Blumlein-Generator with a GaN-HEMT in gate-boosted Operation as Closing Switch

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***Abstract*—Gate-boosted operation of a GaN-HEMT allows for an operation with a rise time significantly faster than listed in the data sheet. For a GaN-HEMT having a rise time of approximately 4 ns under normal operating conditions a rise time of less than 1 ns in gate-boosted operation has been demonstrated. The employed gate boosting circuit compensates for the inductance in the gate circuit and the voltage drop across the inductance in the source path of the GaN-HEMT in such a way that the resonant frequency of the input circuit increases significantly and the gate can be charged more quickly. The voltage reduction due to the resulting capacitive voltage divider formed by the added series capacitor and the input capacitance of the GaN-HEMT is compensated by a sufficiently high driver voltage. A three-stage Marx circuit equipped with avalanche-rated bipolar transistors as closing switches has been used as voltage source for the driver. The gate-boosted GaN-HEMT has been tested as switch in a Blumlein configuration set up with 50-Ohm-cables as transmission lines. The contribution describes selected design details and presents measurement results obtained with the described test setup.**

Keywords—Blumlein generator, GaN HEMT, gate-boosting.

I. Introduction

For the generation of pulses having a rectangular shape a Blumlein generator can be used [1]. It comprises two transmission lines of equal length and characteristic impedance, and a closing switch, as shown in Fig. 1. In order to avoid reflections at the load, the load impedance Z_{load} must be matched to twice the characteristic impedance of each transmission line $Z_{C,TL}$. The pulse length is equal to twice the propagation delay of each transmission line.

In order to achieve a fast rise time of the rectangular pulse, a fast closing switch is required. Among the semiconductor switches a GaN HEMT exhibits a rise time in the order of a few nanoseconds according to the data sheet [2] and, hence, are significantly faster than common Power MOSFETs made of silicon (Si) or silicon carbide (SiC). A SiC-MOSFET has a rise time in the order of 15 ns according to the data sheets [3].

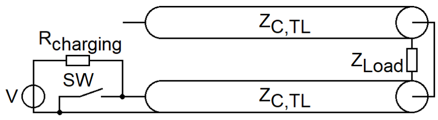

Fig. 1. Blumlein Generator with charging circuit.

However, it has been demonstrated, that in gate-boosted operation a SiC MOSFET can achieve a rise time in the same order as of a GaN HEMT [4]. Apart from the characteristics of the device, the rise time is limited by a low-pass filter in the gate circuit formed by the input capacitance of the device, the stray inductance of the connecting leads, and a damping resistor. The gate-boosting circuit adds a capacitor into the gate circuit in series to the gate terminal of the device such, that the resonance frequency of the gate circuit is increased. However, this capacitor forms together with the input capacitance of the device a capacitive divider. In order to compensate for the effect of this voltage divider, the driving voltage must be increased such, that the amplitude of the gate-source voltage on the die is preserved compared to an operation without gate boosting.

Moreover, the gate driver must provide a voltage having a low rise time in order to charge the gate quickly. The gate driver for gate-boosted operation of SiC-MOSFETs according to [4] features two GaN HEMTs in half-bridge configuration operated at a DC voltage of 150 V and driven by a commercial driver for GaN HEMTs. Hence, the rise time of the driver is limited by the properties of the employed GaN HEMTs. Experiments on further improvements of the gate driver for the gate-boosted SiC MOSFETs showed, that lowering of the series capacitance in combination with an appropriate increase of the driving voltage up to 190 V does not further speed up the turn-on process of the SiC MOSFETs.

In order to achieve for a GaN HEMT a faster turn-on process by means of gate-boosted operation, a voltage pulse with a fast rise time and sufficiently high voltage is required. A bipolar transistor operated in avalanche mode is known to operate as a fast closing switch at a voltage level of up to a few hundred volts [5]. However, the life time of such a switch depends much on the conduction time and its losses. Both needs to be kept small to avoid a significant reduction in life-time. Recently, a two-stage Marx circuit equipped with avalanche transistors as switches has been combined with a GaN HEMT such that the Marx circuit operates as driver for the GaN-HEMT used in source-follower configuration [6]. As intended, a reduction in the output impedance of the cicuit could be demonstrated. However, for the operation of a Blumlein configuration, a switch is needed, which is connected to ground potential. Hence, the combination of a Marx circuit as driver for a GaN HEMT switch in gate-boosted operation has been investigated.

