

Current Measurement of GaN HEMTs Without Insertion Impedance and Unaffected by Magnetic Field Noise Using Two Optical Probe Electric Current Sensors

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Abstract—This paper proposes a current measurement method that precisely utilizes an ultra-low invasive current probe for high-speed switching GaN power devices. A conventional current measurement method using the Optical probe Electric Current Sensor (OpECS) offers advantages including a compact sensor head, a maximum bandwidth of 150 MHz, and no additional insertion impedance. However, it suffers from distorted current measurements due to background magnetic field noise. To address this issue, a new current measurement method employing two OpECSs is proposed. One OpECS measures the magnetic field generated by the target current, while the other detects the background magnetic field noise. The unwanted noise is then canceled by subtracting the two signals. The validity of the proposed method is demonstrated through double-pulse tests of GaN HEMTs, measuring overshoot currents during turn-on switching transitions at 200 V, 4 A and 400 V, 8 A.

Index Terms—current sensor, GaN HEMT, OpECS, switching evaluation.

I. INTRODUCTION

GaN HEMT power devices are being promoted for widespread application to achieve high efficiency and high power-density converters [1], [2]. Since GaN HEMTs exhibit fast switching transients, they are susceptible to oscillations caused by parasitic inductance, including that introduced for current measurement. Thus, the development of a new current measurement method with wide bandwidth, electrical insulation, and ease of implementation is significant challenge in evaluating the performance of GaN devices [3], [4].

Fig. 1 shows a schematic for implementation of current measurement methods and Table I lists a comparison table of current sensors for GaN drain current measurements. Conventional current measurement methods, such as shunt resistors [5] or Rogowski coils [6]–[9], require additional components and wiring on PCB boards for current sensing and probe clamping, which introduce extra impedance into

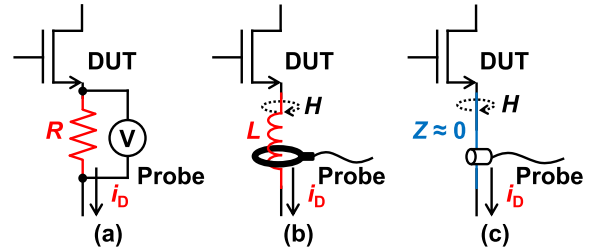


Fig. 1. Implementation of current measurement methods. (a) Shunt resistor, (b) Rogowski coil, and (c) OpECS.

the PCB layout. This insertion impedance can distort high-speed switching current waveforms, reduces measurement accuracy particularly in circuits with fast-switching transients. In addition, in non-isolated measurement methods such as shunt resistors, common-mode noise can be injected into the system, leading to increased noise and potential interference with circuit operation. Consequently, these methods are not suitable for current measurement in power devices, particularly in evaluations of current overshoot and switching losses in GaN devices.

The recently developed “Optical probe Electric Current Sensor (OpECS)” allows current measurement by simply placing the ultra-compact sensor head close to the conductor, eliminating the need for PCB modification for current sensor installation [10]. This method is one of the most promising techniques for measuring the current of high-speed switching devices because it introduces an ultra-minimally invasive impedance into the current conductors. [11].

However, unlike Rogowski coils, which are placed in a closed path to capture magnetic flux variations, the OpECS converts changes in the magnetic field on the conductor surface directly into a voltage, making it susceptible to background magnetic fields, resulting in the current including error is captured. The analysis of turn-on switching of power semi-

TABLE I
COMPARISON OF CURRENT SENSORS FOR GAN DRAIN CURRENT MEASUREMENT

Reference	[5]	[6]	[7]	[8]	[9]	[10]	This work
Operating principle	Shunt resistor	Rogowski coil	Rogowski coil	Rogowski coil	Rogowski coil	Faraday effect	Faraday effect
Sensor head size	72 mm × 18 mm × 18 mm	8 mm × 3.5 mm × 0.8 mm	10 mm × 3.2 mm × 0.6 mm	13.3 mm × 4 mm × 1.6 mm	25 mm × 25 mm × 1.0 mm	1 mm × 0.45 mm × 0.45 mm	1 mm × 0.45 mm × 0.45 mm
Max bandwidth	2 GHz	1 GHz	110 MHz	480 MHz	30 MHz	150 MHz	150 MHz
Max current	N/A	20 A	N/A	30 A	120 A	140 A	140 A
Isolation	No	Yes	Yes	Yes	Yes	Yes	Yes
No additional insertion impedance	No	No	No	No	No	Yes	Yes
Unaffected by magnetic field noise	Yes	Yes	Yes	Yes	Yes	No	Yes
Commercially available	Yes	Yes	No	No	Yes	Yes	Yes

