GaNonCMOS

Results brief

May 2021

In January 2017, the GaNonCMOS consortium set out to develop innovative materials, devices, modules and systems with the potential to drive a new generation of densely integrated power electronics and pave the way towards low cost, highly reliable systems for energy intensive applications. Nearing the end of our project period in June 2021, this results brief focuses on some of the key results and achievements of the GaNonCMOS project.

Materials

Throughout the GaNonCMOS project, the epitaxy of GaN on silicon substrates was developed and fine-tuned towards the fabrication of 25 V class devices based on GaN/AlGaN HEMT. The development, which relied on an optimized single transistor layout and standard process technology, revealed that the inclusion of an in-situ SiN passivation layer enabled the reduction of the leakage current also for large area switches. In addition, magnesium nitride thin films were alternatively explored as gate dielectric material for these devices. A series of Mg_3N_2 films grown by MBE on Si(100) and Si(111) substrates were investigated. In situ RHEED and ex situ XRD experiments reveal that polycrystalline Mg_3N_2 films are successfully grown when using moderate sample temperatures during MBE deposition. Remarkably, the Mg_3N_2 films appear to degrade very rapidly when exposed to ambient conditions. An in situ grown capping layer such as Mg, for example, forms an effective protection for the Mg_3N_2 films in ambient.

Aiming at the fabrication of integrated magnetic devices, the project also explored new magnetic core materials based on magnetic microparticles and thin films. Laminated thin films of a cobalt based amorphous alloy (CoZrTa or CZT) were optimised for use as the magnetic core material for integrated magnetic devices on-silicon or in-substrate. The permeability of this material remains stable up to 100 MHz. In parallel, anisotropic composite core materials for an inductor-based fully integrated voltage regulator were also investigated (see Figure 1 and Figure 2). The main findings out of the fabrication and characterization of composite magnetic materials were:

- The most effective composite assembly consists of a mixture of nano- and micro-particles.
- There is an enhancement of the magnetic properties by both the anisotropic structure and the “necking”.

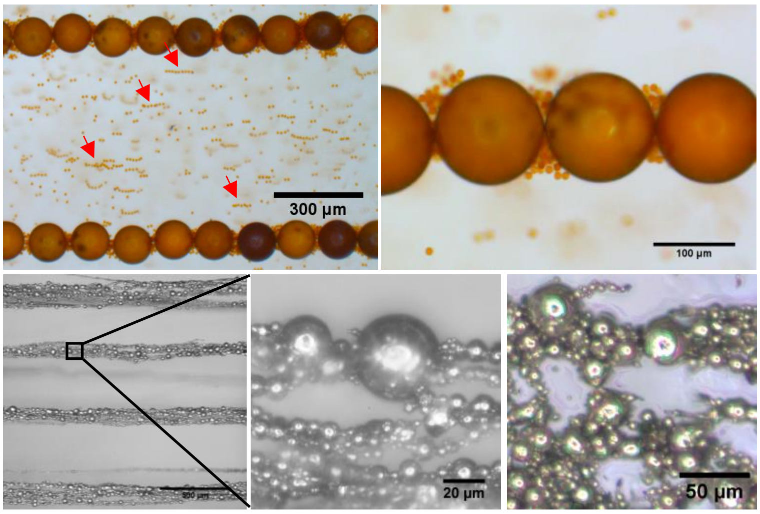


Figure 1: Optical microscope images of a magnetic composite assembly of nano- and micro-particles.

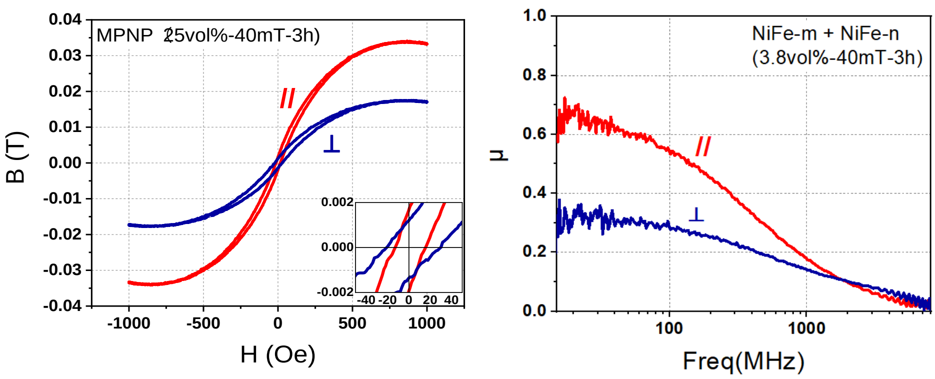


Figure 2: B-H characteristics and permeability versus frequency for composite assemblies.

In terms of characterization and reliability, a wide variety of commercial magnetic sheet materials, potentially suitable for PCB embedding were extensively evaluated for demonstrators and reliability properties. We learned that the CTE mismatch between the magnetic and the surrounding material should be as low as possible to avoid delamination (see Figure 3).

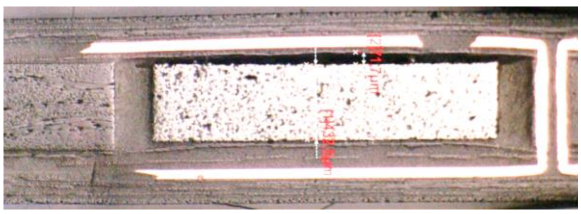


Figure 3: Delamination of embedded inlay.

For the reliability testing and evaluation of those embedded materials, a test array was designed and produced with 10 promising candidate magnetic materials (see "Testing").

Thermal simulations of embedded inductors and complete board systems were conducted. The simulations carried out for the PCB demo 5 resulted in a maximum temperature below

40 °C, implying no anticipated thermal issues even though we are embedding very thin magnetic laminates (see Figure 4).

