MHz-Switching-Speed Current-Source Gate Driver for SiC Power MOSFETs

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Keywords

≪Silicon Carbide (SiC)≫, ≪MOSFET≫, ≪High-speed drive≫, ≪High frequency power converter≫, ≪Automotive application≫

Abstract

We propose a MHz-switching-speed current-source gate driver for Silicon-Carbide (SiC) power MOSFETs. The proposed gate driver uses an inductor as a current source during switching transient. Compared with a conventional gate driver, the proposed gate driver reduces switching time t_{off} and t_{on} by 20% and 32% respectively.

Introduction

Silicon-Carbide (SiC) is one of wide-bandgap semiconductor materials. It has higher breakdown field strength, saturation electron velocity and thermal conductivity than Silicon (Si). SiC power devices have lower ON-resistance and can be operated at higher temperature and frequency[1]. They are used for various applications of power electronics as an alternative of Si power devices.

For the automotive application, downsizing and lightweighting power converters are mandatory[2]. High frequency switching allows for replacing capacitors and inductors used as filters with small ones. To drive fast SiC MOSFETs with high internal gate resistance and large input capacitance, gate drivers must have high drive capability. Since high speed switching causes large Electro-Magnetic Interference (EMI) emission noise, power devices should be operated at ISM bands. The target of this work is to design a MHz-switching-speed gate driver to operate SiC MOSFETs at switching frequency of the 13.56MHz Industry Science Medical (ISM) band.

This paper is organized as follows. First, we describes requirements to drive power MOSFETs fast. After that, we explains the approach and operation of the proposed gate driver. Then we measures the transient characteristics and evaluates the switching characteristics of the conventional and proposed one. Finally, we concludes this paper.

Requirements to Drive Power MOSFETs Fast

Fig. 1 shows a conventional gate driver with gate resistor R_G. Gate resistor is inserted between the gate driver IC and the power MOSFET to reduce surge voltage. It can be reduced by increasing gate resistance. But there is a trade-off between surge voltage and switching time[3].

Gate drivers must supply large gate current during switching transient[4]. Several gate drivers are proposed to achieve large gate current[5][6][7][8]. One possible approach is to minimize output resistance of the gate driver. However, switching speed is limited due to high internal gate resistance of SiC MOSFETs r_G as shown in Fig. 2 [9]. The proposed gate driver utilizes passive components as a current source during switching transient.

The Proposed Gate Driver

Topology and Operation Principle

Fig. 3 shows the proposed current-source gate driver. It consists of p/n-MOSFETs, two diodes and an inductor. MOSFETs are controlled by two independent input signals. The inductor operates as a current source during switching transient.

Fig. 4 shows input and output signals of the proposed gate driver at each step. The turn-ON procedure is explained as follows.

1. Initialization
   p-MOSFET is OFF and n-MOSFET is ON. $V_{GS} = 0$ V.
2. p-MOSFET turns-ON. Current flows along the blue line and increases linearly. The inductor stores magnetic energy.
3. n-MOSFET turns-OFF and diode D_2 turns-ON. Inductor operates as a current source. Current flows to input capacitance C_{iss} of SiC MOSFET through D_2. C_{iss} is charged and V_{GS} increases and goes over V_{DD}.
4. If V_{GS} becomes over V_{DD}, Diode D_1 turns-ON.Current flows to bypass capacitor of V_{DD} through D_1. C_{iss} is discharged and V_{GS} decreases to V_{DD}.
5. D_1 and D_2 turn-OFF and V_{GS} stabilizes on V_{DD}.

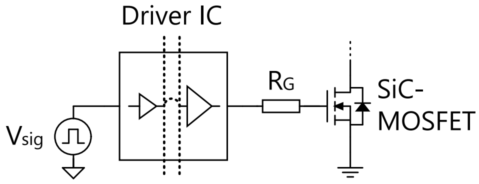


Fig. 1: Conventional gate driver with gate resistor R_G.

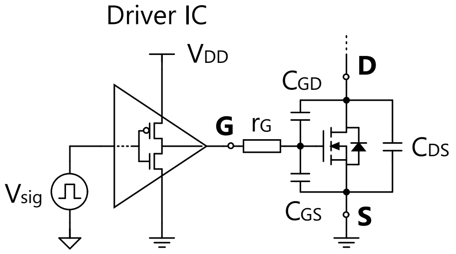


Fig. 2: Internal gate resistance r_G.

