New Embedded Inductors For Power Converter Applications

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Abstract

Power electronics is the key technology to control the flow of electrical energy from the source to the load for a wide variety of applications from the gigawatts in energy transmission lines, the megawatts in datacenters that power the internet, to the milliwatts in mobile phones.

In the frame of the GaNonCMOS project AT&S develops embedded inductors and builds demonstrators for Voltage Regulation Modules (VRM) based on the embedding technology. A mayor advantage is the fact that building the electrical traces around the central core using PCB production processes is much more cost effective than winding wires manually and assembling the coil on top of a board. This advantage is multiplied when a great number of cards are distributed on a big panel format.

For the evaluation of the most promising design simulations have been employed. Then calculations have been done to improve the results and the design has been adapted and redesigned in three iterations. The final design has been realized as a demonstrator to verify the simulation and calculation data and to prepare the development of even more challenging inductors.

The Center Core Embedding method is used for the build of the embedded inductor. Embedding components into the inner layers of a PCB yields several advantages compared to the assembly on the surface of the PCB. In addition there is the opportunity to embed other components like switches, controllers and passives into the same package, forming a fully embedded converter.

Key words: embedded, inductor, GaN, converter, power, electronic

Introduction

In the next years there is a big growth expected in the demand for DC-DC converters especially for automotive, aerospace and server applications. Embedding technology offers mainly benefits in terms of miniaturization and reliability for active and passive components. The embedding of magnetic materials for the realization of inductors gives additional advantages in regard of consistency, labor load and yield. The combined embedding of magnetic material, active and passive components allows the production of highly integrated modules exploiting all possible advantages.

Partners with different expertise came together in the GaNonCMOS [**1**] project with the goal to develop GaN power electronic systems with a high level of integration. Its full title is "GaN densily integrated with Si-CMOS for reliable, cost effective frequency power delivery systems". Within the scope of the project AT&S provides its expertise in embedding active and passive components e.g. controller components and GaN switches provided by the partners and it takes the leading for the development of the embedded inductor.

GaNoCMOS project

The project partners consist of Katholieke Universiteit Leuven, EpiGaN NV, Fraunhofer Gesellschaft zur Förderung der Angewandten Forschung E.V, IBM Research GmbH, AT&S Austria Technologie & Systemtechnik AG, IHP GmbH – Innovations for High Performance Microelectronics / Leibniz-Institut für Innovative Mikroelektronik GmbH, Tyndall National Institute (TNIUCC), RECOM Engineering GmbH & CO KG, PNO Innovation NV, NXP Semiconductors Netherlands BV and X-FAB Semiconductor Foundries AG. The GaNonCMOS project aims to bring GaN power electronic materials, devices and systems to the next level of maturity by providing the most densely integrated materials to date. This development will drive a new generation of densely integrated power electronics and pave the way toward low cost, highly reliable systems for energy intensive applications.

The approach for the achievement of the goals is divided into three integration schemes (**Figure 1**). AT&S activities are concentrated in the package level scheme demonstrators and providing embedding expertise for the controllers and GaN switches provided by the respective partners.

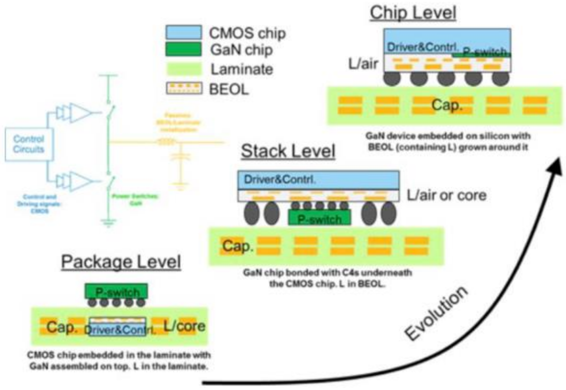

Figure 1: Evolution of the GaN power electronics integration schemes with increasing complexity

CCE technology

Center core embedding is a method to embed active and passive components using an adhesive film to fix the position of the die within a cavity. These cavities are realized in a FR4 material core using a cutting technology like routing or laser cutting. Then the adhesive film is laminated over the whole core and the dies are assembled into the cavities **(Figure 2)**.

