Inspection system of high-density printed circuit board based on eddy-current testing technique with spin-valve giant magnetoresistance sensor

氏名	CHOMSUWAN KOMKRIT
学位の種類	博士（工学）
学位記番号	博甲第791号
学位授与の日付	平成18年3月22日
学位授与の要件	課程博士（学位規則第4条第1項）
学位授与の題目	Inspection System of High-Density Printed Circuit Board Based on Eddy-Current Testing Technique with Spin-Valve Giant Magnetoresistance Sensor （スピンバルブ形巨大磁気抵抗センサを用いたうず電流探傷技術による高密度プリント基板の検査システムに関する研究）
論文審査委員(主査)	岩原　正吉（自然科学研究科・教授）
論文審査委員(副査)	山田　外史（自然計測応用研究センター・教授）， 上杉　喜彦（自然科学研究科・教授），脇若　弘之（信州大学・教授）， 金丸　保典（金沢工業大学・教授）

学位論文要旨

Abstract

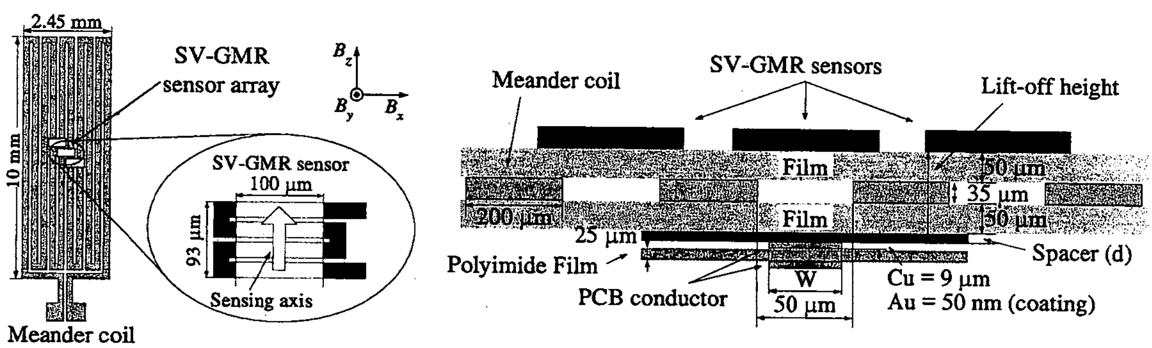
This thesis studied on inspection of high-density printed circuit board (PCB) inspection based on eddy-current testing (ECT) technique. Defects on PCB conductor can be investigated by eddy-current flow. The proposed ECT probe consisted of a planar meander exciting coil and spin-valve giant magnetoresistance (SV-GMR) sensor is developed. The utilization of SV-GMR sensor as a magnetic sensor of the ECT probe provides the feasibility of high-spatial resolution, high-sensitivity to low magnetic fields, and high-operating-frequency range. From the SV-GMR advantage, inspection of microdefect on microconductor can be performed by the proposed ECT probe. Inspection of PCBs evaluates not only imperfections of the PCB conductor but also PCB conductor dimensions and alignment. This kind of inspection is also performed by the proposed method. The characteristics of the proposed ECT probe for high-density PCB inspection are studies. Inspection results of high-density PCB model verify that applying of ECT technique is able to perform accurate PCB inspection.

1. Introduction

Eddy-current testing (ECT) technique is a well known method of nondestructive testing that is, usually, applied to evaluate the material flaws without changing or altering of test material. Generally, ECT technique is used as crack detection in piping systems of nuclear power plants, as imperfect welding spot detection on aircrafts, and etc [1]. In recent year, several kinds of magnetic sensors, such as Hall, Giant magnetoresistance (GMR), Squid, and etc., have been successful in ECT technique for applying to nondestructive testing to detect material cracks. Especially, the spin-valve giant magnetoresistance (SV-GMR) sensor is very interesting because it provides a good performance versus its cost. SV-GMR sensor has high sensitivity over board range of frequency and high-spatial-resolution because it has small dimension [2]. Moreover, it is inexpensive and able to operate at room temperature. From the features above, the applications of SV-GMR sensor to ECT technique will provide the good inspection signals that can easily identify the defect points.

