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NON-MONOTONIC CHANGES OF SILICON MICROHARDNESS RADIATION-INDUCED WITH LOW-FLUX OF ELECTRONS

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Abstract. The multistage process of silicon radiation defects (RD) modification (accompanied by non-monotonic change of mechanical properties) in conditions of irradiation with low-flux ($I = 10^5$ cm^{-2}s^{-1}) is discussed. A qualitative model of quasi-chemical reactions which product is a cluster V_2-O-C, responsible for the first maximum of softening, is offered.

1. INTRODUCTION

Frequently functional materials are maintained in conditions of the higher radiation phon. It is known [1-5], that physical properties of many materials (Si, GaAs, ZnS, fullerite C_{60}, permalloy-79, *etc*.) undergo abnormal changes under irradiation with low-flux. The nature of similar effects remains obscure. It dictates necessity of detailed research of the phenomena induced by irradiation with low-flux. From the listed materials, silicon is the most simple and studied in detail, (concerning radiation defects generation). Silicon becomes the important constructional material remaining the object number 1 in modern microelectronics. Micromachines, sensor controls, micro- and nanoelectromechanical systems (MEMS/NEMS) and other hybrid products of nanotechnologies are made on its basis [6]. Therefore, even the little changes of its mechanical properties induced by irradiation with low-flux become important, and their studying is actual. In this connection, the purpose of work consists in revealing mechanisms of radiation clusters generation reflected on mechanical properties of silicon.

2. METHODOLOGY

In experiments, dislocation-free single-crystals silicon samples were investigated. They were grown by the float-zone technique (Fz-Si) and doped with phosphorus (BIGE-600). The samples were wafers with linear dimensions of 1×4×7 mm. The sources on the basis of ^{90}Y – ^{90}Sr (with an average energy of emitting electrons of 0.20 MeV for ^{90}Sr and 0.93 MeV for ^{90}Y) with intensity $I=10^5$ cm^{-2}s^{-1} were used for sample irradiation. The measurements of Vickers microhardness H were carried out for the (111) plane using a PMT-3 microhardness tester. Further, the duration of the microhardness measurements was taken into account (was subtracted) when plotting the dose dependence. The indenter load was of 1 N. The loading time was of 10 s. The irradiation and microhardness tests were carried out in air at room temperature.

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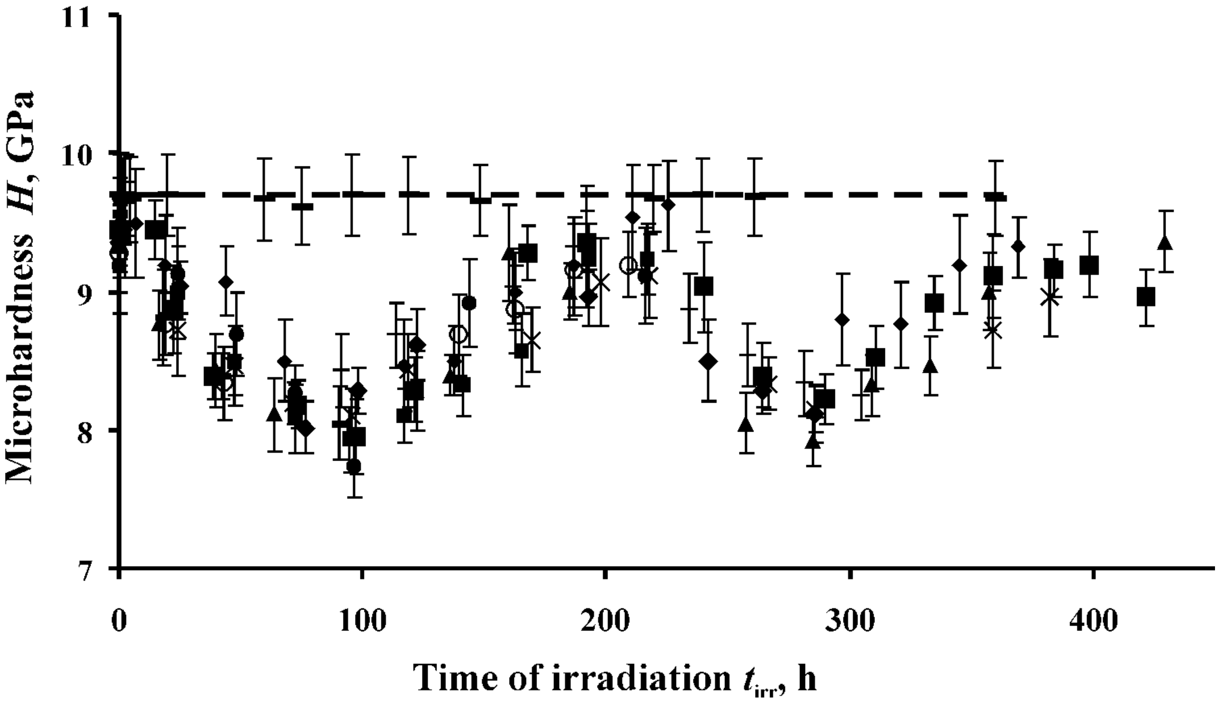

Fig. 1. Dependence of the Fz-Si microhardness on irradiation time by beta particles with intensity I = 10^5 $cm^{-2}s^{-1}$. The curve is plotted by points obtained with several twin samples (different symbols). The dashed line shows the time dependence of the microhardness for blank Fz-Si samples that were not irradiated, which is necessary for measuring the dose dependence.

