SPS internal use

Progress Report Received	

SPS Reference:	G-5748

Emerging Security Challenges Division

Science for Peace and Security Programme

Multi-Year Project Final Report

insert project title

Radiation and electron injection in Gallium Oxide for deep-UV detection

submit completed report in **Microsoft Word format** to sps.admin@hq.nato.int

---

Project Start Date	Project Duration	Date of this Report
November 15, 2020	**36 months**	**November 14, 2023**

Project Co-Directors

	Title and Name	Institution	Country	email
NPD	Dr. rer. nat. Alfons Schulte	University of Central Florida	USA	Alfons.Schulte@ucf.edu
PPD	D.Sc. Arie Ruzin	Tel Aviv University	Israel	ruzin@tauex.tau.ac.il

Abstract & Current Status

provide an abstract of the project and its accomplishments (no more than one-half page)

This project is focused on the exploration of the novel effect of electron injection in the representative range of Ga_2O_3 device structures for electrical mitigation of radiation-induced defects, thus proceeding towards radiation hard and efficient devices for deep-UV radiation detection. **Gallium Oxide is an ultra-wide bandgap radiation hard semiconductor, which is of particular interest in true solar-blind photovoltaic detectors for early missile launch warning.** Fundamental aspects of this research are in better understanding of radiation–semiconductor interaction as well as of the nature of radiation-induced defects and p-type doping limitations in Ga_2O_3.

In **milestone 2** of this project, temperature dependent continuous and time-resolved cathodoluminescence measurements were employed to understand the luminescence from Si-doped β-Ga_2O_3 prior to irradiation and after 10 MeV proton and 18 MeV alpha-particle irradiation.

In **milestone 3** optical signatures of the acceptor levels associated with V_{Ga}^{-}-V_O^{++} complex were identified in p-Ga_2O_3 thin films employing temperature dependent EBIC and cathodoluminescence measurements.

In **milestone 4** we demonstrated that Zn doping of β-Ga_2O_3/r-sapphire thin film grown by MOCVD technique can exhibit a long-time stable room-temperature hole conductivity with the conductivity activation energy of around 86 meV. The origin of this level might be attributed then the donor-acceptor complex $V_O^{++} - Zn_{Ga}^{-}$.

Finally, pending robust Ga_2O_3 based homojunction fabrication, the charge injection effect was demonstrated in p-n NiO/Ga_2O_3 heterojunction. More than 200% increase in photoresponse was achieved within 600 seconds of solid-state charge injection.

In collaboration **with the end-user** (Tower Jazz, Israel), the prototype instrument for controlling and enhancing the photoresponse was demonstrated.

Project Goals

summarize the major goals and objectives of the project; highlight any changes from the project plan or previous reports (this is unusual)

The main objectives of this NATO collaborative project are as follows:

- To investigate the influence of gamma (proton, ion, alpha) irradiation on the minority carrier transport in ultra-wide bandgap semiconductors: minority carrier diffusion length and lifetime.
- To identify and study radiation-induced defects and their impact on fundamental material’s properties on the one hand, and device functionality on the other.
- To characterize the effects of irradiation on the figures of merit (spectral and temporal photoresponse and noise) of photodetector device structures and to determine solid-state forward-bias electron injection regimes leading to improved functionality.
- To study the mechanism and impact of annealing on the above-mentioned properties.

- To demonstrate device applications of charge injection-induced effect.
- To demonstrate a prototype device.

Summary of Accomplishments

summarize accomplishments under these goals

While working on the project, the effect of electron (charge) injection in the solid state was studied in the Gallium Oxide device structures (Schottky barriers and p-n heterojunctions) as a function of temperature and injection duration. The impact of charge injection on minority carrier transport (lifetime and diffusion length) was identified for the structures subjected to the different irradiation types – high energy electrons, protons, and alpha particles was identified. Recovery of transport properties after irradiation was demonstrated as a result of electron beam or solid-state charge injection. Enhancement of photoresponse was also achieved in p-n heterojunction structures. Finally, a prototype instrument for device performance control was demonstrated.

Accomplishments

detail accomplishments and progress achieved by this project

Non-equilibrium carrier recombination in beta Gallium Oxide irradiated with alpha particles and protons

In ref. [1], non-equilibrium minority carrier dynamics was studied using EBIC and TRCL in Ga_2O_3 n-type samples subjected to alpha and proton irradiation. The structures, like those described Fig. 1, were used in the experiments. For the Schottky contacts under test, the calculated maximum electric field was 0.1 MV/cm at zero bias, and the barrier height was estimated at 1.08 V.

Several samples were selected for 10 MeV (5×10^{14} cm^{-2} fluence; 330 μm range in the material) irradiation with protons and 18 MeV (1×10^{12} cm^{-2} fluence; 80 μm range in the material) irradiation with alpha particles. The beam current of the cyclotron (Korean Institute of Radiological and Medical Science) was 100 nA in case of both irradiation types. Removal rates for carriers in the proton-irradiated and alpha-irradiated structures were around 240 cm^{-1} and 400 cm^{-1}, respectively. More details are outlined in ref. [2].

The minority carrier diffusion length dependence on temperature for all above-referenced samples (diodes) is shown in Fig. 2. $\Delta E_{L,T}$ shows a modest dependence on temperature. In previous investigations of GaN [3], ZnO [4], and Ga_2O_3 [4,5], $\Delta E_{L,T}$ having larger values were ascribed to traps in the forbidden gap. A likely reason for reduced (with increasing temperature) activation energy, reported in ref. [1] and shown in Fig. 2, is related to a more pronounced carrier recombination. An additional factor, which contributes to the low values of $\Delta E_{L,T}$, is attributed to the relatively small value of minority carrier diffusion length in ref. [1], as compared to other reported values [6,7]. Lower electron beam current was used in ref. [1] to minimize the impact electron injection-induced effects on minority carrier diffusion length.

A time-resolved CL streak of the UV emission, centered around 380 nm in β-Ga_2O_3, is presented in Fig. 3 (with continuous CL spectra reported in ref. [6]) and is in agreement with a single exponential decay.

