Gallium Nitride for 600V Operation

Especially for mains voltage applications, new efficient 600V class devices are required. These devices are within the main product focus of MicroGaN, as outlined at PCIM. Two basic elements are developed which will enable the layout of all required power circuits: the power diode and the power switch. Additionally, a unique fabrication technology has been developed to reduce chip area, chip price and device parasitics as well as providing compatibility to standard PCB to be competitive on the market. **Ertugrul Sönmez, Ulrich Heinle, Mike Kunze, and Ingo Daumiller, MicroGaN, Ulm, Germany**

Silicon devices are often driven at their physical limits already. In addition, combined with conventional assembly technologies, the established Si based technology is limited to provide solution to these requirements [1]. Therefore, any progress of the power electronics market requires more advanced semiconductor power devices. The required improvements in efficiency of such power circuits may be realized by new approaches only. For this, GaN based power devices are entering the power electronics market [2].

The GaN power HEMT

A lateral HEMT device technology using large area 4-inch as well as 6-inch GaN-on-Silicon wafers is utilized for power device fabrication. In order to reach high area efficient 600V devices, the proprietary 3D-GaN technology is applied. The normally-on HEMT features an output capacitance of about 30pF which leads to an output charge of only 10nC combined with an on-resistance of about 180mΩ (see Figure 1).

The corresponding product of R_{on} x Q_{out} is to our knowledge unique on the 600V device market. This GaN-HEMT is switched off for control voltage values $V_{GS} < -3V$, whereas the full on-state is reached for values above 0V at around 1V. The specific on-state resistance for the complete chip including all pad areas and even its remaining part of the dicing street is reduced to 570mΩmm^2, which is only achievable using 3D-GaN technology. It has been developed a technique to fold up the contact electrodes from the lateral area to above active area, including the high potential pad and via technology contacting the appropriate fingers from top (see Figure 2).

The GaN-HEMT has an additional characteristic, which makes its application beneficial: it has no build-in body diode, preventing any delay and charging/discharging losses caused by minority carrier pile up. This allows hard switched high voltage H-bridge applications delivering the additional degree of freedom in setting switching time and frequency to achieve maximum efficiency, load dependently. The very small Gate and Drain charges allows the transistor to be seen as purely voltage controlled device.

Normally-on power switch in ThinPAK

For evaluation purposes, MicroGaN's

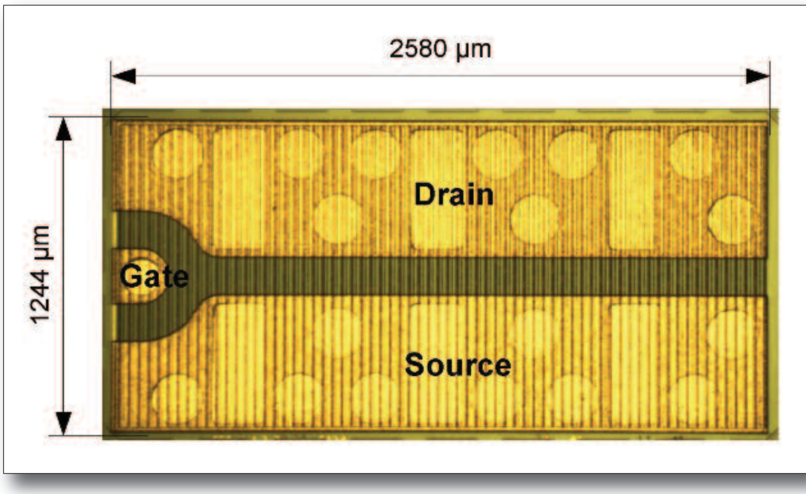

Figure 1: **Extremely area efficient Normally-On 600V 180mΩ GaN-HEMT with R_{on}•A of 570mΩmm^2**