II. Marx circuit as driver for a GaN HEMT in gate-boosted operation

A. Circuit description

Fig. 2 shows a simplified schematic of a Marx circuit connected to the gate of a GaN HEMT as a driver. For some first experiments, for the Marx generator a three-stage arrangement has been chosen. As for an operation as closing switch the pulse voltage is required during the charging process of the gate only, a pulse circuit can replace advantageously a half-bridge configuration. Due to the inherent voltage multiplication of the Marx circuit the charger can be designed for a lower voltage that for a half bridge configuration having the same output voltage. A bipolar transistor specified for avalanche operation has been selected as switch [7].

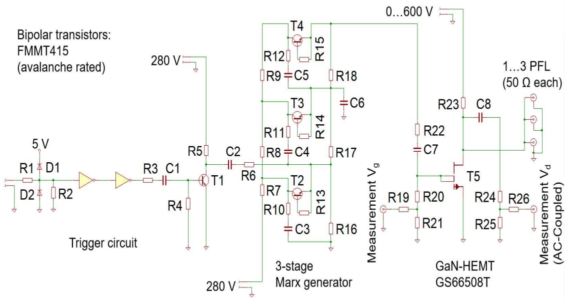

Fig. 2. Simplified schematic comprising the trigger circuit, the 3-stage Marx generator, and the GaN HEMT.

The capacitor C7 has been inserted in order to reduce the capacitance of the gate circuit to increase its resonance frequency. The value of this capacitor has been matched to the peak value of the Marx circuit such that the charge stored in the capacitor C7 equals the charge which needs to be to injected into the gate in order to turn on the GaN HEMT according to its data sheet.

B. Trigger process

Initially, the capacitors of the Marx circuit are charged to approximately 280 V. For triggering, an external trigger signal at TTL level is provided to the trigger input. The avalanche transistor T1 is triggered by injecting a current pulse into its base terminal and serves as booster for the trigger signal. The avalanche transistors of the Marx circuit are triggered by means of applying an over voltage. Via the capacitor C2 a pulse of negative polarity is applied to the output of the first stage such, that its switch closes due to this extra voltage applied to it in addition to the charging voltage of the stage capacitor C3. The switches of the remaining stages close due to the transient over-voltage applied to them while charging the ground stray capacitances, according to the known ignition process of a Marx circuit [1]. Thereby, the capacitor C6 fosters the turn-on process of the second stage's switch, as it increases the capacitance to ground. Moreover, this capacitor operates much like a peaking capacitor. It connects the ground-side terminal of the Marx circuit's third stage via a short connection directly to ground potential. So the series arrangement of C6 together with the capacitor of the third stage (C5) operates as peaking stage with the third stage's avalanche transistor acting as peaking switch. Thereby, the loop of this circuit has been kept small in order to achieve a low inductance. The peaking stage provides a fast rising pulse to the GaN HEMT's gate via C7 and R22. It should be noted, that the input capacitance of the GaN HEMT GS66508T is with 242 pF significantly smaller than the input capacitance of a SiC MOSFET C3M0075120J with 1390 pF, which has been used in a previous gate-boosted arrangement. Moreover, a GaN HEMT requires a lower voltage at its gate to turn on. Hence, C7 can be selected to have a smaller value as for a SiC MOSFET at equal driving voltage. For the test setup, C7 has been selected to 10 pF.

C. Voltage Measurements and connection to the load

For the experiments the voltages at the gate and the drain of the GaN HEMT versus ground potential have been measured. The signal path for measuring the gate voltage V_g comprises a 50 Ω termination (combination of R19 and R20), a coaxial cable for a connection to the oscilloscope, and two 6 dB attenuators. The drain voltage V_d is measured via a resistive divider formed by R24 and R25. The capacitor C8 in series to the divider blocks the DC voltage, which is applied before the pulse. The voltage measurements have been performed using an oscilloscope having 2 GHz bandwidth and a sampling rate of 10 GS/s.