The lifetime, τ, exhibits a decrease from 572 ps to 464 ps, through the intermediate value of 523 ps at 77 K for control, α-, and proton-treated samples, respectively (Fig. 4). The room temperature values are correspondingly 168 ps, 159 ps, and 154 ps. The measured room temperature value of lifetime for the control sample is in agreement with that of 215 ps, previously reported in ref. [6]. The irradiated diodes experience creation of additional point defects because of radiation damage and, therefore, demonstrate a decrease in minority carrier diffusion length and lifetime [5, 8, 9, 10]. L and τ were largest for the control diode, followed by alpha- and proton-irradiated structures. This was explained by the fluence of protons being over a factor of 2 larger, as compared to alpha-irradiation.

Minority carrier transport and radiation impact in undoped highly resistive Ga_2O_3

Undoped and highly resistive 450 nm-thick β-Ga2O3 epitaxial layers were tested [8,11], using the EBIC technique. The epitaxial layers were grown by Metal-Organic Chemical Vapor Deposition with more details on growth and characterization outlined in refs. [12].

The samples under test were denoted as A and B. The minority carrier diffusion length decreased with increasing T in these samples, with values for A and B of 1040 and 8506 nm at 304 K, respectively, and 640 and 6193 nm at 404 K, respectively. Fairly long minority carrier diffusion length in the above-referenced samples was partially ascribed to the low majority carrier concentrations. The root cause for L reduction with T was attributed to phonon scattering [13]. As was already mentioned, minority carrier (holes) diffusion length in n-type β- Ga_2O_3 is within the 50–600 nm range [5, 6, 7, 9] and is lower than that for minority carrier electrons, as reported in ref. [12]. One of the explanations for this experimental finding is related to a large (18.8 m0) effective mass for holes [14]. A similar dependence of L on T is revealed in n-type β-Gallium Oxide, and it is linked to scattering on ionized Si impurities (due to heavy doping) [6].

$\Delta E_{L,T}$, related to decrease of L with T, was found to be 67 meV (sample A) and 113 meV (sample B). This activation energy matches that for thermal quenching of CL intensity (ΔE_{CL}): 67 and 88 meV for sample A ($\Delta E_{L,T}$ and ΔE_{CL}, respectively); 113 and 101 meV for sample B ($\Delta E_{L,T}$ and ΔE_{CL}, respectively). Proximity of the values for $\Delta E_{L,T}$ and ΔE_{CL} serves as a proof for same origin of both processes, with the likely reason related to thermal de-trapping of electrons from the V_{Ga}^{-}-V_O^{++} complexes, creating acceptor levels in Ga_2O_3 forbidden gap.

A series of separate EBIC measurements was carried out on another Ga_2O_3 sample, showing comparable or higher (relative to the samples A and B) free hole concentration [8]. The sample was subjected to high energy proton irradiation (cf. Fig. 5 for doses and energies) with L measurements carried out prior to and following the exposure to proton beam, as demonstrated in Fig. 5. $\Delta E_{L,T}$ was found at 76 meV after irradiation (113 meV prior to irradiation).

Electron injection impact of on minority carrier diffusion and optical properties in Ga_2O_3

A single EBIC line-scan, needed for extraction of L, lasts approximately 10^{-12} s. For electron injection in the region of diffusion length measurements, a motion of electron beam was continuous for up to ~ 350 s (42.8 pC/μm^3 injected charge density) [8], with diffusion length being extracted intermittently. Note that the electrons of SEM beam, which serve for non-equilibrium electron–hole pairs generation in Ga_2O_3, due to transitions of excited electrons from the valence to the conduction band, aren't accumulated in the sample, as it is grounded. The electroneutrality is, therefore, preserved.

Ref. [15] reported the radiation ionization energy, needed for electron–hole pair creation, to be ~ 16 eV for β- Ga_2O_3 Accounting for the density of injected charge to be ~ 43 pC/μm^3 and ~ 625 electron–hole pairs, generated in this volume (10 000 eV/16 eV), ~ 10^{23} cm^{-3} non-equilibrium density of electron–hole pairs was obtained for the experimental regimes of the work outlined in ref. [8]. Hence, L values, given in this sub-section, are relevant to the non-equilibrium carriers with concentrations significantly higher than those, obtained from the Hall effect measurements. In the electron beam proximity (during the EBIC measurements), the amount for non-equilibrium majority and minority carriers is equal (the concentration for both carriers significantly exceeds the equilibrium Hall majority carrier concentration at given T), thus avoiding a high injection level regime [8].

Fig. 6 demonstrates L versus duration of electron injection dependence at variable temperature for highly resistive p- Ga_2O_3. L increases linearly with duration of electron injection before saturation (not shown in Fig. 6). The linear increase of minority carrier diffusion length with injection duration was reported in ref. [5] for n- Ga_2O_3.

The rate R (dL/dt, where t is the duration of electron injection) characterizes the L increase in Fig. 14. R decreases from 2 nm/s at room temperature to about 1 nm/s at 120 °C. R on T dependence is described by [19]:

$$R(T) = R_0 \exp\left(\frac{-\Delta E_{A,T}}{2k_B T}\right) \exp\left(\frac{\Delta E_{A,I}}{k_B T}\right). \tag{1}$$

Here, R_0 is a scaling constant; $\Delta E_{A,I}$ is the activation energy for the electron injection effect.

Eqn. (1) was used in ref. [8] to find $\Delta E_{A,I}$ component for L increase from the Arrhenius plot in the inset of Fig. 7, which shows R decrease with increasing temperature. The Arrhenius plot slope is defined as $\Delta E_{A,I}$ + 0.5 $\Delta E_{A,T}$, from which $\Delta E_{A,I}$ ~ 91 meV was obtained. $\Delta E_{A,I}$ is related to the mechanism responsible for the elongation of minority carrier diffusion length with injected charge. It was suggested that the observed effect is linked with the Gallium Vacancy (V_{Ga},), which is a dominant point defect in undoped Ga_2O_3.

Fig. 6 proves that the negative influence of proton irradiation on L can be fully restored using electron injection. Furthermore, at respective temperatures, L in the irradiated material can increase above the pre-irradiation values. Dynamics of increased L relaxation to the base level was investigated at RT after stopping the electron injection, which lasted up to about 350 s. L was found to stay unchanged for at least several days.

