**White Paper for *Frontiers of Plasma Science Panel***

| Date of Submission: | ***6/15/2015*** |
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| Oral | |
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| Title: | **GaN Radiation Hardened Detectors, Imagers, and Diagnostics Systems for Fusion Plasma Science Experiments** |
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| Corresponding Author: | Ke-Xun Sun |
| • Institution: | University of Nevada, Las Vegas (UNLV) |
| • email: | Ke-Xun.Sun@unlv.edu |
| Co-Authors: | |

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**1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

# GaN Radiation Hardened Detectors, Imagers, and Diagnostics Systems For Fusion Plasma Science Experiments

Ke-Xun Sun
University of Nevada, Las Vegas (UNLV)
Ke-Xun.Sun@unlv.edu

- ***Describe the research frontier* and importance of the scientific challenge.**

Fusion plasma science in nature is an experimental exploration [1]. Its success largely depends on our capability of accurate observing physical processes. high resolution imaging near target at National Ignition Facility (NIF) will be extremely valuable.

However, neutron yield is intrinsic in DT fusion reaction. Neutron radiation damages to diagnostics instruments have become a critical concern for high yield fusion plasma experiments. Expensive diagnostic instrument may need to be removed from NIF target bay before high yield shots, missing the valuable observational opportunities. Films were introduced to avoid electronics radiation damages, but result in inefficiency. Radiation hardened electronic and optoelectronics devices are now recognized as a critical enabling technology for high neutron yield shot diagnostics. With perceived NIF targeted neutron yields of $10^{18}$ neutrons/shot, the neutron fluence per shot at 1 meter away from Target Chamber Center (TCC) will be 2-3 order of magnitude higher today's level, reaching $10^{15}$ neutrons/cm$^2$, at which silicon based electronics functionality will be uncertain.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Gallium Nitride (GaN) is a wide-bandgap semiconductor having excellent radiation properties. GaN crystal is ionic-covalent with significant iconicity resulting in stronger molecular bond strength, which in in turn leads to excellent radiation hardness [2-14]. Further, GaN has ultrafast carrier relaxation time. GaN transistors are promising for high-frequency applications due to their large bandgap (3.9eV) and higher breakdown field (>5MV/cm). These exceptional characteristics make GaN suitable to operate in high radiation flux environment such as fusion plasma facilities, for ultrafast detection. GaN based tertiary and quaternary III-Nitride semiconductors (AlGaN/InGaN/AlInGaN) can be band-engineered to detect light from UV to IR, and can be optimized for measurement needs. The expected detector temporal response is faster than 0.01-1 ns. The quantum efficiency at the peak wavelengths will be greater than 90%.

UNLV group pioneered studies on proton radiation hardness of GaN/AlGaN devices. We have demonstrated its proton radiation hardness using 65 MeV proton beam up to $3\times10^{12}$ protons/cm$^2$ fluence [4-5]. This result led to space deployment of GaN devices. Since then, we have further demonstrated neutron radiation hardness in systematic experiments with escalated neutron fluence levels. In these experiments, we have also used increasingly large numbers and varieties of GaN/AlGaN devices to gain statistical significance, and to provide reliable feedback for further improvements of device design and manufacturing technology.

- In our 2013 experiment at Los Alamos Neutron Science Center (LANSCE), we demonstrated radiation hardness of GaN devices up to $3x10^{11}$ neutrons/ $cm^2$ [6-9].
- In December 2014 LANSCE experiment, we demonstrated neutron radiation hardness of GaN device up to $9.1x10^{11}$ neutrons/$cm^2$, with a large number of samples [11-14].
- In three months from October 2014 to January 2015 at a special high fluence section of LANSCE neutron beam line, we demonstrated neutron radiation hardness of GaN devices up to $1.3x10^{13}$ neutrons/$cm^2$, again with large number of device samples [11-14].
- At NIF we demonstrated neutron radiation hardness of GaN devices with four NIF high yield shots ($8x10^{15}$ neutrons/shot) [11-14].

In these experiments, we characterize electrical and optical performances of GaN device before and after neutron irradiation, and observed no substantial degradation. Figure 1 shows the GaN device forward IV curve measurements monitored at over the three months neutron irradiation time. Figure 2 shows GaN device forward IV curve measurements before and after NIF high yield shot irradiation. Evidently, the devices characteristics were unaffected by neutron irradiation. These experiments firmly established GaN devices as the foundation of the next generation fusion plasma diagnostic instruments.

