ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2021. No. 1 (15)

UDC 621.3.095.2 DOI: https://doi.org/10.30837/ITSSI.2021.15.120

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TECHNOLOGY FOR CREATING THE TOPOLOGY OF PRINTED CIRCUIT BOARDS USING POLYMER 3D MASKS

The **subject** of research is the influence of factors of exposure of two-dimensional images on the topology of conductors in the manufacture of printed circuit boards by the method of three-dimensional polymer photomasks. The **purpose** of the work is ensuring the accuracy and preservation of the geometric dimensions of the conductors of printed circuit boards during LCD exposure of masks on the work piece. To achieve this goal, it is necessary to solve the following **tasks**: to analyze photolithography technology and types of polymer 3D printing; to develop a technological process for exposing photopolymer masks to a printed circuit board blank using 3D printing technologies; to conduct experimental studies to determine the optimal exposure parameters; on the basis of the empirical results obtained, to calculate the correlation coefficients of the factors for recall; to construct a linear regression model of the dependence of the deviations of the geometric dimensions of the printed conductors on the parameters of solutions for etching and exposure conditions. **Results**: The constructed regression models will become the basis for creating a software database that optimizes the initial images of the topology of printed conductors in the automated production of printed circuit boards. This will simplify the process of developing the topology of printed circuit boards, taking into account the real influence of the parameters of the technological operations of etching and exposure on the thickness of the tracks of the conductors of the printed circuit boards, which will reduce the proportion of rejects in the manufacture of single- and double-sided printed circuit boards. **Conclusions**: an LCD exposure technology and a method for studying the effects of exposure factors on the quality of printed circuit board topology are proposed, which provide sufficient empirical data to create regression models for calculating the influence of technological factors on the final dimensions of conductive paths in the production of printed circuit boards. Further development of the proposed technology will make it possible to manufacture rigid and flexible printed circuit boards completely, with conductive paths, a dielectric base, electronic elements that can be used in various devices.

Keywords: printed circuit boards; exposure; polymer photomasks; etching solution; LCD printing; regression analysis; topology; conductor image adaptation.

Introduction

Modern development of technologies in the field of instrument making is aimed primarily at miniaturization of devices and integration in one device of a large number of modules, which in turn leads to the need to miniaturize both products as a whole and their individual components, components and printed modules [1]. Miniaturization of the device involves both reducing the size of electronic elements and the dimensions of printed circuit boards (PCBs) [2]. The process of manufacturing boards using photolithography technology is time consuming and requires additional costs of materials and equipment to create stencils, the use of which in turn does not allow you to quickly adjust production to create new products. Modern automated production is characterized by the lack of such flexibility, which is their significant disadvantage. One of the ways to solve these problems can be the development of methods for adaptation and optimization of technological parameters of exposure of the topology of the PCB, using additive 3D printing technology, in the manufacture of single-sided and double-sided PCB, made on the basis of foil fiberglass and getinax blanks without the use of photoresist films. Thus, this approach can provide not only a solution to the problem, but also provide the necessary parameters of the product, such as:

- preservation of geometric dimensions of the PCB topology;
- accuracy of positioning of conductors;
- ensuring the electrical reliability of PCBs;
- preservation of mechanical stability of conductors;
- avoidance of defects in the PCB topology.

Problem statement and research purpose

The main task of the study is to develop a technology for creating a conductive topology of printed circuit boards using SLA and DLP 3D printing technologies. To solve this problem, it is necessary to perform the following:

- to assess the capabilities of traditional technologies for the production of printed circuit boards;
- to analyze modern methods of 3D printing with photopolymer resins - this will serve as a justification for the new method proposed in this article;
- to develop on the basis of the analysis of 3D printing technology and the principle of operation of the device for LCD exposure;
- to conduct a series of experiments and identify the dependence of the accuracy of the geometric dimensions of the PCB topology on the technological parameters of exposure;
- to compare the quality of PCB conductors made with 3D masks and conductors made with a film photoresistor.

The end result is to obtain empirical data on the basis of which a correlation-regression model of the influence of technological parameters of printing on the preservation of the initial geometric dimensions of the topology of printed conductors is built.

Research and analysis of the obtained results

At the initial stage of the photolithography process, the treated surface is covered with a photoresist, which is applied with an aerosol, or by gluing a photosensitive polymer film. Then through the photomask, with the set topology of the board, the photoresist is illuminated. Next, the exposed areas are removed in the developer. The obtained pattern on the photoresist is used for further technological stages: etching, electrodeposition, vacuum spraying or others. After one of these processes, the remnants of the photoresist in the development are also removed (fig. 1).

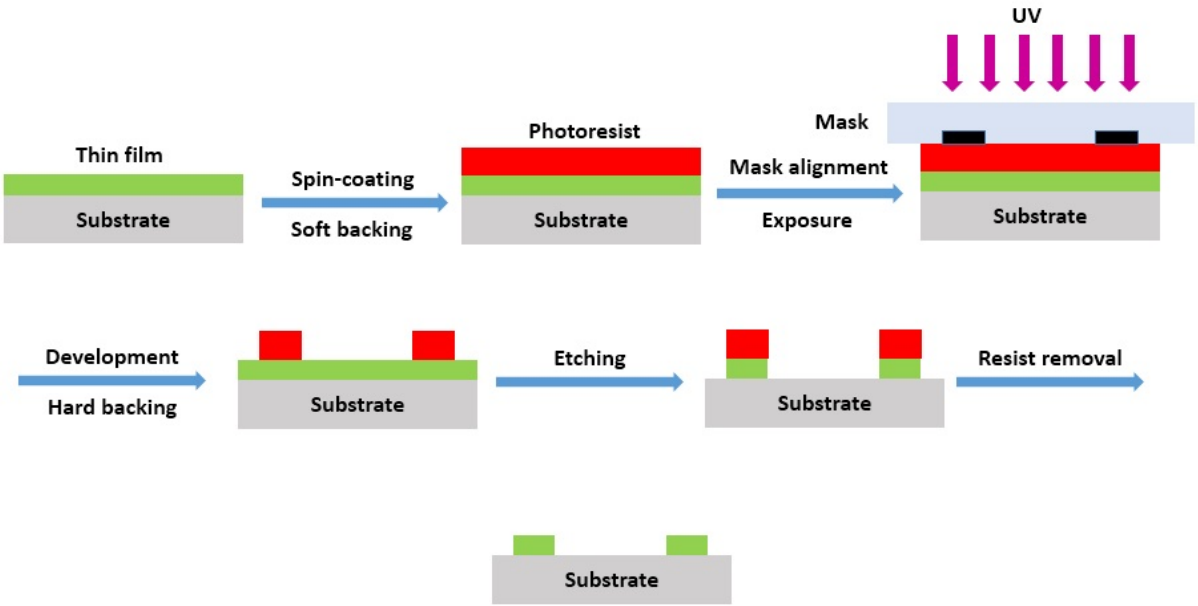


Fig. 1. Simplified photolithography scheme for printed circuit boards

Exposure can be performed both with the use of a photo template and without it (non-mask lithography). In the latter case, the image on the photoresist is formed directly by the movement of the laser spot, or by an electron beam or a group of them focused on the surface of the photoresist. When using photo templates, projection exposure methods are more often used, when the image from the photo template is transferred to the photoresist, using a system of optical lenses.

