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PECULIARITIES OF STRUCTURE DAMAGE ACCUMULATION UNDER THE IMPLANTATION OF IONS OF DIFFERENT MASSES INTO ALPHA-GALLIUM OXIDE AT LOW DAMAGE LEVELS

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Abstract. In the paper, the distributions of structure damage created in alpha-phase of gallium oxide by keV fluorine, phosphorus and xenon ion irradiation, have been obtained at room temperature. A noticeable effect of the average individual collision cascade density on the stable damage production efficiency at the surface was established. In contrast to many other semiconductors, an intermediate damage peak appeared in the alpha-Ga_2O_3 between the surface and bulk maxima. This intermediate peak visible in the RBS/C spectra at low damage levels was discovered for the first time. Characteristic peculiarities of the discovered maximum were investigated.

Keywords: gallium oxide, ion implantation, radiation defect, collision cascades, Rutherford backscattering

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ОСОБЕННОСТИ НАКОПЛЕНИЯ СТРУКТУРНЫХ НАРУШЕНИЙ ПРИ ИМПЛАНТАЦИИ ИОНОВ РАЗНЫХ МАСС В АЛЬФА-ОКСИД ГАЛЛИЯ ПРИ МАЛЫХ УРОВНЯХ ПОВРЕЖДЕНИЯ

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Аннотация. В работе получены распределения структурных нарушений при облучении альфа-фазы оксида галлия ионами фтора, фосфора и ксенона с энергией, измеряемой килоэлектронвольтами (температура комнатная). Установлено заметное влияние усредненной плотности индивидуальных каскадов столкновений на эффективность введения стабильных нарушений для поверхностного пика радиационных дефектов. В отличие от случаев ионной имплантации во многие другие полупроводники, впервые обнаружено, что в альфа-Ga_2O_3 между поверхностным и объемным максимумами структурных нарушений возникает дополнительный пик. Этот промежуточный максимум ясно виден на спектрах резерфордовского обратного рассеяния при малых уровнях повреждения. Изучены характерные особенности впервые обнаруженного максимума.

Ключевые слова: оксид галлия, ионная имплантация, радиационный дефект, каскады столкновений, резерфордовское обратное рассеяние

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Introduction

There are diverse modern technologies and tools for studying the properties of various materials; a crucial method is ion irradiation, allowing to modify the structure of matter. Implantation of ions into semiconductors is always accompanied by stable structural damage. Analysis of ion-stimulated processes, in particular the occurrence of structural damage in materials is mainly required for two applied problems. Firstly, radiation damage is the main limitation to ion beam machining technologies for manufacturing electronic devices. Secondly, it is often necessary to determine the durability of electronic devices operating under high radiation loads, finding ways to improve it. Studies into these problems have long been underway, however, radiation defects in binary or more sophisticated materials have a complex nature and remain poorly understood.

Damage accumulation in the crystal structure under ion bombardment is often studied by Rutherford backscattering by MeV helium ions in combination mode (RBS/C). The method was used to establish that the depth distributions of the accumulated damages have a bimodal nature for many semiconductors irradiated by light ions at least [2–5]. A bulk defect peak (BDP) appears, typically located at the depth of the maximum elastic energy loss of stopping ions [3, 4], i.e., in the region where the majority of the primary point defects are generated. In addition, the crystal structure becomes disordered directly at the surface of the bombarded target. This surface defect peak (SDP) occurs due to diffusion of primary defects to the surface of the semiconductor and their subsequent coagulation on this surface (see, for example, [6]). In addition, sometimes another maximum is found in the depth distribution of defects, located between SDP and BDP; an example is the result obtained by irradiation of zinc oxide with heavy ions. Such a defect peak is commonly defined as intermediate (IDP) [7–9]. In the case of irradiation of zinc oxide with 500 keV xenon ions, IDP appears do to a highly Zn-rich layer [9].

One of the most promising semiconductor materials for high-power electronics and optoelectronics of a new generation is gallium oxide Ga_2O_3, offering such advantages as a wide band gap (4.5–5.3 eV for different phases), high breakdown voltage (about 8 MV/cm), etc. [10]. Some of the earliest data were obtained for the accumulation of structural damage in αGa_2O_3 [11, 12] and βGa_2O_3 [11, 13] for bombardment with accelerated atomic ions. The detected distribution of stable structural defects for both the stable βphase and the metastable αpolytype has a bimodal character. The ion dose required to achieve approximately the same level of disordering for αGa_2O_3 is about 10 times higher than for the stable βphase [11]. Further investigations established conditions for IDP to appear are observed under ion irradiation of alpha gallium oxide.

The goal of this study was to describe the detection of IDP in an αGa_2O_3semiconductor material under ion irradiation and to find out the conditions under which this peak appears.