For next steps, we plan to conduct following research project, and to fully develop GaN devices and systems to practical stages:

- Continue to test radiation hardness of GaN devices at higher neutron fluence level. We are planning $10^{15}$ neutrons/$cm^2$ fluence testing
- Physical modeling of GaN device radiation hardness. This workflow will include modeling of neutron interaction, molecular dynamics, material structures, device physics, device characteristics, system performance, and impact to diagnostics applications.
- Develop dedicated GaN device fabrication capabilities with more device design and manufacturing control, to more precisely correlate radiation hardness and device design.
- Develop specialized radiation hard GaN detectors, imagers, transistors and systems for plasma diagnostics.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

GaN is the next generation semiconductor for future electronics, optics, and functional systems. Radiation hard GaN devices have broad applications. Some examples are:

- Diagnostics instruments for high radiation plasma sciences and fusion energy: NIF, Z, ITER, MagLIF
- Nuclear reactors monitoring especially Small Modular Reactors and Small Fast Reactors
- Sensors, electronics, and systems working under extreme temperature and radiation conditions for emergency response
- Ultrafast radiation and optical detectors and imagers
- Long lifetime space exploration in high radiation zones such as Jupiter-Europa, and exoplanetary missions

**References (Maximum 1 page)**


[1] OA Hurricane et al. "Fuel gain exceeding unity in an inertially confined fusion implosion," Nature 1-6 (2014) doi:10.1038/nature13008

[2] A. Ionascut-Nedelcescu, C. Carlone, A. Houdayer, H. J. von Bardeleben, J.-L. Cantin, and S. Raymond, "Radiation Hardness of Gallium Nitride," IEEE Transactions on Nuclear Sciences, 49, (2002) 2733-2738Ke-Xun Sun et al "UV LED Operation Lifetime and Radiation Hardness Qualification for Space Flights," Journal of Physics CS, doi: 10.1088/1742-6596/154/1/012028

[3] Polyakov, et al "Neutron irradiation effects on electrical properties and deep-level spectra in undoped n- AlGaN⁄GaN heterostructures," J. Applied. Physics 98, 033529 2005

[4] Ke-Xun Sun et al. "Space Qualification for Radiation Hard UV LED," 3rd NASA EJSM Workshop, Applied Physics Lab, John Hopkins University, July 7-9, 2009

[5] K.-X. Sun and L. MacNeil, "Radiation Hardness of AlGaN Photodiodes," 4th NASA/ESA EJSM Workshop, Jet Propulsion Laboratory, July 26-29, 2010

[6] Ke-Xun Sun, Derek Constantino, Vince DiPuccio, Michael Kao, Remis Gaska, Yuri Bilenko, Mikhail, Gaevski, Ron Nelson, "Neutron Radiation Hardness of GaN Devices: LANSCE Experiment," Invited paper, Workshop of Frontier for Electronics, December, 2013, San Juan, Puerto Rico.

[7] Ke-Xun Sun, Derek Constantino, Vince DiPuccio, Michael Kao, Remis Gaska, Yuri Bilenko, Mikhail Gaevski, Ron Nelson, "GaN Devices for Next Generation ICF/HEDP Diagnostics Instruments: Neutron Radiation Hardness Test," High Temperature Plasma Diagnostics (HTPD), Atlanta, GA, June 1-5, 2014

[8] Ke-Xun Sun, "Proton and neutron radiation hardness of GaN optoelectronic devices," Invited presentation at SPIE Optics and Photonics, "Proton and neutron radiation hardness of GaN optoelectronic devices," SPIE invited paper presented August 2014, San Diego, CA

[9] Ke-Xun Sun, "Radiation Hardness Qualification of GaN Optoelectronics Devices for Space Flights and ICF/HEDP Experiments," Invited Colloquium Presentation, Sandia National Laboratory, Albuquerque September 4, 2014

[10] Ke-Xun Sun, "Radiation Hard GaN Devices, and Systems for ICF/HEDP Diagnostics --- An Overview from Spaceflight to ICF Applications," ICF National Diagnostics Workgroup Meeting at Lawrence Livermore National Laboratory, September 9-11, 2014

