Harsh Environment Microwave Diagnostics for Reactor Plasmas

White Paper presented to the NAS: A Strategic Plan for U.S. Burning Plasma Research (Co-Chairs: Michael Mauel, Columbia University and Melvyn Shochet, University of Chicago)

N.C. Luhmann, Jr. (UC Davis), Ahmed Diallo (PPPL), Yang Ren (PPPL), Diana Gamzina (SLAC), Anh-Vu Pham (UC Davis), and Srabanti Chowdhury (UC Davis)

As magnetic confinement fusion research moves into the ITER era, new challenges are unavoidable due to the unprecedented hostile environment of nuclear fusion machines. ITER, which is designed to achieve Q=10, is the first magnetic confinement fusion machine to be able to produce net fusion power and will generate radiation levels, i.e. neutrons and gamma rays, that are orders of magnitude higher than present-day fusion machines. This unique nuclear environment poses challenges to structure and first-wall/plasma-facing material, which have to both survive in this environment and remain functional with a reasonable lifetime. In particular, the amount of neutrons (flux and fluence) generated from a future nuclear fusion reactor is far beyond that from any existing nuclear devices and thus *there is an urgent need to study material responses and degradation with long-time neutron exposure*. The next-step fusion reactor after ITER, e.g. DEMO, will need to demonstrate the feasibility of generating electricity from thermal nuclear fusion reaction. With steady-state discharges, high duty cycle and much higher net fusion power, the urgency of making breakthroughs in material science and technology is even greater for DEMO. This unique challenge is being addressed, led by the fusion community, with emphasis on structure/PFC materials of fusion reactors and diagnostic components that are close to the plasma, e.g. Mirnov coils and first mirrors, [1, 2, 3]. However, insufficient emphasis has yet been given to the survivability of electronic devices in the hostile environment of nuclear fusion machines. It is well-known that reactors are controlled using a suite of diagnostics ranging from plasma position control to mode detection and rotation control. These reactors will challenge the present diagnostic systems for plasma control. It was recommended by the community at large that only a subset of presently utilized diagnostic systems will be able to withstand the harsh environment of burning plasmas [1]. Microwave diagnostics have been identified as a good candidate for diagnostics for future reactors with the added advantage to be used for plasma control. The associated electronics required for these systems are currently silicon or GaAs/InP based electronics with relatively narrow bandgap [1.1 eV and 1.43 eV, respectively] that are sensitive to radiation and their life-time in a true nuclear fusion environment will be severely limited. The successful operation of whole fusion reactors will have to rely on the robustness of the underlying electronic infrastructure. In this paper, we bring to the community's attention the need to move to another family of electronics based on wide bandgap material, e.g. GaN and diamond, which would be ideal for the nuclear fusion environment. In addition, we describe recent activity in the development of ultra-miniature vacuum devices fabricated using solid state technology which are also well suited to the harsh, reactor environment and which can provide the required power for active microwave probing diagnostics.

To provide a specific example for discussion purposes, we consider the ITER low field side reflectometer and ECE receiver systems, both of which employ microwave electronics developed by Virginia Diodes, Inc. (VDI). Looking to the future (both for ITER and follow-on devices), there is a need to develop electronics with higher performance and capability as well as robustness in order to survive in the hostile burning plasma environment. More specifically, the VDI electronics employ GaAs based devices and circuits throughout. The problem is that the relatively low bandgap of GaAs (1.43 eV) results in rather low critical breakdown fields (0.3-0.4 MV/cm) and thus radiation, heat, and microwave tolerance limitations. To address the shortcomings, the electronics are protected in large part by a number of passive and active devices [4, 5] including bandpass and notch filters, isolators, and limiters, but with the electronics including the limiters limited by the capabilities of GaAs.