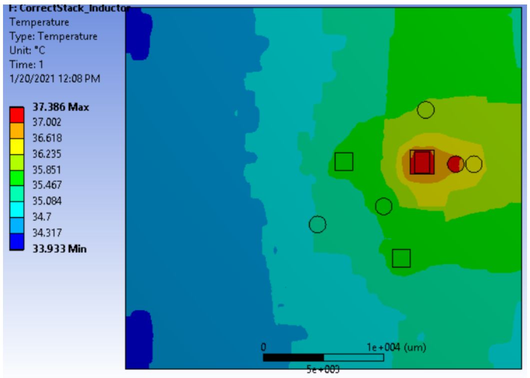


Figure 4: Thermal simulation of PCB demonstrator 5 board

Components

In order to develop demonstrators, the partners have been working to manufacture and qualify the different components needed. The following components have been developed.

Controller and driver ICs

IHP worked on separate controller and driver circuits, which were designed for the evaluations of the key circuit blocks and achieved a measured efficiency of up to 94% in a PCB demonstrator together with IAF's GaN switches. Finally 2 versions of a combined controller/driver IC were developed:

- Half-bridge driver with general purpose PWM controller with minimum die size and extended features compared to the single chips (V1) (see Figure 5). The 1.5 x 1.8 mm² sized chip consumes only 30 mW working at 2 MHz PWM frequency and is able to deliver a driver peak output current of 1.8 A at both the low-side and high-side outputs.

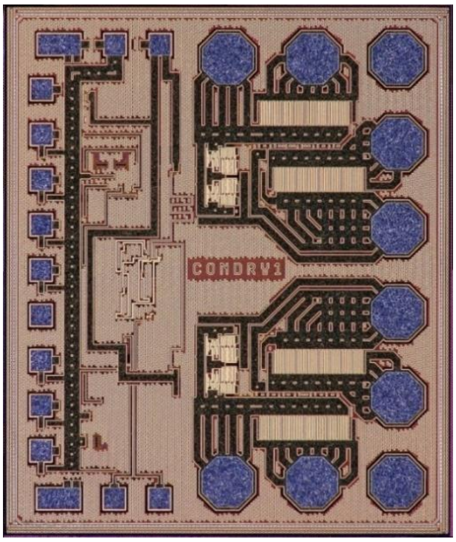


Figure 5: Photo of the combined driver/controller IC V1

- Half-bridge driver for GaN switches with general purpose PWM controller adapted for chip level demonstrator with direct wafer bonding (V2).

In addition, a 48 V driver output stage was produced in order to show the capability of IHP's BiCMOS technology to be prepared for DC-DC converters with isolation voltages higher than 64 V.

GaN switches

At IAF different GaN switches were designed and fabricated based on the HEMTs technology, having a small chip size, a low on-state resistance, a high maximal available current (20 A or 40 A) and a breakdown voltage of 25 V or 100 V. Half-bridge converters were delivered by IAF to the other project partners for use in demonstrators as a single chip or an embedded chip. The monolithic integrated half-bridge circuit consists of two large transistors, the high side switch (SW1) and the low side switch (SW2). The bridge stage is based on GaN HEMTs with a physical layout to give a lowest intrinsic parasitic inductance in the primary switching loop (through a decoupling capacitor) and in the gate driver loops to enable a high switching frequency. As an example, the breakdown voltage measurements, across the 4-inch GaN/Si substrate, for the two switches composing the half- bridge converter are illustrated below. The converter accounts a low side switch (LS) with 306 mm gate width and switch with 153 mm gate width). The SW1 with a gate periphery of 306 mm and the SW2 with a gate periphery of 153 mm achieved an average drain and gate leakage currents of 0.3 µA/mm and 0.2 µA/mm, respectively. They delivered a maximum current of 38 A (SW1) and 22 A (SW1), with a corresponding on-state resistance of 29 mΩ and 52 mΩ (on wafer), respectively.

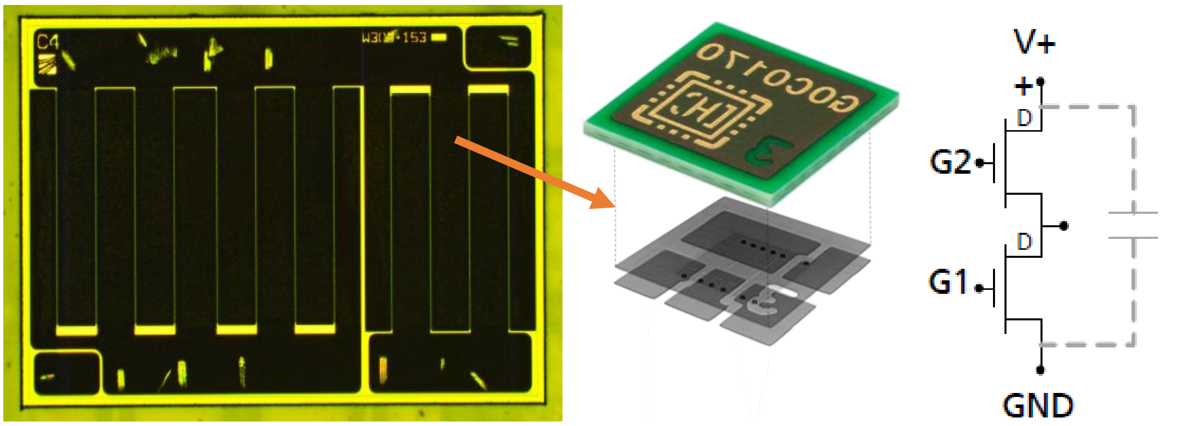


Figure 6: Photography of a fabricated half-bridge switch with a size of 3 x 2 mm², and the X-Ray photo of the GaN embedded device

