Embedded passive components and electronic circuits into the printed circuit board

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Abstract
The paper concerns on the investigations and on the development of high advanced technology of passive elements embedding into multilayered printed circuit board (PCB). The basic technologies, materials, structures and basic properties of embedded components are presented. The electrical, thermographic and environmental testing lead to the conclusion that they can replace the standard passive components assembled in Surface Mount Technology (SMT) and Through Hole Technology (THT) on the printed circuit board. The use of embedded passive components allows increase the speed, functionality, reliability and significant miniaturization of consumer and professional electronics.

1. Introduction
The Printed Circuit Board (PCB) is in the modern electronic equipment a mechanically support for realization electronic circuit. It consists of a dielectric board with or without plated holes, soldering pads and paths forming the electrical connection system for components. In the case multilayer PCB between the layers can be placed the other elements than only copper paths. In relation with it arose the idea to embedding into PCB of passive elements which are the two-terminal elements with known resistance, capacitance or inductance. The applying of typical passive elements nowadays is a huge business which develop mainly in automotive electronics, telecommunications, computers, and in aviation and space industry. The new electronic designs require more and more functionality and miniaturization to match into smaller and more mobile products. For this reason, they require assembling more and more components. The result is a large demand on the surface of a printed circuit board on their location. Therefore the techniques which reduce the number of elements on outside layers of PCB are nowadays very interested. The conception of passive elements embedding was introduced many years ago. On the beginning of ‘70 of last century there was started the applying of NiP layers to manufacturing of thin layer resistors [1]. However, the first trials of capacitors embedding started earlier – at the end of ’60 [2]. Up to present day the many materials which can be used for passive elements were elaborated. But that technology is used in small range, especially in military and aviation electronics as well as in space electronics. Due to the increasing number of elements which are now required to support a single active element, the passive elements are quickly becoming the major bottleneck in the general trend of miniaturization which has become so important in today’s electronics world. As conventional passive elements the miniaturization reaches its limits, and the next obvious choice is to integrate the passive elements into the printed circuit board. The embedding of passive elements into PCB allow a further miniaturization, have the potential of cost reduction and moreover exhibit superior electrical behaviour with respect to the minimization of parasitic effects [3,4].

2. Materials and methods for manufacturing thin- and thick-film passive components
Embedding the passive component into the printed circuit board in the lamination process is inseparable connection this component with the material of board. This results in lack of replacement in case of damage or incorrect work parameters. For this reason, it is necessary to use an optimal and repeatable technology of manufacturing and precise control of their functional parameters during production. Due to the fact that the material of the printed circuit board is mainly an organic material all processes must be carried out below its degradation temperature. On the other side the materials used in the embedded passives must have a resistance to chemically aggressive environment of PCB manufacturing and pressure up to 3 MPa. [5]
2.1. Thin-film resistors

To manufacturing of embedded thin-film resistors Ohmega-Ply® RCM (Resistor - Conductor Material) was used. The thickness of resistive layer in this material is from 1 micron to 0.05 microns. Sheet resistance is from $10 \, \Omega/\square$ to $250 \, \Omega/\square$, respectively. The Ni-P alloy resistive layer is electroplated onto the copper foil and then laminated with the core (e.g. FR-4).

![Diagram showing the structure of Ohmega-Ply® RCM material.](image)

The Resistor-Conductor Material is the difunctional layer. This layer is constructed in such a way that, depending on the needs, it is conductor or a resistive layer. In places where, after etching printed circuit board pattern, is not etched copper layer the RCM is a conductor. By contrast in places where copper layer was removed and the resistive layer was remained in the pattern of PCB there is a resistor.

Currently, the number of available materials for embedded passives manufacturing is growing. Besides NiP layer are also used other materials such as Ni-Cr alloy, NCAS-Aluminum Silicon, CrSiO, doped-platinum.

Because the thickness of the resistive layer is not more than 1,00 um (it depends on the required resistivity layer), embedding resistors inside the PCB does not increase the final thickness of the board. This is of particularly important in the case of manufacturing multi-layer boards with controlled impedance.

