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Abstract—**The paper deals with a bi-directional switch based on N-channel enhancement-mode GaN FET. The proposed device is a Gate Injection Transistor monolithic solution to reduce the volume of the switch with high current density and blocking voltage of 600V. It features a dual-gate control pin and two power terminal. In the paper, the main characteristics of the bi-directional switch and the performance in the four-quadrant of operation are examined and discussed. The device characteristics are compared with the traditional MOSFET and IGBT solutions. The gate driver design issues are considered to optimize the switching transient of the GaN-based switch. Finally, an experimental evaluation of the GaN FET as the bi-directional circuit breaker is carried out in an AC power supply system to validate the effectiveness of the proposed monolithic new device.**

Keywords—GaN FET, GIT, hybrid-drain, Bi-directional switch, AC breaker circuit

I. INTRODUCTION

Nowadays many applications of power electronics use bidirectional switches. In the battery management system applications (BMS) or fuel-cell generators, protection switches are acting in overcurrent or overvoltage conditions [1], [2]. In converters topologies such as T-types, dual-active bridge (DAB) or matrix converter, there are bidirectional switches inside the topology to allow their correct operation [3]-[5]. The bidirectional switch (BSW) can operate as a solid-state relay. It can also be added to the traditional relay to add some features such as to make the electromechanical component both smart and more reliable.

Bidirectional switches in low voltage applications are implemented with MOSFETs while in high voltage application SiC MOSFETs and IGBTs (or GTO and IGCT for very high power BWS) are more useful devices [6], [7]. Generally, the BSW is composed by two power devices and freewheeling diode connected to allow the four-quadrant operative condition for the switch. A suitable driver circuit enables the alternative conduction operation. The main power devices and the relative anti-parallel diode are connected in back-to-back way to achieve the bidirectional way for the current.

Recently High Electron Mobility Transistors (HEMTs) such as GaN-based devices are developing and covering different fields of applications in low and high operating voltages [8]. The absence of body diode typical of MOSFETs and the possibility of current flowing from the drain to the source and vice versa allows using the device easily as BSW. In operating conditions such as BSW, it is necessary to use two GaN devices in back-to-back connection.

The paper describes and experimentally validates a novel, monolithic bidirectional GaN device. The switch is based on the Gate Injection Transistor (GIT) structure. The monolithic BSW device described has a rated breakdown voltage of 600V. The effectiveness of the monolithic devices as protection switches in an AC power supply application are presented and experimental traces are shown.

The paper is composed as follows: in the next paragraph (the second section) the bidirectional switches topology and application are described considering the traditional power devices such as MOSFETs and IGBTs. Furthermore, the power losses are evaluated to define the design constraints of the BSW. In the third section same issues on the GaN devices are treated, and the structure of the bidirectional GIT device is focused. Finally, experimental characteristics of the novel monolithic GaN device an AC bidirectional switch application such as Hybrid Solid State Relay (HSS) is presented and discussed.

II. BIDIRECTIONAL SWITCHES OVERVIEW

A solid-state bi-directional switch is an active device working in four-quadrant operations. The switch in on-state supports a current flow in any direction while when it is turned off is capable of blocking positive or negative voltages. Fig. 1 shows common circuit configurations which can be used to realize a BSW with N channel MOSFETs in common-source CS (Fig. 1a) and common-drain CD (Fig. 1b) and IGBT in common-emitter CE (Fig. 1c) and common-collector, CC (Fig. 1d). The power devices are arranged in the back-to-back connection. In Fig. 1f two IGBTs with a series diode are connected in anti-parallel mode. Among the many applications as a bidirectional switch, in this paper, the attention is focused on the operations as a protection switch to protect AC systems or for DC charging-discharging systems of the batteries as shown in Fig. 2. The power switches considered in this case of Fig. 2 are N-channel MOSFET devices. The input voltage range may be variable starting from 48V to 600V for the battery system, while for the AC source 110V to 400V may be considered [9], [10]. During the turn-

