The destruction of interface of silicon's heterogeneous structures as a result the hydrogen diffusion

E. E. Mukhin A. M. Polyanskiy V. A. Polyanskiy A. G. Razdobarin
Yu. A. Yakovlev
yura.yakovlev@gmail.com

Abstract

One of the most actual problems of modern microelectronics is ratability of semiconductor products. The solution this problem is important to creation of the electronic components for space communication systems, control systems of nuclear and thermonuclear reactions.

In the paper are described results of research work study the reasons exfoliation of films system Ox-Si-Ox, where Ox-is oxide Al_2O_3 or ZrO_2. This type of sensor use in ITER project for data transfer about plasma to sensors located behind biological shielding. Body of sensors-mirrors form the system works like periscope. The mirror surfaces are under thermo-mechanical loading and it is rayed neutrons.

Research work has done with hydrogen analyzer AV-1. We've shown, that hydrogen diffusion from silicon to interface can lead to destruction of interface under thermo-mechanical loading. Large hydrogen flow from silicon may be explained by redistribution the hydrogen on the energy level. The hydrogen inside silicon change bond energy under loading and it turn to diffusion state.

1 Introduction

The problem of the destruction of the interfaces of thin film structures occurs in a variety of industries. Modern sensors are typically multilayer thin-film structures. Similar problems arise in the operation of parts with protective coatings and in a fusion reactor, which is widely used by various reflectors.

This may also include a variety of heterostructures, and other complex semiconductor devices that use composite materials that contain one or more thin layers of dissimilar materials related to each other.

In some cases, [1], on the contrary should be separated by a thin layer of the substrate.

As a rule, the destruction of interfaces because of mechanical stresses arising due to external impact on the material.

For example, rapid cooling or heating in nuclear fusion, accompanied by an even heat and mechanical action of the beam plasma, are also possible radiation (electronics in space) and shock associated with the mode of operation of products that contain sensors or other thin-film devices.

This purely mechanical approach allows us to describe and simulate the destruction of interfaces, but only in rare cases makes it possible to prevent it, because in contrast to other parts the interface can not be made thicker for reducing the mechanical stress. We can only decrease of the external load, but it is not always possible.

For the technology of production and operation of various devices containing thin-film interfaces it is important to understand the basic mechanisms of damage and the parameters that define them. In this case, you can improve the performance of the targeted based on existing ideas about the sources of destruction.

Hydrogen diagnostic is the non-standard method for studying the causes of destruction [2]. Hydrogen is always present in all materials. At low concentrations, its natural effect on the strength is not conclusive, but it was shown [3], the redistribution of hydrogen, which occurs under the influence of external loads can cause a local concentration of hydrogen in the region of the critical strains. In this case, it is one of the reasons for failure.

2 Experimental investigations

Experimental investigations were made with samples of mirror reflectors for Tokomak ITER. Samples represent a multilayer coating based on silicon with a layer thickness of 100 - 300 nm [4].

One layer contains pure aluminum, which is a reflector on top of this layer is covered with a protective transparent layer of oxides. The samples coated with a layer of Al_2O_3 and ZrO_2.

Prepared samples with different types of coatings were exposed inside the test fusion reactor[5]. There they were exposed to the incident beams of plasma. This effect is very rapid heating of surface by heat flux. In the experiments purely mechanical action of the plasma can be neglected, since the flux density of the plasma particles was low.

After exposure were observed blister delamination as a protective coating on the mirror surfaces, and metal layer. This fracture pattern is not limited to thermal stresses, as they have to be uniform in the plane of the mirror. Splits, however, occurred separately. The area of each split is very small same as for Ag mirror shown in Figure 1.

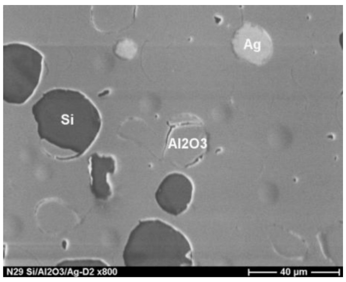

Figure 1: Blisters on the surface of Ag mirror covered with Al_2O_3 film after exposure to a fluence of $1.9{\cdot}10^{20}$ ions/cm^2 [5].

It is seen that most of the blisters peel off together with the Ag layerbut some without one.

Studies using transmission electron microscopy were performed to determine the causes of such a bundle. Photo cross-section under the microscope mirror can be seen in Figure 2.

The photo clearly seen spherical formations in the film Al_2O_3 and delamination of the film. For determination the possible nature of such delamination was measured the concentration of hydrogen in the silicon substrate and a silicon plates coated on both sides of the film Al_2O_3 and ZrO_2.