The resistive layer has very rough surface because is deposited by electrochemical method on prearranged copper foil in lamination process. The resistors can be designed in various shapes but in practice the simplest designs are used in the form of bar or multibar, in which the resistance is calculated by multiplying the resistivity of the resistive layer and the ratio of length to width of the resistor.

For manufacturing of thin-film resistors was applied technology which can be implemented as part of the standard PCB production. Schematically it is shown in Figure 3. The manufacturing process of embedded resistive components in this technology is a multistep process in which high accuracy is required at each stage of realization.

![Diagram showing the processing stages.](image)

After formation of the passive element is it placed in the inside of the circuit board in the lamination process. In the process of lamination thin resistive layer was treated by high pressures (to 30 bars) and temperature ($180 \, ^\circ \text{C}$). With sequential build-up technology the lamination cycles are repeated many times, so the materials used on embedded components must have appropriate properties that ensure resistance to such conditions and repeatability of parameters.

2.2. Thick-film resistors

To manufacturing of polymer thick-film resistors are used polymer resistive pastes. Generally they are materials filled with carbon black and / or graphite (sometimes also with silver flakes) dissipated in an epoxy resin. Pastes can be printed through screens or stencils, and should have a relatively low curing temperature, it is necessary with the temperature at which the board are laminated or slightly higher.

Examples of such materials are pastes ED series 7100 or 7500 of Electra Polymers and Minico® M 2000 Series RS MOD2 Acheson (the curing temperatures in the range 150-200°C).
The thick-film resistors manufacturing process is simple. More simple than in the case of thin-film resistors. After etching the pattern of PCB with contacts for thick-film resistors is the paste printed, which is then cured.

The thickness of resistors obtained after drying is a several to about 25 micrometers. The thickness is greater than in the case of thin-film resistors but also the embedding thick-film resistors inside the PCB does not increase the final thickness of the board. Manufacture thick film resistors carried out with less precision than photographically technique used for thin film resistors. Therefore sizes planar thick-film resistors on the circuit board must be larger to offset the impact of printing inaccuracies.

2.3. Capacitors

Capacitor structures can be very different depending on the availability of space on the PCB layers. The most useful are those for which the easiest way to calculate the volume (square, rectangle, circle). In the investigations were used the materials of Oak-Mitsui FaradFlex. It is possible to a very wide range of materials with different capacity per unit surface area from 180 to 1700 pF/cm2. The capacitance laminate consist of thin film dielectric layer closed between two thick copper foil. Depending on the capacity per area unit the dielectric consist of modified epoxy resin, modified epoxy resin partly filled with barium titanate or modified epoxy resin fully filled with barium titanate. The FaradFlex are ultra-thin laminates, it is necessary to properly handling of them. While before the manufacturing process the FaradFlex is resistant to damage after etching the material has thickness in etched places from 8 to 24 µm thus exposing it to damage.

In the investigation was also used new generation material - a composite Ohmega/FaradFlex. This material consist of a thin film capacitive layer closed between two thick copper foils (FaradFlex) and under one or two of the foil Ni-P resistive layer is applied (OhmegaPly). By using this composite can be formed a simple passive systems, such as band pass filters, which becomes very important with the increasing popularity of wireless technologies. Additionally, designing in this material an induction coil it is possible to create RLC circuit.

2.3. Inductors

The simplest inductive coil integrated with the printed circuit board are made by forming a meander or spiral shape by etching the copper layer. It is also possible the designing of a solenoid coil made up of holes between the layers of the printed circuit board connected by the tracks. Coils are used, for example in embedded RFID systems They can also be used in filters and simple generators integrated with the printed circuit board.

3. Experimental tests of manufacturing passive components and electronic circuit integrated with printed circuit board

The main problem in the formation of integrated components with a printed circuit board is to determine the influence of PCB manufacturing processes on the final parameters of the embedded component in the finished product. It is also important to determine the changes which occur under conditions of system operation with embedded passive, because they can not be replaced in the case improper operation or damage.