RT CL spectra are shown in Fig. 8 before and after proton bombardment. Thorough investigation of the optical properties for highly resistive Gallium Oxide was recently published by the authors in ref. [11]. A narrower FWHM luminescence spectrum after proton bombardment, which is shown in Fig. 8, was ascribed to various complexes (point defects) created between V_{Ga} and hydrogen, incorporated during proton exposure. These point defects likely lead to reduction of strain broadening for the observed luminescence [16] with no additional changes, both in terms of shape and intensity, indicating that the injection-related increase in lifetime for non-equilibrium carriers is mostly non-radiative.

Results, like those in Fig. 6, were obtained for n-type Ga_2O_3 (under similar electron beam excitation conditions) and are presented in Fig. 10 [5]. Fig. 10 (top inset) demonstrates the EBIC line-scans for different incremental injection durations up to 720 seconds. Longer tails for a decay of the EBIC signal correspond to the elongated L. Simultaneously, a pronounced increase of the EBIC amplitude is observed (cf. top and bottom insets of Fig. 9) and is explained by enhanced collection efficiency of minority carriers [17, 18]. I_{max}, in the bottom insert of Fig. 9, increases up to a certain value of L. Afterwards, any increase in L (cf. Fig. 9, top inset) doesn't affect the amplitude of induced currents. Following Imax (see bottom inset of Fig. 9), L saturates as well (not shown in Fig. 9) and persists for more than one day at RT after injection is stopped.

The root cause for the phenomenon of electron injection in Gallium Oxide

Ref. [19] outlines mechanism (cf. Fig. 10) of the electron injection phenomenon for undoped GaN, which is also applicable to Ga_2O_3:

- Direct band-to-band recombination (cf. Fig. 10, a, b) is not available in Ga_2O_3 due to the assumed presence of self-trapped holes. As a result, non-equilibrium electron, generated by an SEM beam, is trapped by V_{Ga}, acting as deep acceptors in Gallium Oxide (cf. Fig. 10, c). A fairly large concentration (10^{18} cm^{-3}) of V_{Ga} remains in the neutral state in the material, thus acting as a meta-stable electron trap. Capturing non-equilibrium electrons on V_{Ga}, prevents recombination of the non-equilibrium conduction band electrons through the trap levels (cf. Fig. 10, d). This results in an increased lifetime and, consequently, to a larger *L* [$L = (Dt)^{1/2}$, where *D* is the carrier diffusivity].
- V_{Ga}-levels, containing trapped electrons, become again available for recombination as these levels capture holes, meaning a transition, which is temperature dependent, of trapped electrons to the valence band (cf. Fig. 10, e). The existence of the activation energy, which prevents near simultaneous hole capture by the negatively charged V_{Ga}, is noted. $\Delta E_{A,I}$, is experimentally estimated at 91 meV.

- With increasing hole capture on Gallium vacancies, the non-equilibrium electrons in the conduction band have more chances for recombination on the respective energetic levels. This leads to a reduced t and a slower rate for L increase at higher temperatures, as seen in Fig. 6.
- Only neutral V_{Ga}-levels may trap non-equilibrium electrons. Therefore, the electrical conductivity of the sample under test is not impacted.

Application of the charge injection effect to performance control of Ga_2O_3-based photodetectors

Pending robust homoepitaxial Ga_2O_3 p-n junction fabrication, application of electron injection effect for device performance enhancement is presented through the example of a p-NiO/n-Ga_2O_3 heterojunction structure, which is shown in Fig. 11. In this structure, the charge is injected from the p-NiO layer into that of n-Ga_2O_3, due to forward bias application (a positive bias was applied to the top Nickel Oxide layer for the duration of up to 600 seconds), thus inducing a current of 100 mA through the structure, corresponding to the charge density of ~ 8 nC/mm^3 (it is two orders of magnitude larger than that, created by an electron beam for the diffusion length increase in Figs. 6, 9).

Similar to electron beam injection in Figs. 6, 9, the forward bias charge injection results in an increase of minority carrier diffusion length in 10-mm thick Gallium Oxide layer. Although L was not directly measured, more than 200% increase of the peak photoresponse, shown in Fig. 12, provides experimental evidence for its elongation. Ref. [20] reported a similar photoresponse enhancement in forward-biased GaN p-n junction and suggested the mechanism for this effect. Experiments are underway [21] for detailed study of the effect of charge injection in Gallium Oxide device structures, and this will be the subject of future publications.

Summary

In summary, while irradiation with energetic particles and increasing temperature lead to decrease of minority carrier diffusion length, charge injection using SEM mitigates the negative influence of radiation on carrier recombination in Ga_2O_3. It is demonstrated that L, decreased because of energetic particle bombardment, could be returned to the initial values or increase above them. The effect was attributed to non-equilibrium carrier trapping on native defects (V_{Ga}) and consequent increase in t. With Ga_2O_3 p–n junctions becoming feasible, a solid-state charge injection, due to bias, will be employed (as in Fig. 12), thus paving the road towards purely electrical (athermal) mitigation of radiation-induced defects in bipolar devices.

