

# Complete suppression of boron transient-enhanced diffusion and oxidation-enhanced diffusion in silicon using localized substitutional carbon incorporation

M. S. Carroll,<sup>a)</sup> C-L. Chang, and J. C. Sturm

*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08540*

T. Büyüklımanlı

*Evans East, 666 Plainsboro Road, Plainsboro, New Jersey 08536*

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In this letter, we show the ability, through introduction of a thin  $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$  layer, to eliminate the enhancement of enhanced boron diffusion in silicon due to an oxidizing surface or ion implant damage. This reduction of diffusion is accomplished through a low-temperature-grown thin epitaxial  $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$  layer which completely filters out excess interstitials introduced by oxidation or ion implant damage. We also quantify the oxidation-enhanced diffusion (OED) and transient-enhanced diffusion (TED) dependence on substitutional carbon level, and further report both the observation of carbon TED and OED, and its dependence on carbon levels. © 1998 American Institute of Physics. [S0003-6951(98)00651-2]

As silicon devices are continuously scaled to smaller sizes, there is an ever greater demand to reduce the diffusion of dopants. However, the enhancement of boron diffusion due to ion implant damage and oxidation, transient-enhanced diffusion (TED) and oxidation-enhanced diffusion (OED), poses severe challenges to this goal. It is generally accepted that boron diffuses primarily via an interstitial mechanism and boron diffusivity is, therefore, dependent on the silicon interstitial concentration. Ion implant damage and oxidation are sources of excess interstitials which enhance the boron diffusivity. Therefore, the reduction of TED and OED depend on the effective ability to trap or annihilate any excess interstitials that are produced during processing. Interest in the relationship between carbon and enhanced boron diffusion was recently spurred after TED was observed to strongly depend on the concentration of substitutional carbon in silicon.<sup>1</sup> Various approaches of carbon incorporation into silicon have been used to explore the carbon effect on boron-enhanced diffusion including: carbon containing alloys [e.g.,  $\text{Si}_x\text{C}_y$  (Ref. 2) and  $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$  (Ref. 3)], uniform carbon doping of silicon,<sup>1</sup> and localized carbon doping of silicon.<sup>4</sup> These approaches may be summarized into two categories. First, silicon or carbon-silicon alloys that have a uniform distribution of carbon in them;<sup>2,4</sup> and second, silicon with localized carbon-doped regions or thin carbon-containing alloy layers.<sup>3,4</sup>

Complete suppression of boron TED and OED has already been reported for the category of uniform carbon concentration.<sup>4</sup> However, for practical use in device applications this approach is hampered by concerns about the electrical activity of carbon defects in silicon,<sup>3,5,6</sup> and carbon's high diffusivity.

Localized carbon-doped regions, however, offer a potential solution to the difficulties presented by uniform carbon doping. Carbon-containing regions may be placed away from

the active region eliminating concerns about electrical defects, and also creating a test structure with which to isolate carbon's effect on interstitial concentration without the complication of carbon effects on the intrinsic boron diffusivity. However, to the best of our knowledge no complete suppression of TED or OED has been reported to date with a localized carbon region. In this letter we show the ability through introduction of a thin  $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$  layer to completely filter interstitials injected by an overlying oxidizing surface or interstitials injected due to ion implant damage, which results in the complete elimination of either OED or TED for underlying boron. We also quantify the OED and TED dependence on substitutional carbon level, and further report both the observation of carbon TED and OED, and its dependence on carbon level.

The test structures were grown using rapid thermal chemical vapor deposition (RTCVD),<sup>7</sup> between 600 and 750 °C using methylsilane as the carbon source. Two boron-doped silicon layers with and without a  $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$  or  $\text{Si}_{1-x}\text{Ge}_x$  layer placed between the peaks were used to test the effect of the layer on boron diffusivities at different locations (above and below) with respect to the SiGe(C) layer. Both boron peaks were approximately 250 Å thick and had a boron concentration of  $5 \times 10^{19}/\text{cm}^3$  centered 2000 and 3000 Å away from the surface, respectively, while the 250 Å thick SiGe(C) layer was centered 2300 Å from the surface (Fig. 1).