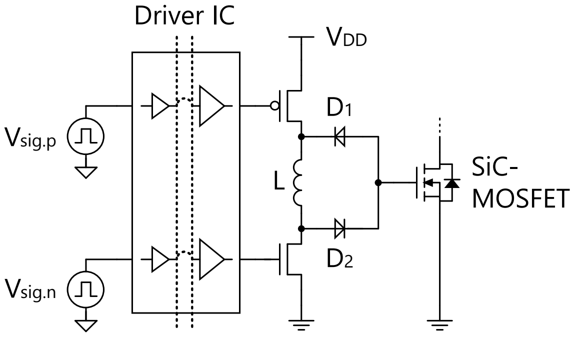


Fig. 3: Proposed current-source gate driver.

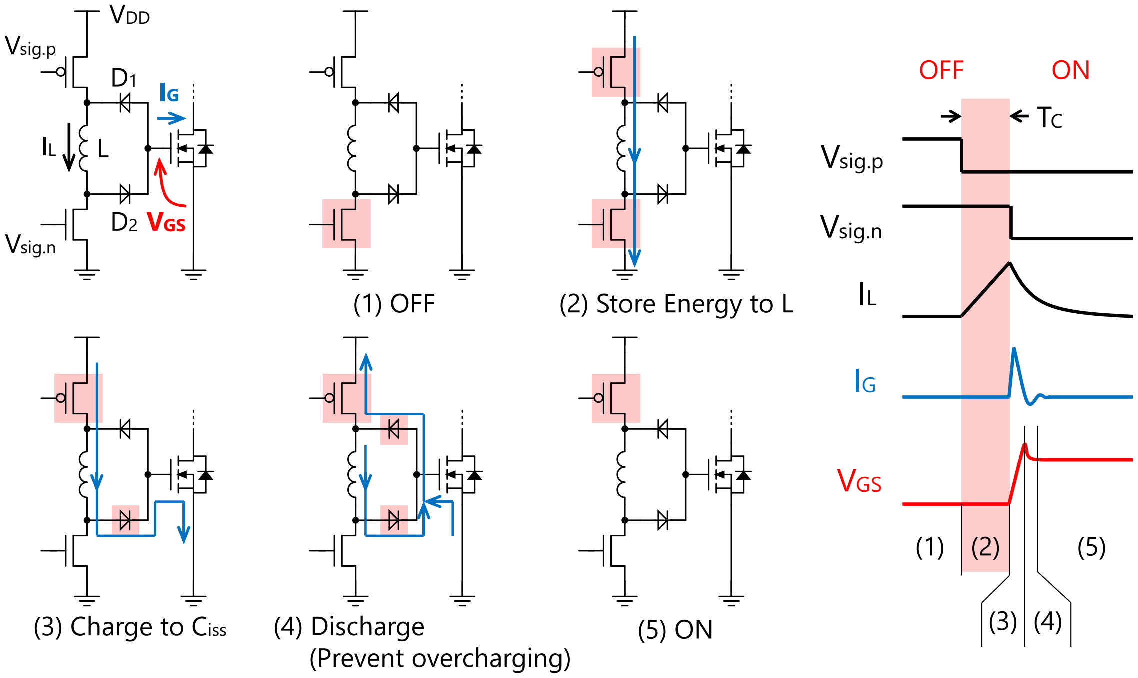


Fig. 4: Input and Output signals and of the proposed gate driver.

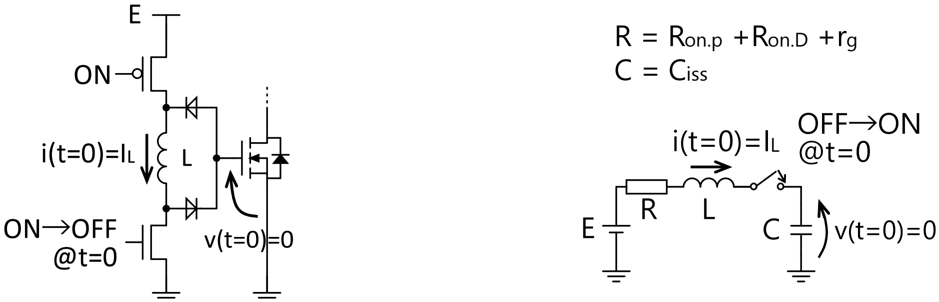
The proposed gate driver has several advantages over the conventional ones. The proposed gate driver has higher speed switching capability. The switching speed of turn-ON and turn-OFF can be controlled separately by $V_{\mathrm{sig.n}}$ and $V_{\mathrm{sig.p}}$ The high driving capability of MOSFETs before the last stage is not required because switching speed of the proposed gate driver depends on stored energy in the inductor.