on, the turn-off and the on-state there are power losses due to the switching and conduction characteristics of the MOSFET and the body diode.
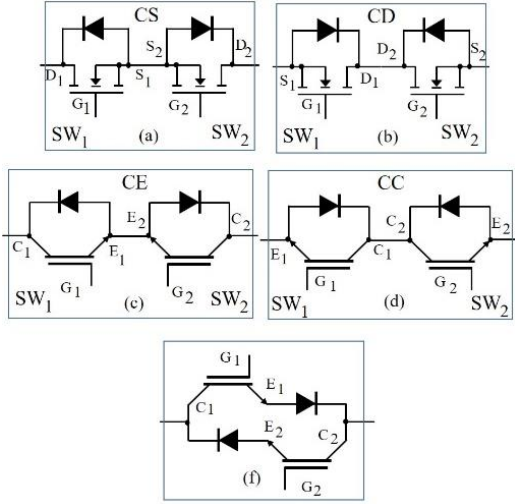

Fig. 1. Bidirectional switch arrangement with MOSFET devices in a) common-source, b) common-drain, with IGBT in c) common-emitter, d) common-collettor, f) anti-parallel leg of IGBT and diode in series connection.

Considering all devices equal in their physical characteristics (ideal case), and neglecting the switching losses compared to the much greater conduction losses, the power losses P_L in a single leg in one current direction (battery or AC source to load and MOSFETs in common-source solution) is given by

$$P_L = R_{DS(ON),SW1} \cdot I_{BSW}^2 + (V_{F,SW2} \cdot I_{BSW} + r_{d,SW2} \cdot I_{BSW}^2) \tag{1}$$

The equation (1) is related to the case of a battery source connected to the load or to a bidirectional converter through BSW device. In the case of AC source, it is necessary to consider the RMS value of the I_{BSW} current. High current MOSFET switches can be made through the parallel of n devices based on the current required. In this case the lost power is the sum of the power losses of the n single MOSFETs and n body diodes as expressed in the following equation.

$$P_{L,tot} = \sum_{i=1}^{n} \left\{ R_{DS(ON),SW1i} \cdot \left(\frac{I_{BSW}}{n} \right)^2 + \left[V_{F,SW2i} \cdot \frac{I_{BSW}}{n} + r_{d,SW2i} \cdot \left(\frac{I_{BSW}}{n} \right)^2 \right] \right\} \tag{2}$$

Where $R_{DS(ON)}$ is the MOSFET on-state resistance, while V_F is the voltage drop and r_d is the differential resistance of the conduction diode.
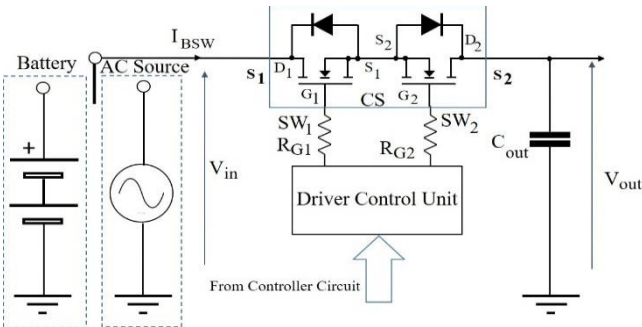

Fig. 2. MOSFET bi-directional switch in common-source connection used as protection circuit in battery charger or AC power source.

In case of IGBT devices the conduction losses are related to the saturation voltage $V_{CEsat,SW1}$ and the power losses $P_{L,IGBT}$ of the full switch in common-emitter solution may be written as follow:

$$P_{L,IGBT} = V_{CEsat,SW1} \cdot I_{BSW} + (V_{F,SW2} \cdot I_{BSW} + r_{d,SW2} \cdot I_{BSW}^2) \tag{3}$$

In every case (MOSFET or IGBT) the losses are related to the contribute of the on characteristics of the on-state device and the diode of the other device in back-to-back connection. Thanks to their favorable characteristic SIC-MOSFET and normally off GaN FET devices are rapidly replacing silicon devices in many applications. These wide-bandgap components are becoming attractive for several applications, including their use as electronic protection switches. GaNs can be considered, with no body diode devices with the possibility of simple reversing conduction by means of the gate command signal. The application of GaN devices as bi-directional switches is worth investigating.

