Carbon Co-Doping of $Si_{1-x}Ge_x$:B Layers: Suppression of Transient Enhanced Diffusion

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$Si/Si_{1-x}Ge_x$ heterobipolar transistors (HBTs) are now commercially available and expected to open the mobile communication market for Si-based electronics. A technological problem is caused by transient enhanced diffusion (TED) of boron in the extremely thin base layer of such transistors. It is mainly caused by injection of interstitials from a subsequent implantation processes. Co-doping of the $Si_{1-x}Ge_x$ base with carbon is shown to significantly reduce TED.

1. Introduction

$Si_{1-x}Ge_x$ is the obvious choice for extending the physical properties of Si through the exploitation of heterostructures without sacrificing standard Si technologies. Most of the worldwide activities in that area are dedicated to the $Si/Si_{1-x}Ge_x$ heterobipolar transistor (HBT), which is now available commercially in integrated analog circuits that will open fast growing high-frequency markets for Si-based electronics. In contrast to even more potent devices based on III-V materials, $Si_{1-x}Ge_x$ is readily integrated with standard Si MOS devices, which allows cost effective monolithically integrated circuits with mixed analog and digital functions. The feasibility of such hetero-BiCMOS circuits with a high degree of complexity in both their bipolar and CMOS components have been demonstrated by several companies [1], [2]. Their introduction is expected to be of major impact on the development of high-frequency electronics up to 20 GHz and beyond.

2. Transient Enhanced Diffusion

Depending on the concept of the HBT, its speed advantage is either caused by an additional drift field in a graded $Si_{1-x}Ge_x$ base (drift transistor; [3]) or by the reduction of the base width and simultaneous increase of the base doping (true HBT; [4]). In either case it is important that the heterointerfaces coincide with the p/n junctions to prevent detrimental parasitic potential barriers. Precise doping control during all fabrication and annealing steps is therefore a stringent condition for successful high frequency operation. It is especially the p-type (boron) doping of the base layer which can cause problems in later process steps, because boron is well-known for its transient enhanced diffusion in the presence of interstitials [5]. Those can be created by an oxidation process (known as oxygen enhanced diffusion; OED), or by implantation of high doses of dopants, which are routinely employed for the n-doping of the poly-emitter above the epitaxially fabricated base layer. Thermal activation of these dopants causes boron in the base to diffuse transiently much faster than would be expected from the well established bulk diffusion constant at that temperature. This can cause severe degradation of the high frequency behavior and other essential characteristics of these devices.

To suppress TED, co-doping with substitutional carbon has been proposed in the literature [6]. At sufficiently high concentrations, carbon is believed to form complexes with the injected Si interstitials [7]. This limits the density of interstitials available to transient boron diffusion, which should therefore be strongly reduced.

3. Experiments

Most experiments dealing with TED and C co-doping are based on Si layers implanted with B and C. But, since the base of a $Si_{1-x}Ge_x$ HBT is grown and doped epitaxially, it appears straightforward to deposit a B-doped $Si_{1-x-y}Ge_xC_y$ layer with a C concentration of 0.5 to 1 at. %. We have shown that such layers can be grown with a high degree of perfection under low-temperature growth conditions that allow substitutional C concentrations of a few at.%, i.e. far below the solid solubility [8].

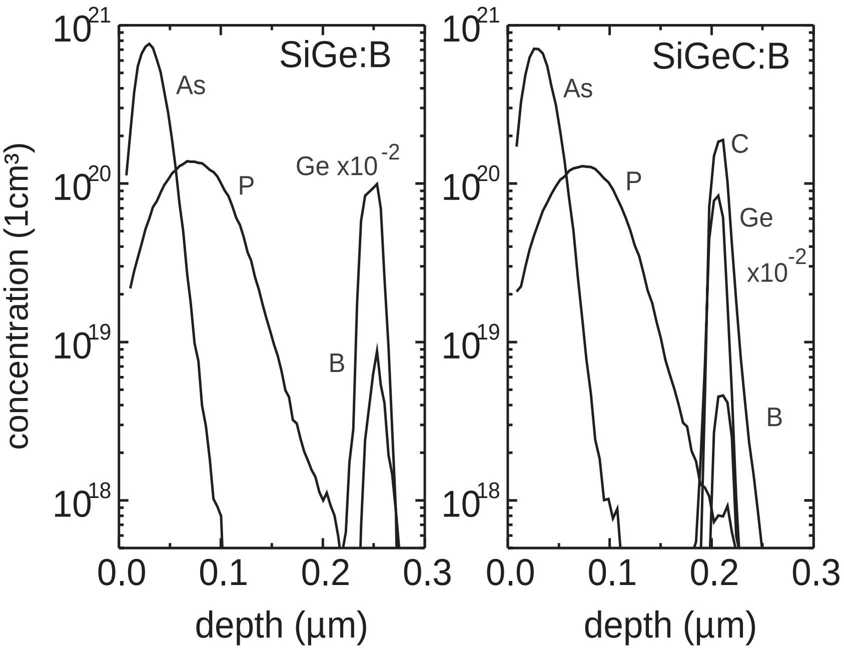

Fig. 1: SIMS profiles of $Si_{1-x}Ge_x$:B and $Si_{1-x-y}Ge_xC_y$:B epilayers with *ex-situ* implanted Si cap layers.

