And this situation is also ambiguous: closely located are donor level (0/+) of center E1 (Ec — (0.27 — 0.28) eV [42], Ec — 0.26 eV [21, 41]) and center X1 (Ec — 0.3 eV [43]). The authors of the latter publication reported the essential dependence of X1 concentration on crystal structural perfection. They stressed that this center was not identical to that of center E1. In turn, level E1 has been identified as the center of the negative correlation energy [43, 21] and dominating intrinsic point defect in n-type 6H-SiC [44]. According to Refs. [44, 21], E1 is related to carbon vacancy. Considering the difference between the X1 and ESC2 energy locations, the configuration VC was associated with the ESC2 level.

The data for every level revealed for gallium arsenide are listed in table 2. The presented data show that the centers are associated with intrinsic vacancy-related defects.

Several factors caused the trap parameters to change. They are as follows.

1. Transformation of the defect complex due to decay, involvement of additional components, change in the distance between defect components, etc.
2. Defect recharging.
3. Changes in the trap environment, which can result, for instance, in the modified strength of the electric field around the defect.
4. An increase in the concentration of a given type of defect; for instance, the change in ionization energy was reported [32] to be proportional to the cubic root of the defect concentration.

Analysis of the observed phenomena should consider the probable mechanisms of the impact of microwave radiation on the crystals. First, the effect of the temperature increase should be analyzed. It is believed that the structural modification in the MWT result is mostly caused by the change in the defect charge state and elastic stress fields arising in instantly heated defect regions. However, these processes are known to intensify with increasing free charge carrier concentrations [6], whereas in our case, the effects weaken with the concentration increase (samples GAS1 and GAS2). Moreover, the applied irradiation mode did not imply long-term continuous exposure to MW oscillations, which reduced the overall heating of the structure. However, numerous studies have shown that the observed effects of MWT cannot be explained only by the mechanisms of fast annealing; therefore, non-thermal factors should also be considered. In recent research, more attention has been paid to the non-thermal mechanisms of MWT action (see, for example, [68] and the references it contains), which cause dislocation generation and result in smaller clusters of point defects in semiconductor wafers [69] or even trigger recrystallization processes [68]. Possible non-thermal processes causing changes in the structural characteristics of binary semiconductors have been reported in [69]. In particular, the processes of dislocation oscillations under the action of an electric field were analyzed, and the decorating impurities were found to influence the behavior of the dislocation segments. On the one hand, the available impurities decrease the resonance frequency of oscillations and provide the presence of electric charge, on the other hand, at high oscillation amplitudes they can escape the dislocation, which causes new chemical defects to arise. In turn, the point defects can perform superhigh-frequency oscillations and diffuse as a result of the MWT.

The observed modifications of deep-level parameters are the result of the above­mentioned structural reconstruction in semiconductor near-surface regions owing to the MWT. The results of X-ray investigations show that MWT increases the convexity of single-crystal samples, which indicates the aggregation of interstitial defects in the near-surface layer, particularly because of the generation of separate dislocations [11, 19]. The defect accumulation effect caused by the MWT in the near-surface region was reported in [11, 18]. To a certain extent, only the SIC3 sample was excluded; however in this case, a rather strong deformation of the near-surface region was also observed prior to irradiation. Researchers have reported [9, 10, 11, 12, 13] that in this stressed state, MWT causes redistribution as well as certain weakening of elastic deformations, which is what occurs in SIC3. The profilometry data correlated with X-ray measurements. Structural investigations show that in the initial GaAs samples, the density of dislocations has a W-like distribution over the plate area; the dislocation density over the plate diameter varied from 2 • 104 cm-2 to 2 • 105 cm-2. This inhomogeneity in the dislocation density distribution is evidence of considerably strong elastic deformation in the sample.

The analysis showed that the ESC1 and ESC2 centers are complexes of carbon vacancies, EGA1 is associated with VAs, and EGA3 — with VAs or VGaGaiVAs complexes. The MWT stimulates the diffusion of point defects, which are mostly intrinsic interstitial atoms, resulting in trap modifications. The ESC1 center in silicon carbide transforms into ESC2 under the influence of closely located interstitial silicon:

Vsi Vc + Si i Vc .

Further modification of the ESC2 parameters in SIC3 is caused by the enhanced electric field of the dislocation. In the GAS2 samples at tMWT = 20 s, the VAs transformed into complex VAsAsi (EGA2 center) because of the increased number of interstitial atoms in the near-surface layer:

VAs + As i VAs As i .

A similar process in GAS1 is more complicated because of its higher charge carrier concentration. It has been reported [7] that with a growth in resistance, the depth of microwave penetration increases, and thus, the volume from which defect gettering begins in the near-surface layer grows as well. In addition, the cause of the weak (in comparison with GAS2) influence of MWT on trap parameters in GAS1 is the absence of pressure stresses, which intensifies the MWT-simulated complex formation process in the system's intrinsic defects. This is supported by data for silicon carbide single crystals. In the GAT sample, which is also characterized by a high concentration of free electrons, the transformation of EGA3 to EGA4 (VGaGaAs complex) occurs in the reaction described in [60]:

VGa Ga i VAs GaGa VAs GaAs VGa

Accumulation of a large number of interstitial atoms in the near-surface layer at high doses of radiation (tMWT « 40 s for gallium arsenide and tMWT > 80 s for silicon carbide) causes complete annihilation of vacancies (or transformation into antisite defects, whose levels are filled in the crystals with electron conductivity); therefore, the TAV signal disappears (samples GAS1, GAS2, SIC1):

SiC : Vsi Vsi + Sii + Sii 0;

GaAs : Vas + As i 0 ; Vas + Ga i GaAs•

It is believed [27, 25, 24] that the TAV that arises in epitaxial structures is mostly caused by defects located at the epi-layer and substrate interface. This difference in the deep-level location is the cause of the difference between the dose-dependent modification of the defect parameters in the epitaxial and single-crystal samples.

In epitaxial structures n-n+-GaAs and n-n+-n++-GaAs, MWT induced increase of curvature radius reported in [11, 19] is the result of forming single dislocations and their further propagation deep into the structure along the glide planes. As a result, the strength of both the electric and stress fields changes, which causes defect transformation and, thus, the shift of the respective deep levels. As shown in table 2, EGA5 and EGA6 levels were associated with the complexes VGaVAs and VAsAsi, respectively. Traps such as EGA2 and EGA4 have also been previously found in epi­structures [48, 55, 34, 61, 62, 66, 67]. The observed MWT-stimulated transformations are caused by an increasing number of interstitial atoms, which are described by the following reactions:

VGa VAs + Ga i + As i VAs As i

for GAE1 and GAE2 and

VGa GaAs + As i GaGa VAs + As i VAs As i

for GAB1 and GAB2. The increase in activation energy EGA6 in sample GAE3 is probably caused by the change in Coulombic interaction of interstitial-vacancy complexes, which is due to a decrease in their concentration, while the growth of capture cross-section EGA4 in GAB1 at tMWT = 20 s and EGA6 in GAE3 are associated with the growth of the electric field strength caused by charged dislocations.

1. Conclusion

The influence of microwave radiation on the parameters of point defects (cross-section of electron capture and energy levels in the gap) was studied experimentally in single crystals of n-6H -SiC and n-GaAs, as well as in gallium arsenide epitaxial structures. The investigation showed that the traps available in the near-surface layer are associated with intrinsic vacancy-related defects. The microwave radiation-induced change in the trap energy level and capture cross-section was caused by the growing number of interstitial atoms in the near-surface layer. The radiation-induced process involving the transformation of defect complexes intensifies under stress conditions.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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