Switching transient operation

Fig. 5 (b) shows the equivalent circuit of the proposed gate driver. It is the RLC series resonant circuit[10]. The transient characteristics of the proposed gate driver can be replaced by the step response of the resonant circuit with the initial current I_{L}. The behavior of current and voltage during turn-on transient can be expressed as in Eq. (1) and (2).

$$i(t) = I_{\mathrm{L}}\mathrm{e}^{-at}\cos\omega t + \frac{E - RI_{\mathrm{L}}/2}{\omega L}\mathrm{e}^{-at}\sin\omega t \tag{1}$$

$$v(t) = E\left(1 - \mathrm{e}^{-at}\cos\omega t\right) + K\mathrm{e}^{-at}\sin\omega t \qquad \left(a = \frac{R}{2L}, \omega = \frac{1}{LC} - a^2, K = \frac{2LI_{\mathrm{L}} - RCE}{2\omega LC}\right) \tag{2}$$



(a) The proposed gate driver.

(b) The equivalent circuit.

Fig. 5: The equivalent circuit of the proposed gate driver.

Fig. 6 shows the calculated $i(t)$ and $v(t)$ curves. The rectifying action of the diode is not considered. The diode is replaced by a resistor $R_{\mathrm{on.D}} = 1.0\ \Omega$. The driven MOSFET is SCT2450KE which has internal gate resistance of $r_{\mathrm{G}} = 25\ \Omega$ and input capacitance of $C_{\mathrm{iss}} = 463$ pF. The time constant of the conventional gate driver, replaced with an RC series circuit, is 17 ns. The time constant of the proposed one is 4.2 ns. The proposed circuit is 4x faster than conventional one due to large peak gate current. Decreasing the inductance and increasing the charge time make switching faster.

Measurement and Results

Measurement Setups

The transient characteristics of the conventional and proposed gate drivers are measured by the Double Pulse Test which is a measurement method for power devices[11]. Drain current I_{D} can be estimated by the width of the first pulse. Switching characteristics are evaluated. Fig. 7 shows the circuit to measure switching characteristics by the Double Pulse Test. Fig. 8 shows the photograph of the PCB. Fig. 9 shows the definition of switching parameters.

The isolated dual gate driver IC Si8235 (Silicon Labs.) is used. DUT is SiC MOSFET SCT2450KE (ROHM) which has 1,200 V breakdown-voltage. Gate resistance R_{G} of the conventional gate driver is 1.0 Ω . The inductance L of the proposed gate driver is 79 nH. The charge time of the inductor T_{c} is 20 ns.

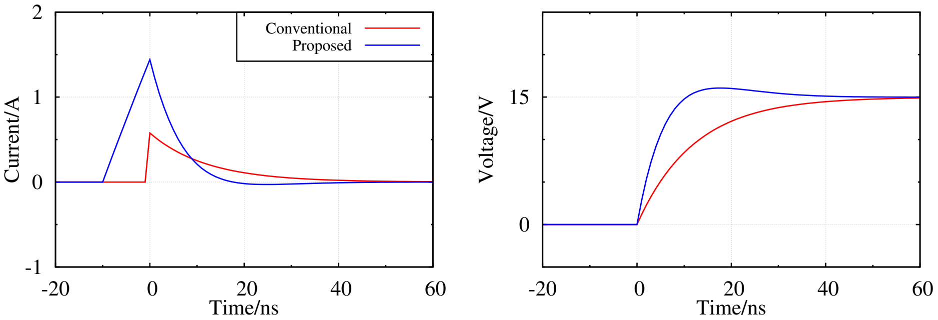


Fig. 6: Calculated $i(t)$ and $v(t)$ curve.