To study boron OED dependence on substitutional carbon level as-grown samples were cleaved and annealed in nitrogen and oxygen ambient atmospheres at 850 °C for 30 min. Boron profiles were characterized using secondary ion mass spectroscopy (SIMS) with 2 keV Cs ions and an estimated 1%–5% error in depth scales. Figure 2(a) shows profiles of boron in a sample with the SiGe(C) layer omitted, with a background carbon concentration below SIMS detection limits. Broadening of both boron peaks is observed after the nitrogen anneal, and in the oxidation case clear enhancement of the boron diffusion is observed by the further broad-

<sup>a)</sup>Electronic mail: malcolmc@ee.princeton.edu

i-Si, 1900Å, 700°C
Si : boron $3 \times 10^{19}/\text{cm}^3$ , 250Å, 700°C
i-Si, 100Å, 700°C
i-Si <sub>1-x-y</sub> Ge <sub>x</sub> C <sub>y</sub> , 250Å, 625°C
i-Si, 400Å, 700°C
Si : boron $3 \times 10^{19}/\text{cm}^3$ , 250Å, 700°C
i-Si, 1500Å, 700°C
Si buffer layer : boron $3 \times 10^{19}/\text{cm}^3$ , 2500Å, 1000°C

FIG. 1. Test structure to study boron oxidation-enhanced diffusion and transient enhanced diffusion. Two boron markers are separated by a Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> interstitial barrier layer ( $x=[0-0.2]$ ;  $y=[0-0.005]$ ).

ening of the boron profile. The profiles were modeled using a numerical simulator PROPHET, obtained from Lucent technologies, to quantitatively compare boron profiles and obtain boron diffusivities. In this case, the boron diffusivity during oxidation is found to be six times that of the average boron diffusivity during nitrogen anneal. Figure 2(b) shows boron profiles before and after anneals for the sample containing an intervening thin 250 Å Si<sub>0.795</sub>Ge<sub>0.2</sub>C<sub>0.005</sub> (0.5% carbon) layer between the boron markers as indicated by the carbon concentration profile. The same broadening is observed in the peak below the Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> layer after annealing in nitrogen, but in this case there is no additional broadening after oxidation, indicating that for this substitutional carbon level the oxidation-enhanced diffusion has been completely suppressed. As interstitials are injected into the sample at the surface, during oxidation, and there is no observed enhancement of boron diffusion below the Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> alloy layer, we may conclude that the excess interstitial concentration has been reduced to zero below the carbon-containing layer. This demonstrates that the Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> layer acts as an effective interstitial sink, blocking interstitials from reaching the layer below the Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub>, and therefore, completely suppressing boron OED.

In addition, for the sample with 0.5% carbon in the in-

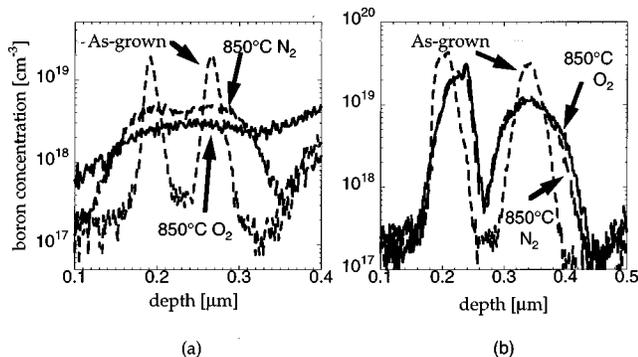


FIG. 2. Boron concentration profiles (measured using SIMS) of as-grown samples, and samples annealed for 850 °C for 30 min in nitrogen ambient, or in oxygen ambient samples. Boron profiles of (a) sample without a SiGeC barrier layer between the boron markers. Oxidation-enhanced diffusion (OED) is demonstrated by the broader boron profile after anneal in oxygen ambient compared to that annealed in nitrogen. Boron profiles of (b) sample with highest level carbon in the SiGeC barrier layer. Boron OED is completely suppressed as indicated by no difference between boron profiles of the deepest marker after anneal in oxygen and anneal in nitrogen ambient.

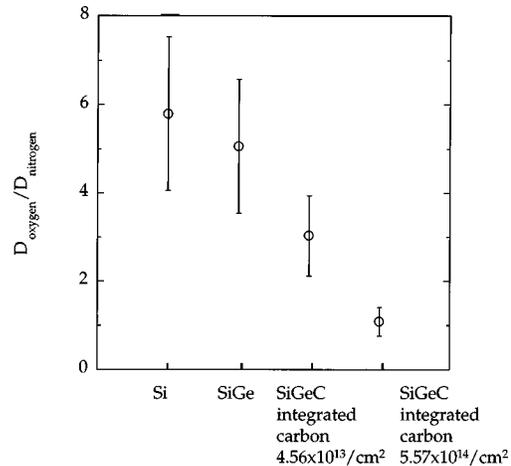


FIG. 3. Relative average boron diffusivity (during oxidation 850 °C for 30 min in O<sub>2</sub>) dependence on carbon levels in SiGe(C) barrier layer. Boron diffusivity of deepest marker is displayed relative to that of the average boron diffusivity during anneal in nitrogen ambient, 850 °C for 30 min in nitrogen. Note: oxidation-enhanced diffusion is completely suppressed at highest carbon level.

