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Online junction temperature measurement of Power MOSFET by dynamic V_{GS}-I_D monitoring system

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Abstract As the demand for high reliability in power electronics systems increases, the online condition monitoring of power devices is becoming crucial. The junction temperature is a vital indicator of the reliability and health of the power semiconductor devices. Therefore, we developed a novel junction temperature measurement method via dynamic threshold voltage. The proposed method uses a specially designed PCB sensor for detecting a drain current and captures the dynamic gate-source voltage at predetermined drain current levels. The analog circuit was designed and experimentally verified by a double pulse test. A 16-bit ADC embedded in the microcontroller is utilized to digitize the captured voltage to demonstrate the monitoring system. The temperature sensitivity of the Power MOSFET was -2.2 mV/°C and was unaffected by the high side device temperature.

Keywords MOSFET, Temperature measurement, Temperature monitoring, TSEP, Threshold voltage, Rogowski coil, PCB current sensor

1. Introduction

Power electronics systems are a rapidly growing technology and are widely used in various applications [1]. They can be found in renewable energy systems, automotive, electric vehicles (EV), and industrial drives. These systems are frequently required to operate under harsh conditions, which demands a high priority on safety and reliability.

Power semiconductor devices are one of the most crucial components in a power system. And they are also the most fragile component of the system [2]. The performance and reliability of power semiconductor devices strongly depend on junction temperature and temperature swings. The junction temperature can be a critical indicator of power device health. Therefore, temperature monitoring of power devices during normal operation is essential for condition monitoring systems [3]. However, the junction temperature measurement is difficult to achieve. Especially measuring in real-time during power device normal operation is quite challenging. Thus, practically applicable methods for measuring junction temperature have been investigated extensively in the last decade. For example, the challenges to extracting junction temperature by measuring a change of polysilicon gate resistance [4] and dynamic threshold voltage using Kelvin terminal [5] have been reported.

Promising approaches for junction temperature estimation are temperature-sensitive electrical parameters (TSEP) [6]. Multiple studies have been conducted on TSEP-based online junction temperature measurement methods [7,8,9]. Generally, these methods use three basic properties: the V-I relationship, the internal gate resistance, and the threshold voltage. The limitation of the conventional methods is that systems are designed based only on measuring voltages between terminals of the devices. Furthermore, some of those are not practical for monitoring devices under operation in the system such as EVs or industrial drives.

The gate threshold voltage is suitable to use as a temperature sensitive electrical parameter (TSEP), due to its high-temperature sensitivity, and good linear relationship with the junction temperature. This study proposes a novel dynamic threshold voltage measurement method to demonstrate a practically applicable, non-invasive, accurate, and low-cost online junction temperature monitoring system for Power MOSFET. The proposed V_{GS}-I_D monitoring system [10] includes a drain current measuring function using a newly designed PCB-based current sensor to improve the accuracy and scalability for future monitoring requirements.

2. Concept of dynamic V_{GS}-I_D monitoring system

2.1. Dynamic gate-source voltage

Figure 1 illustrates an equivalent circuit for a gate loop and the corresponding modeled gate turn-on waveform. After analyzing this equivalent gate loop circuit, a straightforward equation (1) can be obtained for extracting threshold voltage change and other useful parameters.

$$V_{gs}^{m}(I_s) = \frac{(V_{swing} - V_{step})(V_{gs}(I_s) + V_{L_S}) + V_{step} V_{GG}}{V_{swing}} \qquad (1)$$

$$V_{swing} = V_{GG} - V_{EE} \qquad V_{L_s} = L_s \frac{dI_s}{dt} = const$$

In this present study, the measurement of gate voltage $V_{gs}^{m}(I_s)$ at a predetermined source (drain) current I_S level

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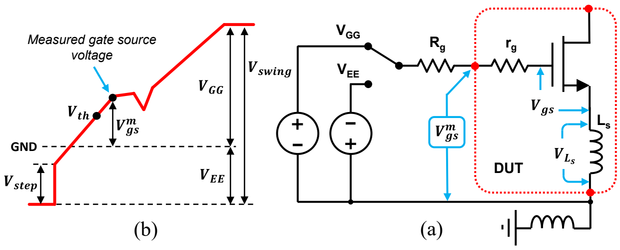

Fig. 1. (a) Equivalent gate loop circuit. (b) Corresponding gate voltage waveform during turn-on.

is demonstrated during the turn-on switching transient of the power device. In the demonstration, we introduced a specially designed PCB current sensor for measuring the drain current.

