**Role of Hole Trapping by Deep Acceptors in Electron Beam Induced Current Measurements in β-Ga2O3 Vertical Rectifiers**

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**ABSTRACT**

Current increases in vertical geometry Ga2O3 rectifiers during electron beam induced current measurements are dominated by impact ionization of deep acceptors in the depletion region. At room temperature, mobile hole diffusion in the quasi-neutral region of Schottky diodes contributes significantly to the charge collection efficiency. Even when electron-hole pairs are created well inside the space charge region, there are significant losses of charge collection efficiency due to trapping of holes by deep acceptors in the lower half of the bandgap. Capacitance-voltage profiling under illumination point to deep acceptors with optical ionization close to 2.3 eV as the most important agents of capture. The collection efficiency can be improved by increasing electric field in the space charge region. The jump in collection efficiency at electric fields close to (5-6)×105 V/cm is attributed to impact ionization of these deep acceptors. These processes can manifest themselves in measurements of the impact ionization coefficients and breakdown voltages of β-Ga2O3 rectifiers and in analyzing the response times of β-Ga2O3 photodetectors.

1. **INTRODUCTION**

β-Ga2O3 is attracting great interest because of its wide bandgap of 4.7-4.8 eV (resulting in expected electrical breakdown field of 8 MV/cm), high saturation velocity of electrons of ~2×107 cm/s, existence of high crystalline quality single crystals prepared by liquid solution growth, and excellent quality epitaxial films [18]. The material can be controllably grown semi-insulating by doping with Fe or Mg, or n-type by doping with Si or Sn. The existence of convenient ternary solid solutions of β-(AlxGa1-x)2/Ga2O3 that form good crystalline quality heterojunctions with β-Ga2O3 allows fabrication of devices with two-dimensional electron gas at the interface [3,4,6]. The material is expected to significantly improve the performance of high-power rectifiers, field effect transistors and solar-blind photodetectors compared to SiC or GaN-based devices that currently dominate the field [2,7,8].

For all applications of β-Ga2O3-based devices, it is essential to know the field dependences of the impact ionization coefficients for electrons, αn, and holes, αp, as a function of electron field strength [9]. The general procedure to extract these values from experiment has been described previously [10,11]. One of the popular approaches is to prepare Schottky diodes on n-/n+ or p-/p+ structures and measure the electron beam induced current (EBIC) as a function of applied voltage and calculate the field dependence of αn from the current multiplication rate M for various applied voltages for n-/n+ or αp from data collected for p-/p+ structures [11]. Experimentally this has not been done for Ga2O3, but theoretical modeling has been reported [12].

Complications arise in the experiments for several reasons related to a lack of detailed understanding of some properties of β-Ga2O3. First is the transport of holes in this material. The authors of Ref. [12] assumed the holes in Ga2O3 are ordinary mobile holes with effective mass of 3mo (mo is the mass of free electron). Some theory, on the other hand, predicts the holes in Ga2O3 to be strongly bound, virtually immobile, polaronic states, so called self-trapped holes, STH, localized near the two inequivalent oxygen ions sites O1 and O2 in the monoclinic lattice [13,14]. The estimated STH binding energy is on the order of 0.5 eV and this should have a profound effect on photoelectrical properties of Ga2O3-based devices [13,14]. For example, the high photosensitivity of Schottky diodes on n-Ga2O3 for above-bandgap photon energies has been ascribed to the build-up of positive charge on these immobile polaronic states near the semiconductor-metal boundary and respective lowering of the Schottky barrier height[15]. Also, the presence of self-trapped holes (STH) polaronic states should seriously handicap the movement of photoelectrons in the electric field of the space charge region (SCR) of a Schottky diode or p-n junction and affect the impact ionization due to the high energy electrons.

