Photothermocapillary detection of conductive track ruptures on a printed circuit board coated with a protective film

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Abstract. The photothermocapillary (PTC) method has been proposed to detect ruptures of the copper tracks of a printed circuit board coated with a black protective film absorbing the pump laser radiation. The ruptures were simulated by obtaining parallel tracks of different lengths by etching in ferric chloride solution. The method consisted of the scanning with the pump laser of the tracks along a line perpendicular to them and passing through their midpoints, and plotting a scan-profile of the diameter of PTC signal as a function of the scan coordinate. The scan-profile was a sequence of maxima and minima the diameters of PTC signal corresponded to the beam position in the middle between adjacent tracks and in the midpoint of the track, respectively. It was found that with an increase in the track length above a critical value, dependent on the laser beam power, the diameter of PTC signal reaches saturation. With increasing power by 1.85 times, the sensitivity of the PTC method increases by 2.57 times. The spatial resolution of the PTC method reaches tens of micrometers. Experimental results have shown that the proposed PTC method is simple and efficient for detecting of hidden defects of the copper tracks on the PCB.

1. Introduction. Photothermocapillary effect

Increasing the compactness of printed wiring and reducing the width of conductors (conductive tracks) and the gaps between them make it necessary to control of the continuity of the electrical circuits. To detect such defects as ruptures of conductors, cavities in soldered contacts, insulation strength of disconnected circuits, insulation thickness heterogeneity and detachments from the surface of the printed circuit boards (PCB) are often not available for standard visual inspection. The control of these defects is complicated when the tracks are covered with a nontransparent protective film. More often, to check the continuity of the printed circuits, contact methods based on measuring the electrical conductivity by using ohmmeters or electric calls are used. However, in recent years, thermal methods allowing the detection of the entire complex of the PCB defects have become increasingly applicable. Among these are optical techniques such as thermoreflectance (infrared microscopy) [1-4], liquid crystal thermography [5] and scanning thermal microscopy [6]. However, the implementation of these methods typically requires both complex experimental setup, highly precise and very expensive instruments and complex algorithms of data analysis that does not allow for realization of cheap, compact and easy-to-use devices. In present work, we propose a novel and simple express-method for...
the control of defects on PCBs, which is based on using of the photothermocapillary (PTC) convection in a thin liquid layer on a tested solid substrate. The mechanism of the PTC convection is as follows [10]. When a laser beam hits an absorbing substrate covered with a thin transparent liquid layer a heat source at a solid-liquid interface arises. The heat distributes into the substrate and into the bulk of liquid. In the latter case, the temperature of the free liquid surface increases, that leads to a local decrease in its surface tension, \( \gamma = \gamma_0 + \gamma_T (T - T_0) \), where \( \gamma_0 \) is the surface tension of the liquid at temperature \( T_0 \); \( \gamma_T \) is the thermocapillary coefficient, which is negative for most pure liquids. As a result, a surface tension gradient along the free liquid surface arises and induces the radially outward thermocapillary liquid flows, which create the concave deformation in the liquid layer in the laser spot (see, figure 1 (c)). The capillary pressure below the deformed surface causes the bottom flow towards the heated spot, wherein it conjoins with the surface flows resulting in the stationary thermocapillary deformation. The deformed liquid interface represents a concave mirror. A probe laser beam reflected from this mirror forms a circular interference pattern on a remote screen, called as the photothermocapillary (PTC) signal, which has a bright and wide outer ring (see, figure 1 (c)). Recently we have shown [7-10] that the PTC diameter is very sensitive to variations of thermal conductivity of substrates, hence the PTC effect can be considered as a simple and easily implemented method for nondestructive control of hidden defects of the PCB. To validate the proposed method a test sample of PCB with parallel conductive tracks of different length, which serve as a model of the ruptured tracks, was used.

2. Experimental part

2.1. The sample preparation

The tracks of different length \((l = 2, 4, 8, 16, 32\) and 64 mm) and 1.4 mm of width, located with a gap (insulation) of 1.3 mm (the gap between the last two tracks was 1.9 mm) were etched out on a one-sided PCB in ferric chloride solution using a mask. After obtaining the desired copper tracks, the surface of the PCB was cleaned from dust and treated with acetone. Then the PCB was glued to a duralumin disc, which works as a heat sink and the PCB stiffness amplifier. After the adhesive had solidified, a ring of 70 mm in diameter was glued to the PCB surface, and then this cell was filled with a liquid black nitrocellulose varnish (Zapon lacquer). After the solvent evaporated a coating film about 30 \( \mu \)m thick was formed on the copper tracks. A cross-section of the sample and the map of the tracks location under coating film are shown in figure 1 (a), (b). To perform the scanning experiment a layer of silicon oil \((\mu = 4.56 \text{ mPa} \cdot \text{s})\) of 300 \( \mu \)m thick was deposited on the sample.

