Phosphorus and arsenic profile control for high performance epitaxial base bipolar junction devices

R. Bashir,[a] A. E. Kabir, and P. Westrom
Process Technology Development, National Semiconductors, Santa Clara, California 95051

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In this study, we report on the incorporation behavior of *n*-type species in undoped layers grown subsequent to doped layers at low temperature (700–750 °C) reduced pressure chemical vapor deposition of silicon/silicon germanium ($Si/Si_{1-x}Ge_x$) performed in a single wafer epitaxial deposition system. Significant amounts of these species are observed even in an undoped layer grown subsequent to the doped layer. The presence of these dopants in the subsequently grown undoped layer is attributed to segregation at the moving growth interface. The arsenic segregation is confirmed to be significantly higher than phosphorus. In addition, an increase in both the phosphorus and arsenic incorporation is observed in the presence of a highly doped boron layer. © *1999 American Institute of Physics.* [S0003-6951(99)03332-X]

Epitaxially grown silicon/silicon germanium bases are utilized in realizing a very high performance bipolar junction transistor (BJT) and heterojunction bipolar transistor for various wireless, radio frequency, and communications applications which use transistors with f_T and $f_{\max}$ in excess of 40 GHz.[1–3] Boron implants suffer from the undesirable channeling effects, and hence, it is very difficult to form very shallow base profiles since the channeling results in undesirably wide base profiles and poor film thickness control. The epitaxial deposition processes can be used to achieve ideal box-like doping profiles resulting in optimum device characteristics.

A drawn cross section of a typical device is shown in Fig. 1. Since the base deposition is usually performed after the isolation oxide regions have been formed, typically, a simultaneous deposition of single crystal silicon on silicon openings and poly-crystalline silicon on oxide is used. If the intrinsic base thickness is aggressively scaled down to the 400–600 Å regime, the extrinsic base region would also become too thin and the extrinsic base resistance would be undesirably high. To circumvent the earlier problem, a two-layer deposition is performed. First, a *n*-type layer is deposited which becomes a part of the underlying collector of the device. Then, a thin $P+$ layer is deposited to form the base. The extrinsic regions are then implanted with P type dopant to turn the stack of $P+/N$ film to P type. The doping of the *n*-type layer can thus be adjusted to form the most optimum collector profile. Figure 2 shows a drawn doping profile through the intrinsic device region (along AA′ of Fig. 1).

Previous authors have studied the doping of arsenic and phosphorus in low temperature silicon epitaxial growth at atmospheric pressure.[4,5] High controlled doping of these *N*-type species was achieved in an ultraclean condition at temperatures below 750 °C. The turn-on characteristics and abruptness of arsenic and phosphorus dopant transients in low temperature and low pressure silicon epitaxial growth has also been studied.[6] These studies show that the transition lengths for arsenic are six to eight times longer than phosphorus. These transition lengths were the same for silane or dichlorosilane source gas. In addition, the authors also found that boron promoted the incorporation of arsenic into silicon but did not significantly enhance the incorporation of phosphorus into silicon. The study did not report on the dopant profile control in undoped layers grown subsequent to a doped layer. As mentioned earlier, the design of advanced bipolar junction transistor base profiles requires an undoped or low doped film after the doped base film growth. The doping in these subsequently grown films depends on the turn-off characteristics (auto-doping), loading effects, and memory effects during the epitaxy.[7]

The base collector junction and the base width are determined by the emitter junction (not shown in Fig. 2) and the boron/*N* dopant junction. Both the *P*- and *N*-dopant profiles need to be characterized and controlled in order to result in optimized base widths. It is the purpose of this letter to experimentally report on the issues relating to optimizing the *N* dopant (Phos or As) and boron profiles. Specifically, it is shown that significant amounts of the *N* type species are found in the upper undoped layer or *P*-type layer. The pile up of these dopants is attributed to segregation at the moving growth interface. In addition, an increase in both phosphorus and arsenic incorporation is observed in the presence of a highly doped boron layer.

The films were deposited in an 8 in. commercially available single wafer reactor from Advanced Semiconductor

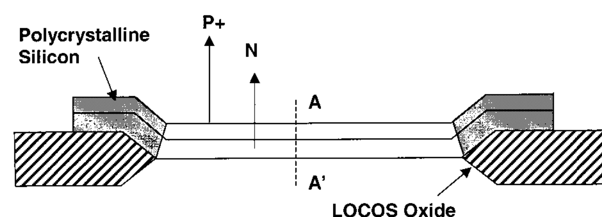

FIG. 1. Drawn cross section of a typical epitaxial base Si/SiGe device.

