Preliminary assessment of the stability of thin- and polymer thick-film resistors embedded into printed wiring boards

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Embedding passive components into multilayer printed wiring boards (PWBs) meet electronic device requirements concerning the necessity of saving the surface board area for active elements, reducing board’s size, improving device functionality and safety as well as overall product cost reduction. Since embedded components cannot be replaced after the board is completed, a long term stability and reliability are the important concerns for manufacturers.

This paper presents the results of examinations of embedded thin-film NiP resistors and polymer thick-film resistors during their continuous operation and the influence of temperature on the resistance values after the simulation of a lead-free soldering process and after the temperature cycling test (−40°C) to 85°C.

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1. Introduction

Passive components (linear and non-linear resistors, capacitors, coils, fuses, etc.) are essential parts of every electronic device and consume a significant area on the surface of printed circuit boards. Simultaneously their small size (e.g. 0402 or 0201) can cause problems in the automatic electronic assembly process and solder joints quality control. Technology of embedding passive components inside multilayer printed circuit board allows overcoming many problems connected with components used in certain high end products such as cell phones. As the components get smaller (e.g. 01005) manufacturers and board assemblers are presented with numerous challenges in attachment, inspection, handling, and cost of these devices. Embedded passives are more reliable by eliminating the number of solder joints. Simultaneous embedded components increase circuit density, improve electrical performance and functionality of electronic devices [1–3].

Although embedded passive components have many advantages, they can introduce other problems associated with cracks, delamination and the different components instability. For components embedding into boards more layers may be needed and different materials used as a substrate can cause significant thermo-mechanical stress due to Coefficient of Thermal Expansion (CTE) mismatch. In contrast to discrete components defect free embedded resistors cannot be replaced, which means that one wrong component can cause rejection of the entire PWB. Consequently, the long-term stability and reliability of components are major concerns for manufacturers to successfully implement this technology [4].

The concept of passive components embedded between inner layers of printed circuit board (PCB) has been introduced many years ago. The first trials of embedded capacitors started at the end of sixties of the last century [5]. In the beginning of seventies started the applying of NiP or NiCr layers for manufacturing of thin layer resistors [1,3,6].

Up to now, many others materials which can be used for embedded passives were elaborated. In addition to, the CTS, 3M, OakMitsui, Sammna-SCI and other companies have also begun to develop embedded passive components and materials in the late 1990s. So far, the embedded thin-film resistor and materials has developed maturely, the representative company include DuPont Electronic Technologies, Ohmega, Ticer, Sheldahl, W.L. GORE & ASSOCIAT and Georgia Inst. of Tech. In this century, the studies have also been carried out in Asia [7].

But the embedding technology is still used in small range, especially in military and air electronics as well as in space electronics. However, the growth of demand for high-advanced, and simultaneously low-cost electronic devices such mobile phones, laptops and network devices cause the wide interest in technologies of passive elements embedding. Currently, technology of embedded passives is experiencing revival and is expected that embedded passives will be the next pivotal technology for PCBs [8]. Previous research focused almost exclusively on one type material. Studied are either thin-film or polymer thick-film resistors only. The combination of thin- and thick-film resistors technology allows to manufacturing resistors in the whole range of useful resistance. This enables to obtain accurate resistance with a high degree of miniaturization in the lower ranges using...
thin-film resistors and a very high resistance at a higher tolerance using thick film resistors.

The polymer thick-film (PTF) resistors are generally formed from polymer resistive inks which are compatible with different base materials of printed wiring boards. Mostly these materials are composed of carbon (in the form of carbon black or graphite) and/or silver filler blended with polymer resin with the addition of solvents and diluters and optionally insulating powder fillers which give appropriate rheological properties [9]. The curing temperature of PTF inks for printed circuit boards should not be higher than 180 °C, but some producers offer pastes with curing temperature of 220 °C. They offer a much wider range of sheet resistance than thin-film resistive materials but their disadvantages are rather unsatisfactory resistance tolerances and limitations connected with their stability. The oxidation between polymer and copper interface can cause drift in resistance values, and they are vulnerable to delamination or cracking due to CTE mismatch.