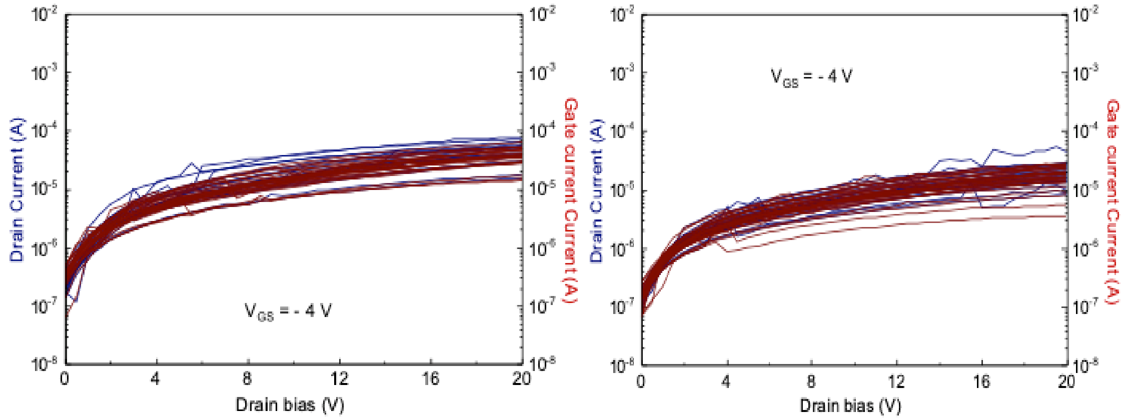
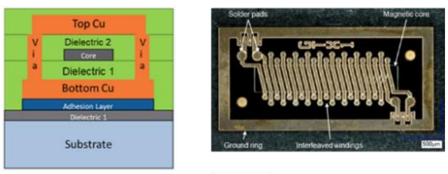


Figure 7: Breakdown voltage mapping across the 4" GaN/Si substrate for Left the low side switch, Right: for the high side switch

For testing the robustness of the embedded chips, (the GaN fabricated devices + the embedding technology). RECOM and AT&S performed two types of environmental tests on the embedded GaN half-bridge chips, first –a high temperature high humidity test of 96 hours at 85°C, 85%RH (HTH) and then a temperature cycling, of 2000 cycles, -55°C to +125°C (TCy). After the HTH testing, the embedded GaN chips did not see any electrical or packaging degradation. These test results show that AT&S' embedding technology successfully packaged the monolithically half-bridge converters. The performance of the embedded chips did not degrade due to this technology and, as expected, a decrease into the on-resistance of each single switch was achieved.

Magnetics-on-Silicon (MoS) Micro-Transformers

At Tyndall, a magnetics-on-silicon micro-transformer (MoS-GD-Tx) for use as a gate drive isolator for a high frequency (10 – 30 MHz) LLC resonant converter was designed, fabricated and characterized[1]. The construction of the solenoidal device is as shown, using electroplated Cu and multiple laminations of sputtered CoZrTaB metal alloy layers, interspersed with AlN dielectric layers. The total device thickness is ~ 40 µm.



a b

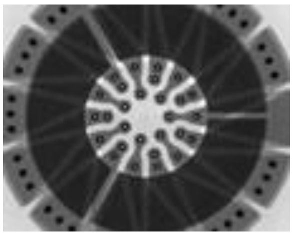
Figure 8: Schematic cross-section of MoS solenoid transformer, b) completed transformer device

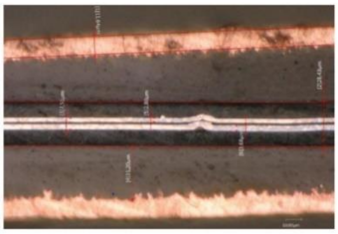
Electrical characterization demonstrated that the transformers are capable of operating at any frequency in the range 20 MHz to 100 MHz. These could ultimately be a part of chip-scale heterogeneously integrated gate driver and switch.

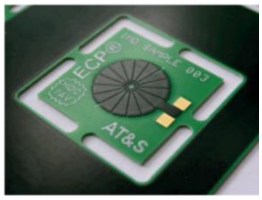
[1] Zoran Pavlovic, Pranay Podder, Dermot Dobbyn, Ansar Masood, Guannan Wei, Daniel Lordan, Paul McCloskey, Cian O'Mathuna, Séamus O'Driscoll, "Thin-film magnetics-on-silicon integrated transformer for isolated power conversion applications", CIPS 2020, Tyndall National Institute , University College Cork, Ireland.

PCB embedded inductors – Tyndall, AT&S and RECOM

A large variety of PCB embedded inductors targeted for use with GaN HEMTs in Point-of-Load (POL or iVR) DC-DC converter applications such as for 12:1 V, 2-level buck converter at multi-MHz were designed, fabricated and characterized[2]. Magnetic materials, analyses and device designs were performed by **Tyndall** and fabricated by **AT&S**, using their advanced Center Core Embedding (CCE) in-PCB technology, as shown in the figure below. The PCB embedded trials used a range of identified candidate magnetic sheet materials and Tyndall's own released sputtered CoZrTaB material. **RECOM** performed some magnetic device characterisations, converter designs and were responsible for all reliability trials.







b

X-ray image of the inductor showing winding turn tilt and vias in the centre of the toroid (Tyndall National Institute, University College Cork, Ireland)

Cross section of Tyndall Released 2-layer (2 µm ea.) Multi-lamination sputtered CoZrTaB metal alloy on polymer[3], embedded in PCB Core by AT&S. Passed automotive grade MSL reliability trials.

Finished test device inductor (AT&S Austria Technologie & Systemtechnik Aktiengesellschaft).

Figure 9: X-ray image, cross-section and finished PCB

Systems

The GaNonCMOS project aims to bring GaN power electronic systems to the next level of maturity by providing the most densely integrated systems to date.

