




## Ultrahigh stability of oxygen sublattice in $\beta$ -Ga<sub>2</sub>O<sub>3</sub>

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Recently reported remarkably high radiation tolerance of  $\gamma/\beta$ -Ga<sub>2</sub>O<sub>3</sub> double-polymorphic structure brings this ultrawide-band-gap semiconductor to the frontiers of power electronics applications that are able to operate in challenging environments. Understanding the mechanism of radiation tolerance is crucial for further material modification and tailoring of the desired properties. In this study, we employ machine-learning-enhanced atomistic simulations to assess the stability of both the gallium (Ga) and oxygen (O) sublattices under various levels of damage. Our study uncovers the remarkable resilience and stability of the O-sublattice, attributing this property to the strong tendency of recovery of the O defects, especially within the more strongly disordered regions. Interestingly, we observe the opposite behavior of the Ga defects that display enhanced stability in the same regions of increased disorder. Moreover, we observe that highly defective  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> is able to transform into  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> upon annealing due to preserved lattice organization of the O sublattice. This result clearly manifests that the ultrahigh stability of the O sublattice provides the backbone for the exceptional radiation tolerance of the  $\gamma/\beta$  double-polymorphic structure. These computational insights closely align with experimental observations, opening avenues for further exploration of polymorphism in Ga<sub>2</sub>O<sub>3</sub> and potentially in analogous polymorphic families spanning a broad range of diverse materials of complex polymorphic nature.

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### I. INTRODUCTION

Current Si-based semiconductor technology is facing the fundamental limits of narrow band gap and low breakdown field [1]. With the key merits of high breakdown electric field strength, ultrawide band gap, and high ultraviolet optical transparency, gallium oxide (Ga<sub>2</sub>O<sub>3</sub>) has attracted significant attention as a promising candidate for next-generation semiconductors [2–7]. Furthermore, the exceptional radiation tolerance of Ga<sub>2</sub>O<sub>3</sub> offers promising applications in demanding environments, including space exploration, nuclear power generation, and medical imaging [8–11]. Investigating radiation damage in Ga<sub>2</sub>O<sub>3</sub> is pivotal for achieving a comprehensive understanding of defect theory and its correlated physical properties; however, it remains a significant challenge.

Recently, experimental studies using ion implantation have revealed that  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> maintains its crystallinity up to extremely high fluences of ion irradiation [12,13], which are much higher than the amorphization thresholds observed in other semiconductor materials, e.g., Si [14], SiC [15], and GaN [16]. Anber *et al.* and Azarov *et al.* illustrated that the amorphization of  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> is notably suppressed by the formation of the  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> phase [13,17]. Huang *et al.* [18,19] provided quantitative analysis of scanning transmission electron microscopy (STEM) images, displaying the

gradual  $\beta$ -to- $\gamma$  phase transformation progress. In most cases, the polymorphic transitions in Ga<sub>2</sub>O<sub>3</sub> crystals arise from lattice adaptation to the minimum-free-energy state at the given temperature and pressure [20–23]. Ion-beam-assisted atom displacement is a novel approach to reaching metastable configurations, yet it has received limited attention in theoretical investigations. In order to understand the radiation effects of this emerging semiconductor material at the atomic scale, He *et al.* [24] and Tuttle *et al.* [25] have conducted calculations to determine the threshold displacement energy, which is crucial for estimating the extent of radiation damage [26,27]. However, the theoretical study of the ultrafast defect dynamics and crystalline phase transformation instead of amorphization during ion implantation is still insufficiently studied.

Here, we utilize machine-learning-enhanced atomistic simulations and reveal that the crystallinity of  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> originates from the resilient lattice structure of the O sublattice. By integrating classical molecular dynamics (MD) simulations with machine-learning Gaussian approximation potentials (MLtabGAPs) [28], we systematically explore how accumulated defects in distinct Ga and O sublattices influence the structure of  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> and examine the recombination behavior of a single interstitial vacancy (Frenkel pair) at various separation distances. Furthermore, we apply collision cascade simulations to explore the dynamic evolution of defects under irradiation. These findings collectively illustrate the ultrahigh stability of the O sublattice and the changeable Ga sublattice. This not only precisely corroborates experimental

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observations but also uncovers the underlying mechanism behind the remarkable radiation tolerance exhibited by  $\text{Ga}_2\text{O}_3$  materials. Moreover, this foundational research paves the way for exploring various polymorphism families and deepens our understanding of defective oxide materials.

## II. METHODOLOGY

In this study, we elucidate the recovery mechanisms of the O sublattice by performing several different types of atomistic simulations. First, we use classical MD simulations to simulate damage buildup in  $\beta\text{-Ga}_2\text{O}_3$  via Frenkel pair accumulation (FPA) runs. We analyze the Frenkel pair (FP) recombination paths by running simulations with isolated FP defects of different types. We also run single-cascade MD simulations to analyze the dynamic effects on damage buildup. All MD simulations are conducted using the LAMMPS package [29] with the recently developed ML interatomic potential (tabGAP) for  $\text{Ga}_2\text{O}_3$  systems [28]. We also perform defective structure relaxation calculations using a density functional theory (DFT) structure optimization enabled by the VASP package [30] to verify the results obtained with the ML-MD method. For visualization of the atomic structures, OVITO [31] is utilized. In the following, we describe the technical details of each applied type of simulation separately.

