GaN-on-Diamond: A Brief History

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***Abstract*—This paper chronicles the historical technical development of Gallium Nitride-on-Diamond wafers and transistor devices by the authors starting from 2003 until the current status in 2014. This paper is not exhaustive in scope; selected accounts have been omitted either inadvertently or to maintain brevity.**

Keywords—GaN-on-Diamond, HEMTs, GaN-on-SiC

I. The GaN-on-Diamond concept (2003–2005)

In early 2003, the world's leading semiconductors by consumption volume were silicon (Si), gallium arsenide (GaAs), gallium nitride (GaN), and indium phosphide (InP). The list was remarkable in that only 10-yrs earlier, GaN was still a research grade material whose use was largely confined to graduate schools and industrial laboratories. By the early 2000s, GaN had been propelled to the top by its intrinsic and commercialize-able merits in solid-state lighting; there were also glimpses of value in radio frequency (RF) electronics. The wafer was at the time typically grown on silicon carbide (SiC) or sapphire substrates, as they aided cost (hundreds of dollars per unit 50 mm wafer) and low-enough defect densities ($\leq 10^7 cm^{-2}$) while accommodating the necessary thermal flux for solid-state lighting. GaN RF devices typically exhibit extreme, highly-localized power densities ($\sim 10^5 W/cm^2$) exceeding that on the surface of the sun ($\sim 10^3 W/cm^2$); the RF community would need a new substrate with extreme thermal conductivity to fully enable GaN's electronics' capabilities.

In mid-2003, one of the authors (FE) founded Group4 Labs, Inc. to investigate if and how GaN (and other III-V) epitaxial layers could be re-deployed onto a foreign substrate so that extreme levels of performance and energy efficiency could be realized. The basic idea held that heat could be efficiently extricated from a transistor's epitaxy via thermal conduction if a good thermally conductive substrate were brought close enough to the epitaxy (or heat generating layers) of a transistor. The new team (now including S. Bashar) would look back in time for inspiration. Exactly 10-yrs earlier, the author then a graduate student with Y.H. Lo's group at Cornell University [1], Z. Liau's group at MIT Lincoln Labs [2], and J. Bowers' group at UCSB [3], had begun to show that world record performance could be attained in basic photonics, MEMs, and electronic devices by simply harvesting the III-V epitaxial layers from one substrate and thermally bonding them to another substrate of a different kind. These early demonstrations inspired the author to consider ways of transferring GaN epitaxial layers comprising the well-known two dimensional electron gas (2DEG), from its original host to a higher thermal conductivity substrate in order to unleash the known potential of GaN's intrinsic properties.

By 2004, extensive customer interviews had informed the author (FE) of the following, a) a thermal ceiling hindered RF microelectronics advancement across virtually all RF and related markets [4], b) GaN had immense and unrealized intrinsic potential owing to its wide band-gap and thus high breakdown voltage [5], c) state-of-the-art GaN-on-SiC was still well short of industry goals in RF microelectronics [6]. A quick review of the substrate landscape indicated that chemically vapor deposited (CVD) diamond substrates stood alone in unmatched thermal conductivity, 1000-2000 W/mK, compared to copper or SiC at 350–450 W/mK [7]. Early simulations and modelling showed that passive thermal extraction by direct contact with diamond could dramatically reduce junction temperatures in a device by 25–50% [8]. The literature is however clear that diamond and GaN exhibit widely mismatched materials properties (such as thermal expansion coefficient and crystalline structure mismatch) making them incompatible as bonded or growth pairs. Thus began the author's efforts to investigate novel approaches developed in the 1990s to render GaN onto polycrystalline CVD diamond substrates.

Approached with a proposal and preliminary experimental results (Figure 1.) for transferring GaN epitaxy to diamond, DARPA in 2005 awarded Group4 Labs (via contract with Emcore Corp.) its first seedling grant to demo a 10 mm × 10 mm GaN-on-Diamond wafer. One of the authors (DF) joined the team to help architect and demo the GaN-on-Diamond wafer formation process; one of the authors (FF), first at P1 Diamond and later at Crystallume Corporation, would develop and grow all of the team's diamond materials.