A major improvement in both robustness in the harsh burning plasma environment as well as performance and capability is to switch to *Gallium Nitride semiconductor devices*, which are wide band gap materials (3.39 eV versus 1.43 and 1.11 for GaAs and Si, respectively) and which have been shown to provide high power and high breakdown voltages. The GaN critical breakdown field, is 3- 3.5 MV/cm in contrast to 0.3-0.4 MV/cm leading to its ability to function in unprecedented extreme circumstances:

- High temperature (1000°C), pressure, shock and stress
- High radiation and electrostatic discharge
- Extreme vibration and shock (50,000 g)
- Extremely corrosive (human body, industrial plants)

To provide concrete numbers, it is instructive to compare the radiation sensitivity between Gallium Nitride (GaN) based high electron mobility transistors (HEMTs) and GaAs-based HEMTs. GaN is several orders of magnitude more resistant to radiation damage than GaAs of similar doping concentrations [6-8]. In addition to wide bandgap, there exist ultra-wide bandgap (UWBG) materials such as diamond (5.5 eV) and AlN (6.1 eV) with even greater robustness. Because of these properties, there has been increasing R&D focus on devices based on these materials in a wide range of applications including automotive, transportation, high energy physics, aviation, energy exploration and production, radar, industrial processing, communication, and space technologies [9-24] which have brought them to a high level of maturity and make them ideal for operation in fusion plasma environments.

At UC Davis, there is a major, multidisciplinary state-of-the art vertically integrated laboratory developing materials to devices to circuits to exploit WBG and UWBG technologies with complete rf test capability to 1 THz and environmental testing including radiation hardness testing at the McClellan Nuclear Research Center, UC Davis. The faculty involved in the activity include six microwave circuit and system designers and three materials and device designers (two National Academy of Engineering and two National Academy of Inventors). Materials of interest include GaN, AlN, Ga_2O_3, and Diamond whose properties are shown in comparison to those of Si and GaAs in Fig.1 below. Both metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) growth facilities are in operation.

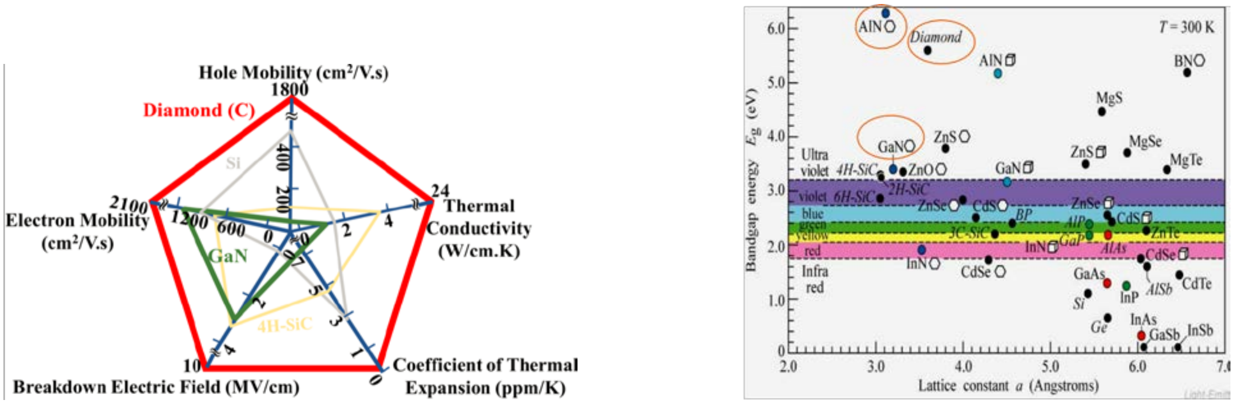

Fig. 1 Material properties of WBG and UWBG semiconductors

Recently, Gallium Nitride (GaN) semiconductor devices have been shown to provide high power, high breakdown voltages, and low noise beyond 200 GHz. Today, GaN high electron mobility transistors have been scaled to 20 nm gate length to result in f_T/f_{max} of 342/518 GHz so that GaN can support applications to 300 GHz [19, 20]. With an unprecedented off-state breakdown voltage of 14 V [19, 20], GaN HEMT circuits with power combiners are expected to produce 100 mW output power in the 200-300 GHz regime. At the same time, GaN HEMTs can also achieve low noise with high breakdown voltage to enable amplifiers to sustain high input power on the receiver. In [23], the authors reported a 2.5 dB noise figure of GaN HEMTs at 200 GHz. GaN HEMTs have been used to demonstrate transceiver front-ends that include both a low noise amplifier, a high power amplifier, and a mixer, and an oscillator on the same chip at E-band (80 GHz) and Ka-band [23, 24].