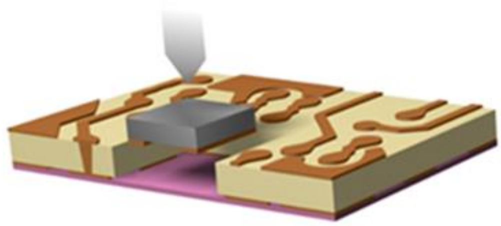

Figure 2: CCE Die assembly

A prepreg is then laminated over the core and dies in a heat assisted pressing process. The resin will fill the gap around the die with resin and fix the position of the die so that the adhesive carrier film can be removed. A second lamination cycle with a prepreg used on the other side of the core at higher temperature will then cure the resin completely (**Figure 3**).

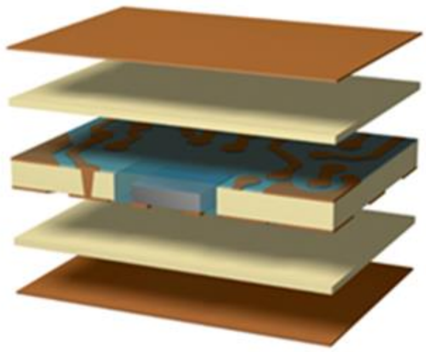

Figure 3: CCE Lamination

In the next steps of production via are realized from the outer layers of the new 4 layer buildup down to the copper pads of the embedded dies followed by structuring the outer layers to provide means for unbundling and connecting the contacts of the dies (**Figure 4**). By using the CCE method it is possible to make contact to the dies from both sides.

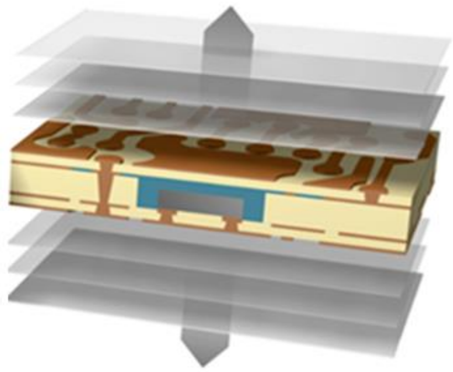

Figure 4: CCE Buildup of additional layers

This embedding method allows simultaneous embedding of many dies (actives, passives, switches and controller) and the magnetic core for the inductor at the same layer of the central core. Also two step embedding processes are possible to embed components with different heights. In the case of the magnetic core it is possible to use structuring and through contacting processes to realize windings around the embedded core.

Inductor demonstrator

A magnetic material was required for the inductor with two major requirements. Firstly it had to have high permeability and secondly it had to be embeddable into the inner layers of a PCB without delaminating at reflow conditions. Additionally it should not go too fast into saturation. Several materials have been tested to select suitable magnetics.

Simulations had been made to find a design for the first demonstrator (**Figure 5**). The goal was to realize an inductor for a 12:1 V buck converter at a frequency of 5 MHz and a peak current of 2,3A. Variating the winding count and the dimensions over three iterations we came up with a toroid inductor with 16 windings at inner radius of 1.5mm and at outer radius of 5.25mm. An ‘air’ gap of 0.5mm was introduced in some of the demonstrators to avoid that the material goes into saturation too fast.

