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# Experimental evaluation of GaN Gate Injection Transistors

***Abstract**. The paper presents experimental evaluation of Gate Injection Transistors produced on the base of Gallium Nitride (GaN). Authors show double-pulse test results and measurements of the half-bridge converter with inductive load. Obtained results indicate very good performance of new devices which are able to operate at high switching frequency and low power losses (0.6% losses of converter power at 150 kHz was achieved).*

***Streszczenie.** Artykuł przedstawia ocenę w trybie eksperymentu tranzystorów typu Gate Injection Transistor zbudowanych na bazie azotku galu (GaN). Autorzy prezentują wyniki testów dwupulsowych a także wyniki pomiarów układu półmostka obciążonego dławikiem. Wyniki wskazują na bardzo dobre parametry nowych przyrządów, charakteryzujących się niskimi stratami mocy nawet przy dużych częstotliwościach przełączeń (uzyskano 0.6% strat mocy przekształcanej przy 150kHz)* ***(Ocena w trybie eksperymentu azotkowo-galowych tranzystorów typu GIT)**.*

**Keywords:** Gallium Nitride (GaN), Gate Injection Transistor (GIT), power losses, double-pulse test.
**Słowa kluczowe:** Azotek galu, tranzystor GIT, straty mocy, test dwupulsowy.

## Introduction

Last year's field of power devices is revolutionized by truly exciting new technologies. Besides continuous improvement in Silicon-based devices, to mention only latest IGBTs with seriously increased switching performance [1] or low power MOSFETs with on-state resistances of single mΩs [2], wide band-gap electronics is also becoming important. Introduction of Silicon Carbide diodes and transistors brought devices in 1200V and 1700V voltage class with outstanding performance: low-on state resistance and fast switching [3]. These devices are currently tested and implemented in variety of power electronic applications [4]-[7]. In the meantime transistors made of another wide band-gap material - Galium Nitride (GaN) are leaving research laboratories. Comparing to Silicon it shows ten times higher critical field strength and more than twice higher saturation electrons velocity [8]. That is why GaN has great potential to built very fast devices (also RF transistors) but thermal properties are not that good as in case of Silicon Carbide. All theses material properties seem to be perfect to make power devices for low power applications. First introduced GaN transistors, High Electron Mobility Transistors (HEMTs) are in voltage class 600V and below [9],[10]. They reach very low on-state resistances due to two-dimensional electron gas with high mobility existing between GaN and AlGaN layers [11], high critical field leads to small size of devices and very low parasitic capacitances. In consequence, recently presented GaN HEMTs show much better $R_{ON}$xC figure of merit than comparable Si MOSFETs [12]. The drawback of most HEMT designs is normally-ON characteristics, which may be application stopper (as has happened to SiC JFETs). Another possible obstacle may be high cost of the device as most of GaN power devices is produced on SiC substrate. This issue is even more important as new GaN transistors are expected to compete with well-established and mass-produced Si MOSFETs. Possible solution is to grow GaN transistors on low-cost Si substrate but this process is very challenging as GaN and Si show different thermal expansion coefficients and lattice constants [13].

This paper is focused on experimental evaluation of a GaN Gate Injection Transistor (sometimes named also Heterojunction Field Effect Transistor - HFET), which is grown on the base of Si substrate. A potential to low-cost manufacturing together with normally-off characteristics make this transistor interesting alternative to HEMTs. The authors provide description of the transistor operation and, then, results of experiments conducted on 600V/15A samples. Switching tests as well as operation in a half-bridge converter are presented.

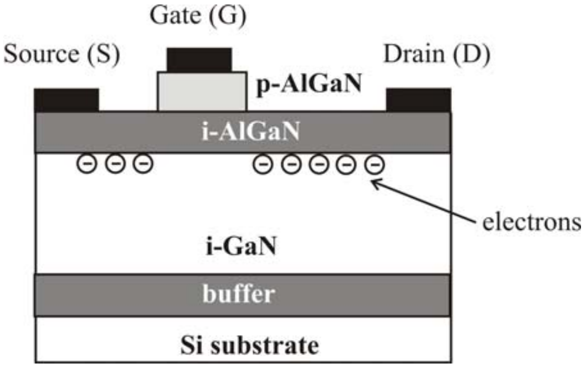

Fig.1. Cross-section of Gate Injection Transistor [13]