References

1. Modak, S., L. Chernyak, A. Schulte, M. Xian, F. Ren, S.J. Pearton, I. Lubomirsky, A. Ruzin, S.S. Kosolobov, and V.P. Drachev, "Electron beam probing of non-equilibrium carrier dynamics in 18 MeV alpha particle- and 10 MeV proton-irradiated Si-doped β-Ga_2O_3 Schottky rectifiers", Appl. Phys. Lett., 118 (20) 202105, (2021).
2. Yang, J., Z. Chen, F. Ren, S.J. Pearton, G. Yang, J. Kim, J. Lee, E. Flitsiyan, L. Chernyak, and A. Kuramata, "*10 MeV proton damage in β-Ga2O3 Schottky rectifiers*", J. Vac. Sci. Technol. B:Nanotechnol. Microelectron., **36** (1) (2018).
3. Modak, S., L. Chernyak, I. Lubomirsky, and S. Khodorov, "Continuous and Time-Resolved Cathodoluminescence Studies of Electron Injection Induced Effects in Gallium Nitride", in Advanced Technologies for Security Applications (2020), Dordrecht, Springer Netherlands.
4. Modak, S. L., A. Ruzin, A. Schulte, and L. Chernyak, "Influence of energetic particles and electron injection on minority carrier transport properties in Gallium Oxide", under review (2023).
5. Modak, S., J. Lee, L. Chernyak, J. Yang, F. Ren, S.J. Pearton, S. Khodorov, and I. Lubomirsky, "Electron injection-induced effects in Si-doped β- Ga_2O_3", AIP Adv., **9** (1) 015127, (2019).
6. Lee, J., E. Flitsiyan, L. Chernyak, J. Yang, F. Ren, S.J. Pearton, B. Meyler, and Y.J. Salzman, "Effect of 1.5 MeV electron irradiation on β- Ga_2O_3 carrier lifetime and diffusion length", Appl. Phys. Lett., 112 (8) 5, (2018).
7. Yakimov, E.B., A.Y. Polyakov, N.B. Smirnov, I.V. Shchemerov, J. Yang, F. Ren, G. Yang, J. Kim, and S.J. Pearton, "Diffusion length of non-equilibrium minority charge carriers in β- Ga_2O_3 measured by electron beam induced current", J. Appl. Phys., 123 (18) (2018).
8. Modak, S., A. Schulte, C. Sartel, V. Sallet, Y. Dumont, E. Chikoidze, X. Xia, F. Ren, S.J. Pearton, A. Ruzin, and L. Chernyak, "Impact of radiation and electron trapping on minority carrier transport in p-Ga_2O_3", Appl. Phys. Lett., 120 (23) (2022).
9. Polyakov, A.Y., N.B. Smirnov, I.V. Shchemerov, E.B. Yakimov, S.J. Pearton, C. Fares, J. Yang, F. Ren, J. Kim, P.B. Lagov, V.S. Stolbunov, and A. Kochkova, "Defects responsible for charge carrier removal and correlation with deep level introduction in irradiated β- Ga_2O_3", Appl. Phys. Lett., 113 (9) 092102, (2018).
10. Pearton, S.J., A. Aitkaliyeva, M. Xian, F. Ren, A. Khachatrian, A. Ildefonso, Z. Islam, M.A. Jafar Rasel, A. Haque, A.Y. Polyakov, and J. Kim, "Review—Radiation Damage in Wide and Ultra-Wide Bandgap Semiconductors", ECS J. Solid State Sci. Technol., 10 (5) 055008, (2021).
11. Modak, S., L. Chernyak, A. Schulte, C. Sartel, V. Sallet, Y. Dumont, E. Chikoidze, X. Xia, F. Ren, S.J. Pearton, A. Ruzin, D.M. Zhigunov, S.S. Kosolobov, and V.P. Drachev, "Variable temperature probing of minority carrier transport and optical properties in p- Ga_2O_3", APL Mater., 10 (3) 031106, (2022).

12. Chikoidze, E., C. Sartel, H. Mohamed, I. Madaci, T. Tchelidze, M. Modreanu, P. Vales-Castro, C. Rubio, C. Arnold, V. Sallet, Y. Dumont, and A. Perez-Tomas, "Enhancing the intrinsic p-type conductivity of the ultra-wide bandgap Ga_2O_3 semiconductor", J. Mater. Chem. C, 7 (33) 10231, (2019).
13. Chi, Z., C. Sartel, Y. Zheng, S. Modak, L. Chernyak, C.M. Schaefer, J. Padilla, J. Santiso, A. Ruzin, A.-M. Goncalves, J. von Bardeleben, G. Guillot, Y. Dumont, A. Perez-Tomas, and E. Chikoidze "Native defect association in β- Ga_2O_3 enables room-temperature p-type conductivity". arXiv:2306.01115 (2023).
14. Adnan, M.M.R., D. Verma, Z. Xia, N.K. Kalarickal, S. Rajan, and R.C. Myers, "Spectral Measurement of the Breakdown Limit of β− Ga_2O_3 and Tunnel Ionization of Self-Trapped Excitons and Holes", Phys. Rev. Appl., 16 (3) 034011, (2021).
15. Yakimov, E.B., A.Y. Polyakov, I.V. Shchemerov, N.B. Smirnov, A.A. Vasilev, P.S. Vergeles, E.E. Yakimov, A.V. Chernykh, F. Ren, and S.J. Pearton, "Experimental estimation of electron–hole pair creation energy in β- Ga_2O_3", Appl. Phys. Lett., 118 (20) 202106, (2021).
16. Karjalainen, A., P.M. Weiser, I. Makkonen, V.M. Reinertsen, L. Vines, and F. Tuomisto, "Interplay of vacancies, hydrogen, and electrical compensation in irradiated and annealed n-type β-Ga2O3", J. Appl. Phys., 129 (16) 165702, (2021).
17. Ledra, M. and N. Tabet, "Monte Carlo simulation of the EBIC collection efficiency of a Schottky nanocontact", Superlattices and Microstructures, 45 (4-5) 444, (2009).
18. Yakimov, E.B., S.S. Borisov, and S.I. Zaitsev, "EBIC measurements of small diffusion length in semiconductor structures", Semiconductors, 41 (4) 411, (2007).
19. Modak, S., L. Chernyak, M.H. Xian, F. Ren, S.J. Pearton, S. Khodorov, I. Lubomirsky, A. Ruzin, and Z. Dashevsky, "Impact of electron injection on carrier transport and recombination in unintentionally doped GaN", J. Appl. Phys., 128 (8) 085702, (2020).
20. Chernyak, L., A. Schulte, A. Osinsky, J. Graff, and E.F. Schubert, "Influence of electron injection on performance of GaN photodetectors", Appl. Phys. Lett., 80 (6) 926, (2002).
21. Schulte, A., S. Modak, Y. Landa, A. Atman, J.-S. Li, C. C. Chiang, F. Ren, S. J. Pearton, and L. Chernyak, "Impact of solid-state charge injection on spectral photoresponse of NiO/ Ga_2O_3 heterojunction", under review (2023).

Figure Captions

Figure 1: Vertical Schottky rectifiers used for EBIC measurements.

Figure 2: Temperature dependence of *L* for various radiation types.

Figure 3: A streak of time-resolved CL, acquired at RT for reference structure, and its raw image (inset).

Figure 4: Lifetime versus temperature dependence for structures irradiated by various particles.