Collectively, the team would uncover three critical findings that lay the ground work for the innovation: a) that GaN can be exposed to extreme temperatures (>600C) for extended periods of time without exhibiting any detectable change in its

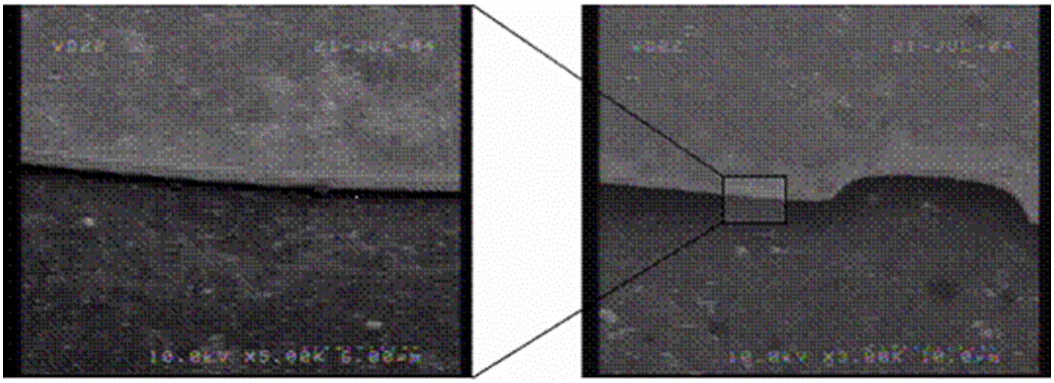

Figure 3 - Earliest SEM photo (2004) of GaN-on-Diamond wafer. Photo shows grazing angle of the GaN-Diamond interface.

fundamental materials or electronic properties [9], b) that the wide CTE-mismatch between a GaN thin film and diamond bulk substrate would not cause problems for device operations [10], and c) that diamond could be deposited on a GaN-on-Si substrate without problems [11]. The authors would spend many years collecting measured data to robustly affirm those findings. Figure 1 shows images of the earliest pieces of GaN-on-Diamond wafers ever made. These wafer pieces were formed by first growing a 25 µm thick CVD diamond directly on a dielectric-coated, Ga-face GaN-on-Si wafer; the Si is etched away, leaving behind an N-face GaN-on-Diamond wafer. The image shows the grazing angle perspective of a GaN-on-Diamond interface.

II. Small wafer pieces and the first HEMTs (2005–2007)

By 2006, the team was able to produce a Ga-face (i.e., right-side-up) GaN-on-Diamond HEMT epitaxial wafer. In the new process (Figure 2) that would generally remain the same to this day, the authors would first bond the GaN HEMT epitaxy (face down) onto a temporary Si carrier, etch away the original host Si substrate, deposit a 50 nm thick dielectric onto the exposed rear of the GaN, and then deposit a 25 µm diamond substrate onto the dielectric. Removing the temporary Si carrier from the composite, a free-standing albeit fragile GaN-on-Diamond wafer is exposed. The GaN-on-Si wafers were purchased from Emcore Corporation (now IQE), and the diamond deposition purchased from P1 Diamond.

During this time, D. Babic joined team to help manage the RF transistor development and characterization internally so that feedback could be obtained rapidly, and wafers improved quickly. J. Wasserbauer also joined the team, ultimately making critical and enabling contributions to the GaN-on-Diamond wafer formation process. J. Felbinger and others in Professor L.F. Eastman's group at Cornell University [12], and engineers at Wright Patterson Air Force Research Labs [13] would be the first to process the first GaN-on-Diamond wafer pieces notwithstanding very challenging properties: ~1–2 mm free-standing wafer bow over a 10×10 mm^2 area, the warp profile was saddle shaped, and the Epi surface exhibited countless particulates that obstructed device processing. The two teams obtained the first ever reported HEMT device results from GaN-on-Diamond wafers. Figure 3 shows performance results from the devices.

More than the actual numbers, the results affirmed one earlier core finding: that GaN's epitaxial 2DEG layer could be transferred from Si to a free-standing CVD diamond, and that the devices made on such wafers could be made operational. The results were also promising enough for DoD to continue funding the team.