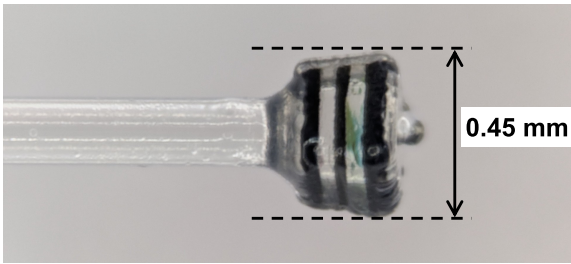


Fig. 2. Photo of OpECS sensor head.

conductor devices requires accurate measurements of losses and overshoot currents, thus the problem should be addressed.

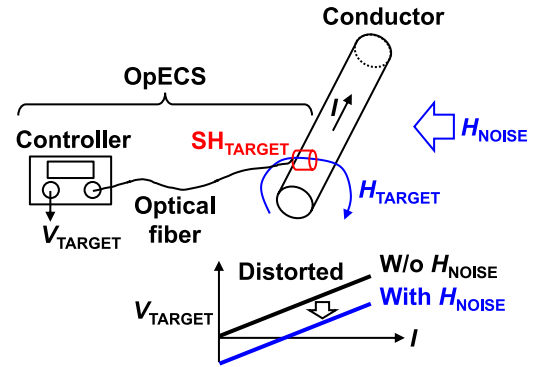
In this paper, OpECS is applied to a commercially available GaN HEMT half-bridge evaluation board, and it is shown for the first time by measurements that the drain current waveform of a GaN HEMT is distorted under the influence of magnetic field noise. To solve this problem, a drain current measurement method for GaN HEMTs using two OpECSs, which is not affected by magnetic field noise, is proposed. The proposed method is demonstrated in a double pulse test of GaN HEMTs at 200 V, 4 A and 400 V, 8 A turn-on switching transitions.

II. OPTICAL PROBE ELECTRIC CURRENT SENSOR (OPECS)

Fig. 2 shows a photo of the OpECS sensor head. The sensor head, with a size of 1 mm × 0.45 mm × 0.45 mm [10], has a probe structure developed based on the Faraday effect, which captures changes in magnetic fields caused by currents in a non-contact manner [12]. The voltage obtained through the Faraday effect is transmitted via an optical fiber and an amplifier to an oscilloscope for measurement.

III. PROPOSED CURRENT MEASUREMENT METHOD USING TWO OPECSs

Fig. 3 shows a conventional current measurement method using OpECS. An OpECS measurement setup consists of a sensor head, an optical fiber, and a controller. As shown in Fig.



Optical probe Electric Current Sensor (OpECS)
Sensor head (SH)
Magnetic field (H)

Fig. 3. Conventional current measurement method using OpECS.

3, an ultra-compact sensor head (SH_{TARGET}) is placed close to the conductor where the current (I) to be measured flows. SH_{TARGET} converts the magnetic field (H_{TARGET}) generated by I into an optical output intensity based on the magneto-optic Faraday effect, and the controller converts the optical output intensity into the output voltage V_{TARGET} . As a result, V_{TARGET} that depends linearly on I is obtained. OpECS, however, has the problem that in the presence of background magnetic field noise (H_{NOISE}), V_{TARGET} is distorted, and I cannot be measured accurately.

To solve this problem, Fig. 4 shows the proposed current measurement method using two OpECSs. In addition to SH_{TARGET} , a sensor head for H_{NOISE} measurement (SH_{NOISE}) is installed at a distance d from SH_{TARGET} . H_{TARGET} is measured with SH_{TARGET} , H_{NOISE} is measured with SH_{NOISE} , and H_{NOISE} is cancelled by subtracting the two output voltages V_{TARGET} and V_{NOISE} . Therefore, the proposed method can measure I without the influence of H_{NOISE} .

