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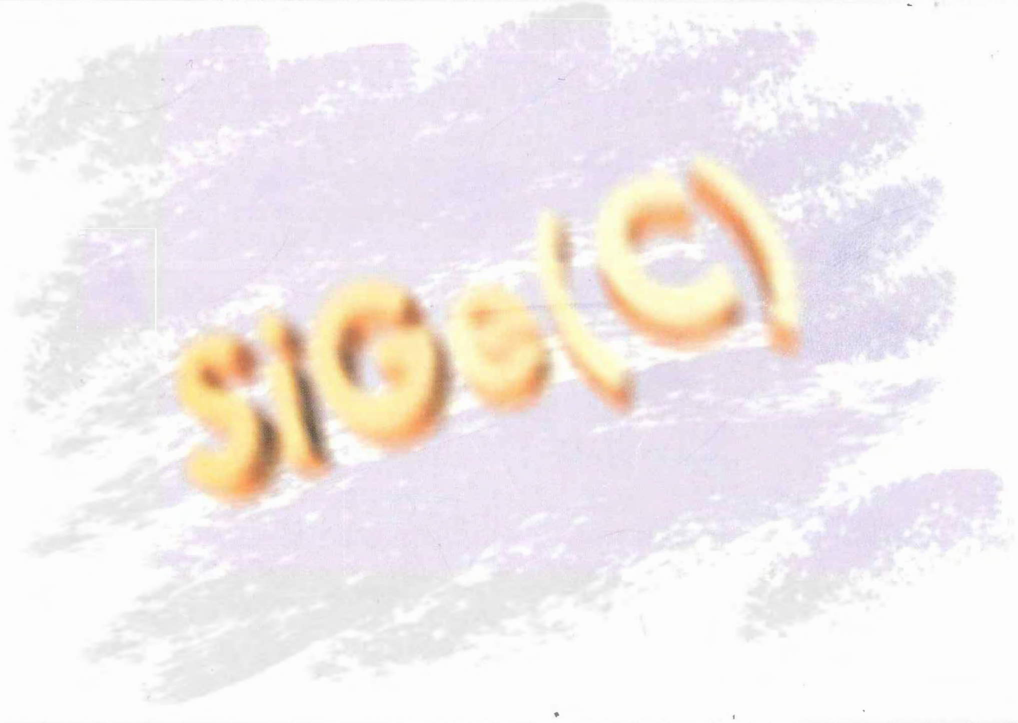
pp. III-02-1 - III-02-4



January 21(Sun.) - 23(Tue.), 2001
HOTEL JAL CITY SENDAI, JAPAN

Supported by

The Ministry of Education, Science,
Sports and Culture, Japan

and

RIEC,
Tohoku University

NEW GROUP IV (Si-Ge-C) SEMICONDUCTORS:
CONTROL OF PROPERTIES AND APPLICATIONS TO ULTRAHIGH SPEED AND OPTO-ELECTRONIC DEVICES
Sendai, Japan, January 21-23, 2001

III - 02

Point Defect Engineering for Dopant Control in Silicon-based Nanodevices

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Abstract

Through the ability of substitutional carbon to react with interstitial silicon atoms, SiGeC layers have been successfully used to greatly reduce the diffusion of boron in silicon-based structures for advanced device fabrication, especially in conditions which involve oxidation or ion implantation. This talk will describe work on four topics related to the fundamental understanding and application of this phenomenon. These are:

-- The determination of the rate of interstitial injection into silicon during oxidation
-- The fundamental mechanism of interaction between substitutional carbon and interstitial silicon
-- The ability to control the diffusion of an n-type dopant, specifically phosphorus
-- Preferential segregation of boron to SiGeC layers

Introduction

Over the past few years there has been increasing interest in using SiGeC layers to control the diffusion of boron, both in these layers as well as in nearby silicon regions. The ability of SiGeC to control boron diffusion in regions outside the SiGeC itself is a consequence of the fact that the diffusion of boron is an interstitialcy-assisted mechanism -- its rate depends on the concentration of silicon interstitial atoms. SiGeC thus must be a sink for these interstitials, depressing their concentration and thus boron diffusion in nearby regions. The effect of the SiGeC is especially beneficial when processing steps are used which introduce excess interstitial atoms -- such as the steps of ion implantation and thermal oxidation, which are routinely used in all kinds of silicon-based processing.

