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Tiny-scale “stealth” current sensor to probe power semiconductor device failure

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Abstract

“Stealthy” electric current probing technique for power electronics circuits, power device modules and chips makes it possible to measure electric current without any change or disassembling the circuit and the chip connection for the measurement. The technique consists of a tiny-scale magnetic-field coil, a high speed analog amplifier and a digitizer with numerical data processing. This technique can be applied to a single bonding wire current measurement inside IGBT modules, chip scale current redistribution measurement and current measurement for surface mount devices. The “stealth” current measurement can be utilized in the failure mechanism understanding of power devices including IGBT short circuit destruction.

1. Introduction

High density assembling with high switching frequency and high current density minimizes power electronics volume, which results in the extreme high power density and improves the mass-productivity of power electronics systems. The reduction in the size with the increase in frequency and current density requires novel measurement technique to probe the “real” electrical operation inside the circuit and system without disassembling the circuit for measurement. Because, for state-of-the-art high power density power electronics systems, the disassembling directly affects the operation of the circuit with increase in sub-nano-Henry level stray inductance. Specially for understanding of failure phenomena related to the assembling and wiring structure, such as short circuit and avalanche

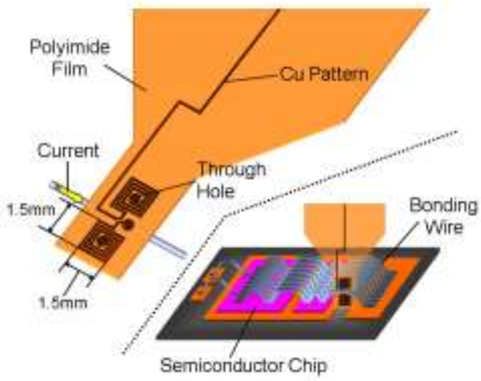

Fig. 1. The concept of “stealth” current measurement technique

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destruction of IGBT and power diode, the novel tiny-scale "stealth" current measurement technique is highly required (see Fig. 1). Real-time destruction measurement with the multiple tiny-scale "stealth" current sensors, for example, can provide new approach for failure analysis research by imaging current redistribution in the chip just before the device destruction.

The "stealth" current measurement technique proposed in this paper, utilizes 60μm thick polyimide film base printed coil with a small size of 1.5mm X 1.5mm which enables to insert the current probe between bonding wires on the power semiconductor chips or legs of the moulded package.

The Rogowski coil approach has been used to minimize the current probes [1,2,3,4,5,6]. Rogowski coils show substantial reduction in volume comparing to the conventional current transformer (CT). Rogowski coils, however, show the limitation in application to state-of-the-art high power density power electronics equipment and real-time power device destruction measurement because of the limitation in the size reduction.

This paper proposes a new approach consists of significantly tiny-scale coils printed on both sides of a polyimide film, a high speed analog amplifier and a digitizer with numerical calculation function, which realized further reduction of the coil size without affecting measurement performance comparing to the conventional CT or Rogowski coil.

2. "Stealth" current measurement technique

The proposed "stealth" current measurement technique with tiny-scale "stealth" current sensor realized the reduction in sensor size with the combination of new coil design and analog part design.

2.1. Coil design

As well known for the Rogowski coil design, the reduction in the coil size affects frequency response profile and signal level. In the new measurement setup design, the coil-field magnetic coupling and signal propagation through the co-axial cable connected the coil and the analog part are considered to maximize the accuracy and frequency performance.

The "stealth" current sensor is designed based on flexible polyimide film printed circuit technology (see Fig. 2).

The sensor has two pair of symmetrically placed flat spiral coils on both sides of a polyimide film and they are connected in series via through holes. The poles of coils are inverted so that the probe senses only close magnetic-field produced by the electric current passing between the coils. In other words, the "stealth" current sensor is hardly affected by external magnetic field with the reversed poles. The printed circuit technology improves the accuracy of the coil pattern and cost performance.

