# Monolithically Integrated Gate Driver for MHz Switching with an External Inductor as a Current Source

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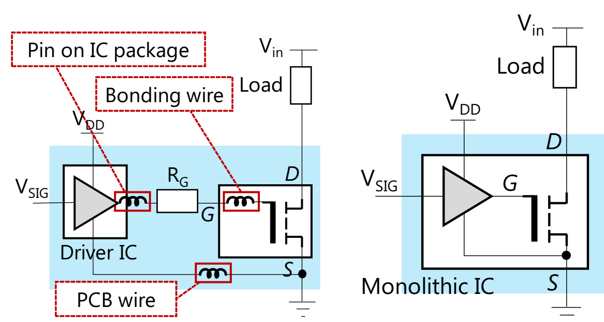
***Abstract*—This work presents the design of a gate driver, which is monolithically integrated on a single die with power p-gate Gallium Nitride High Electron Mobility Transistors (p-GaN HEMT). In order to improve the switching speed of the power device, it is effective to reduce parasitic components on the gate terminal by monolithically integrating a gate driver and the power HEMT. The proposed integrated gate driver works with an external inductor as a current source to charge or discharge the gate terminal of the integrated power HEMT. The fabricated chip can successfully operate at 10 MHz. The measurement results showed that the $V_{\rm DS}$ transition of the GaN IC is faster than the conventional method, and the GaN IC reduced transition time by 46% at turn-on and 20% at turn-off under off state $V_{\rm DS}$ of 100 V and on state $I_{\rm D}$ of 5 A.**

***Keywords*—Gallium Nitride (GaN), GaN-HEMT, Monolithic Integration, Current Source Gate Driver, High-speed switching**




(a) Discrete (b) Monolithic integration

Fig. 1: Gate drivers.

## I. Introduction

Recently, the GaN HEMTs is a promising candidate of next-generation power devices that can substitute Si (Silicon) devices. GaN HEMTs have high speed switching performance and high break down field and have been studied for downsizing and high efficiency of power conversion circuits [1], [2]. Especially, since power conversion circuits are demanded to be miniaturized in motor drive applications like EV (Electric Vehicle) and drones, it is mandatory to improve the switching speed of the power devices because the size of passive components in the power conversion circuits can be reduced by increasing switching frequency [3]. However, conventional methods of driving a discrete power GaN HEMT using a discrete gate driver can not sufficiently obtain high speed switching performance of the GaN HEMTs because the switching speed is limited by the parasitic components between the gate terminal of the power device and the gate driver (Fig. 1(a)). On the other hand, monolithically integrated implementation can reduce parasitic components of gate terminal and switching speed becomes fast (Fig. 1(b)) [4], [5], [6]. Another requirement for high speed switching is to supply large charge and discharge gate current [7]. Since the current source gate driver using an inductor can instantly supply large gate current, it has been reported that MHz-level high speed switching of power devices is possible [8], [9], [10]. Also, we proposed a current source gate driver to achieve fast switching of SiC MOSFETs [11].

In this work, we propose and fabricated a GaN IC (Integrated Circuit) that monolithically integrated p-GaN power HEMT and a gate driver using an external inductor as a current source on a chip by enhancement-mode (e-mode) GaN-on-QST (Qromis Substrate Technology, QST®, [12]) process. The fabricated GaN IC was operated at 10 MHz. In this paper, we report the monolithic integration of the current source gate driver and the power HEMT using an external inductor. We aim to integrate the inductor and the power HEMT into one package.

This paper is organized as follows. We explain operation principle of the proposed current source gate driver at turn-on transient and design of the GaN IC in Section 2. Section 3 shows measurement results and Section 4 concludes this work.

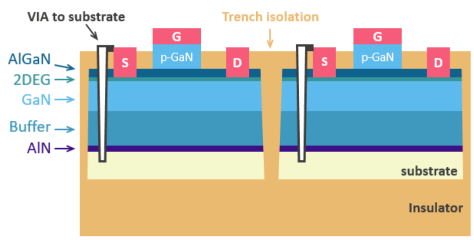


Fig. 2: Cross section view of two isolated GaN HEMTs.