Thus, the process of photolithography consists of successive stages: the application of a photoresist on the product and the subsequent exposure of the photomask on the treated surface, followed by etching. Each stage requires highly specialized equipment and consumables. Expensive, difficult to maintain, dimensional machines (such as installations for direct exposure) cannot be used in the production process of small businesses.

In mass production, each stage takes a significant amount of time, for example, when applying a photoresist by aerosol requires time to dry the products. Also, as a result of an operator error or technical failure of the equipment, defects in the product may occur at each stage. To minimize these negative factors, a higher level of automation is required, which ensures control and synchronous operation of all main and auxiliary equipment.

In addition, at the stage of etching, geometric deviations of the obtained image from the original PCB topology are possible, for example, etching of conductor tracks.

The advent of additive manufacturing technologies (3D printing) allows a new look at the solution to this problem. Photopolymer printing technologies can be used to mask certain areas of the foil dielectric and subsequent etching of the conductor system. This equipment allows quick readjustment for the production of new products, while ensuring high manufacturing accuracy [2].

One of the most popular printing technologies for precision prototyping is printing technology with photopolymer resins and powder materials, which in comparison with other additive manufacturing technologies allow to produce parts for various purposes with high accuracy and detail.

There are several technologies for illuminating the polymer in photopolymer printers. From them it is possible to define the three basics (fig. 2) [3]:

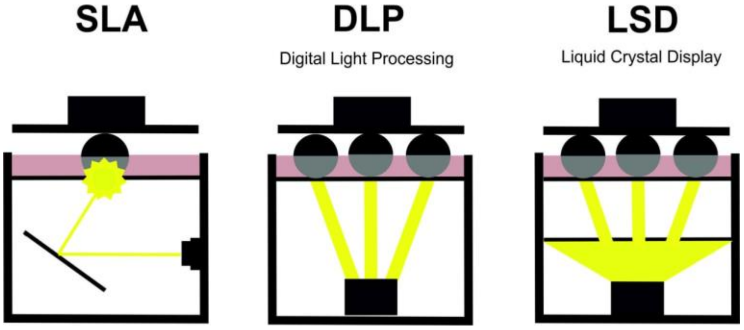


Fig. 2. Types of photopolymer 3D printing technologies

1) SLA technology (Selective Laser Sintering). The method of additive production (3D-printing) called "stereolithography" is the sequential polymerization of thin layers of liquid photosensitive polymer by a low-power ultraviolet laser beam. In the working capacity of the 3D printer there is a platform immersed in liquid resin. Initially, the platform is near the surface of the polymer, covered with a thin layer of 20 microns to 150 microns, on which the laser begins to form a layer of detail [4-5].

The model is cut into thin layers equal to the resolution of the printer along the vertical axis. After creating one layer, the printer immerses the platform in the thickness of the new layer of the model (from 10 µm to 150 µm) and creates the next layer (fig. 3).

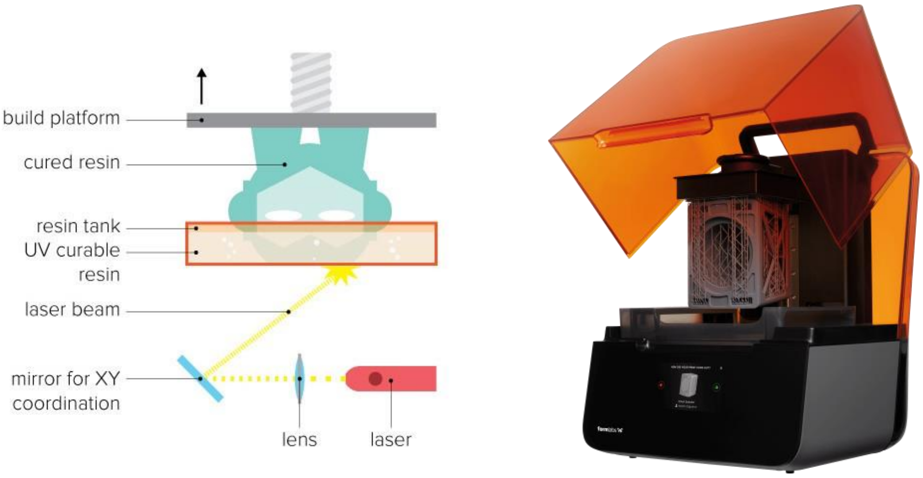


Fig. 3. Scheme of SLA printer operation

Under the influence of a laser, the power of which is relatively small, which makes the printer cheaper than devices working with powder materials SLS, SLM, etc., the polymer hardens, forming the walls of the future product. Thus, the model is created entirely layer by layer. If it has hinged elements, then supports are built for them from the same polymer, which are then mechanically removed. Support in the model is provided and created in CAD-programs at the design stage of the model.

The advantage of this technology: the ability to build large models; high accuracy; the ability to build models of any shape and design; low percentage of material consumption; low operating noise [3].

Disadvantages: the use of photopolymer, which is more expensive than other materials; high cost of the printer; the need to ensure a high class of accuracy when building a printer (ensuring the correct angle of the mirror); the need for precise mechanics (accuracy of the location of the bath at the level of one layer from the surface to the platform); the need for frequent printer maintenance;

2) DLP technology (Digital Light Processing). The principle of operation of 3D printers using 3D printing technology DLP is similar to the operation of the projector [5-6]. The polymer turns into a solid form under the action of light of the visible spectrum and the whole layer is illuminated at once. The light flux is modulated by micromechanical mirrors, each of which is controlled separately. Depending on the position of the mirror, the light either passes to a given point of the layer or not. Thus, the machine has a fixed logical extension - the number of points in the XY coordinates. Their physical size depends on the distance from the radiation source in the system of micro mirrors is the model (fig. 4).