The reverse leakage current in state-of-the-art Ga2O3 rectifiers can be near-ideal and dominated by Schottky barrier tunneling throughout the entire range of the surface electric field to 3.4 MV/cm [1]. There are also a significant number of defect states present throughout the bandgap. The formation of STH polarons in β-Ga2O3 has been directly observed in electron paramagnetic resonance EPR [16], but the self-trapping was destroyed by heating above 90K. Deep level transient spectroscopy with above-bandgap optical excitation (ODLTS) detected doublet peaks that could be assigned to the formation of STH polarons near the O1 and O2 sites, but the activation energies for the formation were lower than predicted by theory, about 0.2 eV versus 0.5 eV, and these states did not survive heating above ~100-120K, in agreement with EPR [17, 18]. The results of EBIC experiments also indicate that at moderately low temperatures and certainly at room temperature and above, a considerable portion of the holes in β-Ga2O3 is mobile and can contribute to the EBIC signal [18, 19], although the STH states can still play some role in the shape of photoluminescence (PL) spectra and explain the general absence of band-edge PL in this material [20].There are reports that at high enough laser intensity, enough free holes are created to enable observation of near band-edge emission in Ga2O3[21].

A second issue is that the absence of p-type doping means [2,7, 22], fabrication of p-i-n or p-/p+ structures with well-defined electric field in the i-layer is not possible. The range of layer thickness and layer doping is currently limited and usually does not allow n- films that are fully depleted at zero bias, thus making it difficult to perform the EBIC experiments in a constant electric field regulated simply by applied external bias. Both considerations limit possibilities when measuring the field dependences of impact ionization coefficients for electrons and holes.

Lastly, the bandgap of β-Ga2O3 is very large and contains a high density of deep electron and hole traps [23]. High energy electrons and holes in EBIC measurements performed under strong electric fields might be impact-ionized and contribute to the excessive reverse current, or the traps might capture the charge carriers created by the electron beam, thus effectively altering the charge collection efficiency in EBIC at low applied fields. Similar problems have been recognized when dealing with GaN and SiC [10, 24]. These considerations turned out to be of high importance in the experiments described below.

Finally, it is worth considering the context of understanding the basic breakdown mechanism in existing material. A key aspect to high power operation is the ability of the device to sustain large reverse voltages without breakdown. In the absence of a large concentration of defects, breakdown can occur by two mechanisms, each of which requires a critical electric field in the depletion transition region [2,7-9]. The first is the Zener effect, in which the energy bands overlap in a heavily doped junction at low voltages. Tunneling of electrons produces breakdown as the bias is increased. This is not applicable in Ga2O3 since majority carrier rectifier structures are used in the absence of p-type doping.

The second mechanism is avalanche breakdown caused by impact ionization [9], resulting from the acceleration of carriers by the electric field, to the point where they have sufficient kinetic energy to ionize atoms in the semiconductor host. In the presence of deep traps, this process can be enhanced due to lowering of the barrier for ionization, as well as direct carrier tunneling processes. The von Hippel criteria indicates that impact ionization will occur when the gain of energy from the electric field by the carriers is larger than the loss of energy by relaxation due to carrier-phonon and carrier-carrier scattering [ 7,8,25-27]. It could be speculated that avalanche breakdown may be a relatively rare event in ultra-wide bandgap semiconductors. In some of these materials, the electron ionization coefficients are much lower than those of holes due to the width of the lowest conduction band being smaller than the bandgap [28-34]. In conventional semiconductors like Si, for which most of the physics of avalanche breakdown has been developed, the electron affinity is larger than the bandgap [28-35], opposite to Ga2O3. The differences in band structure between Si and Ga2O3 suggest the possibility of other dielectric breakdown mechanisms occurring [25-27,33]. The effects of bond-breaking and possible high temperature anharmonicity of phonons on breakdown are unexplored in Ga2O3. For example, it would be important to distinguish between avalanche breakdown and time-dependent destructive dielectric breakdown if trap-assisted processes are insignificant.

The large bandgap of Ga2O3 results in some dopants having large ionization energies and even under high field conditions there may be incomplete ionization. This low ionization fraction could result in a frequency-dependent blocking voltage that reduces the benefit of the high breakdown field. Due to this strong temperature dependence of dopant ionization efficiency, local variations in temperature and fluctuations during device operation, it is possible to encounter thermal runaway and current filamentation [33-40]. The incomplete ionization therefore can have a strong influence on device performance and stability. Additionally, the thermal-runaway effects in conventional semiconductors are generally caused by avalanche breakdown or band-to-band generation, whereas in wide bandgap materials like Ga2O3, they will mostly be related to the thermal ionization of these deep dopants.