[a]R. Bashir is now with the School of Electrical and Computer Engineering, Purdue University, W. Lafayette, IN 47906; electronic mail: bashir@ecn.purdue.edu

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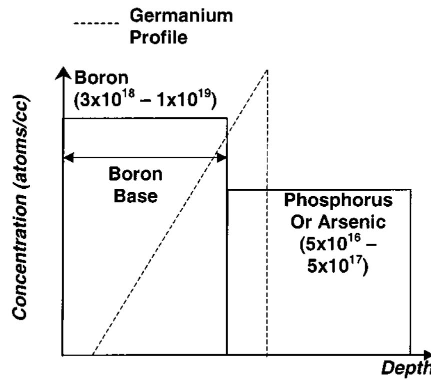

FIG. 2. Typical drawn base profile of a high performance Si/SiGe base BJT.

Materials.[8] The system was a cold-wall radiantly heated chamber where the wafer is placed on a SiC coated graphite susceptor. SiH_4 was used as the silicon source, PH_3 or AsH_3 was used as the N-type source gas, and B_2H_6 was used as the P-type source gas. Deposition temperature was 750 °C for silicon and 700 °C for $Si_{1-x}Ge_x$. (100) substrates with and without local oxidation of silicon patterns were used.

Dopant profiles were measured using secondary ion mass spectroscopy (SIMS) using a Cameca spectrometer using an oxygen primary ion source beam. At the beginning of the analysis, the same surface was flooded with oxygen to minimize transient ion yield. This also helped to maximize the sensitivity of the measurement. For accurate quantification, each impurity was measured as a positive secondary ion. Primary beams with 3 kV energy were used to get the best depth resolution.

Figure 3 shows a SIMS plot of a typical base profile with phosphorus doped silicon layer and a boron doped silicon layer. The arrow indicates where the N-type silicon layer growth was started and where the phosphine dopant gas was turned off. The silicon growth was done at 750 °C using silane as the source gas. As can be seen from the plot, the phosphorus concentration does not decrease but rather tends to increase even after the phosphorus is turned off. The same behavior was observed when a silicon germanium base film

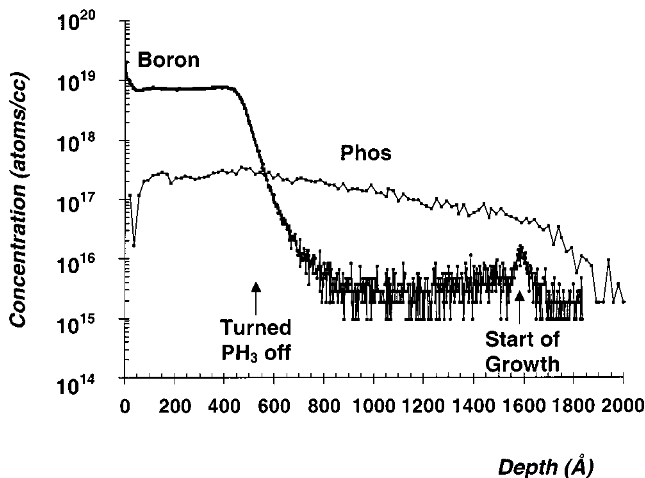

FIG. 3. SIMS profile of a silicon base showing accumulation of phosphorus in the top boron doped layer.

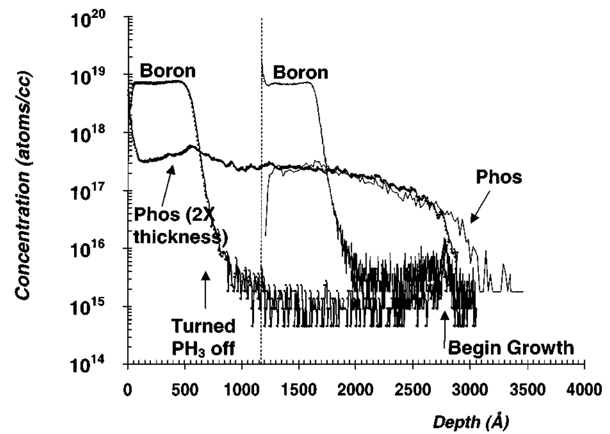

FIG. 4. SIMS profile of sample from Fig. 3 overlaid on the SIMS of sample with 2× the N-type silicon layer thickness.

was used grown at 700 °C. This particular behavior of phosphorus prompted further study.

Experiments were performed with various hydrogen gas purges after the first silicon layer growth with a flow of 20 slm. The increased purges were done in an effort to eliminate any memory effects and to remove and purge out the phosphorus species from the ambient prior to starting the subsequent boron doped layer growth. No difference in the phosphorus profile was observed between the three cases, i.e., no purge, 3 min purge, and 30 min purge. These volumes of hydrogen should be sufficient to purge any residual gases in the ambient. These experiments indicate that the increase in phosphorus concentration is not likely to be due to species in the ambient, outgassing or memory effects.