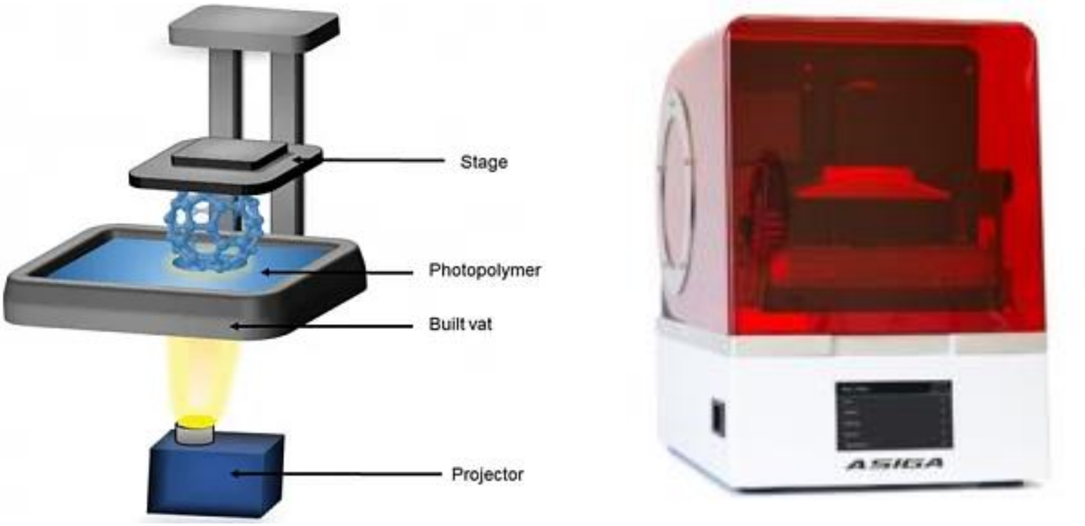


Fig. 4. Scheme of DLP printer operation

The disadvantage of this technology is the dependence on the working area of the projector and the accuracy of the XY axis. Such projectors have a high price, which is also a disadvantage. Use only with a personal computer or microcomputer that controls the projector and control board. It can be large with a small work area to provide the required distance from the projector lens to the bath.

The advantages are: low cost compared to SLA technology; the need for less accurate manufacturing of components; high print speed due to high projector lamp power [7].

3) LCD technology. The printer with illumination of a photopolymer by a light-emitting diode UV matrix with use of the LCD display as a mask (fig. 5).

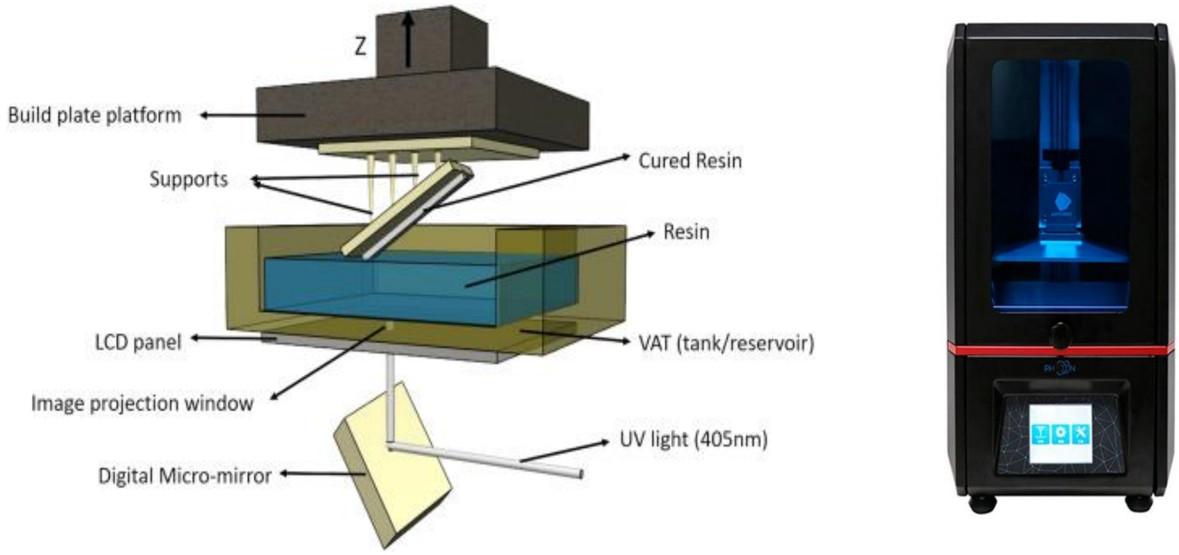


Fig. 5. Scheme of LCD printer operation

The photopolymer is illuminated by an LED matrix, the image is formed due to the LCD display, which displays the cross section of the molded part frame by frame. If the differences between classic SLA technology and DLP and LCD are obvious, then DLP and LCD lighting technology are often confused, which is incorrect, because each of these technologies has its own characteristics that affect the capabilities of the printer, print quality.

The disadvantage of this technology is the dependence of the work area on the screen size, accuracy depends on the screen and its size, today there are no more than 10 inch screens on the market, and with such a screen even with 8K resolution less than 50 microns' pixel size is impossible. Also a relative disadvantage is finding the screen directly under the bath. The bath consists of an aluminum body and a film with a thickness of 50-150 microns, which with minor mechanical damage can pass photopolymer resin, which will get on the screen and electronics and lead to possible fire or damage to the printer [8].

The advantages of this technology are low cost, ease of maintenance and extensive upgrade options. Compared to DLP technology, the advantage is the absence of image distortion on the work area.

As a result of comparison it is possible to draw a conclusion that these three kinds of technology today have a wide field of use, each of which occupies the niche in a life and production. But LCD technology today has the greatest development, thanks to which it has great scientific interest in research and improvement of technology and its use. In the table 1 SLA, DLP and LCD technologies are compared [7-8].

Table 1. *Comparison of SLA, DLP and LCD technologies [9-10]*

Technology	Features
1. XY print area size	
SLA	Not limited, the higher the print area, the lower the speed (the beam must have time to "run around" a large area)
DLP	Unlimited, the higher the print area, the lower the print speed and the lower the printer resolution
LCD	The print area is tightly tied to the size of the LCD display
2. Print speed	
SLA	The slowest of the three technologies. This is due to the consistent illumination and low power of the laser
DLP	The fastest is due to the high power of the projector
LCD	"Average" print speed. Print speed is related to the power of UV matrices. The power of the matrix can not be increased indefinitely, because powerful matrices require powerful cooling and begin to "punch" the "stencil" from the LCD display

The end **Table 1.**

3. Parasitic illumination along the Z axis	
SLA	Minimal
DLP	Maximum. High illumination is associated with both the high power of the projector lamps and the greater share of long-wave actinic radiation in the spectrum
LCD	Average
4. Parasitic illumination along the XY axis	
SLA	Minimal
DLP	Properly focused, it is minimal, but higher than SLA
LCD	Maximum. Strong parasitic illumination is associated with the illumination of neighboring pixels due to the imperfection of the focus of the UV matrix system (more precisely, with its complete absence of light on the mask falls at different angles). This shortcoming is likely to be corrected in the future.
5. Factors affecting the resolution (in addition to the properties of the polymer and the thickness of the layer)	
SLA	1) Laser spot diameter and spot positioning accuracy. Typical values from 100 microns to 200 microns (for a laser spot), from 40 microns to 20 microns (positioning accuracy) 2) on 3D printers with SLA technology you can print, for example, objects with very thin - vertical walls with a thickness of only 100 microns, a horizontal layer - about 30-50 microns
DLP / LCD	1) Pixel size and focus accuracy. Typical resolution - 1920x1080, respectively, the pixel size depends on the print area on XY 2) Lower resolution compared to SLA printers, because the image in them is formed through a pixel matrix (from 33 µm to 47 µm), which does not allow to achieve smoother contours of the part compared to SLA technology
6. Price	
SLA	In the range of $2500-5300, "professional" - from $5300 and above
DLP	$ 4,000 and up
LCD	$ 400-700

The use of these 3D printing technologies will create a camouflage layer on the foil dielectric for further etching. Photopolymer resins, which are chemically inert to most herbalists, are used as masking material. Thus, due to the technologies of photopolymer 3D printing, it is possible to create a fully finished mask of the required thickness and configuration.