Experimental procedure

We considered epitaxial layers of alpha gallium oxide (α-Ga_2O_3) with a corundum structure approximately 2 μm thick with the orientation (0001) grown on the *c*-plane of a sapphire substrate by hydride vapor-phase epitaxy (HVPE).

The samples were irradiated with fluorine, phosphorus and xenon ions at room temperature on a 500 kV HVEE implanter (Netherlands). The irradiation was carried out at an angle of 7° from the direction [0001] to minimize the channeling effects. The irradiation parameters were selected in such a way that the generation of primary defects by inhibited ions was approximately the same over the depth of the target in all cases. For this purpose, the ion energies and fluxes were chosen such that the depth distribution profiles of displaced atom concentrations were similar and differed only in the height of the peak under irradiation with different ions.

Displacement generation profiles were calculated in the binary collision approximation (BCA) [14]. Ion doses were expressed as displacements per atom (dpa), calculated at the maximum depth of the generation function. The dpa magnitude was calculated by the TRIM code (version SRIM-2013, http://www.srim.org) [14]. The ion flux during irradiation with various ions was maintained the same in dpa/s units. The doses were selected such that the damage levels near the SDP were not too high and close to each other so that we could conveniently compare the distribution profiles of structural defects during irradiation with different types of ions. In addition, irradiation with different ions (phosphorus) and with a higher energy (65 keV) was carried out at the same doses and fluxes (in dpa and dpa/s units) that were used earlier for more detailed comparative analysis of the detected effect.

The disordering degree of the crystal structure after irradiation was measured by RBS/C. A 0.7 MeV He^{++} beam probe in the direction [0001] was used for the measurement. The scattered particle detector was positioned at an angle of 103° relative to the direction of the incident beam. The obtained RBS/C spectra were processed using a standard algorithm to construct the distributions of relative depth disordering [15].

Experimental results and discussion

Fig. 1,*a* shows the distributions of structural defects along the depth of the α-Ga_2O_3 target obtained after implantation of ions with different masses. As already noted, the radiation doses were chosen in such a way that the resulting damage levels near the SDP were not too high and sufficiently close to each other. Clearly, the doses that meet these requirements are the lower the greater the ion mass. Indeed, a dose of 0.30 dpa is required to achieve a disordering of the order of 0.15 in SDP by irradiation with Xe ions, a dose of 0.44 dpa is required in the case of irradiation with P ions, while in the case of irradiation with F ions it is as high as 1.50 dpa. Recall that the the

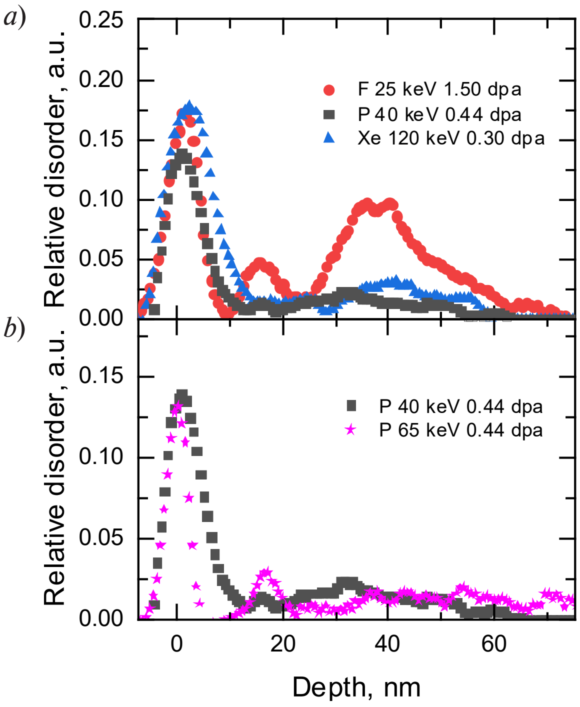

Fig. 1. Distributions of relative disordering concentration over the depth of the α-Ga$_2$O$_3$ target after irradiation with ions of different masses with different energies and doses (given in the caption):
fluorine, phosphorus and xenon ions (*a*); only phosphorus ions with two different energies and the same dose (*b*) Ion fluxes (10^{-3}dpa/s): 2.41 (for fluorine ions) and 0.08 (for other ions)

conditions for ion bombardment were chosen such that the generation rates of primary defects in the BCA [14] and the depth distributions of defects coincide for ions of different types.

It follows from these results that the level of damage to the α-Ga$_2$O$_3$ crystal structure can be greatly affected by another parameter that varies from ion to ion in such an experimental setting; this parameter is the average density of individual displacement cascades. Previous experimental studies found that irradiation with molecular ions is more efficient for producing the SDP; this was indicated by the results obtained for irradiation of gallium oxide with higher ion doses [12]. We earlier proposed to calculate the value of this parameter based on the binary collision approximation [16].

