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Mechanism of Oxygen Redistribution During Ultra-shallow Junction Formation in Silicon

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The transport of dissolved oxygen in the Czochralski silicon towards the arsenic-doped ultra-shallow junction was investigated. Ultra-shallow junction was formed by low-energy **As**$^+$ ion implantation with the subsequent furnace annealing at 750 °C-950 °C temperatures for the dopant activation. Oxygen and arsenic redistributions were investigated by secondary ion mass spectrometry (SIMS) technique. The peculiarities of defect creation and transformation were studied by the X-ray diffuse scattering technique (XDS). It was found that oxygen concentration in the arsenic redistribution region is increased a few times already after 1 minute of annealing. Increase of annealing time leads to decrease of oxygen accumulation as a result of oxygen transportation to the SiO_2/Si interface. As a result the thickness of screen silicon oxide is increased by 0.5 nm. This effect is related with the oxygen gettering from the wafer bulk. A physical mechanism of the oxygen transfer is discussed.

Keywords: Ion implantation, Interface, Arsenic, Oxygen, Junction, Diffusion, Gettering, SiO_2, SIMS, XDS.

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1. INTRODUCTION

The dimension scaling of metal-oxide-semiconductor field effect transistors (MOSFETS) requires the ultra-shallow p-n junctions in the source/drain extensions for the suppression of short channel effects. One of the creation methods of such junctions is a high-dose low-energy implantation of arsenic ions in the Czochralski (Cz) silicon wafer with the subsequent high-temperature annealing. However, the USJ formation is complicated by the dopant deactivation, accumulation at the SiO_2-Si interface [1], and transient-enhanced diffusion (TED) as result of interaction with point defects [2]. Rousseau et al. [3] are shown that arsenic deactivation is a result of As_nV ($n = 2,3,4$) cluster (where V – vacancy) formation with the injection of self-interstitial (I) in the silicon bulk. Also it was found that As TED is explained by both vacancy- and interstitial - mediated As diffusions. The presence of dissolved oxygen in Cz-silicon wafers also plays a significant role in the processing of integrated circuits. It is known that the diffusion – mediated oxygen precipitation in silicon leads to the formation of extended defects and metal gettering that are responsible for leakage currents [4,5]. Also the oxygen can form thermal donors due to the clustering of several oxygen atoms [6]. 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 [7]. In the heavily As-doped Si the oxygen precipitation is retarded. That is related with reduced oxygen diffusion at the increase of arsenic concentration [8]. It was proposed the reduced oxygen diffusion is connected with O-As-V complex where V surrounded by one atom of arsenic, one atom of oxygen and several silicon atoms [9]. Investigations of the oxygen behaviour near of the As USJ are shown that the significant amount of oxygen is gettered from the silicon bulk by the arsenic-implanted region at the annelings [10]. That leads to the increase of screening silicon oxide thickness and uncontrolled accumulation of oxygen in the USJ region at the different thermal budgets.

The lattice structural defects and oxygen redistributions around the arsenic-doped ultra-shallow junction were studied to understand the physical mechanism underlying the transport of oxygen from the silicon bulk to the arsenic implanted region.

2. EXPERIMENT

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 °C-950 °C (the standard temperatures for activation annealing) in nitrogen ambient for 0.5 to 20 minutes. 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 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. Peculiarities of defect creation and transformation were carried out using the X-ray diffuse scattering (XDS) technique with the high-resolution diffractometer PANalytical X'Pert Pro MRD. The method for the determination of the defect concentration consists in finding the Huang and thermo-diffuse scattering ratio, excepting influence of the scattering layer thickness, structure amplitude, spatial angle of scattering, and Debye-Waller factor. So, such important parameters as the micro-defect symmetry, dimension, and concentration may be directly determined from experimental data according to diffuse scattering observed in the investigated sample.

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3. RESULTS AND DISCUSSION

Fig. 1 shows the time dependences of the relative oxygen concentration in the USJ region (10-50 nm) after furnace annealing at two temperatures: 750 °C and 950^{0}C. It can be seen that after 1 min. annealing oxygen concentration in the USJ region increase by 6 times (750 °C) and by 3 times (950 °C) for arsenic-implanted samples. The longer annealing time leads to decrease of the accumulated oxygen concentration and to increase the screen silicon oxide thickness as shown in previous our paper [10].

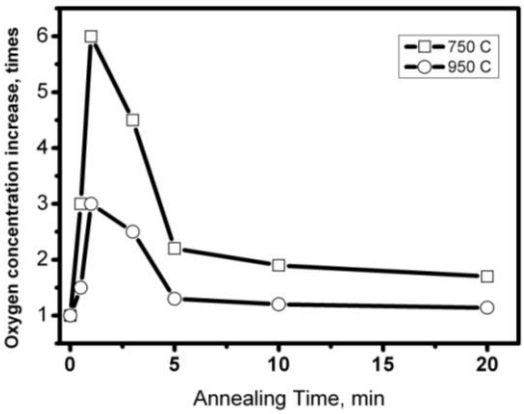

Fig. 1 – Time dependence of the relative oxygen concentration in the USJ region (10 – 50 nm) after furnace annealing

The obtained data confirm that at the USJ formation the process of the volume-dissolved oxygen enhanced diffusion to the implanted surface takes place. Fig. 2 shows the arsenic depth profiles evolution for implanted samples at the furnace annealing at 750 °C. The noticeable arsenic redistribution towards the surface and the sample depth occurs for the annealing time interval of 5 to 20 min.

