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著者	Tsukuda M., Koga M., Nakashima K., Omura I.
journal or publication title	Microelectronics reliability
volume	64
page range	479-483
year	2016-09-18
URL	http://hdl.handle.net/10228/00006908

doi: [info:doi/10.1016/j.microrel.2016.07.011](https://doi.org/10.1016/j.microrel.2016.07.011)

Micro PCB Rogowski coil for current monitoring and protection of high voltage power modules

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Abstract

We have developed a printed circuit board Rogowski coil for monitoring of current and protection of high-voltage power modules and packages. It is small, thin, and inexpensive current sensor and is almost the ideal Rogowski coil because of its fishbone pattern. For noise reduction under high-voltage/-current conditions in a module, shield layers and coaxial connector are employed. In addition, a new, fast simulation tool was developed to optimize the main coil pattern for realization of arbitrary printed circuit board geometry in specific, limited spaces.

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1. Introduction: Impact of micro current sensors

High reliability is required for power semiconductor devices and power modules because they are increasingly demanded as key devices in an energy-saving society. To realize highly reliable power modules, the current distribution of each chip and the total current of the modules should be measured accurately. This is because current crowding breaks the power semiconductor chip and/or shortens power module lifetime by partial heating.

Current transformers (CTs) and Rogowski coils, as representative commercially available current sensors, are widely applied in many power electronics equipment or in experiments [1-4]. However, they are too large to be used in power modules.

In previous studies, certain kinds of small sensor with various technologies have been proposed [5-12]. In this paper, we propose further small, thin, and inexpensive sensors employing printed circuit board (PCB) technology with a method of noise immunity. The main pattern is very close to the ideal Rogowski coil by using PCB technology. In addition, we developed quick output signal simulation for a number of optimizations of arbitrary PCB design and a Rogowski coil for installation in specific, limited spaces.

2. Main pattern of the micro PCB Rogowski coil

We developed a small, thin, low-cost Rogowski coil with PCB technology (see Fig. 1) [13]. The PCB Rogowski coil can be placed on bus bars, bonding wires, and terminals. Therefore, it can be used for monitoring of chip current or for protection as a built-in sensor in power modules/packages or applied to current distribution analysis in modules. For this purpose, a non-clamp and a clamp type of coil have

been developed.

We employ a fishbone coil pattern with PCB technology to cancel noise caused by outside current. Four coil patterns, i.e., fishbone, saw blade, triangle, and fishbone without a return line, have been experimentally produced for a four-layer PCB in

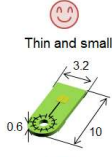
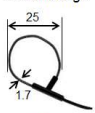









Current sensor	PCB Rogowski coil with fishbone pattern (Novel)	Commercially available Rogowski coil	Commercially available current transformer (CT)
Performance	😊	😞	😞
Example of dimension and appearance (mm)	Thin and small 	Thin and large 	Thick and large 
Variation with conductor position inside the sensor loop	😊 ± 2%	😊 ± 2%	😊 ± 1%
Variation with other conductor position outside the sensor loop	😊 ± 7%	😞 None data	😞 None data
Cost	😊 Inexpensive	😞 Expensive	😞 Expensive

Fig. 1. Performance of the PCB Rogowski coil and benchmarks.

Pattern name	Fishbone (Novel)	Saw blade	Triangle	Fishbone without return line
Picture				
Skeleton				
Max. variation with other conductor position outside the sensor loop	± 7%	± 10%	± 26%	± 218%

*Red line is 2nd layer for return line

Fig. 2. Variation of the fishbone pattern and benchmarks in the experiment.

order to evaluate noise caused by outside current (see Fig. 2). And the concept of the proposed fishbone coil pattern is to eliminate unnecessary magnetic flux pathways to the utmost limit of PCB technology. The noise of the proposed fishbone pattern is the smallest and will become increasingly smaller with advancement of PCB technology.

