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Impact of radiation and electron injection on minority carrier transport in $p\text{-Ga}_2\text{O}_3$

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Highly resistive undoped p-type Gallium Oxide samples were subjected to cumulative proton irradiation with energies ranging from 25 keV to 70 keV and doses in the $1.6 \times 10^{14} \text{ cm}^{-2} - 3.6 \times 10^{14} \text{ cm}^{-2}$ range. Proton irradiation resulted in up to a factor of 2 reduction of minority electron diffusion length in the samples for temperatures between ~ 300 and 400 K. Electron injection into the samples under test using the beam of a Scanning Electron Microscope leads to pronounced elongation of diffusion length beyond the pre-irradiation values, thus demonstrating stable (days after injection) recovery of adverse radiation impact on minority carrier transport. The activation energy of 91 meV, estimated from the temperature dependent diffusion length versus electron injection duration experiments, is likely related to the local potential barrier height for native defects associated with the phenomenon of interest.

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The main limiting factor in Ga₂O₃ technology is related to difficulties of p-type conductivity realization [1-4]. Previous studies indicate that holes in β-Ga₂O₃ have characteristics of low dispersion, high effective mass and high density of states. This results in formation of weak polarons (or localized holes), trapped by lattice distortions [5-9], hindering p-type conductivity. Contradicting to these claims, ref. [3] has experimentally shown a possibility of low p-type intrinsic conductivity in Ga₂O₃. It is additionally reported that the self-trapping nature of holes practically disappears at temperatures above 90-120 K [4]. Given the current state-of-the-art and ever mounting interest in p-Ga₂O₃, one can reasonably claim that a robust p-type Ga₂O₃ electrical conductivity, will be possible in the foreseeable future, in addition to the use of heterojunction p-n junctions [10].

In Ga₂O₃, once bipolar devices become available, minority carrier transport (diffusion length) will be of primary importance. Minority carrier diffusion length defines performance of bipolar devices such as p-n junction diodes, bipolar transistors, and p-i-n detectors [11]. One of the major issues in the current ZnO and GaN device technology, is the low diffusion length of minority carriers, partially due to dislocation scattering [12, 13]. It has been previously shown that in p-type GaN and ZnO, low energy electron injection, either with an electron beam of Scanning Electron Microscope (SEM) or forward bias, results in a significant increase of the minority carrier (electron) diffusion length [12, 14-17]. Similar effects have been very recently observed in n-type Ga₂O₃ subjected to low energy electron beam injection [18-20].

This paper studies minority carrier transport (electron diffusion length) in p-Ga₂O₃ highly resistive samples subjected to proton irradiation following injection from an SEM electron beam. The below-presented results demonstrate feasibility for a significant diffusion length increase

beyond the initial pre-irradiated values, thus paving the road towards solid-state electron injection in the future Ga₂O₃ bipolar devices.

Undoped β-Ga₂O₃ samples, analyzed in this study, were grown in a RF-heated horizontal MOCVD reactor. Trimethylgallium (TMGa) and 5.5 N pure oxygen were used as gallium and oxygen sources, respectively. Argon was used as the carrier gas (cf. ref. [21]). The β-Ga₂O₃ layer was grown on c-oriented sapphire substrate using Ga/O ratio and growth temperature as 1.4×10^{-4} and 775 °C, respectively. The total reactor pressures of 30-38 Torr and variable growth rates (gallium and oxygen precursor fluxes) were used to have different native defect (V_{Ga} and V_o) concentrations in the Ga₂O₃ films, leading to the different values of hole concentrations.. The epitaxial layer thickness was ~ 450 nm. X-ray diffraction revealed highly textured films of gallium oxide in the β-Ga₂O₃ phase with monoclinic space group (*C2/m*) symmetry.

Ohmic contacts for electrical characterization were prepared by silver paint at the four corners of the sample. Hall Effect measurements were performed in a Van der Pauw configuration in the 500-850 K temperature range for magnetic fields perpendicular to the film plane varying from -1.6 to 1.6 T, using a high impedance high temperature custom-designed measurement set-up. Resistivities at highest measured T = 850 K were found in the range from 1.2×10^3 Ohm·cm to 1.3×10^4 Ohm·cm. Hall Effect measurements demonstrated the positive sign for majority carriers in both samples, thus confirming the p-type conductivity. The free hole concentrations and mobilities at 850 K were estimated in 10^{13} - 5.6×10^{14} cm⁻³ range and 8 - 16 cm²V⁻¹s⁻¹ range, respectively. More details could be found elsewhere [22].

