An Overview of Integratable Current Sensor Technologies

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Abstract – An overview is given of current sensing technologies that are suitable for packaging into integrated power electronics modules and integrated passive power processing units, such as integrated shunts and integratable Rogowski coils technologies. Technologies considered in this paper include: integrated current shunts, current transformers, Rogowski coils, Hall-effect current sensors, Giant Magneto Resistive sensors (GMR) and Magneto Impedance sensors (MI). Each of these current sensing technologies is discussed separately along with their advantages, limitations and design trade-offs. Special emphasis is given to features that enhance or limit the technology's potential for being integrated in the packaging process.

I. INTRODUCTION

Current sensors play a critical role in modern power electronics systems and are necessary for purposes of protection and control. In recent years, an integrated systems approach is being developed to standardize power electronics components and packaging techniques in the form of IPEMs [1]. Therefore the need for current sensors suitable for packaging into integrated power electronics modules and integrated passive power processing units increases. As part of the effort of power electronic modular integration other than regular current sensing applications, integrated current sensors specifically aim to achieve the following characteristics:

- Compact size
- Very low profile
- Compatible with manufacturing process
- Low cost
- High bandwidth for high frequency operation
- Fast response
- Low parasitics introduced
- High reliability
- High noise immunity
- High stability with varying module temperature.

At present, comprehensive research work on current sensing technology in power electronic systems has been conducted, including shunt, current transformers, Rogowski coils, Hall effect sensors, Magneto Impedance sensors (MI), Giant Magneto Resistive (GMR) sensors, pilot devices in power semiconductors and optical current sensors. However, only some of them have the potential to be integrated into integrated power electronic modules (IPEMs) without adding significant cost and size. These kinds of sensors can be manufactured during IPEM production as part of the process or integrated in the process steps.

This paper provides an overview of existing current sensing technologies in terms of their integratability and performance. After comparing these current sensing technologies in terms of material technology and process technologies, the study focused on three techniques: shunt, Rogowski coil and MI sensor for their compatibility with current CPES manufacturing technology. The new planar structure shunts and Rogowski coils that are more suitable for integration are proposed in the paper along with their design and implementation.

II. OVERVIEW OF EXISITING CURRENT SENSIING TECHNOLOGIES

A. Shunt

Shunts are the most cost effective sensing elements, having compact package profiles, suitable for DC or AC measurement (although not suitable for applications of up to tens MHz). Since shunts lack galvanic isolation, some isolation techniques are discussed in [2][3][5]. This increases the cost and complexity. Shunts must be inserted in the main current path, and therefore decrease efficiency, particularly in high current low voltage applications. Often shunts have low resistance and a low temperature coefficient of resistance (TCR) and use Kelvin terminals for improved measurement accuracy.

Although current shunts operate on the principle of the Ohmic voltage drop, practical shunts have intrinsic inductance, which limits the accuracy and bandwidth. A typical shunt has a few milli-ohm resistance and the magnitude of the induced voltage due to flux coupling between measuring leads may become comparable to the resistive voltage drop, which will add noise to the measured voltage. At high frequency operation, the resistance of a shunt can be different from the value of DC operation due to skin and proximity effect, so particular care should be given to minimize these adverse effects. Usually wide-bandwidth resistive shunts are coaxial in design, comprising two coaxial resistive tubes which carry current in opposite directions [4]. Coaxial shunts that are commercially available are cylindrical in shape with large dimension, unsuitable for integration in IPEMs. Although they are very noise immune and have fast response (measurement for 5000 A current with a 20n rise time).

B. Current Transformer

Current transformers (C.T.) have been widely used for AC current sensing with its bandwidth up to tens of MHz. This sensing technique provides galvanic isolation and consumes little power. Additional driving circuits are normally not necessary. Pulse currents of up to 5kA with 20 ns rise time can be detected while offering a lower corner frequency of around 1 Hz [6]. If a solid core material is used, saturation must also be considered during the design should any low frequency or DC component be present, which lead to increased size and cost. Meanwhile, the hysteresis of core material degrades the measurement accuracy. Current transformers can be integrated in the form of a planar transformer. However, the core selection and manufacturing for a very low profile and high enough saturation flux density limit its application in IPEMs integration. As far as parasitics is concerned, current transformer introduces additional inductance to the current-carrying conductor, which compromises the high frequency performance of IPEMs [7].

C. Rogowski Coil

A Rogowski coil is an air-cored coil placed around the conductor in a toroidal fashion [8][9][10][17]. The uniformly wound coil on a non-magnetic former of constant cross-sectional area is formed into a closed loop then the voltage induced in the coil is proportional to the rate of change of current. This voltage is integrated, thus producing an output proportional to the current, as illustrated in Fig. 1. The Rogowski coil is a conceptually simple device and is suitable for transient current measurements.

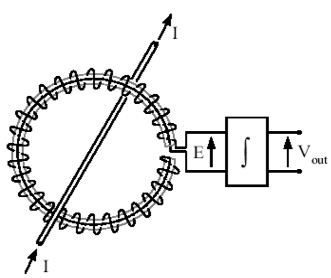

Fig. 1. Basic configuration of a Rogowski current transducer.