[11] Ke-Xun Sun, Vince DiPuccio, Chris Hoolihan, Michael Gacusan, Ron Nelson, Charles Yeamans, Remis Gaska, Max Shatalov, "Radiation Hard GaN Devices: LANSCE High Fluence Neutron Tests and NIF High Yield Shot Tests", NIF and JLF User Group Meeting 2015, February 9-11, 2015

[12] Ke-Xun Sun, Vince DiPuccio, Chris Hoolihan, Michael Gacusan, Ron Nelson, Charles Yeamans, Remis Gaska, Max Shatalov, "Radiation Hard GaN Devices: LANSCE High Fluence Neutron Tests and NIF High Yield Shot Tests", to appear 2015 National Space & Missile Materials Symposium (NSMMS), 22 – 25 June in Chantilly, VA.

[13] Ke-Xun Sun, Vince DiPuccio, Chris Hoolihan, Michael Gacusan, Ron Nelson, Charles Yeamans, Remis Gaska, Max Shatalov, "$10^{13}$ neutron / cm2 radiation hardness testing of AlGaN UV LEDs and Photodiodes" paper in preparation

[14] Ke-Xun Sun, Vince DiPuccio, Chris Hoolihan, Michael Gacusan, Ron Nelson, Charles Yeamans, Remis Gaska, Max Shatalov, "NIF $10^{16}$ neutron per shot testing of GaN radiation hardness", paper in preparation

**Figures (maximum 1 page)**

## 4FP60R P-C High Fluence (1.3E13 neutrons/cm$^2$) Experiment GaN LED/PD Forward I-V Curve

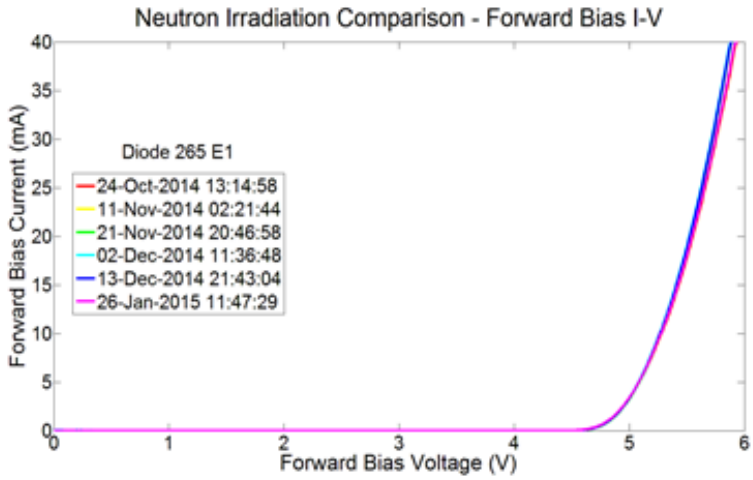


Figure 1. GaN LED/PD IV curves how now no substantial changes after 3 months neutron irradiation, with fluence 1.3E13 neutrons/cm$^2$.

## NIF Irradiated Samples Forward IV Curves After Four (4) High Yield (8E15 neutrons/shot) Shots

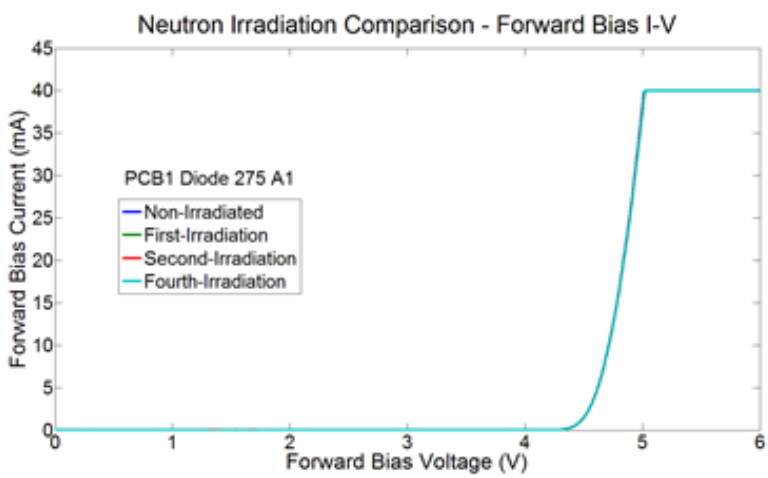


Figure 2. GaN LED/PD IV curves how now no substantial changes after four NIG high yield shots, with yield of 8E15 neutrons/shot.