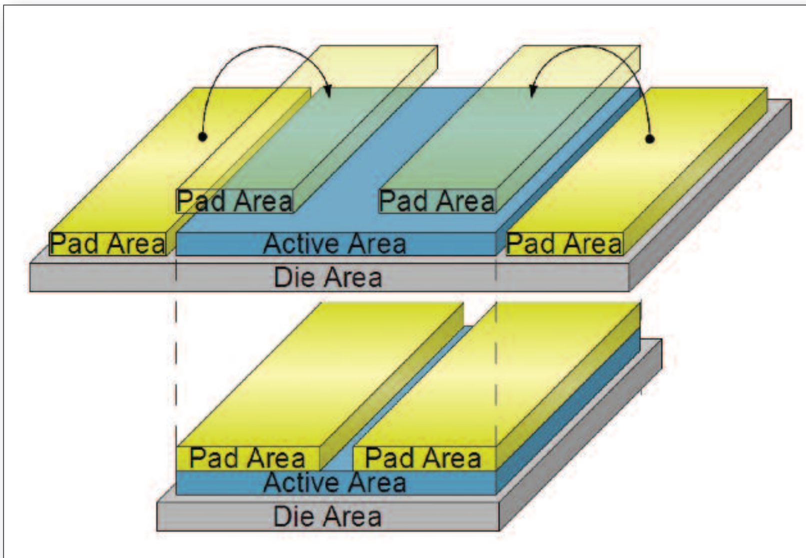

Figure 2: **Schematic of MicroGaN's 3D-GaN Technology**

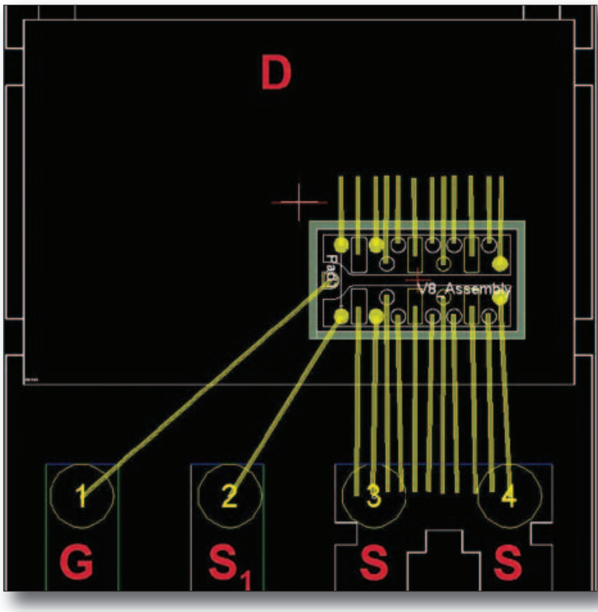

Figure 3: **Normally-on power switch in Infineon's 8x8 ThinPAK**

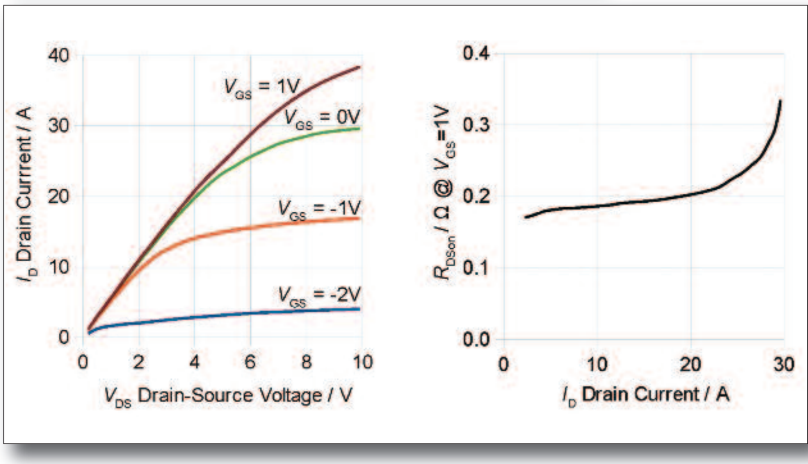

Figure 4: **Output characteristics (left) and on-resistance of GaN power HEMT in ThinPAK**

lateral HEMT device has been packaged in a 8x8 ThinPAK [3] at Infineon AG. This packaging technology provides low inductive parasitics and thin profile. Figure 3 shows the corresponding bonding diagram, providing an additional sense pin at the device's source electrode for accurate biasing purposes. The output characteristics and the derived on-resistance as a function of the drain current is depicted in Figure 4.

