1. INTRODUCTION

The change from silicon wafers, including epitaxial structures, to silicon-on-insulator (SOI) structures in the wide-scale production of semiconductor devices and integrated circuits ensures noticeable advantages over conventionally used bulk material. Among these are a significant decrease in the power consumption of devices and an increase in their operating speed. In order to fabricate modern devices based on silicon, the Si films used should have a thickness of 30–50 nm [1].

The use of SOI structures with films of such thickness in the production of integrated circuits and single-electron devices places very heavy demands on the surface quality of the films.

As is known, the implantation of H in heavily B-doped Si leads to the enhanced formation of microcavities in the latter [2]. Consequently, this process enhances the blistering and exfoliation of thin silicon films. It is also known that hydrogen atoms, which have very high chemical activity, interact with dangling bonds in the Si matrix. Taking these facts into account, we studied both the development of microcavities produced in a narrow portion of the implanted region, owing to the formation of a thin layer enriched with impurity atoms, and the effect of B atoms on the exfoliation of an Si film.

The purpose of this study is to investigate the special features of hydrogen-induced splitting in the presence of a heavily B-doped layer at a depth corresponding to the projected range of H ions.

2. EXPERIMENTAL

The experiments were performed with 100-mm-diameter samples of KDB-12 p-Si (Si:B, ρ = 12 Ω cm) with (100) orientation. A heavily B-doped layer was formed by molecular-beam epitaxy. A 50-nm-thick Si buffer layer was grown on a prepared substrate, i.e., a very narrow (1–2 monolayers) B layer with a sheet concentration of 6 · 10^{14} cm^{-2} was grown on the buffer layer, and then the B layer was coated with a 500-nm-thick Si layer. The Si wafers were implanted with ionized hydrogen molecules with an energy of 100 keV at a dose of 2.5 · 10^{16} cm^{-2}. The simulation of the implantation process with the use of the TRIM-200 software package shows that the projected range of H ions in Si, which also corresponds to the depth at which the B-doped layer is located. When a thin exfoliated film is transferred onto an insulator to form a silicon-on-insulator structure, the surface roughness of the film decreases by a factor of 2–5. © 2003 MAIK “Nauka/Interperiodica”.

Hydrogen-Induced Splitting in Silicon over a Buried Layer Heavily Doped with Boron

D. V. Kilanov*, V. P. Popov*, L. N. Safronov*, A. I. Nikiforov*, and R. Sholz**

*Institute of Semiconductor Physics, Siberian Division, Russian Academy of Sciences, pr. Akademika Lavrent’eva 13, Novosibirsk, 630090 Russia

**Max Plank Institute of Microstructure Physics, 06120 Halle, Germany

Submitted November 11, 2002; accepted for publication November 20, 2002

Abstract—Formation of interior hydrogen-passivated surfaces in hydrogen-implanted single-crystal Si containing a buried layer heavily doped with boron is investigated. With the use of the infrared absorption spectroscopy, it is shown that, upon annealing, the composition of hydrogen-containing defects in Si samples containing a buried heavily doped layer is the same as in Si samples that do not have such a layer. However, the presence of a heavily doped layer enhances the blistering and exfoliation of a thin silicon film from the Si sample, and the activation energies of the relevant processes change. Thus, the process of development of cavities in such layers changes upon thermal annealing. The depth at which hydrogen-passivated surfaces are formed corresponds to the projected range of H ions in Si, which also corresponds to the depth at which the B-doped layer is located. When a thin exfoliated film is transferred onto an insulator to form a silicon-on-insulator structure, the surface roughness of the film decreases by a factor of 2–5. © 2003 MAIK “Nauka/Interperiodica”.

1063-7826/03/3706-0620$24.00 © 2003 MAIK “Nauka/Interperiodica”
implanted H ions are in the form of complexes with Si that, after the implantation, about 50–65% of the implantation dose [1]. It can be seen from Fig. 2 that, after the implantation, about 20% of the implanted H remains in the wafer in the form of complexes with Si atoms. In the initial stage of annealing, the fraction of H chemically bonded to Si decreases. With further annealing, the amount of bound hydrogen remains almost constant. After exfoliation, a large fraction of hydrogen-containing complexes (about 30% of the implantation dose) is in the exfoliated film. About 10–20% of the implanted H remains in the wafer in the

3. RESULTS

When H-implanted Si samples are subjected to heat treatment, the system of crystal defects transforms; as a result, various defects and complexes are either formed or annealed out.