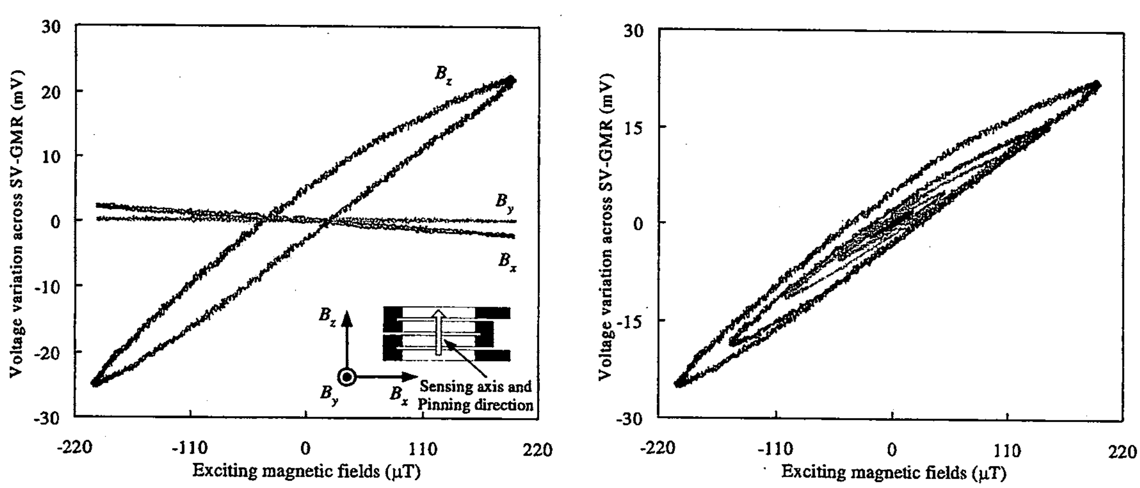
Bare PCB inspection is a new application of ECT technique that has been proposed [3-6]. Many kinds of inspection technique are usually used for bare PCB inspection such as image scanning by CCD camera and conductive testing by pin probe. Image scanning method has an advantage because it is a non-contact method. However, this approach can inspect only visible defect. For conductive testing by pin probe, this approach is able to inspect the short circuit and disconnection whereas inspection of imperfection on PCB conductor can not be inspected. ECT technique is an interesting method for bare PCB inspection because this method likes the combination of the above two methods. These mean that ECT technique is a non-contact method and able to inspect not only conductor disconnections and short circuits but also partial defects on PCB conductor track width and thickness by eddy-currents. Moreover, the construction of bare PCB inspection system by mean of ECT technique is uncomplicated and also inexpensive.

In this thesis, characteristics of high-sensitive micro ECT probe, composed of planar meander coil and SV-GMR sensor, for applying to bare PCB inspection are studied. In addition, inspection of high-density PCB model with 100 μm PCB conductor width and gap is proposed to verify the capability of the proposed ECT probe applied for PCB inspection.



(a) Top view (b) Cross section

Fig.1 Proposed ECT probe for printed circuit board inspection.



(a) Sensitivity of the SV-GMR sensor at each of its axes.

(b) Effect of external magnetic field amplitude change to voltage variation across SV-GMR sensor.

Fig. 2 Characteristics of SV-GMR sensor used in the experiment

2. Configuration of the proposed ECT probe

The proposed ECT probe structure is shown in Fig. 1. The probe consists of a planar meander coil served as an exciter and SV-GMR array sensor. The SV-GMR array sensor was mounted on the planar meander coil sandwiched by two films to separate the coil from the SV-GMR array sensor and the PCB conductors. Therefore, the distance from the SV-GMR sensor surface to the PCB conductor or lift-off height is at least 135 μm. Each of SV-GMR sensors consists of 4 strips and each strip has dimension of 100 μm × 18 μm. Therefore, total effective area of each of SV-GMR sensor is 100 μm × 93 μm with 7 μm gap between strips. Normal resistance of the SV-GMR sensor is around 400 Ω. As shown in Fig. 2 (a), the SV-GMR sensor sensitivity in sensing axis is around 8.4 %/mT whereas it is lower than 1 %/mT in the other axes.

The sensitivity of the proposed SV-GMR sensor in linear region is independent from amplitude of applied magnetic fields as shown in Fig. 2 (b). However, high-hysteresis loop obtains when the large external magnetic fields are applied while low-hysteresis loop obtains when the external magnetic fields are low.