### A. Frenkel pair accumulation simulations

In the FPA simulations, we model the ion-induced accumulation of damage by subsequently inserting randomly distributed FPs into initially perfect  $\text{Ga}_2\text{O}_3$  cells. To emphasize the atom-type-specific effects on damage accumulation in  $\beta\text{-Ga}_2\text{O}_3$ , we generate three 1280-atom simulation cells, where we insert the FPs of three different types: only Ga, only O, and mixed O/Ga FPs. Each FP was subsequently created by displacing a randomly selected atom of the given type (in the O/Ga FPA simulations the  $\text{Ga}_2\text{O}_3$  stoichiometry was maintained) in a randomly selected direction by a vector with the norm randomly selected within the range 5.8–6.2 Å. The insertion of each FP was followed by a relaxation run to reach the local energy minimum; after that, the system was simulated for 5 ps at 300 K and 0 bars in the isothermal-isobaric ( $NpT$ ) ensemble. We also performed longer annealing simulations in the  $NpT$  ensemble, maintaining zero pressure but raising the temperature from 300 to 1500 K with the rate of 6 K/ps after a given number of FPs were accumulated in the cell. Each annealing run was performed for 1 ns, after which the temperature was gradually decreased to 300 K with the same rate of 6 K/ps.

### B. *Ab initio* simulations

To verify the evolution of damage buildup, which we obtained in our ML-MD FPA simulations, we conducted similar simulations using DFT methods. These calculations were performed using the Vienna *Ab initio* Simulation Package (VASP) [30], employing the projector augmented wave (PAW) method [32] with 13 ( $3d^{10}4s^24p^1$ ) and 6 ( $2s^22p^4$ ) valence electrons for Ga and O, respectively. The Perdew-Burke-Ernzerhof (PBE) version [33] of the generalized gradient approximation (GGA) was used as the exchange-correlation functional.

TABLE I. Simulation parameters. The variable  $E_{\text{PKA}}$  represents the initial kinetic energy given to the PKA,  $n_{\text{atoms}}$  is the number of atoms in the simulation cell,  $n_{\text{PKA:O}}$  is the number of simulations in which the PKA is O, and  $n_{\text{PKA:Ga}}$  is the number of simulations in which the PKA is Ga.

$E_{\text{PKA}}$ (eV)	$n_{\text{atoms}}$	$n_{\text{PKA:O}}$	$n_{\text{PKA:Ga}}$
500	81 920	69	61
750	81 920	65	64
1000	81 920	61	63
1500	160 000	62	49
2000	276 480	54	61

In this calculation, FPs were generated cumulatively in a 320-atom  $\beta\text{-Ga}_2\text{O}_3$  cell as the FPA simulation. During the accumulation progress, the cell was relaxed after every five iterative implantations of FPs. Meanwhile, the cells undergo a structure relaxation with ML potential to attain the local energy minimum, serving as a reference for comparison with the GGA-DFT relaxation. In the GGA-DFT calculations, the electronic states were expanded in plane-wave basis sets with an energy cutoff of 700 eV. Given the large supercell, the Brillouin zone was sampled with only the  $\Gamma$  point. Gaussian smearing with a  $\sigma$  width of 0.03 eV was used to describe the partial occupancies of the electronic states. The values  $10^{-6}$  eV and  $10^{-2}$  eV/Å were chosen as the energy and force convergence criteria for the optimization of the electronic and ionic structures, respectively. These simulations were conducted separately for three different types of FPs, inserting 100 FPs in total in each cell.

### C. Simulations of Frenkel pair recombination

In FP recombination simulations of isolated defects, a stable interstitial atom was initially inserted in a 1280-atom  $\beta\text{-Ga}_2\text{O}_3$  cell. Subsequently, a vacancy was created by removing an atom of the corresponding type from a neighboring site around the interstitial within the specific coordination shell to control the recombination radius of the created FP defect. The system was thermally equilibrated for 5 ps under  $NpT$  conditions at 300 K and 0 bars. The statistical averages were obtained over 50 independent runs for Ga and O FPs, separately.

### D. Simulations for single cascades

Single cascade simulations were carried out by giving the recoil energy to the atom randomly selected in the middle of the simulation cell as a primary knock-on atom (PKA). The direction of the initial momentum was also randomly selected in the three-dimensional space. The total number of atoms in each simulation cell was selected to match the recoil energy, so that the initiated cascade did not interact with the thermally controlled border regions. Table I provides the recoil energy values and corresponding numbers of atoms in the simulation cells.

Periodic boundary conditions were applied in all directions, with the Nosé-Hoover thermostat [34] controlling the temperature along the borders of the simulation cell to mimic

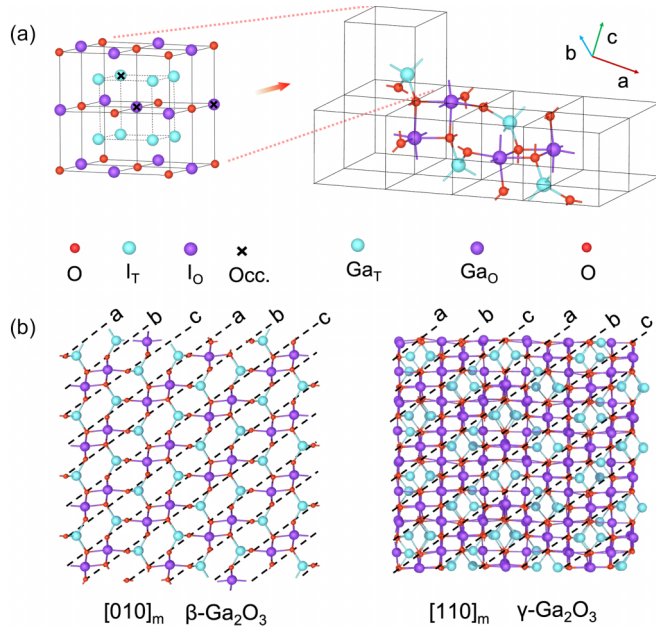


FIG. 1. (a) Schematic representation of O fcc stacking in the  $\beta$ - $\text{Ga}_2\text{O}_3$  unit cell; the right part is the fcc unit cell with tetrahedral ( $I_T$ ) and octahedral ( $I_O$ ) interstitials, and the left part is the  $\beta$ - $\text{Ga}_2\text{O}_3$  unit cell with O fcc frame. Tetrahedral interstitials and  $\text{Ga}_T$  are colored purple, octahedral interstitials and  $\text{Ga}_O$  are blue, O ions are red, and the black cross marks the occupied Ga sites. (b) The snapshots of the pristine  $\beta$ - (left) and  $\gamma$ - $\text{Ga}_2\text{O}_3$  (right) lattice. The dashed line indicates the perfect abc-abc fcc stacking of the O sublattices.