III. GAN GIT DEVICES ISSUES

The enhancement mode GaN FET is available in a breakdown range of 600V. This device is normally-off transistors. It has high-switching frequency with a favorable value of Figure of Merit ($R_{DS(ON)} \cdot Q_G$) parameter compared to silicon Super-junction and SiC MOSFET with the same rated performance [11]. A normally-off GaN-based transistor using conductivity modulation called gate injection transistor (GIT) is introduced to the panorama of high voltage HEMT devices [12]. The GIT device is a lateral structure fabricated on a Si substrate with a heterostructure of AlGaN/GaN layer and a P-GaN thick layer under the gate metallization as shown in Fig. 3a. The p-GaN gate allows the normally-off operation of the GaN device. The device operation principle utilizes hole-injection from the p-AlGaN layer to the AlGaN/GaN heterojunction, which increases the electron density in the channel with a dramatic reduction of the on-state resistance.

In the case of gate-source voltage $V_{GS}=0V$, the p-Gate potential depletes the channel under the gate and no drain current appear. If $V_{GS}>V_F$ (the threshold voltage of GaN-PN junction), hole injection acts with electron generation in the i-GaN layer. Two-dimensional electron gas (2DEG) is formed at the GaN/AlGaN interface as the conducting channel. In this way, conductivity modulation occurs with a reduction of the resistance $R_{DS(ON)}$.
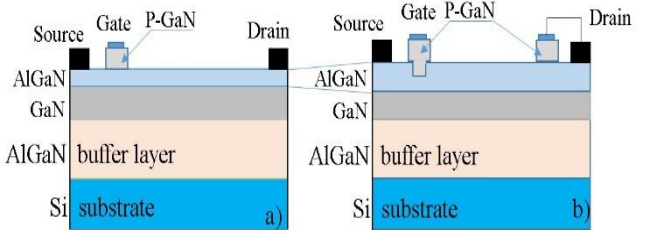

Fig. 3. GIT GaN structure. a) Conventional gate injection transistor, b) enhanced gate injection transistor with hibryd-drain to prevent the phenomenon of current collapse.

In this structure a drawback occurs. The current collapse phenomenon affects the dynamic characteristics of the device by increasing the dynamic resistance $R_{DS(ON)}$ with increasing drain-source voltage [13]. The current collapse phenomenon is a drain current reduction due to charge trapping effects both

at AlGaN/GaN interface and at the top surface of AlGaN barrier [14]. This physical phenomenon leads to limits in the breakdown voltage of the GaN devices. The current collapse phenomena are avoided (until 800V [14]) by the physical structure of the hybrid-drain embedded GIT (HD-GIT) depicted in Fig. 3b. In the structure of Fig. 3b an additional gate connected to the drain is introduced. When the device is in off-state the added P-GaN layer produces holes that diffuse both in the AlGaN layer and in the GaN layer [15]. The holes injected from the P-GaN balance the electrons trapped there during the switching transients. In this way, the phenomenon of current collapse is prevented.

