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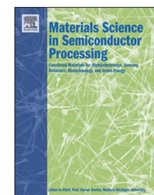

Diffusion and trapping of implanted hydrogen in a Si/Si:B/Si structure

A. Royal[a,b], F. Mazen[b], F. Gonzatti[b], M. Veillerot[b], A. Claverie[a,*]

[a] CEMES-CNRS, 29 rue Jeanne Marvig, 31055 Toulouse, France
[b] CEA, LETI, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble, France

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ABSTRACT

H implantation in Si/Si:B/Si structures is a promising route to improve the Smart Cut™ process and transfer thin Si layers of reduced roughness and controlled thickness onto regular Si wafers. However, the mechanisms driving this process are unknown and thus difficult to model or optimize. For this reason, we have experimentally studied the redistribution of H which takes place in such structures after implantation and during annealing using SIMS and TEM. We show that the Si:B layer already traps H during implantation and form platelets parallel to the wafer surface. During annealing, the H atoms implanted in the Si regions are slowly transferred toward the Si:B layer where they are trapped on large platelets which grow further during annealing. Routes to optimize this process go through the minimization of H precipitation in the pure Si regions. This can probably be achieved by optimizing the implantation conditions.

1. Introduction

Many electronic and sensor devices are fabricated using Silicon-On-Insulator (SOI) wafers. These wafers are, for most, manufactured using the Smart Cut™ process [1–3]. In this process, a silicon wafer is implanted by hydrogen ions, bonded to another wafer, and then annealed. The SOI wafer is obtained by splitting of silicon at the depth where the hydrogen was implanted and precipitates during annealing [1,4,5]. In principle, this depth can be adjusted through the implantation energy but the depth-distribution of hydrogen after implantation inevitably results in thickness variations of the transferred layer. Thus, "finish" steps are performed to control and master thickness and roughness variations over the whole wafer.

To meet the requirements of advanced devices, 300 mm SOI wafers are needed in which the silicon top layer should be only a few nm (typically 8–10) thick and showing very small (± 0.5 nm) thickness and roughness variations over the whole wafer [6]. This is by no mean trivial and requires carefully optimized finish steps which increase costs and reduce yield.

An interesting approach to overcome these difficulties is to force hydrogen to precipitate at some predetermined depth during annealing. This can be achieved by introducing trapping centers located in a plane parallel to the surface at a given depth within the donor substrate prior to hydrogen implantation.

Shao et al. [7,8] have reported that, when implanting hydrogen at 300 °C at an energy such that the hydrogen peak concentration is close to a SiGe buried layer, a continuous crack is formed in the SiGe layer. Okba et al. [9] have studied the formation and the growth kinetics of hydrogen-filled platelets, the precursors of micro-cracks, during plasma hydrogenation of a silicon wafer containing a 5 nm-thick SiGe buried layer. They have reported that while the platelets initially form in the whole region from the surface to the SiGe layer, further hydrogenation leads to the gradual "cleaning" of the top layer and to the development of large platelets then of micro-cracks in the SiGe layer only. These observations demonstrate that the fracture resulting from H implantation and annealing can be localized at the depth where a SiGe layer is buried in silicon. More recently however, it has been shown that platelets and micro-cracks actually do not form within the SiGe layer itself but at the two Si/SiGe interfaces which delimit it. This results in fracture deviations from one interface to the other and finally thickness variations of the transferred layer [10].

An alternative solution to localize hydrogen precipitation and fracture is to use thin boron doped buried silicon layers. Experimentally, it is known for a long time that hydrogen seems "attracted" by boron and finally trapped probably forming B-H complexes [11]. Tong et al. [12,13] have shown that the co-implantation of B and H makes it possible to improve the Smart Cut™ process by reducing both the hydrogen fluence and the annealing temperature required to fracture silicon. Later on, Ma et al. [14] have shown that the use of H and B plasma implantation could result in a much lower surface roughness of the transferred layer than using H only. Kilanov et al. [15] were the first to show that hydrogen precipitation and micro-crack formation could be localized at a Si:B buried layer following H implantation. Again, a substantial reduction of the dose necessary to

* Corresponding author.
E-mail address: alain.claverie@cemes.fr (A. Claverie).

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fracture the layer and a lower surface roughness were observed. More recently, comparing the effect of SiGe and Si:B layers, Mazen et al. [10] have shown that, contrary to what is observed when using SiGe layers, a single and straight fracture line is observed in the middle of the Si:B layer, following H implantation and annealing. Moreover, a lower dose of hydrogen is necessary to obtain the fracture when using a Si:B layer than a SiGe layer and the final roughness of surface of the transferred layer is smaller. For all these reasons, the use of thin Si:B buried layers seems most promising to force hydrogen to precipitate at pre-selected depths and then to transfer thin silicon layers with reduced roughness as required for the fabrication of thin SOI structures able to cope with recent technology needs.

However, the optimization of a process making the best use of such layers requires that the basic ingredients and mechanisms involved in that process are identified and mastered. This is clearly not the case until now. For this reason, we have experimentally studied the effect of the presence of a B-doped 5 nm-thick silicon layer buried into pure silicon onto the redistribution and precipitation of hydrogen after ion implantation and during thermal annealing.