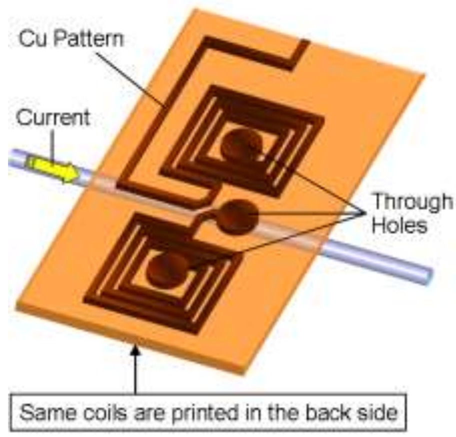


Fig. 2. The structure of "stealth" current sensor that is made by printed circuit technology.

2.1.1 Miniaturization Limit

The output signal is decreased with downsizing the sensor because of the scaling law. When the sensor signal isn't sufficient larger than noise signal, the sensor can't measure the current accurately. Therefore, if more downsized sensor is required, we have to increase the turn number of coil for maintaining the output voltage of the sensor much larger than noise signal (see Fig. 3). V_{min} is the minimum induced voltage that we can measure current accurately. As the coil's turn number is increased, the parasitic capacitance of coil is also increased and the sensor's high frequency characteristics become worse. For increase the turn number of coil together with the sensor's miniaturization, more advanced printed circuit board technology is also required.

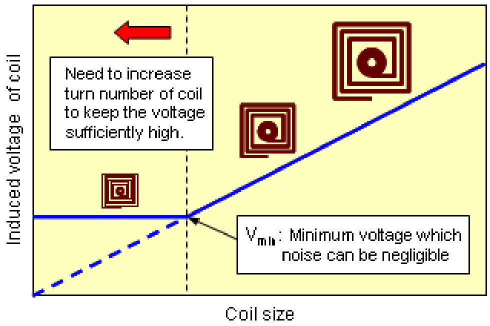


Fig. 3. The relationship of induced voltage and coil size.

2.2. Analog part design

Analog part design is one of the key issues since the tiny-scale coil output signal is weaker than conventional Rogowski coil. We established design method of amplifier, the coil and the co-axial cable taking the signal propagation along the cable. The frequency characteristics of this technique are shown in Fig. 4.

When magnetic-field coil is downsized, the gain spectrum just shifts to higher frequency region with the analog circuit optimization. In other words, the system has better characteristics for high frequency region with the optimum analog design and the gain is reduced in lower frequency region, which appears as droop in the measured waveform. We tried to solve the problem using active digital data processing.

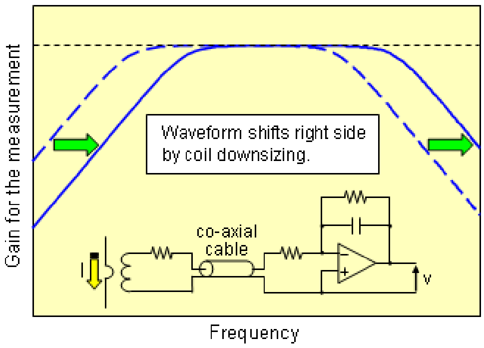


Fig. 4. The frequency characteristics of "stealth" current measurement technique.

2.3. Digital droop compensation

To solve the problem of droop, we propose digital droop compensation by active digital data processing (see Fig. 5). Using this technique, the droop is compensated. We assume incomplete integration with CR time constant for the op-amp feedback circuit and digitally calculate compensation factor in the second member in right hand side of Eq. 1.

$$I(t) \propto V(t) + \frac{1}{CR}\int V(t)\,dt \qquad (1)$$

Where $V(t)$, $I(t)$, C and R are the output voltage of the op-amp, electric current to be measured, the feedback capacitance and resistance.

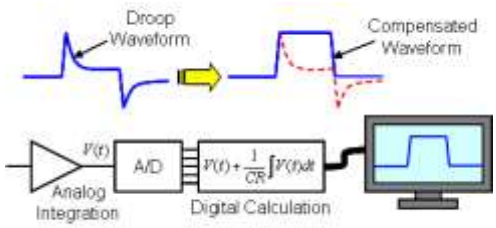


Fig. 5. Digital droop compensation of "stealth" current measurement technique.