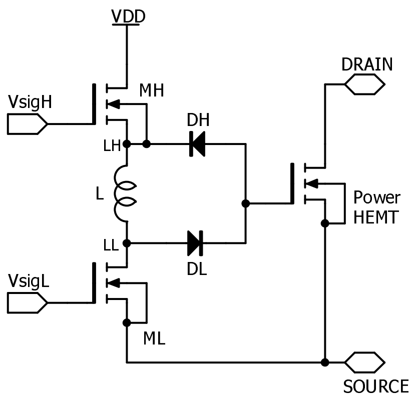


Fig. 3: Proposed current source gate driver [11].

## II. DESIGN OF PROPOSED GAN INTEGRATED CIRCUIT

### A. Fabrication of GaN IC

The integrated circuit was fabricated using p-GaN gate e-mode GaN HEMT transistors on a GaN-on-QST substrate taking advantage of the planar GaN HEMTs to be able to integrate. The GaN-on-QST process enables to isolate the substrate between the high side and low side HEMTs. Substrate potential stabilized to guarantee stable operation in the enhancement-mode (e-mode) due to stable substrate potential isolated by the buried oxide and deep trench isolation. Fig. 2 shows the cross section of the HEMTs by GaN-on-QST process.

### B. Proposed current source gate driver

Figure 3 shows the proposed current source gate driver. It consists of integrated GaN HEMTs (MH, ML), integrated diodes (DH, DL), and an external inductor L. The inductor works as a current source during switching transient. Fig. 4 shows the operation principle of the proposed current source gate driver at turn-on transient. The operation principle at turn-on transient is as follows:

1) MH is OFF and ML is ON. $V_{\mathrm{GS}}$ is 0 V.
2) MH turns ON. Current flows along the blue line and energy is stored in the inductor. At this stage, we have to investigate optimal energy charging time ($T_{\mathrm{C}}$) in order not to charge energy extraordinary.
3) ML turns OFF and DL turns ON. The inductor operates as a current source and current flows to the gate terminal of the power HEMT. Input capacitance $C_{\mathrm{iss}}$ of the power HEMT is charged and $V_{\mathrm{GS}}$ increses rapidly.
4) When $V_{\mathrm{GS}}$ becomes over $V_{\mathrm{DD}}$, DH turns ON and current flows to $V_{\mathrm{DD}}$ from $C_{\mathrm{iss}}$ through DH. $C_{\mathrm{iss}}$ is discharged and $V_{\mathrm{GS}}$ goes down to $V_{\mathrm{DD}}$.
5) DH and DL turn OFF and $V_{\mathrm{GS}}$ settles to $V_{\mathrm{DD}}$.

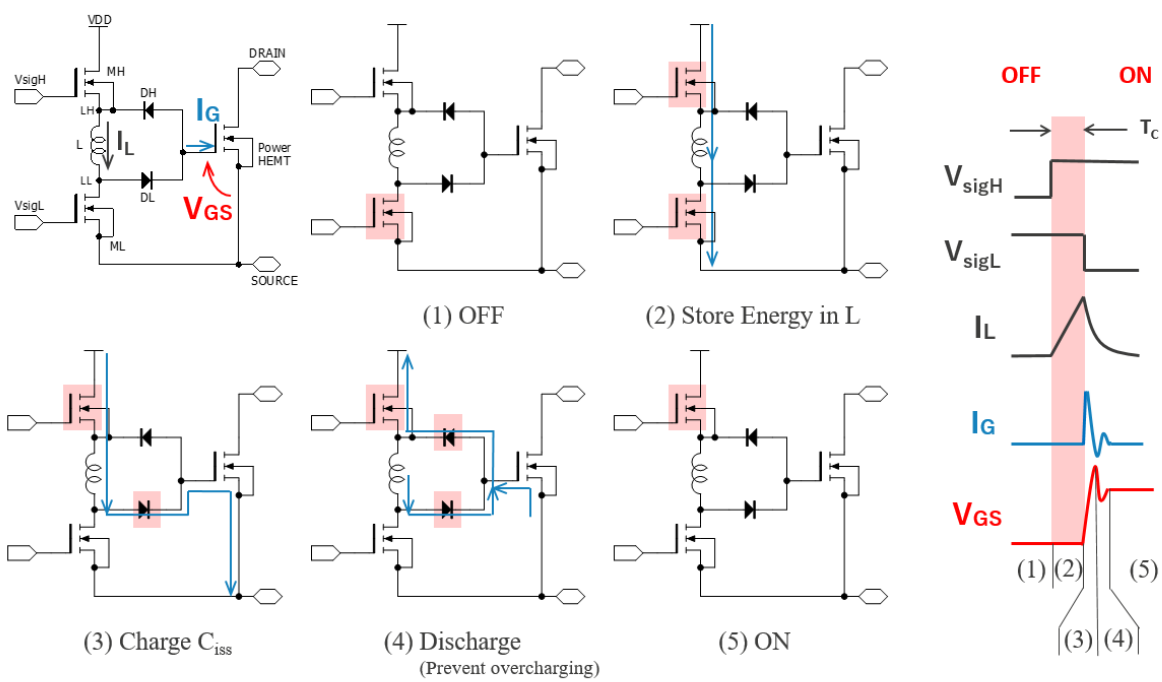
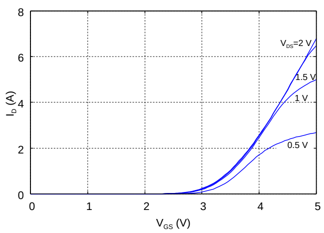