The use of 3D-printing will allow to produce PCBs that meet the requirements of accuracy classes DSTU 53429-2009 (table 2) from the first to the seventh, on the indicator "Width of conductors", and from the first to the fifth class on the indicator "Distance between conductors", examples are microcontroller boards based on Arduino and Raspberry. Such limitations are due to the very physics of the processes used in 3D printing technology.

For the practical implementation of the considered technologies it is necessary to develop software that allows to control the exposure process, to adapt the topological pattern of the PCB taking into account the technological parameters and possible manufacturing defects.

Let’s consider the process of photoexposure using DLP technology and the proposed design of the "mask" printer (fig. 6).

Table 2. *Accuracy class of printed circuit boards according to DSTU 53429-2009*

Name of the parameter	**The smallest nominal size values for the accuracy class**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Conductor width	0,75	0,45	0,25	0,15	0,10	0,075	0,050
The distance between the conductors	0,75	0,45	0,25	0,15	0,10	0,075	0,050
Warranty belt contact pad	0,30	0,20	0,10	0,05	0,025	0,020	0,015
The presence of a metal coating	The maximum dimensional deviation produces the figures for the accuracy class						
	1	2	3	4	5	6	7
Without coverage	±0,15	±0,10	±0,05	±0,03	±0,03	±0,02	±0,015
Coated	+0,25-0,15	+0,15-0,10	±0,10	±0,05	+0,03	±0,02	±0,015
Type of printed circuit board	Position tolerance of the location of the printed conductor for the accuracy class						
	1	2	3	4	5	6	7
UPCB, BPCB, MPCB (outer layer)	0,20	0,10	0,05	0,03	0,02	0,01	0,005
MPCB (inner layer)	0,30	0,15	0,10	0,08	0,05	0,02	0,01

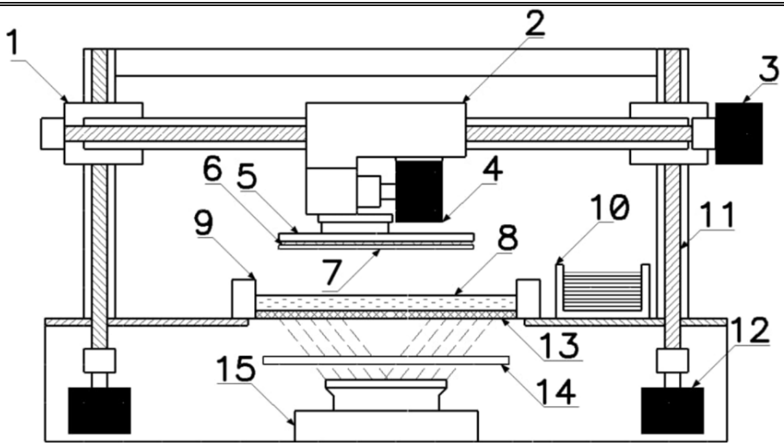


Fig. 6. The design scheme of the "mask" printer based on DLP technology: 1 - vertical axis carriage;2 - carriage of the horizontal axis; 3 - stepper motor of the horizontal axis; 4 - the engine of the rotary mechanism;5 - the basis of the mechanism for capturing boards; 6 - gripping mechanism; 7 - blank; 8 - photopolymer resin;9 - bath for photopolymer; 10 - box for polymerized blanks; 11 - ball-screw transmission (KGP); 12 - stepper motors of vertical axes; 13 - transparent film of the bottom of the bath; 14 - optical system of mirrors; 15 - DLP projector.

The horizontal carriage (2), on which the gripping mechanism (6) is mounted, captures the foil getinax or fiberglass blank (7), moves along the horizontal axis by means of KGP (11) and stepper motor (3).

Reaching the desired horizontal position and descending by means of KGP (11) and stepper motors of the vertical axis (12), the carriage transfers the work piece (7) to the bath (9) with photopolymer resin (8), lowers the work piece to a depth of 20 μm from the transparent bottom baths (13). Then the DLP projector with UV radiation (15) is turned on, through the optical system of mirrors (14) the image is fed to the transparent bottom of the bath (13). As a result of resin polymerization, under the action of radiation, the illuminated areas of the topology harden and stick to the work piece, thus creating a stencil of the future board. The carriage with the polymerized work piece rises up. The rotary mechanism (4) tilts the work piece several times smoothly, at a small angle, so that the excess uncured resin flows into the bath. The finished work piece is moved to a container (10) with isopropyl alcohol for purification from liquid polymer residues. At the next technological stage, the blanks of the boards are etched, after which the photopolymer masks are removed from the blanks.

The use of these 3D printing technologies will create a masking layer on the foil dielectric for further etching. Photopolymer resins, which are chemically inert to most herbalists, are used as masking material. Thus, due to photopolymer 3D printing technologies, it is possible to create a fully finished mask of the required thickness and configuration.

When using photopolymer 3D-printing technologies, it is possible to simultaneously perform the stage of mask application and exposure (fig. 7).

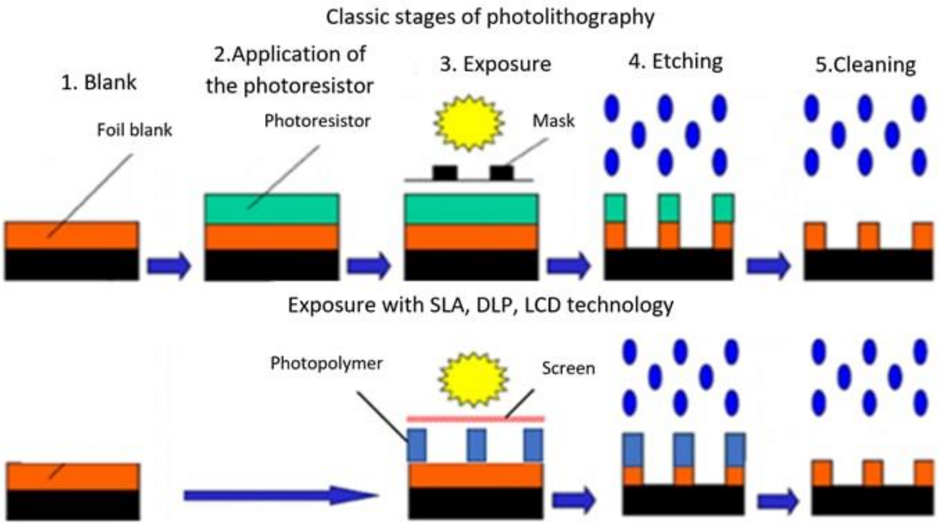


Fig. 7. Stages of 3D exposure of masks

This approach can be implemented using SLA or LCD printing technologies and has the advantages of:

- the installation directly exposes the set topology on the work piece, without prior application of photoresist films or aerosols;

- there is no need for two separate installations for drawing a photoresist and exposure - everything is carried out simultaneously on one installation, it allows to unload production areas;

- since the exposure time of the photopolymer is from 6 to 14 seconds, which is less than the exposure time of the photoresistive films, thus increasing the productivity.