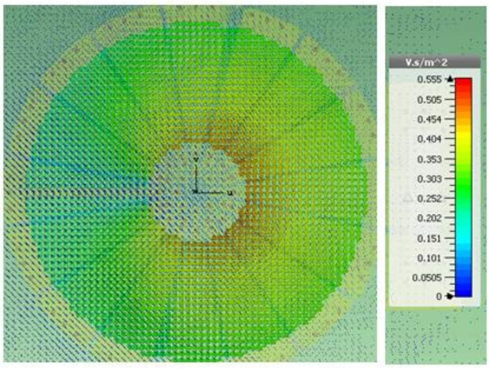

Figure 5: Simulation of inductor with gap

The simulation had been done with CST software package. Simulation results had been verified by calculation [2], [3]:

$$L = \frac{N^2}{\frac{l_e - l_g}{\mu_0 \times \mu_R \times A_e} + \frac{l_g}{\mu_0 \times F \times A_e}}$$

$$F = 1 + \frac{l_g}{\sqrt{A_e}} ln\left(\frac{2l_W}{l_g}\right)$$

L	…	Inductance
N	…	Number of turns
l_e	…	Effective magnetic length
l_g	…	Length of ‘air’ gap
μ_0	…	Permeability in vacuum
μ_R	…	Relative permeability of magnetic material
A_e	…	Effective area of magnetic material
F	…	Fringing factor
l_W	…	Length of windings

The results of the calculation were well aligned with the simulation data.

Inductor manufacturing

The magnetic core materials were cut with a laser into the desired shape. Suitable laser parameter had to be found to cut through the different materials. The demonstrator has been designed and materials selected (**Figure 7**). A regular PCB production was prepared with stops at which it was required to take the intermediate product out of the production process and perform steps in R&D.

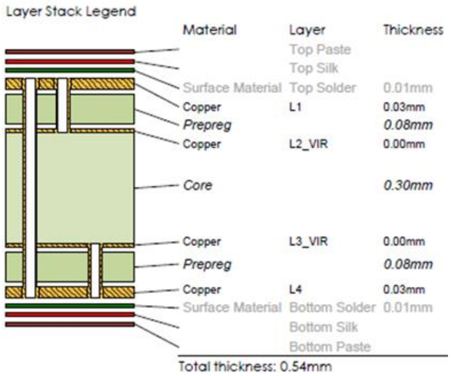

Figure 7: Layer buildup

The core materials had to be assembled with semi-automatic equipment in R&D the lab. Then intermediate product was passed into production again and passed the remaining production steps yielding the functional demonstrator (**Figure 8**). X-ray measurements proved that the magnetic cores were well embedded at the right position and that the structure and holes matched the design.

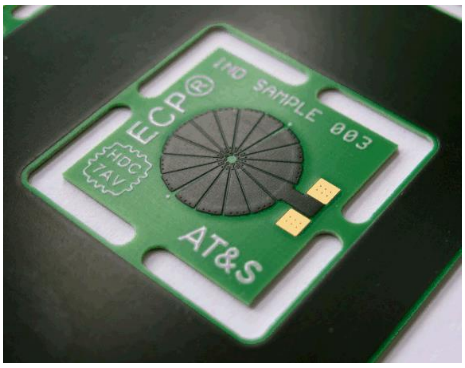

Figure 8: Functional demonstrator

Inductor measurements

The measurements of the inductor have been done with the equipment at AT&S and RECOM (project partner).

Permeability is a function of current. In a first step the inductance of the demonstrator was measured in a function of permeability using an impedance analyzer. The values show a good fit between measurement, calculation and simulation for the sample with the core material with gap (**Figure 9**). For an embedded full toroid core the measurement, calculation and simulation graphs matched perfectly.

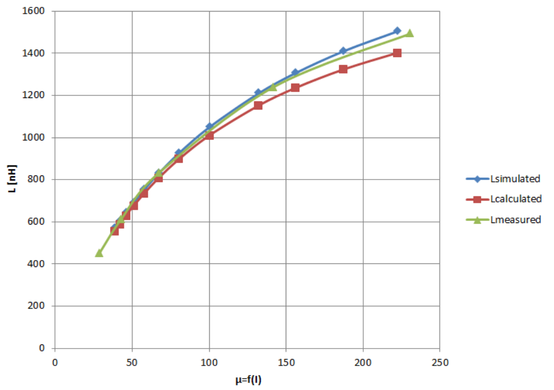

Figure 9: Inductance vs. permeability

In a second step the inductor samples were connected with a DC/DC converter evaluation board in order to verify the results on a real application. Inductor current and switching voltage were measured. (**Figure 10**).