2. Experimental

The structure of the wafer and the implantation conditions have been kept the same than those used by Mazen et al.[10] to demonstrate the transfer of 100 nm-thick Si and the fabrication of a 300 mm SOI wafer using this transferred layer. Only the fluence was reduced by a factor of 4 to prevent the sample from fracturing and instead let the H-related defects evolve all along the annealing time. Thus, a structure consisting of a 5 nm-thick boron doped (1.10^{19} at/cm^3) layer buried below a 100 nm-thick undoped Si top layer (Si: B) was grown on a 300 mm (001) Si wafer by Reduced Pressure Chemical Vapor Deposition (RP-CVD) using respectively silane and diborane as Si and B precursors. In the following, samples from this wafer will be called "Si:B structure". The wafer was then implanted at room temperature with hydrogen ions at an energy of 6 keV and a fluence of 5.10^{15} H+/cm^2, insuring that most of the hydrogen ions are implanted close to the Si:B layer. The ionic current was about 5 mA and the beam was spread over about 100 cm^2 on the wafer surface and finally scanned over the whole wafer. This wafer was efficiently maintained at room temperature during implantation. Following implantation, pieces of about 1×10 cm^2 were cleaved and submitted to annealing at 350 °C for 15 min, 1 h, 4 h and 16 h, respectively. For comparison, when implanting a dose of 2.10^{16} H+/cm^2, fracture of the layer occurred after 3–4 h at this temperature.

The depth-distributions of hydrogen before and after annealing were obtained by Time-of-Flight Secondary Ion Mass Spectroscopy (ToF-SIMS). Transmission Electron Microscopy (TEM) was used to image and analyze the populations of H-related hydrogen precipitates such platelets and nano-cracks which appear after annealing [16,17] following the rigorous methods developed by Cherkashin et al. [18]. The TEM samples were prepared in cross-section by combining mechanical and ion polishing until electron transparency.

3. Results and discussions

3.1. SIMS profiles

Fig. 1 compares the profiles obtained after implantation at room temperature in our Si:B structure and in a reference plain Si wafer. In the Si wafer, the hydrogen profile shows a quasi-Gaussian shape centered at a depth of approximately 100 nm quite similar to that predicted by Monte Carlo simulations [19]. The profile obtained in the Si:B structure is very different. We note a strong peak in the Si:B layer as well as the appearance of two «bumps» on both sides of this peak. These characteristics show that hydrogen has diffused and was redistributed during or after implantation and this, at room temperature. The observation of H diffusion at room temperature is not uncommon and has been related under different conditions (see Ref. [20] for example). It is generally admitted that H diffusion at room temperature is not evidenced after implantation in pure silicon because it is limited by the trapping of hydrogen by the vacancies and interstitials generated in close proximity by the implantation. This process, which leads to the formation of various complexes, takes place as soon as the implanted ion comes to rest [21]. However, we note that, in the the Si:B structure, this diffusion has led to the massive transfer of hydrogen from the two Si regions on both sides of the Si:B layer towards this layer, where it has accumulated. This characteristic evidences that H traps exist in the Si:B layer with binding energies larger than in pure Si and that these traps can be found by H during its free diffusion in the region after implantation [21]. It is also worth noticing that the two bumps are inscribed in the profile obtained in pure Si. The perceptible differences (larger surface and amplitude on the left side than on the right side) only results from the regular asymmetry of the hydrogen profile shown in pure silicon.

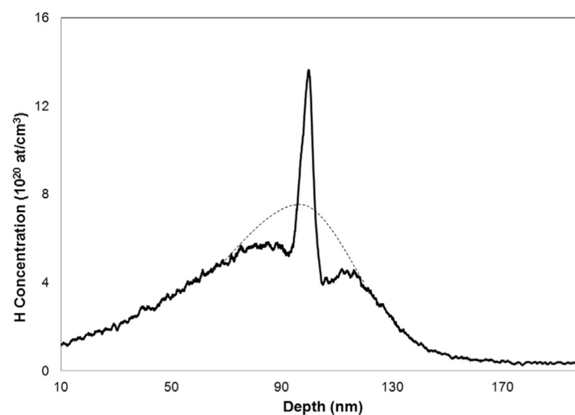

Fig. 1. Comparison of the SIMS profiles of hydrogen obtained after ion implantation at 6 keV and for a fluence of 5.10^{15} H$^+$/cm^2 in pure Si (dotted line) and in a Si/Si:B/Si structure (plain line).

Fig. 2 shows the evolution of this hydrogen profile when the sample is annealed at 350 °C for increasing times. During annealing, while the depth-positions of the bumps do not change, their amplitudes and the areas they delimit decrease, showing further transfer of hydrogen from the bumps towards the Si:B layer as the annealing proceeds.

This type of redistribution, leading to the formation of one central peak surrounded by two well defined bumps, is typical of the trapping of a mobile specie. For example, it has been observed in the case of boron trapping on End-Of-Range defects, actually extrinsic dislocation loops, during annealing in silicon [22]. Later on, a simple model has been developed and integrated into a process simulator which perfectly simulates this redistribution assuming only that boron is everywhere

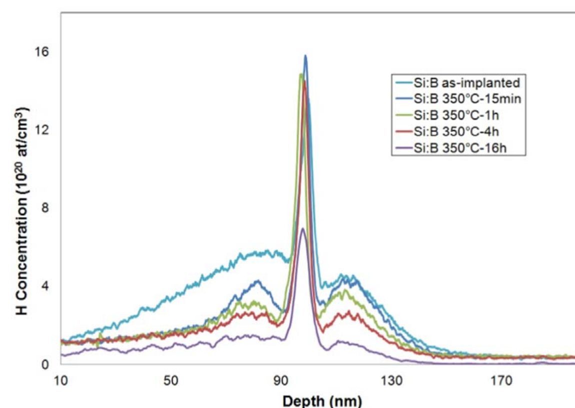

Fig. 2. Time-evolution of the SIMS profiles during isothermal annealing at 350 °C.

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