Advancements in the chip level demonstrators

An innovative step considered in the project is to integrate GaN power switches with CMOS drivers (Figure 10), being wafer-wafer bonding - a key technology to enable high frequency chip-scale demonstrators.

Throughout the project, the progress realized on the wafer bonding included the development of a suitable planarization technology (IHP GmbH) to achieve bonding-ready wafers. An optimized version of the combined controller/driver chip was adapted to meet the requirements for direct wafer bonding (IBM Research, Zurich) in the chip level demonstrator. At the same time, a double direct wafer bonding process for the co-integration of GaN devices and CMOS was designed (Figure 11). A process to perform aligned wafer bonding on two processed wafers was realized, and the first demonstration of this process was applied to integrate GaN epitaxial layers on silicon without change of polarity.

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[2] Ruaidhrí Murphya, Zoran Pavlovica, Paul McCloskeya, Cian Ó Mathúnaa, Séamus O'Driscolla, Gerald Weidingerb, "PCB Embedded Toroidal Inductor for 2MHz Point-of-Load Converter", CIPS 2020

[3] D. Jordan et al, "High Q-Factor PCB Embedded Flip-Chip Inductors with Multi-Layer CZTB Magnetic Sheet for Power Supply in Package (PwrSiP)", DOI 10.1109/JESTPE.2020.2983125

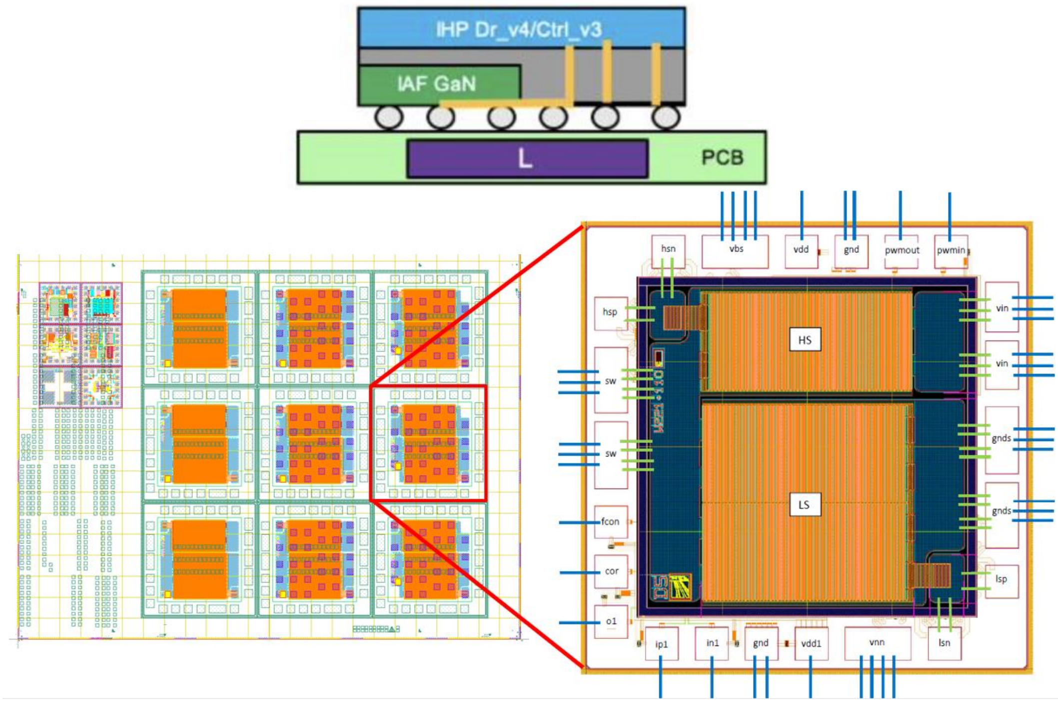


Figure 10: Highly integrated CMOS/GaN power switch.