Based on this, an experiment was conducted to manufacture a PCB using LCD technology. The created 3D topology of conductors (PCB 40 × 40 mm) was transferred to foil fiberglass (brand SF DSTU 10316-78) and etched in a solution of ferric chloride ($FeCl3$) (fig. 8).

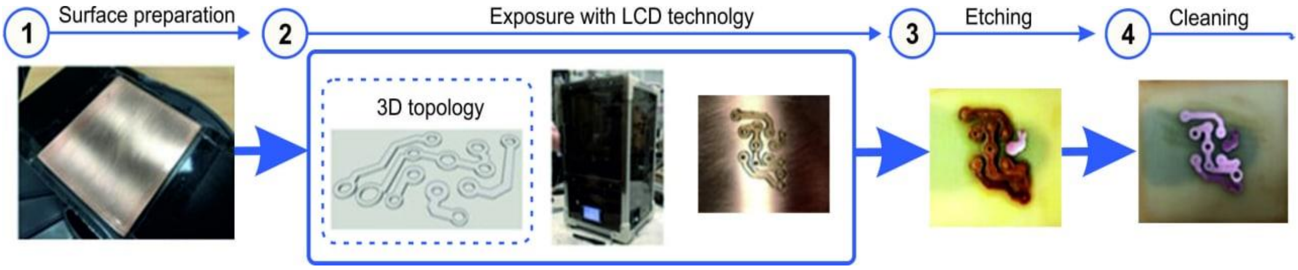


Fig. 8. Manufacturing of PCB topology using LCD printer

Plexiwire Resin Basic Orange Transparent photopolymer resin was used to make the sample, which was chosen due to its high mechanical and technological parameters: short exposure time; minimum layer thickness; no harmful effects on staff; slight shrinkage during polymerization; high resistance to chemical reagents.

In the first experiment, the adhesion of the photopolymer resin to the foil blank was tested. The result shows the resistance of the photopolymer resin to the effects of ferric chloride and high-quality adhesion to the surface, but there is a deviation of ± 0.06 mm at a base conductor size of 2 mm.

This is due to the long duration of illumination of the photopolymer in the first experiment, namely 17 seconds. The obtained result allowed to make the following assumptions:

1) there is a linear dependence of the geometric size of the conductors on the duration of illumination. The longer is the illumination time, the greater is the deviation of the size to the larger side, respectively, at a shorter illumination time - the deviation is less [12];

2) at low light intensity, the photopolymer resin may not be sufficiently polymerized. Thus, insufficient ultraviolet radiation can lead to poor adhesion to the work piece, which can lead to etching of the conductors and reduce the size of the conductors [12-13];

3) the greater is the height of the base layer of the photopolymer mask, the greater is the gap between the screen and the work piece, which can lead to greater diffraction of light flux, in accordance with the greater parasitic illumination of the conductors [12].

To verify these assumptions, 40 measurements of the deviation of the obtained dimensions from the original geometric were performed and a linear regression model was built taking into account the following parameters:

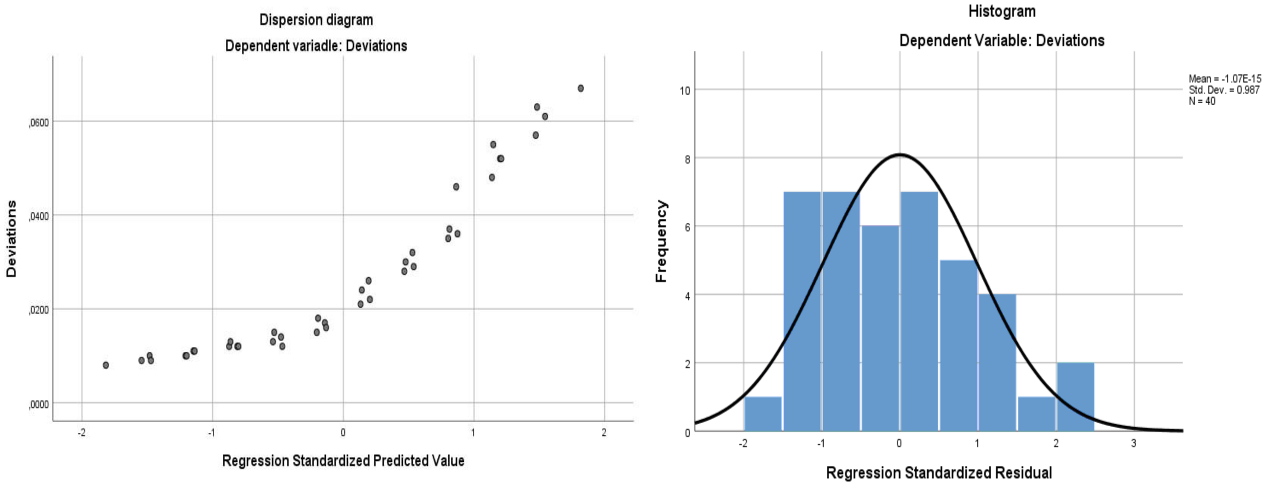
- duration of illumination of resin - from 7 to 16 seconds;
- radiation intensity: maximum - 2800 lm and minimum - 1600 lm;
- the thickness of the base layer is 20 µm and 50 µm.

The results of measuring the deviations of the obtained dimensions from the original geometric dimensions, to build a model of linear regression, are shown in the table 3.

Table 3. *Deviation of geometric dimensions*

Layer thickness, 20 µm										
Intensity of a light stream, 1600 lm										
Polymerization time, s	7	8	9	10	11	12	13	14	15	16
Deviation, mm	0,008	0,010	0,011	0,012	0,014	0,017	0,026	0,032	0,046	0,052
Layer thickness, 20 µm										
Intensity of a light stream, 2800 lm										
Polymerization time, s	7	8	9	10	11	12	13	14	15	16
Deviation, mm	0,009	0,01	0,012	0,013	0,015	0,021	0,028	0,035	0,048	0,057
Layer thickness, 50 µm										
Intensity of a light stream, 1600 lm										
Polymerization time, s	7	8	9	10	11	12	13	14	15	16
Deviation, mm	0,009	0,011	0,012	0,012	0,016	0,022	0,029	0,036	0,052	0,061
Layer thickness, 50 µm										
Intensity of a light stream, 2800 lm										
Polymerization time, s	7	8	9	10	11	12	13	14	15	16
Deviation, mm	0,01	0,013	0,015	0,018	0,024	0,03	0,037	0,055	0,063	0,067

We enter the obtained data to perform basic linear regression analysis of exposure parameters in the program *IBM SPSS Statistics*. Fig. 9 graphically shows the dependence of the deviation of the basic dimensions of the PCB conductors from the exposure time [14-15].