It has the following features [8][19]:

1) high bandwidth enabling measurement of switching transients in semiconductors;
2) capability of measuring large currents; (The same size coil can be used for measuring 100 A or 100 kA.)
3) non-saturation because of air core;
4) isolation and non-intrusive measurement between testing circuit and transducer;
5) ease of use and inexpensive;
6) good linearity due to absence of magnetic material;
7) compact and light weight.

The main difficulty in achieving a wide bandwidth is the conflicting constraints on the coil for operation at very low or very high frequencies [10]. However, a combination of active integrators for the lower range of frequencies and passive integration for higher frequencies has been used to solve this problem. At the same time this integrator design achieved a bandwidth up to 10 MHz [8][16][18].

A PCB-based Rogowski coil.is presented in [15]. The combination of this PCB Rogowski coil with Hall sensor forms a new current measuring principle: HOKA [11][12][13], which combines the advantages of both sensors and eliminates the integrator circuit needed for the Rogowski coil. DC current as well as transient current with several kA/μs can be measured using this new technique.

A miniature current probe based on Rogowski coils is presented in [15] for the non-invasive current measurement in IGBT modules. It provides an easy and high performance method of measuring currents, in compact low-inductance circuits at the chip level.

D. Hall Effect Sensor

The Hall effect sensor is a magnetic field sensor based on the Hall effect. It is an isolated, non-intrusive device that can be applied to both DC and AC current sensing, normally up to hundreds of kHz. Due to its simple structure, compatibility with the microelectronic devices, a Hall device can be monolithically integrated into a fully integrated magnetic sensor [20][21]. The Hall sensor can be fabricated using a conventional CMOS technology. However, it is usually more costly than a current transformer or a Rogowski sensor. A Hall transducer has normally a limited peak current due to core saturation and has limited bandwidth (< 1MHz), though it can measure DC current. In addition, it is very sensitive to external magnetic fields. The Hall effect sensors mainly operate in closed loop modes for better accuracy and wider dynamic range.

Though microelectronics technology is used to fabricate a Hall device with lower offset voltage [22], the offset voltage is not stable and may vary with temperature and time. The future of the Hall devices will depend on the improvement in the basic materials and integrated processing to increase the sensitivity and decrease the offset. The bulky core of the Hall devices, the limited bandwidth, and the temperature dependence make it hard to be a strong candidate for integration in IPEMs.

E. GMR current sensor

Integrated GMR current sensors are based on the Giant Magnetoresistive (GMR) effect, i.e. change of electrical resistance with the magnetic field [23][24][25][26][28][29]. Due to its high sensitivity to the magnetic field, the GMR sensors can be effectively used to sense the current by measuring the magnetic field generated by the current

[33][38]. Fig. 2 shows the typical curve of resistance vs. magnetic field.

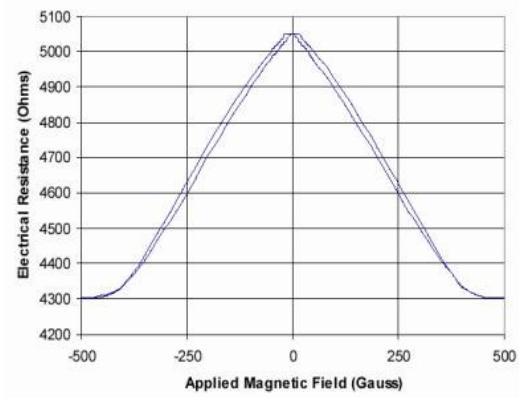

Fig. 2. Resistance vs. magnetic field for typical GMR sensor.

A GMR device consists of alternating ferromagnetic and non-ferromagnetic thin layers, each a few atomic layers thick, which makes them possible for integrated current sensor. Among many combinations of ferromagnetic /non-ferromagnetic layers, Co, Fe, NiFe or NiFeCo alloys are used as magnetic layers, which are separated by Cr, Cu, Ag or Au. The layers are produced using molecular beam epitaxial growth (MBE), various kinds of sputtering, electron beam evaporation and even the electrodeposition method [24][25].

GMR sensors are typically deposited and etched into a Wheatstone bridge pattern (Fig. 3) to improve the sensitivity and minimize the temperature dependent effects. The whole die size is 1.2mm × 0.7mm. Fig. 4 shows the magnetic sensing from a current-carrying wire [27].

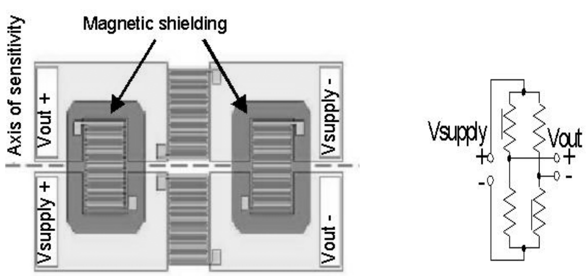

Fig. 3. Structure of a GMR sensor.