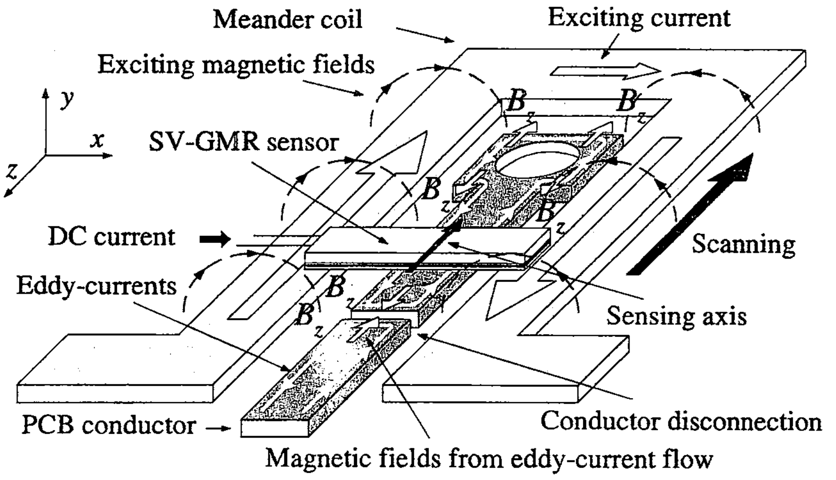


Fig. 3 Basic principle of ECT technique for printed circuit board inspection.

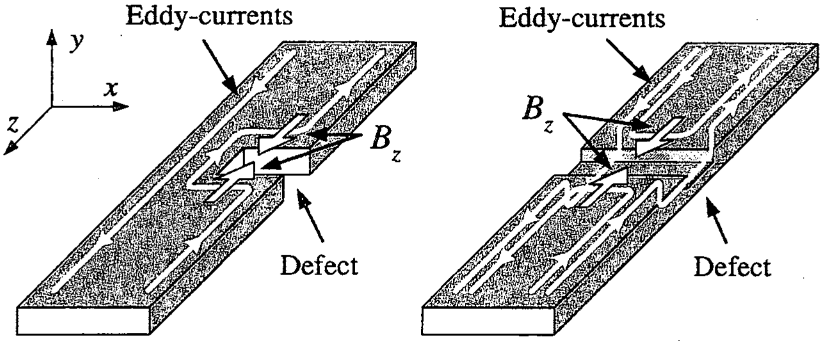


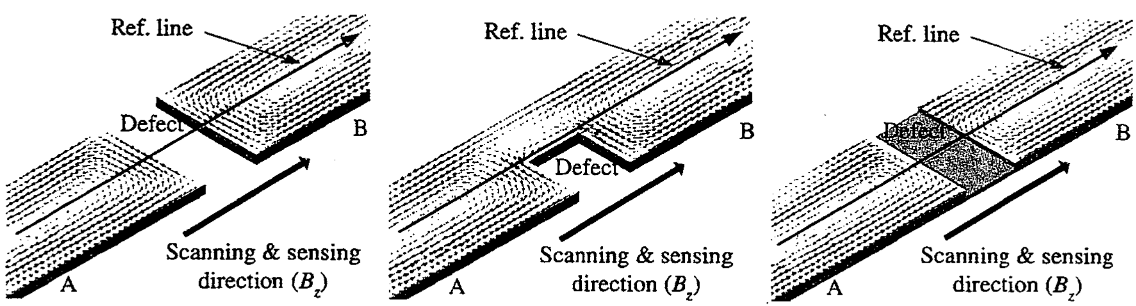
Fig. 4 Eddy-current paths in case of partial defect occurring on PCB conductor in width (left) and thickness (right).

3. Basic principle of ECT probe for high-density PCB inspection

High-frequency exciting currents are fed to the planar meander coil to generate the magnetic fields distributed over the PCB conductor as shown in Fig. 3. The exciting currents normally flow in z axis or scanning direction and generate magnetic fields only in x and y axis. An eddy-currents flowing in the PCB conductor are induced by the applied magnetic fields and also flow in z axis or scanning direction. Because of skin dept effect, the eddy-currents flow very close to surface or boundary of the PCB conductor. Whenever the defect or the PCB conductor boundary that perpendicular to scanning direction is found, the eddy-currents will change its path and flow in x direction. These eddy-currents generate the magnetic fields B_z therefore the defect on the PCB conductor or the conductor boundary can be identified if the magnetic fields B_z are detected.