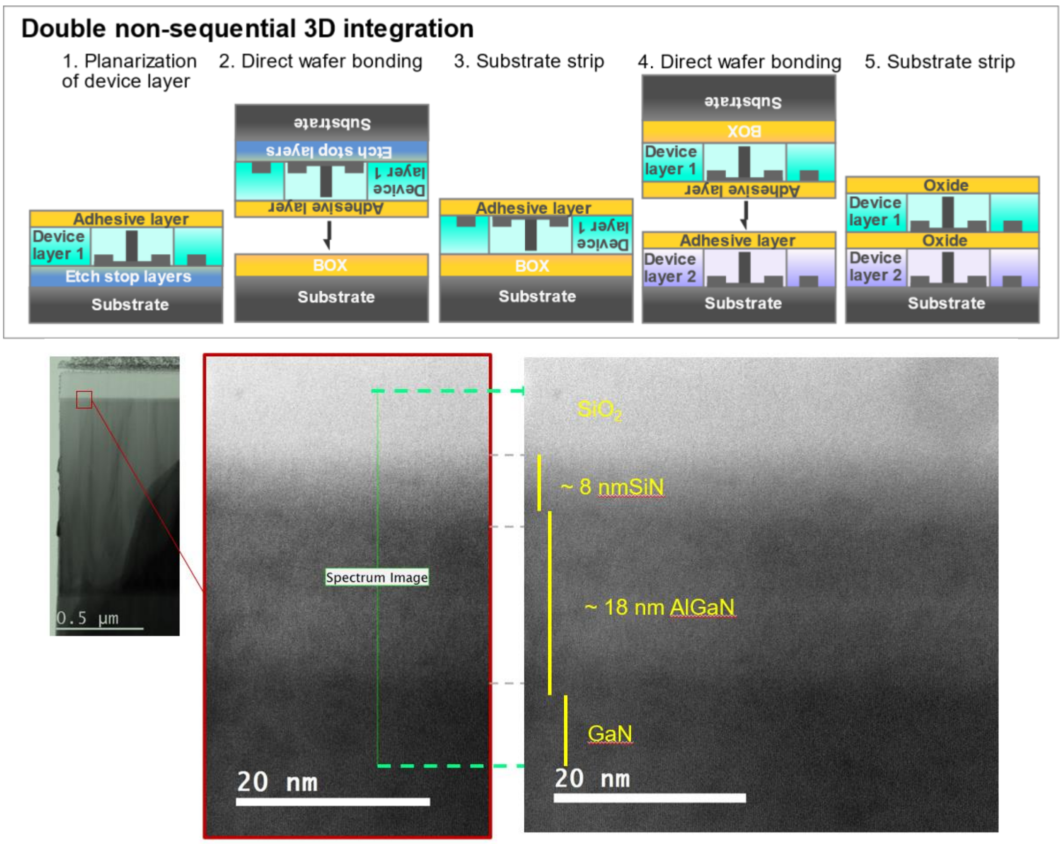


Figure 11: Double direct wafer bonding process for the co-integration of GaN devices and CMOS (top), EDS at the top SiO_2/III-V interface (bottom).

Advancements in the package/stack level demonstrators

The GaN-based monolithically integrated half-bridge wire bonded chip or embedded chip was used in demonstrators (Fraunhofer IAF) to evaluate the quality and the performance of our design and fabrication as well as the efficiency of the embedding technology (AT&S AG):

- As first demonstrator, a wire bonded GaN/Si half-bridge switch has been used in a complete IAF-designed PoL (Point of Load) buck converter. The converter yields a system efficiency that approaches 82% at 2 A (for the half bridge alone), and 78% at 2 A (for the GaN switch + gate driver), when switching at 1 MHz and converting from 24 V to 1 V and from 12 V to 1 V (Figure 12).

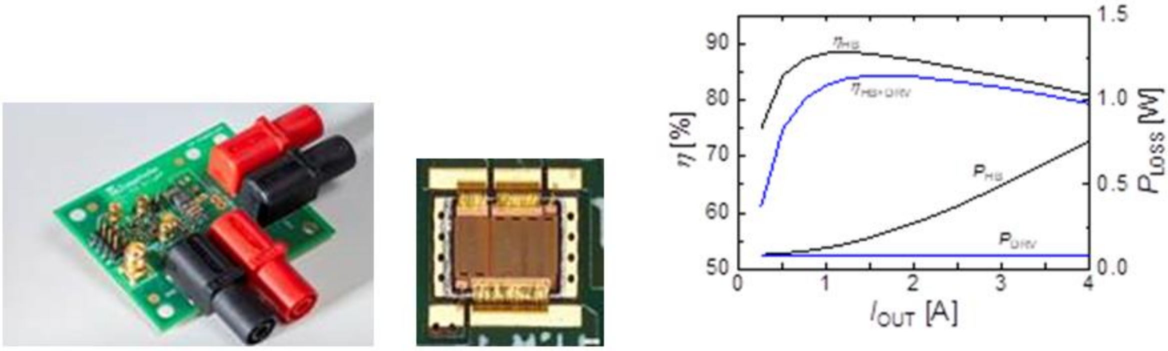


Figure 12: Performance of the bonded GaN PoL demonstrator (12 V-1V PoL).

- The second designed PoL buck demonstrator included an embedded monolithically integrated GaN chip associated to an embedded inductor chip. The performance of the buck converter is presented in Figure 13.

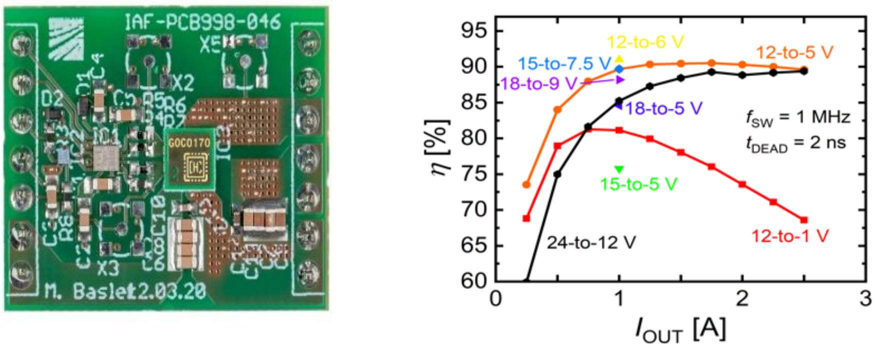
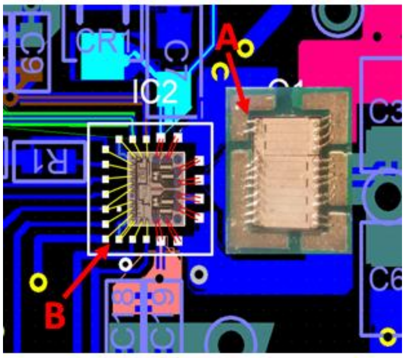


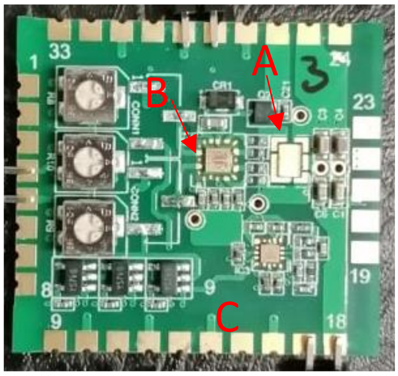
Figure 13: Embedded chip D5 (left), performance of the embedded PoL demonstrator (right).

The heterogeneous integration of the GaN HEMT switch (Fraunhofer IAF) and CMOS driver-controller (IHP GmbH), thin film magnetic materials (Tyndall) and advanced substrate embedding technologies (AT&S AG) is being considered for 12–48V Server Power Supply applications (IBM Research, Zurich), and Automotive (48V) and Aerospace (24V) products at RECOM, Austria.