In this paper the influence of high temperature during a lead-free soldering process and temperature cycling in the range from −40 °C to +85 °C on stability of thin- and polymer thick-film resistive components embedded within multilayer PWB are presented.

2. Materials and construction of resistors

Thin-film resistors are manufactured using NiP as a resistive material on FR-4 laminate in accordance with Ohmega-Ply technology [1,10]. In this technique firstly a thin layer of Nickel–Phosphorous alloy is electroplated on copper foil, afterwards a composite foil called RCM (resistor–conductor material) is laminated to FR-4 substrate. Finally copper circuitry and planar resistors are realized by subtractive processes.

In the study embedded resistive elements were created from Ohmega-Ply resistive materials with sheet resistances of 25 Ω/□ and 100 Ω/□ respectively and laminated on the polymer base materials FR-4. Their basic parameters are shown in Table 1.

PTF resistors were made using a standard thick-film method [9]. All used pastes from Electra Polymers & Chemicals Ltd. (Table 2) were screen-printed through yellow PET screens (77 T) with a capillary film of thickness 25 μm.

Several types of constructions and finishing structures of resistors contact termination, such as copper (Cu) (Fig. 1a), Cu in asymmetric design (Fig. 1b), Ni/Au (Fig. 1c) and Ag (Fig. 1d) were investigated. The asymmetric Cu contact termination design was used to compensate mechanical stresses (Fig. 1b), and electroless Ni/immersion Au layer or Ag layer (Electrodag PF-050 paste) were protective layer of Cu surface.

The thin- and polymer thick-film rectangle (bar) resistors were designed in three configurations: 1.5 mm × 4 squares, 1.0 mm × 2 squares, and 0.5 mm × 1 square. Additionally, the thin-film resistors were designed in three basic geometrical shapes: a bar, a multibar, and a meander with the following widths of resistive tracks: 1.4 mm, 1 mm, and 0.75 mm. Test boards T1 (160 mm × 180 mm) consisted of Ohmega-Ply material with 240 shaped thin-film resistive elements were laminated from both sides with external layers of Resin Coated Copper foil (RCC) material. 189 screen-printed on FR-4 laminate thick-film structures were covered with RCC material in a laminating process (Test Boards T2, 177 mm × 192 mm).

3. Experimental

3.1. Thermal effects

Thermal stability of embedded resistors during operation is a critical factor of success embedded resistor technology. When current flows through a resistor, it generates heat, which can be effectively dissipated through the board and to the ambient.

The dissipation of heat generated by current flowing through resistors was examined by means of the FLIR A320 thermographic camera with lens Closeup ×2 and the power source (stabilized power supply HMP2020 HAMEG). Before the temperature measurements the compensation of various radiation sources was performed automatically when the following camera parameters were set up: a resistive layer emissivity, environment temperature and a relative humidity.

Thermographs with temperature distribution in resistors were recorded for surface and embedded thin-film elements with bar, multibar and meander shapes and for polymer thick-film bar resistors. Resin Coated Copper foil (RCC) was laminated as an external layer. Fig. 2 presents examples of thermal images of non-embedded resistors, respectively thin- and thick-film rectangular resistors.

In all recorded thermographs of thin-film resistors it was observed that the temperature distribution along resistors was not uniform. For bar shaped resistors the highest temperatures were usually located at the central part of the resistor. It should be noted that areas in which more heat is cumulating are alternated by areas with visibly lower temperature. The heat transfer from areas near copper contacts was clearly better. In case of thin-film meander resistors the heat was cumulated in the inner corner of the meander. This construction was therefore more exposed for damages in these areas.

In the case of polymer thick-film resistors the temperature graph was more regular (Fig. 2b). The warmest areas were in central part of resistor. The temperature decreased regularly from high values in the centre to lower ones at the edge and contacts of the resistor.

Thermal images of embedded resistors were almost identical as observed for surface ones; probably because of rather small thickness of the resin layer laminated on the resistors (60 μm).

An example of temperature differences observed on the surface of bar thin-film resistor is presented in Fig. 3. During operation the resistor was quickly heated up to an average temperature of 78 °C ± 4 °C; such temperature remains stable for the established period of observation.

Exceeding permissible power value leads to excessive heating of resistors and after achieving strength border had caused its damage. Thermographs of damaged resistors in results of overheating are presented in Fig. 4 and an example of changes in the temperature measured for such resistors is shown in Fig. 5.