To further investigate the behavior of phosphorus under these conditions, a sample was grown at the same conditions as earlier, except that the phosphorus doped layer was twice as thick. The SIMS plot of the samples are shown in Fig. 4. The slight boron pile up at the epi/substrate interface is used as the marker to overlay the two plots. The initial phosphorus increase is the same in both the samples for the first 1000 Å. After that, the phosphorus settles to a more uniform profile in the next 2000 Å (in the sample with 2× the phosphorus doped silicon thickness). Once the phosphine gas is turned off, there is a 3 min hydrogen purge after which the boron is turned on and the silicon growth is continued. The phosphorus behavior in the two samples is the same once the phosphine gas is turned off, i.e., there is an initial small increase when the boron is turned on and then the phosphorus concentration declines slightly.

A closer examination of Figs. 3 and 4 also indicates that the phosphorus concentration is increased once the boron is turned on. This was further verified by growing a sample without the boron doped layer, i.e., once the phosphine is turned off and purged, only the silane is passed through the system. Figure 5 shows these SIMS profile and as can be clearly seen, an increase in phosphorus concentration by factor of two is achieved. Again, it should be noted that the concentration of phosphorus does decrease with time in the boron doped layer.

An experiment was also conducted with arsenic as the n-type dopant in the silicon layer. As shown in Fig. 6, the

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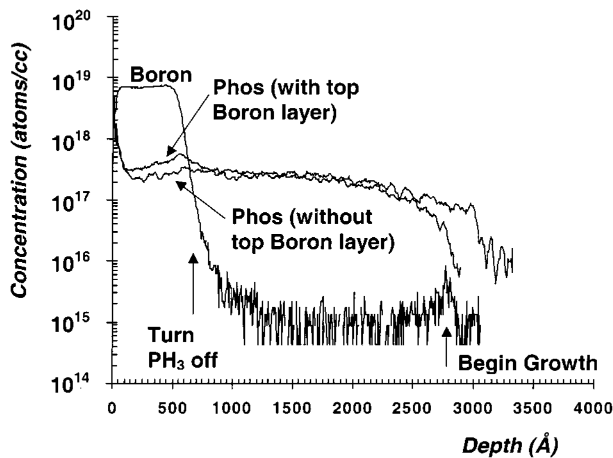

FIG. 5. Phosphorus SIMS profile with and without the presence of boron in the top silicon layer.

arsenic accumulation in the upper undoped layer is considerably higher when compared to phosphorus. The arsenic concentration actually increases by about a factor of 30 (3×10^{16}–1×10^{18}) from the point where the arsine is turned off to the top of the surface. In Fig. 6, the actual boron concentration is identical to the ones in Figs. 3 and 4, and hence, is not shown. Just like the case with phosphorus, the arsenic concentration increases with the presence of boron.

The increased tendency of arsenic to pile up in the top undoped layer when compared to phosphorus can be attributed to an increased segregation of arsenic at the growing silicon interface. In previous reports, the increased segregation of arsenic when compared to phosphorus explained the greater turn-on time and transition length.[7] The same behavior can also account for a continuing increase/pile up of the arsenic on the growing interface. However, since the dopant source is turned off and the chamber is purged thoroughly, the main source of the extra dopant is most likely at the surface of the first doped layer and/or from within the first doped layer (it should be noted that purging the chamber from some time does necessarily eliminate other sources of dopant out diffusion and out gassing).[7] The dopant continues to accumulate and build up at the growing interface even if the source gas is depleted from the chamber. The comparison between arsenic and phosphorus conclusively show that the surface segregation of arsenic is significantly higher than phosphorus.

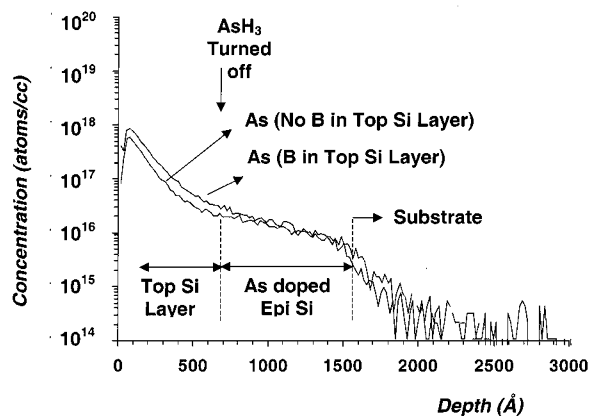

FIG. 6. SIMS profile of base profile with arsenic in the first *N*-type layer. Arsenic profiles with and without the presence of the top boron doped silicon layers are shown.

In this letter, we reported on the dopant incorporation behavior of *N*-type dopants in undoped layers grown subsequent to doped layers at low temperature (700–750 °C) RPCVD growth performed in a single wafer epitaxial deposition system. Significant amounts of these species are observed even in an undoped layer grown subsequent to the doped layer. The presence of these dopants in the subsequently grown undoped layer is attributed to segregation at the moving growth interface. The arsenic segregation is confirmed to be significantly higher than phosphorus. In addition, an increase in both the phosphorus and arsenic incorporation is observed in the presence of a highly doped boron layer.

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