## Structure and operation principles of GIT

As was mentioned above main issue, when goes to growth of GaN layers on Si substrate, is a mismatch in lattice constant (GaN 3,189 vs. Si 3,84) and thermal expansion coefficient (GaN 5,45 vs. Si 3,59). This problem is especially important taking into account operation of power devices under thermal cycles. A solution for discussed GIT is a buffer layer between Si and GaN based on AlN - see Fig.1, described closer in [13]. In consequence an epitaxial growth of intrinsic GaN layer is possible on large area substrates (up to 200mm diameter), which will lead to decrease transistor's production cost. Then, the AlGaN barrier layer is grown and 2 dimensional electron gas appears as can be seen in Fig.1. This gas has very high mobility and makes possible conduction of the current between drain (D) and source (S) electrodes at very low resistance. It should be noted that conduction in both direction is possible. Another layer, p-AlGaN, placed on the top forms gate (G) electrode that moves up potential of the channel and conduction of the current from D to S is not possible. This means that without any GS voltage device is blocked and shows normally-off characteristics. When the applied to GS electrodes voltage is higher than threshold value holes from p-type gate are injected into the channel. This phenomenon decreases on-state resistance by increase of number of electrons (conductivity modulation). Therefore, the device requires a gate current to remain in low on-state resistance area but amount required current is significantly lower than in case of other current driven devices, such as bipolar transistors. For discussed example of 600V/15A transistor this value is on the level of 50mA, which is acceptable for any of discrete gate driver. Main parameters of PGA26C09DV are presented in Table I.

Table 1. The main parameters of evaluated GIT (PGA26C09DV)

| Parameter | Value | Unit |
|---|---|---|
| Drain source voltage $V_{DSS}$ | 600 | V |
| Drain current $I_D$ | 15 | A |
| On-state resistance $r_{ON}$ | 71 | mΩ |
| Threshold voltage $V_{GS(TH)}$ | 1,2 | V |
| Gate-source charge $Q_{GS}$ | 0,5 | nC |

## Double pulse test of the GaN GIT/SiC Schottky pair

According to manufacturers recommendation a simple gate driver based on ACPL-346 optocoupler supplied from 12V supply from Traco was designed. In general, a concept of the RC driver (Fig.2a) is the same as for SiC BJT [14] but necessary amount of the gate current is definitely lower. In this case single source $V_{CC}$ seems to be enough to meet the GIT driving requirements: dynamic pulses during turn-on/off and steady-state current during transistor's conduction. The gate resistor $R_G$ was set to 150Ω while speed-up capacitor was C = 2nF and dumping resistor $R_{DP}$= 20Ω.

The transistor was investigated in the double-pulse test (DPT) circuit (Fig. 2b) with 600V/10A SiC Schottky diode. Drain current $i_D$ was measured with CWT mini Rogowsky coil, while drain-source voltage $v_{DS}$ was observed with P5200 voltage probe. Both waveforms recorded for turn-on and turn-off processes are presented in Fig. 3 respectively. The data suggest that changes of the $v_{DS}$ are very fast: 21kV/µs for turn-on and above 25kV/µs for turn-off. That fast transients are possible due to low parasitic capacitances of the tested GIT, even if very simple gate drive unit was applied. The recorded waveforms of the drain current are not that rapid but it is very possible that bandwidth of the used Rogowski coil was limitation. All in all, presented measurements show very good switching performance of tested GaN GIT.

## Double pulse test of the GaN GIT/GIT pair

The discussed device, 600V/15A GIT, is able to conduct reverse currents and, therefore, in many applications transistors may operate in the bridge leg configuration without external diodes (operation mode called synchronous rectification). That is why the devices were also tested in double-pulse procedure according to schematic in Fig. 2c. Both transistors, upper $T_H$ and lower $T_L$ were equipped with the same type of the gate driver unit (GDU), controlled by inverted signal with short dead-time (100ns). In fact, two modes of reverse conduction occurs in GaN GITs. At first, during dead-time, when lower transistor $T_L$ is turned-off but applied to $T_H$ gate-source terminals voltage is still zero a reverse current starts flowing from its source to drain. This is possible when drain-source voltage of $T_H$ is below zero (forced by inductor L) and gate-drain voltage is higher than threshold voltage. After dead-time period the gate source voltage of $T_H$ is increased by the GDU and the transistor enters in normal conduction mode, however the current is still reversed.

Measurements conducted during switching processes of two GITs are shown in Fig.4 for turn-on and turn-off respectively. Again very fast changes of drain-source voltage are observed but behaviour of the current waveforms is affected by some additional effects. One of Rogowski coils was attached to measure source current of the upper transistor $T_H$ due to lack of available space. Therefore, two measured current differs during first 60ns when the gate current is non zero recharging GIT capacitances. With the use of $v_{DSL}$ and $i_{DL}$ waveforms in Fig.4 a switching energy was estimated to be approximately $E_{ON}$ = 80µJ and $E_{OFF}$ = 35µJ (at $U_{DC}$ = 350V and $I_L$ = 20A).