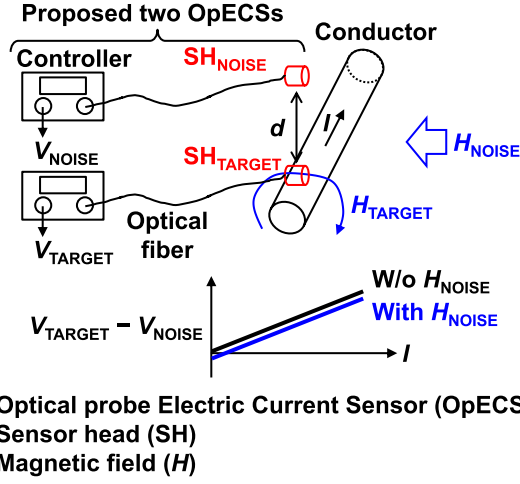


Fig. 4. Proposed current measurement method using two OpECSs.

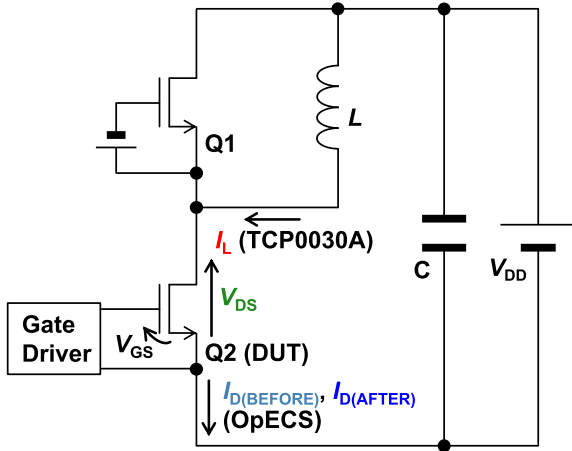


Fig. 5. Circuit schematic of double pulse test.

IV. EXPERIMENTAL SETUP

Fig. 5 shows a circuit schematic of the double pulse test. The half-bridge circuit is obtained from commercially available Infineon's evaluation board (450 V, 12 A rated) [13]. The GaN HEMTs Q1 and Q2 are implemented from Infineon IGOT60R070D1 (600 V, 60 A rated) [14].

Table II lists measurement probes used in this experiment. The inductor current (I_L) measured with a hall sensor probe (TCP0030A) is used as a reference to calibrate the amplitude of V_{TARGET} and V_{NOISE} measured by OpECSs to the drain current $I_{D(BEFORE)}$ and $I_{D(AFTER)}$, where $I_{D(BEFORE)}$ is the drain current measured by the conventional method using only V_{TARGET} in Fig. 3 and $I_{D(AFTER)}$ is the drain current measured by the proposed method using V_{TARGET} and V_{NOISE} shown in Fig. 4.

Figs. 6 and 7 show photos of the experimental setup. The evaluation board is fixed with a fixture, and the positions of the two sensor heads of OpECSs are precisely controlled by two positioners while viewing them with a camera. These jigs are necessary to prevent sensing errors due to positional deviation.

TABLE II
MEASUREMENT PROBES

Measurement point	Probe	Type
V_{DS}	Tektronix TPP0850	Passive
V_{GS}	Tektronix TPP1000	Passive
I_L	Tektronix TCP0030A	Hall sensor
$I_{D(BEFORE)}$, $I_{D(AFTER)}$	Citizen OpECS (Horizontal type)	Faraday effect

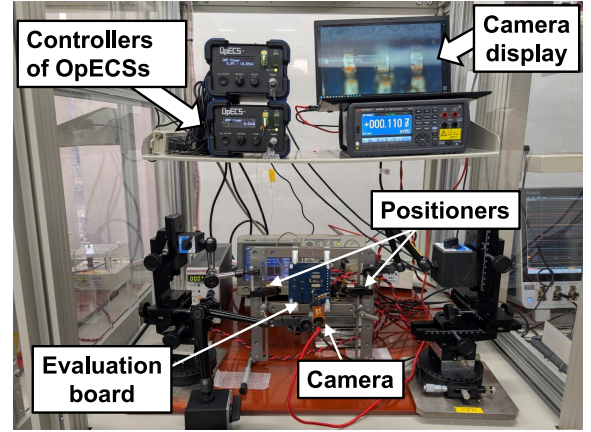


Fig. 6. Overview of experimental setup.