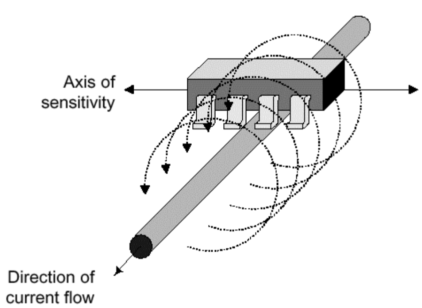

Fig. 4 . GMR sensor for current sensing.

Since the processing technology for building GMRs involves MBE, as well as the processing of materials not compatible with the present technology for integrating IPEMs, it is not possible to integrate these sensors into the IPEMs manufacturing process at present. If used, they will have to be an add-on component in the IPEM.

F. Giant MI Current Sensor

Recently there has been a considerable upsurge of interest in the Magneto Impedance (MI) effect, found in soft, amorphous, ferromagnetic materials. The MI effect refers to the variation of the impedance $Z=R(\omega,H)+iX(\omega,H)$ of a magnetic material carrying a low intensity, high frequency AC current when subjected to an external magnetic field. The effective permeability (μ_{eff}) of the MI material is very sensitive to an applied external magnetic field. By measuring the impedance variation, the magnetic field generated by the current can be derived to find the value of the current. This effect is expected to be promising with high sensitivity, quick response and small dimensions.

The MI effect in various magnetic structures has been investigated, firstly in wires and ribbons, and lately in thin films [33-48]. To be integratable, it is necessary to make the MI sensor in the form of thin film. The multi-layered films are preferred with respect to single-layered films due to their better MI effect. Typically the multi-layered MI sensors take the form of sandwich: two ferromagnetic layers sandwich a highly conductive layer. Further enhancement of the layered structure can be achieved by introducing an additional insulator separation - SiO_2 layer [48].

Fig. 5 shows a sandwiched MI element (10mm in length, 2 mm in width) based on FeCoSiB/Cu/FeCoSiB [33] with no hysteresis, good linearity and good stability even with temperature variation as well as high sensitivity. The detecting MI elements (Fig. 5a) exhibited a large impedance change ratio of over 100% even at a low frequency of about 1 MHz. A detection resolution of 80A/m which is higher than any other conventional thin film sensors is obtained.

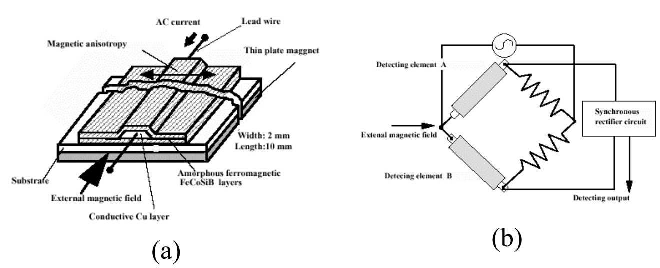

Fig. 5. Configuration of thin film magnetic field detecting element [39].

MI sensor is more field sensitive than GMR sensor. Although GMI sensors are still in an emerging stage, their low cost, high flexibility, small size, high sensitivity and wide bandwidth provide the potential as an alternative to the existing current sensors.

As far as materials and processing technology is concerned, integrating MI sensors into IPEM will be less onerous than GMR sensor, but is still very complicated and out of the present reach of CPES technology. It also has to be an add-on component in the IPEM.

G. Comparison of the current sensors

The comparison of the performance and characteristics of the current sensors above is listed in Table I.

TABLE I. COMPARISON OF EXISTING CURRENT SENSORS.

	Cost	Bandwidth	DC capability	Sensitivity	Saturation, hysteresis	Linearity	Operating temperature	Footprint	Integratability	Material Technology
Shunt	low	DC~10 MHz	Yes	mV/A	No	Very good	-55~125 °C	8×6×2.5 mm	Excellent	simple
CT	medium	0.1 Hz~100 MHz	No	1 V/A	Yes	Fair	-50~150 °C	N.A.	Good	simple
Rogowski	low	0.1~100 MHz	No	10 mV/(A/μs)	No	Very good	-20~100 °C	O.D.<20 mm, Height<4mm	Excellent	simple
Hall	high	< 1 MHz	Yes	10 Gauss	Yes	Poor	-40~125 °C	6×5×1.7 mm	Fair	complicated
GMR	medium	DC~5 MHz	Yes	10^{-2} Gauss	Yes	Fair	-40~150 °C	1.2 ×0.7mm	Excellent	Very complicated
GMI	medium	DC~ 30 GHz	Yes	10^{-6} Gauss	No	Fair	-40~150 °C	4×3mm	Excellent	Very complicated

III. INTEGRATED CURRENT SENSORS FOR IPEMS

From the previous sections, the following comments can be given: Typically, current transformer has an intrinsic phase shift of 0.1° to 0.3° and introduces extra inductance. A magnetic core is required to implement the current ratio conversion, which is bulky for packaging into the IPEM. Hall sensor is basically limited by the bandwidth and poor temperature characteristics. From a manufacturing point of view, the integration of Hall-effect sensor may be hard to achieve in IPEMs. GMR sensor has a compact size but normally needs extra DC current or a permanent magnet as bias. Also the processing technology and materials are not compatible with the present technology for integrating IPEMs. In addition, the commercial products of GMR sensors cannot meet the bandwidth requirement so far. Therefore, the main focus of our research would be: MI sensor, integrated Rogowski coil and integrated shunt.

