Precision formation of PCB topologies by femtosecond laser radiation

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Abstract The paper describes the classical methods of internal installation of embedded electronic components, their advantages and disadvantages. The technology of precision formation and correction of the topology of printed circuit boards using laser pulses of ultrashort duration is proposed. Physical processes occurring under the action of femtosecond laser radiation on the treated surface are described. A consistent description of the proposed technique is given.

1. Introduction
To form the topology of the conductive, resistive or dielectric layers of printed circuit boards, various methods are used: masking (the corresponding materials are deposited onto the substrate through removable masks) [1]; photolithography (the photoresist is applied to the entire surface of the substrate, after which the exposed areas are removed) [2]; electron-beam lithography (some parts of the coating are removed from the substrate by evaporation under the action of an electron beam) [3], etc. Despite the rather high efficiency of traditional methods, with the development of the miniaturization process, the technological problems of these approaches are becoming increasingly significant. Thus, reducing the size of integrated circuits has significantly complicated the technology of embedding electronic components in printed circuit boards by internal mounting.

In the classical form, this technology is used to embed passive and active chips inside a printed circuit board in two ways: face up and face down (Figure 1) [4]. These two variants differentiate in the way of interconnecting the component with the outside world and use different materials and processes. In a face-up process, the component is placed on a carrier material and the contact pads of the component can be seen after assembly. This approach offers some very good thermal properties and is well suited for power component embedding. In a face-down process, the component is assembled with the component image to the carrier material. Normally, a screen printed electrically non-conductive adhesive polymer is used to fix the component on the carrier. This method offers a better thickness control of the dielectric material between the component and the carrier.
Figure 1. PCB embedding process flows: face-up (left) and face-down (right).

Despite the fact that the process for a long time allowed to achieve a more dense component mounting, the inconsistency of traditional technology with modern requirements for the size and accuracy of the land patterns formation in the dielectric and conductive layers of PCB to accommodate the integrated components leads to defects formation. As a result, the yield of acceptable boards is reduced, increasing the cost. Against the background of these shortcomings, the technology of selective laser ablation (SLA) by ultrashort pulses (USP) offers an excellent solution for precision micromachining of complex printed circuit boards for small-scale or debug production.

2. Laser processing of printed circuit boards

Laser systems for a long time are actively used in the processing of printed circuit boards. The main area of their application is the formation of microvias with a diameter of up to 40 microns in the conductive layer. For these purposes, nanosecond laser systems are predominantly used, which is caused by their relatively low cost, high average power, and radiation stability. The mechanism of interaction of nanosecond laser radiation with materials is exclusively thermal in nature [5]. The surface of the target material is heated to the melting point, and then up to the evaporation temperature. Thus, the removal of material occurs after the formation of a liquid (molten) layer formed by heating and propagation of the temperature front into the target [6].

In contrast to the pulses of longer duration, the impact of USP on the surface of the treated metal with a sufficiently high intensity of $10^{12}$-$10^{14}$ W/cm$^2$ entails ionization of the region exposed to the initiated photoelectron emission, which contributes to the formation of a plasma plume (laser-induced plasma). The energy of the laser radiation is transferred to the processed material through the excitation of the bound electron shells of the sample atoms. The prerequisites for intense electron emission is a high electron temperature maintained during the action of the laser pulse on the target surface [7]. When the threshold of plasma formation is exceeded, the emission of both signs charges is nonlinear. In view of the above, for the materials processing it is advisable to use exposure modes characterized by the formation of plasma. Dispersion of the material under cold ablation conditions is inefficient due to the low productivity of the process.

Another important factor arising from the interaction of ultrashort laser pulses with a material is the dynamic erosion of the surface. This process is characterized by two main effects.
The first effect, which has a direct impact on the process of the material removal from the radiation exposure area, is the accumulation of heat. The effect occurs if the time interval between subsequent laser pulses is less than the time required to dissipate the residual heat generated by the radiation. This is about the thermal load, which in the case of processing isotropic materials with a sufficiently large thickness does not contribute to the development of the ablation process, but leads to volumetric heating followed by melting of the material, which explains the occurrence of the liquid phase during processing by ultrashort laser pulses. A peculiar indicator of the process is the formation of melt emissions at the entrance edge of the formed cavity. The effect of heat accumulation is more pronounced in materials with low thermal conductivity [8], however, in the case of processing the conductive layers of printed circuit boards with laser radiation, the thermal conductivity of copper foil is limited by the presence of an insulating layer. Thus, for the treatment of metal coatings, it is necessary to take into account the impact of the plasma plume on the dielectric separating the conductive layers.

The second effect, which has a significant effect on the dynamics of surface erosion, is due to the interaction of laser radiation with material emitted as a result of ablation in the form of particles, vapor, or plasma. It leads to scattering of the incident radiation, reflection or absorption by laser-induced plasma, which significantly increases the thermal effect. In accordance with the studies of the parameters of the plasma plume resulting from the ablation of a material by ultrashort laser pulses [9], the radiation intensively interacts with clusters and melt drops exceeding ~ 1 μm. This process dominates for pulse repetition rates of the order of a few MHz.

Considering the examined effects, it can be concluded that the formation of topology in multilayer printed circuit boards by direct processing of USP is inefficient, since an increase in the radiation energy leads to the destruction of both the metallized and the dielectric layers. Thus, the optimal solution is to use an additional protective coating applied to the surface of PCB designed to form a stencil of the desired topology.

3. Femtosecond laser micromachining technology

The method involves the masking of the PCB, local laser removal of the applied coating, followed by etching and washing off the protective layer. On classic printed circuit boards with a composite metallic coating of Cu - 15 μm, Ni - 5 μm, Au - 0.1 μm, the formation of landing pads for micro-sized unpackaged mounting components is difficult to implement. Industrial technologies provide reproducible obtaining of a conductive pattern with a width of tracks and gaps between them not less than 50 microns. The proposed approach allows the formation of land patterns with high accuracy (up to 1 μm) and reproducibility. When using blanks with a metallization thickness of about 15-20 microns, the minimum width of the tracks and the distance between them is 20 microns. For thin-film blanks with a conductive layer thickness of 5–9 μm, the stable track width reaches up to 10 μm. The operation is characterized by high productivity and lower cost due to the exclusion of the photomasks preparation and photoexposure stages.

The processing technology includes four key stages, schematically presented in Figure 1. The board is covered with a layer of protective mask (Figure 2a), capable of actively absorbing the laser radiation used for processing, and at the same time resistant to chemical etching that allows to protect the metal coating from destruction. This is followed by surface treatment of the masked layer by laser radiation along a predetermined trajectory (Figure 2b). At the stage of chemical etching of the preform, the unprotected areas of the conducting layers are removed (Figure 2c), after which the sample is cleaned from the remaining mask at the washing phase (Figure 2d).
Figure 2. The sequence of blanks processing: a) blank with applied mask; b) blank with locally removed protective layer; c) blank after etching; d) blank after washing off the mask.

4. Conclusion
The use of ultrashort laser pulses as a tool for forming a topology pattern of masking layer allows to avoid physical and thermal damage of surrounding areas. Properly selected exposure mode allows to remove the protective layer without adversely affecting the conductive coating. The operation can be performed both as a finishing treatment, and in the process of topology correction during the layer-by-layer assembly of the board-blank.

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