Minority carrier diffusion length (L) measurements were carried out using Electron Beam-Induced Current (EBIC) technique *in-situ* in Phillips XL-30 Scanning Electron Microscope (SEM). Details on EBIC techniques could be found in refs. [12, 13, 22]. The measurements were

carried out in the temperature range of 294-404 K using temperature-controlled stage integrated into the SEM. For EBIC measurements, electron beam energy was kept at 10 keV. The EBIC line-scans for diffusion length extraction were carried out in planar configuration using Ni/Au (20 nm/80 nm) asymmetrical pseudo-Schottky contacts created on the film with lithography/lift-off techniques. Single line-scan takes approximately 12 seconds, which is sufficient for extraction of minority carrier diffusion length value. To perform electron injection in the region of EBIC measurements, line-scans were not interrupted for the total time of up to 400 seconds. The values of diffusion length were extracted intermittently. EBIC signal was amplified with Stanford Research Systems SR 570 low-noise current amplifier and digitized with Keithley DMM 2000 controlled by a PC using a home-made software.

Cathodoluminescence (CL) measurements were carried out under 10 kV accelerating voltage using Gatan MonoCL2 attachment to the SEM. Spectra were recorded with a Hamamatsu photomultiplier tube sensitive in 150-850 nm range and single grating monochromator (blazed at 1200 lines/mm).

Ga₂O₃ samples were irradiated with protons having a dose/energy sequence to create a near-uniform hydrogen concentration around 10¹⁹ cm⁻³. This consisted of 25 keV/1.6 x10¹⁴ cm⁻², 50 keV/1.7x10¹⁴ cm⁻² and 70 keV/3.6x10¹⁴ cm⁻². EBIC and CL measurements were carried out before and after proton irradiation and the results were compared.

The temperature dependence of L before and after proton irradiation is shown in Fig. 1. L decreased with increasing temperature with room temperature values being at 1200 and 630 nm, respectively. Relatively large values of L are partially due to the very low majority carrier concentration. Within the current temperature range of measurements, it is likely that the origin of L decrease is due to phonon scattering [22].

The activation energy for temperature dependence of L is given by [12, 22]:

$$L(T) = L_0 \exp\left(\frac{\Delta E_{A,T}}{2kT}\right). \quad (1)$$

Here, L_0 is a scaling constant, $\Delta E_{A,T}$ is the thermal activation energy, k is the Boltzmann constant, and T is the temperature. The activation energy pertaining to the reduction of L with temperature is estimated at 76 meV after irradiation (113 meV pre-irradiation). A detailed discussion regarding the origin of $\Delta E_{L,T}$ is presented in ref. [22].

Fig. 2 presents results of the electron injection experiments carried out at variable temperature. Minority electron diffusion length exhibits a linear increase with duration of electron injection before saturation occurs (not shown in Fig. 2). The linear increase of L with electron injection duration was previously observed in p-GaN [14], p-ZnO [11], unintentionally doped GaN [23] and n-Ga₂O₃ [18]. Minority carrier diffusion length increase in Fig. 2 is characterized by the rate R (dL/dt; where t is duration of electron injection), which drops from 1.6 nm/s at room temperature to about 0.9 nm/s at 120 °C.

The effect of temperature on rate R is described by [22]:

$$R(T) = R_0 \exp\left(\frac{\Delta E_{A,T}}{2kT}\right) \exp\left(\frac{\Delta E_{A,I}}{kT}\right). \quad (2)$$

Here R_0 is a scaling constant and $\Delta E_{A,I}$ is the electron injection effect activation energy. Equation (2) can be used to find the activation energy of injection-induced component for the increase in L from the Arrhenius plot in the inset of Fig. 3. The latter figure shows R decrease with increasing temperature. The slope of the Arrhenius plot is $\Delta E_{A,I} + 0.5 \Delta E_{A,T}$, from which $\Delta E_{A,I} \sim 91$ meV is obtained. $\Delta E_{A,I}$ is associated with the mechanism responsible for the elongation of L with injected charge. The latter effect is likely associated with gallium vacancy (V_{Ga}), which is a pervasive point defect in undoped Ga₂O₃.