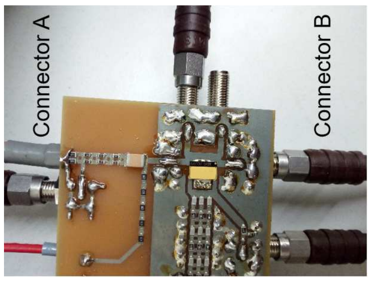

Fig. 3. Detail of the printed circuit board showing the GaN HEMT and the components for measurements of gate voltage V_G and drain voltage V_D.

The employed GaN HEMT GS66508T has a rated voltage of 650 V and a rated continuous current of 30 A. In order to allow for an operation near these limiting parameters, the characteristic impedance of the load has been chosen to 16.6 Ω, which can be set up as a parallel connection of three 50 Ω cables. The cables are connected via SMA connectors. Fig. 3 shows a photo of the GaN HEMT and the circuit components required for the measurements.

III. Experimental Results

A. 50 Ω cable as pulse forming line

The closing switch has been tested with an open 50 Ω cable of 1 m length as load. The cable has been charged to voltages between 100 V and 600 V. The load has been connected to the SMA connector 'A' according to Fig. 3. Fig. 4 shows the measurement results. The voltage at the gate exhibits an overshoot up to a peak voltage of approximately 16 V before the voltage settles to a gate voltage of approximately 6 V. The open cable as load causes a travelling-wave oscillation having a period T equal to four times of the propagation delay of the cable resulting in T= 4·5 ns = 20 ns. Thereby the current through the switch reverses every 10 ns. Related voltage peaks are measured in both voltage signals. When connecting the load to the SMA connector 'B' the voltage peaks related to the oscillation disappear.

A closer look at the layout shown in Fig. 3 reveals that the current paths to the SMA connector marked as 'A' and the divider for measuring the drain voltage share an approximately 8 mm long fraction of a connecting line. When using the connector B instead, the signal of the drain voltage is no longer disturbed by a voltage drop along the connecting line.

According to the measurement, the drain voltage falls within 0.6 ns from 90% to 10 % of its initial value when considering the curve measured at 600 V charging voltage.

B. Blumlein configuration with 50 Ω pulse forming line

A Blumlein configuration has been set up using two 50 Ω cables of 1 m length as pulse forming lines. The cables have been connected via SMA connectors and a printed circuit board, which carries also the terminating resistor of 100 Ω. The resistor includes a resistive divider for voltage measurements. Fig. 5a shows this arrangement and Fig. 6 the measurement results. For the measurements the charging voltage has been varied between 100 V and 700 V. At a charging voltage of 600 V the voltage at the switch falls within 0.6 ns from 90% to 10 % of its initial value. The rise time at the load impedance of the Blumlein configuration has been measured to be 0.9 ns at 600 V charging voltage. The rectangular pulse has a pulse width of 10 ns. There is a slight mismatch in the load impedance. Therefore, the amplitude of the output voltage of the Blumlein generator is lower than the charging voltage and a reflection of the pulse with opposite polarity appears 25 ns after closing of the switch.

C. Blumlein configuration with 16.6 Ω pulse forming line

A pulse forming line having a characteristic impedance of 16.6 Ω has been set up as parallel arrangement of three 50 Ω cables of 1 m length. The cables have been connected via a printed circuit board carrying also the load impedance of 33.2 Ω including a resistive divider for measurements. Fig. 5b shows a photo of the arrangement and Fig. 7 the measurement results. The charging voltage has been varied between 100 V and 600 V. The drain voltage falls at a charging voltage of 600 V within 0.7 ns from 90% to 10%, the voltage across the load rises within 0.8 ns.