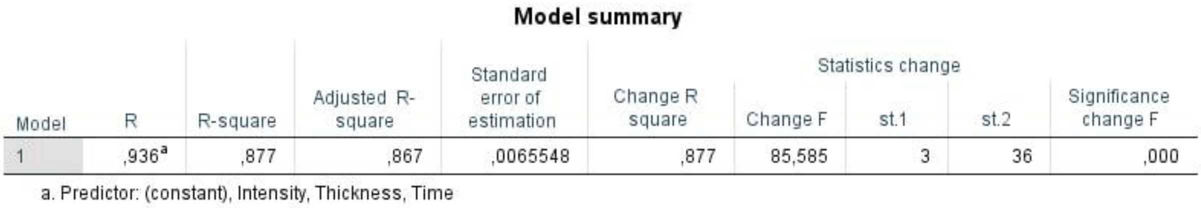


a) *b*)

Fig. 9. The results of deviations of the geometric dimensions of the PCB with increasing values of the parameters: a) a graph of the deviations from a series of experiments; b) diagram of the normal distribution

Using the calculations *"Summary for the model"*, we obtained the value of the coefficient of determination "*R*" - 0.936. This indicator corresponds to the values calculated by the model (linear regression) and the results obtained during experimental studies.

For greater accuracy of the test, the obtained result is listed on the model with non-standardized predicted values (fig. 10, a) and the correlation of deviation parameters from standardized values (calculated deviations) is calculated (fig. 10, b and 10, c).

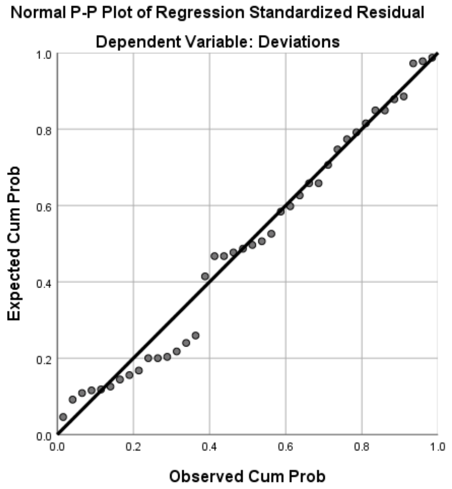


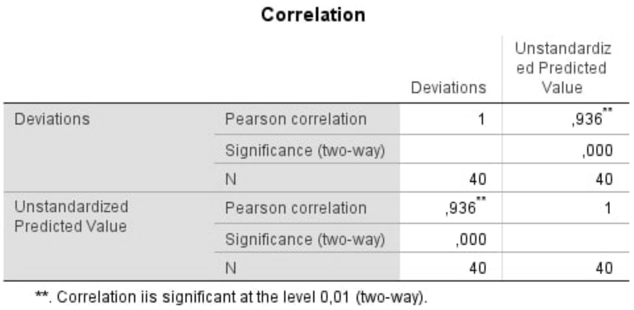
Model summary

Model	R	R-square	Adjusted R-square	Standard error of estimation	Statistics change				
					Change R square	Change F	st.1	st.2	Significance change F
1	,936^a	,877	,867	,0065548	,877	85,585	3	36	,000

a. Predictor: (constant), Intensity, Thickness, Time

a)





Correlation

		Deviations	Unstandardized Predicted Value
Deviations	Pearson correlation	1	,936**
	Significance (two-way)		,000
	N	40	40
Unstandardized Predicted Value	Pearson correlation	,936**	1
	Significance (two-way)	,000	
	N	40	40

**. Correlation iis significant at the level 0,01 (two-way).

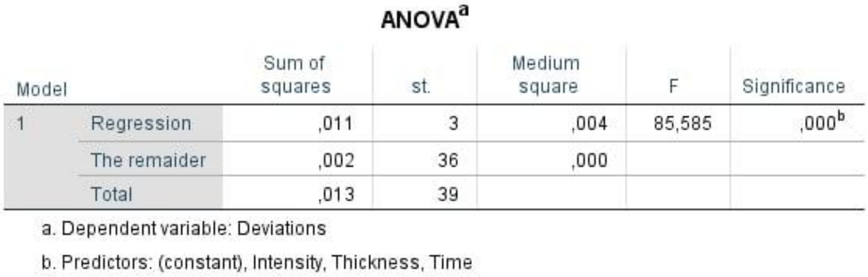
b) *c*)

Fig. 10. The results of calculations of coefficients: a) consolidated models; b) regression line; c) correlation of values

The value of "*R*" in the recalculation is equal to 0.936, which proves that there is a correlation between the obtained and predicted values.

The coefficient of multiple determination "R^2" is equal to 0.877. This means that the parameters included in the system, 87.7% affect the result. The adjusted coefficient "R^2" is equal to 0.867 or 86.7%. The standard estimation error is 0.0065548.

According to the table ANOVA (fig. 11) we test the hypothesis of equality "R^2" = 0. Since the level of "*Significance*" <0.05, it confirms the accuracy of previous results.



ANOVA[a]

Model		Sum of squares	st.	Medium square	F	Significance
1	Regression	,011	3	,004	85,585	,000[b]
	The remaider	,002	36	,000		
	Total	,013	39			

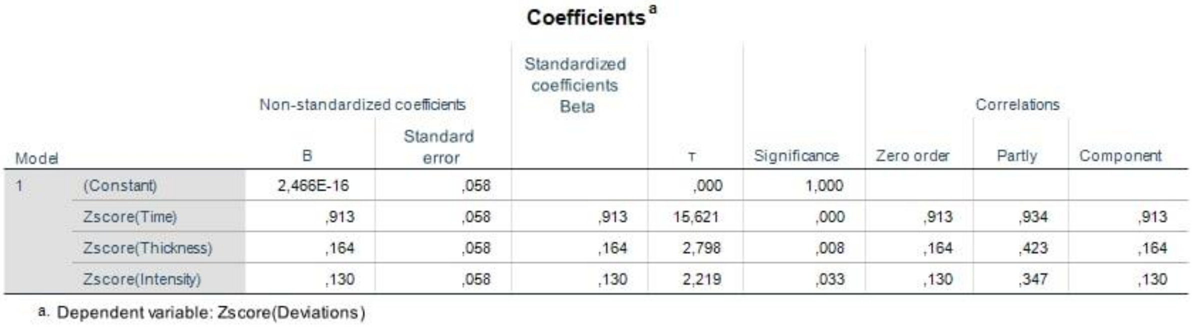
a. Dependent variable: Deviations

b. Predictors: (constant), Intensity, Thickness, Time

Fig. 11. Results of significance calculations

To determine the weight of each variable, we use the "*Beta-coefficient*", which shows how much the value of the parameter changes from an increase of one of the factors. To search for "*Beta-coefficients*", the calculation will be performed using standardized values of "*Z-points*".