2.2. Dynamic V_{GS}-I_D measurement method

The dynamic V_{GS}-I_D monitoring method simultaneously captures the gate-source voltage and drain current during the dynamic turn-on transition of Power MOSFET. For this, a printed circuit board (PCB) based Rogowski coil with a fishbone pattern [11] is utilized to detect the rapidly rising drain current and trigger the dynamic gate-source voltage capturing operation.

There are several advantages to using a PCB current sensor (Rogowski coil) in our proposed method. It includes: PCB-based Rogowski coil is small, thin, and low cost; it can respond very quickly to the change of current, making it suitable for high-speed triggering; the system safety is greatly improved by fully isolating the low voltage measurement circuit from the high voltage devices circuit; gate-source voltage capturing is triggered by the drain current (not voltage drop on stray inductance), consequently no particular prerequisites on the power device packages and terminals (Kelvin terminal not required); the drain current corresponding to the measured threshold voltage is known; gate-source voltage can be measured at a different drain current level by controlling reference current which gives the possibility to improve the accuracy and scalability for future monitoring necessities.

The block diagram of the proposed system is shown in Fig. 2, which can be divided into an analog measurement circuit, an analog-to-digital converter (ADC), and a digital control unit. The analog measurement circuit consists of a differential amplifier connected to a sample-hold amplifier to measure the gate-source terminal voltage, and a PCB current sensor with an integrator to trigger the sample-hold amplifier to capture the dynamic gate threshold voltage. The captured output voltage will be converted into a digital signal using an ADC. The digital control unit provides a reset signal for the integrator circuit and PWM pulses for the gate driving circuit.

An illustration of waveforms and their inter-timing relation is shown in Fig. 3. First, the digital control circuit generates the *PWM* pulse, and the gate-source voltage V_{GS}' will rise and reaches the threshold voltage V_{TH} shortly, and then the drain current begins to flow. As a result, the integrator voltage increases in proportion to the drain current as it integrates the PCB current sensor pulse. Once the integrator output voltage V_{INT} exceeds the reference voltage, then the comparator output *Trig* signal is changed to logic low which triggers the sample-hold amplifier. The sample-hold amplifier will capture and hold the dynamic threshold voltage, and ADC digitize the V_{OUT}. It is possible for ADC to take multiple samples during a single switching period. Digitized binary results can be further processed using digital signal processing techniques.

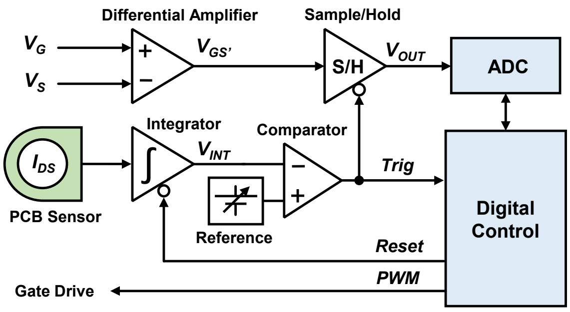

Fig. 2. Block diagram of the proposed method

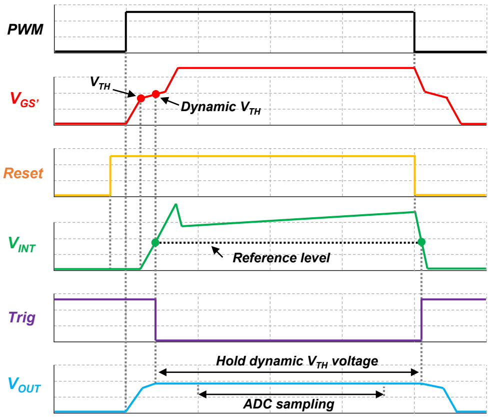

Fig. 3. Timing relation of the signal waveforms.