3.1. Thin-film resistors

Ni-P layer has low sensitivity to the majority of the printed circuit board manufacturing operations and the soldering process. Changes in resistance when the technological operations are strongly controlled do not exceed 2%.

The biggest influence on the resistance of the resistors has a process of oxide treatment a copper
surface before lamination. The resistance changes in this process can exceed 10%. Some of the chemical solutions used in this process can cause changes in resistance up to 60%. The oxide treatment of the copper surface is the most critical process, and the solution should be strictly monitored. Changes in resistance can be compensated by the addition of appropriate design corrections in the topography of the resistor. Taking into account the a surface resistance of thin-film materials Ohmega-Ply, the useful resistance range is from 10 Ω to 22 kΩ. This range is changeable and depends mainly on the availability of area for thin-film resistors and used type of resistive layer. The minimum width of the resistors obtained depend on the resolution of etching on technology line. In the experimental tests were manufactured properly functioning resistors with a width of 0.25 mm. The tolerance of the resistors can be reduced to less than 1% by using the laser trimming. The thin-film resistors are also characterized by a relatively high resistance to changing environmental conditions. The climatic tests (thermal cycles -40°C ÷ 85°C, thermal shocks -40°C ÷ 125°C) resistance changes were between 0.5% to 3%, and they were higher for thinner layers.

3.1. Thick-film resistors

The thick-film resistors are resistant to technological operations of the multilayer printed circuit boards manufacturing and the reflow soldering process. Changes in resistance when the technological operations are strongly controlled do not exceed 3-4%. However, the specificity of screen-printing process causes quite a significant scatter of the obtained resistance results (up to 20%). The minimum practical width of the thick-film resistor which can be printed using the screen-printing process is 0.5 mm. It is important to prepare the appropriate contacts for printing thick film resistors. The printing on clean copper layer has a poor stability in the conditions of use. The printing on Ni/Au contacts (ENIG) and in particular silver contacts allow made resistors which resistance changes in climatic tests (cycle and thermal shock) does not exceed 3%. The useful resistance range using the available polymer resistive pastes is 1 Ω - 20 MΩ. Also in this case, the tolerance of the resistors can be reduced below 1% using the laser trimming.

3.2. Capacitors

Technological operations the multilayer printed circuit boards manufacturing have no noticeable effect on the capacity of the embedded capacitors. The most important is in this case the accuracy of electrodes etching and the tolerance of positioning electrodes to each other. Possible to obtain capacitances by using FaradFlex material are between 1 pF to 10,000 pF. The upper limit can vary depending on the available space on layers of printed circuit board.

3.3. Inductors

The accuracy of the coils inductance integrated with the printed circuit board depends on the accuracy of the obtained pattern in the etching operation. Technological processes manufacturing of multilayer printed circuit boards have no influence on inductance of the coils. The useful range of inductance reaches values to tens of µH. More inductances are obtained by combining together a number of coils placed in successive layers in the printed circuit board.

3.4. Electronic circuits with embedded passives

Elaboration of technology of embedded passive components in printed circuit board allowed for design and construction of electronic circuits integrated with printed circuit board. It has been made many model systems, some of which are shown below.

RC filters

For the investigation the test board containing the electronic circuit composed of capacitor and resistor forming a low-pass filter was designed. All resistors were designed with the width of 0.5 mm. Filters are made with difunctional Ohmega/FaradFlex material