2.4. Future possibility of "stealth" current sensor

A small sensor or built-in the sensor on the power device chip by using semiconductor technology will effectively measure the chip current density distribution. Therefore, the "stealth" current sensor has the possibility of utilizing for the current density distribution on the power device surface.

3. Demonstration with 1.5mm X 1.5mm coil

We demonstrate the "stealth" current measurement technique with the 60μm thick polyimide film base printed coil with a small size of 1.5mm X 1.5mm (see Fig. 6). The experimental setup is shown in Fig. 7. We compared the experimental result of the "stealth" current sensor with the widely used current sensor CT (Fig. 8). The measured waveforms agreed very well. Thus, the "stealth" current sensor has sufficient accuracy the same as the conventional CT.

The IGBT short circuit current measurement results with "stealth" current sensor and CT also agreed very well (see Fig. 9). Therefore, the sensor can apply for the failure mechanism analysis of power device short circuit destruction.

The accuracy of current measurement with "stealth" current sensor is affected by the positional relationship between the sensor and measured wire.

To measure current accurately, we have to set the central of the sensor on the current pass.

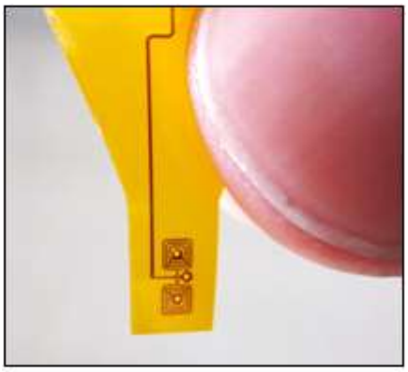
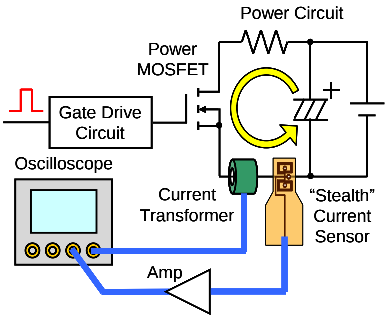
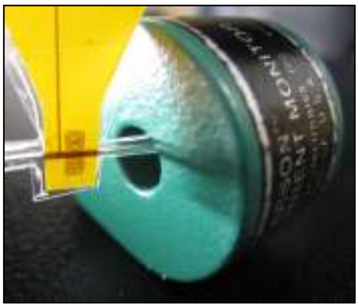


Fig. 6. Tiny-scale "stealth" current sensor with the 1.5mm X 1.5mm coil on 60μm thick polyimide film.

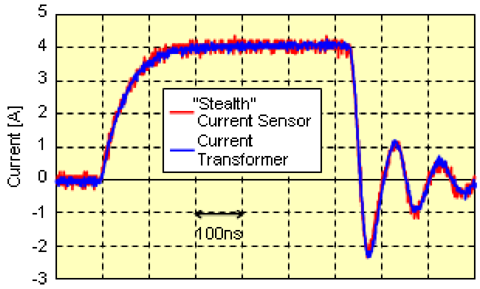


(a)

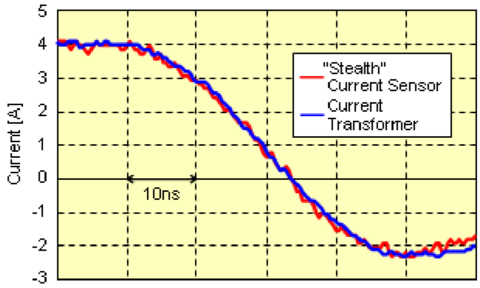


(b)

Fig. 7. (a) Experimental setup. (b) The measurement point by "stealth" current sensor and CT.



(a)



(b)

Fig. 8. (a) The comparison of current measurement result by "stealth" current sensor and CT. The size of coil is 1.5mm X 1.5mm. (b) The falling edge of current waveform.