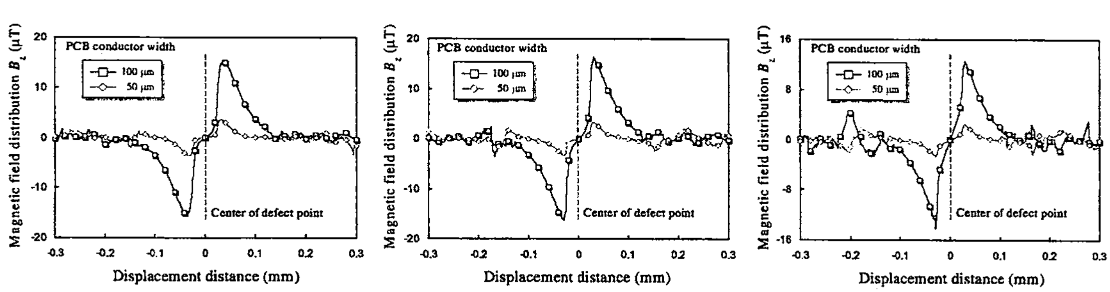
For partial defects, these defects, both partial defects occurring on PCB conductor track width and track thickness, also have the effect to the eddy-current path. As show in Fig. 4, small amount of eddy-current flow in x axis and these eddy-currents generate magnetic fields B_z although the magnetic fields are not too strong.

Measurement of magnetic fields B_z seems to be more difficult than the measurement of magnetic fields B_y, because magnetic fields B_z appears in a very short distance from the test PCB conductor, and it's value is not as high as of magnetic fields B_y. However, the



(a) Conductor disconnection. (b) Partial defect on track width. (c) Partial defect on thickness.

Fig. 5 Eddy-currents flowing in PCB conductor at difference type of defect.



(a) Conductor disconnection (b) Track width defect (c) Track thickness defect

Fig. 6 Magnetic field distribution (B_z) over the ref. line on PCB conductor from A to B, as shown in Fig. 5, that they are generated by eddy-current flow.

magnetic fields B_z appears only in specific cases - together with defects or at boundary of PCB conductor. In case of a defectless PCB conductor, there is no magnetic fields B_z generated by the test PCB conductor. The output signal does not have to be extracted from others signal as in case of the inspection of the magnetic fields B_y. The magnetic sensor moving above the test PCB conductor is not penetrated by the magnetic fields B_z until it encounters a defect. Therefore, the magnetic sensor is less susceptible to noise in the output signal. This is a big advantage of the proposed ECT probe and main reason for its high sensitivity.

4. Eddy-currents flow in PCB conductor and its magnetic field distribution

The Maxwell programs, finite element method (FEM) program for electromagnetic analysis, were used to analysis the magnetic field distribution obtaining from eddy-currents flowing in the PCB conductor. Three types of defect on the PCB conductor that are conductor disconnection, partial defect on PCB conductor track width and on PCB conductor track thickness are analyzed. Disconnection length of 50 μm is allocated on the conductor disconnection model. For partial defect, the disconnection region also is set at 50 μm and it has the disconnection region only 50% of the PCB conductor track. Eddy-currents flowing in PCB conductor when the defect is found on the PCB conductor are shown in Fig. 5. Eddy-currents usually flow along scanning direction whenever there is the defect or soldering point occurred on the PCB conductor, the eddy-currents change its path and the magnetic fields in the scanning direction (B_z) generated as discussed above. Moreover, eddy-currents, also, distribute very close to the PCB conductor boundary because of skin dept effect. Therefore, peak values of magnetic fields in the scanning direction (B_z) appear over the defect point region or the PCB conductor boundaries.

The magnetic field distribution in the scanning direction (B_z) obtained from FEM analysis is shown in Fig. 6. For conductor disconnection, the magnetic fields in the scanning direction (B_z) fluctuates at the defect point or displacement distance at 0 mm. The wider PCB conductor generates higher magnetic field variation in scanning direction (B_z) than the narrow PCB conductor because of high-density eddy-current flow. For partial defect on the PCB conductor track width, the magnetic fields in the scanning direction (B_z) also fluctuates at the defect point or displacement distance at 0 mm as shown in Fig. 6 (b). Magnitude of magnetic field variation at partial defect on PCB track width is not differs from that at conductor disconnection point. For partial defect on PCB thickness, the magnetic field in the scanning direction (B_z) varies at the defect point or displacement distance at 0 mm as shown in Fig. 6 (c). This type of defect generates lowest magnetic field variation because of low-eddy-current flow. However, the magnetic field variation is enough high to detect by the magnetic sensor.