From the measurement results it can be stated that the normally-on HEMT provides an unsaturated current of more than 35A at a Gate bias of 1V, providing a comfortable head room for a 200mΩ-device for surge current levels - not limited by the device's channel properties. For the given R_{DSon} it is also an excellent result to have over 20A drain current range, for which the on-resistance keeps within a 10% deviation.

The promising DC-characteristics are paired with beneficial capacitive characteristics. This is not a straight forward result which may be expected from a material system originally used for RF applications because of the significant influence by the 3D technology approach. Therefore the result already indicates successful optimization of this technology. The input, output and reverse capacitance together with the corresponding output charge and energy are displayed in Figure 5. Here the Input-, Output-, and Reverse-Capacitance of GaN power HEMT in ThinPAK with its corresponding output charge of Q_{OSS} = 17nC and energy E_{OSS} = 3.5μJ at V_{DS} = 400V are shown.

With these values a figure of merit "output-charge • R_{DSon}" value of 3.1nCΩ is achieved leading to an extremely low time constant of 3.1ns. This value is uniquely low for packaged 600V GaN switches and indicates, that hard-switched, high-speed and efficient circuit topologies are feasible using this switch. The combination of the resulting low output energy of E_{OSS}=3.5μJ with the reverse capacitance of 8pF making the miller charge negligible and are to our knowledge unique on the wide bandgap device market.

Low barrier SiGaN power diode

The so-called SiGaN Diode consists of a low voltage (30V) Si-SBD (Schottky Barrier Diode) and a 600V GaN-HEMT (see Figure 6). The resulting behavior of this 2-port circuit is a 600V SBD with a barrier of a low voltage Si-SBD. This in-package hybrid cascade circuit provides a voltage barrier of only 0.3V with a differential resistance of about 200mΩ, which is dominated by the on-resistance of the GaN HEMT.

For the SiGaN diode operated in the reverse direction, the Si-SBD is biased in reverse direction, and also is charged to about -3.5V, which is the switch-off voltage of the HEMT. Up to only this voltage level, the capacitive parasitics of the Si-SBD do play a role. For reverse SiGaN diode voltages higher than -3.5V, the GaN-HEMT switches off and isolates the SiGaN diode cathode from the Si-SBD cathode. Therefore, the high voltage SiGaN diode capacitance and charge are dominated by the low capacitive parasitics of the GaN HEMT.

The resulting I-V and C-V characteristics

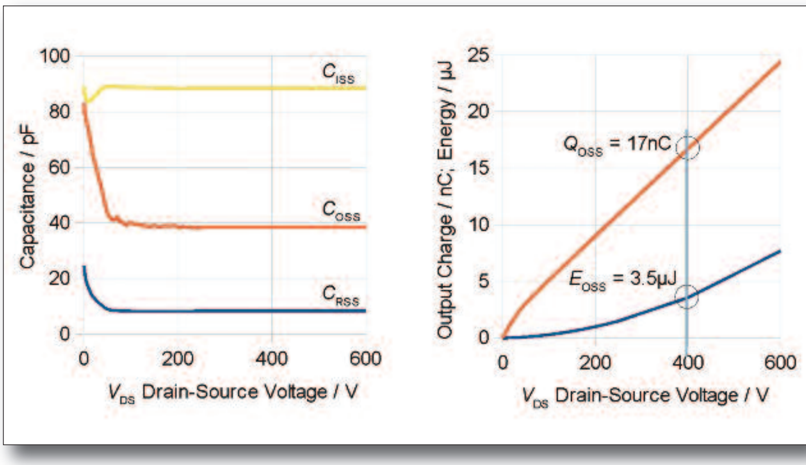

Figure 5: **Input-, Output-, and Reverse-Capacitance of GaN power HEMT in ThinPAK (left) with its corresponding output charge**