3. Experimental setup

The circuit implementation of the dynamic V_{GS}-I_D monitoring system consists of an analog measurement circuit (Fig. 4.b) and a real-time microcontroller unit (Fig. 4.c) to realize the proposed method. And an additional device under test (DUT) circuit (Fig. 4.a) for verifying the operation of the monitoring system.

3.1. Analog measurement circuit

Implementation of the analog measurement circuit is mainly constructed from high-speed, but low-cost integrated circuits (U1, U3, and U4 are inexpensive, an exception is U2) as shown in Fig. 4b. For the input, a pair of compensated voltage dividers attenuate the gate and source terminal voltage by a factor of ten to simplify interfacing with low voltage integrated circuits. A high-

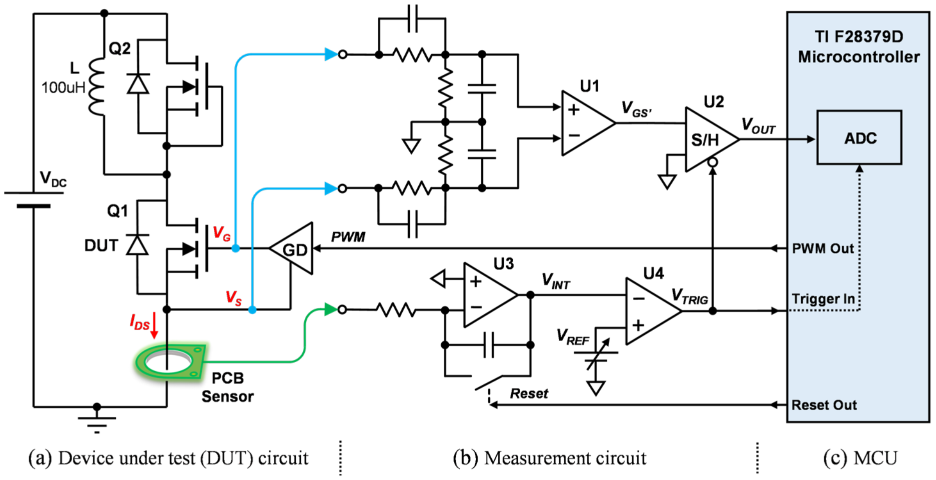

Fig. 4. Complete experimental setup for V_{GS}-I_D monitoring system. DUT circuit (a), analog measurement circuit (b), and microcontroller unit (c).

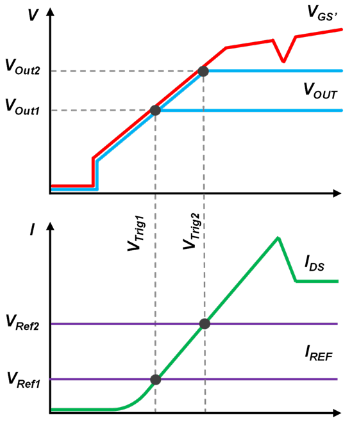

Fig. 5. Dynamic gate voltage capturing at different reference current level.

speed differential amplifier (U1) AD8130 from Analog Devices is chosen to calculate the difference between the gate and source terminal voltages. An integrator circuit is based on a high-speed operational amplifier (U3) and uses an analog switch for discharging the feedback capacitor. A very fast, low propagation delay comparator (U4) compares the output voltage of the integrator to a reference voltage, which then generates a trigger signal for the AD783 sample-hold amplifier (U2), a high-speed, monolithic sample-hold amplifier from Analog Devices.

As mentioned earlier, the analog measurement circuit captures dynamic gate-source voltage at different drain current levels, illustrated in Fig. 5. For this function, the adjustable voltage regulator controls the reference level of the current. When the reference voltage is in the range of 100mV to 400mV, the corresponding reference current level is between 3.5A and 9.6A, at which dynamic gate-source voltage gets captured.

3.2. Microcontroller unit

The microcontroller unit (MCU) executes an analog-to-digital conversion, digital input/output interfacing, and storing the measurement data in the memory. We used a TI LaunchPad development board, which is equipped with a Texas Instruments TMS320F28379D high-performance 32-bit real-time microcontroller. The microcontroller generates a PWM control signal for the gate drive and a reset control signal for an integrator's analog switch. Also, an external interrupt input takes a trigger signal to initiate the analog-to-digital conversion.