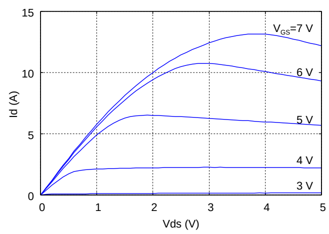
Fig. 4: Operation principle of the proposed gate driver at turn-on transient.

TABLE I: Size of HEMTs and diode in $\mu$m.

| | Wg | Lgd | Lgs | Lfp | Lg |
|---|---|---|---|---|---|
| Power HEMT | 70 | 4 | 0.75 | 0.65 | 1.3 |
| MH | 24 | 1.5 | 0.75 | 0.25 | 1.3 |
| ML | 23.7 | 1.5 | 0.75 | 0.25 | 1.3 |
| DH | 23.1 | 1.5 | 0.75 | 0.25 | 1.3 |
| DL | 23.7 | 1.5 | 0.75 | 0.25 | 1.3 |




(a) $I_{\rm D}-V_{\rm GS}$




(b) $I_{\rm D}-V_{\rm DS}$

Fig. 5: DC characteristics of the HEMT.

Turn-off operation of the proposed gate driver is the same procedure as turn-on. In order to perform the operation above, the proposed driver is controlled by the two independent input signals (VsigH, VsigL). The proposed gate driver can supply large current by storing energy in the inductor working as a current source. Therefore, it has high switching capability. The energy stored in an inductor ($E_{\rm L}$) must be larger than the energy needed to charge and discharge $C_{\rm iss}$ ($E_{\rm C}$) before switching. The energy $E_{\rm C}$ required for switching of the power HEMT is expressed as Eq. (1). The energy $E_{\rm L}$ stored in the inductor during $T_{\rm C}$ is expressed as Eq. (2). From Eqs. (1) and (2), $T_{\rm C}$ required for high speed switching is given by Eq.(3).

However, too much energy storage causes large ringing and increasing power consumption. Therefore, it is necessary to determine appropriate $T_{\rm C}$. In this work, the inductor is 47 nH and input capacitance $C_{\rm iss}$ of the power HEMT is about 90 pF. From Eq.(3), $T_{\rm C}$ must be larger than 2.1 ns.

$$E_{C_{\rm iss}} = \frac{1}{2}C_{\rm iss}{V_{\rm DD}}^2 \qquad (1)$$

$$E_{\rm L} = \frac{1}{2}LI^2 = \frac{1}{2}(\frac{V_{\rm DD}T_{\rm c}}{L})^2 \qquad (2)$$

