**Artículo de investigación**

# Epoxy-glass composite materials for substrate printed circuit boards gigabit electronics

Эпоксидно-стеклянные композиционные материалы для подложек печатных плат гигабитной электроники

Materiales compuestos de vidrio epoxi para placas de circuito impreso de sustrato de gigabit electronics

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## Abstract

The development of printed circuit board technology is a subject to the general trend of electronics development, an increase in functionality and performance. This requires printed circuit boards to increase the assembly density of electronic components and interconnections and reduction of constructive delays in transmission lines of information. Seemingly, this will require the use of high frequency materials such as polytetrafluorethylenes **(PTPE)** or radiofrequency ceramics. However, this would require a multi-billion dollar restructuring of the industry of printed circuit boards. The article shows that under certain conditions it is possible to do without the restructuring of the industry, remaining on traditional foil epoxy-glass composite dielectrics. But for this purpose, it is necessary to take into account their characteristics and properties of their components.

**Keywords:** Avionics, dielectric, epoxy-glass composite Materials, LTCC-ceramics, printed circuits boards, PTFE, scin-effect.

## Аннотация

Развитие технологии печатных плат зависит от общей тенденции развития электроники - увеличения функциональности и производительности. Это требует от печатных плат увеличение плотности компоновки электронных компонентов и соответствующего увеличения плотности межсоединений и их длины для уменьшения конструктивных задержек в линиях передачи информации. По-видимому, это потребует использования высокочастотных материалов, таких как политетрафторэтилен или радиочастотная керамика. Однако это потребует многомиллиардной реструктуризации индустрии печатных плат. В статье показано, что при определенных условиях можно обойтись без перестройки отрасли, оставаясь на традиционных фольгированных стекло-эпоксидных композитных диэлектриках. Но для этого необходимо учитывать их характеристики и свойства составляющих.

**Ключевые слова:** LTCC-керамика, PTFE, скин-эффект авионика, диэлектрик, печатные платы, стекло-эпоксидные композиционные материалы.

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**Resumen**

El desarrollo de la tecnología de placa de circuito impreso sigue la tendencia general del desarrollo de la electrónica: se busca producir un aumento tanto en la funcionalidad como en el rendimiento. Esto requiere placas de circuito impreso para aumentar la densidad de ensamblaje de componentes electrónicos e interconexiones y reducir los retrasos constructivos en las líneas de transmisión de información. Aparentemente, esto requeriría el uso de materiales de alta frecuencia como tereftalato de polietileno o cerámica de radiofrecuencia. Sin embargo, ello conllevaría una reestructuración multimillonaria de la industria de placas de circuito impreso. El presente artículo muestra que, cumpliéndose ciertas condiciones, es posible prescindir de la reestructuración de la industria, permaneciendo el uso de dieléctricos compuestos de lámina de vidrio epoxi tradicionales. Sin embargo, para lograr este propósito es necesario tener en cuenta las características y propiedades de sus componentes.

**Palabras clave:** Aviónica, cerámica LTCC, dieléctrico, efecto scin, materiales compuestos de vidrio epoxi, placas de circuitos impresos, PTFE.

## Introduction

Printed circuit boards (PCB) are the physical basis of all electronic devices. In the production of PCB more than 200 operations and numerous basic and auxiliary materials are used (Coombs, 2008).

Usually in the formation of the prime cost of printed circuit boards (PCB), the cost of basic materials stays in the first lines. New materials with improved properties are obviously more expensive than usual ones. Is the use of expensive materials justified? It is justified: if ordinary multilayer printed circuit boards have the structure of prime cost 46%, then complex multi-layer PCBs has about 15%. Reducing the share of the cost of materials in the price of multi-layer PCBs is achieved not only by redistributing the share of the costs of manufacturing operations of complex multi-layer PCBs, but also (principally) by significant yield enhancement mainly due to the high quality of materials.

Traditionally it is believed that materials Hi-Tech PCB for devices gigabit electronics and microwave electronics is mainly based on polytetrafluoroethylene (PTFE). Several displaced accents aside Low Temperature Co-Fired Ceramic (LTCC-ceramics) and do not consider the possibility of the use of modern epoxy-glass compositions (EGC) specially designed for microwave use. However, if you approach the choice of materials, using multivariate criteria, you can find a place for modern foil EGC in the microwave range, widely used in the manufacture of printed circuits (Coombs, 2008; IPC, 2018).