2.2. Experimental setup and method

The experimental setup is shown in figure 1 (c). The pump laser beam \((P_p = 21.3 \text{ mW}, \lambda = 632.8 \text{ nm}, d_e = 2.5 \text{ mm})\) passing through the optical system (2)-(4) (figure 1(c)) and focused with a lens (20) \((d^*_e = 0.5 \text{ mm})\) falls almost vertically on the silicone oil layer (5), with the thickness controlled with the calibrated wire (6). The liquid layer is protected from dust by a transparent lid (9). The probe laser beam \((P_b = 0.3 \text{ mW}, \lambda = 632.8 \text{ nm}, d_p = 5 \text{ mm})\) is expanded with a spherical mirror (16) and directed to the TC depression in the liquid layer with the mirror (17). The reflected from the liquid surface the probe beam forms on a remote screen (19) the PTC signal. The horizontal position of the sample is provided by the system consisting of a massive base (11), on which a Teflon cell (12) with a solidified layer of Wood’s alloy (13) is placed. A plane-concave lens (14) was laid down with a concave surface onto the Wood’s layer. To scan the PCB sample, the cell is shifted horizontally using the micrometric screw (21). The diameter of the PTC signal, \( D \), is measured with a ruler (22). In experiments, the power of the pump beam was chosen according to the following requirements: (i) the absence of the liquid layer rupture, and (ii) the clearly visible external wide ring of the PTC signal, which can be measured with sufficient accuracy. The power of the pump laser beam was changed using a set of light filters.
The scanning of the PCB sample was performed with a step of 100 μm starting at the track of 2 mm length in the direction perpendicular to the tracks and passing through their midpoints (figure 1 (b)). The scan-profiles as the dependency of $D$ on $x$ were plotted, where $x$ is the horizontal scan coordinate.

![Figure 1](image1.png)

**Figure 1.** (a) Schematic cross-section view of the printed circuit board test sample. (b) A map of the location of the copper tracks of different lengths (the horizontal arrow indicates the scan direction). (c) The experimental setup: 1, 15 – the pump and probe lasers, 2 – attenuator, 3 – shutter, 4, 17, 18 – mirrors, 5 – liquid layer, 6 – calibrated wire, 7 – test substrate, 8 – ring, 9 – cover, 10 – absorbing film, 11 – massive base, 12 – Teflon cell, 13 – solidified Wood’s alloy, 14 – plane-concave lens, 16 – spherical mirror, 19 – PTC signal on a screen, 21 – micrometric screw, 22 – ruler.

3. Results and discussion

Figure 2 (a) shows the scan-profiles of the PCB sample obtained at the powers of the pump laser beam 2.8 and 5.2 mW. The maximum, $D_{\text{max}}$, and minimum, $D_{\text{min}}$, values of the PTC diameter correspond to the position of the beam in the midpoints between the copper tracks (the isolation gaps) and in the midpoints of the conductive tracks, respectively. The decreasing $D$ on the copper tracks is related with a sharp increase of the thermal losses due to dissipation into the copper track due to its high thermal conductivity in comparison with the textolite ($k_c/k_t \approx 1176$), where $k_c$ and $k_t$ are the thermal conductivity of copper and textolite, respectively. It turned out that the increasing $l$ of the copper tracks leads to a slight decrease in $D_{\text{max}}$ that is caused by the influence of the size of the heat-conducting tracks on the amount of dissipated heat into the substrate, i.e., by the increasing of the so-called “effective” thermal conductivity of the substrate. However, for the track of 64 mm length, an opposite behavior is noticed, that is an increase in $D_{\text{min}}$ and $D_{\text{max}}$, which can be related to the larger isolation gap with the adjacent track ($l = 32$ mm) on the one side and the absence of heat-conducting tracks on the other side.

To analyze the obtained results the dependency of $D_{\text{min}}$ on the length of the copper tracks was plotted in the semi-logarithm scale (figure 2 (b)). As is seen, with increasing $l$ of the tracks, $D_{\text{min}}$ of the PTC signal decreases and at a critical value of $l_c$ reaches a constant value. Thus, the limit of applicability of the PTC method of the scanning of the tracks is determined by the reaching of $D_{\text{min}}(l)$ saturation. The critical $l_c$ is determined as a cross point of the straight lines fitting the decreasing and stationary parts of $D_{\text{min}}(l)$ dependency (figure 2 (b)). For the pump laser power of 2.8 and 5.2 mW, the values of $l_c$ are 4.6 and 5.0 mm, respectively. The constant value of $D_{\text{min}}$ implies that the tracks in the region $l > l_c$ can be considered as the thermally “long”. With increasing the power of the pump
laser beam, there is a tendency to increase the value of $l_c$ and this fact is the starting point for further research and increasing the range of applicability of the photothermocapillary method. The sensitivity of the method is defined as the slope $\Delta D_{\text{min}}/\Delta l$ of the $D_{\text{min}}(l)$ dependence. As can be seen in figure 2 (b) the sensitivity $\Delta D_{\text{min}}/\Delta l$ depends on $P_e$ and takes on values of 16 and 43 at 2.8 and 5.2 mW respectively, i.e., with increasing $P_e$ by 1.9 times $\Delta D_{\text{min}}/\Delta l$ grows by 2.7 times. Taking into account that the error of $D_{\text{min}}$ measurement is around 1 mm, one may conclude that the PTC method allows detecting the minimal changing of the copper track length down to 20 and 60 µm, respectively.

![Diagram of PTC signal](image)

**Figure 2.** (a) Scan-profiles of the copper tracks at powers of the laser beam: ○ - 5.2 mW, ● - 2.8 mW. (b) The PTC signal of the copper track as a function of the track length.

4. **Conclusions**

The photothermocapillary method for detecting ruptures of the copper tracks of the PCB coated with a black protective film has been proposed. The method involves the covering of the PCB sample with a liquid layer, the scan of the copper tracks along a line perpendicular to tracks and the plotting of a scan-profile as the diameter of PTC signal versus the scan coordinate. The minima diameter of the PTC signal on the scan-profile, corresponding to the position of the pump beam in the midpoints of tracks, decreases with an increase in the track length until reaching a constant value. The latter determines the limit of applicability of this method in terms of the track length. The resolution of the PTC method reaches tens of micrometers. The method is simple in implementation and does not require special equipment and software for processing the optical signal.

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