A. GIT GAN Driver Circuit Requirement

In GIT devices an accurate design of the gate driver circuit must be provided to guarantee the correct operations of the switch. GaN features a low threshold voltage V_{th} (1.2V) and it can commutate very fast. On-state is obtained by applying a voltage up to 6 V between the gate and the sense source. The device structure requires constant gate current to keep the GIT in on-state because of the gate input characteristic of the GaN GIT corresponds to a diode. From the physical characteristics of the inner gate diode, more than 5mA are required to keep it in on-state condition. At a gate current equal or greater than I_G=5mA a voltage of about 2.8V appears across the gate – source terminals. The gate voltage $V_{GS,ON}$ during the on-state is equal to a diode forward voltage V_{FD}. From which the GaN GIT device is driven in mixed mode. It is like a field-effect transistor because the device is turned on by a voltage over the threshold voltage and charging the equivalent gate capacitance C_{iss} ($C_{iss}=C_{GS}+C_{GD}$). Moreover, the GIT maintains the on-state by a suitable constant current flowing in the gate like a bipolar transistor. The transistor is switched off by removing the voltage from the gate-source terminals. When the gate current is reduced to zero, the channel is closed, and the transistor is blocked again. A schematic of the driver circuit is depicted in Fig. 4a. In Fig. 4b the gate control signals of the GIT are reported with the gate-source, the drain-source voltage and the drain current. The resistors and capacitor network act to energises the gate of GIT with a topology typical of bipolar devices [16]. The C_G is a speed-up capacitor that accelerates the turn-on and turn-off transients.
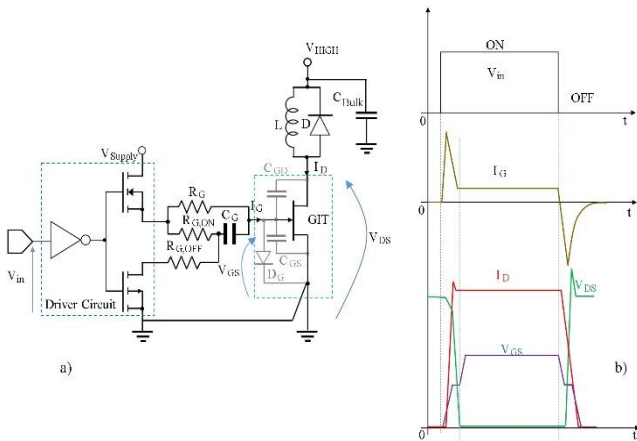

Fig. 4. a) GIT GaN driver circuit b) control command signal of driver circuit and main device voltage and current switching waveforms.

The design of the resistor R_G is related to the gate current $I_{G,ON}$ that maintains the diode D_G in on-state. The range of choice for the gate current in on-state may be extracted from

the datasheet (for 600V/56mΩ GaN Power Transistor is 5mA<$I_{G,ON}$<50mA). To reduce the power loss, about $I_{G,ON}$ = 10mA setting is chosen. The R_G is designed by the relation

$$R_G = \frac{V_{supply} - V_{GS,ON}}{I_{G,ON}} \quad (4)$$

$V_{GS,ON}$ in (4) is the equal to the value aforementioned (2.8V). The peak current $I_{G,peak}$ at turn-on and turn-off transients depends on the device choice (for 600V/56mΩ GaN GIT is $I_{G,peak}$ <1.5A) from which $R_{G,ON}$ is

$$R_{G,ON} = \frac{V_{supply}}{I_{G,peak}} \quad (5)$$

$R_{G,OFF}$ can be designed by an equivalent relation of (5). The capacitor C_G is related to the gate charge to reach a peak value ($Q_{G,peak}$) in order to speed-up the transient switching.

$$Q_{G,peak} > Q_{GD} + Q_{GS} \quad (6)$$

From which

$$C_G = \frac{Q_{G,peak}}{(V_{supply} - V_{GS,ON})} \quad (7)$$

The C_G capacitor must be a fair compromise in order to have a current peak that extinguishes quickly enough so as not to interfere with the next switching if the frequency is high. At turn-off, C_G is settled to provide enough negative gate-source voltage value immediately after turn-off that does not cause wrong turn-on.

IV. BIDIRECTIONAL GaN SWITCH

The GaN-based GIT monolithic bidirectional switch (B-GIT) is obtained by an integration of a dual-gate structure. The GIT simplified structure is depicted in Fig. 5. Bidirectional GAN switch is more attractive in protection electronic fuse application compared with MOSFET and IGBT devices solution due to the favourable $R_{DS,ON}$ characteristics and the absence of the body diode. In Fig. 6 The four-quadrant operation of IGBT (Fig. 6a), MOSFET (Fig. 6b) and B-GIT (Fig.6c) are reported.
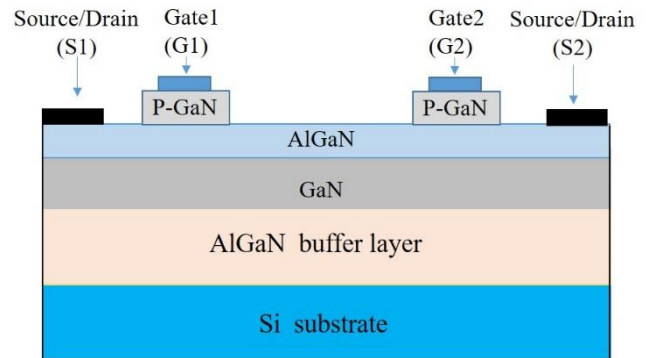