Detailed mechanism for the electron injection-induced L increase is presented in ref. [22] for undoped GaN. This mechanism is also applicable to p-Ga₂O₃ and its key points are outlined as follows:

- A non-equilibrium electron, generated by a Scanning Electron Microscope beam gets trapped by gallium vacancies, which are deep acceptors in Ga₂O₃ [23]. Because of its energetic position in Ga₂O₃ forbidden gap and fairly large concentration in the material ($\sim 10^{18} \text{ cm}^{-3}$) a pronounced number of V_{Ga} remains in neutral state, thus acting as meta-stable electron trap. Trapping non-equilibrium electrons on the V_{Ga} -levels prevents recombination of the conduction band electrons through these levels. This leads to an increase of lifetime, τ , for a non-equilibrium electron in the conduction band and, as a result, to an increase of L ($L = (D\tau)^{1/2}$, where D is carrier diffusivity).
- The V_{Ga} -level containing a trapped electron becomes again available for recombination of a non-equilibrium conduction band electron as this level captures a hole. Capturing a hole means a transition of the trapped electron to the valence band. The rate of this transition increases with increasing temperature, and one notes the existence of the activation energy, preventing the immediate hole capture by negatively charged gallium vacancy. This activation energy is $\Delta E_{\text{A.I.}}$, experimentally estimated at 91 meV.
- As the rate of hole capture on the V_{Ga} -level increases, the conduction band electrons have more chance for recombination on this level. This results in a shorter non-equilibrium minority electron lifetime and a slower rate for L increase at higher temperatures as seen in Fig. 2.

The results in Fig. 2 demonstrate that the adverse impact of proton irradiation can be fully recovered due to electron injection and the diffusion length in the irradiated material can increase even beyond the pre-irradiation values at respective temperatures. Stability of electron injection-

induced increase of diffusion length was studied at room temperature after stopping the electron injection (up to 400 seconds total time at each temperature). It has been found that the increased diffusion length stays unchanged for at least several days.

Fig. 4 demonstrates normalized room temperature CL spectra before and after proton irradiation. Detailed studies of p-Ga₂O₃ optical properties prior to irradiation were recently presented in ref. [22]. Narrowing of CL spectrum after proton irradiation in Fig. 4 is likely related to a variety of complexes, created between V_{Ga} and implanted hydrogen. These complexes may reduce strain-induced broadening of the CL peaks [23]. CL measurements after electron injection into proton-irradiated Ga₂O₃ did not reveal any additional changes in the spectrum (both in terms of shape and intensity), indicating that the injection-induced increase of non-equilibrium carrier lifetime is mostly non-radiative in nature.

In summary, electron injection from SEM beam was employed to “heal” the adverse impact of proton irradiation on minority carrier transport in p-type Ga₂O₃. The obtained results demonstrate that reduction of the diffusion length due to irradiation could be fully recovered, and L can even exceed the pre-irradiation values. The effect was ascribed to non-equilibrium electron trapping on native defects (V_{Ga}) and consequent increase of minority carrier (electron) lifetime in the conduction band of Gallium Oxide. Once Ga₂O₃ p-n junctions become available, a solid-state electron injection due to forward-bias (injection of electrons from n-side of p-n junction into p-side due to applying a negative voltage to n-type material) will be attempted, thus paving the road towards purely electrical (athermal) mitigation of radiation-induced defects in bipolar devices. This type of defect mitigation does not require high temperature annealing or changes in technological processes, which are both costly. Additionally, based on the results obtained so far,

the process of electron injection requires only seconds, while the induced improvements of minority carrier transport are stable for days.

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Data Availability

The data that supports the findings of this study is available within the article.

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Figure Captions

Figure 1:

Temperature dependence of diffusion length in the structure before and after irradiation with high energy protons (25 keV $1.6 \times 10^{14} \text{ cm}^{-2}$ + 50 keV, $1.7 \times 10^{14} \text{ cm}^{-2}$ + 70 keV, $3.6 \times 10^{14} \text{ cm}^{-2}$).

Figure 2:

The change in diffusion length as a function of duration of electron injection for temperatures in 294-393 K range. Pre-irradiation diffusion length values are shown in red color. The activation energy $\Delta E_{A,I}$, obtained from L dependence on electron injection duration at variable temperature, is estimated at 91 meV using equation (2).