For example, Fig. 1 (a) and (b) show the effect of oxidation on vertical p-n-p structures grown for eventual use in vertical p-channel MOSFET's. The structures were grown using Rapid Thermal Chemical Vapor Deposition (RTCVD) at temperatures between 625 and 700 °C. In an all-Si structure (no SiGeC), the profiles are sharp after growth, but the source and drain regions rapidly diffuse together after a wet oxidation step as short as 30 min at 750°C (Fig. 1(a)). In the structure of Fig. 1(b), the heavily-boron-doped source/drain regions were made primarily of SiGeC, although thin heavily doped Si regions were placed just inside the source-drain regions on both ends of the channel. In this case the diffusion from the boron-doped layers into the channel was suppressed for the same gate processing step, so that the vertical devices could be scaled to sub 30-nm dimensions.

Device applications of this principle have been published to date by several groups for both Si/SiGeC/Si heterojunction bipolar transistors (restricting base dopant outdiffusion) [3-5], for vertical MOSFET's (reducing the diffusion of the source-drain dopant) [1,2], and for lateral MOSFET's (reducing boron diffusion in the channel) [6].

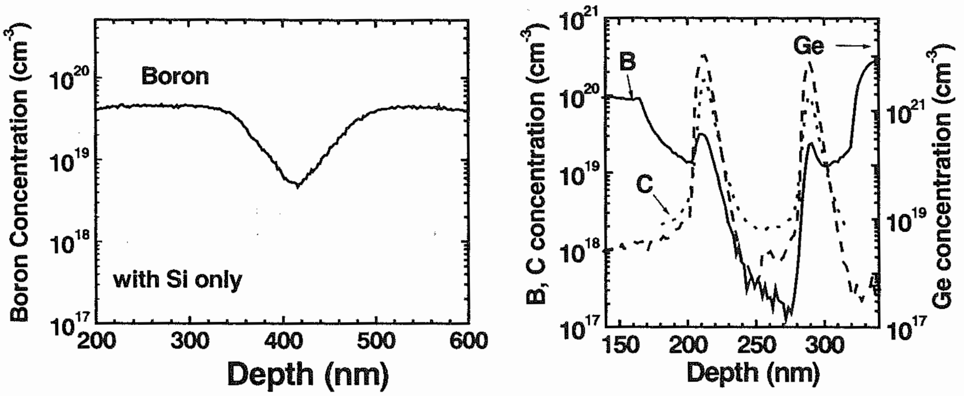

Fig. 1. Boron, carbon, and germanium profiles after growth and all processing including 750 °C 30 minute wet oxidation of vertical p-channel MOSFET structures, with as-grown structures of (a) p^+Si/n-Si/p^+/Si (all silicon) and (b) p^+SiGeC/p^+Si/n-Si/p^+Si/p^+SiGeC [1,2].

Interstitial Injection Rates during Oxidation

A central practical and fundamental question is "how many substitutional carbon atoms are required to sink a given number of interstitial silicon atoms?" Thus one needs to know the number of injected interstitial atoms, for example as occurs when silicon is oxidized. While it has been known for well over 30 years that the oxidation of silicon causes the injection of interstitial atoms [7], until recently the rate of such injection was not known. Therefore we studied the diffusion of boron in multiple marker layers above the SiGeC to determine the interstitial concentration profile. The results (Fig. 2) show that the profile decays linearly, suggesting that the SiGeC layer is a simple sink, and that the driving force for interstitial motion is diffusion. From this data one can calculate the rate of injection in various structures [8,9] and compare the result to other relevant data [10,11].

Fundamental Mechanisms

What is the mechanism by which SiGeC reacts with interstitial silicon atoms? It is clear that substitutional carbon atoms are lost -- the question is what then happens to these carbon atoms. For example, several groups have postulated that the carbon and the interstitial silicon react to form some kind of SiC precipitate [12] or perhaps C-C pair defects [13]. Given the phase diagram of silicon and the low solid solubility of carbon in silicon, the formation of SiC is thermodynamically favored. However, there is little direct experimental evidence available to support these conclusions, and defects are inconsistent with the high carrier lifetimes and low leakage currents observed in many structures. We have used combinations of X-ray diffraction and SIMS to determine the state and location of the substitutional carbon as a function of annealing time and ambient. Furthermore, we can correlate the loss of substitutional carbon with the number of injected interstitials. In many cases there is a one-to-one correlation between these two quantities, and a simple mechanism for the carbon loss will be presented.