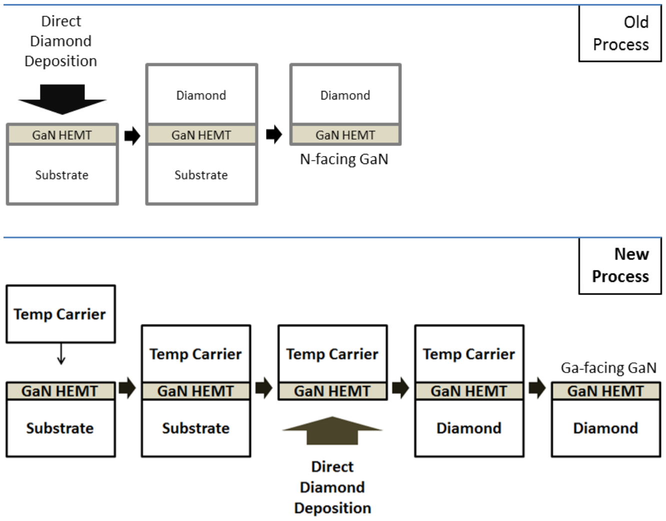

Figure 2 –Overview of 2006 version (above) and more recent (below) version of GaN-on-Diamond wafer formation process. More recent version was adopted in 2007.

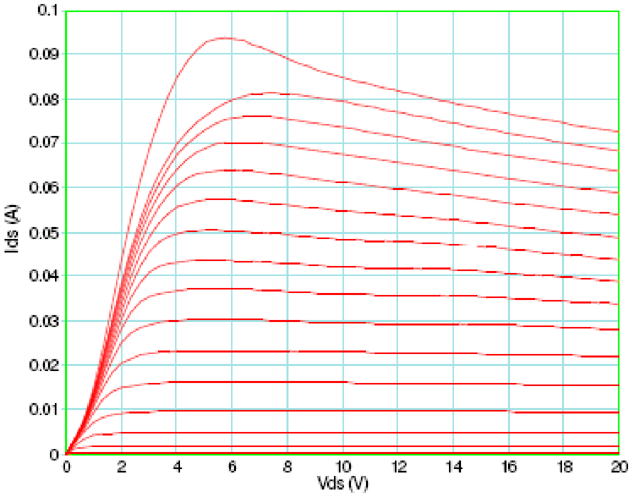

Figure 1 - First ever DC-IV Family of DC-IV curves from GaN-on-Diamond by AFRL (CSICS, 2006). Devices are unpassivated 1.5x2.150µm HEMTs.

Much of the work during this time was funded by many SBIR Phase-I awards from the Missile Defense Agency (MDA), DARPA, and the U.S. Navy.

III. Larger wafers, better HEMTs, and the first Power Amplifiers (2007–2010)

By 2007, the GaN-on-Diamond wafer process had been executed enough times (~100) that yields were improving and larger pieces (~2" diameter) could be produced [14]. Additionally, wafer bow and surface quality reached levels where significantly higher performing HEMTs and the first RF Power Amplifiers (PAs) [15] could be made. Raytheon Company and TriQuint Semiconductor, Inc. would be the first commercial entities [16] to fabricate transistors on the team's GaN-on-Diamond wafers – funded in part by several SBIR Phase-II awards from MDA, Navy, and AFRL. In 2008, the GaN-on-Diamond team would enter into a seminal partnership with Element Six (E6) – the world's largest synthetic diamond maker; this would lay the groundwork for improved wafers in the years to come.

Figure 4 showcase images of GaN-on-Diamond wafers manufactured during this time. The diamond substrate thickness was taken up to 100 µm for the first time; this also represented a significant milestone for hot-filament diamond technology. Figure 5 shows photos of a GaN-on-Diamond X-band PA module [15] developed by the team, and wafers processed by a 3rd party GaN foundry.

