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Peculiarities of the Impurity Redistribution Under Ultra-Shallow Junction Formation in Silicon

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Abstract. Ultra-shallow junctions (USJs) were formed by low-energy As ion implantation with the subsequent furnace annealing. It was found that the significant amount of oxygen is redistributed from the silicon bulk to the arsenic-implanted region. We present the effect of oxygen gettering at the creation of arsenic-doped USJs using the marker layer created by ion implantation of ^{18}O isotope.

Introduction

The processes for formation of the source/drain regions of metal-oxide-semiconductor field effect transistors (MOSFET) become increasingly important as device dimensions are scaled down. In order to suppress the short-channel effect the creation of ultra-shallow junction (USJ) with the high dopant activation is required [1]. Low energy implantation of arsenic is widely used for creation of n-type region. However, the USJ formation is complicated by the dopant deactivation, accumulation at the SiO_2-Si interface [2], and transient-enhanced diffusion (TED) as result of interaction with point defects [3]. Directions of overcoming these problems are discussed in many papers [4-6]. Another factor affecting on the properties of the ultra-shallow junctions in Czochralski Si may be an oxygen impurity. It is known that the oxygen precipitation in silicon leads to formation of defects that act as gettering center for impurities that are responsible for leakage current [7, 8]. Also the oxygen precipitation is strongly dependent on the presence of vacancies generated by ion implantation and the existing mechanical stresses at different thermal treatment. Oxygen is rapidly gettered into residual damage regions, forming stable SiO_x precipitates during annealing [9]. It was found [10] that compared with that in lightly doped wafers, the oxygen precipitation was enhanced in B- doped wafers and was retarded in As -doped wafers during the annealing process.

Earlier papers have shown that the high-energy implanted arsenic can influence stoichiometry of screen oxide [11]. This leads to degradation of the devices. But the information about the behavior of oxygen near the USJ is almost absent for the ion implantation of dopants.

In the presented work the USJ's were created by the low-energy As^+ implantation with the subsequent high temperature annealing. The arsenic and oxygen redistributions were studied by the SIMS method. The buried oxygen marker layer was used for the verification of the oxygen diffusion toward the arsenic distribution region. The marker layer was created by the ion implantation of ^{18}O oxygen isotope. The physical model of oxygen redistribution with the mechanical stress influence is proposed.

Experimental

All the experiments were performed on 100-oriented p-type 10 Ohm×cm silicon wafers. The samples were implanted through the 2.2 nm screen oxide by As ions with a dose of 4×10^{14} cm^{-2} and

energy of 5 keV. Furnace annealing of the as implanted samples was carried out at the temperature range of 750^0C - 950^0C (the standard temperatures for activation annealing) in nitrogen ambient for 0.5 to 20 minutes. Some of the samples were additionally implanted by ^{18}O oxygen isotope with the energy of 100 keV and dose of 1.2×10^{14} cm^{-2}. Analysis of the dopant depth profiles was performed by secondary ion mass spectrometry (SIMS) method by Cameca IMS 4F instrument. Cs^+ primary ion beam with the energy of 1 keV was used for secondary ion generation. The sample sputtering area has a rectangular shape with the size of 250×250 μm. The analyzed area was of 150 μm in diameter at the center of the sputtering area. The sputtering rate was approximately 0.5 nm/s. The depth scale was determined for each profile by measuring the crater depth with a Dektak 3030 profilometer.

Results and discussion

SIMS depth profiles of arsenic and oxygen in Si before and after annealing at the temperatures 750 - 950^0C for 5 minutes are shown in Fig. 1. It is seen that after annealing implanted arsenic is redistributed towards the surface and the sample depth. After annealing at 750°C only a small shift of the As distribution maximum towards the SiO_2/Si interface is observed. Increase of annealing temperature leads to As extrinsic diffusion and pileup phenomenon at the SiO_2/Si interface. Arsenic accumulation at the SiO_2/Si interface is increased with annealing at higher temperature and duration. It was also found that arsenic redistribution is accompanied with changes of oxygen concentration in the vicinity of the USJ location. Oxygen distribution for the 40 – 60 nm region is presented in the inset to Figure 1 for different annealing temperatures. One can see that oxygen concentration in this region substantially increases, especially for low annealing temperatures.

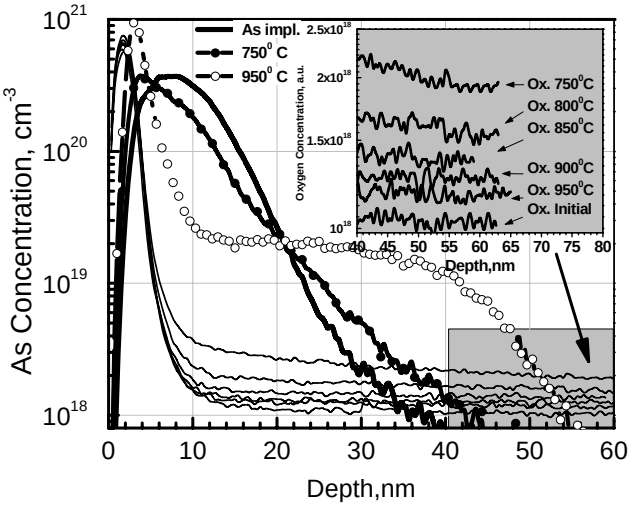

Fig. 1. SIMS depth profiles of arsenic and oxygen distributions at different annealing temperatures. Inset shows the change of oxygen concentration at the tail of arsenic depth profile after annealing.