With all this framework, we performed EBIC measurements as a function of electron energy in vertical geometry Ga2O3 rectifiers. We find that deep acceptors in the depletion region dominate the current at reverse bias voltages near breakdown.

**II. METHODS AND ANALYSIS**

**II.1. Samples**

The samples used were from Tamura/Novel Crystals Technologies (Japan). They were 10 µm-thick (010) oriented n-type (Si doped) β-Ga2O3 films grown by halide vapor phase epitaxy (HVPE) on bulk n+-Ga2O3 Sn doped substrates grown by edge-defined film-fed (EFG) technique [41]. The net donor concentration in the substrates was 3×1018 cm-3. The net donor doping of the films was either ~ 1016 cm-3 or to 1017 cm-3. Some properties of the structures are summarized in Table I. The samples were processed into vertical Schottky diodes by e-beam evaporation on the film side of either Ni (20 nm thick) (samples S1 and S2 in the Table) or Ni/Au (20 nm/80 nm) (samples S3, S4) in the Table. The back Ohmic contact was prepared by e-beam evaporation of Ti/Au (20 nm/80 nm) [42]. The diameter of the Schottky diodes was 1 mm, the surface of samples S3, S4 was passivated by deposition of Si3N4, the surface of samples S1 and S2 was not passivated.

**II.2. Electrical properties characterization**

Characterization included current-voltage (I-V), capacitance-voltage (C-V) profiling in the dark and DLTS [43] measurements in the temperature range 100K-500K. All experiments were performed using a custom-built setup including E4980A LCR meter (KeySight Technologies, USA, frequency range 20Hz-1 MHz), B2902A voltage/current source/meter (KeySight Technologies, USA), a custom-built cryostat (Cryotrade company, Russia) for temperature control and measurements over the 77-500K temperature range. The E4980A LCR meter was used, together with the external pulse generator 33500B (KeySight Technologies, USA), for DLTS measurements [44,45]. the collected data were processed into standard DLTS spectra using the standard two-gate processing [43] in order to determine the trap energies, capture cross sections and concentrations.

**II.3. EBIC measurements**

The EBIC measurements were carried out at room temperature in a scanning electron microscope JSM-840A (JEOL) using a Keithley 428 current amplifier. Under electron beam excitation, the number of generated carriers can be estimated with rather high precision that allows quantitative calculations of current collected in the EBIC mode.

As shown in [19, 46], the most reliable method to obtain the submicron diffusion length from the EBIC measurements is to fit the dependence of collected current *Ic* on beam energy *Eb*. Besides the diffusion length measurement, this also allows to make some additional conclusions. Firstly, let us consider the way *Ic* can be calculated. For the Schottky barrier excited through a metal, *Ic* can be calculated as [19, 46]

, (1)

where *W* is the depletion region width, *tm* is the metal thickness, *L* is the diffusion length and

, (2)

where *R*(nm) = 7.34·*Eb*(keV)1.75 and  [14, 24].

The total generation rate of electron-hole pairs is , where *Ib* is the beam current, *η* is the fraction of beam energy absorbed inside the sample and *Ei* is the average energy necessary for electron – hole pair creation. For β-Ga2O3 a value of  can be estimated as 5.8·10-2eV-1. The results of fitting using the calculated h(z) function, the electron-hole generation rate, with the width of the space charge region, the diffusion length and the metal thickness are commonly represented as the dependence on the beam energy Eb of the measured and calculated values of the EBIC current Ic normalized by the product of the beam current Ib and beam energy Eb [19, 46].