The basic technology of PCB focused on use of the EGC. In this regard, we make two questions: "Will a circuit board made of EGC laminate work for my High Speed or Hi-Tech design?" and "If EGC isn't OK, where do I turn?" The answers to these questions are specific to each individual circuit and can only be answered through analysis of the characteristics of FR4 verses other material choices, relative to the demands of the circuit's noise budget.

This article will outline the material parameters that affect circuit performance and give some direction about how decide when choose the correct material for any specific application. The objective of this article is to justify the use of epoxy glass compositions for Hi-Tech PCB and show features of their application.

## Materials and methods

One of the major goals of this article is to provide information that allows designers and engineers to select a material for every PCB application that optimizes both performance and cost of Hi-Tech PCB. As the fundamental building block for printed circuits, base materials must meet the needs of the printed circuit board (PCB) manufacturer, the circuit assembler, and the original equipment manufacturer (OEM). A balance of properties must be achieved that satisfies each member of the supply chain. In some cases, the desires of one member of the supply chain conflict with another. For example, the need for improved electrical performance by the OEM, or improved thermal performance by the assembler, may necessitate the use of resin systems that require longer multilayer press cycles or less productive drilling processes, or both of them (Microwave journal, 2014).

Other trends are also driving the need for greater performance. They include the following:

- Circuit densification;
- Higher circuit operating frequencies.

Today for the manufacture of Hi-Tech PCB provided a limited number of materials: polytetrafluoroethylene (PTFE, Teflon-RTFE, Rogers is a ceramic filling RTFE), LTCC ceramics and new foiled glass-epoxide composites. Of course, from the viewpoint of dielectric properties the best MICROWAVE-material is PTFE: its dielectric permeability, loss tangent and the lowest water absorption from all variety of solid dielectrics. However, technological difficulties processing make use it only in very exceptional cases, where its unique microwave properties take precedence over constraints its use in production (Medvedev, 2017).

The same applies to the ceramics ones: the complexity of the formation of these products are cause a relatively limited range of use. This primarily refers to her unpredictably large shrinkage (up to 15% along layers and up to 30% in transversal-direction) that for the larger sizes of mounting substrates is unacceptable. Moreover, the production of circuit boards of LTCC ceramics, very specific production, is fundamentally different from the widespread production of printed circuits on the underlying technology that uses foiled dielectrics EGC. The foiled glass-epoxide dielectrics are the best materials for a wide and mass production of electronics. But the possibility of their use in the microwave range cause undeserved doubt that cannot be categorical today. If you approach the choice of materials of substrates from the standpoint of the formation of lines of communication, it is the main function of the printed circuits for fast digital electronics, that can distinguish two main parameters determining their performance: attenuation (loss) signals in communication lines and signal propagation speed (Tsunooka, Andou, Higashida, Sugiura, Ohsato, 2003).

It is known that the loss of lines is proportional to the permittivity and dielectric loss angle tangent (IPC, 2018). Power loss is measured in lines evaluated as $P = U^2\omega C \text{ tg } \delta$, where U is the voltage on the line, C is the line capacitance and tg $\delta$ is the tangent of angle losses.

Power losses in 1 $cm^3$ of the dielectric in a homogeneous field (e) equal: $p = E^2\omega\ \varepsilon_r \text{ tg } \delta$, where $\varepsilon_r$ is the relative permittivity.

$L = \text{tg } \delta\ \varepsilon_r$ called dielectric loss factor. This parameter determines the degree of loss of signal in the communication lines.

Second discuss the speeds at which signals propagate on a PCB interconnect. As you know, in a vacuum the speed of propagation of the signal (speed of light) is 299 000 km/s, which corresponds to the delay in the signal line 3.3 ns/m. The speeds of signals on a PCB is less than that in air or vacuum by the square root of $\varepsilon_r$. If $\varepsilon_r = 4$ (like for EGC material types), then the speed of signals on a transmission line is 6-7 ns/m.

Now you can compare a variety of basic materials for these and another important criterion (Table 1) (Coombs, 2008; Cuming Microwave Corporation, 2016).

