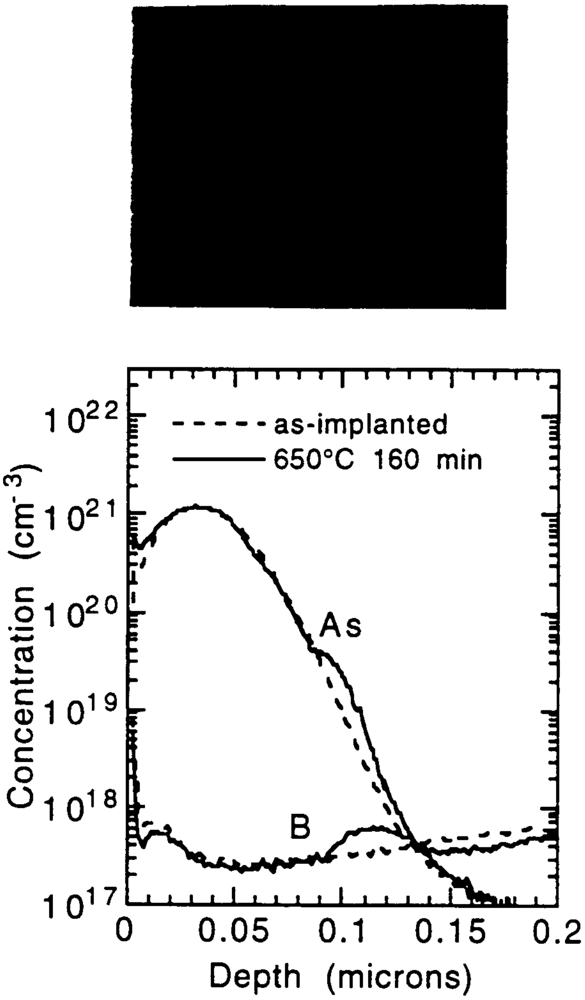

FIG. 1. Comparison of the XTEM of the sample annealed at 650 °C for 160 min after As implant with the SIMS profiles before and after annealing. The scale of the XTEM is the same as that of the *x* axis of the SIMS profiles.

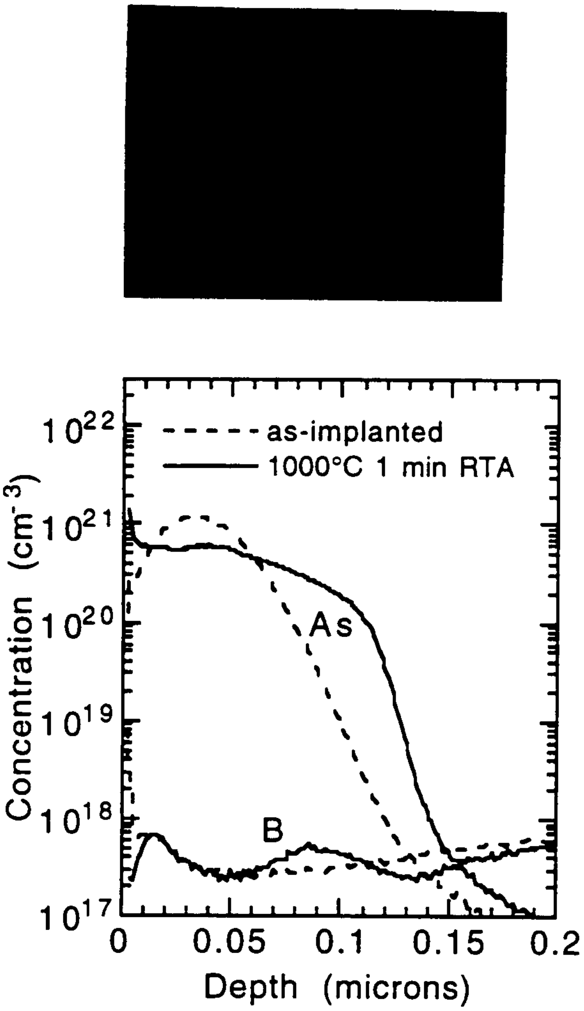

FIG. 2. The XTEM for the sample with 1 min RTA at 1000 °C and the SIMS profiles before and after RTA. The XTEM has the same scale as that of the *x* axis of the SIMS profiles.

side the arsenic layer. Similar results were found in the samples annealed from 10 to 320 min at 650 °C. The arsenic diffusion and boron segregation increased with annealing time as the TED continued. Comparing the boron SIMS profile with the XTEM picture, the location of the *a*/c interface dislocation loops seems to correlate with the boron segregation peak reported by Ref. 2 which suggests dislocation as the segregation mechanism. However, the segregation peak is also close to the junction formed by active arsenic dopants which cause the low sheet resistance of about 150 Ω/□ of the sample. The internal electric field in the junction region may also cause the boron segregation by pushing ionized boron dopants into the As profiles.[8]