The ADC embedded in the microcontroller is employed for digitizing the captured dynamic threshold voltage. The microcontroller has 16-bit, 1.1Mbps successive-approximation differential input ADC that can provide enough resolution for accurate measurement. The ADC has a full range of 3V and an LSB step of 45.77uV which is sufficient for sensing dynamic threshold voltage shift with 1°C temperature change.

3.3. Test setup

The proposed dynamic V_{GS}-I_D monitoring concept is verified by the double pulse switching test on a half-bridge Power MOSFET configuration with an inductive load. Fig. 4 displays complete schematics of the experimental setup that include a DUT circuit, analog measurement circuit, and microcontroller unit. In the verification circuit for the

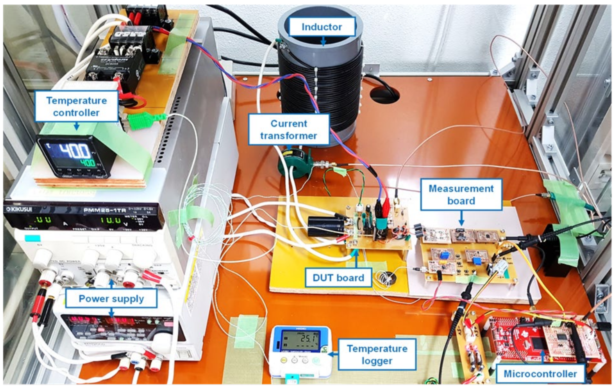

Fig. 6. Photograph of the experimental setup

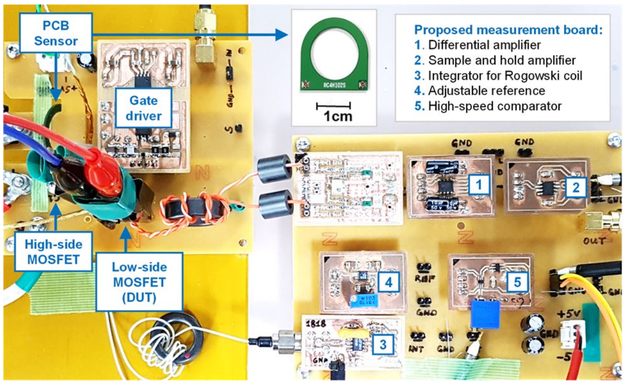

Fig. 7. Photograph of the measurement circuit boards.

double pulse test (Fig. 4a), we used Si Power MOSFET IRFP2907PbF from International Rectifier as a high side device (Q2) and low side DUT (Q1), 100uH load inductor (L), and 10Ω external gate resistor for gate drive.

Fig. 6 and 7 show the photograph of the experimental setup. Accurate temperature control of the device under test is essential to validate the dynamic threshold measurement circuit. A planar thin sheet heating element is placed on the backside of the TO-247 package to heat the DUT. A type-K thermocouple sensor is used for measuring the temperature of the device. PID-based digital temperature controller receives a signal from the thermocouple sensor and supplies the current to the heating element to achieve stable and precise temperature control.

4. Experimental results

The proposed dynamic threshold voltage measurement circuit based on the PCB current sensor was successfully implemented and verified by a double pulse test. The sample-hold amplifier output voltage V_{OUT} (dynamic V_{TH}) was successfully converted into digital binary bits using the ADC of the microcontroller. Therefore, the proposed monitoring system could capture and digitize dynamic V_{TH}, and acquired data is stored in the microcontroller memory. Furthermore, the oscilloscope is only required for verifying the circuit operation, because the dynamic V_{GS}-I_D monitoring system can work independently. Fig. 8 shows double pulse test waveforms of the analog measurement circuit under room temperature conditions. When the drain current measured by the PCB current sensor reached the predetermined current level of 5.5A, the gate-source voltage was captured by the sample-hold circuit.