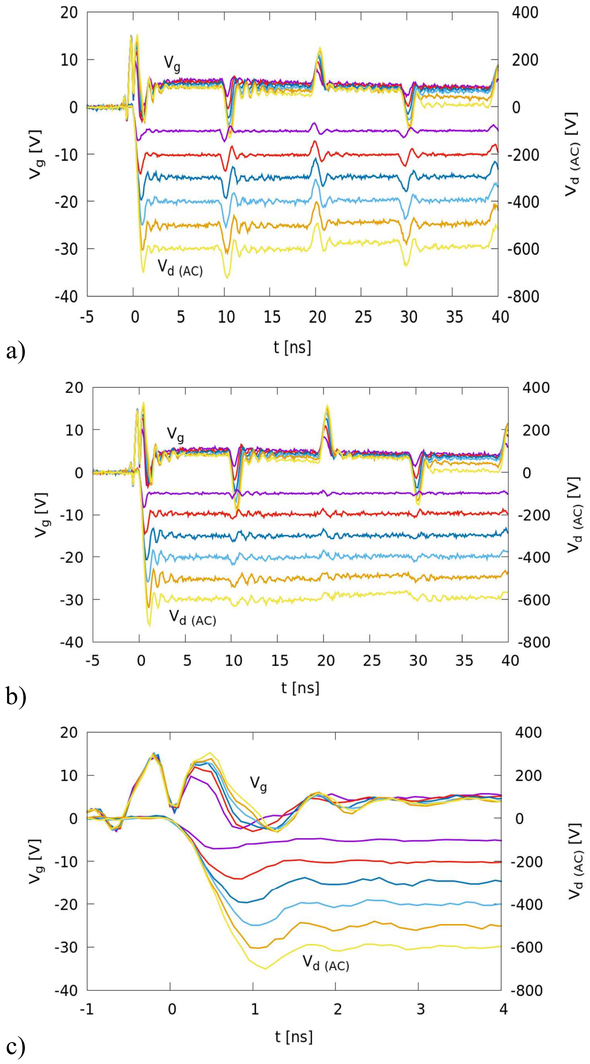

Fig. 4. Measurements of V_g and V_d with an open 50 Ω cable as load: a) load connected to connector A, b) load connected to connector B, c) load connected to connector B (detail).

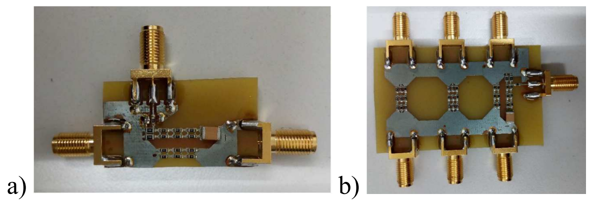

Fig. 5. Printed circuit board for Blumlein arrangement: a) for Z_C=50 Ω, b) for Z_C=16.6 Ω.

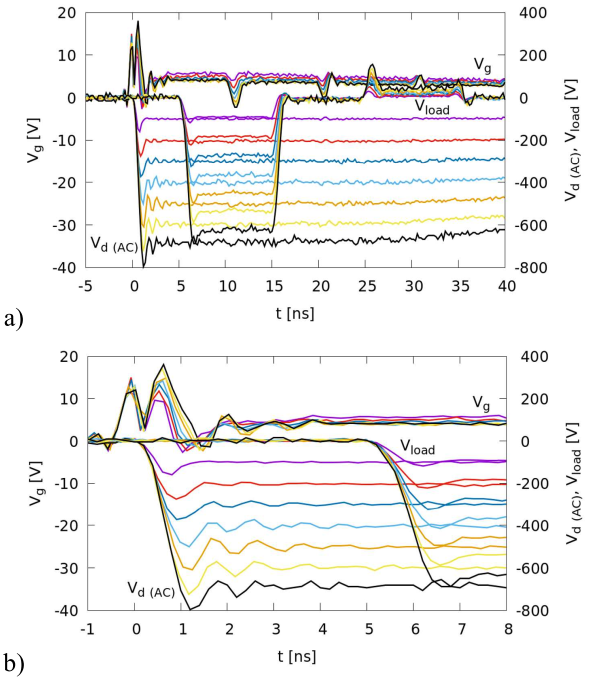

Fig. 6. Measurements of V_g, V_d, and V_{load} for a Blumlein generator having 50 Ω pulse forming lines: a) whole pulse, b) detail.