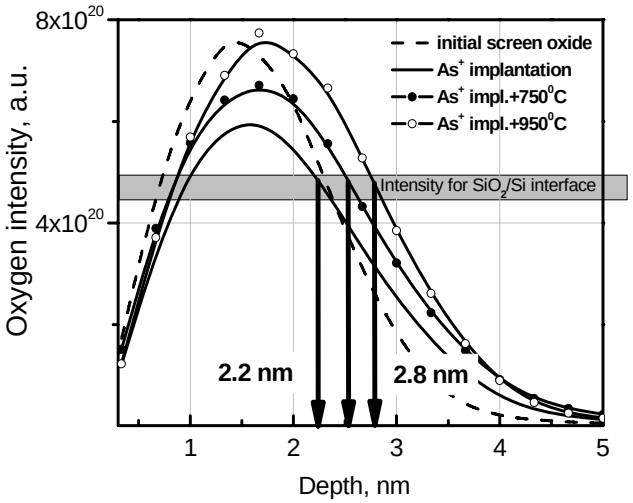

Fig. 2. SIMS depth profile of oxygen close to the SiO_2/Si interface before and after annealing at different temperatures (5 min.)

Fig. 2 shows the oxygen depth profiles near the SiO_2/Si interface before and after the thermal treatments. It is seen that arsenic implantation leads to decrease of oxygen concentration in the screen silicon oxide and to some enlargement of oxygen concentration in the Si subsurface layer. It is related with removal of the oxygen atoms by sputtering at the oxide-vacuum interface and recoil implantation of oxygen atoms from screen oxide into underlying silicon substrate [11].

Annealing of the arsenic-implanted structure leads to the increase of the screen silicon oxide thickness. The estimation of the oxide thickness at the 0.707 level from maximum of initial oxygen depth profile shows that the increase of annealing temperature leads to increase of screen silicon

oxide thickness from 2.2 nm to 2.7 nm. Such effect may be possible only due to additional oxygen incoming to the interface from some external source. Location of such source (ambient or Si bulk) is not perfectly clear.

In our experiments the annealing of samples was carried out in the high purity nitrogen ambient. In this case the oxygen transportation would be absent from the surface towards the SiO_2/Si interface. Also TRIM calculations show that the low-energy arsenic implantation almost does not lead to the recoil oxygen implantation from the screen silicon oxide to the depth more than 10 nm.

We have supposed that silicon bulk is the source of oxygen. In this case the shallow-implanted arsenic acts as a getter layer of the background oxygen. To confirm this idea we have created an ^{18}O marker layer that will act as oxygen source in silicon (0.3 μm from the sample surface). It is necessary to use oxygen isotope with a mass of 18 a.m.u. to separate the implanted oxygen from the background oxygen in silicon.

Fig. 3 shows SIMS depth profiles of the implanted ^{18}O atoms before and after annealing at the temperature of 950^0C for 5 minutes in the arsenic-implanted silicon. Projected range of oxygen was of 300 nm. It is seen that the implanted ^{18}O is strongly redistributed towards the arsenic-implanted surface and incorporates into surface screen oxide layer.

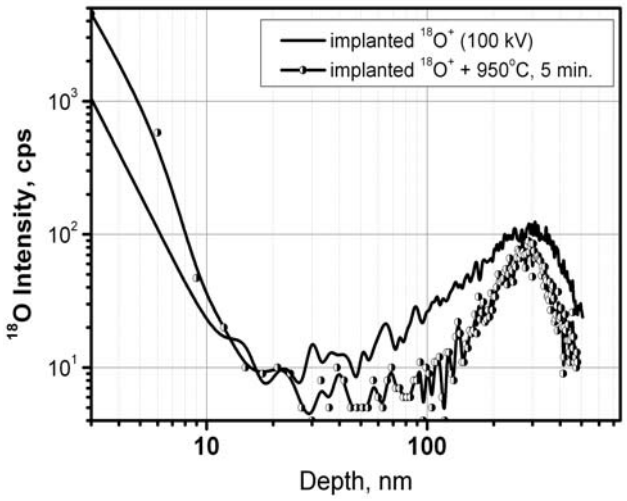

Fig.3. SIMS oxygen depth profiles after ^{18}O implantation in the arsenic-implanted structure before and after annealing at the temperature of 950^0C for 5 min.