Studies were performed by an industrial mass spectrometry analyzer hydrogen AV-1. The flow of hydrogen and deuterium from substrate samples with different coatings was separately measured. Samples were pre-saturated by deuterium. For what they were exposed in the flux of deuterium ions with energies from 50 to 100 eV and different fluences.

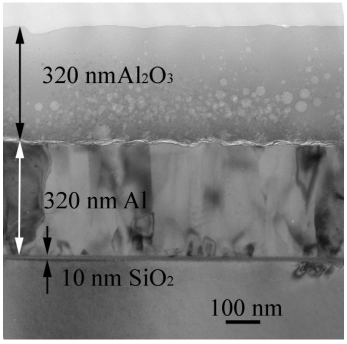

Figure 2: Mirror covered with Al_2O_3 film after exposure

During the experiments, it was found that irradiation leads to saturation of the sample by deuterium. It was found a significant amount of hydrogen in the silicon substrate (polysilicon), it was about four times higher than in similar samples of monocrystalline silicon.The results obtained on the samples after irradiation are shown in Figure 3.

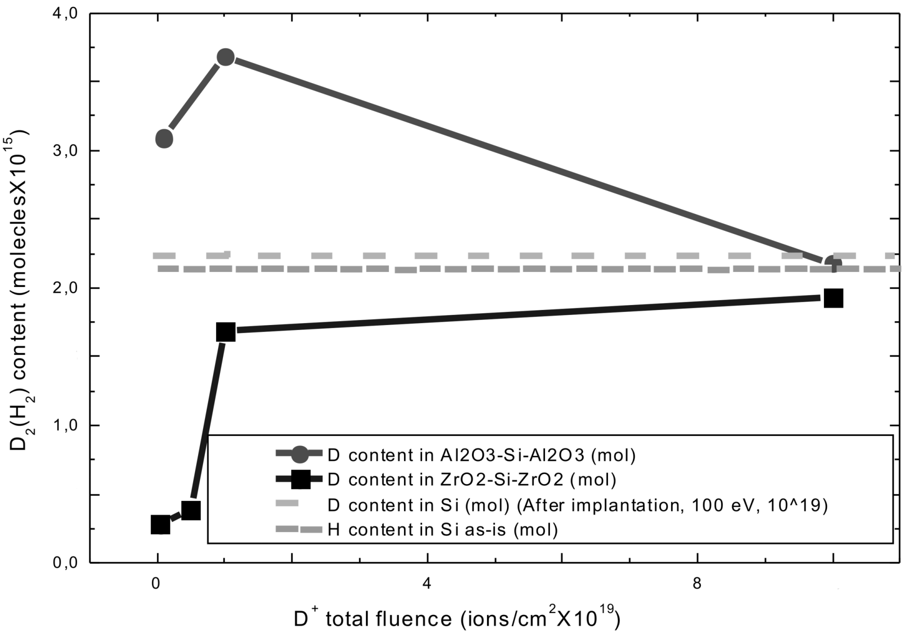

Figure 3: Comparison of the deuterium content in the samples of ZrO_2-Si-ZrO_2 and Al_2O_3-Si-Al_2O_3, exposed to the full fluence $3{\cdot}10^{17}$ - 10^{20} deyteriya/sm^2 ions with deuterium content in irradiated silicon wafer without coating and hydrogen dissolved in normal samples.

As can be seen in samples without coating deuterium content is same as content of hydrogen in the initial silicon samples. It can be concluded that the irradiation of silicon samples with the low-energy deuterium ions leads to the substitution of dissolved in the sample volume hydrogen by deuterium. The same value of deuterium content is volumed in the samples with oxide coatings of both types after exposure to full fluence - 10^{20} ions/sm^2.

General view of the dependence of the deuterium content from the fluence is different for samples with different oxide coating. For samples of ZrO_2-Si-ZrO_2 content increases monotonically with fluence until it reaches the deuterium content in the uncoated silicon.

For samples of Al_2O_3-Si-Al_2O_3, the dependence is nonmonotonic with a peak at about

10^{19} ions/sm^2. This can be explained by the non-monotonicity accumulation of deuterium in the blisters on the sample Al_2O_3-Si-Al_2O_3, that were bursted when a large fluence. As a resul, the deuterium content in the sample decrease. In the limit of the sample is dissolved in a volume of silicon deuterium.

This interpretation is confirmed by microscopic examination of samples. Their entire surface is covered by point defects, which are revealed the bubbles detached oxide film.

3 Modeling

Simulation of diffusion of hydrogen from the silicon plates was performed using models and approaches [2]. Diffusion parameters were determined from fitting the model to the real experimental extraction curves obtained during the research.

Simulation of the diffusion of hydrogen and deuterium during the analysis can not only adequately describe the nature of diffusion, but also to determine the binding energy of hydrogen and deuterium in the samples.