The upper-limit frequency of the PCB Rogowski coil is around 110 MHz or more (see Fig. 3). The frequency of the inductance was measured by using an impedance analyser. The frequency of the coil's self-inductance was almost constant up to a frequency of 110 MHz. It is expected that the mutual inductances of the coils were almost also constant over 110 MHz. It was not possible to evaluate performance over 110 MHz with the impedance analyser used in this experiment.

Monitoring of current with a very small PCB Rogowski coil is successfully demonstrated (see Fig. 4). The waveform corresponds to the waveform measured by a commercially available CT (411 [1]). The Rogowski coil is placed on the terminal of the TO-220 package and monitors the switching current. It is thought that the difference in ringing is due to the sensor characteristics. Monitoring of current is also demonstrated with parallel IGBT chips on a direct copper-bonded (DCB) substrate (see Fig. 5). The switching circuit has a resistive load of 5Ω and the DC voltage is set to 180 V. A PCB Rogowski coil is placed on the bonding wires of both IGBT chips, and a commercially available CT (411 [1]) is placed on the wiring of the total current path. The current waveform is changed with gate resistance (R_G). In the case of connecting the same R_G , the signals of the PCB

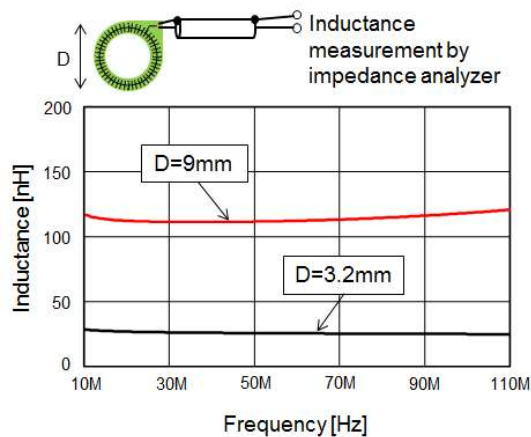


Fig. 3. Frequency characteristic of inductance for the PCB Rogowski coil.

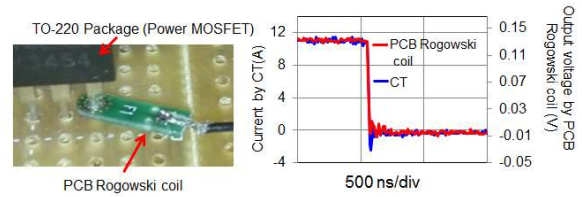


Fig. 4. Demonstration of a very small PCB Rogowski coil.

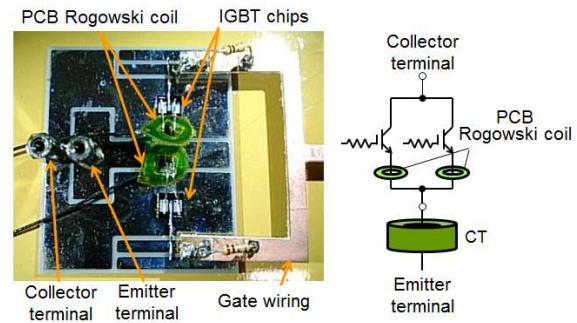
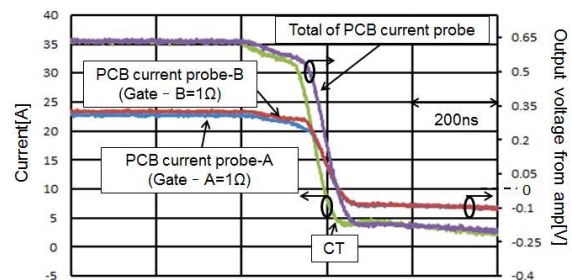
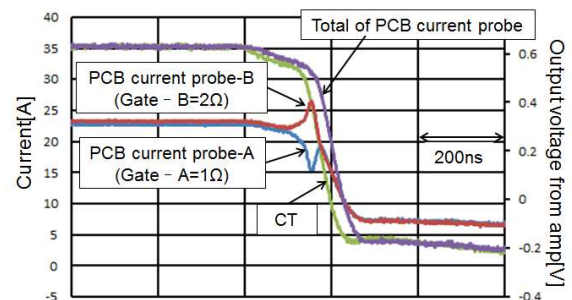


Fig. 5. Setup of parallel IGBT chips with the position of the PCB Rogowski coil and CT for the circuit.