the heat dissipation of bulk materials. To ensure simulation efficiency and system stability, an adaptive time step was employed. Electronic stopping power as a friction term was applied to the atoms with kinetic energies above 10 eV [35]. The simulation time of the single cascades was 50 ps. To guarantee sufficient statistics, parallel simulations were conducted for each recoil energy with varying PKA. The detailed simulation amounts are presented in Table I. The point defects formed in collision cascades were identified using the Wigner-Seitz analysis method.

### III. RESULTS

#### A. Stability of cation and anion sublattices in $\beta$ - $\text{Ga}_2\text{O}_3$

Figure 1 demonstrates the face-centered-cubic (fcc) unit cell of the O sublattice of  $\beta$ - $\text{Ga}_2\text{O}_3$ , which is common for both  $\beta$  and  $\gamma$  phases of  $\text{Ga}_2\text{O}_3$ . The difference between these two phases is in the location of Ga cations that occupy different tetrahedral ( $\text{Ga}_T$ ) and octahedral ( $\text{Ga}_O$ ) sites [36,37]. It has been previously observed that  $\beta$ - $\text{Ga}_2\text{O}_3$  transforms into the  $\gamma$  phase under ion implantation [12,18,19,38], indicating that the integrity of the O sublattice is maintained, while Ga atoms intricately rearrange with the accumulated damage dose. In the monoclinic  $\beta$  phase, the molar ratio of tetrahedral ( $\text{Ga}_T$ ) and octahedral ( $\text{Ga}_O$ ) cations and O anions is 1 : 1 : 3, while within the fcc unit cell [see Fig. 1(a)], the ratio of the tetrahedral ( $I_T$ ) and octahedral ( $I_O$ ) sites and O lattice sites is 8 : 4 : 4. In Fig. 1(a), we indicate all tetrahedral and octahedral sites potentially available for Ga cations within the O fcc

lattice unit cell: the purple balls show the potential  $\text{Ga}_O$  sites and the cyan balls the potential  $\text{Ga}_T$  sites. The O sublattice is shown by the small red balls. For clarity, we cross the sites that are occupied by Ga cations in the  $\beta$  phase [compare with the conventional image of the  $\beta$ - $\text{Ga}_2\text{O}_3$  monoclinic unit cell shown in Fig. 1(a) to the right]. As one can see, the majority of the tetrahedral and octahedral sites are unoccupied. On the other hand, the cubic  $\gamma$  phase exhibits the defective spinel structure with partially occupied  $\text{Ga}_T$  and  $\text{Ga}_O$  in random order, which is challenging to show in a unit cell [39,40].

To enable the visual comparison between the two lattices of pristine  $\beta$  and  $\gamma$  phases, in Fig. 1(b) we analyze the composition of the Ga layers between the abc-abc stacked close-packed planes in the O fcc sublattice, which are shown by the dashed lines. In the defective spinel structure of the  $\gamma$  phase, one Ga layer is primarily composed of  $\text{Ga}_O$ , while the other layer contains both  $\text{Ga}_T$  and  $\text{Ga}_O$ , contrasting with the perfectly ordered  $\beta$  phase, where  $\text{Ga}_T$  and  $\text{Ga}_O$  appear alternatively in the different Ga layers.

In our study, we aim to investigate in detail whether the phase transformation in  $\beta$ - $\text{Ga}_2\text{O}_3$  during ion irradiation depends on the type of the defects (cation or anion). We conducted the type-specific FPA simulations to systematically analyze the damage buildup in both sublattices separately as well as the damage buildup in the entire structure without separation into sublattices. Figure 2 illustrates the evolution of the crystal structure of  $\beta$ - $\text{Ga}_2\text{O}_3$  with the accumulation of the various types of FPs. Five different colors are used to show crystallographically different types of two Ga cation (Ga-I, Ga-II) and the three O anion (O-I, O-II, O-III) sites in the pristine lattice to facilitate the analysis of atom displacements.

In the O FPA simulations [top row in Fig. 2(a)], we observe that the  $\beta$ - $\text{Ga}_2\text{O}_3$  persistently retains its initial phase structure with only a few remaining defects, although the locations of some O atoms have changed [compare the colors of O atoms in the outlined regions in the snapshots showing the initial and damaged structures in Fig. 2(a)]. The outlined vertical region shows the same column of O anions in all three snapshots. Initially, in the pristine cell, all sites in this column are consistently colored orange, showing O-II anions. With the increase of the accumulation of O FPs, some of these sites are replaced by yellow (O-I) and red (O-III) anions. In the Ga FPA simulations [bottom row in Fig. 2(a)], the crystal structure remains highly ordered; however, with the increase of the number of FPs, it gradually resembles more the  $\gamma$  phase with denser occupied Ga sites in the [010] direction covering the open channels of the  $\beta$ -phase lattice in the same direction.