To identify the contribution by the electric field to boron segregation, high temperature RTA was applied to eliminate dislocation loops and their effects. The experimental results for the sample with 1000 °C 1 min RTA after As implant are shown in Fig. 2. The TEM picture shows no dislocation loops at the original *a*/*c* interface and less density of dislocations at the projected range region than that in the 650 °C annealed sample. The elimination of the dislocation is possibly enhanced by vacancy emission from the dissolution of arsenic clusters at high temperature.[9] Even though the *a*/*c* interface dislocations have been annealed out, the SIMS profiles in Fig. 2 still demonstrate boron segregation in the As layer. In addition, the location of the boron segregation peak between the original *a*/*c* interface and the projected range indicates that the segregation is not related to any dislocation layers. The inconsistency between segregation peak and dislocation strongly suggests the internal electric field of the junction as the mechanism of boron segregation. The arsenic doping is much higher than the intrinsic carrier concentration around $5\times10^{18}$ cm$^{-3}$ at 1000 °C and thus provides a remarkable internal electric field to induce boron segregation. Comparing the SIMS profiles and results from SUPREM-IV[10] simulation, the arsenic diffusion is dominated by high concentration steady state diffusion while the boron accumulation much larger than the steady state estimation is supposed to be dominated by TED in a very short time. With an internal electric field, the location of the boron segregation peak is determined by the junction depth at the beginning of annealing. At high temperatures, the junction depth depends on intrinsic carrier concentration. As the intrinsic carrier concentration increases with temperature, the boron segregation peak shifts toward the surface with shallower junction depth. This agrees with the experimental result that the location of the segregation peak is closer to the surface in the 1000 °C RTA sample than that in sample annealed at 650 °C.

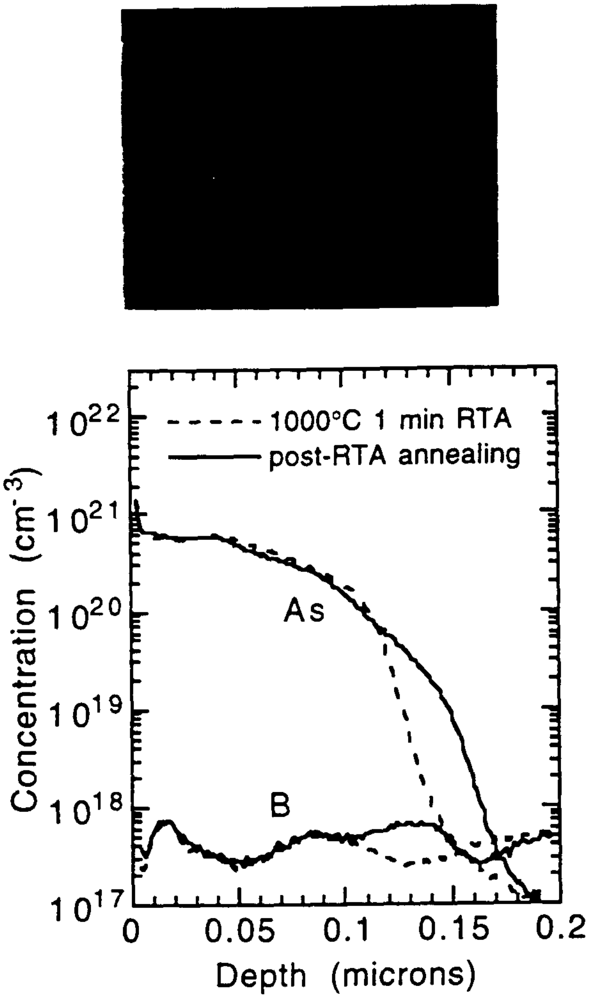

FIG. 3. Comparison of the XTEM of the sample annealed at 750 °C for 160 min following the RTA with the SIMS profiles before and after the post-RTA annealing. The XTEM and the $x$ axis of the SIMS profiles have the same scale.

The electric field driving boron segregation has been further confirmed by the 750 °C 160 min arsenic deactivation annealing after 1000 °C 1 min RTA according to the XTEM picture and SIMS profiles shown in Fig. 3. The sheet resistance increasing from 59 to 76 Ω/□ after 750 °C annealing indicates that the arsenic deactivation occurred as a result of the clustering of supersaturated arsenic during annealing. The arsenic clustering at the high concentration region generates additional dislocation loops[11] near surface in the XTEM picture and induces point defect emission[12] which causes the TED of As and B as is shown in the SIMS profiles. Additional boron segregation driven by TED has been found to be correlated with junction depth but not with dislocation loops. The junction dependence implies that the electric field is a major mechanism for boron segregation. It should be noted that both electric field and TED are required for boron segregation. In previous research done by Sadana *et al.*,[12] an As-doped epilayer was grown on a B-doped substrate. That structure provided an electric field but there was no point defect source to generate TED. Without TED, the diffusion of boron is too slow to cause the segregation even with the presence of an electric field. The absence of segregation observed in previous research cannot be applied to neglect the electric field mechanism.

In summary, the internal electric field of the junction formed by an As implant has been demonstrated to cause the boron segregation in the arsenic profiles. The segregation is driven by TED introduced by either ion implantation or arsenic deactivation. The location of the segregation peak is determined by junction depth which is correlated with doping profiles and intrinsic carrier concentrations. Additional boron segregation was found during arsenic deactivation annealing due to the electric field mechanism.

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