(a) Under balanced R_G of parallel IGBT



(b) Under balanced R_G of parallel IGBT

Fig. 6. Current measured by a CT and current signal waveforms measured by the PCB Rogowski coil.

Rogowski coil show the same output results (see Fig. 6(a)). The signals of the PCB Rogowski coil show valid results for the R_G value. The current difference during turn-off is larger with different R_G (see Fig. 6(b)). The sum of signal waveforms is the same as the current waveform measured by the CT.

3. Noise reduction under high-voltage/-current conditions

We employ noise-shield layers and a coaxial connector to reduce the electrostatic/electromagnetic noise in high-voltage-current power modules. Next,

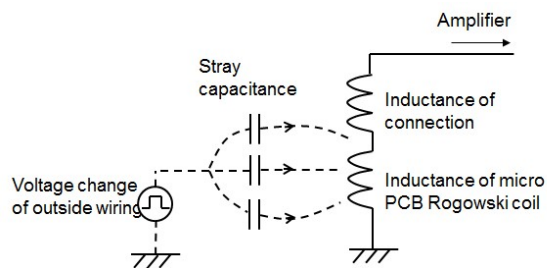


Fig. 7. Noise model by voltage change.

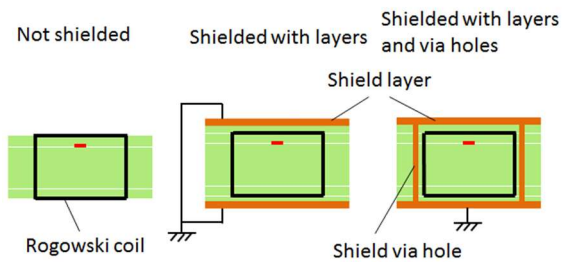


Fig. 8. Three kinds of PCB Rogowski coil for the experiment on the shield effect.

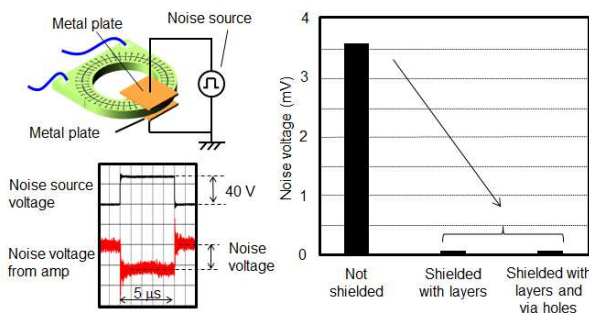


Fig. 9. Electrostatic noise reduction by shield layer of PCB.

the cause of noise, the measures, and the effect of the measures are precisely described.

Stray capacitance exists between the Rogowski coil and the nearby wiring including the target wiring for current measurement. When the displacement current to charge/discharge the stray capacitance flows to the Rogowski coil, electrostatic noise is generated (see Fig. 7). To remove the charge/discharge for stray capacitance, noise-shield layers connected to the ground line are additionally employed with a copper layer in the PCB. Next, three kinds of PCB Rogowski coil are fabricated for the experiment on the shielding effect (see Fig. 8). The Rogowski coil without a shield layer is composed of a four-layer PCB. The Rogowski coil with shield layers is composed of a six-layer PCB. The Rogowski coil with shield layers and shield via holes is also composed of a six-layer PCB. The noise voltage in the signal is obviously reduced by the shield layers in the switching of 40 V (see Fig. 9). We decided to employ the Rogowski coil with shield layers for electrostatic noise shielding, because the effect of

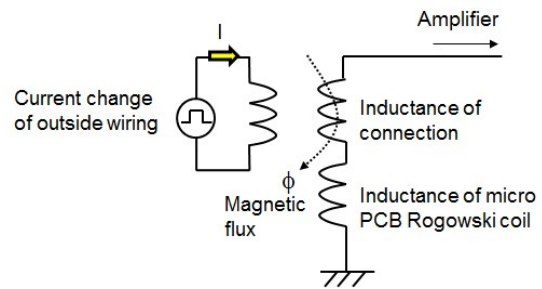


Fig. 10. Noise model by current change.