**III. RESULTS and DISCUSSION**

Current-voltage characteristics of all samples were well behaved, with room temperature ideality factor of 1.0-1.1, and saturation current density of 10-14-10-13 A/cm2 in the forward direction and reverse current density close to (1-100) nA/cm2 (the lower range in the quoted above saturation current values and reverse leakage refers to the lower doped samples S1 and S3, the higher values in the range to the heavier doped samples S2 and S4 (Table I). The Schottky barrier height determined from the temperature dependence of saturation current was 1.1 eV. Measurements of reverse current up to high voltages showed that, for passivated samples, the onset of strong reverse current increase with voltage occurred for about -40V for the heavier doped sample S4 and at about -70V for the lighter doped sample S3 (Fig. 1(a)). For unpassivated samples S1 and S2, the leakage current was generally higher, the reverse current started to increase with voltage near -20V for the heavier doped sample S2 and near -40 V for the lighter doped sample S1 (Fig. 1(b)).

Capacitance-voltage profiling yielded the net donor concentration profiles shown in Fig. 2. The profiles are reasonably flat, the voltage cut-off in 1/C2 versus voltage plots was close to 1 V in agreement with the I-V data. The net donor concentrations Nd are presented in Table I. Fig. 3(a) shows the SCR width WSCR as the function of voltage. For comparison, in Fig. 3(b) we present the dependence of the projected range of the probing electrons in EBIC on their energy as calculated for β-Ga2O3 [19]. This gives idea of where in respect to the SCR edge the electron-hole pairs were created in the EBIC experiments described below (the energy losses in the Schottky metal decrease the actual penetration depth and have to be taken into account).

DLTS spectra measurements revealed the presence of the well-known electron traps E1 (Ec-0.6 eV), E2\* (Ec-0.74 eV), E2 (Ec-0.8 eV), E3 (Ec-1 eV), and E4 (Ec-1.2 eV) often observed in bulk EFG and in n-type HVPE films of β-Ga2O3 [17, 23, 25]. Fig. 4 shows the measured spectra for samples S1 and S3 from Table I. The y-axis in the figure is 2Nd ×(ΔC/C)× F-1, where ΔC is the DLTS differential signal, C is the steady-state capacitance, F-1 is the DLTS spectrometer function converting the difference of capacitances at time windows t1 and t2, ΔC above, into the full amplitude of capacitance change at the given temperature [43]. Thus, the magnitude of the peaks in such spectra gives the concentration of the traps without taking into account the λ-correction when the deep traps are empty only in the part of SCR where the level of the trap lies above the Fermi level [43]. Figure 4 indicates the main centers are the native-defects-related E2\* centers and the E2 traps corresponding to the acceptor state of Fe atoms in β-Ga2O3 [47]. The spectrum for S3 was similar to that of S1. In sample S2, the E2 state was dominant, with some contribution from the E3 electron traps belonging to native defects [23, 46-50]. In Table I we present the densities of most important traps calculated taking into account the λ-correction.

Because of the large bandgap of β-Ga2O3 not all deep traps can be easily probed by DLTS and with our limit of upper temperature of 500K allows to detect deep traps with levels not deeper than ~Ec-1.4 eV [44]. A standard way around this difficulty [48, 49] is to perform C-V profiling experiments in the dark and with monochromatic illumination and get the optical excitation spectra and the densities of the traps deep inside the bandgap by subtracting the profiles obtained in the dark from the profiles under illumination [51, 52]. Fig. 5(a, b) compares such spectra for samples S1 and S2. In sample S1 the dominant feature is the optical transition with optical threshold of 2.3 eV often reported for light C-V profiles spectra (LCV) and in deep level optical spectroscopy of β-Ga2O3 samples [48-52] and recently attributed to gallium vacancies complexes with off-center Ga interstitials [53]. The density of these centers in sample S1 can be estimated from the values of photoconcentration for high-photon energy plateau in Fig. 5(a). For the S2 sample (Fig. 5(b)), one observes in addition to the 2.3 eV centers, shallower centers with optical ionization threshold of 1.3 eV and deeper centers with optical ionization threshold of 3 eV.