Figure 1 shows the transformation of the spectra of infrared (IR) absorption of H-implanted p-Si(100) containing a buried B-doped layer at a depth of 500 nm (spectra a) and without such a layer (spectra b), depending on the time of isothermal annealing at $T_{\text{ann}} = 400^\circ\text{C}$.

It can be seen from Fig. 1 that, in the presence of a B-doped layer, no additional hydrogen-containing defects appear. However, a number of features can be distinguished in the IR-absorption spectrum. Immediately before the exfoliation of a thin Si film, new lines appear in the IR-absorption spectrum which correspond to the vibrations of H atoms on the surfaces of the internal cavities formed in the implanted layer. After the exfoliation, some of the lines in the IR-absorption spectrum disappear. For example, in the sample containing a B-doped layer, a line appears at 2098 cm$^{-1}$ in the absorption spectrum due to the vibrations of monohydride complexes on the reconstructed surface Si(100)–(2 $\times$ 1)H [4]. Upon isothermal annealing, this line gradually shifts to the region at 2091 cm$^{-1}$, which corresponds to the vibrations of dihydride complexes on atomically smooth surfaces Si(100)–2H [4]. For the Si sample without a buried layer, we failed to detect a change in the state of hydrogen on the interior surfaces of Si. In the IR-absorption spectrum, a band only at 2091 cm$^{-1}$ was observed.

Figure 2 shows the dependences of the fraction of hydrogen involved in the formation of Si–H bonds in relation to the time of isothermal annealing at 400°C. The use of the relation [5]

$$N(\text{Si–H}) = 1.1 \times 10^{30} \int_{\omega} \frac{a(\omega)}{\omega} d\omega$$

(where $\omega$ is the wave number and $a$ is the absorption coefficient), the concentration of Si–H bonds and, consequently, the concentration of chemically bound H were determined. Previously, we showed that the fraction of chemically bound H ranges from 20 to 70% of the implantation dose [1]. It can be seen from Fig. 2 that, after the implantation, about 50–65% of the implanted H ions are in the form of complexes with Si.
form of SiH complexes, which indicates that the variation in the fraction of H bonding to Si is insignificant during the splitting.

Figures 3a and 3b show images of cross sections of Si samples implanted with H ions; these images were obtained by transmission electron microscopy (TEM). The sample shown in Fig. 3b contains a buried layer doped heavily with B. The images were obtained after implantation with H and annealing at 200°C for two hours. It can be seen from Figs. 3a and 3b that such annealing is sufficient for the formation of microcavities in the implanted layer. The width of the region where microcavities are formed ranges from 100 to 120 nm in both cases. However, in the samples containing a buried layer, microcavities are mainly formed at a depth at which the impurity content is highest. It can also be seen from Fig. 3b that not all of the interior surfaces developing in the sample with a buried layer are parallel to the wafer surface. Formation of microcracks along the [111] direction is also observed, which is in good agreement with the IR-spectroscopy data. Figure 3b shows that, even after annealing at $T_{\text{ann}} = 200^\circ\text{C}$ for two hours, the microcracks form an almost unified cavity at the depth where the B content is highest.

Figure 4 shows the time $t$ required for blisters to be formed as a function of the annealing temperature $T_{\text{ann}}$. It can be seen from Fig. 4 that the formation of blisters on the surface of an Si sample containing a heavily B-doped layer occurs significantly more rapidly in comparison with the implanted Si samples containing no buried layer. The activation energy of the blister formation on the surface of the H-implanted Si without a buried layer is equal to $1.3 \pm 0.2$ eV. At the same time, the activation energy of blister formation on the surface of H-implanted Si containing a buried layer is only $0.8 \pm 0.2$ eV.

Figure 5 shows the AFM images of the surface of an Si film, obtained in the course of splitting of the Si wafers containing a heavily B-doped layer (Figs. 5a, 5c) and of those without such a layer (Figs. 5b, 5d). After conventional hydrogen-induced exfoliation of the Si film, the roughness of the film surface is rather high (the root-mean square roughness is equal to 10.5 nm). It can be seen from Fig. 5 that the roughness of the surface of the Si film transferred from the wafer containing a buried layer onto an insulator substrate is lower by a factor of 2–5 in comparison with the case of conventional exfoliation. Thus, for the windows of $30 \times 30 \mu\text{m}^2$ in size, the root-mean square roughness of such surfaces is equal to 5.6 nm.