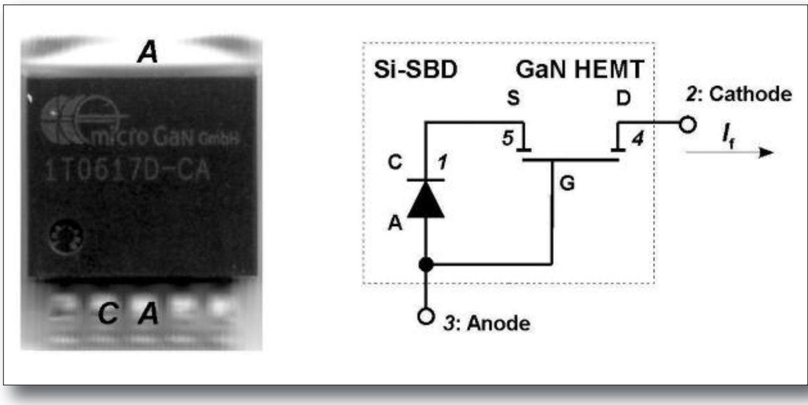

Figure 6: SiGaN Diode - cascade circuit of a low voltage Si-SBD with a high voltage GaN-HEMT

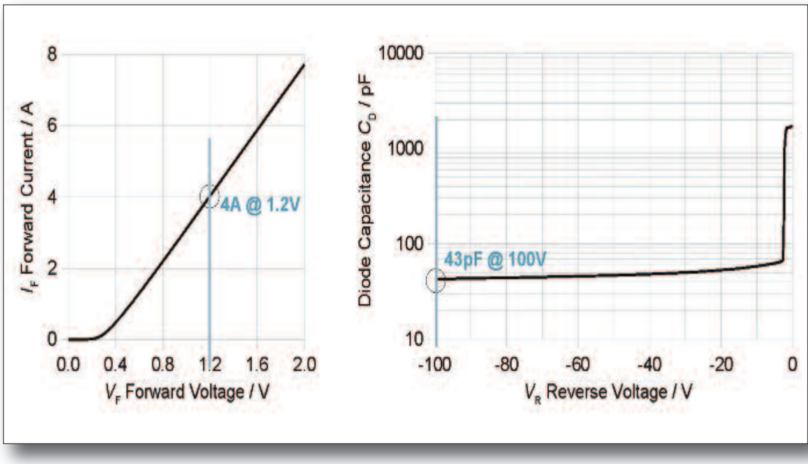

Figure 7: Power Diode forward characteristics showing its typical low on-set voltage of 0.3V (left) and its reverse C-V-Characteristics with the low capacitance of 43pF

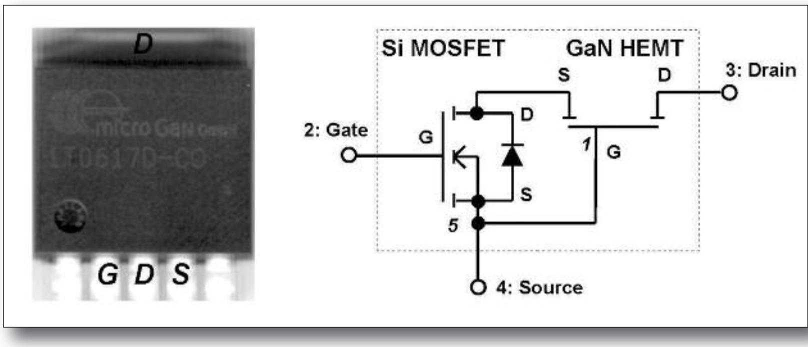

Figure 8: Normally-off power switch by cascode circuit made of a low voltage Si-MOSFET and a high voltage GaN-HEMT

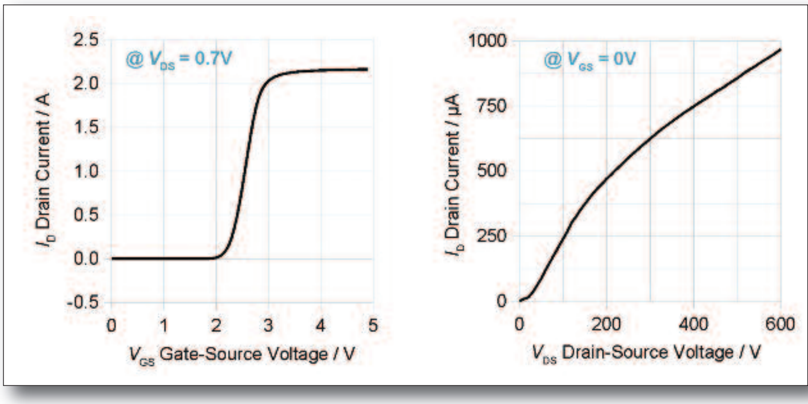

Figure 9: Transfer-characteristics of the cascode using HV GaN-HEMT (left) and its off-state characteristics up to 600V for V_{GS}=0V