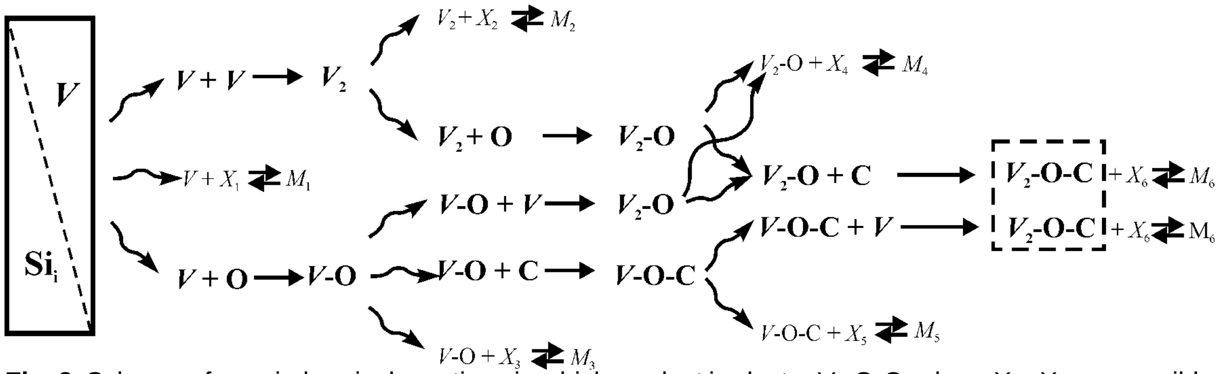

Fig. 2. Scheme of quasi-chemical reactions in which product is cluster V_2-O-C, where X_1 - X_6 are possible components (atoms of an impurity, RD) of alternative quasi-chemical reactions (not leading to generation of complex V_2-O-C finally); M_1 – M_6 are the products of corresponding reactions (for example, V + P $\rightarrow$ V-P; V_2-O + O $\rightarrow$ V_2-O_2, *etc*.).

3. RESULTS AND DISCUSSION

The exposition of samples in the field of beta-particles leads to non-monotonic change of microhardness (Fig. 1). The data obtained with several twin Fz-Si samples (different symbols in Fig. 1) demonstrate the reliable reproducibility of the effect. The microhardness value for a blank sample, not exposed to irradiation, remains constant (within the experimental error) during the time $t = t_{irr}$ necessary for obtaining the dose dependence (Fig. 1, dashed line). The forming of the imprint can be carried out due to: movement of dislocations, phase transitions under an indenter and mobility of non-equilibrium radiation point defects. Dislocations in silicon are motionless at room temperatures. Earlier [5], it was revealed that the phase transitions under an indenter did not affect irradiated softening. Hence, non-monotonic dependence of microhardness on irradiation time is connected with multistage transformation of point (own and radiation) defects. The results received by independent methods (isochronous annealing at different stages of irradiation, research of *H* change rate dependence on irradiation intensity, and also synchronous researches of *H* changes and concentration electrically active RD by deep-level transient spectroscopy method), have allowed us to identify defect clusters dominating at different stages of irradiation.

The first maximum of softening is connected with accumulation of clusters consisting of two vacancies, oxygen atom and carbon atom. The clusters, including interstitial and substitution atoms of carbon and/or interstitial atoms of carbon and oxygen are dominant at the stage of repeated softening. The most difficult cluster (V_2-O-C) is a product of consecutive quasi-chemical reactions. It is necessary to consider some possible channels of clusters V_2-O-C formation. The scheme of such reactions is presented in Fig. 2.

Dependence of V_2-O-C concentration on irradiation time can have a maximum because this cluster is a component of further reactions. The presence of the first maximum on dependence $H(t_{irr})$ in conditions of irradiation with low-flux is apparently explanation of it. Increase of stream density of particles, apparently, leads to domination of alternative reactions. Thus researched clusters (V_2-O-C) "are shielded" and "the effect of low doses" disappears.

4. CONCLUSIONS

In the work, radiation defects in silicon responsible for microhardness change at different stages of irradiation are identified. A qualitative model of quasi-chemical reactions which products are clusters V_2-O-C (responsible for the first maximum softening of silicon in conditions of irradiation with low-flux) is offered.

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