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Nam Chol Yu
School of Science and Engineering, Kimchaek University of Technology, Pyongyang, North Korea

Son Guk Pak
Semiconductor Institute, Kimchaek University of Technology, Pyongyang, North Korea

Jin Sim Kim
International Technology Cooperation Center, Kimchaek University of Technology, Pyongyang, North Korea

Corresponding Author:
Nam Chol Yu
School of Science and Engineering, Kimchaek University of Technology, Pyongyang, North Korea

A manufacturing method of the flexible copper sensor for protection of hydro generators and transformers

Nam Chol Yu, Son Guk Pak and Jin Sim Kim

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Abstract
Protection of hydro generators and transformers is very important for managing of the power station. In this paper, we present the low-cost copper thick film flexible sensor for measuring the temperature in the stator of hydro generators and iron core of transformers. This sensor is based on PCB (printed circuit board) technology. A new design is proposed to avoid the defects on the resistive lead of the sensors. The detour leads are added in the resistive lead layout of the sensor. There were the improvements of the actual extract rate of sensor in the fabrication process and the accuracy of initial resistance of the sensor (the resistance at 0 °C). The actual extract rate is 100% in the sensor fabrication process by handling and deviations of the initial resistances (R_0=100Ω) are less than 0.1Ω in the fabricated sensors.

Keywords: Flexible temperature sensor, copper, thick film, PCB, detour lead, defect

Introduction

The flexible temperature sensor plays important roles in some modern engineering applications such as the temperature measurements of the curved surface or the interlayer structure with narrow gap in the industry equipment (e.g. iron cores of generator, motor and transformer) [5-10].

The platinum is generally used for the metallic film temperature sensors owing to high accuracy and stability, but that is expensive [1]. Also, several kinds of metallic materials like copper is occasionally used for special temperature measurement or less accuracy one [11-17]. Recently, copper film temperature sensors are widely utilized for the measurement of temperature in industry instead of platinum one because the design of the sensor based on PCB technology allow cost-efficient fabrication, easy handling, and simple retrofitting and replacement [2]. And then many kinds of flexible temperature sensor are developed by different sensing principles [27-30] and several sensing materials [31, 32]

But, the defects in flexible temperature sensor are usually being on the substrates, and decline the performance of the sensor like stability [18-26]. The lethal defect can be divided into two types, and one is disconnection and other is fall [3-4]. The disconnection defect decreases the actual extract rate in the sensor fabrication process and fall one decreases the stability and lifetime of sensor. It is therefore important to inspect and avoid the defects on the PCB leads. In this paper, we present the new featured copper thick film flexible temperature sensor to avoid the defects on the PCB leads.

Design of sensor

In this work, we make the thickness of copper film 25µm for robust structure of flexible temperature sensor. The number of defects on the PCB leads is increased by increasing of etch time when the thickness of film is increased in the etching process. The lethal defects like disconnection and fall are shown in Fig. 1, which are appeared on the PCB leads.

The detour leads are added in new design to avoid such the defects of leads. Fig. 2 shows the proposed layout design of the sensor. As shown in Fig. 2, the copper film resistive lead feature of the sensor is consists of four parts: main resistive lead, detour one, correction one and pads. Also, Fig. 3 shows the feature of connection between the main and detour leads by connection leads.