The temperature to which the resistors could be heated by the flowing of excessive electric current has exceeds 300 °C. Heat accumulations especially in narrow areas of the resistor were the highest thermal effect places, which were the reason for damages (burns).

There were different kinds of thermal damages of embedded resistors. It depended on the type of resistor and the surrounding material, usually epoxy resin.

The thermal damage of thin-film NiP resistors was mostly caused by the resin degradation in FR-4 laminate, on which surface the resistor was placed. Gases formed during the thermal decomposition of resin caused tearing of the resistor surface (Fig. 6a). Carbondized resin material was also observed.

| Type of | Sheet resistance (Ω/□) | Tolerance R (±% | NIP thickness (μm) | TCR (ppm/°C) | Initial typical resistor range |
|---------|------------------------|-----------------|---------------->|---------------|-------------------------------|
| R25     | 25                     | ±5              | 0.40           | −50           | From 40 Ω to 680 Ω          |
| A100    | 100                    | ±5              | 0.10           | −80           | From 100 Ω to 3300 Ω        |
In the case of thick-film resistors the degradation of polymer material in the cured film was also stated. Under the influence of heat generated by current flowing through resistors the temperature significantly increased and the polymer material began to burn; this was visible as light effect (red yellow glowing surface). The thermal disintegration of the polymer resistive material caused cracks of resistors usually at its centre (Fig. 6b).

### 3.2. Soldering process simulation

The embedded resistors passed twice through the convection belt furnace for the simulation of lead-free reflow soldering conditions and determined stability of their resistance value after such the thermal stress. Process was performed using a reflow time-temperature profile for the SAC305 solder paste. A maximum

<table>
<thead>
<tr>
<th>Type of ink</th>
<th>Type of filler</th>
<th>Ink sheet resistance</th>
<th>Initial typical resistor range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED7500_20 Ω</td>
<td>Carbon and silver</td>
<td>20 Ω/□/25 μm</td>
<td>From 100 Ω to 240 Ω ± 15%</td>
</tr>
<tr>
<td>ED7100_200 Ω</td>
<td>Carbon</td>
<td>200 Ω/□/25 μm</td>
<td>From 450 Ω to 1100 Ω ± 15%</td>
</tr>
<tr>
<td>ED7500_5 kΩ</td>
<td>Carbon and silver</td>
<td>5 kΩ/□/25 μm</td>
<td>From 35,000 Ω to 85,000 Ω ± 15%</td>
</tr>
</tbody>
</table>

**Fig. 1.** Type of resistor contact design and materials: (a) Cu; (b) asymmetric Cu; (c) Cu with protective Ni/Au coating; (d) Cu with protective Ag layer.

**Fig. 2.** Thermal images of 820 Ω resistors with connecting source of 21 mA current (supplied power 361 mW): (a) thin-film, (b) thick-film resistor; both of the bar shape.

**Fig. 3.** Temperature changes on the surface of bar thin-film resistor 820 Ω (width of 1 mm, layer 100 Ω/□) when voltage was applied.
temperature at the PCB surface was 250 °C and the time above liquidus (217 °C) 76 sec (Fig. 7). Tests were performed for the four T1 boards with thin-film resistors (measurements of 18 resistors on each board) and six T2 boards with PTF resistors (measurements of 40 resistors on each board).

The resistance of tested resistors before and after reflow simulation was measured by a four-point probe method using a precise Agilent 34401A digital multimeter. Measuring probes were connected to the resistors through laser ablated holes with the diameter of 800 μm. The observed changes in resistance values are presented in Figs. 8 and 9 for thin-film embedded resistors, and in Fig. 10 for polymer thick-film ones. High soldering temperature resulted in negligible changes in the resistance of thin-film resistors, although the observed resistance drift towards negative or positive values depended on the parameters of resistive layers. The

![Thermal image of thin-film resistors (width of 1 mm) with visible damage.](image1)

![Temperature and power changes of the thin film resistor 820 Ω loaded with increasing current.](image2)

![Thermal damage of: (a) thin-film and (b) thick-film resistors.](image3)

![The used reflow soldering profile.](image4)
changes were in the range from 0% to 0.5% for resistors made from 25 Ω/□ resistive layer and from 0% to −1.6% for the 100 Ω/□ resistive layer. It indicates that embedded thin-film resistors, independent on their shape, were not sensitive to the condition of lead-free soldering process. Repeatedly conducted measurements of embedded thin-film resistors during other experimental trials of lead-free reflow soldering confirmed the obtained results.