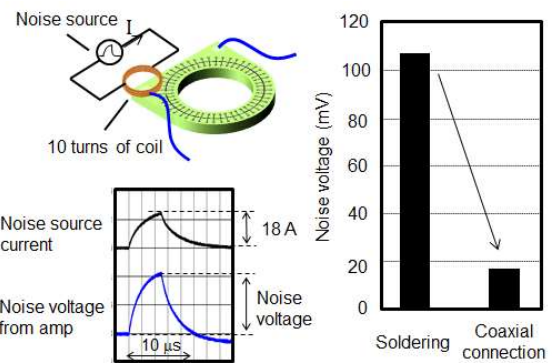


Fig. 11. Electromagnetic noise reduction by coaxial connector.

shielding via holes is not clearly found in this experiment.

Stray inductance exists along the loop with connector wiring between the PCB and the coaxial cable. When the magnetic flux from the nearby wiring including the target wiring for current measurement passes through the loop, electromagnetic noise is generated (see Fig. 10). To remove the loop, a coaxial connector is employed instead of direct connection of the coaxial cable by soldering. The noise voltage in the signal is dramatically reduced by the coaxial connector in the switching of 18 A (see Fig. 11).

We measured the switching current with inductive load for demonstration with the shield layer and coaxial connector. The Rogowski coil is placed on the load terminal of the two-in-one IGBT module, and the rated voltage and current is 1200 V and 450 A, respectively (see Fig. 12). The condition of inductive load switching is 600 V and 35 A. On the wiring for the load inductor, a commercially available Rogowski coil (CWT3Bmini [2]) is also installed for comparison (see Fig. 13). The inductive load current of the power module is successfully measured by the PCB Rogowski coil on the load terminal with a voltage change of 600 V (see Fig. 14).

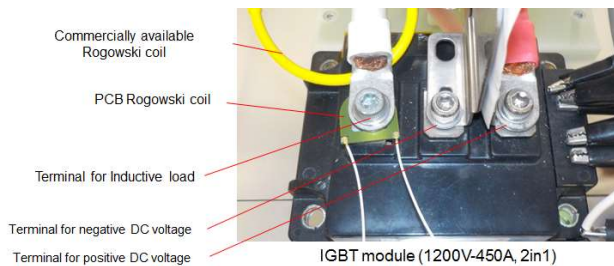


Fig. 12. Demonstration with a shield layer and a coaxial connector for a high-voltage power module.

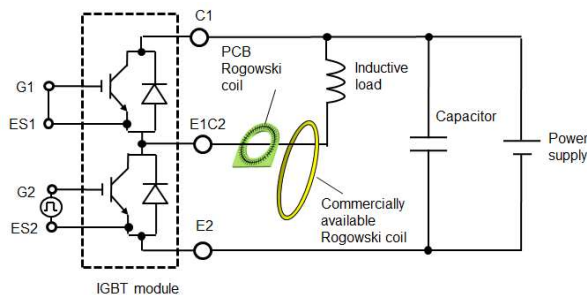
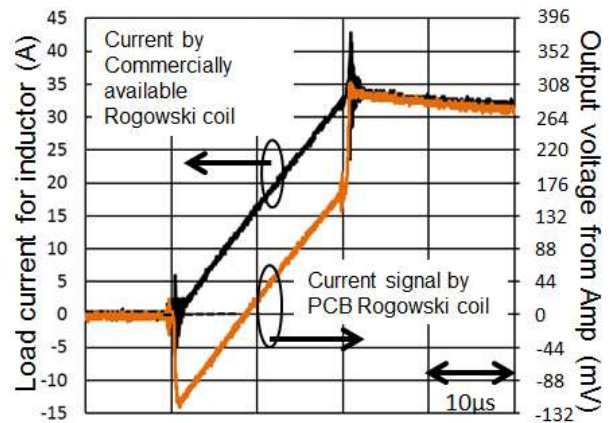
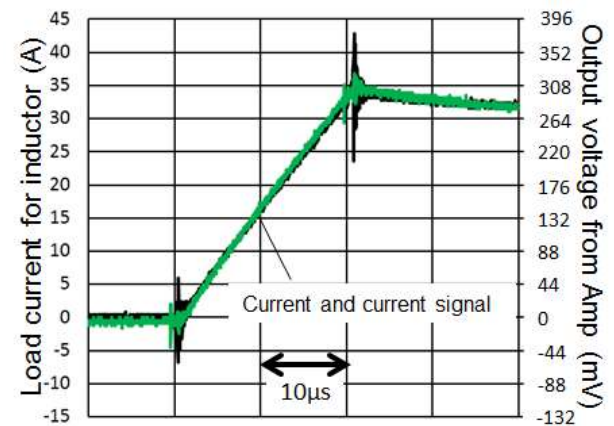