The O/Ga FPA simulations [the middle row of Fig. 2(a)] result in a complete disorder of the  $\beta$  phase, although the simulations up to the low damage dose (about 100 FPs) showed similar structural evolution to that in the Ga FPA simulations. However, further accumulation of O/Ga FPs (see 500 and 1200 FPs) leads to a rapid crystallinity deterioration, transforming the structure into an amorphous phase. Surprisingly, we see that within the ordered but defective regions that exist in the cells with Ga FPs and O/Ga FPs, the fcc stacking of the O sublattice is mostly maintained. Hence, we plot in Fig. 2(b) the O-O partial radial distribution functions (PRDFs) for the O sublattices in the cells, highlighting three



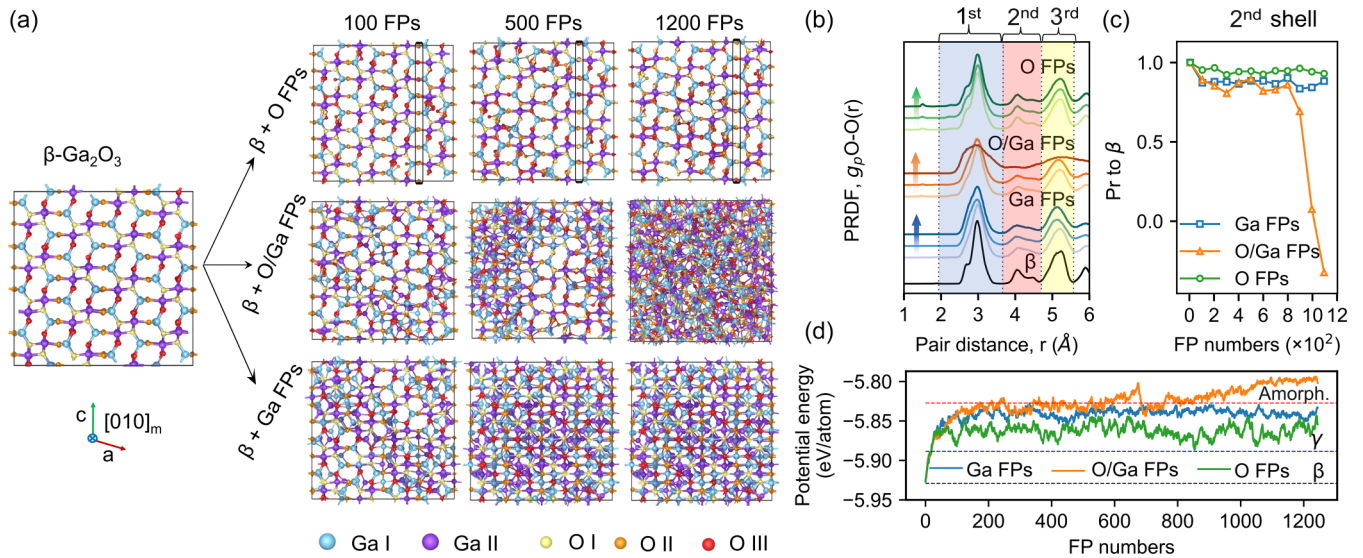


FIG. 2. Accumulated different types of FPs in  $\beta$ - $\text{Ga}_2\text{O}_3$ . (a) The snapshots of the pristine  $\beta$ - $\text{Ga}_2\text{O}_3$  lattices after introducing different types of FP. The five distinct crystallographic sites Ga-I, Ga-II, O-I, O-II, and O-III in the pristine lattices are colored separately in cyan, purple, yellow, orange, and red, respectively. (b) Analysis of the partial radial distribution functions (PRDFs) of O sublattices with different amounts and types of additional FPs in  $\beta$ - $\text{Ga}_2\text{O}_3$  lattices (blue, Ga FPs; orange, O/Ga FPs; and green, O FPs; the color intensity increases systematically with the quantity of Frenkel pairs, specifically designated as 100, 500, and 1200 FPs, respectively.). (c) The Pearson correlation coefficient,  $\text{Pr}$ , calculated within the second shell for the O-O PRDFs of the increasing damaged O sublattices concerning the pristine  $\beta$ -O PRDFs as a function of the FP number. (d) Potential energy of the cell as a function of FP number. The dashed lines correspond to the potential energy of  $\beta$ ,  $\gamma$ , and amorphous  $\text{Ga}_2\text{O}_3$  at 300 K, respectively.

coordination shells: the first (2.0–3.6 Å), the second (3.6–4.6 Å), and the third shell (4.6–5.6 Å). In the systems where the damage accumulation proceeded separately either within the anion or the cation sublattices, we observe that the peaks in the O-O PRDF persist, indicating the anion sublattice structure resists the damage, while in the cells with the accumulation of O/Ga FPs, the main characteristic peaks of the fcc structure disappeared, indicating amorphization of the lattice.

The similarity of the O-O PRDFs of the cells with the increased damage to the O-O PRDF of the pristine  $\beta$ - $\text{Ga}_2\text{O}_3$  is analyzed in Fig. 2(c), where we plot the Pearson correlation coefficient ( $\text{Pr}$ ) for the corresponding curves in the second shell. The O-O PRDFs exhibit a high degree of positive correlation with the  $\beta$ -O structure in the case of pure O FPs and Ga FPs, demonstrating a significant degree of structural similarity. As the accumulation of the mixed FPs, the  $\text{Pr}$  value initially fluctuates around a rather high value of 0.8, but then it drops abruptly, signifying the robustness of the O sublattice that is able to maintain its structure up to a high threshold damage level (800 O/Ga FPs in this case), whereas surpassing this level results in the direct collapse of the structure. However, the defect accumulation in experiments is not likely to occur in stoichiometric proportion, as it has been proposed in Ref. [12]. This is why the threshold which we obtained in the present study by accumulating the mixed FPs proportionally to the stoichiometry of  $\text{Ga}_2\text{O}_3$  must be understood as the underestimation of the damage level leading to the loss of crystallinity in this material.