The polymer thick-film resistors (bare Cu contacts) revealed a quite different behavior from NiP ones. After the soldering test a moderate decrease of resistance, dependent on the resistor width and type of the paste (particularly of a filler material), was observed (Fig. 10). The largest changes – decrease about −4% were stated for the smallest width of resistors (0.5 mm) made using pastes with Ag filler, such as ED7500_20 Ω and ED7500_5 kΩ. It seemed that for shorter resistors, the contact resistance at the terminations represented a significant fraction of the total resistance and that was why resistance changes were noticeable. For longer resistors, the contact resistance was less significant. The changes about −2% were stated for all tested resistors made using carbon paste ED7100_200 Ω irrespective of the resistor width.

3.3. The temperature cycling test

To determine the sensitivity of embedded resistors to high and low temperatures the boards were subjected to 120 cycles between −40 °C and +85 °C in the CTS-70/200 Climatic Chamber. Parameters of one cycle are presented in Fig. 11.

Resistance of embedded resistors were measured before and after 120 cycles. Percent resistance changes caused by temperature cycling for embedded thin-film resistors (25 Ω/□ and 100 Ω/□ resistive layers) are presented in Fig. 12 and for polymer thick-film resistors in Fig. 13. Table 3 provides a comparison of the changes in resistance of resistors, depending on the type of used resistive material and the type of thick film resistors contacts.

After 120 temperature cycles resistance changes were from 0 to +2% independent of the thickness of NiP layer and the resistor width. These values were achieved even for a 0.1 μm thick resistive layer and 0.5 mm resistor width. Generally, resistors with smaller width were less stable.

Polymer thick-film resistors (ED7500_20 Ω and ED7500_5 kΩ inks) printed on bare copper contacts exhibited a drastic increase in resistance in case of resistors with the width of 1.0 mm and 0.5 mm. For example changes of resistance for resistors made of ED7500_20 Ω ink were 24% or 50%, respectively (Fig. 13 and Table 3). For resistors of 1.5 mm width the increase in resistance was significantly smaller (to 5%).

The polymer thick-film resistors with Cu contacts protected by Ni/Au or Ag finishes (Fig. 13 and Table 3) revealed a quite different behavior than resistors printed directly on etched copper terminations. In these resistors, irrespective of resistor width, resistance changes after temperature cycling stress were similar and they were weighted toward decreases in the range from 0% to −6%. The smallest changes of resistance values were observed
Table 3
Resistance changes during exposure to the temperature cycles.

<table>
<thead>
<tr>
<th>Resistance change (%)</th>
<th>Type of resistor</th>
<th>Termination</th>
<th>Resistive material</th>
<th>Width of resistors (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Thin-film resistors</td>
<td>Cu</td>
<td>Cu</td>
<td>NIP 5 Ω</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>Cu</td>
<td>NIP 100 Ω</td>
<td>1.7</td>
</tr>
<tr>
<td>Thick-film resistors</td>
<td>Cu contacts</td>
<td>Cu contacts</td>
<td>ED7100 200 Ω</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 20 ΩΩ</td>
<td>5.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 5 kΩΩ</td>
<td>−2.28</td>
</tr>
<tr>
<td></td>
<td>Asymmetric Cu contacts</td>
<td>Asymmetric Cu contacts</td>
<td>ED7100 200 Ω</td>
<td>4.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 20 ΩΩ</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 5 kΩΩ</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Ni/Au contacts</td>
<td>Ni/Au</td>
<td>ED7100 200 ΩΩ</td>
<td>−1.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 20 ΩΩ</td>
<td>−2.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 5 kΩΩ</td>
<td>−5.14</td>
</tr>
<tr>
<td></td>
<td>Ag contacts</td>
<td>Ag</td>
<td>ED7100 200 ΩΩ</td>
<td>−1.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 20 ΩΩ</td>
<td>−3.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ED7500 5 kΩΩ</td>
<td>−5.64</td>
</tr>
</tbody>
</table>

Fig. 13. Average percentage changes of resistance values after 120 temperature cycles for PTF resistors printed on different contact materials: bare Cu, asymmetric Cu, Ni/Au, and Ag.