5. ECT probe characteristics for high-density PCB inspection

5.1 Detection of defect on PCB conductor

PCB model with 9 μm PCB conductor thickness made from Cu coated by 0.05 μm Au

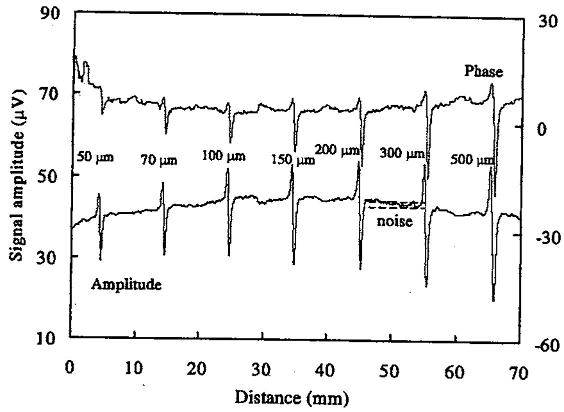


Fig. 7 ECT signal and its phase obtained from SV-GMR sensor scanning over PCB conductor with width of 200 μm.

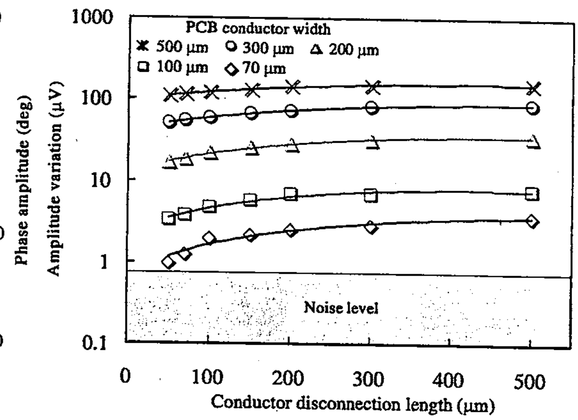


Fig. 8 ECT signal variations against conductor disconnection length

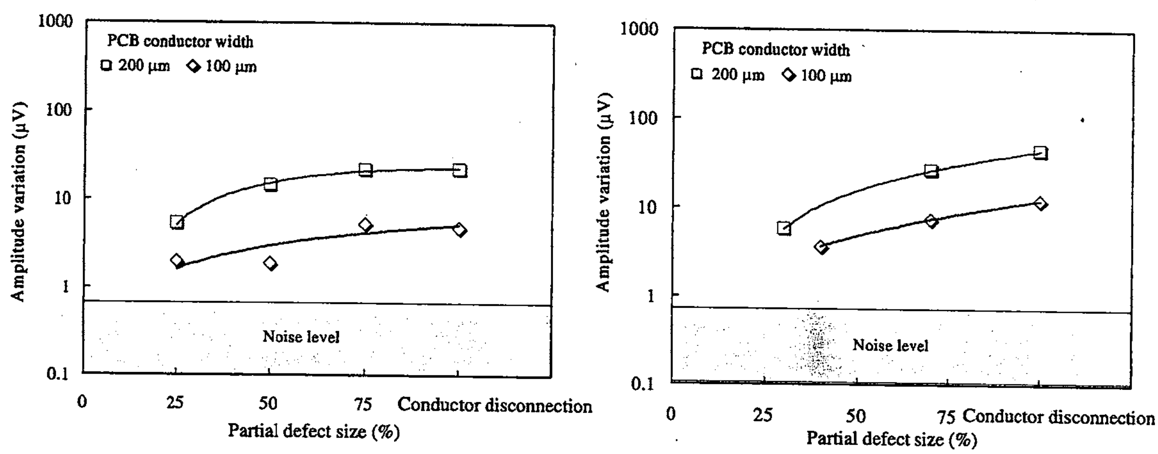
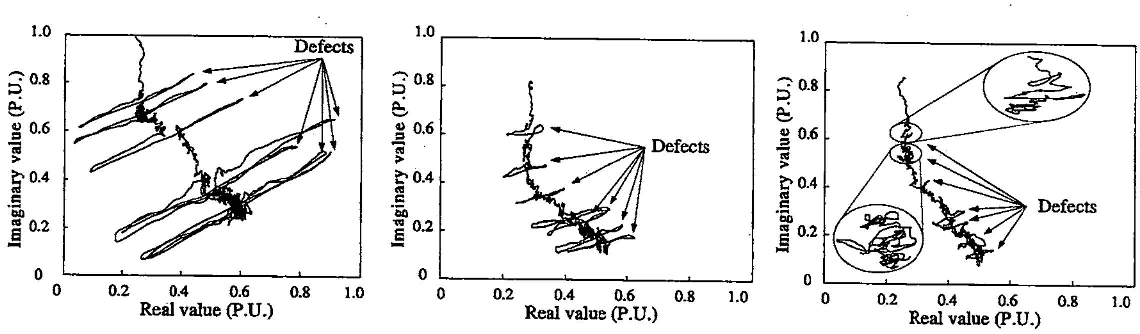