The proof-of-concept voltage regulator (VR) prototypes by Tyndall focus on 12V “Buck” PoL converters employing the IAF 25V GaN HEMT switches (see Figure 14) and 48V LLC resonant converters employing 100V GaN HEMT switches. The LLC resonant has been used as a test-bed for new gate-driver ICs (Tyndall) employing MoS signal isolation and PCB embedded transformer with leakage resonant inductor. Throughout the project several modules were developed to implement a variety of topologies such as basic buck, 3-level buck and coupled inductor 2-phase modules. The basic buck is for in-converter evaluation of the controller, drivers and switching bridge, while the 3-level buck and the coupled-inductor 2-phase buck are to reduce the inductance value requirement and enable higher density integration



GaNonCMOS partner components



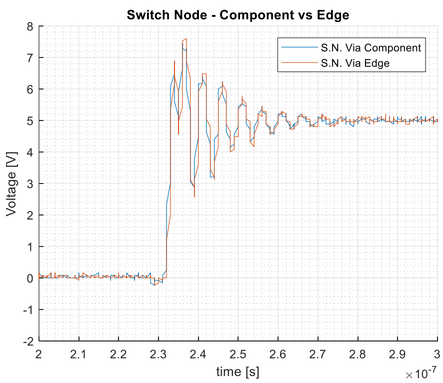
Tyndall PCB Demo 0-5

(A) Monolithic IAF 25 V GaN HEMT bridge with asymmetric switch area ratios to suit low duty cycles
(B) IHP 15 MHz PWM Controller-Driver (v2)

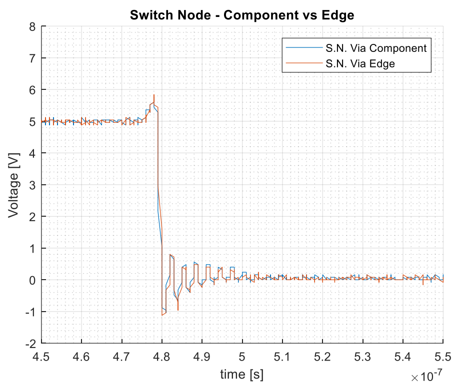
(A) IAF GaN HEMT
(B) IHP 15 MHz PWM Controller (v1)
(C) IHP Driver (v1)

Figure 14: 2–10 MHz, 12 V Point-of-Load (PoL) Converter Modules – PCB-DEMO-5.

The “PCB-DEMO-5” test-bed has been used to characterize the in-converter performance of the new IAF and IHP magnetic components, individually, as well as collectively in a full closed loop system. The controller (v1), operates to 15 MHz (versus commercial PWM ICs which operate to about 2 MHz) and has a quiescent current draw, I_Q, of 680 µA. The challenges identified include achieving better control performance for duty cycles in the range 0–10% at the higher frequencies. Regarding the closed-loop converter, although we are at early stages, we have full functionality. The 25 V GaN d-HEMT switches are performing as expected (Figure 15).



V_Switching_Node – rising edge @ 50% Duty, 2 MHz with IAF C4 GaN d-HEMT Switching Bridge



V_Switching_Node – falling edge @ 50% Duty, 2 MHz with IAF C4 GaN d-HEMT Switching Bridge

Figure 15: Performance of the 25 V GaN d-HEMT switches.

A full DC/DC converter (see Figure 16 and Figure 17) with embedded material in the inner layers of the PCB was also designed, developed and produced (RECOM, AT&S AG). This converter integrates the inductor in the PCB under a commercial LDMOS monolithic PMIC switcher. It is a functional demonstrator with a buried inductor based on a single IC solution. The single IC with silicon MOSFETs used is the same as in a standard RECOM power module, which allows the benchmark. The assembled DC/DC convertor demonstrates the embedded inductor technology in a real-like full-feature non-isolated converter. The main advantage here is a flat design – height reduction.

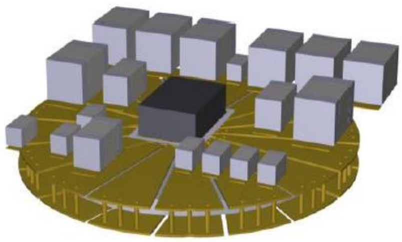


Figure 16: Components of the DC/DC converter designed by RECOM and AT&S.

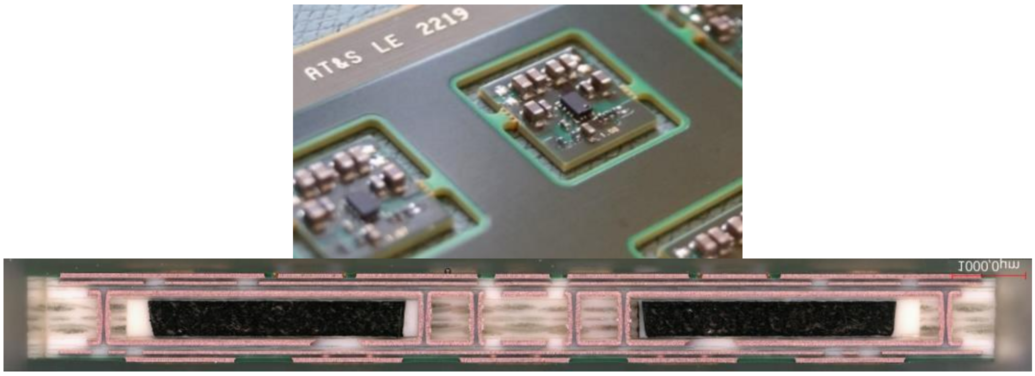


Figure 17: Assembled DC-DC converter and cross-section of PCB.