A. Giant MI Current Sensor

To develop technology for integrated current sensors in IPEMs, we chose a MI sensor as one of the candidates because of its high sensitivity, large impedance change ratio, wide frequency bandwidth, small size, and high reliability. However, when MI sensors are applied to IPEMs, external magnetic fields affect their accuracy. Furthermore, the current distribution in the main conductor will become more and more non-uniform with increasing frequency. Fig.6 shows the different current distributions at 100Hz, 100kHz and 1MHz. These also affect the accuracy of the sensors.

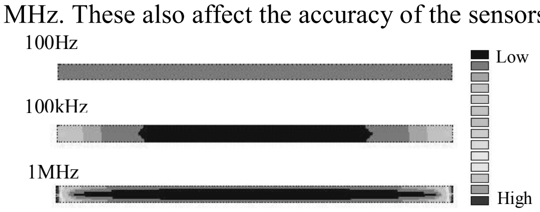

Fig. 6. Current distributions at different frequencies.

To eliminate both the influence of frequency and external magnetic fields, a structure shown in Fig.7 is proposed. Two main conductors, where currents flow in the opposite directions, are positioned in the window of the core. The MI sensor, whose axis of sensitivity is in the horizontal direction, is placed between the two conductors and a small core leg is located over the MI sensor.

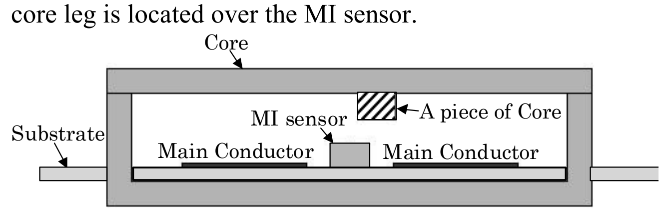

Fig.7. Cross section of the MI current sensor.

Fig. 8 shows the simulation results of the frequency response of the MI. The vertical axis indicates magnetic field detected by the MI sensor. In the structure shown in Fig. 7, when the main conductors, the MI sensor and the added small core leg are located in certain positions, the influence of frequency on the MI sensor can be eliminated. In addition, the external magnetic fields are also blocked by the main core. Meanwhile, the stray inductance added can be minimized since the conductors in the main core window carry opposite currents.

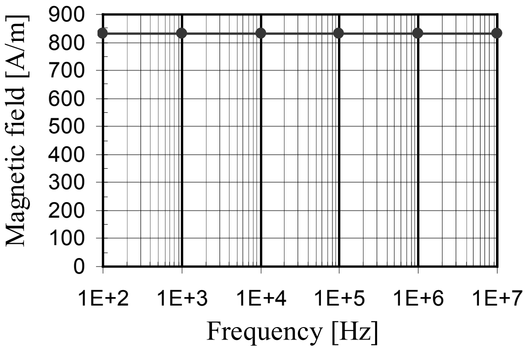

Fig. 8. Frequency response of the MI sensor.

B. *Planar Embedded Rogowski Sensor*

Rogowski coil has wide bandwidth and excellent linearity, but the commercial products are hard to directly integrate in IPEMs for its size and configuration. A new structure based on a similar principle, so-called planar embedded Rogowski sensor is proposed, as shown in Fig. 9.

Similar to the conventional Rogowski sensor, the proposed planar embedded Rogowski sensor consists of a signal pick-up coil and an integrator. The coil is embedded in between the two bus conductors which carry balanced currents, as shown in Fig. 9(a). It is constructed with parallel conductor traces on both sides of a substrate that are connected by vias, as shown in Fig 9(b). Dielectric insulation material is deposited between the coil and the busbar conductors. Fig. 10 shows the exploded view of the proposed Rogowski coil configurations.

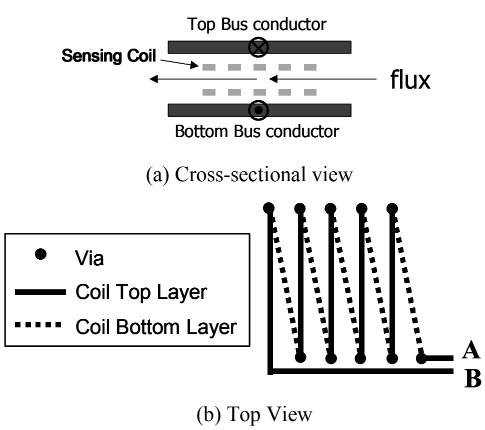

Fig. 9. Configurations of the proposed embedded Rogowski coil.