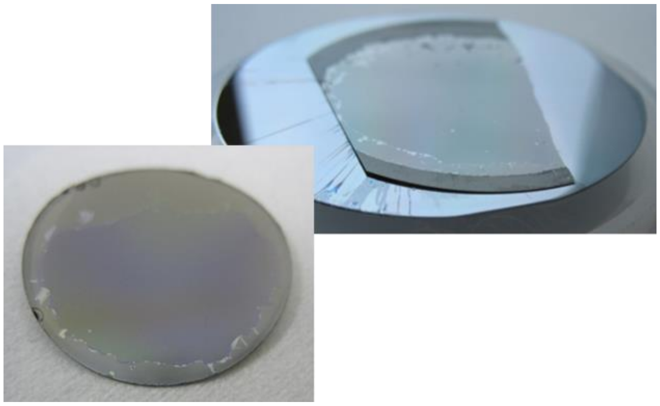

Figure 5 - Early generations of GaN-on-Diamnod wafers showing fragments of GaN epitaxy. Sections of 2" (left) and 3" (right) wafers are shown.

As the team entered 2009, development efforts opened on two fronts: a) improving several mechanical and materials properties of the wafer, including the diamond's internal stress so that 3" and 4" wafers would be possible and usable; b) HEMT/MMIC device improvements which are directly affected by materials properties, e.g., ohmic contact development. The authors also published the first demo of a 4" GaN-on-Diamond wafer albeit with still very high bows [17]. Q. Diduck from Cornell's Eastman group would join the authors to help bring down the wafer's bow to their lowest levels (double-digit microns) yet. The Navy commissioned the first reliability study from the authors, and the results from that work indicated for the first time that GaN-on-Diamond can outperform GaN-on-Si (its original source epitaxy) along reliability-related parameters [18]. Raytheon, Cornell, and the authors separately published preliminary thermal measurements for the first time that indicated GaN-on-Diamond's fundamental merits as a thermal management solution [19-21].

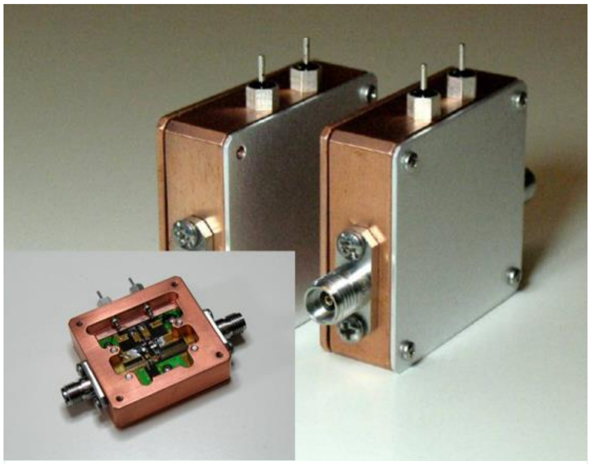

Figure 4 - Photo shows first ever demonstration of an X-band RF PA; demo was performed in 2009 at Group4 Labs.

IV. DARPA-NJTT and "3X" (2011–2013)

Entering a new decade in 2011, DARPA introduced the Near Junction Thermal Transport (NJTT) effort of the Thermal Management Technologies (TMT) program focused on heat extraction from within 1-µm of a transistor's active region, where the heat is generated. The authors partnered with several prime defense contractors in bidding for and winning multiple NJTT programs to show that GaN-on-Diamond as earlier described can be much more effective than others in a GaN transistor's thermal management strategy. NJTT enabled the authors to fully characterize and minimize for the first time, the thermal boundary resistance (TBR) between GaN and diamond. GaN-on-Diamond's TBR was found to be the least after elimination of the poor thermal conducting AlGaN/AlN transition layers under the GaN 2DEG. By the end of the NJTT program, Raytheon and TriQuint were separately announcing that by using GaN-on-Diamond as opposed to GaN-on-SiC, they had successfully reduced the operating junction temperature of a GaN transistor by 40-45%, and that the thermal improvement had tripled the areal RF power density from a GaN transistor [22, 23].