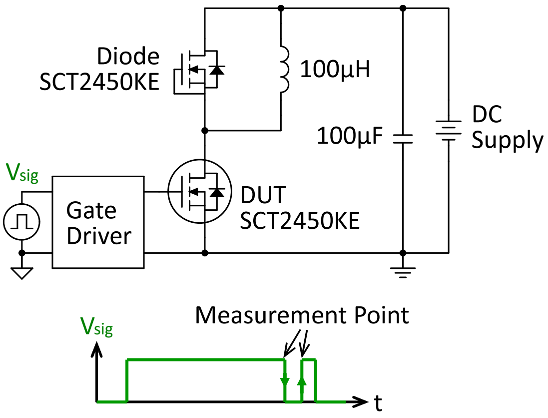


Fig. 7: Circuit to measure switching characteristics by the Double Pulse Test.

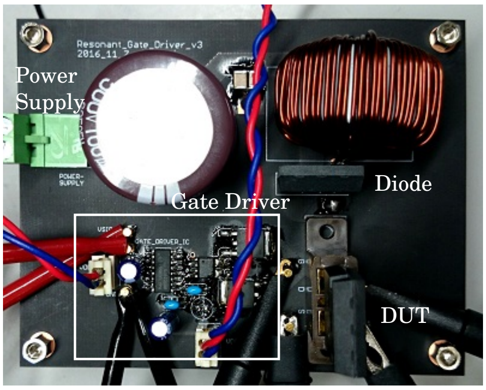


Fig. 8: Photograph of the PCB.

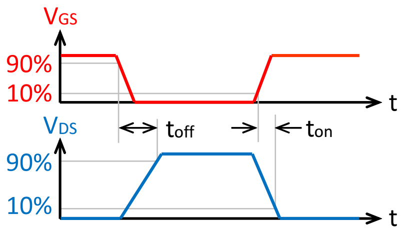


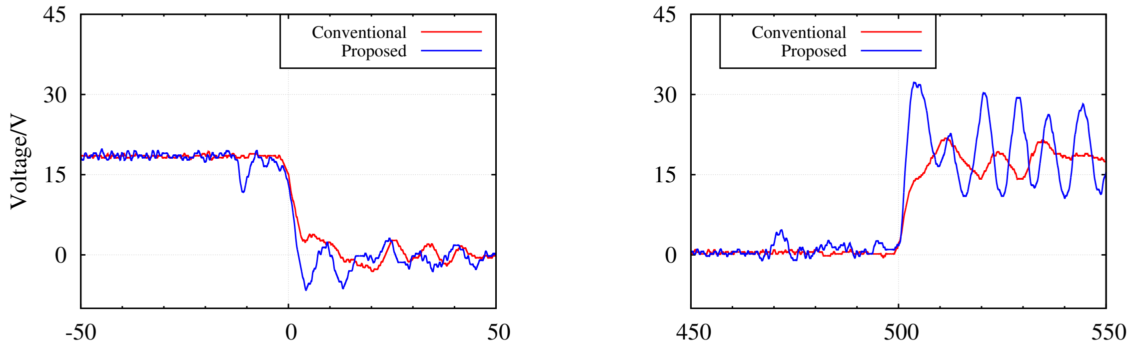
Fig. 9: Definition of the switching parameters.

Results

Fig. 10 and 11 shows the measurement results of the transient characteristics. V_{GS} of the proposed gate driver rises and falls faster than the conventional one due to larger peak gate current. Since the channel is formed fast, the delay time from V_{GS} rising/falling to V_{DS} falling/rising is shorter.