Fig. 14. Cracks after the thermal cycle test, Mag. 5000× and 50,000×.
for resistive elements made from ED7100_200 Ω paste (without silver filler).

The applying immersion silver or screened silver paste to the copper terminations considerably improved resistors stability under thermal stress and indicated that these metals changed the reaction occurring at the copper/carbon ink interface.

4. Discussion and conclusions

Findings obtained in the lead free soldering simulation test and in the temperature cycling test explicitly showed differences in the stability of thin resistive layers and thick polymer resistive layers of resistive elements embedded into multilayer printed wiring boards.

High lead free soldering temperature caused negligible changes in the resistance of thin-film resistors. Independent on their shape the resistance changes were in the range from 0% to 0.5% for resistors made from 25 Ω□ resistive layer and from 0% to −1.6% for 100 Ω□ resistive layer. Range of resistance changes indicated that the lead-free soldering conditions had small influence on the stability of embedded thin-film resistors.

After soldering process simulation thick-film resistors printed on copper contact terminations demonstrated considerably larger changes than those observed for thin-film resistors. Such changes, irrespective of resistance values, depended on the resistor width and the type of used resistive ink. The largest changes (about −4%) were stated for the smallest width of resistors (0.5 mm) made of an ink including Ag filler. Changes about −2% were stated for all tested resistor printed with carbon paste irrespective of the resistor width.

The temperature cycling test has shown that the interface resistive film/bare Cu could be the reason of poor stability of polymer thick-film resistors with bare copper contacts. A considerable increase in resistance, even 50% and 70% for 1.0 mm and 0.5 mm width resistors was observed. Using of contacts with chemical Ni/immersion Au finish or screen-printed polymer thick-film silver paste lead to much better stability of polymer thick-film resistors under the temperature cycling stresses. For resistive elements with these types of contacts the decrease in the resistance was noted in the range from −1% to −5.5%. In the Salzano study [4] the failure in long-term temperature cycling test was defined as a shift in embedded resistance value greater than ±50% of the initial un-stressed resistor condition, or the development of an open or short circuit as a consequence of a particular test. Accepting this evaluation it is questionable to take into the consideration a construction variant of polymer thick-film resistors with bare copper contacts.

In the case of polymer thick-film resistor stability the effect of drastic resistance increase was considered in several areas. One of the key stability issues was how well resistive material was able to adhere to the surface of the terminations onto which they were deposited. The second key issue was the chemical interaction between resistive film and copper materials and delaminations between the resistive film and Cu termination. It appeared that adhesion of the carbon paste as well as the carbon–silver paste to copper terminations for resistors narrower than 1.5 mm was so low in some areas that after temperature exposures breaks of conducting connections between resistor’s structure and cooper’s surface could be found [13]. Our SEM examination of resistors after exposure showed some small cracks between contact terminations and resistive layer (Fig. 14). Such cracks could increase the resistance in reversible or irreversible manner.

Another key stability issues was thickness of patterned copper of PWB [14]. The thick copper foil could affect the temperature of the adjacent resistor material during curing, since Cu conducts heat to the resistor it was cooled by solvent evaporation. The resistor paste tends to pool at the edge of the patterned copper. Both of these effects could contribute to a lower sheet resistance in the resistor near the termination. For relatively long resistors these end portions of the resistors comprised only a small fraction of the total resistance, and their effect could be minimal. For short resistors the affected end portions could comprise a significant portion of the resistor, led to a low resistance value. Taking into consideration the influence of termination thickness it would be necessary to establish a design rule of 10–14 μm maximum copper thickness.

The presented results indicate the importance of protective coatings of resistor Cu terminations. Interposing Ni/Au finish or screen-printed polymer thick-film Ag layer between the copper and the resistive film resulted in considerably more stable resistors because those protective layers reduced interfacial oxidation or, in drastic case, corrosion at the copper/carbon film interface.

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