V. GaN-on-Diamond goes commercial (2013–Present)

In mid-2013 E6 acquired the GaN-on-Diamond technology and team to help drive the technology into defense applications (radar and EW), and commercial applications (cellular base stations, and communications/weather satellites). E6 uses a microwave CVD diamond process. The acquisition enabled the team to achieve three significant milestones within a few months: 1) the quality of the diamond substrate was dramatically improved in terms of thermal conductivity (now at 1500+ W/mK), wafer bow (~ 20 µm across 100 mm), TTV (~10 µm across 100 mm), LTV (<10 µm), and sheet resistivity uniformity (<10% across 100 mm), 2) DARPA's NJTT program was successfully completed – tripling the areal power density from a GaN transistor, and 3) preliminary demonstrations (in early 2014) of HEMTs made at Professor H. Xing's group at the University of Notre Dame [24] indicated evidence that E6-made GaN-on-Diamond wafers exhibit significantly lower channel temperatures compared to NJTT-class ("3X") HEMTs. The implication of this Notre Dame improvement is that (subject to other HEMT process limitations), E6-class GaN-on-Diamond HEMTs could reach densities of 4X or more compared to GaN-on-SiC, or that E6-class devices could be operated at even higher ambient temperatures than NJTT-class devices, or that E6-class devices could exhibit much greater reliability parameters (e.g. longer MTTF and lifetimes). Figures 6-7 show photos and property maps capturing the uniformity of E6-class GaN-on-Diamond wafers.

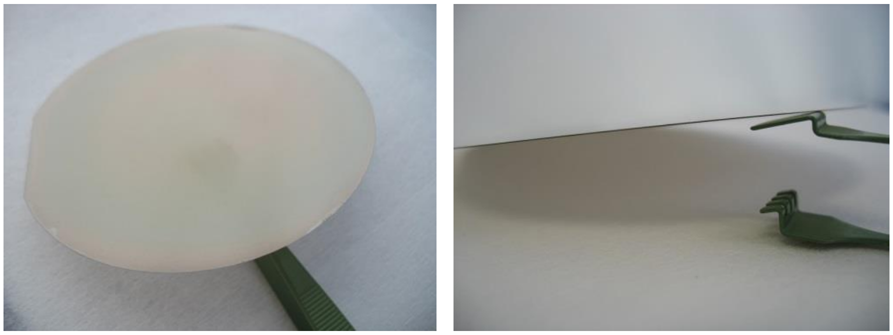

Figure 6 - Photos of Free-standing 4" GaN-on-Diamond HEMT wafers manufactured at Element Six using a microwave CVD process.

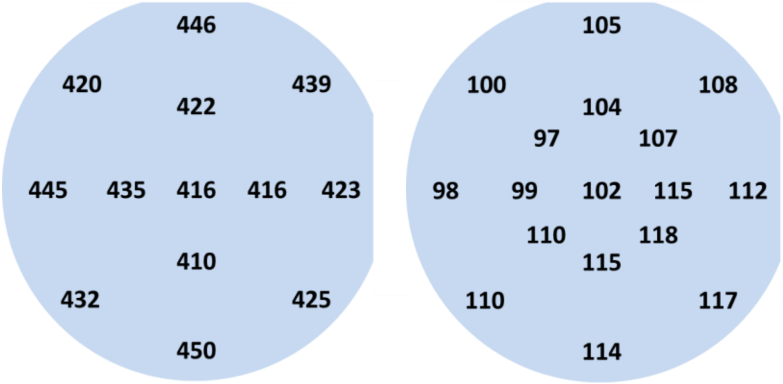

Figure 7 - Lehighton (Left, Ohms/sq.) and Thickness (Right, microns) maps of free-standing 4" GaN-on-Diamond HEMT epitaxial wafers.

VI. The Future

Element Six (the Company) expects to release a GaN-on-Diamond wafer product by the fourth quarter in 2014. This product release would also coincide with the company implementing a volume manufacturing process. While reusable diamond carriers are currently used to ship wafers to early-adopting strategic partners, E6 expects to develop a disposable and cheap carrier for shipping GaN-on-Diamond wafers. Bow, surface quality, and the thermal boundary resistances are variables that the company will continue to improve in the months and years to come. A 6" wafer has also been included in the technology's roadmap.

In summary, GaN-on-Diamond wafers offer commercial and Defense markets, a new generation of RF devices that are three times more powerful in areal RF power density, and 40-45% cooler operating channel temperatures compared to competing state-of-the-art GaN-on-SiC devices. These fundamental advantages are anticipated to result in orders of magnitude greater reliability (e.g., longer MTTF) and lifetimes, smaller size and weight systems due to reduced cooling needs, and significantly cheaper total life cost of operations due to the system's dramatically reduced energy consumption.

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