$$T_{\rm c} > \sqrt{LC_{\rm iss}} \qquad (3)$$

### C. Layout of proposed GaN IC

Table I shows the size of the HEMTs and diodes in the GaN IC in Fig. 3. The definition is as follows. Wg: gate width (mm), Lgd: gate-drain distance ($\mu$m), Lgs: gate-source distance ($\mu$m), Lfp: gate field plate ($\mu$m), Lg: gate length ($\mu$m). The diodes were constructed using schottky junction on GaN IC [13]. The power HEMT in the GaN IC has 67 m$\Omega$ on-resintance $R_{\rm DS(ON)}$ and can be used yp to 200 V drain-source voltage. The DC characteristics of the power GaN HEMT is shown in Fig. 5. The gate drive voltage required to fully turn on is about 6~7 V. Fig. 6 shows a simplified layout of the designed GaN IC. The fabricated chip size is 2.3 mm×2.6 mm. Except for the inductor, the proposed gate driver and the power HEMTs are integrated on a chip. The inductor was not integrated since 47 nH is too large to be fabricated on a chip. The photograph of the proposed GaN IC is shown in Fig. 7. It was implemented in a DIL-18 (Dual In Line 18) package.

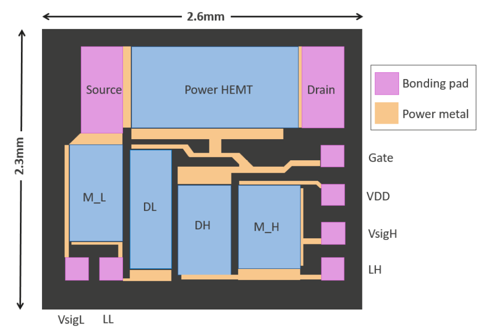



Fig. 6: Layout of the proposed GaN IC.

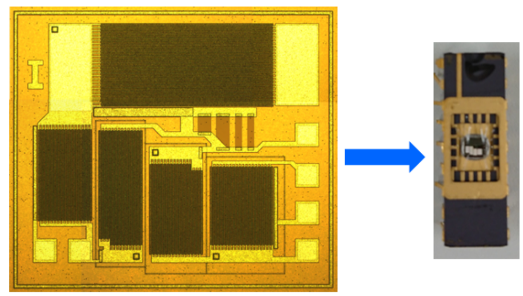


Fig. 7: Photo of GaN IC packaged in DIL 18.

## III. MEASUREMENT AND RESULT

### A. Measurement setups

The measurement circuit for the GaN IC (monolithic integration method) and the discrete driver (conventional method) are shown in Figs. 8 and 9, respectively. The external inductor L is a 47 nH chip inductor (Vishay, IHLP1616BZ). $T_{\rm C}$ was 4 ns, which is slightly larger than 2.1 ns calculated by Eq. (3) considering the parasitic component and the fluctuation of $C_{\rm iss}$ and L. Fig. 10 shows a photograph of the measurement system.

Control signals (VsigH and Vsig L) were generated by a function generator (KEYSIGHT, 81160A). The pre-driver for driving MH and ML shown in Fig. 3 was an isolated gate driver IC (Silicon Labs, SI8235AB) which amplified input signals from the function generator. It was used for the conventional method. The oscilloscope used for the experiment was DPO 7054C of Tektronix. The voltage was measured at the test points (TP_G,D,S) in Figs. 8 and 9. $I_{\rm D}$ was measured by the voltage drop on Rload. Vin determines off-state $V_{\rm DS}$, and Rload determines on-state $I_{\rm D}$ during the measurement. The DUT (Device Under Test) for the monolithic integration method is shown in Fig. 7. The DUT for the conventional

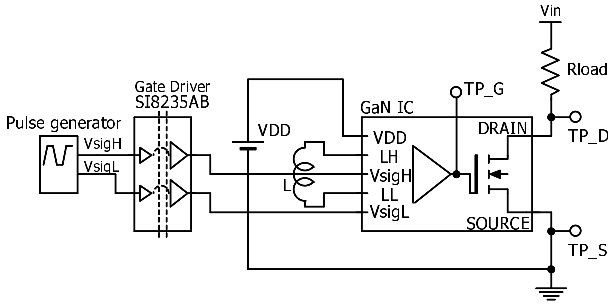



Fig. 8: Measurement circuit for the GaN IC (monolithic integration method).