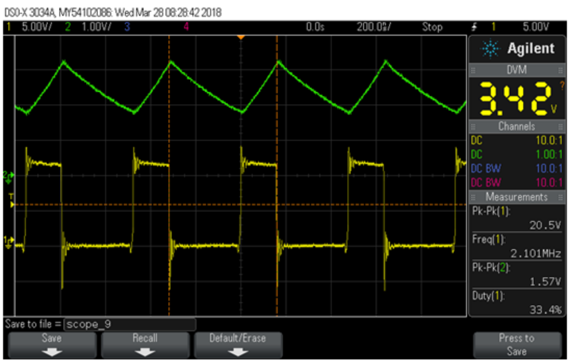

Figure 10: Measurement on inductor inside DC/DC converter

The inductance was calculated using the following formulas:

$$\Delta t_{on} = \frac{D}{f}$$

$$L = \frac{V_{in} - V_{out}}{\frac{\Delta I_L}{\Delta t_{on}}}$$

Δt_{on}	…	'On' time
D	…	Duty cycle
f	…	Frequency
V_{in}	…	Input voltage
V_{out}	…	Output voltage
ΔI_L	…	Inductor current ripple

The results of the calculations according above formula and the comparison with the measurement with the impedance analyzer are shown (**Table 1**). As can be seen, there is a good match between the inductance values obtained by two different measurement method.

Table 1: Inductance measurements on DC/DC converter and impedance analyzer

I [A]	*Sample without gap*		*Sample with gap*	
	Analyzer	*DC/DC converter*	*Analyzer*	*DC/DC converter*
1	1.828 µH	1.724 µH	1.758 µH	1.724 µH
2	0.952 µH	1.062 µH	1.238 µH	1.224 µH
2.5	0.806 µH	0.881 µH	1.052 µH	1.106 µH

Thermal measurements have been done with an infrared camera in order to evaluate the thermal behavior of the inductor (**Figure 11**). At 2,5A the temperature raised from an ambient 25°C to a steady state reached at approximately 100°C.

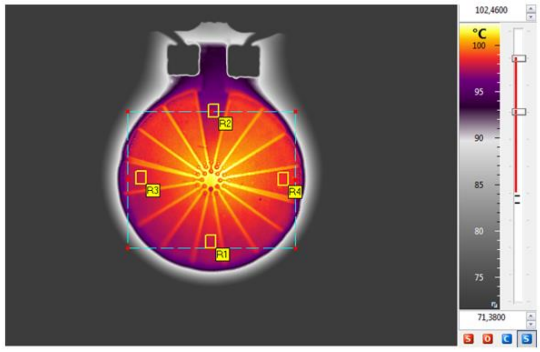

Figure 11: Thermogram for 2.5A

Summary & Conclusion

CCE embedding method was used for the realization of the demonstrator of an embedded inductor because of the following advantages:

- More even layer thickness
- Better planarity
- Smaller dielectric thickness tolerance
- Improved reliability due the fact that only one epoxy resin composition is used for the embedding

A functional embedded inductor demonstrator was manufactured and tested for a realistic application. Simulation, calculation and measurement results showed a good match.

Acknowledgements

The authors would like to express their thanks to all the participating partners of GaNonCMOS project and especially the European Commission for the funding of this project within the Horizon 2020 Research and Innovation program H2020-NMBP-02-2016 under Grant Agreement No 721107.

References

[1] http://ganoncmos.eu

[2] E. C. Snelling, "Soft Ferrites Properties and Applications", Iliffe Book Ltd, first edition, London, Chapter 4, pp. 171-193, 1969.
[3] Colonel Wm. T. McLyman, "Transformer and Inductor Design Handbook", Marcel Dekker, Inc., third edition, New York, Chapter 8, 2004.