Figure 5: *L* versus *T* dependence prior to and following bombardment with high energy protons having energy/dose sequence as: 25 keV, 1.6 x 10^{14} cm^{-2} + 50 keV, 1.7 x 10^{14} cm^{-2} + 70 keV, 3.6 x 10^{14} cm^{-2}.

Figure 6: *L* versus duration of electron injection dependence at variable temperature for highly resistive p-Ga_2O_3. *L* values for 0 injected charge are shown in open circle (21 ^oC), square (75 ^oC), and triangle (120 ^oC). $\Delta E_{A,I}$, obtained from *L* dependence on injection duration at varying *T*, is estimated at 91 meV using eqn. (1).

Figure 7: *R* versus *T* dependence. Inset: Arrhenius plot of eqn. (1) for calculation of $\Delta E_{A,I}$.

Figure 8: Normalized continuous RT CL spectrum before and after proton irradiation. A blue shift and smaller full width at half-maximum (FWHM) were observed for CL spectrum after irradiation.

Figure 9: L increase as a function of electron beam injection. Inset (top): EBIC line-scans for different incremental electron injection durations. Inset (bottom): Electron Beam-Induced Current amplitude dependence on duration of injection.

Figure 10: Model for the electron injection-induced effect (on the example of electron beam irradiation, which generates non-equilibrium electron-hole pairs).

Figure 11: Architecture of the vertical p-NiO/n-Ga_2O_3 heterojunction structure.

Figure 12: Spectral photoresponse of the structure in Fig. 11 before and after incremental charge injection. The charge, corresponding to 600 seconds of injection, is 60 mC. The effect persists for at least several hours.