of the SiGaN diode are shown in Figure 7, where the described characteristics of the SiGaN diode circuit elements can be located individually. From the SiGaN diodes forward characteristic, the typical low barrier voltage can be extracted as well as the differential resistance of about 200mΩ, resulting in 4A diode current at 1.2V forward voltage. To our knowledge this behavior also is unique for a diode missing minority carrier stored charge with just 18.6nC overall charge. With at least comparable charge values to SiC-SBD one obtains an unbeatable low onset voltage.

From the C-V-characteristics, the GaN HEMT switching off can be seen which isolates the Si-SBD during the measurement: within a few volt sweep the capacitance of the SiGaN diode drops from over 1700pF to about 60pF and reaches a value of just 43pF at -100V.

The application benefit of this cascade is manifold. Used as a PFC-Diode, it will pass current starting already at 0.3V, which gives an excellent tool for wide efficiency bandwidth solutions. The low SiGaN diode charge allows a high switching speed from this device point of view, providing the possibility to go for higher power density designs. Used as a freewheeling diode, it catches the current at already 0.3V, preventing the on-set of the body diode current flow of a Si-600V-HV device. Thus, charging of several µC and a harming recovery time of several hundred ns are prevented.

A normally-off functionality can be derived from a normally-on core unit device by an in-package hybrid cascode circuitry (see Figure 8). The cascode consists of a low voltage (30V) Si-MOSFET in common-source and a high voltage GaN-HEMT in common-gate configuration. The resulting 3-port circuit again acts as a switch. In its on-mode the parasitic on-state resistance of the Si-MOSFET (<20mΩ) and the one of the GaN-HEMT are added to about 320mΩ. The obvious increase above the expected sum value is due to the internal biasing of the GaN HEMT which leads to on-state bias condition slightly below full open channel. In the off-state of the cascode the Si-MOSFET is switching off the GaN-HEMT and is charged to about 3.5V, analog to the SiGaN diode. Here again, the Drain of the GaN-HEMT is defining the 600V behavior of the cascode.

Figure 9 displays the transfer characteristics and the off-state characteristics of the cascode. As expected, the Si-MOSFET defines and controls the drain current of the cascode, which results in an off-state for V_{GS}=0V. The high voltage off-state characteristics reveal the present leakage current level of MicroGaN's normally-on devices of around 900µA at 600V, here measured at V_{GS}=0V.

In the reverse operation mode of the cascode (V_{DS}<0V), the GaN-HEMT is in the on-state as a parasitic resistor (180mΩ) in series to the Si-MOSFET. If the Si-MOSFET is in the off-state, its body diode provides a current path at its characteristic voltage.

By using a cascode, one combines the advantages of the LV Si-MOSFET (usually a high quality body diode, low charge as operated at 3.5V) and these of the GaN-HEMT (high speed, no body diode, lowest possible charge). On the other hand, one has to pay attention to the setup parasitics of the circuit in order to prevent ringing.

The setups of the cascade and cascode are designed carefully to prevent the commonly made error of inductive setup technology ceasing the chip-device from operation at high di/dt in the package.

This cascode is predestinated to be used in hard switched high switching speed PFCs as well as in H-bridge, maintaining the high peak and wide bandwidth in efficiency.

Conclusions

The market demand for high efficient new approaches is discussed using the example of a mains voltage down-conversion and its specific need of high efficient 600V power devices. The basic circuit construction elements - the low barrier (0.3V) power diode and the normally-off power switch - were presented and discussed in detail [4] as they are derived from a unique core unit device: the GaN power HEMT, which has been packaged and tested in a 8x8 ThinPAK by Infineon AG. Next steps will be the transfer of the presented characteristics into their dynamic equivalents and the setup of application demonstration.

As a result, surpassing circuit efficiencies will be possible using the presented elements.

Furthermore, by combining the cascode and cascade, one may obtain an unique pair of design elements for realization of efficient motor drive applications, also.

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Literature

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