We also analyzed the Ga-Ga PRDFs (see the Supplemental Material (SM), Appendix A, Fig. S1 [41]) to demonstrate the effect of the damage buildup in specific sublattices on the

structural integrity of the Ga sublattice. In this analysis, we observe that only the formation of Ga and O/Ga FPs leads to the appearance of the  $\gamma$ -Ga-like phase, whereas displacing only O atoms does not trigger this transformation.

In Fig. 2(d), we also follow the evolution of the potential energy in all three simulation cells after the insertion of every FP and subsequent relaxation at 300 K. Despite fluctuations of the energy values, the comparison of the three curves clearly illustrates the different effect that the accumulation of different types of FPs causes in the corresponding cells. For instance, we see that the potential energy rises the fastest in the cell with the accumulation of the O/Ga FPs, with the highest value exceeding the potential energy of the relaxed amorphous phase. We also note a sharp drop of this value at about 700 FPs, which exceeds the fluctuation uncertainty bar in the rest of the potential energy curve. The drop indicates the phase transformation from a highly damaged but still crystalline structure of  $\beta$ - $\text{Ga}_2\text{O}_3$  to the amorphous state; hence we can conclude that in these simulations we reached the damage tolerance threshold for the  $\beta$ - $\text{Ga}_2\text{O}_3$  structure before collapsing into the amorphous state.

Insertion of Ga FPs brings the potential energy in the simulation cell very close to the amorphous level, but not exceeding it at any point. We also note that the level of the potential energy in this cell is consistently above the pristine  $\gamma$ - $\text{Ga}_2\text{O}_3$  level, which is the footprint of unstable defects in the gradually damaging lattice. Since we do not observe any abrupt changes in the value of the potential energy, which would indicate a phase transition, we conclude that the accumulation of the FPs themselves does not yet transform  $\beta$ - $\text{Ga}_2\text{O}_3$  into a stable  $\gamma$ - $\text{Ga}_2\text{O}_3$  structure and

additional annealing of created defects is needed to complete this transformation. Moreover, we notice that the potential energy reaches the saturation level after less than 200 Ga FPs and continues to fluctuate around this value up to the very high doses of 1200 FPs, which we reached in our simulations. This behavior can be interpreted as randomization of the Ga sublattice; however, after it has been randomized the following displacements do not introduce additional disturbance, which would lead to the increase of the potential energy in the cell.

The insertion of O FPs introduced the smallest disturbance in the simulation cell [see the lowest green curve in Fig. 2(d)]. The inevitable accumulation of the defects in this cell brings the potential energy to higher values than the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> and  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> phases [the corresponding grey and blue dashed lines in Fig. 2(d)]. However, we see much stronger fluctuations in this curve, which indicates stronger relaxation effects in this cell even during the short relaxation runs after insertion of a subsequent O FP. Again, no indication of phase transformation is found in this curve either, while overall the potential energy fluctuates the strongest out of the three curves with barely noticeable increasing tendency. Even at the highest number of FPs (1200 at the end of the simulation) the potential energy in the cell is not remarkably higher than that after the first 200 O FPs. The saturation trends observed in both curves for Ga and O FPs separately indicate that the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> lattice is capable to accommodate the damage in separate sublattices more easily compared to the damage accumulation via displacement of both types of ions at the same time.

Our results showcase the resilience and stability of the O sublattice in  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> even at very high damage levels. The response of the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> to FP type-specific damage accumulation demonstrates that the ordered O sublattice is the only possible structural backbone that is able to preserve the crystallinity of the material exposed to extreme irradiation conditions. Our results also indicate that the crystal structure collapses into an amorphous state only after the damage in the O sublattice reaches a critical damage threshold. Without the assistance of displaced Ga atoms, the threshold value is very high ( $\gg 1$  dpa) because of the strong recombination trend in the O sublattice. However, with the assistance of Ga FPs, this threshold is lowered by more than half ( $\sim 0.5$  dpa in our simulations). We note here that the damage level in atomistic simulations corresponds to the experimental damage level measured at higher dpa because of the short relaxation times between the FP insertions.

Moreover, in FPA simulations, FPs are introduced randomly within the lattice, which may lead to formation of shallow metastable defects, effectively enhancing the defective state of the lattice not expected as a result of collision cascades.

To verify the FPA results, we utilized DFT to relax the ML-MD  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> atomic structures damaged in the same FPA manner, but of a smaller size manageable within the DFT method. Appendix B, Fig. S2(a), of the SM [41] illustrates the very small (below 1 Å) displacements of the atoms in the lattice after GGA-DFT relaxation of the system obtained in the ML-MD simulations, demonstrating the reliability of the applied ML potential for description of defective structures

of Ga<sub>2</sub>O<sub>3</sub>. Meanwhile, we compared the potential energy per atom with GGA-DFT relaxation and structure relaxation with ML potential in Fig. S2(b) of the SM [41]. These results show that the ML relaxation agrees closely with the GGA-DFT calculations, further verifying the accuracy and reliability of the ML potential for the FPA simulations.