Fig. 2 shows the calculated density dependences of the cascades generated by ions along the depth of the alpha gallium oxide target. Evidently, the density of cascades generated by fluorine ions is less than that generated by phosphorus and xenon ions. Thus, an increase in the density of displacement cascades leads to an increase in the SDP production efficiency even in this case, at rather small ion doses and fluxes.

Notably, another pronounced peak appears between SDP and BDP on the curve shown in Fig. 1,*a* (distribution of defect concentration during bombardment with 25 keV F ions). This intermediate peak is located at a depth about 17 nm in the α-Ga$_2$O$_3$ target. In our opinion, a similar peak is present in the distribution obtained

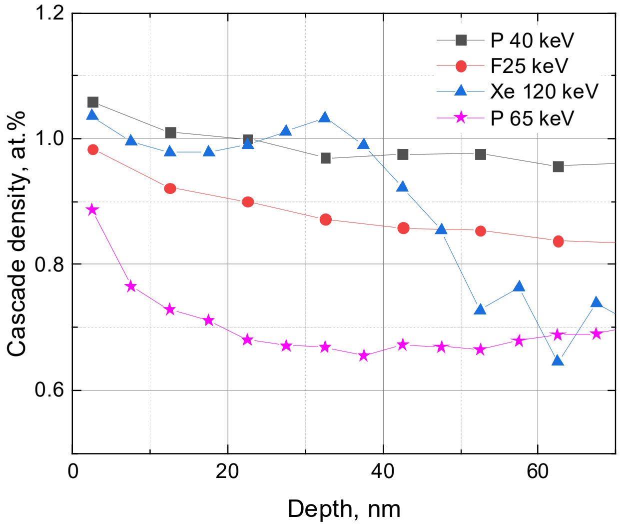

Fig. 2. Density distributions of individual displacement cascades over the depth of the α-Ga$_2$O$_3$ target after irradiation with ions of different masses with different energies (given in the caption).
The calculations were performed based on the binary collision approximation [14] by the technique proposed in [16]

by irradiation with 40 keV phosphorus ions. This peak is not detected in the case of bombardment of gallium alpha oxide with heavier xenon ions. We should note that the appearance of the IDP is a new phenomenon that we have not observed for implantation of ions to higher doses.

To further investigate this phenomenon, irradiation of phosphorus ions with higher energy (65 keV) and the same dose (0.44 dpa) was carried out. The resulting distribution of structural defects is shown in Fig. 1,*b*. Evidently, the width of the surface peak becomes slightly smaller with an increase in the energy of phosphorus ions. Furthermore, a rather pronounced intermediate peak is observed in gallium alpha oxide in this case, approximately at the same depth as the one previously observed for fluorine ions (see Fig. 1, *a* and *b*). Thus, the IDP is produced not only by irradiation with fluorine ions, but also with phosphorus ions. The IDP becomes more pronounced with an increase in the energy of phosphorus ions.

As noted above, the IDP was previously detected during implantation of ions into zinc oxide. However, the mechanism by which this peak is produced in this case (α-Ga_2O_3) is likely different than for ZnO. Indeed, the IDP in zinc oxide appears under irradiation with heavy ions and is noticeable in a wide range of doses. The magnitude of the IDP in zinc oxide did not depend on the type of the ion. In the case of α-Ga_2O_3 oxide, we observe the IDP only under irradiation with light ions and at low doses. The magnitude of IDP in gallium oxide under the same conditions of ion bombardment is different for phosphorus and fluorine ions, increasing with increasing energy for phosphorus ions.

Notable differences are observed in the behavior of density distribution curves of individual displacement cascades for all experimental cases (see Fig. 2). It can be seen that the highest value of the parameter is detected for stopping of heavy xenon ions near the surface. Phosphorus ions with an energy of 40 keV produce cascades with a lower density, and the densities are even lower for fluorine ions. The density of the displacement cascades decreases with an increase in the energy of phosphorus ions from 40 to 65 keV. Thus, the IDP in the α-Ga_2O_3 target appears at a low cascade density rather than at a high one as is the case with ZnO.

The reasons why the IDP appears in the spectrum are not yet clear. Further in-depth studies covering all aspects of the phenomenon are necessary for understanding the behavior and mechanism of IDP production in α-Ga_2O_3.

Conclusion

We experimentally obtained the depth distributions of structural damage under implantation of small doses of fluorine, phosphorus and xenon ions into the α-Ga_2O_3 semiconductor material in the keV energy range. The average density of individual displacement cascades was calculated; the calculation results, along with experimental data, indicate an increase in the efficiency of radiation damage to gallium oxide with an increase in such density.

We found that ion bombardment of a gallium oxide target (unlike other target materials) causes an additional structural defect peak to appear for the ions with the average masses and selected technological doses; this peak is located between the surface and bulk peaks on the corresponding distribution curves.

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