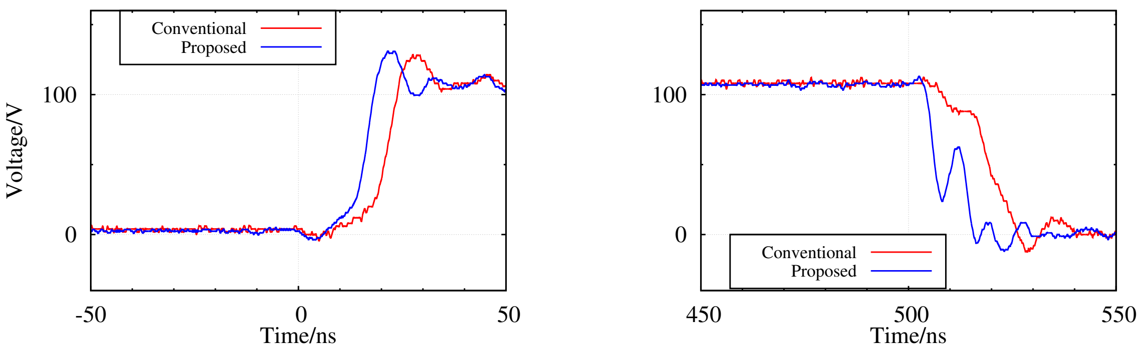
Delay time $t_{\mathrm{d\_off}}$ and $t_{\mathrm{d\_on}}$ of the conventional gate driver are 19.7 ns and 16.8 ns. $t_{\mathrm{d\_off}}$ and $t_{\mathrm{d\_on}}$ of the proposed gate driver are 15.1 ns and 5.0 ns. Delay time of the proposed gate driver $t_{\mathrm{d\_off}}$ and $t_{\mathrm{d\_on}}$ are both 77% and 30% of the conventional one.

Switching time t_{off} and t_{on} of the conventional gate driver are 23.7 ns and 24.7 ns. t_{off} and t_{on} of the proposed gate driver are 18.6 ns and 16.7 ns. Switching time of the proposed gate driver t_{off} and t_{on} are both 75% and 75% of the conventional one.



(a) Turn-OFF transient. (b) Turn-ON transient.

Fig. 10: Measured V_{GS} waveform.



(a) Turn-OFF transient. (b) Turn-ON transient.

Fig. 11: Measured V_{DS} waveform.

V_{GS} ringing of the proposed gate driver is larger. This is due to that V_{GS} falls/rises fast and the current flows through the mirror capacitance is large because V_{DS} rises/falls fast. However, since this ringing is temporary as shown in Fig. 12, it is not a fatal problem.

Fig. 13 shows the switching characteristics of drain current I_D. Power supply voltage is 100 V. The proposed gate driver always drives SiC MOSFET faster than the conventional one. Switching time of the proposed gate driver t_{off} and t_{on} are 80% and 68% of the conventional one on average respectively.

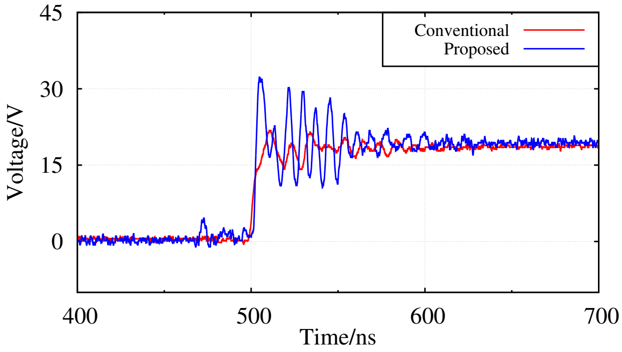


Fig. 12: Measured V_{GS} waveform at Turn-ON transient.

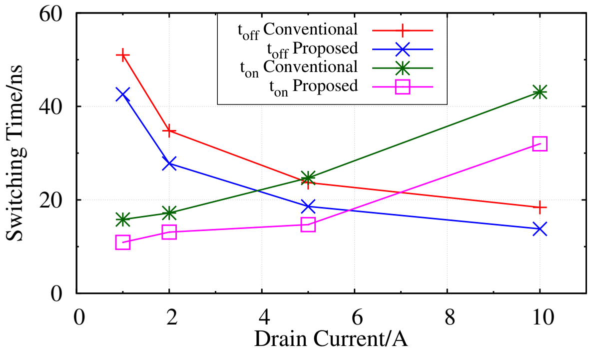


Fig. 13: Switching characteristics of the proposed gate driver

Conclusion

We propose a MHz-switching-speed gate driver for SiC MOSFETs . The inductor in the proposed gate driver behaves a current source during switching transient. Compared with the conventional gate driver, the proposed gate driver has capability to reduce switching time due to large peak gate current. The proposed gate driver improves t_{off} and t_{on} to 80% and 68% respectively .

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