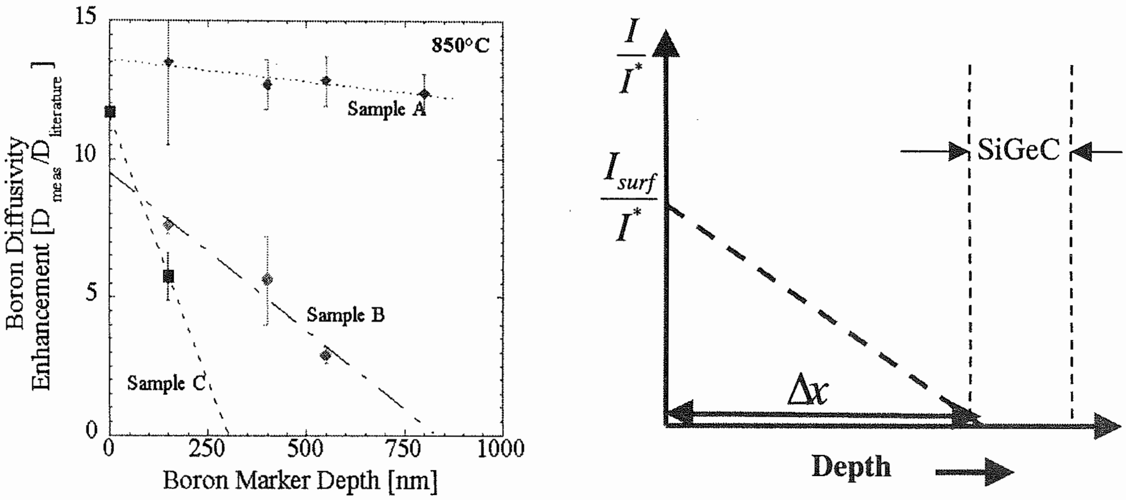

Fig. 2. (a) Extracted profiles of the enhancement of silicon interstitial concentrations above their equilibrium values for (A) no SiGeC layer, (B) SiGeC layer at a depth of 700 nm from the surface, and (C) SiGeC layer 300 nm above the surface). (b) Schematic profile indicating linear decay of interstitial density vs. depth to zero at the SiGeC layer.

N-type Dopants

To date the effect of SiGeC on boron motion has been studied, but there has been little work on n-type dopants. Phosphorus diffuses primarily via an interstitialcy mechanism, so that its diffusion should be affected by SiGeC similar to that of boron. The experiments are slightly harder, since obtaining sharp phosphorus profiles by CVD in the first place is difficult. However, with proper growth procedures, one can obtain sharp phosphorus profiles (< 15 nm/decade), and these profiles rapidly broaden during oxidation in all -silicon structures. As with boron, the introduction of SiGeC near the phosphorus doped silicon regions reduces the diffusion to virtually undetectable levels. This will be demonstrated through vertical MOSFET structures.

Segregation of Boron to SiGeC Layers

Finally, we regularly observe that boron segregates preferentially to SiGeC layers from silicon. This is unusual since it can lead to sharper doping profiles over time instead of broader ones. This effect is most pronounced in polycrystalline layers with high carbon fractions. In these cases, the boron not only segregates from the Si into the SiGeC, but also diffuses uniformly throughout the SiGeC and appears to remain electrically active. This effect has previously been used to demonstrate that heavily boron-doped polycrystalline gates with SiGeC layers show reduced boron penetration through the gate oxide and into the substrate in MOS capacitors [14], and MOSFET results are qualitatively similar [15]. While this effect is of great interest technologically, at present the fundamental driving force for the segregation is not yet clear.

Summary

SiGeC can be used to control dopant profiles on the nanometer scale for advanced silicon-based devices. Such control is especially important for the integration advanced device structures. The fundamental physical mechanism is the interaction of silicon interstitial atoms with substitutional carbon in the SiGeC layer. This mechanism can be used to greatly reduce the diffusion of both boron and phosphorus. Boron also segregates to SiGeC layers, although the driving force in this case is not yet clear. There are applications of these phenomena in heterojunction bipolar transistors, vertical MOSFET's, and lateral MOSFET's. While some of the fundamental mechanisms are now clear, many other aspects of these processes remain to be understood.

This work has been supported by the US ARO (MURI Program) and DARPA.

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