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Physical Modeling of the Enhanced Diffusion of Boron Due to Ion Implantation in Thin Base npn Bipolar Transistors

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Abstract

Using the most advanced physical models of diffusion, we have simulated boron diffusion in the context of a low thermal budget technology for thin-base integrated bipolar transistors. We demonstrated that simulation was able to account for the base broadening due to arsenic implantation in a monocrystalline emitter. Moreover, even in polysilicon emitter bipolar transistors, where the effect of the emitter implantation is suppressed, we found that the extrinsic base implantations could still induce a non negligible base broadening.

The trend in bipolar technology is towards highly doped thin base devices, where both base transit time and base resistance are low, resulting in higher operation frequencies. This is achievable only if the base fabrication and the whole technology process allow the fabrication of very steep doping profiles. Low thermal budgets are of course essential. But it is well known that some technological steps induce an enhanced diffusion of boron and a detrimental broadening of the base.[1,2,3] There is a general agreement to attribute this base broadening to the acceleration of boron diffusion in the presence of implantation defects.[4] Although there has been a lot of progress in the analysis of the physical mechanisms involved in defect and dopant diffusion, there has been to our knowledge no attempt to apply the corresponding physical models to the enhanced diffusion of boron in devices. Yet, it is essential to predict such an effect, especially in bipolar transistors where the base width is a critical parameter. In this paper, we evaluate base broadening by using the most advanced physical models of diffusion, which have recently been implemented in the process and device simulation software TITAN developed at CNET.[5] First, we studied the boron diffusion induced by arsenic implantation in a monocrystalline emitter. We simulated a bipolar transistor based on the layer structure of Table 1. Simulation results show very good agreement with the SIMS profiles of non implanted annealed structures (curves a-b, Fig. 1). For implanted structures, a standard simulation gives the same amount of diffusion whereas the SIMS profile shows a very strong enhancement of boron diffusion, consistent with a defect assisted diffusion mechanism

Layer	Doping	Thickness
Si emitter	$n = 10^{18}$ cm^{-3}	300 nm
Si cap		20 nm
Si spacer		50 or 100 nm
Si base	$p = 7 \times 10^{18}$ or 2×10^{19} cm^{-3}	25 nm
Si spacer		50 or 100 nm
Si buffer		
Substrate		

Table 1 :
Layer structure of the bipolar structures. As (30 keV) was implanted in the monocrystalline emitter (except for some reference wafers). A rapid thermal anneal (RTA) was then performed at 800, 850 or 900°C.

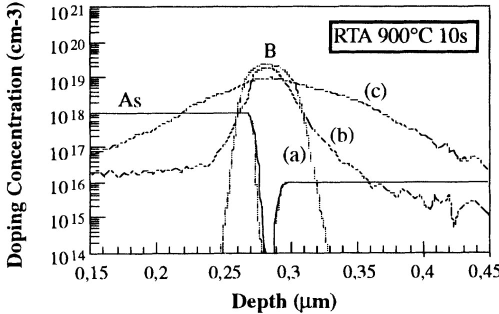

Figure 1 :
Dopant profiles measured by SIMS in (b) the non-implanted and (c) the implanted wafers. The result of a standard simulation neglecting coupling with defects is shown for comparison (a). The nominal base doping is $2x10^{19}$ cm^{-3}

Process simulation was then carried out using advanced diffusion models.[6] We assumed perfect recrystallisation of the amorphised layer at the beginning of the RTA and defects were therefore introduced by implanting free interstitials beyond the amorphisation limit. The defects were first assumed to be free at t=0. Simulation results are shown in Fig. 2. Although significant, the calculated base broadening could not reach the measured values, unless non realistic (i. e. much too high) initial interstitial supersaturations were used. However, implantation related point defects are in reality aggregated into small clusters and during RTA, free defects are only progressively released by cluster dissolution.

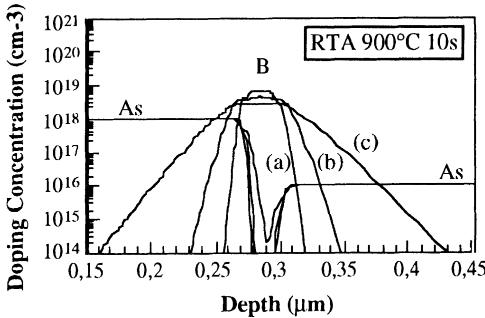

Figure 2 :
Calculated dopant profiles when coupling with implantation defects is ignored (a) or is taken into account (b, c : maximum supersaturation for the initial defect distribution of about $4x10^5$ and $4x10^6$; all defects assumed free at t=0). The nominal base doping is $7x10^{18}$ cm^{-3}.

As a first attempt at modelling this situation, we simulated the cluster dissolution kinetics by a time discretization technique. Fig. 3 compares the final dopant profiles obtained after the implantation of the same initial supersaturation, either at the beginning of the RTA or at several successive stages of the RTA. It shows clearly that the kinetics of cluster dissolution is not a negligible phenomenon : it strongly enhances diffusion by maintaining the interstitial supersaturation in the base during a longer time. Therefore, significant

diffusion is obtained without the need for non realistically high supersaturations. Accounting for cluster dissolution will be necessary for precise modelling.