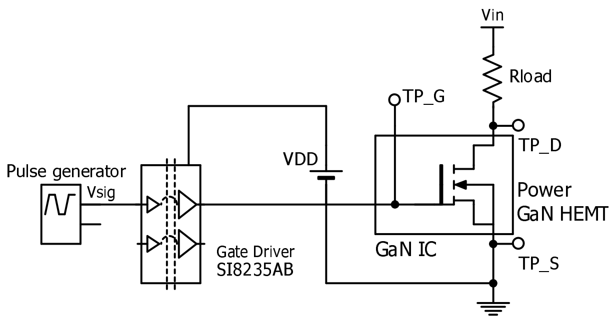



Fig. 9: Measurement circuit for the discrete gate driver (Conventional method).

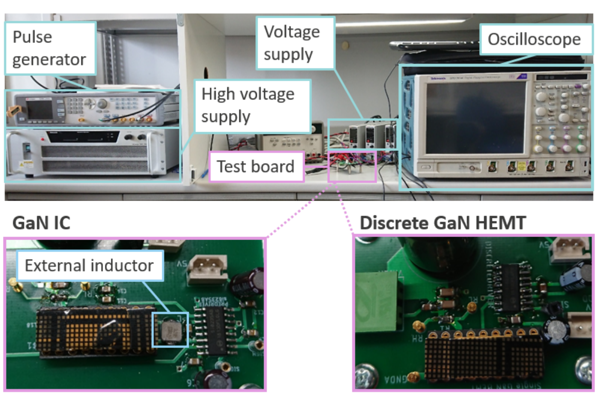



Fig. 10: Measurement environment.

method is the power HEMT in the GaN IC. The metal wire between the gate driver in the GaN IC and the power HEMT was cut off by a FIB (focused ion beam) system so as not to be affected by the gate driver in the GaN IC in the conventional method. This enables evaluation of switching characteristics of the power HEMT itself fabricated by the same process with the same layout pattern as in the GaN IC. In this work, the transition times $T_{\mathrm{fall}}$, $T_{\mathrm{rise}}$ and slew rate $\mathrm{dV_{DS}}/\mathrm{dt}$ were evaluated for using the GaN IC and the discrete driver, respectively. The switching times $T_{\mathrm{fall}}$ and $T_{\mathrm{rise}}$ are defined in Fig. 11.

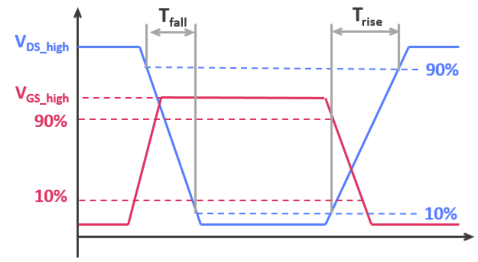



Fig. 11: Definition of switching time.

### B. Measurement results

Fig. 12 shows 10 MHz switching waveforms of GaN IC at 100 V of Vin and Rload of 20 Ω. From the measurement results shown in Fig. 12, 10 MHz switching operation of the proposed GaN IC was confirmed with smaller amount of ringing in $I_{\mathrm{D}}$. Figs. 13, 14 and 15 show the waveforms of the $V_{\mathrm{GS}}$, $V_{\mathrm{DS}}$ and $I_{\mathrm{D}}$ on the GaN IC and the discrete gate driver. Evaluation results of transition time are shown in Table II. GaN IC reduces the transition time $T_{\mathrm{fall}}$ by 46% and $T_{\mathrm{rise}}$ by 20%, respectively. The slew rate of the GaN IC when $V_{\mathrm{DS}}$ is 50V, was 27.6 V/ns at turn-on and 9.5 V/ns at turn-off, while they were 17.0 V/ns at turn-on and 7.2 V/ns at turn-off on the discrete driver. From the measurement results, it was confirmed that switching speed of the GaN IC faster than the discrete gate driver. Although an external inductor which causes an increase in parasitic components was connected, the proposed current source type GaN IC has high-speed drive capability compared to the conventional method of driving a discrete power HEMT.