**Table 1. Base materials for printed circuits**

| Type of Materials | Dielectric Constant, $\varepsilon_r$ | Loss Tangent, tg $\delta$ | Signal Speed, nc/m | Coefficient of Loss, $\varepsilon_r \cdot$tg $\delta$ | Manufacturability (ball) | Thermal Conductivity, W/m K |
|---|---|---|---|---|---|---|
| Vacuum | 1.0 | - | 3.3 | - | - | |
| PTFE | 1.8 — 2,2 | 0.001 | 4.7 | 0.002 | 6 | 0.3-0.6 |
| LTCC-ceramic | 10 — 12 (20**) | 0.006 | 10.4 — 11.4 (15) | 0.07 (0.12) | 4 | 2-4 |
| Epoxy-glass | 3.3 — 3.5*** | 0.0015 | 5.8- 6,0 | 0.005 | 1 | 0.3-0.4 |


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As a result, we will consider the main properties of Epoxy-glass-composition with respect to Hi-Tech PCB in detail.

**Results**

Epoxy-glass-composition are characterized by a large number of parameters, we consider only the numbers that are related to the topic of the article.

**Binders - Polymer System**

Binders (resin) are the weakest link in composite materials. As a rule, they determine such important parameters as the heat resistance of the multi-layer PCBs and the dimensional stability of the layers of the multi-layer PCBs, which is necessary for the exact combination of elements of interconnections in the three-dimensional structure of the multi-layer PCBs.

Heat resistance is needed to ensure the stability of boards to the group of heating of boards for soldering of surface-mounted components. When heating reaches the soldering temperatures, the metallization of the holes experiences large stresses, which are created due to the expansion of the base of printed circuit boards along the Z-axis. With insufficient plasticity of copper galvanic deposition, the metallization of the holes under the action of an expanding dielectric deforms to the point of destruction (Medvedev, 2016). In this case, heat resistance is characterized by the glass-transition temperature, above which the deformation of the base of the board is particularly high (Figure 1). Domestic materials, developed 50 years ago in relation to manual installation, are not suitable for group soldering today, since their glass transition temperature (Tg) does not exceed 105 °C. Today's materials have a Tg of not more than 140°C. New materials are very diverse and can have Tg up to 220°C (Figure 1 and Table 2) (IPC, 2018)

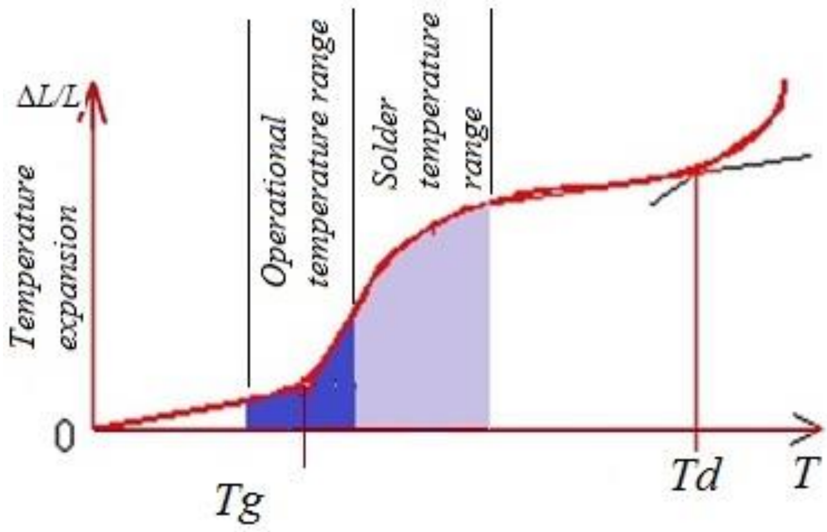


**Figure 1. Dependence of the temperature expansion of the composite base of the printed circuit board along the Z axis: Tg is the glass-transition temperature, Td is the temperature at which the polymer begins to decompose**