This is necessary to make sure that the standardized values and the non-standardized one's match (fig. 12).



Coefficients[a]

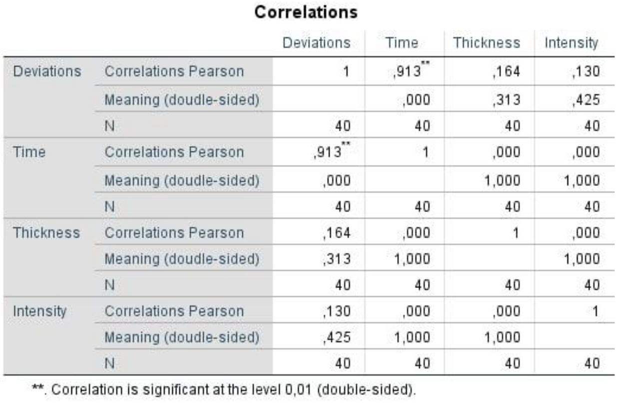
Model		Non-standardized coefficients		Standardized coefficients Beta	T	Significance	Correlations		
		B	Standard error				Zero order	Partly	Component
1	(Constant)	2,466E-16	,058		,000	1,000			
	Zscore(Time)	,913	,058	,913	15,621	,000	,913	,934	,913
	Zscore(Thickness)	,164	,058	,164	2,798	,008	,164	,423	,164
	Zscore(Intensity)	,130	,058	,130	2,219	,033	,130	,347	,130

a. Dependent variable: Zscore(Deviations)

Fig. 12. Results of calculations of "Beta-coefficients"

Based on the level of significance of the coefficients, it is possible to compare whether the "Beta-coefficient" of this factor differs from zero. In this case, all values of "Significance" are less than 0.05, which proves that all the factors that are included in the model are true.

The results of the Pearson correlation of response factors are shown in fig. 13.



Correlations

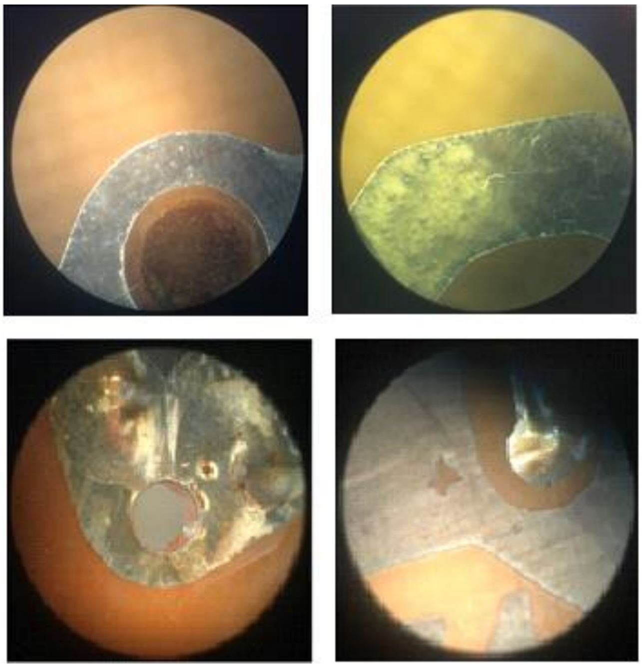
		Deviations	Time	Thickness	Intensity
Deviations	Correlations Pearson	1	,913**	,164	,130
	Meaning (doudle-sided)		,000	,313	,425
	N	40	40	40	40
Time	Correlations Pearson	,913**	1	,000	,000
	Meaning (doudle-sided)	,000		1,000	1,000
	N	40	40	40	40
Thickness	Correlations Pearson	,164	,000	1	,000
	Meaning (doudle-sided)	,313	1,000		1,000
	N	40	40	40	40
Intensity	Correlations Pearson	,130	,000	,000	1
	Meaning (doudle-sided)	,425	1,000	1,000	
	N	40	40	40	40

**. Correlation is significant at the level 0,01 (double-sided).

Fig. 13. The results of Pearson's correlation calculations

Conclusions

Experiments show that when using the technology of photopolymer 3D printing, it is possible to transfer the image of the topology on the PCB, combining the processes of photoresist application and exposure of the topology simultaneously in one installation. In the course of experiments and construction of a linear regression model, in contrast to the results of classical photoresist films, good adhesion of the polymerized photopolymer to the surface of the PCB blank was observed, as a result of chemical etching avoided etching of track ends (fig. 14).



a) *b*)

Fig. 14. Comparison of the results of the ends of the tracks after etching PCB a) the ends of the tracks of the conductors using a photopolymer mask; b) the ends of the conductor tracks using photoresist film

Based on the obtained values of "*Beta-coefficients*" it is possible to make conclusions:

- an increase of one unit of time affects the increase in the value of the deviation of the dimensions by 0.931;

- an increase of one unit of radiation intensity affects the increase in the value of the deviation of the dimensions by 0.130;

- an increase of 30 units of thickness affects the increase in the value of the deviation of the dimensions by 0.164;

This proves that the most important factor in 3D exposure is time. That is, the regression equation is as follows:

$$\begin{aligned} Y &= b_0 + b_1x_1 + b_2x_2 + b_3x_3 = \\ &= 0{,}11 + 0{,}931x_1 + 0{,}130x_2 + 0{,}164x_3 \end{aligned}; \qquad (1)$$

where Y is a factor of deviation of geometric dimensions of PCB topology; b_0, b_1, b_2, b_3 – coefficients of linear regression of the influence of parameters on the factor; x_1, x_2, x_3 – parameters of influence on the factor.

However, in further research, it will be possible to include additional factors in the model and build a more accurate regression model that can be used in the development of software for 3D-exsonation of PCBs.

Graphs of the dependence of the influence of technological parameters on the geometric dimensions of the conductor topology are shown in fig. 15.