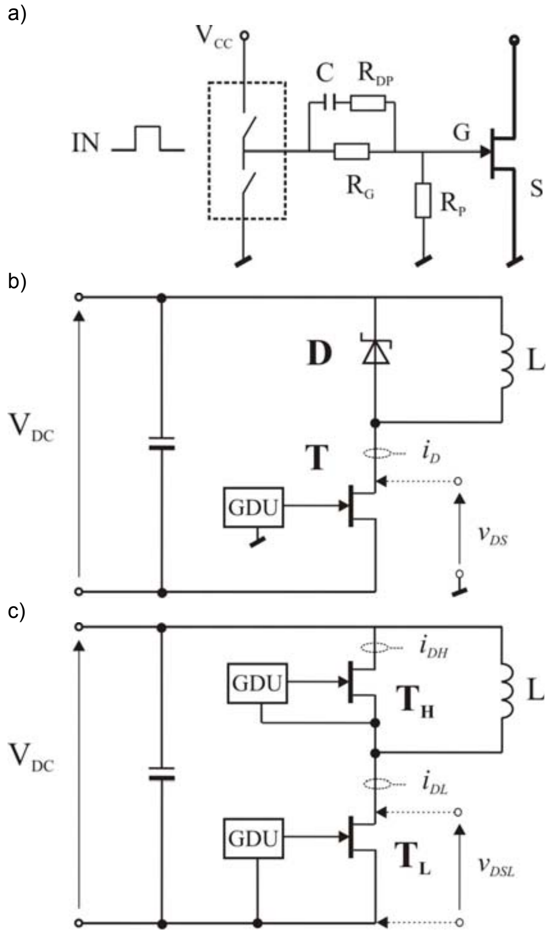

Fig.2. Scheme of the applied gate driver unit - GDU (a) and double pulse test (DPT) circuit with diode (b) or pair of GITs (c).

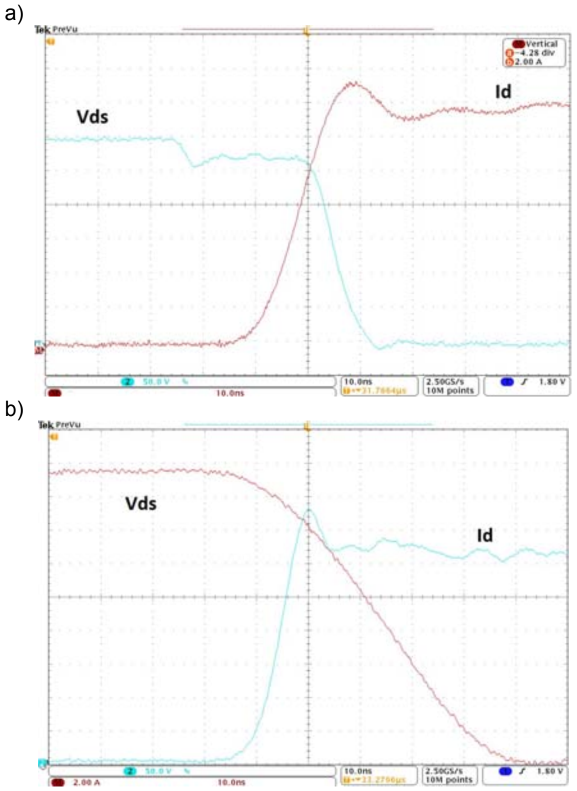

Fig.3. Drain-source voltage and drain current of GIT during turn-on (a) and turn-off (b) process of the GIT/SiC Schottky pair (2/A/div, 50V/div,10ns/div)

### Operation in half-bridge with inductive load

Presented above switching waveforms show fast transients and accuracy of switching energies determination is not high. This issue becomes important when transistors are aimed to operate at very high frequencies and switching power losses will be dominant over conduction power losses. Inaccurate determination of the switching energy and, then, switching power losses will make a correct design of power converter challenging.

The authors decided to find switching energies out during the test of a half-bridge built with two GITs (Fig.5). The idea is to measure input power when the half-bridge is operating with a pure inductive load and square wave control signal. In consequence, a triangular shape of the load current waveform is observed – see example for $f_S$=150 kHz in Fig.6. The DC component is zero and reactive power is circulating between two capacitors and inductor. At the same time transistors operate in the same manner: each of them is conducting during 50% of the switching period, starting from reverse conduction, then, the drain current becomes positive. Thus, they are expected to have equal power losses: on-state and switching.