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**Table 2. Basic properties of binders of various firms - suppliers of basic materials of the printed circuit board (Mittal, 2018)**

| Parameter | Method | Unit of measurement | Parameter estimator | HITACHI MCL-BE-67G | Panasonic MC-100MS/EX | Isola DE-104 |
|---|---|---|---|---|---|---|
| Glass-transition temperature, $T_g$, °C | Thermo-gravimetric analysis | °C | Better more | 140 | 137 | 135 |
| | Thermo-mechanical analysis | | Better more | 220 | 147 | Not norm |
| Thermal-expansion coefficient | along the *X*-axis, | ppm | Better less | 15 | 15 | 16 |
| | along the *Y*-axis, 30-120°C | ppm | Better less | 17 | 15 | 16 |
| | along the *Z*-axis below $T_g$ | ppm | Better less | 40 | 65 | 70 |
| | along the Z axis above Tg | ppm | Very critical | 170 | 210 | 250 |
| Moisture absorption | E-24/50+D-24/23 | % | Better less Very critical | 0.02 | 0.1 | 0.8 |

The moisture absorption is especially important parameter for microwave devices: the relative dielectric constant of water εr = 81 can affect the performance of communication lines of multi-layer PCBs. In addition, if the printed circuit boards are not dried before soldering (it is possible), intensively evaporating moisture at soldering temperatures inflates the composite dielectric base, which can lead to irreversible delamination of the boards.

**Glass - glass fiber material**

Electrically insulating alkali-free glass based on aluminoboronsilicate has traditionally been used as glass filaments. It was well drawn in the thread and maintained the processes of formation of yarn and fabric without destruction. However, recently it has ceased to meet the requirements of the formation of high-frequency electronic devices: its relative dielectric permittivity is too high $\varepsilon_r = 9$. In the composition with a binder ($\varepsilon_r = 3.2$), its total dielectric permittivity ranges from 5 to 6, depending on the resin content (Coonrod, Horn III, 2011). To reduce the dielectric permittivity ($\varepsilon_r$) and the dielectric loss tangent (tgδ), it is proposed to use a different glass composition - E-glass (boron-free aluminosilicate with light additions of oxides of alkaline-earth metals) with a dielectric permittivity $\varepsilon_r = 6$ and tgδ ≤ 0.004. In combination with the binder properties of such composite at gigahertz frequencies $\varepsilon_r = 3.5–4.0$, tgδ ≤ 0.002 (Atams, Atamas, Bulavin, 2005).

**Weave of glass fiber**

Usually glass threads are twisted into yarn, from which the fabric is woven. The thickness of the yarn density diversifies the range of glass fabrics (Table 3).

**Table 3. Parameters of impregnated fiberglass (prepreg) (Medvedev, 2017)**

| Type of Materials | Dielectric Constant, $\varepsilon_r$ | Loss Tangent, tg $\delta$ | Signal Speed, nc/m | Coefficient of Loss, $\varepsilon_r \cdot$tg $\delta$ | Manufacturability (ball) | Thermal Conductivity, W/m K |
|---|---|---|---|---|---|---|
| Vacuum | 1.0 | - | 3.3 | - | - | |
| PTFE | 1.8 — 2,2 | 0.001 | 4.7 | 0.002 | 6 | 0.3-0.6 |
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In the process of pressing the material during the transition of the resin of binder from the stage B to the stage C (Tsunooka, Andou, Higashida, Sugiura, Ohsato, 2003), the resin undergoes polymerization shrinkage and during cooling it undergoes thermal shrinkage. The stresses arising at the same time are fixed by the pressed foil and weaving of glass fiber. Then they realize themselves by shrinking (changing linear dimensions) after etching of the pattern (removing part of the foil). Twisted yarn and weaving of glass fiber as springs take on some of the stresses and entail a certain amount of shrinkage of the material of the layers of multi-layer PCBs.

To prevent this phenomenon, the glass threads do not twist into yarn and get a flat weave (Figure 2).