4. DISCUSSION

The formation of microcavities at a depth of 500 nm in the samples containing a buried layer doped heavily with B is caused by the accumulation of H in the region where the B content is highest. High-temperature annealing during the oxidation of Si at $T_{\text{ann}} = 900^\circ\text{C}$ for 20 min is not sufficient to obtain a uniform distribution of the B impurity in this region. The enhanced formation of microcavities possibly indicates that centers of their nucleation exist in the samples under study [6] or that the mechanism of accumulation of H in cavities changes from reaction-limited aggregation to diffusion due to a decrease in the incorporation-barrier height (which is confirmed by the decrease in the activation energy).
Analysis of the IR absorption spectra shows that the composition of hydrogen-containing defects in the Si samples containing a buried layer doped heavily with Boron in the samples without such a layer is identical after annealing. It is also possible that the mechanism of development of microcavities due to the accumulation of hydrogen in them also does not change [7]. However, the kinetics and the activation energy of this process change significantly. It is possible that the mechanism of H diffusion to the microcavities changes too.

A mechanism of influence of the high B content on the blistering and exfoliation was suggested previously in [6]. The enhanced formation of microcavities in the region where the B content is highest in attributed to the large number of nucleation centers. Boron atoms can serve as such centers. The significant enhancement of the development of microcavities is due to the enhanced accumulation of gaseous H in these microcavities.

The line at 2091 cm$^{-1}$ in the IR-absorption spectrum of the implanted Si appears immediately before the splitting of the implanted layers and vanishes immediately after the exfoliation. This spectral line corresponds to the state of the surface at which a surface Si atom is bonded to two H atoms. We managed to trace the transformations in the spectrum at the instant when a passivated surface is formed on the Si film; specifically, when the line corresponding to vibrations of the monohydride complexes on the dimerized surface and the appearance of dihydrides in the course of exfoliation completely disappears. Apparently, the disappearance of this line after the exfoliation is caused by the oxidation of the surface. In our opinion, the increase in the content of hydrogen in microcracks, as well as the large concentration of B atoms, which impede the dimerization of Si atoms on the (100) surface (due to the decrease in the number of dangling bonds), facilitates the formation of dihydrides.

Evidently, the increase in the time required to split the sample containing a buried B-doped layer, in comparison with that for the sample without such a layer, is due to the presence of small (1–2 μm) regions in the wafer that remained unimplanted. The real time required to split an H-implanted sample containing a B-doped layer was additionally determined (Fig. 4, curve 2'). In the presence of a heavily doped layer, the
processes of formation of blisters on the Si surface and exfoliation of a thin Si film are enhanced by approximately a factor of 7–10.

The enhanced formation of microcavities in a narrow portion of the implanted region makes it possible to obtain smoother interior surfaces during annealing, since it is this portion that is responsible for the enhanced trapping of the diffusing hydrogen.

The heavily B-doped region in Si is depleted of intrinsic point defects and enriched with molecular hydrogen [6]. Boron atoms serve as nucleation centers for microcracks in this region. Apparently, these are the reasons for the enhanced formation of cracks in the heavily B-doped region.

The enhanced formation of extended cracks in a sample containing a heavily B-doped layer indicates that such a layer can be used as the formation center for microcavities. In our opinion, the use of a heavily B-doped layer as a boundary over which the splitting of the H-implanted wafer occurs will make it possible to exfoliate very thin films, thus decreasing the implantation energy and the depth at which the heavily doped layer is located.

5. CONCLUSIONS

On the basis of the results obtained, we concluded the following:

(i) The composition of hydrogen-containing defects in the Si samples containing a buried layer doped heavily with B and in the samples without such a layer is the same after annealing. However, the activation energy and the kinetics of the processes of blistering and exfoliation are significantly different in these cases. The presence of a heavily doped layer enhances the processes of formation of blisters on the Si surface and exfoliation of a thin Si film by approximately a factor of 7–10. The enhanced formation of microcavities in the thin layer doped heavily with B makes it possible to decrease the implantation dose of H ions.

(ii) The formation of microcavities in the region near the buried layer significantly affects the roughness of the exfoliated film. The decrease in the surface roughness is due to the fact that film exfoliation is initiated by the microcracks located in the region whose width is considerably smaller than the width of the region within which the boundary of the exfoliated film is formed in the case of conventional hydrogen-induced splitting.

(iii) A line is observed at 2091 cm\(^{-1}\) in the IR-absorption spectra. This line appears and disappears within a short period of time corresponding to the exfoliation of a thin Si film. On the basis of an analysis of the absorption spectra, we may state that, at the instant when the surface film is formed, the reconstruction of the surfaces of the interior cavities occurs. In the course of this process, the state of hydrogen changes from Si(100)–\((2 \times 1)\)H to Si(100)–2H.

REFERENCES