The input power taken from the input supply $P_{DC}$ is dissipated in transistors ($P_{TR}$) and inductor ($P_L$). Magnetic losses are neglected as the half bridge was tested with two types of air-cored inductors ( see Tab. 2). Copper losses of the inductor $P_{RL}$ are determined with the use of RMS value of the load current and, therefore, power losses in the transistors $P_{TR}$ are found by substraction of $P_{RL}$ from $P_{DC}$. Results of half-bridge measurements are shown in Fig.7 for two types of inductors. Total losses of 2,75W are observed at 100kHz for first inductor $L_1$ and 9W at 150kHz for second one. After assumption that on-state resistance of transistors was 70mΩ (datasheet value) this results in switching energy per transistor: $E_{TOT}$ = 9,5μJ (switching at 300V/6A) for inductor $L_1$ and $E_{TOT}$ = 22,7μJ (300V/10A) inductor $L_2$.

Observed values of switching energies are lower than determined by means of double-pulse test, even if are recalculated for the same voltage/current rating 350V/20A (for instance $E_{TOT}$ for $L_2$ rises to 54 μJ). The first reason is slightly different type of the transistor switching in the half-bridge than in the DPT. Connection of the inductor to the middle-point of the capacitors instead connection to the positive pole of $V_{DC}$ changes flow of the currents recharging parasitic capacitances in the switching circuit. But the main cause is, most likely, that drain current during DPT is faster than shows measurement with the use of Rogowski coil. Thus, if the true drain current is more rapid, switching times and switching energies will be definitely lower and closer to values observed for half-bridge operation. All in all, results of the half-bridge tests can be more trusted than obtained with DPT. Errors of the measurements: the input power (power meter using DC voltage and current), inductor on-state resistance measurement (RLC bridge) and RMS of the inductor current (oscilloscope current probe) are definitely lower than inaccuracies during the fast changes of the voltages and currents.

In spite of mentioned differences conducted tests show very good performance of the GITs, which is much better than in comparable 600V Si MOSFETs. Low on-state resistance and fast switching results in low transistor power losses operating and high switching frequency. This is very good prediction of future converters performance, to mention two examples already built with GaN GITs [15],[16],[17]. In presented example, the half-bridge was operating with $L_2$ in conditions comparable to transfer of the 1,5kW active power at switching frequency of 150 kHz. Therefore, the measured 9W power losses in transistors are in the range of 0.6% rated power.

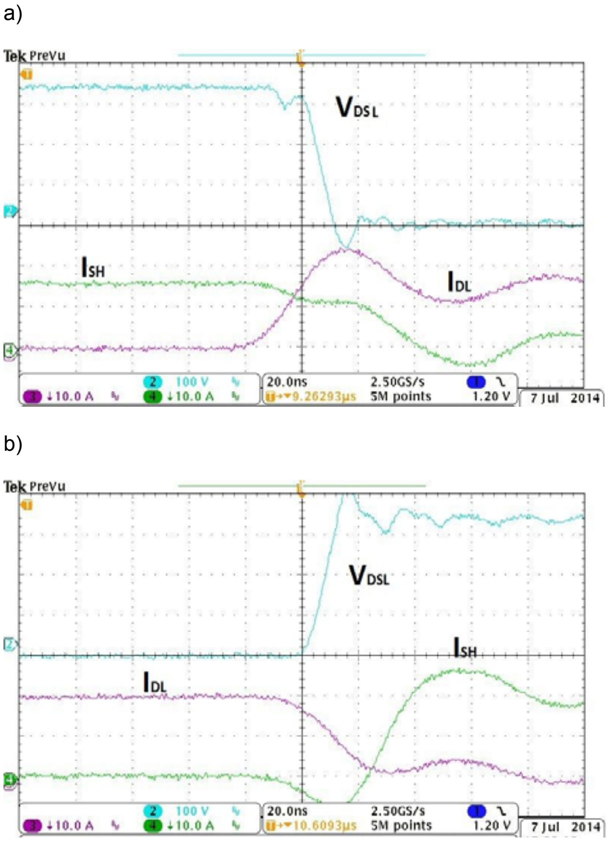

Fig.4. Drain-source voltage and drain current of $T_L$ together with source current of $T_H$ during turn-on (a) and turn-off (b) process of the GIT/GIT pair (10A/div, 100V/div, 20ns/div).