Spin-off system product development

A wireless charging unit was also developed and produced with the embedded inductor technology (AT&S AG). The wireless charging unit was constructed to prove that big inlays of magnetic material could be embedded in a PCB. With the working demonstrator it was possible to charge commercial phones and wireless earplugs.

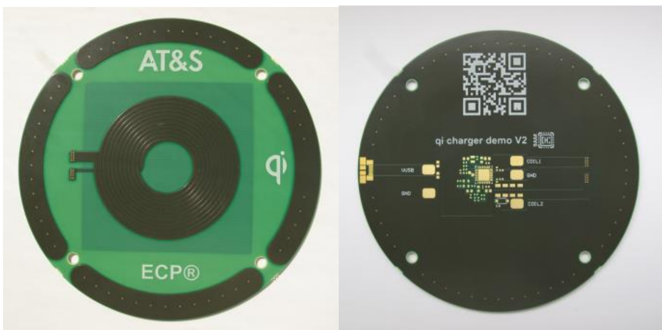


Figure 18: Wireless charging unit front and back side.

Testing

An extensive test in industrial conditions, including both electrical and reliability tests, of the demonstrators and materials developed and fabricated throughout the project was performed.

Embedded magnetic sheet materials in different configurations –as a transformer or as an inductor with three gap options (no gap, 1 gap or 3 gaps inductors) – were fabricated (AT&S AG) and tested (RECOM). The inductance was selected as a main parameter and the influence of various environmental tests and production processes on the inductance and mechanical properties was analysed. The effect of these configurations on the inductance along with the temperature dependency and bias current was investigated using a customized semi-automated test system developed for this purpose (Figure 19).

Moreover, 50 panels with 33 samples on each panel of the embedded transformer were manufactured (AT&S AG). 10 different magnetic materials were used (5 panels each material). A customized fully-automated test setup was developed to be able to measure, record and process the primary and leakage inductance of each transformer sample of the panel (Figure 20). 5 types of environmental tests were performed (RECOM, AT&S AG) for each material:

- HST 1000h – 1000 hours High Temperature Storage at + 125°C
- LST 1000h – 1000 hours Low Temperature Storage at -55°C
- THB 1000h – Temperature Humidity Bias at 85°C/85%RH
- TCy – Temperature Cycling, 2000 cycles (-55°C to +125°C)
- HAST – Highly Accelerated Stress Test – 96 hours at 130°C, 85%RH, performed two times

All the panels went through a drying step and three times reflow before the environmental test started. These long-term tests were one to two times interrupted to perform the intermediate inductance measurements and visual check to assess the effect of any sudden change of the parameters.

An isolation test using hipot was performed on selected samples of each panel. Based on these measurements the current design is capable of at least 1kV.

All the panels were x-rayed before the environmental tests started to check if the material was not damaged during the embedding process (high pressure).

As a result, we were able to determine which materials out of these 10 tested were suitable for embedding. With the toroidal design with 10.5 mm diameter it is possible to reach inductance of about 1.6 uH using a magnetic material suitable for up to 2-3 MHz and currents up to 2-3 A. Other suitable material can go to about 10 MHz with the inductance up to 350 nH.

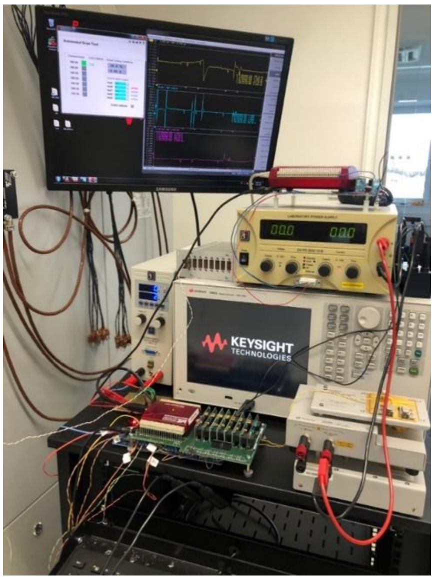


Figure 19: Semi-automated test setup for inductance measurements in temperature with bias current.

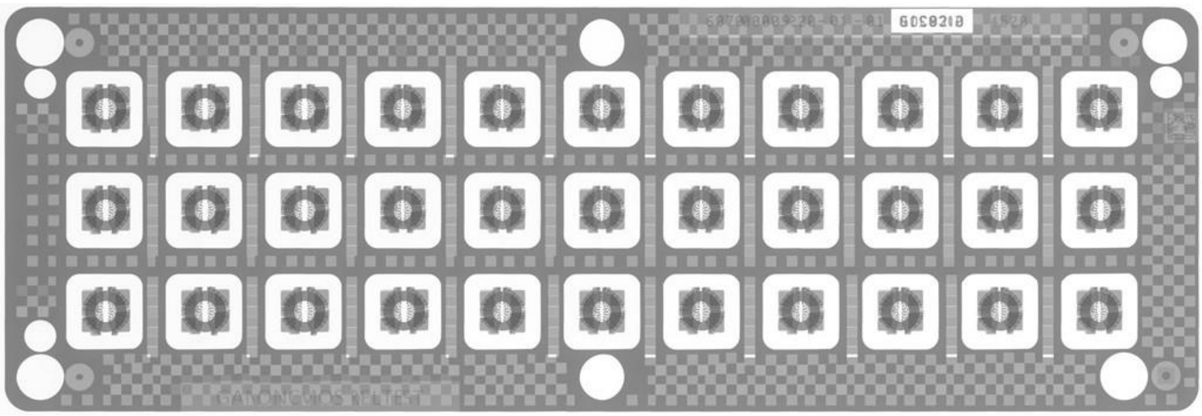


Figure 20: X-ray of the test panel

The DC/DC converter with embedded inductors (PCB DEMO 6) was also tested (Figure 21) by means of electrical tests (line and load regulation, ripple and efficiency) as well as environmental reliability tests (HTHH - 96 hours moisture test, HALT test and EMC measurements).