tervening Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> layer the boron profiles of the shallowest boron marker are nearly identical after anneals in both oxygen and nitrogen [Fig 2(b)], indicating that the excess interstitial concentration must also be reduced to nearly zero even as far as 100–200 Å above the intervening Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> layer. The asymmetric diffusion of the boron in the upper peak may be attributed to boron segregation into the Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> alloy layer. Boron segregation into strained Si<sub>1-x</sub>Ge<sub>x</sub> has been previously reported,<sup>8,9</sup> and further study is in progress to determine the boron segregation dependence on carbon content.

Samples with different substitutional carbon levels in the Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> alloy layer were grown and annealed to test the OED carbon level dependence. Figure 3 summarizes the relative diffusivities, boron diffusivity of the deepest peak during anneals in oxygen versus nitrogen ambient, for carbon levels of 0%–0.5%. To within experimental error there is no difference between the OED of boron in the cases of boron markers in pure silicon and that with an intervening Si<sub>1-x</sub>Ge<sub>x</sub> alloy layer (no carbon) between the boron markers. This demonstrates that the interstitial trapping is not a result of the addition of the Si<sub>1-x</sub>Ge<sub>x</sub> alloy layer and is in agreement with previous work.<sup>3,10</sup> Finally, we observe a monotonic decrease in boron OED with increasing carbon level in the alloy layer and the total carbon level required to completely suppress the OED for these conditions is bound between the  $4.56 \times 10^{13}$  and  $5.57 \times 10^{14}/\text{cm}^2$  carbon level.

To the dependence of boron TED on the substitutional carbon level, as-grown samples (Fig. 1) with and without buried Si<sub>1-x-y</sub>Ge<sub>x</sub>C<sub>y</sub> layers were cleaved and subjected to implant levels of  $5 \times 10^{13}$  and  $5 \times 10^{14}/\text{cm}^2$  silicon with implant energies of 30 keV, then annealed in nitrogen ambient for 15 min at 800 °C. The depth of the silicon implanted profile is estimated to be 600 Å. Migration of interstitials from the ion implant damaged region leads to excess diffusion of the lower boron peak (as measured by SIMS), which decreases as the carbon level of the barrier layer is increased. At the highest carbon levels no significant difference in the lower boron profiles can be seen between samples with or

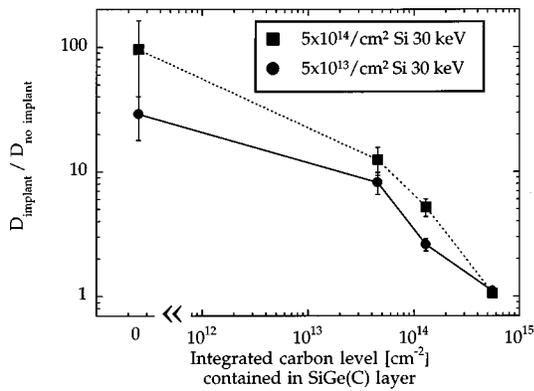


FIG. 4. Average boron diffusivity (during 800 °C 15 min anneal after ion implantation for Si doses of  $5 \times 10^{13}$  or  $5 \times 10^{14}/\text{cm}^2$  at 30 keV) dependence on carbon levels in SiGe(C) barrier layer. Boron diffusivities of deepest marker is displayed relative to that of the average boron diffusivity during an 800 °C 15 min anneal in nitrogen ambient atmosphere without ion implantation. Note: transient-enhanced diffusion is completely suppressed at highest carbon level.

without ion implant damage, again indicating complete filtering of the excess interstitials. Average boron diffusion constants were then extracted by fitting measured boron profiles to simulation. Figure 4 summarizes, for different carbon levels in the barrier level, the average boron diffusivity after ion implantation, for two different silicon implant doses, relative to the measured boron diffusivity without silicon implantation in the same samples. For both implant doses of  $5 \times 10^{13}$  and  $5 \times 10^{14}/\text{cm}^2$  silicon the total carbon level required to completely suppress the TED for these conditions is bound between the  $4.56 \times 10^{13}$  and  $5.57 \times 10^{14}/\text{cm}^2$  carbon level.