The demonstrated sample-hold output voltages waveforms for different junction temperature conditions are shown in Fig. 9. Under the condition of V_{DC} = 30V, I_L = 20A, we increased the junction temperature from 28°C to 120°C (ΔT_J = 92°C), and measured dynamic V_{TH} was decreased by 21mV, the actual variation of the device threshold voltage was 210mV and the temperature coefficient of the DUT is found to be -2.2mV/°C. We heated the low side DUT and high side devices separately to see if the low side was affected by the high side temperature. Fig. 10 shows the temperature sensitivity of low side DUT with different high side device temperatures. It is confirmed that high side MOSFET temperature does not affect low side junction temperature measurement.

Also, the analog measurement circuit's operation under different DC-voltage and load current conditions was investigated. Fig. 11a shows obtained dynamic V_{TH} voltage as a function of junction temperature (T_J) for different DC-voltage of 20V, 30V, and 40V. The shift in digitized dynamic threshold voltage for different DC-voltage is due to the source stray inductance voltage V_{Ls} changes with different dI_D/dt caused by DC-voltage. Fig. 11b shows measured dynamic V_{TH} temperature sensitivity under different load currents, 10A, 20A, and 30A. The digitized output had a minor shift, but temperature sensitivity was not affected by the load current change. It is due to the drain-source current rate-of-change will be constant for different load currents as shown in Fig. 12a. Therefore, the source stray inductance voltage $L_S dI_D/dt$ will be constant at the trigger, under different load current conditions.

We studied temperature sensitivity at various reference

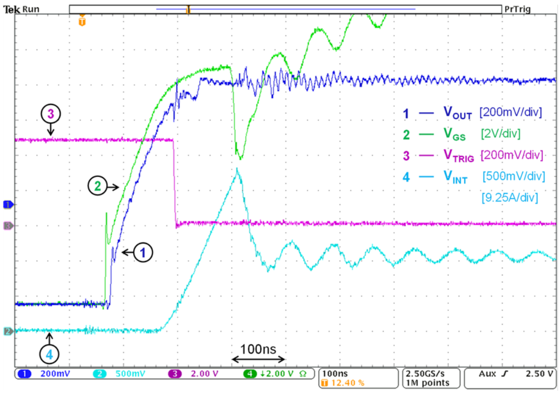

Fig. 8. Double pulse test waveforms of the measurement circuit at room temperature. The reference voltage set to 200mV, which result in reference current level of 5.5A.

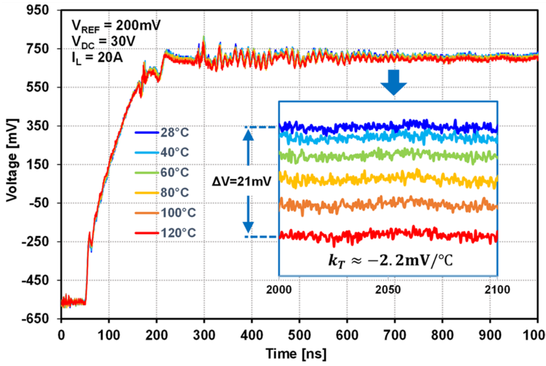

Fig. 9. Waveforms of dynamic gate threshold voltage dependence on temperature. Setup condition: V_{DC} = 30V, I_L = 20A, V_{REF} = 200mV → $I_{D(REF)}$ = 5.5A, R_{GEXT} = 10Ω

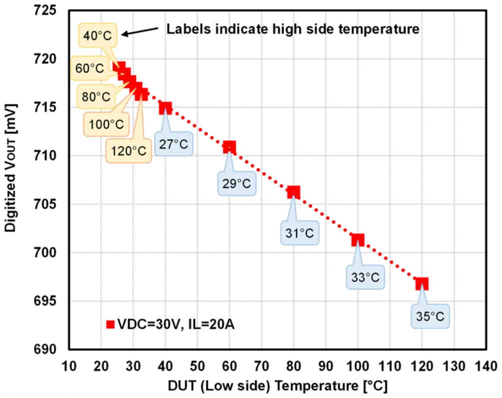

Fig. 10. Low side temperature sensitivity, including different high side temperature. Plotted from acquired ADC data. Setup condition: V_{DC} = 30V, I_L = 20A, V_{REF} = 200mV → $I_{D(REF)}$ = 5.5A, R_{GEXT} = 10Ω