The density of the 1.3 eV centers could be determined from the photoconcentration at photon energy 2.3 eV, where the signal from the 2.3 eV traps is negligible. The density of the 2.3 eV traps can be estimated by subtracting the signal at 3 eV from the signal at 2.3 eV. And the density of the 3 eV traps is arrived at by subtracting from the signal on the high energy plateau the signal at 3 eV [52]. Thus the concentrations of all three traps are close to 2×1015 cm-3. Both the 1.3 eV and 3 eV centers have been observed previously in LCV and DLOS spectra of β-Ga2O3 [49] and the 3 eV centers have been tentatively associated with gallium vacancy related acceptors based on LCV spectra of films after irradiation [51,52]. In Table I we compare the densities of the 2.3 eV traps for samples S1 and S2. For the S3 and S4 samples LCV spectra measurements were not practical because of the large thickness of the Schottky barrier metal.

Turning to the EBIC results, Figure 6 shows the normalized EBIC signal dependence on beam energy for sample S1 measured at 0 V bias. Fig. 6(a) presents the dependence of the EBIC current Ic normalized by the product of beam current Ib and the probing beam electrons energy Eb on the beam energy Eb. Fig. 6(b) is the same dependence redrawn as a function of the electron projected range for respective beam energies taken from Fig. 3 and calculated previously [19]. The solid line in both figures is the result of calculation of EBIC collection efficiency [19, 46] and Eq. (1, 2) above. In this calculation, the contribution of holes formed at high beam energies outside the space charge region SCR and diffusing to the SCR has been neglected. For many wide-bandgap semiconductors these calculations are in reasonably good correspondence with measured collection efficiencies for beam energies creating electron-hole pairs inside the SCR [46]. For our sample S1, the SCR width at 0V is close to 300 nm and one would expect the modeling and experiment to be close to each other for the beam energies below ~10 keV (the thickness of the Ni Schottky barrier metal in sample S1 is low and does not alter significantly the energies of the probing electrons within the sample [19, 46]). Instead, we observe that the calculated peak value in the SCR region in Fig. 6 is considerably higher than the measured value. This suggests that some part of electrons and holes within SCR is trapped and recombines, thus not contributing to the collected current.

We have observed a similar phenomenon previously for GaN films containing multiple quantum wells (MQW) of GaN/InGaN within the SCR [54, 55]. The explanation offered in Ref. [54, 55] was that electrons and holes are trapped and recombine in MQWs, thus decreasing the collection efficiency. In our Ga2O3 films one can think of several possible reasons giving rise to the observed effect. First, one could assume that instead of mobile holes, there are STH states localized near the metal/Ga2O3 Schottky boundary [15]. The mechanism of the EBIC signal formation would then be radically different from the standard version and be related to the lowering of the Schottky barrier by the charge accumulated at the interface by the STH states.

However, this option does not seem to be viable [18, 19]. A clear EBIC signal can be measured in the planar EBIC geometry [19, 46] in which the probing beam is scanned along the Schottky diode surface starting away from the Schottky diode edge and moving towards the edge. In that case, no modification of the Schottky barrier height is expected and the EBIC signal should be formed by holes diffusing towards the edge of the Schottky diode (electrons cannot play any significant role in the process because of the repulsive electric field of the high Schottky barrier [19, 46]. This experiment was performed for all studied samples and yielded a clear EBIC signal that, for sample S1, gave the diffusion length L of 0.12 µm from the slope of the dependence of the logarithm of Ioexp (-x/L)/x0.5 on x, the distance from the edge of the Schottky diode [14] (Io here is the EBIC signal measured with the beam position on the Schottky diode). This value is in reasonable agreement with the L value calculated for sample S1 from fitting the dependence of EBIC collection efficiency on beam energy, L=0.18 µm (the reasons for the discrepancy between the two values and the arguments in favor of a higher accuracy of the latter value are discussed elsewhere [19, 46].