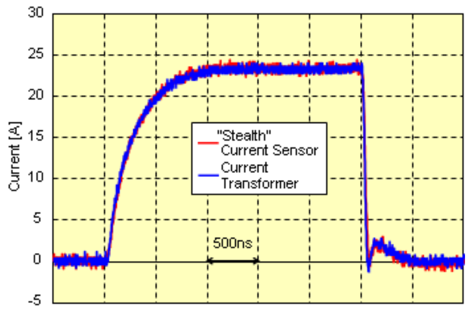


Fig. 9. IGBT short circuit current measurement by "stealth" current sensor and CT.

3.1. Demonstration of digital droop compensation

We also demonstrate digital droop compensation. Digital calculation with Eq. 1 successfully compensated the droop waveform and experimentally confirmed by comparing the measurement result with CT (see Fig. 10).

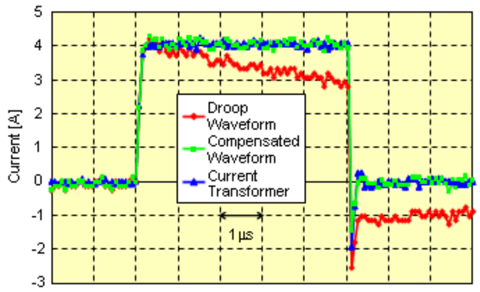


Fig. 10. The digital droop compensation result of droop current waveform measured by “stealth” current sensor and the result comparison with CT.

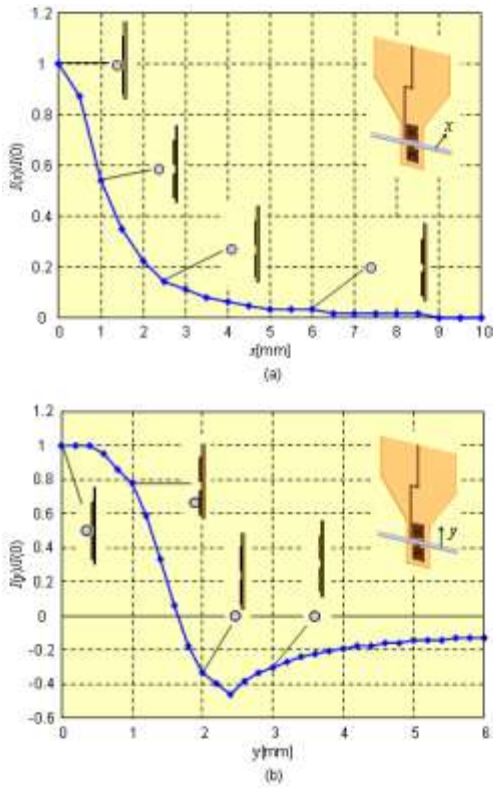


Fig. 11. (a) Change of current when the “stealth” current sensor is moved to horizontal direction. (b) Change of the current when the “stealth” current sensor is moved to vertical direction.

3.2. Influence of wire position

To obtain the influence of wire position on output signal, we measured the relationship between the sensor’s output signal and the distance from measured wire to the sensor. The experimental results of current ratio when the sensor is moved horizontally or vertically from the wire are shown in Fig. 11. The “stealth” current sensor is influenced by nearby wires within in 5mm. The influence is reduced by downsizing the sensor. We can also eliminate the nearby wires influence by multiple coils configuration.

4. Conclusion

We developed the tiny-scale “stealth” current sensor for power devices measurement. The sensor is significantly small and has sufficient accuracy so that the sensor can be applied to a single bonding wire current measurement inside IGBT modules, chip scale current redistribution measurement and current measurement for surface mount devices.

Appendix A. Comparison with other current sensors

Giant magneto-resistance (GMR) sensors and superconducting quantum interference devices (SQUIDs) are widely used as the magnetic-field-based current sensor.