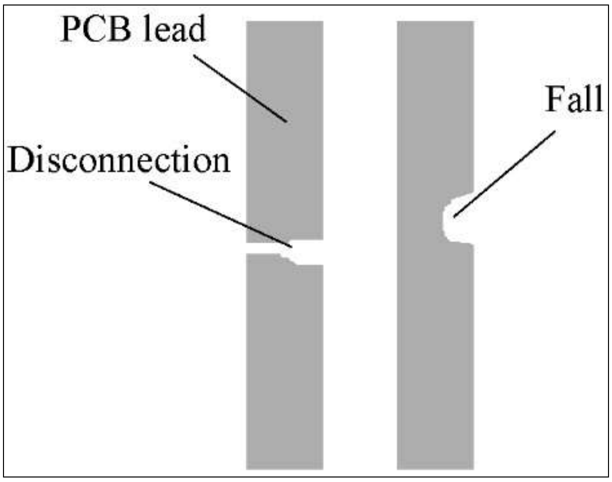

Fig 1: The lethal defects on the PCB leads

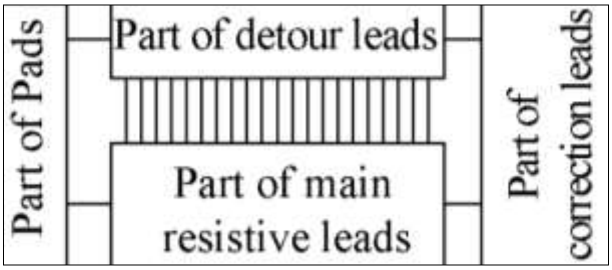

Fig 2: Layout design of sensor

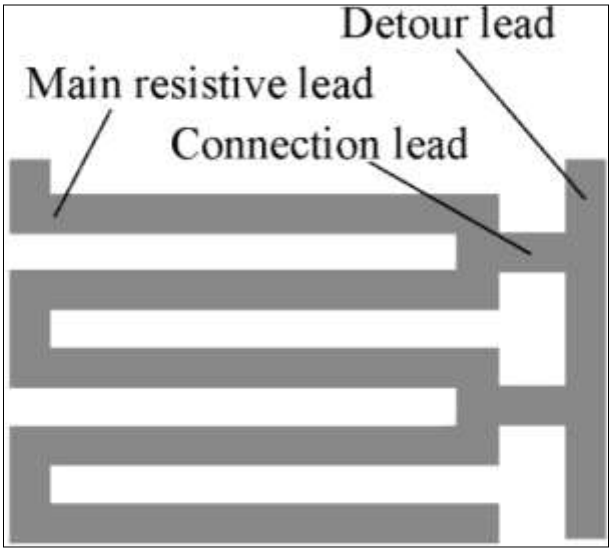

Fig 3: Connection between the main and detour leads

The connection leads by parts of main lead without defects are cut and that with defects are remained to avoid the defects on the main leads. In this way, we can avoid all the defects on the main resistive PCB leads and the actual extract rate is nearly equal to 100% in the sensor fabrication process by handling. If there is not any defect on the detour and connection leads, the actual extract rate of senor handling will be 100%. The actual extract rate of senor handling can be calculated when there are some defects on the main, detour and connection leads.

The existence probabilities of defects on a part of detour and parts of main leads connected to a one can be respectively calculated by following equations:

$$P_{dj} = \frac{K_j \cdot m_d}{N_j} \quad (1)$$

$$P_{dr} = \frac{N_i \cdot K_r \cdot m_d}{N_r} \quad (2)$$

In above equations, P_{dj} and P_{dr} are the existence probabilities of defects on a part of detour and parts of main leads connected to a one, K_j and K_r are rates of sum length of the all connection and detour and main leads to the one of all leads and N_r, N_j and N_i are the number of parts of leads, connection ones and parts of main ones connected to a one, respectively. The relationship between K_j and K_r is determined by Eq. (3) and Eq. (1) can be rewritten to Eq. (4).

$$K_j = 1 - K_r \quad (3)$$

$$P_{dj} = \frac{(1-K_r) \cdot m_d}{N_j} \quad (4)$$

Following equation expresses the existence probability (P_{drj}) of defects on a part of detour and parts of main leads connected to a one together.

$$P_{drj} = \frac{N_i K_r (1-K_r) \cdot m_d^{\,2}}{N_r N_j} \quad (5)$$

On the other hand, when N_s is number of unit copper area (1mm^2), the number of defects on the copper can be calculated by following equation:

$$m_d = P_{ds} N_s \quad (6)$$

In the above equation, P_{ds} is the existence probability of defects on the unit copper area. By substituting Eq. (6) to Eq. (5), P_{drj} is obtained by:

$$P_{drj} = \frac{N_i K_r (1-K_r) \cdot N_s^{\,2}}{N_r N_j} P_{ds}^{\;2} \quad (7)$$

And, the actual extract rate (Y_{ch}) without detour lead can be calculated by Eq. (8).

$$Y_{ch} = (1 - P_{ds})^{N_s} \quad (8)$$

When the thickness of copper layer is 25μm and the width of the lead is 40μm, the area of copper leads is obtained to 280mm^2 for 100Ω, the resistance of the sensor.
Then, the number of unit area (N_s) is 280 and K_r is 0.954.
Also, N_r is about 1000, N_i is 4 and N_j is 250 when the width of sensor is 8mm.
Table 1 shows the calculated values of P_{drj} and Y_{ch} by different P_{ds}.

Table 1: The calculated values of P_{drj} and Y_{ch} by different P_{ds}.