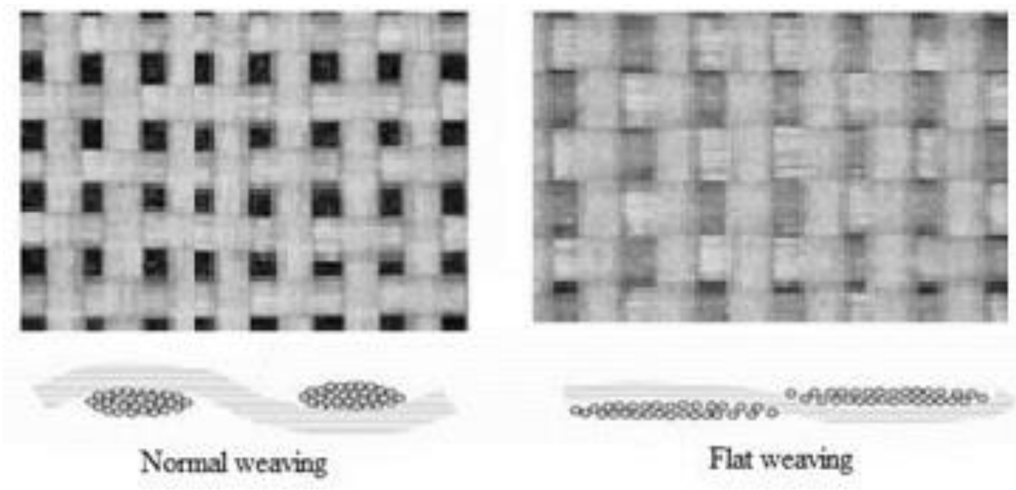


**Figure 2. Types of glass fiber weaving**

There is another advantage of flat weaving: dielectric uniformity for communication lines.

## Migration

For the long-term operability of electronic devices, it is very important to ensure the complete absence of electrochemical migration processes on the surface and in the volume of the composite material of the processes of electrochemical migration, alignment of current paths between different potential circuits (Figure 3). For their formation, a combination of two factors (moisture and voltage) is necessary. Moisture-protective lacquers are more or less successfully protected from surface moisture. But since moisture has a unique property of penetrating everywhere, it finds the ability to condense in the capillaries of composite materials. In this sense, a weak point in composite dielectrics is the surface of glass fiber


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in adhesion with a binder. When this adhesion is weak, thin capillaries are formed, in which moisture condenses even in conditions close to normal. For mobile devices, the source of moisture can be the evaporation of the human body, condensation when bringing cold devices into a warm room, etc. Automotive electronics and avionics are devices constantly under stress from moisture. So, one of the conditions for equipment failure is moisture, which accompanies the maintenance of electronic devices. The only deliverance from such degradation processes of isolation is the use of materials in which there are no micro pores and micro capillaries.

A phenomenon that characterizes the stability of composite dielectrics to electro migration processes is called Conductive Anodic Filament (CAF) in international standards (Coombs, 2008; IPC, 2018) (Figure 3).

Composite materials in which conditions are created for good impregnation of glass yarn and good adhesion of the binder to glass show good results for long-term resistance to the effects of a moist environment.

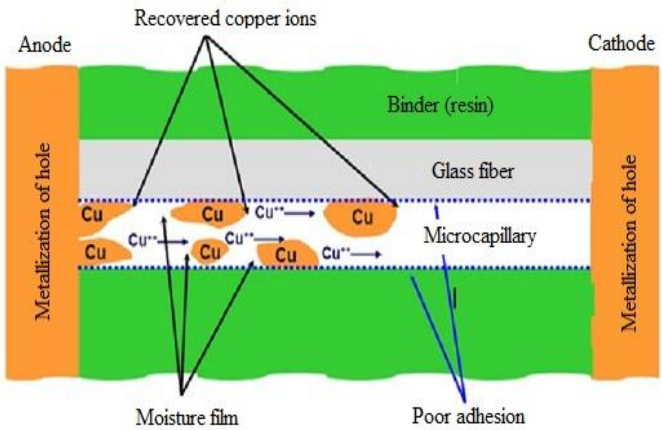


**Figure 3. Mechanism of formation of conductive paths in the volume of printed circuit boards, conductive anode filaments**

## Foil

Since we are moving farther and farther into the region of high frequencies (high performance of electronic devices), we have to reckon with such a phenomenon as the skin effect, it is a displacement of the conduction of high-frequency signals to the surface region (Medvedev, 2016). This effect is shown in numbers here (Table 4). The skin effect is already significant when working at gigahertz frequencies typical of today.

**Table 4. Approximate representation of the skin effect (Horn III, Reynolds, LaFrance, Rautio, 2010)**

| Frequency | Thickness of conductive layer, μm |
|---|---|
| 10 kHz | 660 |
| 100 kHz | 210 |
| 1 MHz | 65 |
| 10 MHz | 21 |
| 100 MHz | 6.6 |
| 1 GHz | 2.1 |
| 10 GHz | 0.7 |


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At high frequencies the size of the skin effect is comparable with the irregularities (roughness) of the foil (Figure 4). This affects the worse for signal propagation. Obviously, it is very difficult to create a foil without any roughness. Moreover, the roughness creates the best conditions for ensuring of adhesion of the foil to the dielectric ones. Nevertheless, as for the materials for microwave devices, the roughness of the foil is normalized. According to IPC 4562 (IPC, 2018; Brook, 2010), here are the maximum values of the height of the copper foil profile (Table 5).