As mentioned above, the FPA simulations produce highly defective structures, where the transition to the  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> phase is not easy to detect. In experiments, the defects generated in cascades may annihilate or relax into energetically more favorable configurations during the long time between subsequent cascade events. To take into account these relaxation processes, we further applied annealing runs at elevated temperature, to promote relaxation dynamics within the MD time span, for 1 ns in the cells with the high damage level (several hundred Ga FPs). In agreement with our previous results [42], we also observe that not all defective structures transformed into the  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub>, but up to a certain threshold damage level, the structure collapsed back into the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub>. Only surpassing the threshold level prompted the lattice to undergo a transition into the  $\gamma$  phase, as shown in Fig. 3. We see that the energy curve after the annealing of the 1280-atom cell with 600 Ga FPs approached the level of the potential energy of the  $\gamma$  phase [the dark blue curve in Fig. 3(a)], indicating the phase transformation, while the annealing of the cell with 500 Ga FPs resulted in the system energy being very close to that of the  $\beta$  phase [the light blue curve in Fig. 3(a)]. Moreover, we draw attention to a steplike feature at  $\sim 1$  ns in the light blue curve, which indicates a transition from the defective to the perfect  $\beta$  phase, which subsequently only cooled down to the level of the perfect  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> at 300 K. The potential energies of the  $\gamma$  and  $\beta$  phases are shown by blue and black dashed lines, respectively. Hence, our theoretical findings reveal that the displaced Ga atoms tend to occupy metastable  $\gamma$ -Ga sites, prompting the lattice to transit into this phase after surpassing the threshold damage level. However, if the large number of Ga atoms still occupy the stable sites of the  $\beta$  phase, the lattice does not undergo the transition to a new phase, but inevitably returns back to the original one upon annealing.

In Fig. 3(b), we show the bond angle distribution for the cell with 600 Ga FPs before and after annealing. For comparison, the same distribution for the pristine  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> is shown in red. We see that after the annealing (green curve) the distribution becomes much closer to that of the  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> structure with the stronger pronounced peak around 120°.

The snapshots in Fig. 3(c) illustrate the lattice structures of the cells with 500 and 600 Ga FPs before (top row) and after (bottom row) the annealing. Here we also see that a clear spinel structure [43,44] appears after the annealing of the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> with higher number of Ga FPs; we see the alternating cation layers of only Ga<sub>O</sub> sites and of a mixture of Ga<sub>O</sub> and Ga<sub>T</sub> sites. It is evident that in the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> with fewer Ga FPs (500) the occupation of metastable  $\gamma$ -Ga sites was insufficient and, hence, the structure collapsed back into the initial  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> lattice. The finding confirms that the  $\beta$ - to  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> phase transformation requires sufficiently high density of displaced Ga atoms, which occasionally occupy metastable  $\gamma$ -Ga sites. When the occupancy of these sites reaches a threshold value the full recovery back to the  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> phase requires

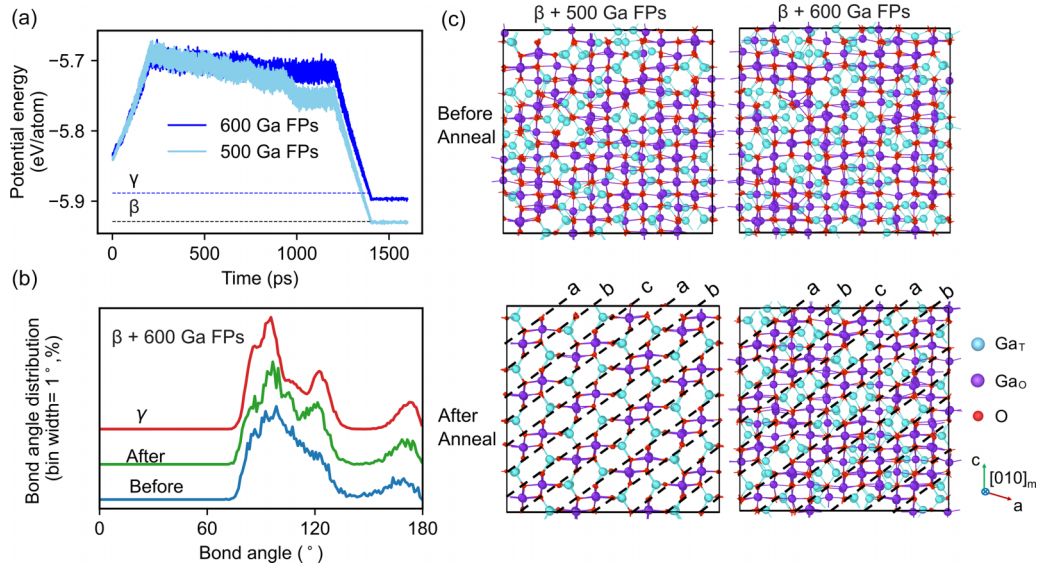


FIG. 3. Analysis of the cells with 500 and 600 Ga FPs in 1500 K annealing. (a) Potential energy of the cell during the annealing; the light blue line is for cells with 500 Ga FPs, the dark blue line is for cells with 600 Ga FPs, and the dashed lines correspond to the potential energy of  $\beta$ - and  $\gamma$ - $\text{Ga}_2\text{O}_3$ , respectively. (b) The bond angle distribution of cells with 600 Ga FPs before (blue line) and after (green line) annealing; the red line is for the pristine  $\gamma$ - $\text{Ga}_2\text{O}_3$ . (c) Snapshots of the cells with 500 and 600 Ga FPs before and after annealing; the dashed line indicates the perfect abc-abc fcc stacking of the O sublattices; tetrahedral interstitials and  $\text{Ga}_T$  are colored purple; octahedral interstitials and  $\text{Ga}_O$  are blue; O ions are red.

too many atomic transitions, which increases dramatically the kinetic path. Instead, the damaged structure transforms into a metastable, but still energetically favorable,  $\gamma$ - $\text{Ga}_2\text{O}_3$  structure during the simulation annealing run (experimentally, the process corresponding to postirradiation relaxation of the lattice). Although some relaxation of radiation-induced defects takes place between the cascades during high-fluence ion irradiation, without thermal assistance the residual defects survive until the next cascade, slowly accumulating until the threshold value for a phase transformation is reached.