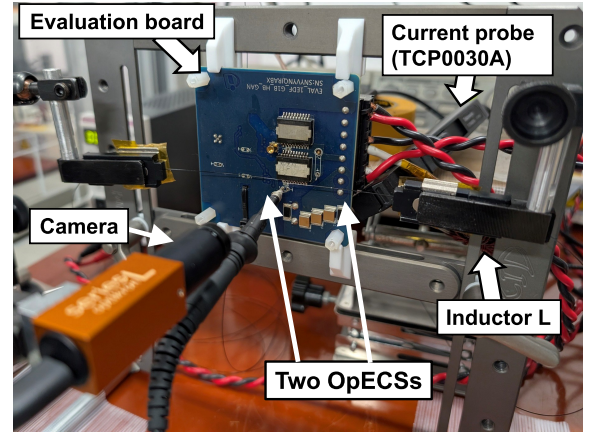


Fig. 7. Detailed setup for two OpECSs.

Figs. 8 and 9 show photos of the installation of two sensor heads of OpECSs. This GaN HEMT package has seven pins (each pin is 0.4 mm width) in parallel as source terminals. Of the seven pins, SH_{TARGET} is placed in contact with the leftmost pin, as shown in Fig. 8, and SH_{NOISE} is placed $d = 3$ mm above and away from SH_{TARGET}, as shown in Fig. 9. V_{TARGET} of SH_{TARGET} in Fig. 3 is calibrated to $I_{D(BEFORE)}$ using I_L waveform in first turn-on period of the

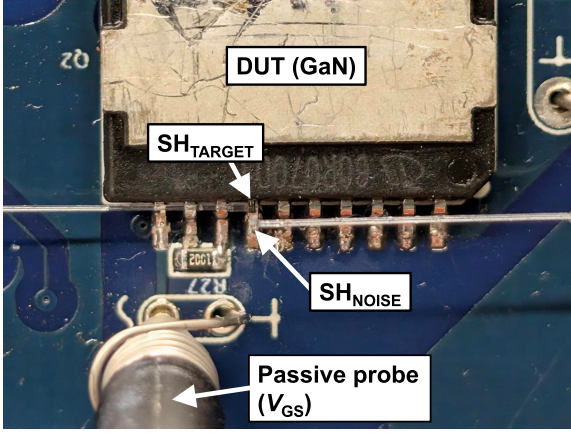


Fig. 8. Two sensor heads of OpECS positioned on DUT.

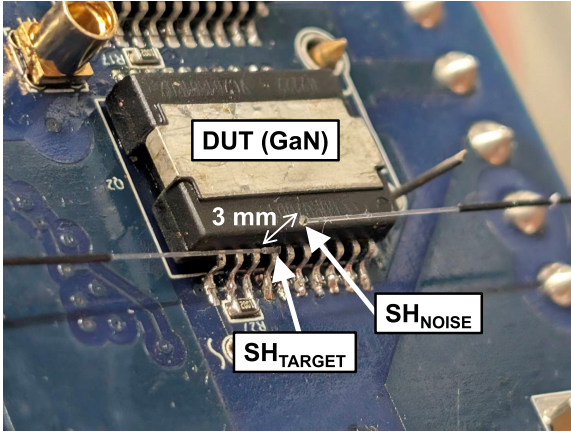


Fig. 9. Diagonal view of SH_NOISE position.

double pulse test as follows;

$$I_{D(BEFORE)} = A_{BEFORE} (V_{TARGET} - V_{OFFSET}) \quad (1)$$

where V_{OFFSET} is offset voltage of the controller and A_{BEFORE} is a parameter for amplitude calibration.