Fig. 9 ECT signal variations against partial defect on PCB track width (left) and thickness (right)



(a) Lift-off height = 135 μm (b) Lift-off height = 185 μm (c) Lift-off height = 235 μm

Fig. 10 Complex plane of ECT signal obtained from scanning over PCB conductor, 100 μm width, with different distance from sensing level to PCB conductor.

was used in the experiment. Three kinds of defect were allocated on the model to study the characteristics of the ECT probe for PCB inspection. The first is conductor disconnections and the second and third are partial defects on the PCB track width and track thickness respectively.

As shown in Fig. 7, the SV-GMR sensor can detects the magnetic field variation at defect points and provides variation of signals both amplitude and phase. The variations of signal are directly proportional to the defect size and they also depend on conductor width whereas noise signal, defined in Fig. 7, are constant with less than 0.6 μV as shown in Fig. 8. The signal is larger than noise around 2 times although the thin PCB conductor with 70 μm width and 50 μm disconnection length is inspected. Inspections of partial defects on PCB track width and track thickness are also performed by the proposed ECT probe as shown in Fig. 9. The partial defect effects to decreasing of signal variation, comparing with the signal variation in the case of conductor disconnection.

5.2 Lift-off height effect

Distance between PCB conductors and sensing level is very important for the inspection of bottom-layer PCB conductor. The complex plane is convenience to represent the variation of signals both amplitude and phase at defect points as a real and imaginary component as shown in Fig. 10. Inspection results obtained from scanning over PCB conductor with 100 μm width. Conductor disconnections ranged from 500 to 50 μm were allocated on the PCB conductor. The results show that the proposed ECT probe is able to inspect the defects on the PCB conductor with 235 μm lift-off height although the signal variations are very small. It means that the probe is capable of inspecting the defects at the bottom-layer if the distance between PCB conductor and sensing level is not over 200 μm.

6. High-density PCB inspection results

Fig. 11 presents the single layer PCB photograph with dimension of 5 mm × 5mm and scanning results after image processing was applied. Numerical gradient technique is a simple image processing technique that is used to eliminate signal offset and to enhance the signal at the defect points. The smallest conductor disconnection was only 20 μm. Furthermore, different kinds of partial defects were located on this model. The scanning results present that the proposed ECT probe is able to inspect the defects on the PCB conductor. The defects on PCB conductor are not difficult identification although the images are not clear.