### B. Recombination of Frenkel pairs

As described in the previous section, we observed in the FPA simulations that it is nearly impossible to accumulate only O FPs in the  $\beta$ - $\text{Ga}_2\text{O}_3$  lattice. This remarkable feature is counterintuitive, bearing in mind the difference in atomic masses of the cation and anion atoms in  $\text{Ga}_2\text{O}_3$ . To investigate the mechanism of such ultrahigh stability of the O sublattice, we inserted a single  $\text{O}_i$  or  $\text{Ga}_i$  interstitial into the simulation cell and tested the recovery of the created defect back to a perfect lattice site when a vacancy of the corresponding type appeared in vicinity of the created interstitial. We tested different distances from the interstitial to a vacancy placed in random locations around the former but within specific coordination shells.

Figure 4(a) shows statistical averages of the recovery percentage of both interstitials with a vacancy of the corresponding type placed in the first, second, and third coordination shells away from the interstitial. The averaging is done over the relaxation runs of the scenarios where the vacancy changes its position, but within the same coordination shell. The error bars show the standard error of the mean. The comparison of the recovery fractions for both  $\text{Ga}_i$  and

$\text{O}_i$  demonstrates a strong recombination tendency of  $\text{O}_i$  with vacancies in the first and second coordination shells with the recovery fractions of approximately 80% and 30%, respectively.  $\text{Ga}_i$ , on the other hand, recombines with vacancies less efficiently. The recovery fraction of  $\text{Ga}_i$  with a vacancy in the first coordination shell is down to  $\sim 30\%$ , while we found only very few recombinations of  $\text{Ga}_i$  with a vacancy in the second shell. Exemplary recombination paths for  $\text{O}_i$  and  $\text{Ga}_i$  are shown in Fig. 4(b). It is also noteworthy that  $\text{O}_i$  is an unstable defect and is eager to give a “push” to the O atoms in its vicinity, prompting them to occupy the vacant site, while the  $\text{O}_i$  defect itself recombines with the vacancy newly

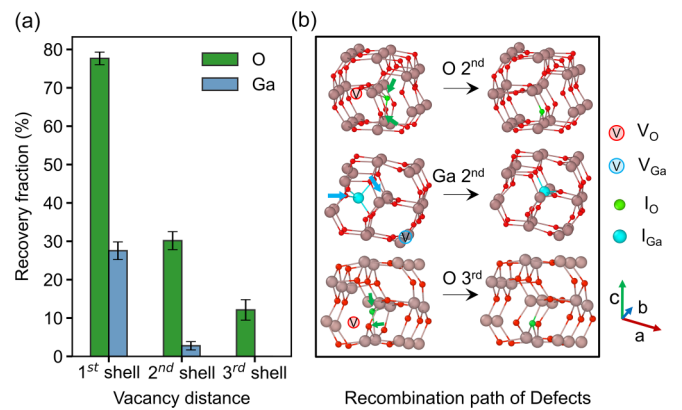


FIG. 4. Frenkel pair recombination. (a) Recovery fraction of interstitials ( $\text{Ga}$  in blue,  $\text{O}$  in green) to vacancy sites within different coordination shells. (b) Three representative recombination paths of Frenkel pairs where interstitials recombine with vacancy sites in the second (interstitial O and Ga ions) and third coordination shells (interstitial O ions).



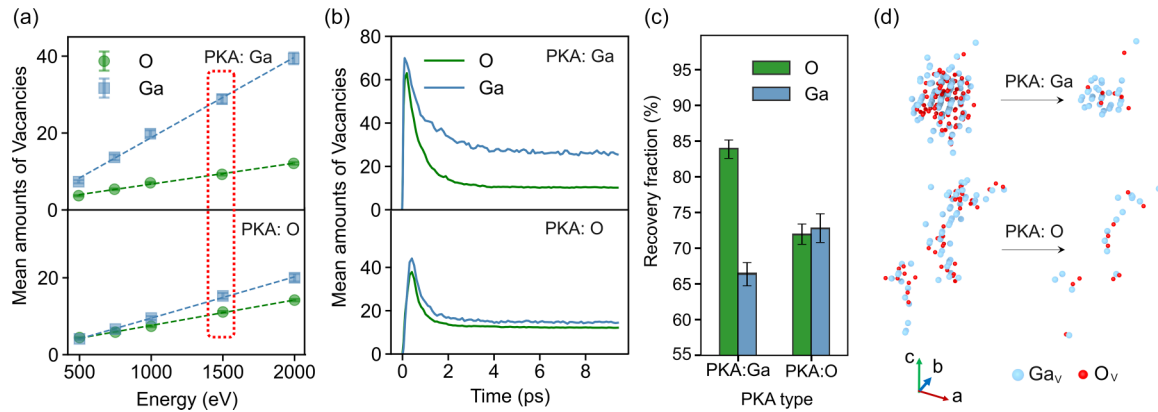


FIG. 5. Single-cascade simulations of  $\beta$ - $\text{Ga}_2\text{O}_3$ . (a) Mean number of Ga and O vacancies as a function of PKA energy in single-cascade MD simulations. The upper panel represents Ga PKA, and the lower panel represents O PKA. Vacancies resulting from a recoil energy of 1500 eV are emphasized with the red outline. (b) The dynamic changes in Ga and O vacancy sites over time in  $\beta$ - $\text{Ga}_2\text{O}_3$  during 1500-eV single-cascade MD simulations. The upper panel represents Ga PKA, and the lower panel represents O PKA. (c) Recovery fraction of O and Ga vacancies in different PKA simulations. (d) Snapshots of the vacancy sites (red dots are  $\text{O}_v$  and light blue dots are  $\text{Ga}_v$ ) generated during a 1500-eV single-cascade MD simulation, with defects at both maximum damage and the final primary damage at the end of the simulation. The upper panel represents Ga PKA, and the lower panel represents O PKA.