<table>
<thead>
<tr>
<th>Lp</th>
<th>R [kΩ]</th>
<th>R length [mm]</th>
<th>C [pF]</th>
<th>C size [mm]</th>
<th>cutoff frequency [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1.000</td>
<td>17.00</td>
<td>318.31</td>
<td>13.68x13.68</td>
<td>500.00</td>
</tr>
<tr>
<td>2.</td>
<td>0.330</td>
<td>5.61</td>
<td>482.29</td>
<td>16.84x16.84</td>
<td>1 000.00</td>
</tr>
<tr>
<td>3.</td>
<td>0.150</td>
<td>2.55</td>
<td>212.21</td>
<td>11.17x11.17</td>
<td>4 999.92</td>
</tr>
<tr>
<td>4.</td>
<td>0.082</td>
<td>1.39</td>
<td>194.09</td>
<td>10.69x10.69</td>
<td>10 000.08</td>
</tr>
<tr>
<td>5.</td>
<td>0.056</td>
<td>0.95</td>
<td>56.84</td>
<td>5.78x5.78</td>
<td>50 000.97</td>
</tr>
</tbody>
</table>

Fig. 5. RC filters.
The low-pass filter cut-off frequency was at a level of -6.5% to -13.5% of designed one. Smaller value of frequency than designed one was caused mainly by the higher capacitance of the capacitors. The exact analysis showed that the material had a higher capacitance per area unit than the capacity in the Datasheet. This points to the need to test the material before manufacturing process. This operation is not complicated and applying corrections on the project also does not cause problems. Therefore before designing of capacitors (and also other passives) it should be carefully checked the real capacitance density of the base material from which they will be made. The achieved capacities were different from catalogue data even up to 10%. The verification of capacity can be made quickly on the base of test coupons placed in the production structures which allows for significant improvement in tolerance of production.

RFID keyboard

The mobile wireless keyboard with passive RFID tags was made also from bi-functional Ohmega/FaradFlex material which permit to fabricate three embedded components - coil (antenna), capacitor and resistor. (Fig. 6). This test circuit The keyboard operation is based on activation of proper tag by pressing a key at the moment when the circuit is in the electromagnetic field generated by a reader. For each chip a unique code (command) is assigned. When the keyboard is close to the reader, it is powered and if a key is pressed the circuit sends the unique code. The keyboard does not contain battery and is powered only from the reader.

Strain gauge

The strain gauge manufactured using Ohmega-ply material with a surface resistance of 25 \( \Omega/\square \) and 100 \( \Omega/\square \) is shown in Figure 7. It was indented to make a complex strain gauge with embedded resistors into PCB – on the one side pressed and on the other tensioned when tee plate is deform. Due to limitations of the material results in a structure with two resistors embedded inside the PCB and two discrete resistors. It make impossible to compensation of the temperature influence and scattering of the resistance values on balance the strain gauge. In this circuit, a differential amplifier was added to increase sensitivity. The functionality tests of the strain gauge integrated with PCB showed that the resistance change due to deformation of strain gauge are enough large that can do displacement, force or vibration sensors. They can be constructed for applications which do not require accurate measurements due to hysteresis and visco-elastic properties of the substrate. It has been seen as the long time (a few seconds) determine of the values measured after deformation. The sensor is not suitable for high-speed precision measurements. The strain gauge has several times better response (change in resistance) to change the size in comparison with metallic strain gauges.

Presented above electrical circuits are only an example part of made structure. The integration technology passive components with the PCB allows for replace a large part of the passive components especially in microelectronics. This technology is still being developed, new materials coming with better parameters, allowing to extend the field of application. This is confirmed by the investigations of embedding active components into the PCB [7].

4. Conclusion

Resistors, capacitors and inductive elements are necessary in every electronic device, and in many cases they represent the considerable part of all elements. The applying of embedding technology for these components allows for the release at the
surface on the outer layers for active components. The space on the inner layers of a multilayer printed circuit board is largely unused and is ideal for placing in it the components of the electronic circuit. In the researches were combined manufacturing technique of passive elements so that the resistors can be produced in a wide range of resistance (from one ohm to mega ohms) and a number of RLC electronic circuits necessary for operation modern electronics. The use of such a solution should be carefully considered by designers of advanced electronic systems, because the possibilities of application of embedded passive components are very promising. The potential benefits from application of embedded passive components, including increased density of interconnections, miniaturization and also the improvement of some electrical parameters and improvement of electronic components reliability offers the new opportunities for the designing of modern PCBs.

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Bibliography


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