Fig. 5. Simplified structure of N- channel enhancement-mode GaN FET bi-directional switch with dual P-GaN gate.

In the IGBT switch, the offset voltage due to the diode increases the conduction losses. In the bi-directional switch realized with silicon MOSFET, the gate control circuit allows switching the devices in synchronous mode without the voltage offset [17]. The slope of the straight line in the current-voltage graph is rather low compared to the case of the B-GIT increasing the power losses. However, the main advantage in the case of the B-GIT is the use of a single device with a drastic reduction in size with a very low drop in direct voltage in the two directions of current conduction. The device blocks

600V between S1-S2 with a $R_{ON} = 32m\Omega$ in the two directions. Furthermore, it can withstand a drain-source current pulse $I_D=135A$ (at $T_C=25$ °C). The device is encapsulated in a package PSOP20. The main electrical device quantities to design the gate driver circuit are reported in Table I. All parameters are measured at 25 ° C.
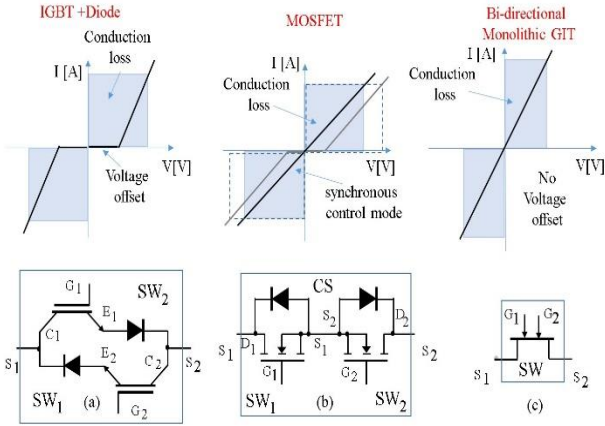

Fig. 6. Four quadrant operation of the bi-directional switch in the case of a) IGBT, b) MOSFET (in synchronous mode or not), c) B-GIT

The gate charge is related to the charge and discharge of the parasitic capacitances depicted in Fig. 7 [18], [19]. The capacitances reported in Table I are correlated with the parasitic capacitors in the following way

$$C_{iss1} = C_{G1S1} + C_{G1G2};$$

$$C_{iss2} = C_{G2S2} + C_{G1G2};$$

$$C_{oss} = C_{S2S1} + C_{G1G2};$$

$$C_{rss} = C_{G1G2}.$$

A. Operation Modes of the Bidirectional Switch

The operation mode depends on the gate bias condition. The dual gate B-GIT in the structure is equivalent to a back to back common drain connection as shown in Fig. 8a. There are four operation modes based on the gate-source voltage bias of the dual gate GaN FET (on $V_{GS}=4V$, off $V_{GS}=0$). Four quadrant operations are described in Fig. 8b.

TABLE I. MAIN ELECTRICAL QUANTITIES OF THE B-GIT TO DESIGN GATE CONTROL CIRCUIT

Gate Control Quantities			
Gate1-source1 $I_{G,peak1}$ [A]	Gate1-source1 $I_{G,ON}$ [mA]	Gate threshold voltage V_{TH} [V]	Gate forward voltage V_{G1S1} [V]
4.6A	157.8 Max	1.7 Max	2.6 min, 4 max
Parasitic Capacitances (at $V_{S2S1}=400V$, $V_{G1S1}=0V$, $f_{sw}=1MHz$)			
C_{iss1} [nF]	C_{iss1} [nF]	C_{oss} [nF]	C_{rss} [nF]
1.02	1.02	0.19	0.04