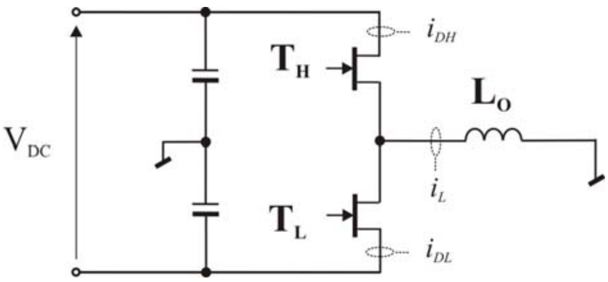

Fig.5. The GIT half-bridge test-circuit with the inductive load.

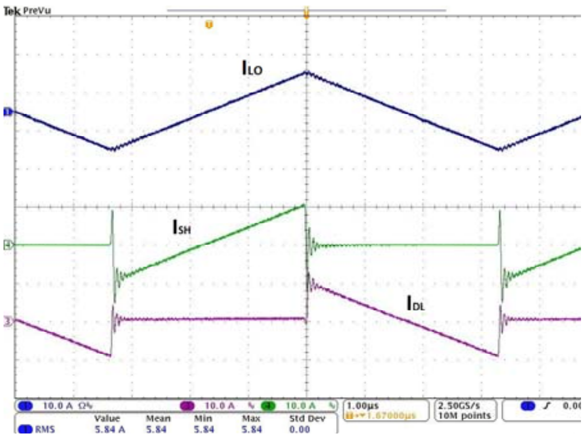

Fig. 6 Waveforms of the load current $i_{LO}$, and currents of transistors: $i_{SH}$, $i_{DL}$ during the half-bridge operation at 150kHz (D=50%) with $L_2$=24μH.

Table 2. The main parameters of applied air-core inductors

| Inductor/ parameter | Inductance [μH] | Resistance [mΩ] | Test frequency [kHz] |
|---|---|---|---|
| $L_1$ | 62 | 184 | 100 |
| $L_2$ | 24 | 140 | 150 |

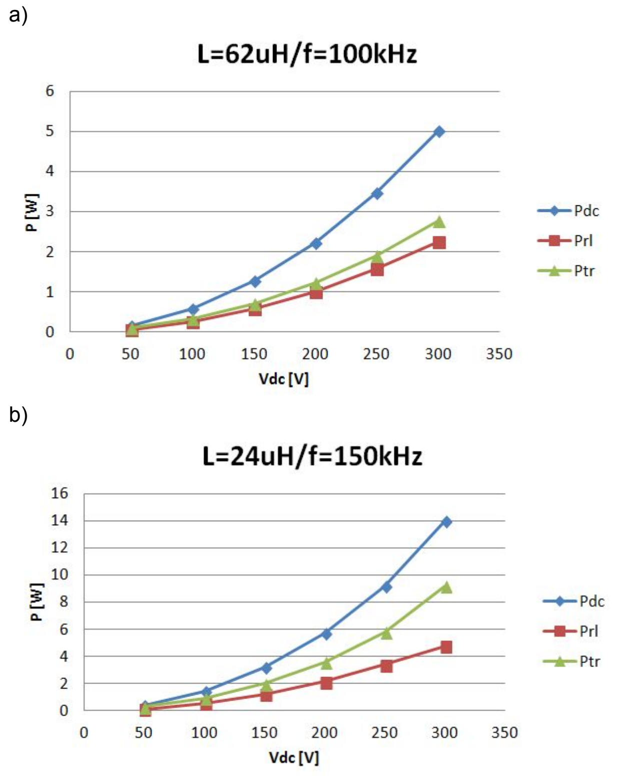

Fig.7. Power losses versus input voltage for two different inductors and frequencies ($P_{DC}$ - input power, $P_{RL}$- inductor copper losses, $P_{TR}$.- transistors total losses).

## Summary

The paper describes experimental evaluation of GaN Gate Injection Transistors rated at 600V/15A. At first devices were tested in double-pulse procedure with SiC Schottky diode and, then, as a GIT/GIT pair. Both measurements shown very good switching performance of tested transistors confirmed by measurements performed in half-bridge configuration. The circuit with two GITs and inductive load was operating at 150kHz with only 14W power losses, including 9W in the transistors. All measurements prove that it is very possible to built high-frequency converters with GaN GITs having reasonable efficiency close to 99%. This means that in future power converters built with tested devices the size of passive components and heatsink may be significantly reduced.

***Acknowledgements***

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