Fig. 13. Demonstration circuit and sensor installation position.



(a) Without a shield layer



(b) With a shield layer

Fig. 14. Demonstration circuit and sensor installation position.

4. Quick simulation tool for the Rogowski coil with a fishbone pattern

We developed an original-design tool using MATLAB to calculate the mutual inductance between the Rogowski coil and hundreds of thousands of current flow points. The calculation speed is at least one hundred times faster than the speed of commercially available tools, which means that the developed tool is able to perform calculation in 30 minutes, while it takes a couple of days using commercially available tools. In the design tool, the mutual inductance per turn of the Rogowski coil is calculated by Neumann's formula. The mutual inductance of the Rogowski coil is calculated by adding together the mutual inductance per turn of the Rogowski coil (see Fig. 15). Furthermore, to improve

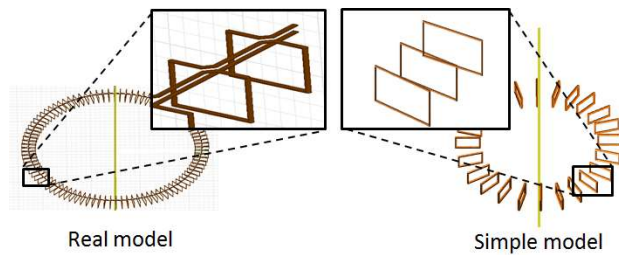


Fig. 15. Rogowski coil model of the simulation tool with a fishbone pattern.

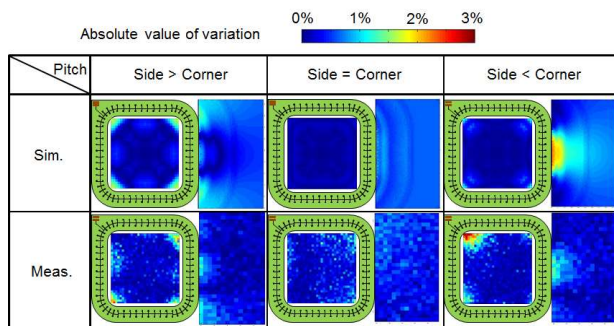


Fig. 16. Correspondence between the simulation and experimental results.

the calculation speed, the design tool incorporates two approaches. The first approach is that mutual inductance is calculated by using a simplified fishbone-like model of the Rogowski coil to eliminate complicated calculations with the connecting line of each turn and the return line. The second approach is that the mutual inductance is calculated in advance and tabulated as a function of the distance in order to eliminate integral calculation for Neumann's formula. With this tool, the sensitivity and a part of the noise can be estimated in advance and designed to be of a practical level despite the arbitrary geometry (see Fig. 16). The error (%) of mutual inductance or output voltage in the experiment is defined to be at the center of the PCB Rogowski coil.

5. Conclusion

We developed a printed circuit board Rogowski coil. A fishbone coil pattern is proposed to realize high accuracy with noise-shield layers and a coaxial connector for high-voltage/-current modules. A new simulation tool is also developed to optimize the main pattern for arbitrary geometry. It is expected to be installed in specific, limited spaces in power

modules/packages or power systems to improve reliability.

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