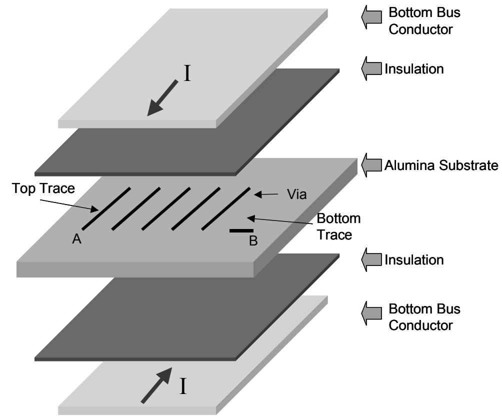

Fig. 10. Exploded view of the proposed Rogowski coil.

Since the major component of the flux generated by the other conductors on the same substrate is perpendicular to the axis of sensitivity of the pick-up coil, the proposed sensor structure is less susceptible to external noise by nature. On the other hand, the top and bottom busbars already serve as shielding conductors. Therefore, extra shielding is not needed in this application.

Due to the high bandwidth of the coil itself, the only limitation of the sensor bandwidth stems from the op-amp based integrator. In our design, a non-inverting integrator is implemented with a low-noise and high GBW (16MHz) op-amp. All the components are surface mounted. A prototype is shown in Fig. 11 while the test circuit is shown in Fig. 12 along with some experiment results. It can be seen that the sensor is able to follow the input current waveform very well.

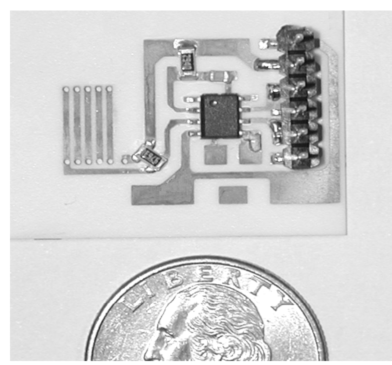

Fig. 11. Prototype of an embedded Rogowski sensor

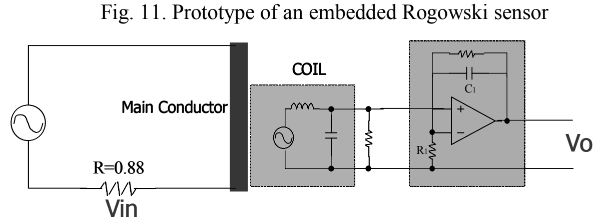

Fig. 12. (a) Test circuit for the proposed embedded Rogowski coil.

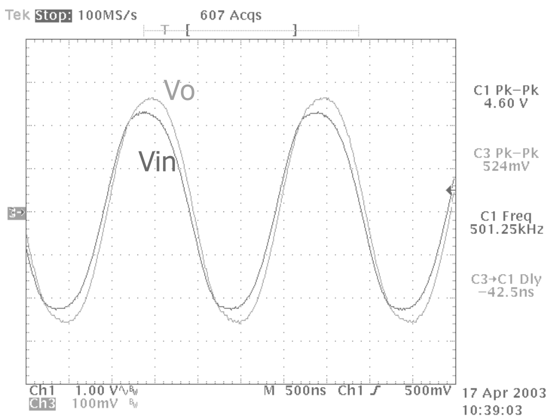

Fig. 12. (b) Experiment waveforms for 500 kHz sinusoidal current input

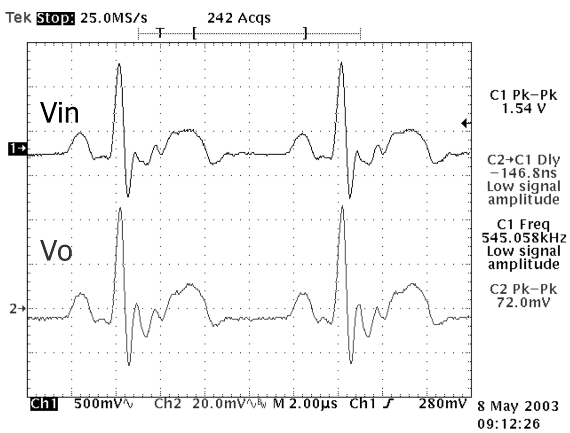

Fig. 12. (c) Experiment waveforms for arbitrary 500 kHz current input.

The proposed embedded Rogowski coil can be easily integrated in IPEMs with small size. The manufacturing processes of this proposed structure are fully compatible with the planar metallization technology developed for CPES IPEMs. It also has the following advantages:

a) small size;
b) no significant losses or parasitic added;
c) low inductance of the main conductor;
d) no extra shielding needed;
e) excellent stability with frequency;
f) excellent linearity;
g) not sensitive to the distance between the top and bottom bus bars;
h) not sensitive to other current-carrying traces on the same substrate.
i) wide bandwidth.

C. *Integrated Planar Shunt*

To achieve an integrated low profile shunt, a flat structure shunt should be taken into account. Based on these requirements and shunt's potential for integration, a planar integrated shunt using thick film metallization processing technology is proposed. The integrated shunt comprises of a number of interleaving parallel metal strips deposited onto the both sides of the thin Kapton substrate as shown in Fig. 13. For N pairs of metal strips in parallel, the resistance is:

$$R = \rho \cdot \frac{2 \cdot L}{N \cdot W \cdot t} \qquad (1)$$

where L is the length of metal strips on one side, W is the width and t is the thickness of each metal strips.