created by the displaced neighboring O atom. Similar remote recombinations with vacancies from the second coordination shell are more rare for  $\text{Ga}_i$  [see the middle row in Fig. 4(b)]. The nonzero recovery percentage was also seen for the  $\text{O}_i$  with the vacancies placed in the third-nearest-neighbor positions. The exemplary scenario of such recombination is shown in the bottom row of Fig. 4(b). The high percentage of defect recovery in the remote recombination paths indicates the close-to-zero energy barriers for these processes to occur, i.e., spontaneous recombination of the defects. Moreover, we calculated previously [24] several direct recombination barriers for O FPs and Ga FPs, demonstrating that the recombination barriers for O FPs are consistently lower than those for Ga FPs. This finding aligns well with the recovery percentage shown in Fig. 4(a). The observed flexibility in defect recombination of  $\text{O}_i$  within long distances (up to  $\sim 6 \text{ \AA}$ ) explains the low accumulation rate of O FPs providing a strong backbone to maintain the crystallinity of the entire structure.

### C. Collision cascades

Radiation effects in materials are conventionally studied by MD simulations of collision cascades initiated by a randomly selected PKA within the simulation cell [45]. Unlike the FPA simulations, defects in collision cascades are generated naturally, reducing the probability of the creation of high-energy unstable defects. In our previous work [12], we have observed the enhanced recrystallization of the O sublattice in single cascade simulations in  $\beta$ - $\text{Ga}_2\text{O}_3$ . In the present study, we analyze the evolution of the number of defects in both Ga and O sublattices during collision cascades triggered by different types of PKA with several different PKA energies. In Fig. 5(a), we plot the number of vacancies (both types  $\text{O}_v$  and  $\text{Ga}_v$ ) created by Ga and O PKA separately as a function of PKA energy. We see the linear dependence of this relation with the slope depending on the vacancy and PKA types. While the O PKA produces approximately the same amount of  $\text{O}_v$  and  $\text{Ga}_v$  at

almost all PKA energies (with a slightly higher slope for  $\text{Ga}_v$ , though), we see a much larger difference in the number of  $\text{O}_v$  and  $\text{Ga}_v$  created by Ga PKAs. The growth of  $\text{Ga}_v$  with PKA energy is much faster than that for the  $\text{O}_v$  defects. Moreover, by comparing the slopes of  $\text{O}_v$  growth created by O and Ga PKA, we observe a surprising trend of even slower growth of  $\text{O}_v$  in the latter case. In this graph, the error bars show the standard errors of the mean calculated over the simulations, which were performed with the different seed numbers for random selection of the initial position and the direction of the PKA atom in the middle of the simulation cell.

In Fig. 5(b), we illustrate the temporal evolution of vacancy defects during the 1500-eV cascade. It is clear that both Ga and O PKAs generate similar numbers of  $\text{O}_v$  and  $\text{Ga}_v$  during the ballistic phase of the cascade, but the recombination of  $\text{O}_v$  defects proceeds much more efficiently, in particular in the cascades triggered by Ga PKAs. The O PKA generates a somewhat higher number of  $\text{Ga}_v$  which, however, are formed by the atoms that were not displaced sufficiently far from their original positions, resulting in nearly as efficient recombination of these defects as of  $\text{O}_v$ . This difference is further emphasized in Fig. 5(c), where the recovery fractions in percent are shown for Ga and O PKA, respectively. Here, the bars indicating the recovery fraction for  $\text{O}_v$  and  $\text{Ga}_v$  in case of the O PKA are similarly above 70%, while the recovery fraction for  $\text{O}_v$  created by the Ga PKA reaches nearly 85%, while almost the same recovery for  $\text{Ga}_v$  is only slightly above 65%. We explain this behavior by the different shapes of cascades triggered by the two types of PKA [see Fig. 5(d)], where only the vacancy sites produced throughout the collision cascades are shown. Light O PKAs transfer energy less efficiently in collisions with the lattice atoms; hence, the cascades triggered by these PKAs are widely spread with lower density of the displaced atoms. At the same time, the energy transferred by a Ga PKA is able to generate occasional localized thermal spikes, which contribute to the enhancement of recombination rates of the point defects.

#### IV. CONCLUSIONS

In the present study, we show that the stability of the O sublattice in  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> plays the predominant role in preserving the crystallinity under high fluence ion irradiation. The ultrahigh stability of the O sublattice is attributed to its robust fcc stacking structure, which facilitates strong recombination dynamics between interstitial and vacancy defects with a higher likelihood of recovery in the presence of denser defect concentrations. In contrast, Ga ions more flexibly occupy different tetrahedral and octahedral interstitial sites available within the fcc O sublattices and hence do not preserve or recombine to their original  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> structure as strongly. With increasing damage, Ga ions exhibit reduced preference for sites within the  $\beta$ -Ga sites, which eventually causes the transition to the  $\gamma$ -Ga<sub>2</sub>O<sub>3</sub> phase at high-dose damage accumulation. Our results demonstrate the extraordinary stability of O sublattices, elucidating the micromechanism governing the

radiation resistance of Ga<sub>2</sub>O<sub>3</sub>, providing insights for material modification and practical applications in the future.

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