Moreover, if one inspects Fig. 6, for high beam energies corresponding to charge generation outside the SCR, the experimental EBIC collection efficiency is higher than predicted if no hole diffusion is taken into account as in the fitting curve in Fig. 6. This clearly indicates the necessity to take into account additional contribution of holes diffusion in the quasi-neutral part of the sample. Finally, the formation of STH states is a basic intrinsic process supposedly behaving in the same way for all samples. However, the value K by which the peak of the calculated EBIC signal within the SCR of our samples should be multiplied to bring it into correspondence with measured values differs in the S1, S2, S3, S4 has K= 0.52, 0.34, 0.21 and 0.12, respectively. All this suggests the formation of STH states is not the major issue in our room temperature measurements.

Two other possibilities are a) capture of electrons in the SCR by empty electron traps with levels above the Fermi level, with subsequent recombination with either free holes travelling through the SCR or with holes captured on deep acceptors and b) capture of holes by deep acceptors with recombination with either free electrons or electrons captured by deep electron traps in the upper half of the bandgap. Measurements of the EBIC collection efficiency as a function of applied bias performed for probing electron energies such that they generate electron-hole pairs only near the Ni/Ga2O3 boundary allows to clarify the issue. Fig. 7 presents such a dependence for samples S1 and S3 having similar low doping of ~1016 cm-3, but differing by the thickness of Schottky diode metal (20 nm Ni for S1, 20 nm Ni and 80 nm Au for S3) and the density of deep traps (higher for S1, see Table I). For sample S1, the measurements were performed with beam energy 4 keV and the beam current of 95 pA. Fig. 8 shows the generation function of electron hole pairs calculated using Eq. (1, 2) and taking into account the energy loss in the Schottky diode metals for both samples. For sample S1, the generation function essentially dies out near 50 nm from the interface, so that the main processes are holes collection from the distance very close to the interface and electrons injection into the bulk of SCR.

For all four samples, the build-up and decay times of the EBIC current when turning on or off the probing beam were slow, on the order of many seconds requiring long waits when changing the beam energy. For sample S1 the collection efficiency rapidly increased for reverse voltages up to ~5 V, then, for higher voltages, the slope decreased and near 40 V the collection efficiency showed a measurable jump (the normal behavior is for the collection efficiency not to change with increased reverse voltage [19, 46]. The trend shown in Fig. 7 for sample S1 is much easier to reconcile with the assumption that the trapping involves capture of holes by deep acceptors in the lower half of the bandgap. Indeed, for capture of electrons by electron traps in the upper half of the bandgap, the increase in reverse voltage increases the distance that electrons have to traverse through the SCR and should decrease the collection efficiency by enhancing electrons capture. For holes, the width of the region from which they are collected is determined by the depth at which the probing electrons are absorbed and does not change with increasing the reverse bias. On the other hand, the velocity of holes increases with increasing the electric field, thus facilitating better hole collection at the Schottky electrode. This is particularly important given the expected high effective mass of mobile holes in Ga2O3 and their low mobility. The high- voltage jump in collection efficiency could then be related to the impact ionization of holes from deep acceptors at which they are captured. The threshold electric field for this impact ionization cannot be calculated accurately because the field is not constant in the SCR of our samples, but the maximal electric field Em in the junction can provide a ballpark value as Em=2(V+Vbi)/WSCR=4.6×105 V/cm (the reverse voltage corresponding to the jump in efficiency is close to 40V, the built-in voltage of the Schottky diode is close to 1V and the space charge region width at reverse voltage of 40V is 1.8 µm according to Fig. 3). This value is too low for the intrinsic impact ionization of Ga2O3 [12], but does not seem unreasonable for the deep acceptors with ionization threshold of 2.3 eV dominating the deep acceptors spectra in sample S1. The normalized collection efficiency at large voltage approaches the expected value of 58 keV-1, meaning that at such bias hole trapping is almost totally suppressed or that their release from the traps is fast.

For sample S3, the thickness of the Schottky diode metal is ~ 80 nm. The collection efficiency versus reverse voltage experiment was performed at beam energy of 10 keV and current of 180 pA which places the maximum of the generation function near 20 nm (Fig. 8). The dependence is similar to that of sample S1, but the jump in the collection efficiency occurs at a higher reverse voltage of 110 V. This would correspond to Em of 6×105 V/cm, in reasonable agreement with the result for sample S1. For sample S3, capacitance-voltage profiling under monochromatic illumination was not practical because of the high thickness of the Schottky diode metal, but in both cases the main deep acceptors participating in trapping are the same.