Figure 1

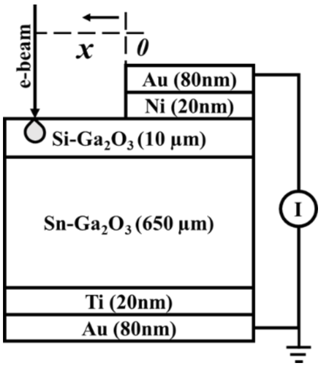


Figure 2

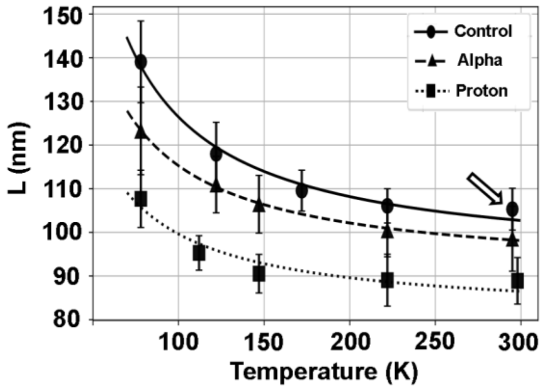


Figure 3

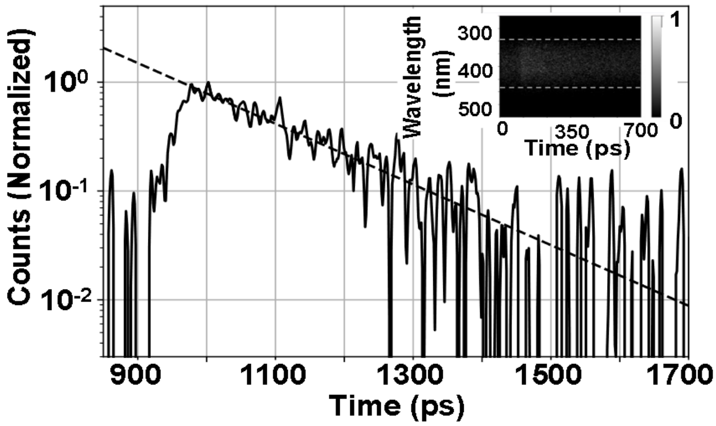


Figure 4

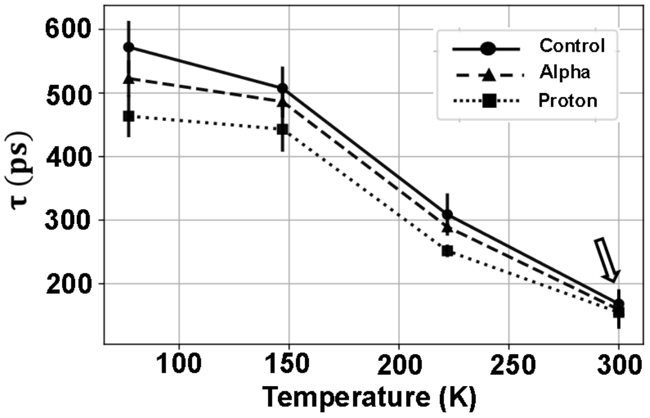


Figure 5

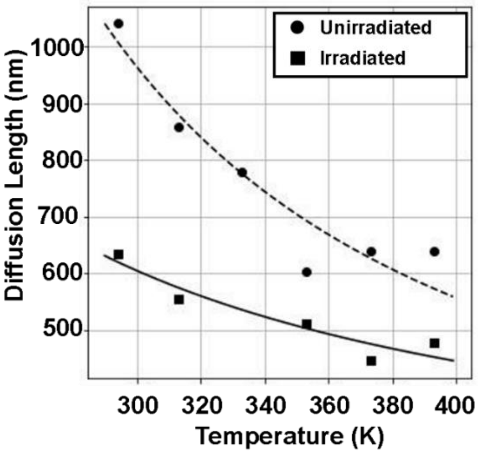


Figure 6

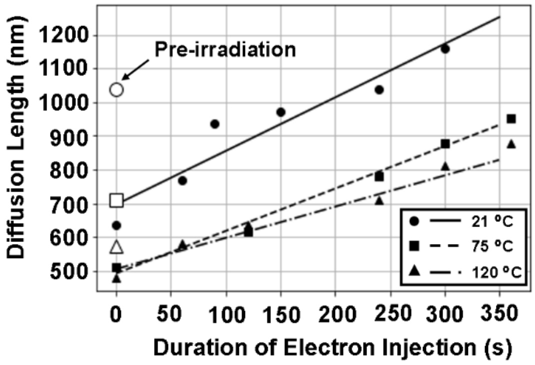


Figure 7

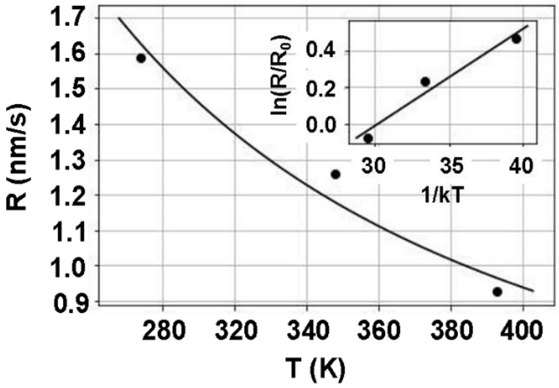


Figure 8

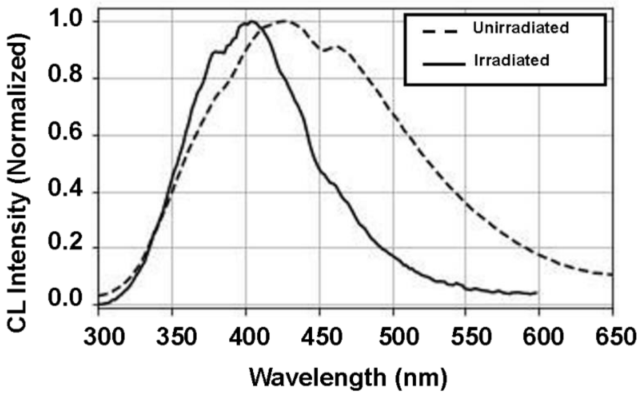


Figure 9

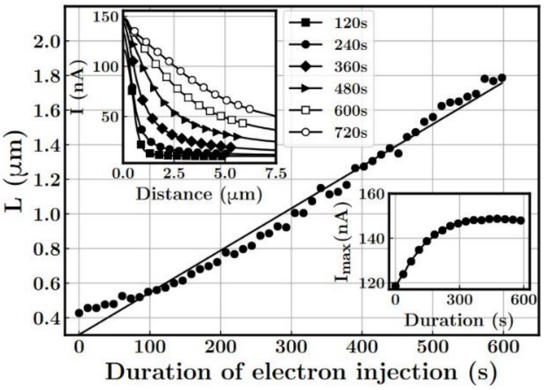


Figure 10

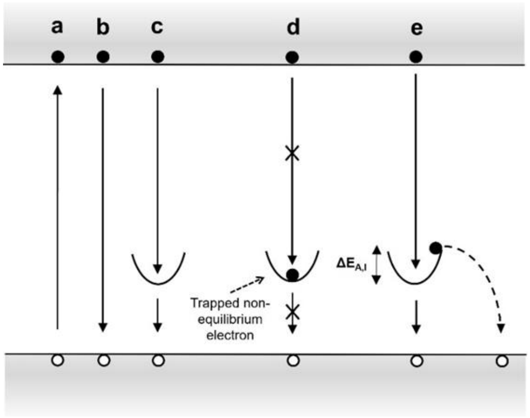


Figure 11

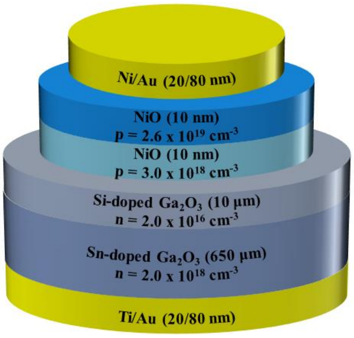
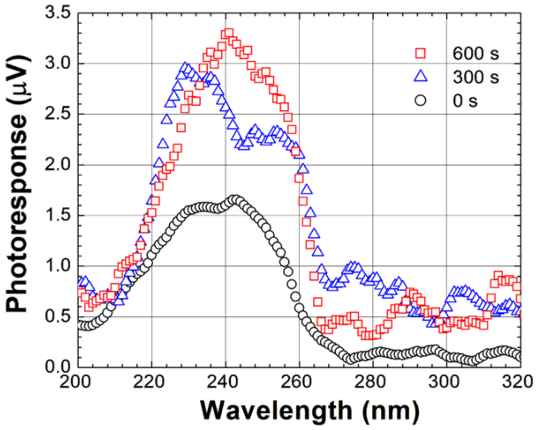


Figure 12



Collaboration

detail the collaboration and consultation among co-directors and their groups

Since the kickoff meeting in November 2020, both groups worked according to the time-schedule shown below.

Milestones & Deliverables

list project milestones and deliverables their current status; if they are not complete, explain and detail the impact on the project outcomes

		1st year				2nd year				3d year				
	Quarter:	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	
Milestone														
1	UV photodetector processing	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
2	Irradiation of devices	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
3	Dark property characterization		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
4	Spectral and temporal testing before and after gamma irradiation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					
5	Irradiation impact on minority carrier transport		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
6	Irradiation impact on minority carrier lifetime			🟩	🟩	🟩	🟩							
7	Irradiation impact on extended defects				🟩	🟩	🟩	🟩	🟩	🟩				
8	Irradiation impact on point defects			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
9	Correlation of electron injection regimes and thermal budget with gamma irradiation dose		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
				Device structures and irradiation regimes are defined			Irradiation impact on majority carrier transport is determined		Irradiation impact on minority carrier transport is determined	Irradiation impact on extended defects is determined	Irradiation impact on point defects is determined	Irradiation impact on lifetime is determined	Injection & thermal regimes & irradiation dose are correlated	**Deliverable**
			Rep. 1		**Rep. 2**		**Rep. 3**				**Rep. 4**		**FINAL**	

All project objectives were met and milestones reached.

Training & Professional Development

detail training and professional development activities

Leonid Chernyak, a participant in the project, made several extended trips to the NPD laboratory to deploy a DLTS setup and study the technique.

Arie Ruzin, PPD, visited UCF (two visits) to participate in time-resolved CL experiments.