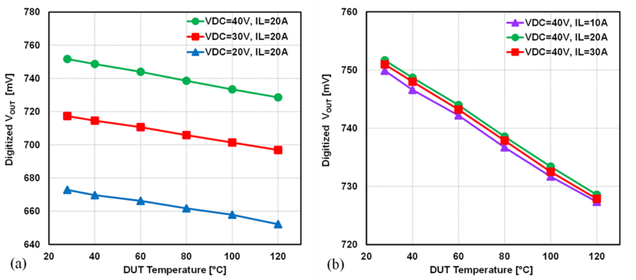

Fig. 11. Temperature sensitivity on DC-voltage (a) and load current (b). Both plotted from acquired ADC data. (V_{REF} = 200mV, R_{GEXT} = 10Ω)

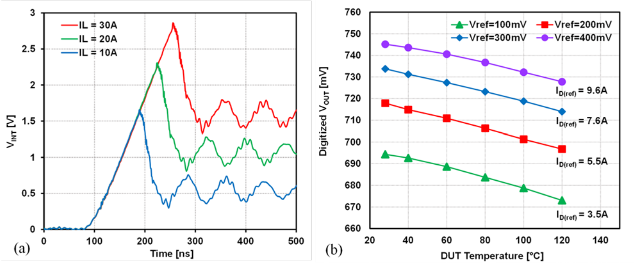

Fig. 12. The source current waveforms by the PCB current sensor with an integrator (a) (V_{DC}=30V) and temperature sensitivity at different reference current level that plotted from acquired ADC data (b) (V_{DC}=30V, I_L=20A).

current levels. Fig. 12b shows the results of capturing dynamic gate-source terminal voltage at different source current levels by controlling the reference voltage in the range between 100mV and 400mV. Under the conditions of V_{DC} = 30V, I_L = 20A, and V_{REF} = 100mV, the corresponding reference current level was 3.5A. Each 100mV increment of reference voltage resulted in an approximately 2A increase in the current level.

Fig. 13 shows the next step of the study. By implementing an adjustable time delay and current capturing function, the system can extract dI_D/dt to eliminate the influence of source inductance inside the package. With this function, the proposed method can be applied to high current power modules in combination with other condition monitoring systems such as V-I curve-based monitoring system [12].

5. Conclusion

This study proposed an electrical method for junction temperature extraction of the Power MOSFET. The main parameter of the approach is dynamic threshold voltage dependence on junction temperature. In this dynamic V_{GS}-I_D monitoring method, the dynamic gate-source voltage is measured at the predetermined drain current level during the turn-on process of the Power MOSFET, and the junction temperature is estimated using the measured voltage shift. A newly designed PCB-based Rogowski coil is introduced for the drain current measurement. The novelty of the proposed method is the use of this low-cost, tiny PCB current sensor and the full integration of its advantages into the system.

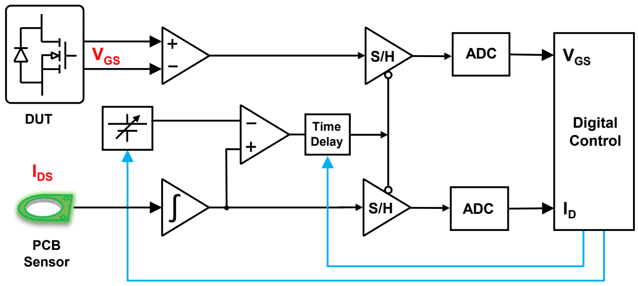

Fig. 13. Intended future improvement of V_{GS}-I_D monitoring system.

The complete dynamic V_{GS}-I_D monitoring system consisting of the analog measurement circuit and the microcontroller is developed to demonstrate the proposed method. The double pulse test results have shown that this system successfully monitors the junction temperature. Experimental results demonstrated good temperature sensitivity and a linear relationship with the device temperature. The measured temperature coefficient of the tested Power MOSFET was -2.2 mV/℃.

We confirmed that high side MOSFET temperature does not affect low side power device junction temperature. The monitoring system operation is accomplished without interrupting the normal operation of the DUT. Additionally, the method is independent of load current variation. Thus, it is advantageous to be used in junction temperature monitoring during the online operation of Power MOSFET.

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