Finally, we compared the samples in terms of diffusion lengths estimated by fitting the experimental normalized Ic values as a function of beam energy [19, 46] using Eq. (1, 2). In these calculations, the diffusion length, the metal thickness and the K value were varied in order to achieve the best fit of the calculated collection efficiency and the measured efficiency. Fig. 8 (a, b) compares the experimental and calculated dependences for the low doped samples S1 and S3 (Fig. 8(a)), and high doped samples S2 and S3 (Fig. 8(b)) using the diffusion length of holes as a fitting parameter and taking into account the differences in the Schottky metal thickness. For S1, S2, S3 samples, the quality of fitting was good and the estimated diffusion lengths in Table I are reliable. For sample S4, the data was noisy and the accuracy of the diffusion length fitting was less precise. The differences in the peak magnitudes for similarly doped samples S1, S3 and S2, S4 come from the difference in the metal thickness. There is a correlation between the density of deep traps measured in DLTS and the diffusion length: the higher the density of defect related E2\* traps and Fe-related E2 traps the lower the diffusion length. Previously we have observed the decrease of the diffusion length after irradiation [51, 52], which suggests that Fe-related centers, while possibly contributing to the diffusion length degradation are perhaps not the major factors in the phenomenon (the concentration of Fe acceptors is not expected to change as a result of irradiation). We could not carry out the deep acceptor concentrations comparisons for all samples because of the thick metallization of samples S3 and S4. Thus, the question of whether these deep centers play a significant role in determining the lifetime of non-equilibrium charge carriers is left open for now. For the deep acceptors with optical threshold near 2.3 eV, they likely play significant role in hole capture within the space charge region, but it is not likely that these centers will be effective recombination centers because they possess a high barrier of capture of electrons [48-52]. These centers are similar to Ga vacancy acceptor complexes in n-GaN where they are effective hole traps, but not recombination centers because of the very low efficiency of electrons capture [56,57].

**IV. SUMMARY AND CONCLUSIONS**

Our results show that in β-Ga2O3 vertical rectifiers, at least part of holes created by electron beam excitation are mobile at room temperature and can contribute to EBIC signal collection. The charge collected in EBIC from the space charge region has measurable losses due to capture and recombination via deep traps. Measurements of the EBIC collection efficiency dependence on reverse voltage for electron beam energies causing charge carrier generation near the surface suggest there is capture of holes by deep acceptors in the lower half of the bandgap. Comparison with deep acceptor spectra point to the well-known centers with optical ionization threshold at 2.3 eV as defects responsible for the observed phenomena. Increasing the electric field strength in the space charge region improves the hole collection efficiency by increasing their velocity in a similar way observed for radiation detectors based on compensated bulk HVPE n-GaN [58].

At electric fields close to 5×105 V/cm one observes a jump in charge collection efficiency due to the impact ionization of the hole traps. If the density of deep hole traps is high, they could contribute to the increase of reverse current of the Schottky diodes at voltages much below the voltages corresponding to intrinsic impact ionization (this is perhaps causing the lower than expected breakdown fields observed in the samples studied here). A question that still remains and has to be addressed by detailed measurements on samples grown under different conditions changing the density of deep hole traps and performed with different surface treatments before the deposition of Schottky diodes is whether the deep acceptor density near the surface is determined by varying the "bulk" density of grown-in defects or the variations in surface treatment. If the former scenario is operative, one would expect that growth under oxygen-rich conditions should aggravate the problem since the deep acceptors are believed to be Ga vacancy related. In terms of surface treatment, argon plasma treatment or treatment in harsh hydrogen plasma of the surface of n-Ga2O3 can facilitate the formation of deep acceptors near the surface [43, 45] and the effect could be sensitive to the surface orientation [59].