P_{ds}	0.1	0.05	0.01	0.005	0.001
P_{drj}	5.50×10^{-4}	1.37×10^{-4}	5.50×10^{-6}	1.37×10^{-6}	5.50×10^{-8}
Y_{ch}	0	0	5.99	24.5	75.6

As shown in Table 1, the P_{drj} nearly is zero even in the bad condition (P_{ds}=0.1) and the actual extract rate can be almost 100% in the sensor fabrication process. If there are not the detour leads in the layout of sensor, the actual extract rate is very low. The very high actual extract rate (nearly 100%) can be given by the detour reads in the sensor fabrication process.

Fabrication and Test

The cost-effective fabrication process of sensor is presented in Fig.4.

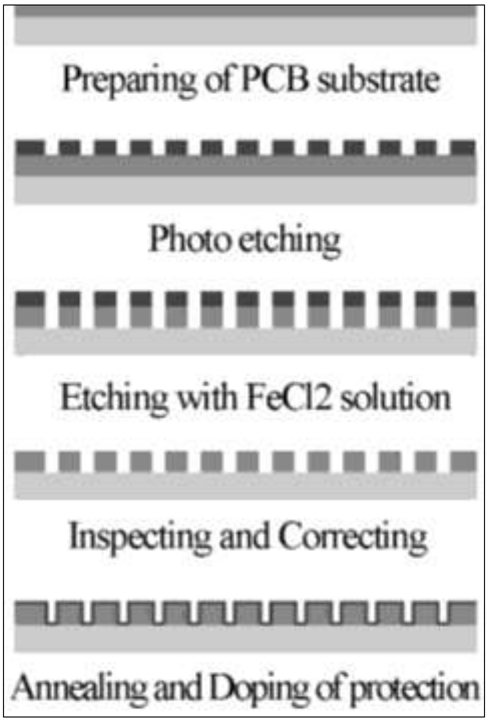

Fig 4: The sensor fabrication process

The fabrication starts with the PCB substrate. The minimal thickness for the flexible the PCB thickness is 100 µm by the fabrication limits of the PCB technology and the thickness of copper layer is 25µm for robust structure of flexible temperature sensor. The PCB substrate is etched with $FeCl_2$ solution after photo etching. Next, the patterned PCB substrate is inspected and corrected to avoid the defects and for 100Ω. The corrected PCB substrate is annealed after the doping of protection layer on the surface of one. Finally the wafer is cut to each sensor. The actual extract rate of sensor is 100% in the fabrication process. Fig. 5 shows the fabricated temperature sensor and the corrections of one.

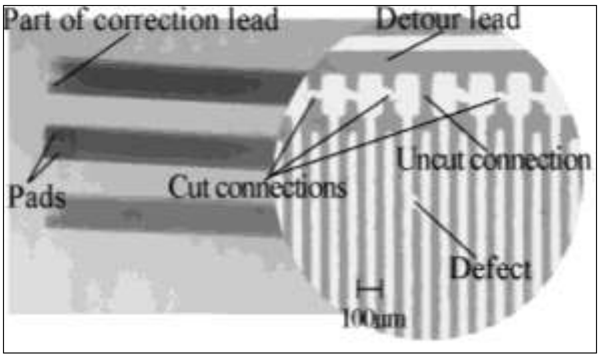

Fig 5: The photo of the fabricated temperature sensor

The sensor is tested for the long time of 3000 hours in 150°C and deviation rate of resistance of sensor is less than 0.1%. The measured characteristics of sensor are shown in Table 2.

Table 2: The characteristics of sensor

Deviation of initial resistance	TCR	Operating range	Maximum Current
100±0.1Ω	4.1×10^{-3} °C^{-1}	-70~160 °C	10mA

In this way, the cost of the sensor and the deviation of initial resistance can be decreased.

Conclusion

This paper presents the low-cost copper thick film flexible temperature sensor based on PCB technology. We proposed the new layout design of sensor to avoid the defects on the PCB leads. In the new layout design of sensor, the calculated actual extract rate is nearly 100% by adding the detour leads. The sensor is fabricated and tested for the long time of 3000 hours in 150 °C. The actual extract rate of sensor is 100% in the fabrication process. The deviation rate of resistance of sensor is less than 0.1%, TCR is 4.1×10^{-3} °C^{-1} and the maximum current is 10mA. In this way, the cost of the sensor and the deviation of initial resistance can be decreased. New sensors were already used in many power stations of our country.

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