# Monolithically Integrated GaN-on-Si Power Circuits

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## Abstract

This paper presents different monolithically-integrated power circuits, fabricated in a 600 V-class GaN-on-Si heterojunction technology. High performance and high functionality are demonstrated by examples of a HEMT with integrated gate driver, of an integrated temperature sensor, of a half-bridge, and of a multilevel inverter topology.

#### 1. Introduction

Power transistors based on AlGaN/GaN-on-Si heterojunction technology feature an outstanding performance in terms of the static- and dynamic-properties [1]. However, beyond single device performance this technology offers new opportunities of integration. In contrast to most conventional power technologies, such as power MOSFETs or IGBTs, the GaN-on-Si heterojunction technology is of lateral nature and allows the integration of several components side-by-side on a single chip. The monolithic integration of power circuits improves performance due to lower parasitics, and reduces the effort for assembly and joining technology.

This paper presents a number of highly-integrated power circuits with advanced performance achieved by monolithic integration. These power circuits are fabricated in a custom-izable 600 V-class GaN-on-Si technology [2].



Fig. 1 Technology cross section of a GaN-on-Si power circuit with typical components. (left) HEMT structure with double field plate, (middle) resistance temperature detector (RTD), (right) heterojunction Schottky diode.

#### 2. Integrated Power Circuits

## Integrated Gate Driver

GaN devices are predestined for fast slew-rates and high switching frequencies due to very low switching charges [1]. Nevertheless, the speed of GaN-based switching units is often limited by the parasitics of the assembly- and interconnection-technology. The monolithic integration of gate





driver and power HEMT reduces the gate loop inductance as well as disturbances caused by drain-gate coupling. Thus, fast slew-rates with values up to 240 V/ns during turn-on and turn-off transitions are achieved and published in [3]. The measurements were performed with an off-state voltage of  $V_{\rm DS} = 450$  V and an on-state current of  $I_{\rm D} = 14$  A. In [4] the integrated gate driver has been extended with a mono-lithic depletion-mode logic inverter to achieve a single control input (Fig. 2). In contrast to CMOS technologies the discussed heterojunction GaN-technology is unipolar and the whole circuits are based on only n-channel devices. *Integrated Temperature Sensor* 

The high melting point of GaN enables an operation at high temperatures and reduces the effort for cooling. None-theless the device performance and reliability suffers from these conditions. A precise in-chip temperature sensor can be used to control the operation condition adapted to the matters of the application. A highly-linear, temperature sensor with short response time is monolithically integrated in a 600 V/30 A power-HEMT. The realization and characterization of this sensor is published in [5].

#### Integrated Freewheeling Diode

A disadvantage of conventional HEMT structures is the absence of an intrinsic body diode, however, a low resistive-, high current-carrying, fast freewheeling-diode behavior is required for many power topologies (Fig. 3 a). An improved intrinsic HEMT-structure with monolithic-integrated freewheeling diode is introduced in [6] and shown in Fig. 3 b). Schottky contacts which are combined with the source connected field plate provide a path for reverse conduction, which is independent of the state of the gate. The area-consuming depletion zone is used for both components, for the HEMT and the antiparallel diode. Therefore, the in-



Fig. 3 a) HEMT with freewheeling diode. b) Cross section and top view of a GaN HEMT with integrated freewheeling diodes. c) Forward and reverse performance of the HEMT with integrated freewheeling diodes compared to state-of-the-art power devices. Data are taken from [7].

trinsic structure requires little additional chip area and does not contribute significant parasitics. Fabricated devices using this structure achieve low switching charges in forward and reverse operation (Fig. 3 c). The relevant figure-of-merit  $R_{ON} \cdot Q_G$  is about 10 times lower compared to state-of-the-art Si-superjunction MOSFETs and in the range of the best GaN-HEMTs. The figure-of-merit for reverse operation  $R_{ON} \cdot Q_{RR}$  is about 500-1000 times lower compared to Si-superjunction MOSFETs and in the range of wide bandgap Schottky diodes. In the following this base structure is used for monolithically integrated power topologies. *Integrated Half-Bridge* 

The core topology in most converter applications is a half-bridge circuit, which is shown in Fig. 4 a). Publication [7] presents the design and performance of a monolithically integrated high-voltage half-bridge. Its operation is demonstrated in a 400 V-to-200 V soft-switched buck converter and published in [8]. The work discusses undesired effects resulting from the commonly-used conductive Si-carrier substrate, as backgating and crosstalk. The converter operates at high voltages up to 400 V and high switching frequencies up to 3 MHz by the introduction of a high-ly-resistive voltage divider for a semi-floating common substrate termination as shown in Fig. 4. This demonstrator discloses the opportunities, as well as the challenges of monolithically integrated high-voltage circuits.

# Integrated Multilevel Inverter

The new HEMT structure with intrinsic freewheeling diode and their lateral property enables the integration of



Fig. 4 a) Circuit diagram of a resonant buck converter with monolithic half-bridge IC in a 600 V-class GaN-on-Si technology. b) Output voltage and current at 3 MHz switching frequency.



Fig. 5 a) Circuit diagram of monolithic three-level- diode-clamped multilevel converter. b) Photograph of the multilevel converter assembled in a PCB-embedding technology (AT&S-ECP). c) X-ray image of embedded multilevel chip.

complex power converter topologies into a single area-efficient power IC. The entire topology of a  $V_{\rm DS} = 400 \text{ V}/$  $I_{D,MAX} = 5$  A diode-clamped multilevel inverter with 4 transistors and 6 diodes is integrated on a  $A = 2 \times 3 \text{ mm}^2$  power chip and characterized in [9]. The highly functional and compact power chips represent a challenge for conventional interconnect technologies based on bond wires. New possibilities open up through printed circuit board (PCB) embedded technologies. This is demonstrated by the embedded multilevel converter chip shown in Fig. 5. A DC/AC-converter was built to demonstrate the performance of the device. The inverter is designed to generate a mains voltage sine wave with 120  $V_{RMS}$  at the output. The converter has a DC input voltage of 300 V between the supply nodes  $V_{++}$  and  $V_{--}$ . With a peak-peak output current of 1 A the inverter provides an output power of about 45 W.

#### 3. Conclusions

The lateral GaN-on-Si technology offers various opportunities of monolithic integration and combines wide-bandgap performance with high functionality. An integrated gate driver demonstrates fast switching rates up to 240 V/ns. An intrinsic HEMT structure with integrated freewheeling diode features high performance and is applied in a monolithic half-bridge working at 400 V and 3 MHz. Furthermore it is used as base structure for a monolithic multilevel converter.

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#### References

- [1] J. Chen et al., IEEE Trans. Electron Devices 64.3 (2017) 779.
- [2] P. Waltereit et al., Phys. Status Solidi. 10.5 (2013) 831.
- [3] S. Moench et al., in Proc. of the 3<sup>rd</sup> IEEE WiPDA (2015) 92.
- [4] S. Moench et al., in Proc. of the 4<sup>th</sup> IEEE WiPDA (2016) 204.
- [5] R. Reiner et al., in Proc. of the IEEE APEC (2016) 2083.
- [6] R. Reiner et al., in Proc. of the 25th ISPSD (2015) 45.
- [7] R. Reiner et al., in Proc. of the PCIM-Europe (2016) 319.
- [8] B. Weiss et al., in Proc. of the 4<sup>th</sup> IEEE WiPDA (2016) 215.
- [9] B. Weiss et al., in Proc. of the 35th IEEE CSICS (2015) 156.