The output waveforms of B-GIT in bi-directional mode with the V_{G1S1} and V_{G2S2} as variable parameters are reported in Fig. 9a. The output waveforms in single directional mode (diode operation with the current flowing from S_2 to S_1

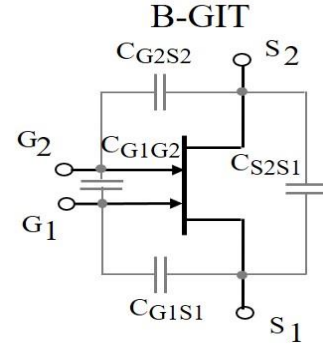($V_{S1}<V_{S2}$) and the reverse blocking condition are depicted in Fig. 9b.

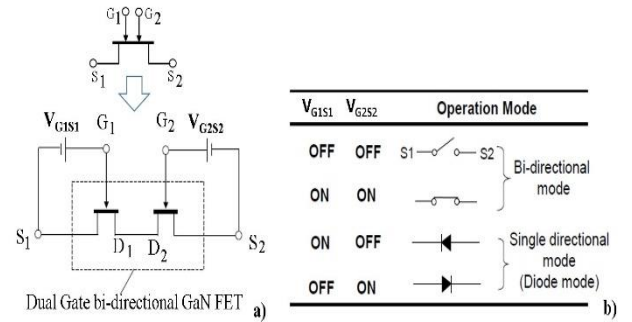Fig. 7. Parasitic capacitors distribution in the B-GIT.

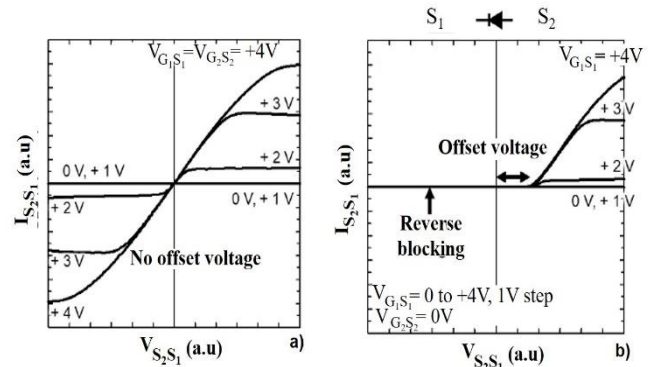Fig. 8. a) Bi-directional GaN transistor with the dual gate polarization, b) operation modes of B-GIT.

Fig. 9. a) Bi-directional mode autput waveforms, b) single directional mode diode operation with current flowing from S1 to S2. The waveforms depicted are qualitative, a.u is abbreviation for arbitrary unit.

The maximum current flowing in bi-directional mode of operation depends on the junction temperature. The actual output characteristic with the current flowing from S_2 to S_1 with a fixed gate –source voltage $V_{G2S2}=3V$ are reported in Fig. 10 at $T_j=25$ °C.

B. Experimental Operation Modes of the B-GIT in AC and DC Switching Applications

The B-GIT is tested on a resistive load in AC and DC operative conditions. The schematic of the AC test circuit with resistive load and GaN bi-directional switch with the dual driver circuit is reported in Fig. 11. The tested solution is typical of hybrid solid state relay device (HSS) application. The HSS devices are components that combine a semiconductor switch with a conventional electromechanical

contactor and are mostly used in industrial applications such as motor control and protection [20].
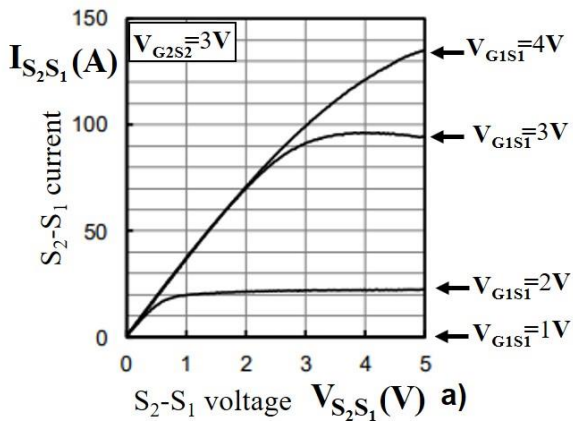

Fig. 10. Output characteristics with the current flowing from S2 to S1 with a gate-source voltage V_{G2S2}=3V at T_j=25°C.