To study TED in a realistic, HBT-like situation we grew by molecular beam epitaxy (MBE) highly boron-doped $Si_{1-x}Ge_x$ and $Si_{1-x-y}Ge_xC_y$ layers, which were capped by an initially undoped Si layer. Figure 1 shows SIMS profiles of a $Si_{0.79}Ge_{0.2}C_{0.01}$:B layer in comparison with a reference layer that was lacking the C co-doping. Ge concentrations are of the order of 20 at.%, and scaled down in Fig. 1 by a factor of 100 to fit the logarithmic concentration scale of the dopants. The Si cap layers were subsequently implanted ex-situ both with As and P to create the interstitials required for TED.

Figure 2 shows the development of the B profile as a function of oven anneals in the temperature range between 550 and 900°C. Since the Ge profile is not affected in this temperature range it is just indicated by a shaded area for reasons of clarity. As expected, the reference sample shows strong TED, which leads to a basically useless doping profile after the 900°C anneal. In contrast, the presence of about 1 at.% of carbon suppresses boron TED almost completely. The B profile remains within the

$Si_{1-x-y}Ge_xC_y$ layer, and only a minor reduction of the peak concentration is observed, which lies within the accuracy of SIMS. Obviously, C co-doping is a very efficient means to stabilize the doping profile of a $Si_{1-x}Ge_x$ n-p-n HBT during integrated circuit processing.

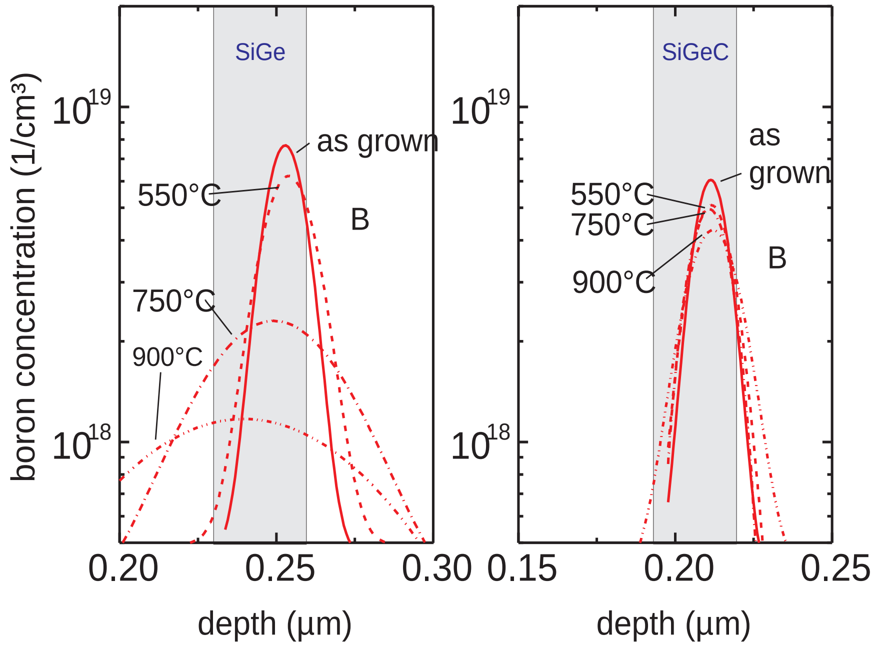

Fig. 2: Transient enhanced (TED) boron diffusion after annealing cycles in the temperature range 500° – 900°C. Left: $Si_{1-x}Ge_x$:B epilayers shows strongly enhanced diffusion at all temperatures studied. Right: $Si_{1-x-y}Ge_xC_y$:B epilayer suppresses TED of B almost completely.

4. Conclusions

We demonstrated that the use of a ternary $Si_{1-x-y}Ge_xC_y$ base layer with a C concentration $\leq 1\%$ for the usually employed pure $Si_{1-x}Ge_x$ layer can drastically improve the notorious transient enhancement of boron diffusion, and thus conserve the basic speed advantages associated with an HBT. Further work will concentrate on possible side effects associated with the presence of substitutional and non-substitutional carbon, and on an process-compatible optimization of the carbon concentrations necessary (and tolerable) for device operation.

Acknowledgments

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