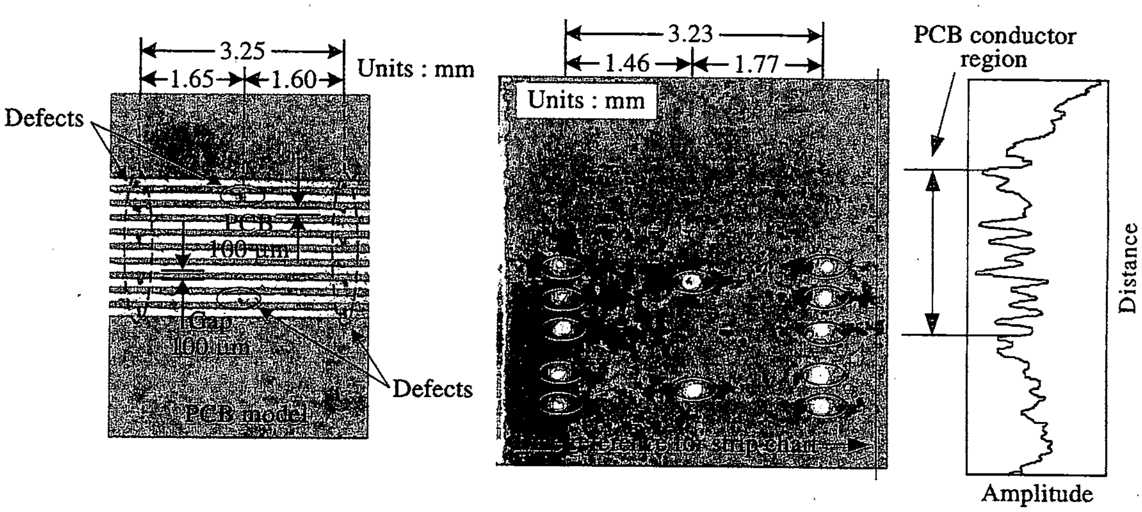


Fig. 11 Single layer PCB model (area of 5 mm × 5 mm) inspection example

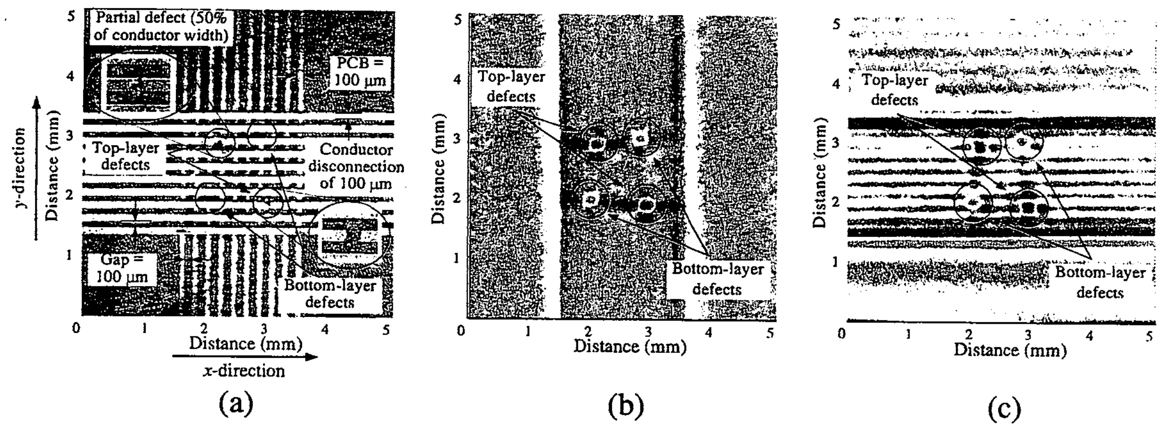


Fig. 12 Double layer PCB model (area of 5 mm × 5 mm) inspection example

High-density double-layer PCB model and it inspection results is shown in Fig. 12. The PCB conductors that parallel to x-direction are the top-layer conductor and the others are the bottom-layer conductor. The disconnection and partial defects are also allocated on both the top- and the bottom-layer of the PCB model. 2D-images reconstructed from ECT signal obtained from scanning over the top-layer of the PCB model in x- and y-direction are shown in Figs. 12 (b) and (c), respectively. The 2-D images show that the probe is capable of inspecting the defect clearly although the defect points are allocated on bottom-layer PCB conductor.

7. Conclusion

This thesis concentrated on the development of an ECT probe for high-density PCB inspection and studied on the possibility and performance of the proposed ECT probe for this purpose. Because ECT technique has advantages of high-sensitivity with crack or flaw, non-contact method, capable of microcrack detection by using proper magnetic sensor, and simple structure, ECT technique was selected for the purpose of high-density PCB inspection. The proposed ECT probe with SV-GMR sensor is capable of defect detection on PCB conductor with width of 70 μm and thickness of 9.05 μm. Three kinds of defect were tested in the experiment. The first was conductor disconnection, the second was partial defect on PCB track width, and the third was partial defect on PCB thickness. The results also show that the well inspection results can be performed by the proposed ECT probe.