However, Fig. 13 shows that the ringing of $V_{\mathrm{GS}}$ of the GaN IC is larger than the conventional method. In this work, due to the external inductor, parasitic components is larger than that of monolithic integrated circuit in [5]. In addition to that, the gate resistance between the power HEMT and the gate driver is minimized by the integration and then $V_{\mathrm{GS}}$ suffers from ringing. Ringing can be suppressed by increasing gate resistance, but the switching speed becomes slow on a conventional gate driver using resistors. In contrast, the proposed current source gate driver can operate at high speed even at large gate resistance. Therefore, the proposed GaN IC, with the gate resistor, is able to suppress ringing with relatively small impact on switching time. Of course, if faster switching of the power HEMT is required, it is better not to connect the gate resistor. However, this research is in progress of monolithic integration of the current source gate driver and the power HEMT in a package. If the inductor can be formed on the chip by using wire or a 3D printer, high-speed switching may be possible compared to monolithic integration with the conventional resistor type gate driver and the power HEMT while suppressing parasitic components and ringing of $V_{\mathrm{GS}}$.

## IV. CONCLUSION

In this paper, we proposed a monolithically integrated circuit with the power HEMT and the gate driver on a chip using

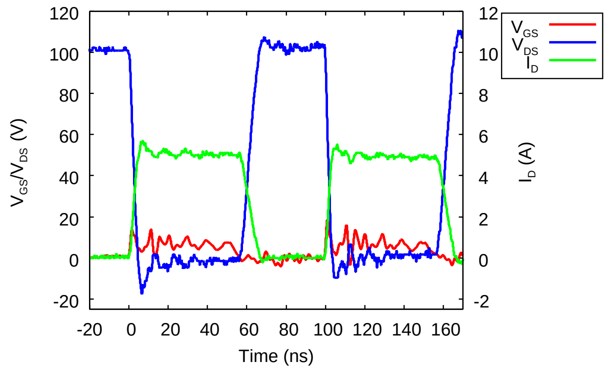
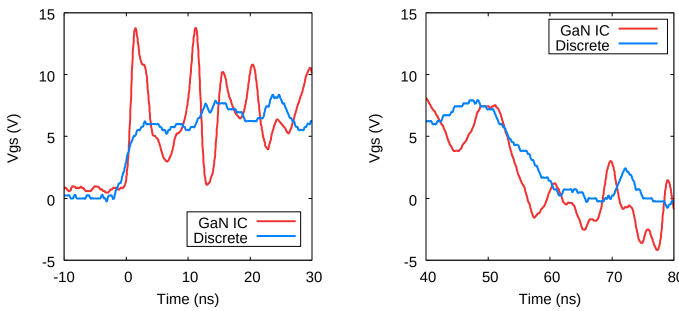
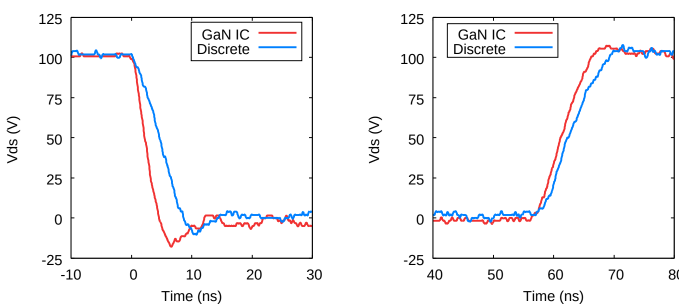



Fig. 12: Measurement waveforms at 10 MHz operation.



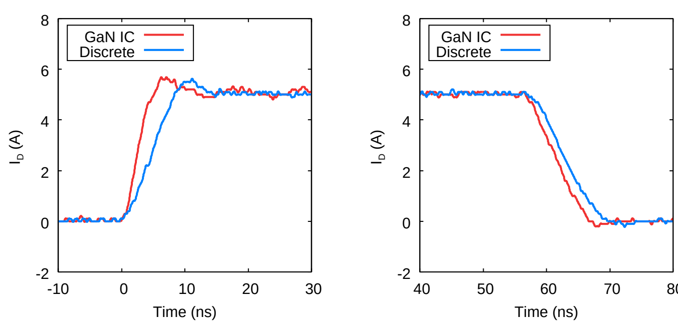

(a) Turn-on transient (b) Turn-off transient

Fig. 13: Measured $V_{\mathrm{GS}}$ waveforms.




(a) Turn-on transient (b) Turn-off transient

Fig. 14: Measured $V_{\mathrm{DS}}$ waveforms.




(a) Turn-on transient (b) Turn-off transient

Fig. 15: Measured $I_{\mathrm{D}}$ waveforms.