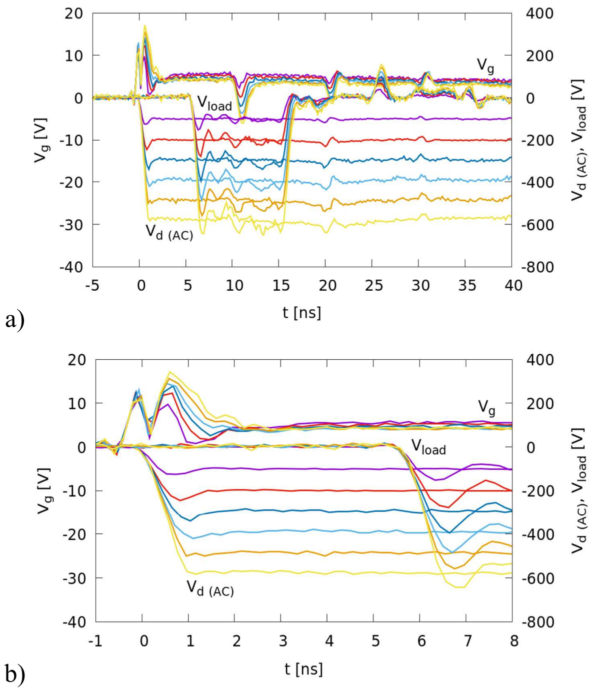

Fig. 7. Measurements of V_g, V_d, and V_{load} for a Blumlein generator having 16.6 Ω pulse forming lines: a) whole pulse, b) detail.

D. Repetitive operation

For an initial test of the device in repetitive operation, the Blumlein configuration with 16.6 Ω pulse forming line has been operated at a charging voltage of 600 V and a pulse repetition rate of 1.4 Hz for a duration of 6.25 h, resulting in approximately 33000 pulses. A superposition of the first and the last pulse shape of the test together with four randomly selected additional pulse shapes shows no deviations in the pulse shapes (Fig. 8).

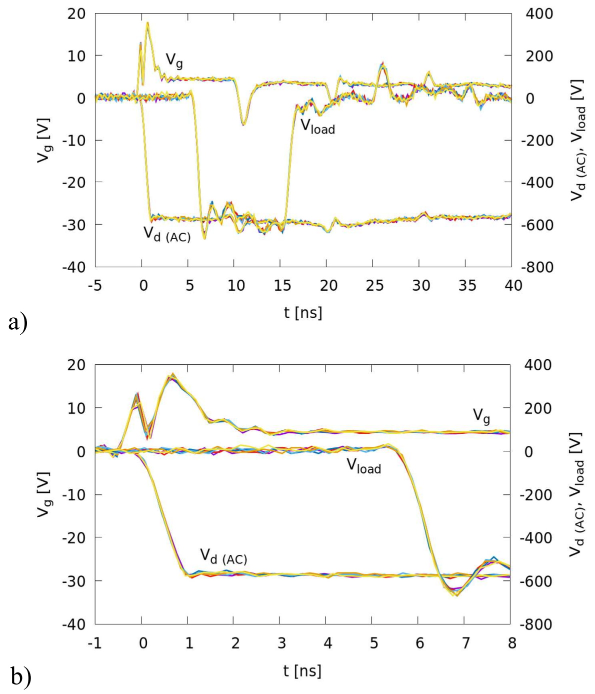

Fig. 8. Measurements of V_g, V_d, and V_{load} for a Blumlein generator having 16.6 Ω pulse forming lines, repetitive operation at 1.4 Hz: a) whole pulse, b) detail.

IV. Conclusion

A gate-boosting circuit for a GaN HEMT featuring a three-stage Marx configuration has been set up and tested in a Blumlein configuration. Pulse rise times of less than 1 ns have been achieved for characteristic impedances of the pulse forming lines of 50 Ω and 16.6 Ω. Future work will be devoted to further tests and improvements of the circuit.

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