We stress the urgent need to develop a fully integrated receiver and transmitter using GaN integrated circuits (**TRL 6**) for plasma fusion diagnostic systems ranging from ITER to beyond (Fig. 2). The receiver is composed of a GaN low noise amplifier and a mixer with an LO multiplied from a low frequency signal. The transmitter will have a similar topology with a power amplifier that can provide > 100 mW in the 200-300 GHz range. In the front of our millimeter-wave circuits, we propose to develop limiter circuits to protect the sensitive electronics up to 14 W in 200-300 GHz. Limiter circuits are widely used in radar and communications receivers and consist of several shunt diodes and series transmission lines. GaN technologies bring tremendous benefits here as GaN HEMTs can achieve both high frequency (~500 GHz) and high breakdown voltage (14 V). A diode stacking topology can also help improve the maximum power that the limiter can sustain. Fig. 3 demonstrates a 10-W stacking diode limiter that we designed in GaAs [18]. Based on a 20 nm GaN process [18], we can develop a limiter with a similar circuit topology to achieve 14 W (41 dBm) in the 200-300 GHz region.

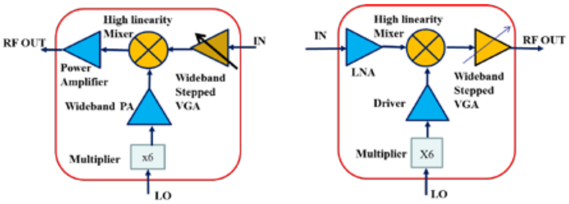

Fig. 2. Fully integrated transmitter and receiver in GaN integrated circuit

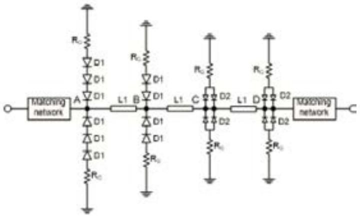

Fig. 3 Stacked diode limiter

The ultimate wide bandgap material is, of course, vacuum. Vacuum electron devices (VEDs) are well known to deliver high continuous wave power and high efficiency; they are commonly employed in space communications due to their optimized power per size and weight metric (SWaP) as well as robustness to operation in such an environment. The primary technological drawbacks to employing vacuum electronics are their high voltage operation (usually kilovolts), their size, and the complexity of the VED manufacturing process. However, in a SLAC/UCD collaboration, a revolutionary approach is underway aimed at realizing a completely new low voltage, ultra-compact vacuum electronics technology (**TRL 3**), comparable in size to current state-of-the-art solid state RF devices and compatible with standard large scale microfabrication techniques. The current activities are focused on watt level, broadband amplifiers operating in the 30- 100 GHz region (see Fig. 4) and requiring only 250-500 V DC power. However, it should be noted that this approach is well suited for devices operating up to 1 THz. The devices currently employ UC Davis developed nano-composite scandate tungsten thermionic cathodes which exceed the commercial state-of-the-art by an order of magnitude providing high emission current densities at reduced temperature [25]. Further performance enhancement as well as simplified fabrication and increased reliability can be achieved by replacement of the thermionic cathode by a field emission cathode. The primary advantage of employing field emission cathodes is their “cold” temperature of operation simplifying the gun design (no thermal isolation required) and fabrication (compatible with microfabrication technologies) significantly. Unfortunately, at high current densities over a significant period of operation these electric-field-assisted cathodes are prone to catastrophic failure. An extremely promising approach employs wide-bandgap (>5 eV) materials such as MgO and SiO_2, where the conduction band lies close to the vacuum energy level and used for achieving stable cathodes. Diamond, with its conduction band close to the vacuum energy level, even in the presence of O, and H, O, stands out from the rest due to its very attractive material properties, which include high thermal conductivity, high breakdown field, and chemical inertness. Here, diodes are fabricated employing a dedicated CVD reactor for deposition of the n-type layer on B-doped diamond layer, all grown on single crystalline diamond substrate. When the diodes are forward biased, electrons are injected into the p-type diamond. Once the electrons are in the p-type semiconductor, they can be emitted into vacuum (**TRL 2**).