TABLE II: Evaluation result.

| | Discrete gate driver | GaN IC (integration) |
|---|---|---|
| $T_{\mathrm{fall}}$ | 6.1 ns | 3.3 ns (-46%) |
| $T_{\mathrm{rise}}$ | 8.8 ns | 7.0 ns (-20%) |

an external inductor by a p-GaN gate e-mode GaN-on-QST process. The inductor in the proposed gate driver behaves as a current source during switching transient. Experimental results showed that proposed GaN IC achieved 10 MHz switching operation at 100 V of off-state voltage and 5 A of on-state current. Compared to the conventional method of using discrete gate driver, the GaN IC reduced switching transient time $T_{\mathrm{fall}}$ by 46% at turn-on and $T_{\mathrm{rise}}$ by 20% at turn-off, respectively. From experimental results, the proposed GaN IC has high switching speed capability due to supply large gate current by an inductor. In this work, an inductor was connected externally to form a current source gate driver. But it causes ringing of the $V_{\mathrm{GS}}$ waveform due to increased parasitic components. We finally aim to form an inductor on the chip and integrate all components in a package. We plan to integrate an inductor and GaN IC in a package by forming th inductor using a 3D printer or metal wires on a chip.

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## References


[1] K. J. Chen, O. Häberlen, A. Lidow, C. l. Tsai, T. Ueda, Y. Uemoto, and Y. Wu, "Gan-on-si power technology: Devices and applications," *IEEE Transactions on Electron Devices*, vol. 64, no. 3, pp. 779–795, March 2017.

[2] J. W. Kolar, J. Biela, S. Waffler, T. Friedli, and U. Badstuebner, "Performance Trends and Limitations of Power Electronic Systems," in *2010 6th International Conference on Integrated Power Electronics Systems*, March 2010, pp. 1–20.

[3] S. Kimura, Y. Itoh, W. Martinez, M. Yamamoto, and J. Imaoka, "Downsizing Effects of Integrated Magnetic Components in High Power Density DC-DC Converters for EV and HEV Applications," *IEEE Transactions on Industry Applications*, vol. 52, no. 4, pp. 3294–3305, July 2016.

[4] S. Moench, M. Costa, A. Barner, I. Kallfass, R. Reiner, B. Weiss, P. Waltereit, R. Quay, and O. Ambacher, "Monolithic Integrated Quasi-normally-off Gate Driver and 600 V GaN-on-Si HEMT," in *2015 IEEE 3rd Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Nov 2015, pp. 92–97.

[5] Y. Yamashita, S. Stoffels, N. Posthuma, S. Decoutere, and K. Kobayashi, "Monolithically integrated e-mode gan-on-soi gate driver with power gan-hemt for mhz-switching," in *2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Oct 2018, pp. 231–236.

[6] Y. Zhang, M. Rodriguez, and D. Maksimovi, "High-frequency Integrated Gate Drivers for Half-bridge GaN Power Stage," in *2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL)*, June 2014, pp. 1–9.

[7] P. Anthony, N. McNeill, and D. Holliday, "High-Speed Resonant Gate Driver With Controlled Peak Gate Voltage for Silicon Carbide MOSFETs," *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 573–583, Jan 2014.

[8] H. Fujita, "A resonant gate-drive circuit capable of high-frequency and high-efficiency operation," *IEEE Transactions on Power Electronics*, vol. 25, no. 4, pp. 962–969, April 2010.

[9] Y. Long, W. Zhang, D. Costinett, B. B. Blalock, and L. L. Jenkins, “A high-frequency resonant gate driver for enhancement-mode gan power devices,” in *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2015, pp. 1961–1965.

[10] H. Jedi, A. Ayachit, and M. K. Kazimierczuk, “Resonant gate-drive circuit with reduced switching loss,” in *2018 IEEE Texas Power and Energy Conference (TPEC)*, Feb 2018, pp. 1–6.

[11] S. Inamori, J. Furuta, and K. Kobayashi, “Mhz-switching-speed current-source gate driver for sic power mosfets,” in *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, Sep. 2017, pp. P.1–P.7.

[12] Qromis, http://qromis.com/.

[13] GaN-on-silicon technology, https://www.imec-int.com/en/200mm-GaN-on-Si-technology.