A GMR sensor is a magnetic sensor utilized giant magneto-resistance effect and detects magnetic-field as the change of resistance. The GMR current sensor measures both of ac and dc current. The GMR current sensor has output saturation characteristics under high current measurement condition and requires an external dc current source or permanent magnet as bias [7,8,9,10,11,12,13].

A SQUID is a sensor which utilizes Josephson Effect. The SQUID current sensor has very high magnetic-field and low noise sensitivity. A cooler is required to lower the temperature of the SQUID current sensor [14,15].

The “stealth” current measurement approach has the following merits. The “stealth” current sensor can measure large current. In addition, the sensor has good heat-resisting property and cost performance. Therefore, the sensor can be utilized failure mechanism understanding of power devices.

References

[1] Yoshiko Ikeda. Yoshihiro Yamaguchi. Yusuke Kawaguchi. Masakazu Yamaguchi. Ichiro Omura , Tomokazu Domon. Non-Destructive Current Measurement for Surface Mounted Power MOSFET on VRM board using Magnetic field probing technique. Proc. of ISPSD 2009. pp. 65 - 68. 2009.

[2] W. F. Ray and C. R. Hewson. High Performance

Rogowski Current Transducers. Conference Record of the 2000 IEEE. pp. 3083 - 3090 vol.5. 2000.
[3] W. F. Ray. Current measuring device. U.S. Patent. US 6,614,218 B1. 2003.
[4] Ray W.F. et al. Developments in Rogowski Current Transducers. EPE’97. Aug. 9. 1997. pp. 3.308-3.312.
[5] L. Zhao. J. D. van Wyk. W. G. Odendaal. Planar Embedded Pick-up Coil Sensor for Integrated Power Electronic Modules. Proceedings of 19th Annual IEEE Applied Power Electronics Conference and Exposition. 2004. 945-951.
[6] Chucheng Xiao. Lingyin Zhao. Tadashi Asada. W. G. Odendaal. J. D. van Wyk. An Overview of Integratable Current Sensor Technologies. IEEE. 2003. pp. 1251-1258.
[7] G. Laimer. J. W. Kolar. Design and Experimental Analysis of a DC to 1MHz Closed Loop Magnetoresistive Current Sensor. 20th Annual IEEE Applied Power Electronics Conference and Exposition. 6-10 March. vol.2. pp. 1288-1292.
[8] Teodor Dogaru and Stuart T. Smith. Giant Magnetoresistance-Based Eddy-Current Sensor. IEEE TRANSACTION ON MAGNETICS. VOL. 37. SEPTEMBER 2001. p. 3831 - 3838.
[9] J.M. Daughton. GMR applications. Journal of Magnetism and Magnetic Materials 192 (1999) 334-342.
[10] K. Ludwig. J. Hauch. R. Mattheis. K.-U. Barholz. G. Rieger. Adapting GMR sensors for integrated devices. Sensors and Actuators A 106 (2003) 15-18.
[11] P. Ripka. CURENT SENSORS USING MAGNETIC MATERIALS. Journal of Optoelectronics and Advanced Materials Vol. 6. No. 2. June 2004. p. 587 - 592.
[12] Pavel Ripka, Jan Kubik. Maeve Duffy. William Gerard Hurley. Stephen O’Reilly. Current Sensor in PCB Technology. IEEE SENSORS JOURNAL. VOL. 5. NO. 3. JUNE 2005. pp. 433-438.
[13] J. Pelegrí. J.B. Ejea. D. Ramírez. P.P. Freitas. Spin-valve current sensor for industrial applications. Sensors and Actuators A 105 (2003) 132-136.
[14] D. Drung. C. Aßmann. J. Beyer. A. Kirste. F. Ruede. and Th. Schurig. Highly sensitive and easy-to-use SQUID sensors. Paper 5EB01 at ASC2006. to appear in IEEE Trans. Appl. Supercond. 17 (2007).
[15] M.Mück. M.v.Kreutzbruck. U.Bady. J.Tröll and C.Heiden. Eddy Current Nondestructive Material Evaluation based on HTS SQUIDs. Physica C 282-287 (1997) 407-410.