Fig. 4: Miniature Vacuum Electron Device offering 1 Watt of power with 50% overall efficiency at frequencies spanning 30-100 GHz and beyond.

REFERENCES

[1] G. Vayakis, “The ITER radiation environment for diagnostics”, N 55 RI 38 04-05-06 W 0.1

[2] M. Greenwald et al. “Fusion Energy Sciences Advisory Committee Report on Opportunities for Fusion Materials Science and Technology Research Now and During the ITER Era”, February 2012

[3] A.J.H. Donne et al., Nucl. Fusion 47 (2007) S337–S384

[4] G. Hanson, et al., 10th Inter. Reflectometry Workshop, May 4-6, 2011

[5] G. Taylor, EPJ Web of Conferences 87,03002 (2015)

[6] S. J. Pearton et al., “Review—Ionizing Radiation Damage Effects on GaN Devices”, 2016

[7] S. J. Pearton et al., “Review of radiation damage in GaN-based materials and devices”, 2013

[8] B. D. Weaver et al., “On the Radiation Tolerance of AlGaN/GaN HEMTs”, 2016

[9] Jean-Louis Cazaux, Prospective and Issues for GaN Microwave Electronics into Space Satellites, 2006

[10] S. Armstrong, et al., Radiation Effects in Emerging Technologies for Hardened Systems, 2015

[11] D. Klimm, Electronic materials with a wide band gap: recent developments, IUCrJ (2014). 1, 281–290

[12] C. Abbate, et al., Inter. Conf. on Large Scale Applications and Rad. Hardness of Semiconductor Detectors 2013

[13] C. Lanzieri Rad. Hardness Assurance for Space Systems: Neutron Induced Damage on Micro. Devices and Solar Cells, ASI Workshop: A neutron irradiation facility for space applications, 8 June 2015

[14] Y. Won, Cooling Limits for GaN HEMT Technology, 978-1-4799-0583-6, 2013 IEEE

[15] K.W. Kobayashi, Broadband GaN MMICs: Multi-Octave Bandwidth PAs to Multi-Watt Linear LNAs, 2012

[16] K. Shinohara,et al., “Self-Aligned-Gate GaN HEMTs with Heavily-Doped n+-GaN Ohmic Cont. to 2DEG,” 2012

[17] A. Margomenos, et al., “GaN Technology for E, W, and G-band Applications,” 2014

[18] A, T. Ohki, et al., “GaN MMIC amplifiers for W-band transceivers,” 2009

[19] J. Schellenberg, et al., “W-Band, 5 W Solid-State Power Amplifier/Combiner,” 2010

[20] A. Brown,et al., “W-band GaN power amplifier MMICs,” IEEE International Microwave Symposium, 2011.

[21] S. Lardizabal, et al., “Wideband W-band GaN LNA MMIC with State-of-the-Art Noise Figure,” 2016

[22] Y. Nakasha, et. al, “E-band 85-mW Oscillator and 1.3 W Amplifier ICs using 0.12 µm GaN HEMTs for Millimeter-wave Transceivers,” IEEE Compound Semiconductor Integrated Circuit Symposium, (CSICs), October, 2010

[23] N-N. Do, et al., “AlGaN/GaN Mixer MMICs, and RF Front-End Receivers for C-, Ku-, and Ka-band Space Applications,” IEEE Proceedings of the 4th European Microwave Integrated Circuits Conference, 2010.

[24] B. L. Pham, D. P. Nguyen, A. V. Pham and P. D. Le, "High Power Monolithic pHemt GaAs Limiter for T/R Module," *2016 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, Austin, TX, 2016, pp. 1

[25] Zhao, J., et al., “High Current Density and Long-Life Nanocomposite Scandate Dispenser Cathode Fabrication,” IEEE Transactions on Electron Devices, vol. 58, pp. 1221-1228, 2011.