Impact

describe the impact of the project on the scientific community and the public

The impact of this project is in finding regimes of solid-state electron injection for improving the minority carrier transport in UV-blind photodetectors. To the best of our knowledge, this study for the first time experimentally demonstrates that in β-Ga_2O_3:

1. The diffusion length of the minority carriers can be manipulated (significantly improved) using electron injection in β-Ga_2O_3.
2. At room temperature and above, holes may contribute substantially to the current in the material, as opposed to their self-trapping nature reported previously.
3. The effect of charge injection can be used for device (photodetector) performance control.

Implementation

detail how the results of this project have been, are being, and will be implemented

With the recent demonstration of device applications for charge injection-induced effects and in view of approved continuation of the project, the team will be working with the end user to improve a demonstrated prototype and to achieve a TRL 4 in the near future.

Our technology will first be implemented in UV imagers based on the NiO/Ga_2O_3 heterostructures and intended for missile seekers that must operate in an environment with energetic particle radiation. Rapid technology transfer and low-risk commercial opportunity will be sought through strategic alliance with Tower Jazz.

Our technology will be applicable to Balistic Missile Defense System (BMDS) components that include UV imaging arrays for interceptor seekers such as Space Tracking and Surveillance System (STSS), with satellites orbiting at 1350 km since 2009. STSS uses UV sensors as part of an experimental space tracker for the BMDS. STSS is validating remote sensor and fire control integration to influence the design and operations of the next generation tracker. Our technology is applicable to those next generation trackers.

Electric circuitry and a prototype instrument for photoresponse monitoring and electron injection are shown in Fig. 13 below.

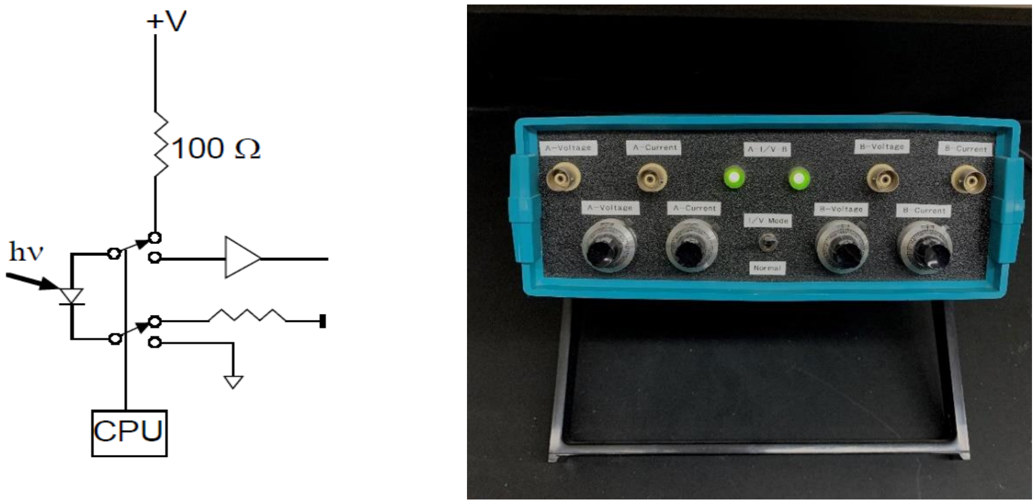


Figure 13. Left: Schematics of photodetector integration with biasing/monitoring circuitry. The logic switch, controlled by CPU, is shown in the upper position and the photodetector (diode) is connected to current/voltage source for forward bias pulsing. Once a pulse is completed, CPU connects the photodetector to the amplifier for a normal operation (lower switch position). **Right:** Prototype instrument for photoresponse monitoring and electron injection

Project Participants and Roles

list the participants in the project and the rough fraction of their time spent on it;
describe briefly how each contributed to the project;
add or subtract rows as needed

Name	cAffiliation	Position/Title	% Time	Role
Alfons Schulte	University of Central Florida (UCF)	Professor	25%	Studies of irradiation impact on Ga_2O_3 fundamental properties and point defects. Studies of irradiation impact on photodetector's performance. Coordination of device irradiation with Nordion and Orlando Health Center. Supervision and project management. Leading virtual coordination meetings. Visit the PPD site at Tel Aviv University and the End-User site in Israel.
Arie Ruzin	Tel Aviv University (TAU)	Associate Professor	25%	Coordination of efforts at Tel Aviv University. Studies of irradiation impact on point and extended defects and on dark performance. Study of annealing effects. Participation at virtual coordination meetings and coordination of efforts with the End-User. Visit the NPD site at UCF.
Leonid Chernyak	UCF	Professor	15%	Studies of irradiation impact on minority carrier transport and lifetime.
Sushrut Modak	UCF	Ph.D. student	100%	Studies of irradiation impact on photodetector’s figures of merit.
A Brovko	TAU	Ph.D. student	100%	Study of irradiation effect on deep level formation and afterward annealing.
A Adelberg	TAU	Young Scientist	100%	Maintenance of scientific equipment, help with experimental work and training of graduate students, operation of atomic force microscope.
Yakov Roizin	Tower Jazz Ltd.	Director of Emerging Technologies	10%	Device fabrication. Biasing and monitoring circuitry design and prototyping. Interaction with NPD and PPD and their groups.
Eric Rende	UCF	Ph.D. student	10%	Operation of UV spectrometer, help with experimental work
Atman Atman	UCF	Undergrad student	10%	Assist with photorespone measurements
Yander Landa	UCF	Undergrad student	10%	Assist with photorespone measurements; data processing
			%	

Criteria for Success

list the Criteria for Success established in the Project Plan and your evaluation of their completion

Criterion	Relative Weight	Complete	Comments
Device structures are processed and irradiation regimes are defined	**15%**	**15%**	**Structures are received**
Irradiation impact on minority carrier transport is determined	**15%**	**10%**	**Studies done for n-Ga_2O_3**
Irradiation impact on extended defects is determined	**5%**	**5%**	**Done**
Irradiation impact on point defects is determined	**5%**	**5%**	**Done**
Irradiation impact on lifetime is determined	**15%**	**15%**	**Evidence for lifetime increase obtained**
Injection & thermal regimes & irradiation doses are correlated	**15%**	**15%**	**Regimes of injection are partially identified for Ga_2O_3 Schottky structures**
Irradiation impact on macroscopic properties (photoresponse.)	**10%**	**10%**	**Demonstrated**
Circuitry for photoresponse monitoring and electron injection is designed (End-User)	**10%**	**10%**	**Circuitry is designed**
Prototype is demonstrated (End-User)	**10%**	**10%**	**Demonstrated**

Products & Dissemination

please list all products and outcomes of the project

Journal articles, conference papers, book chapters, and other publications (please do not attach copies)

1. Sushrut Modak, Leonid Chernyak, Alfons Schulte, Minghan Xian, Fan Ren, Stephen J. Pearton, Igor Lubomirsky, Arie Ruzin, Sergey S. Kosolobov, Vladimir P. Drachev (2021)
“Electron beam probing of non-equilibrium carrier dynamics in 18 MeV alpha particle- and 10 MeV proton-irradiated Si-doped β-Ga_2O_3 Schottky rectifiers”, *Appl. Phys. Lett.* ***118***, 202105; https://doi.org/10.1063/5.0052601.

