**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  
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**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$_2$O$_3$ 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$_2$O$_3$.

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$_2$O$_3$ 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$_2$O$_3$ thin films employing temperature dependent EBIC and cathodoluminescence measurements.

In **milestone 4** we demonstrated that Zn doping of β-Ga$_2$O$_3$/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$_2$O$_3$ based homojunction fabrication, the charge injection effect was demonstrated in p-n NiO/Ga$_2$O$_3$ 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.
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.

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Summary of Accomplishments
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
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 Ga2O3 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 (5x10^14 cm^-2 fluence; 330 μm range in the material) irradiation with protons and 18 MeV (1x10^12 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. ΔE_L, T shows a modest dependence on temperature. In previous investigations of GaN [3], ZnO [4], and Ga2O3 [4,5], ΔE_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 ΔE_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 on the relatively small value of minority carrier diffusion length.

A time-resolved CL streak of the UV emission, centered around 380 nm in β-Ga2O3, 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 Ga2O3
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 used 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- Ga2O3 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].

ΔE_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 (ΔE_L, T and ΔE_CL, respectively); 113 and 101 meV for sample B (ΔE_L, T and ΔE_CL, respectively). Proximity of the values for ΔE_L, T and ΔE_CL serves as a proof for same origin of both processes, with the likely reason related to thermal detrapping of electrons from the V_{Ga} - V_{Ga}^+ complexes, creating acceptor levels in Ga2O3 forbidden gap.

A series of separate EBIC measurements was carried out on another Ga2O3 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. ΔE_L, T was found at 76 meV after irradiation (113 meV prior to irradiation).

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The root cause for the phenomenon of electron injection in Gallium Oxide (Ga$_2$O$_3$) is the large difference in minority carrier diffusion length with injection duration reported in ref. [5].

The linear increase of minority carrier diffusion length with injection duration (as shown in Fig. 9) can be explained by the mechanism of hole trapping, which is temperature dependent. The rate R of the increase in minority carrier diffusion length with injection duration can be described by

$$R(T) = R_0 \exp \left( -\frac{\Delta E}{k_B T} \right)$$

Here, $R_0$ is a scaling constant; $\Delta E$ is the activation energy for the electron injection effect; $k_B$ is the Boltzmann constant; and $T$ is the temperature.

The electron injection in Gallium Oxide (Ga$_2$O$_3$) is a highly resistive material, where the electron injection effect is significant. The electron injection rate decreases with increasing temperature, as shown in Fig. 10. The electron injection effect is also dependent on the type of electron beam used in the experiments.
Radiation and electron injection in Gallium Oxide for deep-UV detection  SPS Programme Multi-Year Project Final Report G-5748

- 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$_2$O$_3$-based photodetectors

Pending robust homoepitaxial Ga$_2$O$_3$ p-n junction fabrication, application of electron injection effect for device performance enhancement is presented through the example of a p-NiO/n-Ga$_2$O$_3$ 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$_2$O$_3$, 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 $\sim 8 \times 10^{10}$ C/mm$^2$ (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$_2$O$_3$. 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$_2$O$_3$ 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

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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, $1.6 \times 10^{14}$ cm$^{-2}$ + 50 keV, $1.7 \times 10^{14}$ cm$^{-2}$ + 70 keV, $3.6 \times 10^{14}$ 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 °C), square (75 °C), and triangle (120 °C). $\Delta E_{A,I}$, 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$_2$O$_3$ 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.
Radiation and electron injection in Gallium Oxide for deep-UV detection

Figure 1

Figure 2

Figure 3

Figure 4
Radiation and electron injection in Gallium Oxide for deep-UV detection

Figure 5

Figure 6

Figure 7

Figure 8
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Figure 9

Figure 10

Figure 11

Figure 12
**Radiation and electron injection in Gallium Oxide for deep-UV detection**

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**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

<table>
<thead>
<tr>
<th>Milestone</th>
<th>1st year</th>
<th>2nd year</th>
<th>3d year</th>
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<tr>
<td>1</td>
<td>UV photodetector processing</td>
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<td>2</td>
<td>Irradiation of devices</td>
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<tr>
<td>3</td>
<td>Dark property characterization</td>
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<tr>
<td>4</td>
<td>Spectral and temporal testing before and after gamma irradiation</td>
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<tr>
<td>5</td>
<td>Irradiation impact on minority carrier transport</td>
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<td>6</td>
<td>Irradiation impact on minority carrier lifetime</td>
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<td>7</td>
<td>Irradiation impact on extended defects</td>
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<td>8</td>
<td>Irradiation impact on point defects</td>
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<td>9</td>
<td>Correlation of electron injection regimes and thermal budget with gamma irradiation dose</td>
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</table>

All project objectives were met and milestones reached.
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**Training & Professional Development**

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**

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 $\beta$-Ga$_2$O$_3$:

1. The diffusion length of the minority carriers can be manipulated (significantly improved) using electron injection in $\beta$-Ga$_2$O$_3$.
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**

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$_2$O$_3$ 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](image)
## 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.

<table>
<thead>
<tr>
<th>Name</th>
<th>cAffiliation</th>
<th>Position/Title</th>
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<th>Role</th>
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<tbody>
<tr>
<td>Alfons Schulte</td>
<td>University of Central Florida (UCF)</td>
<td>Professor</td>
<td>25%</td>
<td>Studies of irradiation impact on Ga&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt; 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.</td>
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<tr>
<td>Arie Ruzin</td>
<td>Tel Aviv University (TAU)</td>
<td>Associate Professor</td>
<td>25%</td>
<td>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.</td>
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<tr>
<td>Leonid Chernyak</td>
<td>UCF</td>
<td>Professor</td>
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<td>Studies of irradiation impact on minority carrier transport and lifetime.</td>
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<tr>
<td>Sushrut Modak</td>
<td>UCF</td>
<td>Ph.D. student</td>
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<td>Studies of irradiation impact on photodetector’s figures of merit.</td>
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<td>A Brovko</td>
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<td>Ph.D. student</td>
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<td>Study of irradiation effect on deep level formation and afterward annealing.</td>
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<tr>
<td>A Adelberg</td>
<td>TAU</td>
<td>Young Scientist</td>
<td>100%</td>
<td>Maintenance of scientific equipment, help with experimental work and training of graduate students, operation of atomic force microscope.</td>
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<tr>
<td>Yakov Roizin</td>
<td>Tower Jazz Ltd.</td>
<td>Director of Emerging Technologies</td>
<td>10%</td>
<td>Device fabrication. Biasing and monitoring circuitry design and prototyping. Interaction with NPD and PPD and their groups.</td>
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<tr>
<td>Eric Rende</td>
<td>UCF</td>
<td>Ph.D. student</td>
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<td>Operation of UV spectrometer, help with experimental work</td>
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<td>Atman Atman</td>
<td>UCF</td>
<td>Undergrad student</td>
<td>10%</td>
<td>Assist with photoresponse measurements</td>
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<tr>
<td>Yander Landa</td>
<td>UCF</td>
<td>Undergrad student</td>
<td>10%</td>
<td>Assist with photoresponse measurements; data processing</td>
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Criteria for Success

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<td>Irradiation impact on lifetime is determined</td>
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<td>Prototype is demonstrated (End-User)</td>
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Products & Dissemination

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


2. A. Brovko, P. Rusian, Leonid Chernyak, Arie Ruzin (2021)


6. Sushrut Modak (2022)

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Conference presentations and public lectures


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


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.