The corresponding metal strips on both sides have opposite current direction. The neighboring metal strips on the same side also have the opposite current direction. This configuration results in a low inductance in the shunt, which ensures a wide bandwidth. By simulation using Maxwell, the inductance of the designed shunt is 0.25 nH when L=15 mm, W= 0.5mm and t= 35 um. The thickness of the resistive metal is chosen so that the skin effect can be minimized at high frequency operation. The metal that has low temperature coefficient of resistance (TCR) is chosen as the resistive material. The design requires careful consideration of several exacting and conflicting requirements: resistance value, dissipated power, skin effect and voltage drop across the shunt.

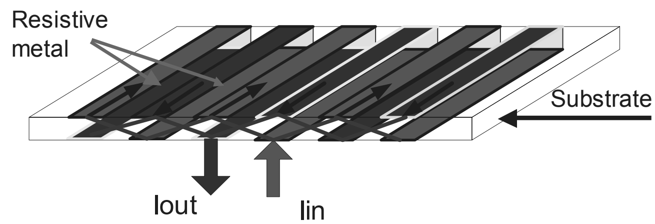

Fig. 13. Schematic of integrated planar shunt.

In the shunt design, the standard 2-terminal shunt may have significant error because the contact resistance, lead resistance, and their TCR may be greater than that of the resistive element itself. Therefore the 4-terminal Kelvin connection is required for our low Ohmic shunt design. Fig. 14 shows the Kelvin connection schematic and layout.

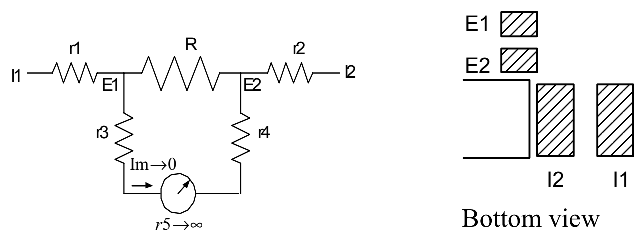

Fig. 14. 4-terminal Kelvin connection.

From Faraday's law, the voltage induced in the loop enclosed by the sensing leads will be a function of the changing magnetic field within it. Clearly, the flux coupled by the measuring leads affects the accuracy and bandwidth of the shunts. So the sensing terminals E1 and E2 should be in the low magnetic field region (as shown in Fig. 15). In order to obtain a low magnetic field region, two layers of planar shunts are stacked together and separated by the insulating Alumina substrate, and enough space exists to let the sensing leads go through the low magnetic field region.

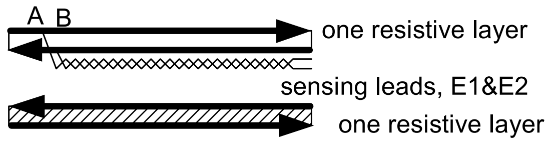

Fig. 15. Sensing leads arrangement in a two-layered shunt.

IV. CONCLUSION

Several typical current sensing technologies such as shunt, current transformer, Rogowski coil and Hall effect sensor have been discussed in this paper. Emerging commercial current sensors, such as GMR and GMI sensors, have also been evaluated due to their high sensitivity and small size. After evaluation and comparison between these current sensing technologies in terms of integratability, three types of integrated current sensors: MI sensor, Rogowski coil and shunt, that may have the potential to be compatible with IPEMs material and processing technology have been presented. MI sensors has been determined to be an add-on component to the IPEMs because of the unavailability of the processing technology in CPES. Planar embedded Rogowski coil and integrated planar shunt have been proposed as two candidates for fully integrated current sensors in IPEMs. The preliminary design and experimental results associated with these three technologies have been presented in this paper.

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REFERENCES

[1] F.C. Lee, J.D. van Wyk, D. Boroyevich, T.M.Jahns , R.D.Lorenz, T.P.Chow , R.J.Gutmann, and P. Barbosa, "An Integrated Approach to Power Electronics Systems," EPE-PEMC 2002, Dubrovnik &Cavtat pp.1-14, 2002.

[2] J. A. Ferreira, W. A. Cronje, W. A. Relihan, "Integration of high frequency current shunts in power electronic circuits," *IEEE Transactions on Power Electronics*, vol. 10, No. 1, pp. 32 – 37, 1995.

[3] Y. Xu, R. D. Lorenz, "Design of integrated shunt current sensors for IPEMs," *Proc. of CPES Seminar 2002*, pp. 404-411, 2002.

[4] C. M. Johnson, P. R. Palmer, "Current measurement using compensated coaxial shunts," *IEE Proceedings of Science, Measurement and Technology,* vol. 141, issue: 6, pp. 471 -480, Nov 1994

[5] F. Castelli, "The flat strap sandwich shunt," *IEEE Transactions on Instrumentation and Measurement*, vol. 48, issue: 5 , pp. 894 -898, Oct 1999.