Because carbon is electrically active it is important to determine where carbon is after processing. Carbon is reported to diffuse quickly in silicon.<sup>6</sup> Figure 5(a) shows the carbon profiles of as grown, annealed in nitrogen, and annealed in oxygen for a sample with an intermediate carbon level ( $4.6 \times 10^{13}/\text{cm}^2$ ). Comparison of carbon profiles after annealing in oxygen versus nitrogen shows an enhanced diffusion in the oxygen case. This carbon OED is, however, completely suppressed in samples with higher carbon levels, Fig. 5(b), where no difference can be seen in the carbon profiles between anneals in nitrogen and oxygen. Similar carbon diffusivity dependence on total carbon level is also observed in TED samples.

In summary, boron OED and TED in silicon has been completely suppressed by trapping excess interstitials in an overlying  $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$  layer. Carbon diffusion is enhanced during oxidation, however, at the highest carbon levels this

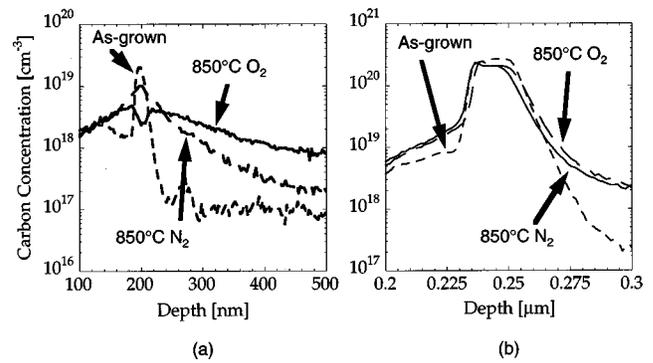


FIG. 5. Carbon concentration profiles (measured using SIMS) of samples that were annealed for 850 °C for 30 min in oxygen ambient. Carbon profiles of (a) samples with the lowest level of carbon used in the SiGeC barrier layer between boron markers. Carbon oxidation-enhanced diffusion demonstrated in this sample by the additional broadening of the carbon profile after anneal in oxygen ambient compared to that annealed in nitrogen. Carbon profiles of (b) samples with highest level carbon in the SiGeC barrier layer. Carbon OED completely suppressed as indicated by no difference between carbon profiles after anneal in oxygen and anneal in nitrogen ambient.

enhancement was completely suppressed so that the boron-doped silicon region remains free of carbon under conditions when boron OED/TED is also suppressed. Due to recombination of interstitials at the surface and other uncertainties, further investigation is still needed to determine the relationship between carbon level and silicon interstitials, in order to effectively model carbon's effect on boron and carbon diffusion.

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- <sup>1</sup> P. A. Stolk, H.-J. Gossman, D. J. Eaglesham, J. M. Poate, *Mater. Sci. Eng. B* **36**, 275 (1996).
- <sup>2</sup> A. Mocuta, R. Strong, and D. Greve, 40th Electronic Materials Conference 98, Charlottesville, VA, H5, June 1998.
- <sup>3</sup> L. D. Lanzerotti, J. C. Sturm, E. Stach, R. Hull, T. Buyuklimanli, and C. Magee, *Appl. Phys. Lett.* **70**, (1997).
- <sup>4</sup> P. A. Stolk, H.-J. Gossman, D. J. Eaglesham, D. C. Jacobson, C. S. Rafferty, G. H. Gilmer, M. Jaraiz, J. M. Poate, H. S. Luftman, and T. E. Haynes, *J. Appl. Phys.* **81**, (1997).
- <sup>5</sup> H. J. Osten, G. Lippert, P. Gaworzewski, and R. Sorge, *Appl. Phys. Lett.* **71**, 1522 (1997).
- <sup>6</sup> G. Davies and R. C. Newman, in *Handbook on Semiconductors*, edited by T. S. Moss (Elsevier, New York, 1994), Vol. 3b, pp. 1558–1629.
- <sup>7</sup> J. C. Sturm, P. V. Schwartz, E. J. Prinz, and H. Manoharan, *J. Vac. Sci. Technol. B* **9**, 2011 (1991).
- <sup>8</sup> N. Moriya, L. C. Feldman, S. W. Downey, C. A. King, and A. B. Emerson, *Phys. Rev. Lett.* **75**, 1981 (1995).
- <sup>9</sup> S. M. Hu, D. C. Ahlgren, P. A. Ronsheim, and J. O. Chu, *Phys. Rev. Lett.* **67**, 1450 (1991).
- <sup>10</sup> W. Fang, P. Griffin, and J. Plummer, *Mater. Res. Soc. Symp. Proc.* **379**, 379 (1995).