HSS Relays are already available in the market, but they are all based on conventional silicon structures, typically two anti-series MOSFETs. The use of a B-GIT switch allows for a simplification of the structure of the HSS device as only one single, monolithic components is used and offers the advantages of the GaN structure (absence of body diode vs. channel condition and high current density at low $R_{DS(on)}$).
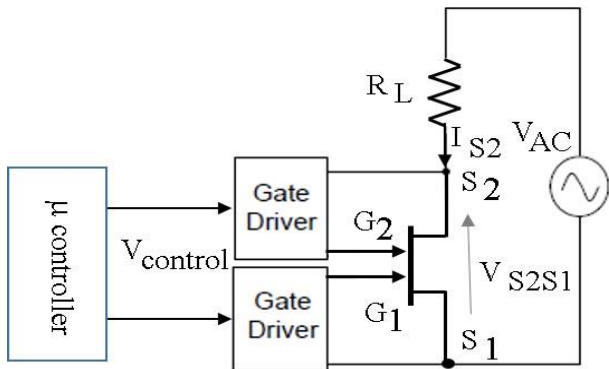

Fig. 11. Bi-directional esperimental set-up with an AC power supply and resistive load.

The experimental evaluation of bidirectional operation mode of B-GIT in the case of zero-voltage switching is reported in Fig. 12. The test conditions are $V_{AC,max}$=311V and $I_{S2,max}$=5A. The control signal $V_{control}$ is in the range -3V to 3V. The gate driver manages the control signal to obtain the two gate driver suitable voltages. The bidirectional current operation was obtained maintaining the switch in on state by V_{G1S1}=V_{G2S2}=4V ($V_{control}$=3V) while the current I_{S2} was stopped at V_{G1S1}=V_{G2S2}=0V ($V_{control}$=-3V) as is described in Fig. 12. In Fig. 13 the B-GIT is commanded open in correspondence of the AC peak current. During the B-GIT turn-off a dangerous over-voltage appears, to reduce the dv/dt a suitable snubber capacitor is inserted across the power device. The behavior in the case of resistive load and DC supply was also considered in the test conditions at V_{S2S1}=300V and I_{S2}=5A. Fig. 14 shows the direct conduction in the first quadrant operative condition with the current flowing from S_2 to S_1. While Fig. 15 shows the reverse switching behavior in the third quadrant with the current

flowing from S_1 to S_2 and negative DC voltage. In both cases the dv/dt was controlled by a suitable snubber capacitor to avoid over-voltage.
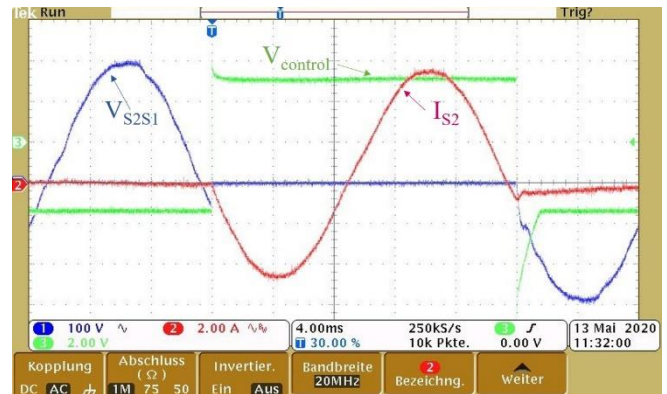