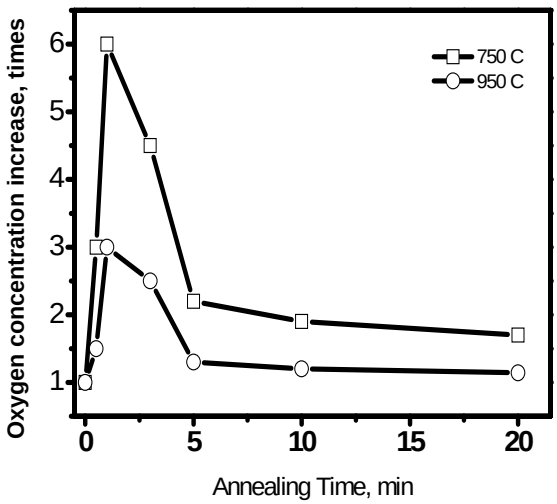

Fig.4. Time dependence of the relative oxygen concentration in the USJ region (10 – 50 nm) after furnace annealing.

Such redistribution may be associated with oxygen gettering by the arsenic implanted region. Fig. 4 shows the time dependences of the relative oxygen concentration in the USJ region (10 – 50 nm) after furnace annealing at two temperatures: 750^0C and 950^0C. It can be seen that after 1 min. annealing oxygen concentration in the USJ region increase by 6 times (750^0C) and by 3 times (950^0C) for arsenic-implanted samples. The longer annealing time leads to decrease of the accumulated oxygen concentration and to increase the screen silicon oxide thickness (Fig. 2.).

The data obtained confirm that at the USJ formation the process of the volume-dissolved oxygen enhanced diffusion to the implanted surface takes place. Fig. 5 shows the arsenic depth profiles evolution for implanted samples at the furnace annealing at 750^0C. The noticeable arsenic redistribution towards the surface and the sample depth occurs for the annealing time interval of 5 to 20 min. This time interval correlates with the results shown in Figures 2 – 4 when screen oxide thickness increases utilized gettered from the bulk oxygen. In the region of arsenic distribution large mechanical stresses exist; their values are dependent on implantation dose and energy. At the beginning of the low temperature (750^oC) annealing process, concurrently with the implanted region defect structure rebuilding, intensive oxygen gettering from the wafer volume occurs (Figure 4) due to the mechanical stress gradient. As annealing duration increase, a fraction of arsenic atoms

is sited at the crystal lattice sites, and other arsenic atoms are accumulated at the SiO_2-Si interface; Mechanical stress value decreases, and gettered oxygen flow diminishes. Portion of oxygen atoms respond to the surface oxide layer formation (Fig. 2).

When annealing temperature increases, mechanical stress gradient decreases, and quantity of gettered oxygen diminishes. In this case the gettering process is effective during the first 5 – 10 s.

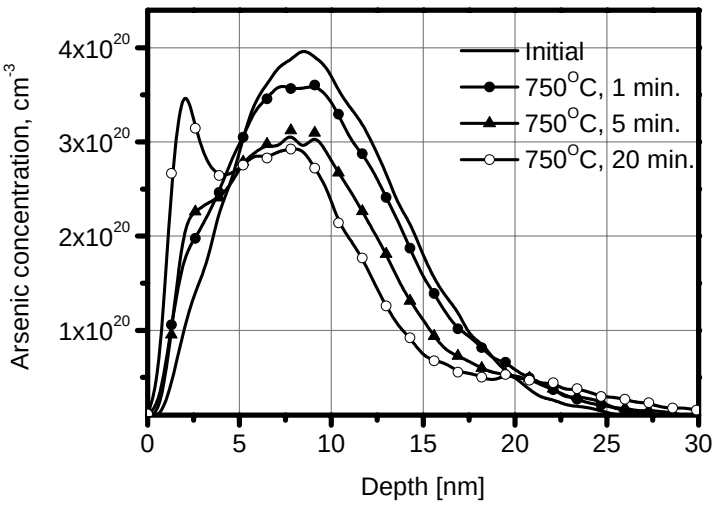

Fig.5. SIMS arsenic depth profiles before and after furnace annealing at 750^{0}C for different times.

Thus, the USJ formation using low-energy ion implantation is followed by an increase of oxygen concentration in the arsenic distribution region. With increasing of annealing temperature from 750^{o}C to 950^{o}C accumulated oxygen concentration at the arsenic distribution region decreases. However, an increase in oxide thickness with increasing of annealing temperature is observed. The increase of the annealing time also increases thickness of the surface oxide. Our model experiments clearly show that at high-temperature annealing implanted ^{18}O diffuses from the depth of 300 nm towards the surface and accumulates in the arsenic distribution region, indicating the gettering effect.

Summary

The effect of oxygen redistribution at thermal activation of As^+, implanted into silicon was found. Arsenic and oxygen depth profiles depending on temperature and duration of thermal annealing have been investigated. It is determined that during annealing the surface oxide thickness increases as a result of oxygen gettering from Si wafer volume towards the USJ region. This effect was confirmed by the model experiment with additional implantation of $^{18}O^+$ ions into Si substrate. It was shown that implanted ^{18}O atoms strongly redistribute towards the arsenic-implanted surface and incorporate into surface screen oxide layer. Oxygen redistribution is connected with tensile mechanical stresses in implanted Si.

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