2. A. Brovko, P. Rusian, Leonid Chernyak, Arie Ruzin (2021)
“High quality planar $Cd_{1-x}Mn_xTe$ room temperatures radiation detectors”, *Appl. Phys. Lett.* ***199***, 062103; https://doi.org/10.1063/5.0060706.

3. Sushrut Modak, Leonid Chernyak, Alfons Schulte, Minghan Xian, Fan Ren, Stephen J. Pearton, Arie Ruzin, Sergey S. Kosolobov, Vladimir P. Drachev (2021)
“Temperature dependence of cathodoluminescence emission in irradiated Si-doped β-Ga_2O_3”, AIP Advances 11, 125014; https://doi.org/10.1063/5.0073692.

4. Sushrut Modak, Leonid Chernyak, Alfons Schulte, Corinne Sartel, Vincent Sallet, Yves Dumont, Ekaterine Chikoidze, Xinyi Xia, Fan Ren, Stephen J. Pearton, Arie Ruzin, Denis M. Zhigunov, Sergey S. Kosolobov, and Vladimir P. Drachev (2022)
“Variable temperature probing of minority carrier transport and optical properties in p-Ga_2O_3”, Appl. Phys. Lett. Mater. 10, 031106; https://doi.org/10.1063/5.0086449.

5. Sushrut Modak, Alfons Schulte, Corinne Sartel, Vincent Sallet, Yves Dumont, Ekaterine Chikoidze, Xinyi Xia, Fan Ren, Stephen J. Pearton, Arie Ruzin, Leonid Chernyak (2022)
“Impact of radiation and electron injection on minority carrier transport in p- Ga_2O_3”, Appl. Phys. Lett, 120, 233503; https://doi.org/10.1063/5.0096950

6. Sushrut Modak (2022)
“Impact of electron injection and radiation damage on minority carrier transport properties in Gallium Oxide and Gallium Nitride”, Ph.D. Thesis, University of Central Florida.

7. Zeyu Chi, Corinne Sartel, Yunlin Zheng, Sushrut Modak, Leonid Chernyak, Christian M Schaefer, Jessica Padilla, Jose Santiso, Arie Ruzin, Anne-Marie Gonçalves, Jurgen von Bardeleben, Gérard Guillot, Yves Dumont, Amador Pérez-Tomás, Ekaterine Chikoidze (2023)

“Native defect association β-Ga_2O_3” enables room-temperature p-type conductivity”, J. Alloys and Compounds 969, 172454; https://doi.org/10.1016/j.jallcom.2023.172454.

8. Sushrut Modak, James Spencer Lundh, Nahid Sultan Al-Mamun, Leonid Chernyak, Aman Haque, Thieu Quang Tu, Akito Kuramata, Marko J. Tadjer, Stephen J. Pearton (2022) Growth and characterization of α-Ga_2O_3 on sapphire and nanocrystalline ß-Ga_2O_3 on diamond substrates by halide vapor phase epitaxy”, J. Vac. Sci. Technol. A 40, 062703. https://doi.org/10.1116/6.0002115

9. Sushrut Modak, Arie Ruzin, Alfons Schulte, Leonid Chernyak. Influence of Energetic Particles and Electron Injection on Minority Carrier Transport Properties in Gallium Oxide. Preprints 2023, 2023100914. doi: 10.20944/preprints202310.0914.v1

10. Alfons Schulte, Sushrut Modak, Yander Landa, Atman Atman, Jian-Sian Li, Chao-Ching Chiang, Fan Ren, Stephen J. Pearton, and Leonid Chernyak. Impact of solid-state charge injection on spectral photoresponse of NiO/Ga2O3 p-n heterojunction. Preprints 2023, 2023101814 doi: 10.20944/preprints202310.1814.v1

Conference presentations and public lectures

1. Leonid Chernyak, “Electron injection-induced effects in AlGaN semiconductors and devices”, Department of Electrical Engineering, Ben-Gurion University of the Negev, August 1, 2022.
2. Leonid Chernyak, “Blending GaN and silk technologies for biohazard detection”, Department of Molecular Chemistry and Materials Science, Weizmann Institute of Science, April 3, 2023.
3. Leonid Chernyak, “Minority carrier dynamics is AlGaN-based photodetectors”, Department of Physical Electronics, Tel Aviv University, October 23, 2022.
4. Atman Atman, Yander Landa “Spectrally resolved measurements of the photoresponse in wide bandgap semiconductors for solar-blind ultraviolet detection”, UCF Student Scholar Symposium, University of Central Florida, March 27, 2023
5. Leonid Chernyak, “Electron Injection Effects in Gallium Oxide device structures”, September 29, 2023, Gebze Technical University, Turkey.
6. Leonid Chernyak, “Impact of Radiation and Electron Injection on Minority Carrier Transport in n- and p-type Gallium Oxide”, Conference on Materials Science and Engineering, Dubai, UAE, November 8, 2023.

Inventions, Patents, & Licenses

NONE

Other products such as web sites, databases, etc. released to the scientific community or the public

Prof. Schulte and Prof. Ruzin will be supporting the website for the project: the site is under construction at https://english.tau.ac.il/profile/ruzin

Project publicity (please attach copies of articles or reports about the project)

Leonid Chernyak, a participant on this project, made two public presentations on the project results. The presentations were made at Gebze Technical University, Turkey, and at the Materials Conference in Dubai, UAE.