Figure 3:

Temperature dependence of the rate (R) for change in L with time. **Inset:** Arrhenius plot of equation (2) for calculation of activation energy for the effect of electron injection.

Figure 4:

Normalized room-temperature cathodoluminescence spectrum before and after proton irradiation. A slight blue shift of the irradiation peak with smaller full width at half-maxima was observed after irradiation.

Figure 1

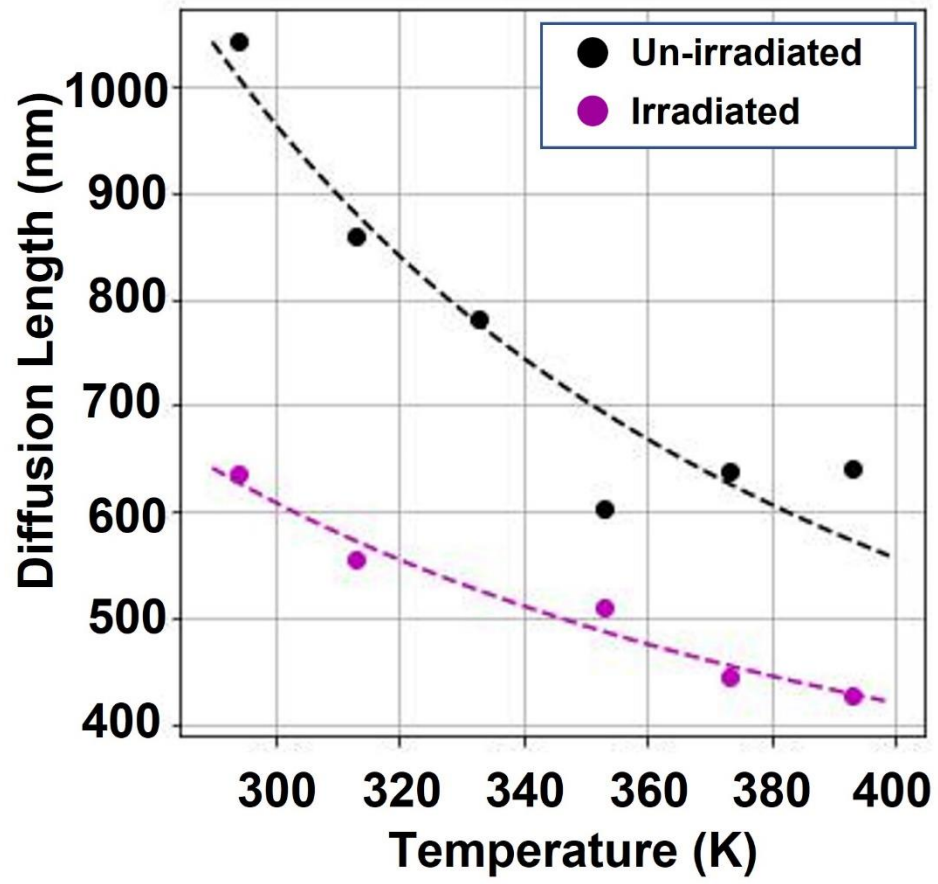


Figure 2

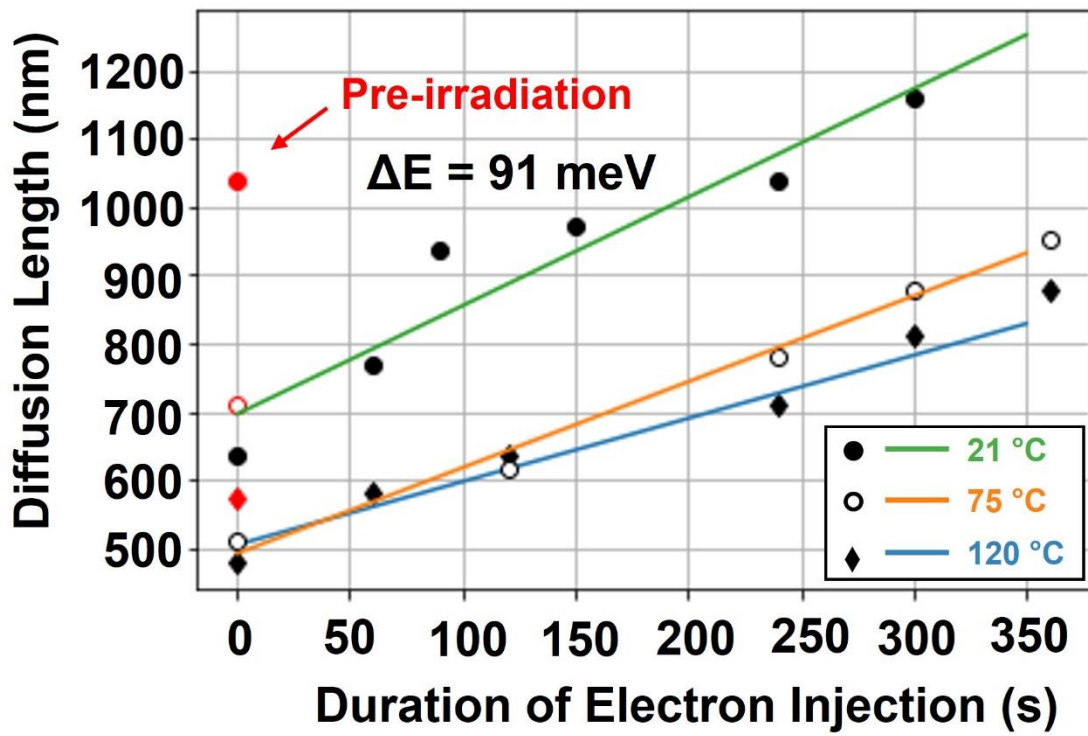


Figure 3

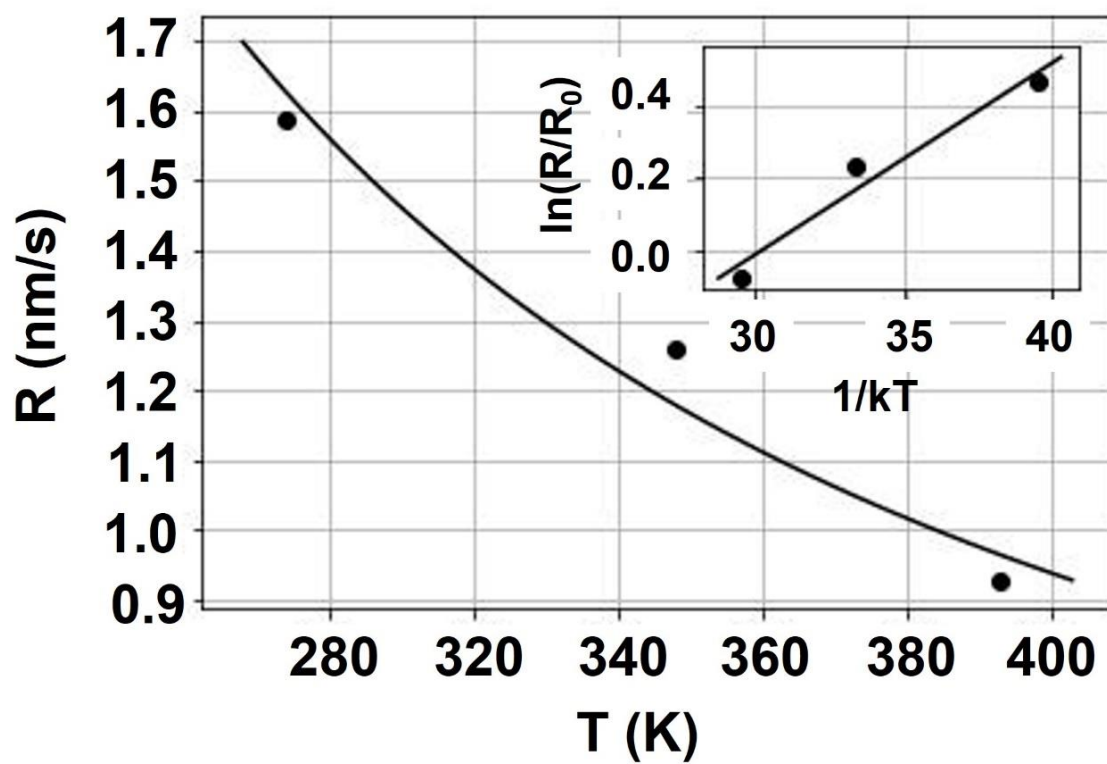


Figure 4