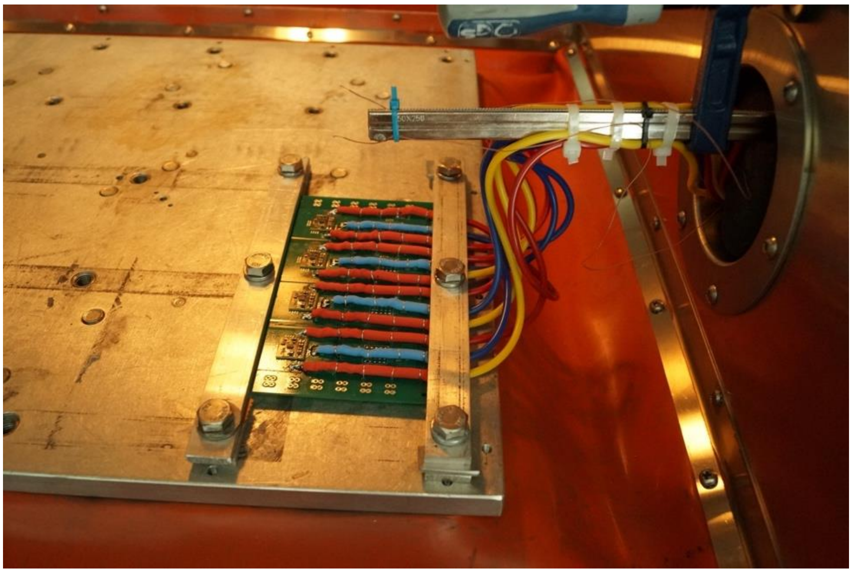


Figure 21: HALT test board with 4x PCB DEMO 6 in the chamber installed on the vibration pad.

Business

GaNonCMOS value propositions

Based on the technical research and extensive market research during the project, two main value propositions for data centres and the automotive industry were identified.

For data centres, the value proposition builds on increasing the power density of current data servers, mostly through reducing the height and area of the magnetics. Flatter server boards will allow to install more units into one rack and simplify the heatsink design, using GaNonCMOS-developed technologies such as embedded magnetics, discrete GaN switches and GaN on silicon chip design. The solution will be suitable for 12V and 48V bus systems.

For the automotive industry, the value proposition of the GaNonCMOS technologies is the strongest for short-term Mild Hybrid Electrical Vehicles (MHEV) 48-12V power system and mid-term MHEV 48V power system, as well as for the Plug in Electric Vehicles (PEV). The value propositions for the short-term and mid-term MHEV applications are respectively, around 6 and 27Kg reduction in the car weight, 500 and 1600€ cost reduction in components, 350 and 650L saving in petrol over the lifetime of the car representing 1200 and 2200 KgCO2-eq/vehicle. As for the PEV, a similar weight reduction of about 27Kg is expected, which will increase the driving range for the same battery by about 30Km, while reducing the cost of components by about 250€, and at the same time reducing the electricity consumption during the lifetime of the car by about 1600 kWh (eq. to 300€), corresponding to a reduction in GHG emission of about 650kgCO2-eq. Although the weight reduction is not huge compared to the total weight of the car, GaNonCMOS technologies could allow certain cars to fit into a certain weight categories and associated emissions, which would be a selling argument for the automotive industry. Additionally the gain on cost and weight using GaNonCMOS could be converted in more powerful battery for PEV which will result in a significantly higher driving range.

GaNonCMOS exploitation success

In addition to the proposed value propositions for the exploitation of the GaNonCMOS technology as a whole, the project results already led to concrete business developments for the project partners. For example, a leading semiconductor chip manufacturer wants to develop a new generation of high frequency inductors to improve power delivery networks jointly with AT&S. Moreover, in cooperation with a hearing aid company, a joint development project for using the embedding technology for charging implants was started at AT&S. And, a leading manufacturer of electronic components has together with AT&S initiated a project to realize a power supply with an embedded transformer. At Tyndall, the thin-film MoS technology has been successfully licensed for use in silicon foundry back-end-of-line (BEOL). It is expected that the GaNonCMOS results will allow Tyndall in cooperation with AT&S to extend released-from-wafer MoS thin film materials to mass-market embedded-in-PCB applications. A technical and commercial feasibility study is currently underway with a major European IC company to validate this proposition.

After GaNonCMOS

The GaNonCMOS project is considered to be highly successful by the project partners. As described in this results brief, the project resulted in many promising developments at material, component and system-level. After the conclusion of the project, the partners would like to further build on the executed work. Here a few examples:

- In parallel to the GaNonCMOS project, IHP was successful in developing their LDMOS transistor with a much higher voltage swing compared to the standard high voltage transistors in SG13S technology used for GaNonCMOS driver chips. The next step for IHP would be to integrate these LDMOS transistors into the output stages of driver circuits.
- IAF looks forward to continuing the development of the GaN-based devices technology toward more integration (GaN converter, GaN driver, GaN based logics, GaN sensors) to improve the performances, reduce the size and cost of the chip and be able to offer an all-in-one GaN integrated circuit for different type of converters.
- Tyndall expects an on-going and continued research into achieving chip-scale heterogeneous integration of MoS based inductors and transformers in voltage reglators and gate driver applications. It is anticipated that the immediate area of interest for transitioning from surface mount technology (SMT) to embedded-in PCB is for ultra-low power POL converters for IoT.
- RECOM is planning to design 200-500W DC/DC power module using GaN suitable for low voltage e-mobility (48V bus).
- At AT&S, the GaNonCMOS results already led to the initiation of several joint development projects with customers (see previous paragraph) and AT&S plans to continue the exploitation of the developed technologies and newly gained business contacts.

Want to know more?

Visit our website **here**.

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