In the proposed current measurement method, to cancel H_{NOISE} , V_{TARGET} and V_{NOISE} in Fig. 4 are calibrated to $I_{D(AFTER)}$ using I_L waveform in first turn-on period of the double pulse test as follows;

$$I_{D(AFTER)} = A_{AFTER1} (V_{TARGET} - V_{OFFSET1}) - A_{AFTER2} (V_{NOISE} - V_{OFFSET2}) \quad (2)$$

where A_{AFTER1} and A_{AFTER2} are parameters for amplitude calibration, and $V_{OFFSET1}$ and $V_{OFFSET2}$ are offset voltages of the controllers.

V. EXPERIMENTAL RESULTS

Figs. 10 (a) and (b) show measured waveforms of the double pulse test at input voltage $V_{DD} = 200$ V, drain current $I_D = 4$ A and $V_{DD} = 400$ V, $I_D = 8$ A, respectively. Calibration from V_{TARGET} and V_{NOISE} to $I_{D(BEFORE)}$ and $I_{D(AFTER)}$

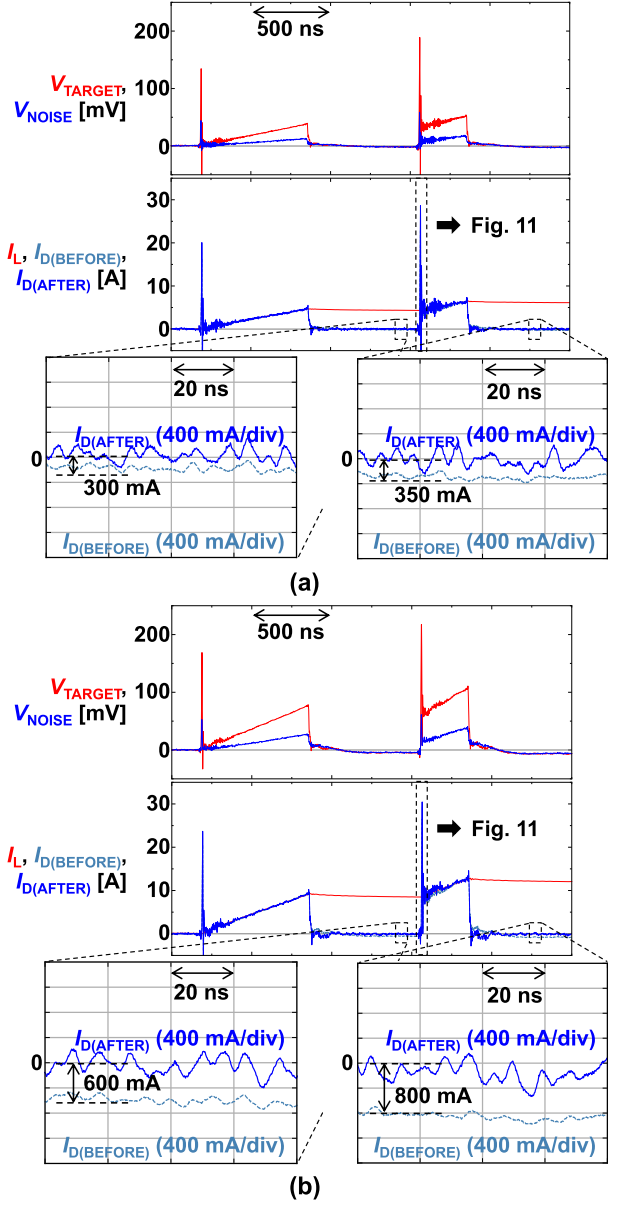


Fig. 10. Measured waveforms of double pulse test using OpECSs. (a) $V_{DD} = 200$ V, $I_D = 4$ A and (b) $V_{DD} = 400$ V, $I_D = 8$ A.

are performed based on (1) and (2). To quantitatively discuss the current measurement error of the conventional and proposed methods, Fig. 10 also shows magnified views of the measured waveforms of $I_{D(BEFORE)}$ and $I_{D(AFTER)}$ with Q2 off. Regarding a measurement result of $V_{DD} = 400$ V, $I_D = 8$ A in Fig. 10 (b), in the conventional method shown as $I_{D(BEFORE)}$, the current measurement errors during the first and second off periods were around 600 mA and 800 mA, respectively. 600 mA corresponds to a 7.5% ($= 600 \text{ mA} / 8 \text{ A}$) error. This error is caused by H_{NOISE} generated by the reverse current in a high-side GaN HEMT Q1 and an inductor L in Fig. 6. In contrast, in the proposed method shown as $I_{D(AFTER)}$, the current measurement error is almost zero.