[6] E. Laboure,F. Costa,F. Forest, " Current measurement in static converters and realization of a high frequency passive current probe (50 A-300 MHz)," Fifth European Conference on Power Electronics and Applications, vol. 4, pp. 478 -483, Sep 1993

[7] F. Costa, E. Laboure, F. Forest, C. Gautier, "Wide Bandwidth, Large AC Current Probe for Power Electronics and EMI Measurement," *IEEE Transactions on Industrial Electronics*, vol. 44, No. 4, pp. 502 – 511, 1995.

[8] W. F. Ray, C. R. Hewson, "High performance Rogowski current transducers," *Conference Record of the 2000 IEEE Industry Applications Conference*, vol. 5, pp. 3083 – 3090, 2000.

[9] D. W. Ackermann, "The Rogowski coil revisited," *Proc. of EPE'01*, Graz, 2001.

[10]W. F. Ray and R. M. Davis, "High frequency improvements in wide bandwidth Rogowski current transducers," *Proc. of EPE'99*, Lausanne, 1999.

[11] N. Karrer, P. Hofer-Noser, "A new current measuring principle for power electronic applications," *Proceedings of The 11th International Symposium on Power Semiconductor Devices and Ics (ISPSD '99)*, pp. 279 –282, 1999.

[12] N. Karrer, P. Hofer-Noser, D. Henrard, "HOKA: a new isolated current measuring principle and its features," *Conference Record of the Thirty-Fourth IAS Annual Meeting*. vol. 3, pp. 2121 –2128, 1999.

[13] N. Karrer, P. Hofer-Noser, D. Henrard, "A new current probe with a wide bandwidth", *Proc. of EPE'99*, 1999.

[14] N. Karrer, P. Hofer-Noser, "PCB Rogowski coils for high di/dt current measurement," *Record of IEEE 31st Annual Power Electronics Specialists Conference*, vol. 3, pp. 1296 –1301, 2000.

[15] P. R. *Palmer*, B. H. *Stark*, J. C. *Joyce*, "Noninvasive measurement of chip currents in IGBT modules," *Record of IEEE 28th Annual Power Electronics Specialists Conference*, vol. 1, pp. 166 -171, 1997.

[16] D. A. Ward, J. La. T. Exon, "Using Rogowski coils for transient current measurements," *Engineering Science and Education Journal*, vol. 2, No. 3, pp. 105 – 113, 1993.

[17] A. Radun, "An alternative low-cost current-sensing scheme for high-current power electronics circuits*," IEEE Transactions on Industrial Electronics*, vol. 42, No. 1, pp. 78 –84, 1995.

[18] W. F. Ray, "Rogowski transducers for high bandwidth high current measurement," *IEE Colloquium on Low Frequency Power Measurement and Analysis (Digest No. 1994/203)*, pp. 10/1 -10/6, 1994.

[19] D. A. Ward, " Measurement of current using Rogowski coils," *IEE Colloquium on Instrumentation in the Electrical Supply Industry*, pp. 1/1 -1/3, 1993.

[20] J. Frounchi, M. Demierre, Z. Randjelovic, R. S. Popovic*, "*Integrated Hall sensor array microsystem," *Digest of Technical Papers on 2001 IEEE International Solid-State Circuits Conference*, pp. 248 -249, 2001.

[21] R. S. Popovic, "Hall devices for magnetic sensor microsystems," *1997 International Conference on Solid State Sensors and Actuators (TRANSDUCERS '97 Chicago)*, vol. 1, pp. 377 –380, 1997.

[22] J. Trontelj**,** "Optimization of integrated magnetic sensor by mixed signal processing," *Proceedings of the 16th IEEE Instrumentation and Measurement Technology Conference*, vol. 1, pp. 299–302, 1999.

[23] Bill Drafts, F. W. Bell, "New Mangetoresistive current sensor improves power electronics performance," sensors, Sept. 1999

[24] S. Tumanski, "Thin film Magnetoresistive sensors," Institute of Physics Publishing, ISBN 0 7503 0702 1

[25] E. Hirota, H. Sakakima, K. Inomata, "Giant magneto-resistance devices," *Springer*, ISSN 0931-5195.

[26] www.infeneon.com/products/sensors "Magnetic senors-Giant Magneto resistors," .

[27] Engineering and Application Notes Giant Mangetoresistive (GMR) sensors, www.nve.com.

[28] E. R. Olson, R. D. Lorenz, "Design of integrated magnetoresistive current sensors for IPEMs," *Proc. of CPES Seminar 2002*, pp. 39-44, 2002.

[29] T. Mizuguchi, S. Terada, T. Miyauchi, A. Matsuzono, "Characteristics of NiFe/CuNi multilayer GMR sensors for vertical GMR heads," *IEEE Transactions on Magnetics*, vol. 34, No. 4, Part 1, pp. 1504 -1506, July 1998.