Fig. 12. Bi-directional AC esperimental waveforms on resistive load at zero-voltage switching. $V_{control}$=2V/div, I_{S2}=2A/div, V_{S2S1}=100V/div, t=4ms/div.
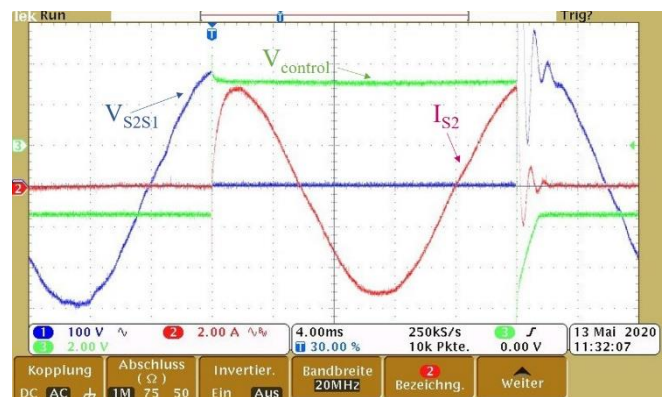

Fig. 13. Bi-directional AC experimental waveforms on resistive load at peak-voltage switching. $V_{control}$=2V/div, I_{S2}=2A/div, V_{S2S1}=100V/div, t=4ms/div.
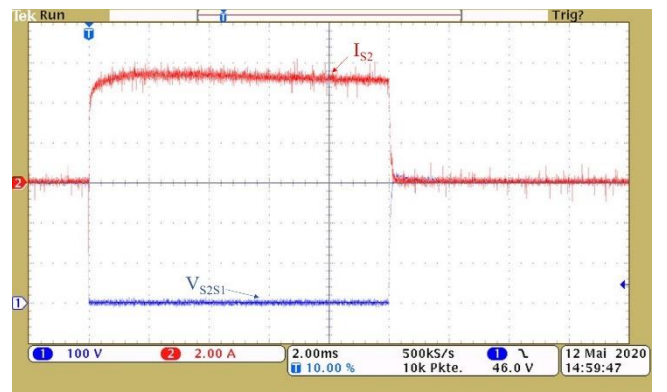

Fig. 14. Bi-directional DC experimental waveforms on resistive load at first quadrant operative condition.. I_{S2}=2A/div, V_{S2S1}=100V/div, t=4ms/div.

V. CONCLUSIONS

In the paper, a bidirectional monolithic switch based on enhancement mode GaN FET is presented. The GaN device belongs to Gate Injection Transistors and features dual gate with two power terminals. The GaN FET technology have reduced $R_{DS(ON)}$ with fast transients, it is much attractive for the use in bidirectional switch applications. The equivalent switch device is composed by two integrated GIT in the same chip in back-to-back connection (common drain). The design constraints of the gate driver circuit are treated to understand

as optimize the switch application. The static output characteristics in the bidirectional and diode mode operation are presented and discussed. Finally, the experimental waveforms in the case of study of a circuit breaker for AC power supply at industrial frequency (50Hz) and resistive load at output rated power of $P_{out,max}$=1.5kW are carried out to show the effectiveness of the proposed new monolithic device solution. The B-GIT features a reduced volume compared with the MOSFETs and IGBTs of same rated current and voltage with a high current density.
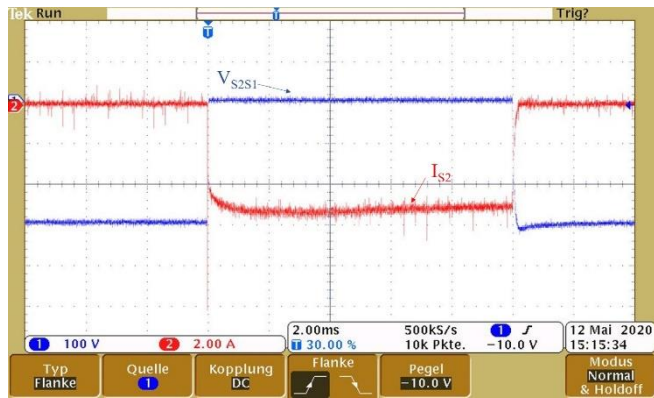

Fig. 15. Bi-directional DC experimental waveforms on resistive load at third quadrant operative condition. I_{S2}=2A/div, V_{S2S1}=100V/div, t=4ms/div.

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