Figs. 11 (a) and (b) show measured waveforms during a

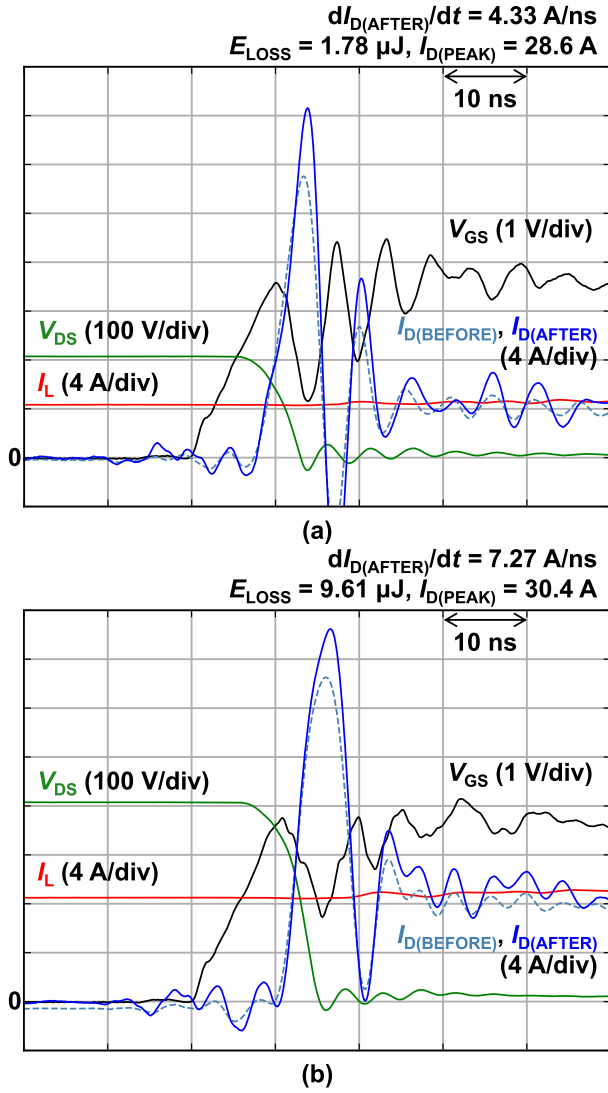


Fig. 11. Measured waveforms during turn-on switching transient. (a) $V_{DD} = 200$ V, $I_D = 4$ A and (b) $V_{DD} = 400$ V, $I_D = 8$ A.

turn-on transient at $V_{DD} = 200$ V, $I_D = 4$ A and $V_{DD} = 400$ V, $I_D = 8$ A, respectively, which are enlarged views of a portion of Figs. 10 (a) and (b). Regarding a measurement result of $V_{DD} = 400$ V, $I_D = 8$ A in Fig. 11 (b), the current overshoot was observed with a peak drain current $I_{D(PEAK)} = 30.4$ A, a switching speed $dI_{D(AFTER)}/dt = 7.27$ A/ns, and a switching loss $E_{LOSS} = 9.61$ μ J. The results demonstrate sufficient measurement performance for a fast current transient response. These findings suggest that OpECS is useful for analyzing switching losses and current overshoot in fast-switching GaN HEMTs.

VI. CONCLUSION

This paper proposed a current measurement method using the OpECS under the condition of background magnetic fields. As shown in Table I, for fast switching GaN HEMTs, a current measurement method using two OpECSs was proposed that had high bandwidth (150 MHz), no additional insertion

impedance, and was not affected by background magnetic field noise. The proposed method canceled the influence of the background magnetic field noise on the measured current by using two probes, one for the target and the other for the noise. In the 400 V, 8 A double pulse test using commercially available GaN HEMT half-bridge evaluation board, the measured current error was improved by 7.5% and the drain current switching with a fast turn-on speed up to 7.27 A/ns was measured without additional insertion impedance. The proposed method is suitable for the analysis of switching loss and current overshoot of GaN HEMTs.

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