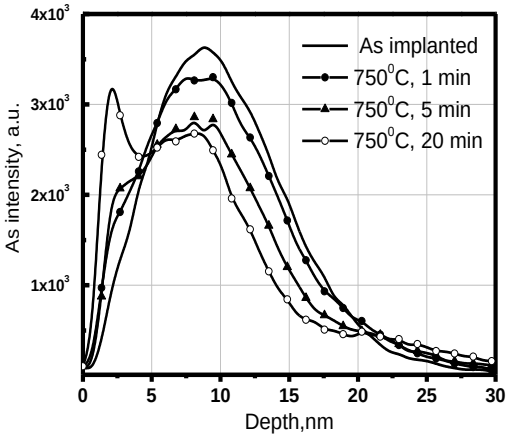

Fig. 2 – SIMS arsenic depth profiles before and after furnace annealing at 750 °C for different times

Fig.3 shows the normalized intensities I(q) of XDS curves for the arsenic - implanted samples before and after annealing at the temperature of 750 °C-950 °C for 5 min. The shapes of curves indicates that all the samples have the defects both of vacancy ($q_z < 0$), and interstitial ($q_z > 0$) type, where q_z is reciprocal lattice vector. Defect concentrations of both types are increased after annealing at 750 °C. Moreover the sizes of vacancy type defects are increased but the sizes of interstitial type are decreased. After annealing at the temperature of 950 °C the vacancy defects almost disappear but the

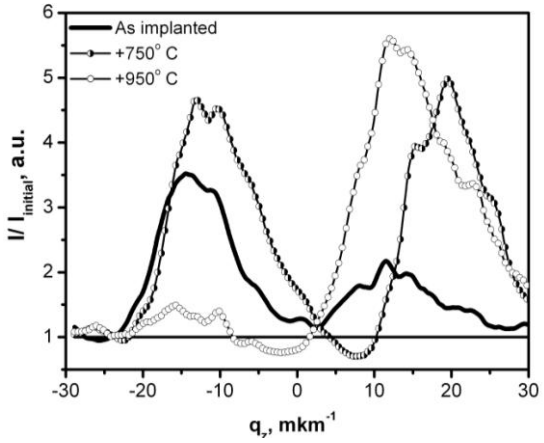

Fig. 2 – Dependence of the normalized intensity I(q) on q_z vector: for as implanted sample and after annealing.

concentration of interstitial defects are increased. It is known that the amorphous/crystalline interface, {311} rodlike and EOR defects disappear instantly after annealing at the temperature of 700 °C for the high-dose low-energy arsenic implantation (< 10 keV) in the silicon [11]. The SiO_2/Si interface acts as a strong interstitial sink, absorbing the interstitials released from the defects during the Ostwald ripening process. This significantly reduces the amount of silicon self-interstitial atoms in the depth. Obviously only the arsenic clustering (As_nV) creates a some amount of self-interstitial defects in silicon. In this case the arsenic enhanced diffusion is weakly related with the silicon interstitials. We suppose that the increase of vacancy and interstitial shoulder on a XDS curve after annealing at temperature 750 °C is connected only with the generation and transferring of AsV and As_2V complexes (TED) into the silicon depth. In this case the oxygen diffusion toward the arsenic distribution region can be performed according to the reaction AsV+O → As+VO, where VO is a mobile vacancy-oxygen complex. Also it can lead to the VO_2 complex formation. The interaction of VO_2 and VO complexes with a self-interstitial silicon atom leads to the formation of mobile O_2 complex and interstitial oxygen Oi. The interstitial oxygen and oxygen complexes will diffuse towards the source of vacancies. Since the arsenic stressed silicon lattice will be stretched and generate the arsenic – vacancy complexes during the annealing the oxygen precipitation is suppressed [8]. The process will continue until the lattice stress compensation. At the same time the arsenic segregation (with the accumulated oxygen) at the SiO_2/Si interface will lead to the additional oxidation of the silicon surface.

4. CONCLUSION

The quantitative characteristics of oxygen accumulation and defect structure of the silicon lattice during the USJ formation were studied. The physical mechanism of the oxygen transfer from the silicon bulk toward the USJ region is proposed. The mechanism involves the interaction of oxygen with point defects in the field of mechanical stresses.

Oxygen is gettered by arsenic implanted region due to the mechanical stress gradient. At the increase of the annealing time the one part of arsenic atoms is sited at the crystal lattice sites. The other part is accumulated at the SiO_2/Si interface. Arsenic redistribution leads to decrease of the mechanical stress. The result is that the flow of oxygen is reduced. Part of oxygen atoms respond to the surface oxide layer formation. The increasing of annealing temperature leads to decrease of the mechanical stress gradient and consequently the quantity of gettered oxygen. In this case the gettering process is effective during the first 5-10 s. 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 °C to 950 °C accumulated oxygen concentration at the arsenic distribution region decreases.

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