[30] J. Daughton, J. Brown, E. Chen, R. Beech, A. Pohm, W. Kude, "Magnetic field sensors using GMR multilayer," *IEEE Transactions on Magnetics*, vol. 30, No. 6, pp. 4608 –4610, 1994.

[31] J. E. Lenz, G. F. Rouse, L. K. Strandjord, B. B. Pant, A.Metze, H. B. French, E. T. Benser, D. R. Krahn, "A high-sensitivity magnetoresistive sensor," *IEEE 4th Technical Digest Solid-State Sensor and Actuator Workshop*, pp. 114 –117, 1990.

[32] R.L. White, "Giant magnetoresistance: a primer," *IEEE Transactions on Magnetics*, vol. 28, No. 6, pp. 2482 –2487, 1992.

[33]Yuji Nishibe, Norikazu Ohta, " Thin film Magnetic Field Sensor Utilizing Magneto Impedance Effect," *R&D Review of Toyota CRDL*, vol. 35, No. 4, Dec. 2000

[34] K. Hika, L.V. Panina, K. Mohri, " Magneto-impedance in sandwich film for magnetic sensor heads," *IEEE Transactions on Magnetics*, vol. 32, issue 4, pp. 4594 –4596, Sep. 1996.

[35] *Yong Zhou, Jinqiang Yu, Xiaolin Zhao, Bingchu Cai, "* Giant magneto-impedance effect in the sandwiched FeSiB/Cu/FeSiB films," *IEEE Transactions on Magnetics*, vol. 36, issue 5, pp. 2960 –2962, Sep. 2000.

[36] T. *Morikawa, Y. Nishibe, H. Yamadera, Y. Nonomura, M. Takeuchi, Y. Taga, "*Giant magneto-impedance effect in layered thin films," IEEE Transactions on Magnetics, , vol. 33, issue 5 , pp. 4367 –4372, Sep. 1997.

[37] L.V. Panina, K. Mohri, T. Uchiyama, M. Noda, K. Bushida, *"*Giant magneto-impedance in Co-rich amorphous wires and films," IEEE Transactions on Magnetics, , vol. 31 issue 2 , pp. 1249 –1260, Jun. 1994

[38] T. *Morikawa, K. Mohri, L.V. Panina, K. Furuno, "*Magneto-impedance in sputtered amorphous films for micro magnetic sensor," IEEE Transactions on Magnetics, , vol. 31, No. 6, pp. 3182 -3184, Nov. 1995.

[39] K. Mohri, T. *Kohsawa, K. Kawashima, H. Yoshida,* L.V. Panina, "Magneto-inductive effect (MI effect) in amorphous wires," IEEE Transactions on Magnetics, vol. 28 No.5 , pp. 3150 -3152, Apr. 1992.

[40] K. Mohri, K.Bushida, M. Noda, H. Yoshida,L.V. Panina, T. Uchiyama, "Magneto-impedance element," IEEE Transactions on Magnetics, vol. 31 No.4, pp. 2455 -2460, Jul. 1995.

[41] K. Mohri, *K. Kawashima, T. Kohzawa,*H. Yoshida, "Magneto-inductive element," IEEE Transactions on Magnetics, vol. 29 No.2, pp. 1245 -1248, Aug. 1992.

[42] F. Amalou, M. Gijs, "Giant magneto-impedance in multilayers of magnetic amorphous ribbons," Proceedings of IEEE on Sensors, vol. 2, pp. 753 -756, 2002.

[43] H. Hauser, L. Kraus, P. Ripka, "Giant magnetoimpedance sensors," IEEE Instrumentation & Measurement Magazine, vol. 4 No.2, pp. 28 -32, Jun. 2001.

[44] H. Hauser, J. Nicolics, A. Pohl, "Magnetic field sensor by giant magneto-impedance," Proceedings of the 16th IEEE on Instrumentation & Measurement Technology Conference, vol. 1, pp. 275 -278, 1999.

[45] M. Senda, O. Ishii, Y. Koshimoto, T. Toshima, "Thin-film magnetic sensor using high frequency magneto-impedance (HFMI) effect," IEEE Transactions on Magnetics, vol. 30 No.6, pp. 4611 -4613, Jun. 1994.

[46] M. *Takezawa*, H. *Kikuchi*, K. *Ishiyama*, M. *Yamaguchi*, K.I. Arai, "Micro magnetic thin-film sensor using LC resonance," IEEE Transactions on Magnetics, vol. 33 No.5, pp. 3400 -3402, Sep. 1997.

[47] A. *Takayama*, *T. Umehara*, A. *Yuguchi*, H. Kato, K. Mohri, T. Uchiyama, "Integrated thin film magneto-impedance sensor head using plating process," IEEE Transactions on Magnetics, vol. 35 No.5, pp. 3643 -3645, Sep. 1999.

[48] T. *Morikawa*, Y. *Nishibe, H. Yamadera, Y. Nonomura, M. Takeuchi, J. Sakata, Y. Taga,* "Enhancement of giant magneto-impedance in layered film by insulator separation," IEEE Transactions on Magnetics, vol. 32 No.5, pp. 4965 -4967, Sep. 1996.