Inspection of high-density single and double layer PCB models were demonstrated. Inspection of the PCB model with conductor width and gap of 100 μm was performed by the proposed ECT probe. In case of double layer PCB inspection, the probe is capable of inspecting the defects at the bottom layer if the distance between PCB conductor and sensing level is not over 200 μm. Moreover, dimension and alignment of PCB conductor can also examined. Consideration the peak of magnetic field density that usually occurs at boundary of PCB conductor is useful for investigation the PCB dimension and alignment. The inspection results represented that the proposed ECT probe is able to examine the PCB conductor dimension and alignment.

In future research, how to apply the proposed technique to PCB manufacturer is an importance. The research should concerns about improving the inspection capability and decreasing time consuming.

References

[1] K. Chomsuwan, Y. Fukuda, S. Yamada, M. Iwahara, H.Wakiwaka, and S. Shoji, "GMR Sensor Utilization for PCB Inspection Based on the Eddy-Current Testing Technique," *Transaction of the Magnetics Society of Japan,* vol. 4, no. 1, pp. 39-42, Feb. 2004.

[2] Y. Fukuda, C. Komkrit, S. Yamada, M. Iwahara, H.Wakiwaka, and S. Shoji, "High-Frequency, Low-Amplitude Magnetic Field Characteristics of SV-GMR Sensor for ECT Technique," *Journal of the Magnetics Society of Japan,* vol. 28, no. 3, pp. 405-408, Mar. 2004.

[3] S. Yamada, K. Chomsuwan, Y. Fukuda, M. Iwahara, H. Wakiwaka, and S. Shoji, "Eddy-Current Testing Probe With Spin-Valve Type GMR Sensor for Printed Circuit Board Inspection," *IEEE Transaction on Magnetics,* vol. 40, no. 4, pp. 2676-2678, Jul. 2004.

[4] K. Chomsuwan, S. Yamada, M. Iwahara, H.Wakiwaka, and S. Shoji, "PCB Conductor Dimension and Alignment Inspection Using an ECT Probe With an SV-GMR snesor," *Transaction of the Magnetics Society of Japan,* vol. 5, no. 2, pp. 93-96, Mar. 2005.

[5] K. Chomsuwan, S. Yamada, M. Iwahara, H. Wakiwaka, and S. Shoji, "Application of Eddy-Current Testing Technique for High-Density Double-Layer Printed Circuit Board Inspection," *IEEE Transaction on Magnetics,* vol. 41, no. 10, pp. 3619-3621, Oct. 2005.

[6] S. Yamada, K. Chomsuwan, T. Hagino, H. Tain, K. Minamide, and M. Iwahara, "Conductive Microbead Array Detection by High-Frequency Eddy-Current Testing Technique With SV-GMR sensor," *IEEE Transaction on Magnetics,* vol. 41, no. 10, pp. 3622-3624, Oct. 2005.

学位論文審査結果の要旨

当該学位論文に対して、平成18年2月1日に第1回論文審査委員会を開催し、同年2月2日に行われた口頭発表後に第2回論文審査委員会を開催し討議した結果，以下の通り判定した。

本研究は、プレーナ形励磁コイルと高感度巨大磁気抵抗素子（SV-GMR）で構成したうず電流探傷（ECT）プローブを用いた高密度プリント配線の性状検査法に関するものである。ECT技術を用いたプリント配線検査は独創的なアイデアであり、プリント配線導体の断線、短絡のみならず導電体の性状の検査が可能であることを明らかにした。主な成果は以下の通りである。

（1）マルチ巨大磁気抵抗素子（GMR）付ECTプローブの開発

4素子のアレーセンサを製作し、プリント配線検査用のECTプローブを製作した。1素子の大きさは、幅50、100μmであり、周波数特性20MHzまでの計測ができた。

（2）ECTプローブによるプリント基板検査試験

70-100μm幅、厚さ9μmのモデルプリント基板の断線・短絡、20％までの欠け傷、50％厚さ欠陥に対して検出可能であることを実験により明らかにした。

（3）高速検査のためのデータ処理法

高速AD変換とフーリエ展開を用いた高速のデータ処理法を検討し、データ取得速度を従来法に比較し100倍以上改善し、信号対ノイズ比10dB以上でデータ取得速度10 kS/s以上を実現した。

（4）画像処理による欠陥部分抽出システムの製作

導体としては不均一なプリント配線より得られる2次元検出信号イメージから、傷信号を抽出する信号処理ソフトウエアを試作した。

以上の研究は、うず電流探傷技術を電子工学分野の高密度実装基板の検査技術に適用した独創的な内容であり、博士（工学）論文に値するものと判定した。