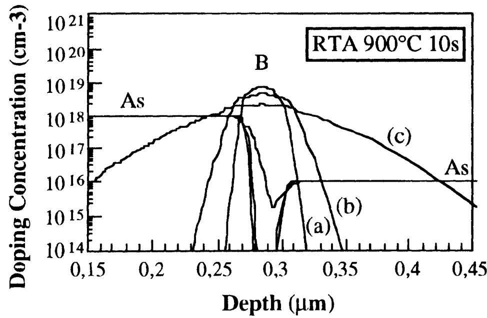

Figure 3 :
Calculated dopant profiles with an interstitial supersaturation of 4x10^5 applied once at t=0 (curve b) or 40 times during the RTA (curve c). The diffusion without coupling with defects is given as (a).

Finally, in most integrated bipolar and BiCMOS circuits, the contacts are implanted and their distance from the active base is usually short compared to the defect diffusion length (about 30-40 μm). Typically, the collector contact is around 2 μm from the intrinsic base, while the extrinsic base may even be self-aligned.[7]

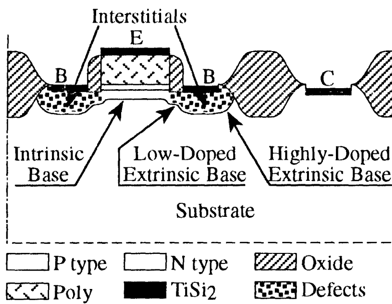

Figure 4 :
Schematic view of the simulated polysilicon-emitter bipolar transistor : the defects induced by the lightly-doped extrinsic base (LDEB) and of the highly-doped extrinsic base (HDEB) self-aligned implantations enhance B diffusion in the intrinsic base.

Therefore, it is useful to evaluate the influence of the contact implantations. We studied a self-aligned polysilicon-emitter bipolar transistor with a thin epitaxial base (Fig. 4). To simulate the whole structure, we used the latest version of TITAN, with a precise modelling of the grain structure. Coupled diffusion of dopants and defects was of course accounted for. The base broadening induced by collector implantation was found to be negligible due to the small solid angle offered to defects coming from the collector to the intrinsic base. In contrast, the base implantation generates defects close to the intrinsic base. It has been shown that the defects induced by boron implantation were mainly associated to the activated boron atoms themselves and were of the interstitial type.[8] In addition, we found that, when accounted for, vacancies relaxed in the first 0.5 s by diffusing towards the silicon surface, and did not affect significantly boron diffusion. Therefore, the only defects which have to be accounted for are interstitials. Fig 5 shows the base profile calculated with no defects and with two different intestitial supersaturations, respectively generated by the lightly-doped extrinsic base and by the highly-doped extrinsic base implantations. With a typical 10^{17} cm^{-3} doping concentration

in the collector, the calculated base width was 60% larger when accounting for the defects generated by the extrinsic base implantation.

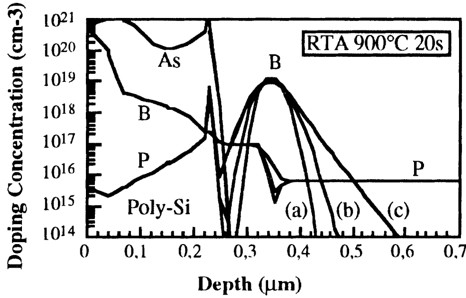

Figure 5 :
Calculated dopant profiles in the bipolar transistor of Fig. 4, a) with no implantation induced defects, b) accounting for interstitials induced by the LDEB implantation ($5x10^4$ supersaturation), c) accounting for interstitials induced by the HDEB implantation ($3.5x10^6$ super-saturation).

To conclude, we have simulated boron diffusion in the context of a low thermal budget technology for thin base integrated bipolar transistors. Using the most advanced physical models of diffusion presently available, we demonstrated that simulation was able to account for the diffusion enhancement arising from coupling with crystal defects. Information about the global distribution of defects can be found (e.g. from Monte-Carlo simulations of implantation) but it was found that accounting for their arrangements into clusters and for the cluster dissolution kinetics during the RTA will be essential to obtain quantitative agreement with measurement. Valuable information can however be obtained through qualitative comparisons. In addition to the emitter implantation effect which leads to a large enhancement of the boron diffusivity in the intrinsic base, we have also investigated the possible broadening induced by extrinsic base and collector implantations.

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References :
1 P. R. Pukite, S. S. Iyer, G. J. Scilla, Appl. Phys. Lett. **54** (10) (1989) 916-918
2 D. J. Gravesteijn et al., MRS Symposium Proceedings **vol. 220** (1991) 3-14
3 A. Pruijboom et al., Microelectronics Engineering **19** (1992) 427-434
4 A. E. Michel, 2nd Int. Symp. on Modelling in Semiconductor Technol., Proceedings **vol. 91-4** (1991) 242-253
5 A. Gerodolle et al., Proceedings of NASECODE VI, 56-57 (1989, Boole Press)
6 D. Mathiot, S. Martin, J. Appl. Phys. **70** (6) (1991) 3071-3080
7 A. Marty et al., Microelectronics Engineering **19** (1992) 547-550
8 F. Marou et al., Nuclear Instr. and Methods in Phys. Research **B55** (1991) 655-660