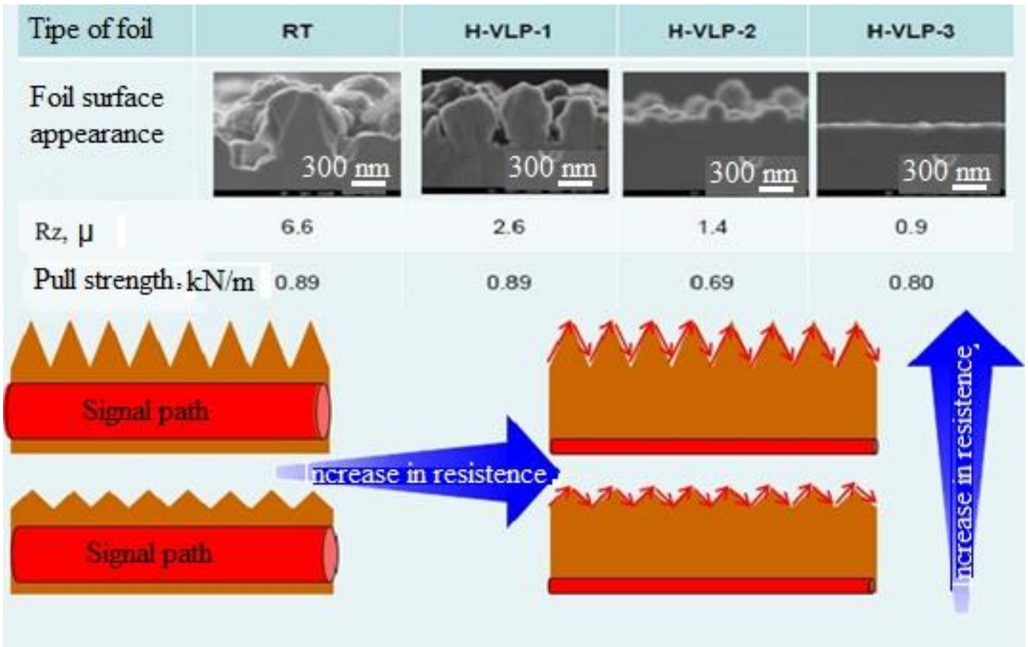


**Figure 4. Influence of the scin-effect on signal propagation**

**Table 5. Foil roughness standards for microwave device materials according to IPC 4562 (IPC, 2018)**

| Profile type | Maximum profile height, μm |
|---|---|
| Standard profile (S) | not indicated |
| Low profile (L) | 10.2 |
| Very low profile (V) | 5.1 |

**Discussion**

Under certain conditions, the use of epoxy-glass composition acceptable for printed circuit boards, which are made on the underlying technology. However, the designers have to contend with elevated losses and delay signals in these materials (Qin, Peng, Prunier, Brosseau, 2010; Qin, Brosseau, Peng, 2011; Qin, Brosseau, 2012). As a rule, there are offset by a decrease in size of boards by increasing density layout of electronic components and interconnections between them on the PCB. This conform general tendencies of development of technology of modern electronics (Rautio, 2007; Rautio, 2016). The analysis shows that the heterogeneity of the composite material does not affect the operability of communication lines due to their sufficiently large critical yet. The roughness achieved in the production of copper foil is not noticeable on the skin effect. Epoxy glass compositions provide other undeniable advantages: strength, dimensional stability, manufacturability and, most importantly, widespread development in the manufacture of printed circuit boards (Rahimi, Yoon, 2016). So, they remain leading in the manufacture of electronics.

**Conclusion**

Electronic devices increasingly require the use of Hi-Tech PCB, in particular for microwave range, that requires the use of appropriate materials.

Recent developments and proposals for the composite materials market with improved dielectric properties in the direction of microwave allow PCB manufacturers to remain within the framework of basic technologies, i.e. without significant restructuring of production.

The use of materials of high quality, but more expensive materials, reduces production costs, which makes the final product cheaper.

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