Thus, the use of additive 3D printing technologies allows:

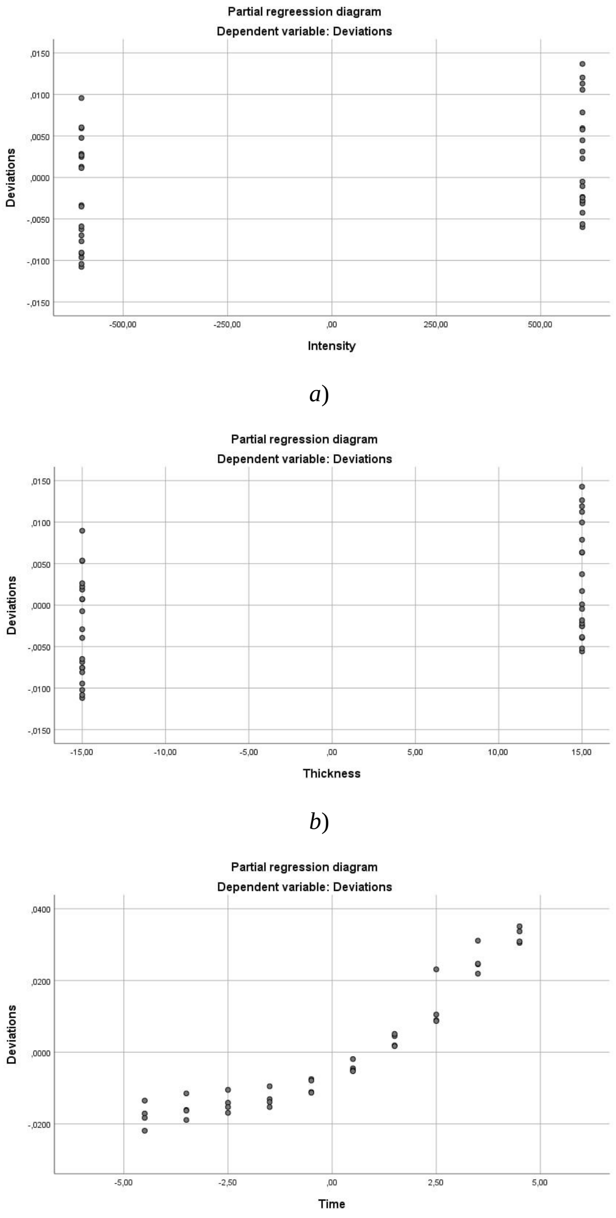
- significantly simplify and reduce the cost of manufacturing PCBs, eliminating from the production process the stage of applying a photoresist to the work piece;

- use production areas more efficiently;

- adapt the original PCB topology, taking into account the influence of technological factors (in the presence of appropriate software);

- to achieve high accuracy of manufacturing of conductors.

Further development of the proposed technology will allow to manufacture rigid and flexible PCBs completely, with conductive tracks, dielectric basis, electronic elements that can be used in various devices.



a)

b)

c)

Fig. 15. Deviation of the sizes of PCB topology at increase of values of factors: a) deviation at the maximum and minimum values of radiation intensity; b) deviations at different values of the layer thickness; c) deviation from the increase in exposure time

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Received 19.02.2021

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ТЕХНОЛОГІЯ СТВОРЕННЯ ТОПОЛОГІЇ ДРУКОВАНИХ ПЛАТ ЗА ДОПОМОГОЮ ПОЛІМЕРНИХ 3D МАСОК

Предметом дослідження є вплив факторів експонування двовимірних зображень на топологію провідників при виготовленні друкованих плат методом тривимірних полімерних фотомасок. **Мета** роботи – забезпечення точності та збереження геометричних розмірів провідників друкованих плат при LCD експонуванні масок на заготовку. Для досягнення поставленої мети необхідно вирішити наступні **завдання**: проаналізувати технологію фотолітографії та види полімерного 3D друку; розробити технологічний процес експонування фотополімерних масок на заготовку друкованої плати, використовуючи технології 3D друку; провести експериментальні дослідження для визначення оптимальних параметрів експонування; на основі отриманих емпіричних результатів розрахувати коефіцієнти кореляції факторів на відгук; побудувати лінійну регресійну модель залежності відхилень геометричних розмірів друкованих провідників від параметрів розчинів для травлення і умов експонування. **Результати**: побудовані регресійні моделі дають можливість спрогнозувати вплив технологічних параметрів експонування на точнісні показники геометричних розмірів топології провідників друкованих плат при 3D масочному виготовленні при LCD експонуванні, оптимізуючого вихідні зображення топології друкованих провідників при автоматизованому виробництві друкованих плат. Це спростить процес розробки топології друкованих плат з урахуванням реального впливу параметрів технологічних операцій травлення і експонування на товщину доріжок провідників друкованих плат, що зменшить частку браку при виготовленні односторонніх та двосторонніх друкованих плат. **Висновки:** запропонована технологія LCD експонування та метод дослідження впливів факторів експонування на якість топології друкованих плат, які дають достатні емпіричні данні для створення регресійних моделей розрахунку впливу технологічних факторів на кінцеві розміри провідникових доріжок при виробництві друкованих плат. Подальший розвиток запропонованої технології дозволить виготовляти жорсткі та гнучкі ДП повністю, зі струмопровідними доріжками, діелектричною основою, радіоелектронними елементами, які можуть застосовуватися в різних пристроях.

Ключові слова: друковані плати; експонування; полімерні фотомаски; розчини для травлення; LCD друк; регресійний аналіз; топологія; адаптація зображення провідників.

ТЕХНОЛОГИЯ СОЗДАНИЯ ТОПОЛОГИИ ПЕЧАТНЫХ ПЛАТ С ПОМОЩЬЮ ПОЛИМЕРНЫХ 3D МАСОК

Предметом исследования является влияние факторов экспонирования двумерных изображений на топологию проводников при изготовлении печатных плат методом трехмерных полимерных фотомасок. **Цель** работы – обеспечение точности и сохранения геометрических размеров проводников печатных плат при LCD экспонировании масок на заготовку. Для достижения поставленной цели необходимо решить следующие **задания:** проанализировать технологию фотолитографии и виды полимерной 3D печати; разработать технологический процесс экспонирования фотополимерных масок на заготовку печатной платы, используя технологии 3D печати; провести экспериментальные исследования для определения оптимальных параметров экспонирования; на основе полученных эмпирических результатов рассчитать коэффициенты корреляции факторов на отзыв; построить линейную регрессионную модель зависимости отклонений геометрических размеров печатных проводников от параметров растворов для травления и условий экспонирования. **Результаты:** Построенные регрессионные модели станут основой для создания базы данных программного обеспечения, оптимизирующего исходные изображения топологии печатных проводников при автоматизированном производстве печатных плат. Это упростит процесс разработки топологии печатных плат с учетом реального влияния параметров технологических операций травления и экспонирования на толщину дорожек проводников печатных плат, что уменьшит долю брака при изготовлении одно- и двусторонних печатных плат. **Выводы:** предложена технология LCD экспонирования и метод исследования воздействий факторов экспонирования на качество топологии печатных плат, которые дают достаточные эмпирические данные для создания регрессионных моделей расчета влияния технологических факторов на конечные размеры проводящих дорожек при производстве печатных плат. Дальнейшее развитие предлагаемой технологии позволит изготавливать жесткие и гибкие печатные платы полностью, с токопроводящими дорожками, диэлектрической основой, радиоэлектронными элементами, которые могут применяться в различных устройствах.

Ключевые слова: печатные платы; экспонирование; полимерные фотомаски; травильный раствор; LCD печать; регрессионный анализ; топология; адаптация изображения проводников.

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