Figure 4 shows the real extraction curve obtained for a plate of pure silicon.

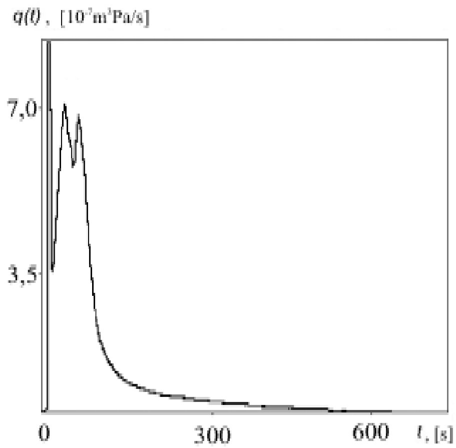

Figure 4: The extraction curve for a plate of pure silicon

Figure 5 shows the result of simulation. Also in Figure 5 are indicated the binding energies of hydrogen, corresponding to each peak of the extraction curve.

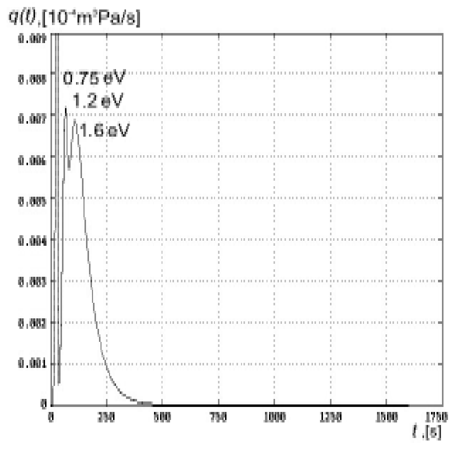

Figure 5: Approximation extraction curve obtained in modeling of the diffusion process

4 Conclusion

Studies carried out with samples of silicon, which have different coverage. It is showed that the destruction of the interfaces is a point that is difficult to explain purely mechanical reasons.

Comparison of results with electron microscopy revealed that the main cause of delamination is the diffusion and redistribution of hydrogen and deuterium in the interface layer, which lead to the destruction of the interface, the formation of hydrogen bubbles and the destruction of the coating under the pressure of hydrogen.

ZrO_2 coating showed significantly better performance, which is associated with much higher hydrogen permeability of the coating in comparison with Al_2O_3.

Thus, it is experimentally proved that the diffusion and redistribution of hydrogen are the main cause of the destruction of the interfaces of thin film structures on a silicon substrate. Thermal stresses only increase the probability of failure. Heating leads to faster diffusion of hydrogen in semiconductor elements and this leads to a rapid redistribution of hydrogen and the destruction of the structure.

The use of hydrogen diagnosis showed its greater efficiency in the development of resistant to the flow of plasma mirror coatings.

Acknowledgements

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References

[1] S. J. Jeng, G. S. Oehrlein "Microstructural studies of reactive ion etched silicon" Appl. Phys. Lett. 50, 1912 (1987)

[2] A.M Polyanskii, V.A Polyanskii, Yu.A. Yakovlev "Investigation of the completeness of specimen degassing in an analysis of the hydrogen content of aluminum alloys" Metallurgist, Vol. 55, 3, (2011) 303-310

[3] A.K. Bekyaev, V.A. Polyanskiy, Yu.A. Yakovlev Stresses in a pipeline affected by hydrogen "Acta Mechanica", 223, (2012) 1611-1619

[4] Kochergin M.M., Mukhin E.E., K.A.Podushnikova, et al. "Research on mirror cleaning in inductively and capacitively driven radio-frequency discharges" Plasma Devices and Operations, Vol.14, 2, (2006) 171-176

[5] Razdobarin A.G., et al. "2009 High reflective mirrors for in-vessel applications ITER" 1th International Conference Frontiers in Diagnostic Technologies Id:P92

E.E. Mukhin, Ioffe Pysical Technical Institute RAS, 194021 Politekhnicheskaya, 26 St.-Petersburg, Russia

A.M. Polyanskiy, RDC Electron & beam technology Ltd, 195220 p.b. 162 St.-Petersburg, Russia

V.A. Polyanskiy, IPME RAS, V.O., Bolshoj pr., 61 , 199178 St.-Petersburg, Russia and St.-Petersburg State Polytechnic University, 195251 Politekhnicheskaya, 29 St.-Petersburg, Russia

A G. Razdobarin, Ioffe Pysical Technical Institute RAS, 194021 Politekhnicheskaya, 26 St.-Petersburg, Russia

Yu. A. Yakovlev, IPME RAS, V.O., Bolshoj pr., 61 , 199178 St.-Petersburg, Russia and St.-Petersburg State Polytechnic University, 195251 Politekhnicheskaya, 29 St.-Petersburg, Russia