Our experimental conditions did not allow estimation of the bulk impact ionization coefficients in Ga2O3 because the electric fields that could be achieved were not high enough due to the premature growth of reverse current with voltage. Additional experiments on samples with better surface passivation and edge electric field management are necessary, but the effects due to hole capture near the surface by deep acceptors will have to be taken into account. The experimentally measured photocurrent build-up and decay times in solar blind detectors tend to be [15, 60] slower than expected and these slow relaxation times could be related to the release of the trapped charge from deep acceptors. Finally, we observe that the diffusion length of holes in HVPE Ga2O3 films tends to decrease in tune with increasing density of deep traps detected in DLTS spectra.

**ACKNOWLEDGMENTS**

The work at NUST MISiS was supported in part by Grant № K2-2020-011 under the Program to increase Competitiveness of NUST MISiS among the World Leading Scientific and Educational centers (Program funded by the Russian Ministry of Science and Education). The work at UF was sponsored by Department of the Defense, Defense Threat Reduction Agency, HDTRA1-17-1-011, monitored by J. Calkins, DTRA Interaction of Ionizing Radiation with Matter University Research Alliance (Jacob Calkins) and also by NSF DMR 1856662 (James Edgar).

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Table I. Characteristics of samples used in these experiments

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sample # | Nd (x1016) (cm-3) | L(nm) | Trap concentrations (cm-3) | | | | |
| E2\* | E2 | E3 | E4 | 2.3 eV |
| S1 | 1.4 | 180 | 9.1×1013 | 2.1×1014 |  | 3×1013 | 2×1014 |
| S2 | 11 | 90 |  | 7×1015 | 1.7×1015 |  | 2×1015 |
| S3 | 1 | 600 | 2.8×1013 | 5.6×1013 |  |  |  |
| S4 | 13 | 600 | 2.8×1013 | 5.6×1013 |  |  |  |

**Figure Captions**

Fig. 1 (Color online)(a) Reverse current versus voltage for samples S3 and S4 with surface passivation; (b) the same for samples S1 and S2 with no surface passivation

Fig. 2 (Color online) Room temperature doping profiles

Fig. 3(Color online) (a) The dependence of space charge region width WSCR on voltage for the four studied samples (actual measurements up to reverse voltage of -20V, for higher voltages the data obtained by calculation); (b) the calculated dependence of the projected range of probing electrons on the probing electrons energy

Fig. 4. DLTS spectra measured for samples S1 and S3 with reverse bias -5V, forward bias pulse +1V (length of 50 ms), with time windows of 1.5 s/15s

Fig. 5 (Color online) (a) LCV spectrum of sample S1; (b) LCV spectrum of sample S2

Fig. 6 (Color online) (a)Normalized EBIC current as a function of beam energy for sample S1, blue squares represent the experiment, the red line is the result of calculations; (b) the figure redrawn as a function of the projected ranges of the probing electrons

Fig. 7 (Color online) (a)Normalized EBIC signal as a function of reverse voltage for S1 measured with Eb=4 keV and Ib=95 pA; (b) same for S3 measured with Eb=10 keV and Ib=180 pA.

Fig. 8 (Color online) Calculated generation functions for Eb=4 keV (metal thickness 20 nm) (red line) and Eb=10 keV (metal thickness 80 nm) (blue line); the functions were normalized so that the integral of generation function over depth is equal to 1; metal thicknesses assumed in the calculation are shown by dotted lines.

Fig. 9 (Color online )(a) Measured normalized EBIC signal as a function of Eb and the fitting with the diffusion length L as fitting parameter; blue squares -the data for sample S1, solid line the fitting with L=180 nm; red squares-the data for sample S3, the solid line is the result of fitting with L=600 nm; (b) measured normalized EBIC signal as a function of Eb for sample S2 (red squares)and the fitting with the diffusion length L=120 nm; same for sample S4 (blue squares) and the results of fitting with L=600 nm as fitting parameter; blue squares -the data for sample S1, solid line the fitting with L=180 nm; red squares-the data for sample S3, the solid line is the result of fitting with L=600 nm.





























