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Review of Modern Three-Dimensional Integration Technologies and Analysis of Prospects of Their use for High Power Micro-Assemblies

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ABSTRACT

The new miniaturization technologies of electronic devices find extensive application in the design for any industry, whether it is civil electronics or appliances designed to operate in harsh environments. This article presents an overview of prospective technologies of three-dimensional integration at substrates level for use in the field of power electronics. The review describes the basic principles of three-dimensional integration technologies, their applicability for manufacturing electronic devices, the main advantages and disadvantages.

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1. INTRODUCTION

Miniaturization of electronic devices is one of the main aspects of technological progress. Nowadays the standard technique of mounting discrete components on printed circuit boards is not able to provide the required dimensional characteristics of electronic products. In this regard technologies of three-dimensional integration are actively developing. They allow not only the reducing of the device size or its elements, but also the improvement of key characteristics such as performance, functionality, reliability, protection from external influences etc.

This article provides an overview and comparison of key technologies of three-dimensional integration at the substrates level that found application in the devices manufacture of the real economy sectors, particularly in the production of power electronics.

2. 3D-MID TECHNOLOGY

One of the promising miniaturization technologies is the 3D-MID technology (Three-dimensional Molded Interconnect Device). The key feature of this technology is to use the thermoplastic basis, produced by molding under pressure applied with the formed conductors and pads. It can realize the miniaturization of the device by replacing the standard printed circuit boards to the frame with integrated topology of interconnects.

The use of 3D-MID technology provides ample opportunities in the field of design through the implementation of mounting base with conductive tracks, electronic, mechanical or optical elements in the same scheme. In addition, this technology provides the designer with greater freedom for designing the shape of the device. Moreover there are other positive aspects of 3D-MID, such as the acceleration of the assembly process with the growth of production reliability due to fewer mechanical parts [1].

Today 3D-MID is mainly used in auto electronics, medical equipment, antenna mobile devices (Figure 1) [2].

Figure 1. Examples of 3D-MID technology realization

Despite all the advantages of the described technology, it has a number of drawbacks from the economic point of view:

- Necessity to develop and set unique manufacture tooling for each product;
- Expensive specific technological equipment;
- Limited selection of thermoplastics that provide the necessary adhesion of metals;
- Limited field of application due to the low heat resistance of thermoplastics;
- Lack of CAD for product development in three-dimensional space;
- 3D-MID does not allow the integration of electronic components into the structure, it provides only surface mount.

Modern production does not require complex structures based on 3D-MID. The most constructive approach in the design of complex devices is the selective application of 3D-MID along with standard technologies. Such a combination of technologies can be implemented more efficiently if the role of the basis for complex electronic systems is implemented by an element built on SoC (System on Chip) technology instead of printed circuit board.

In general, 3D-MID has a number of advantages, allowing the producer to implement mechanical, electronic, optical and other functions in one product. In power electronics it can be used for low to medium capacity. But today this technology is not able to displace traditional technologies used in manufacturing. However it can be widely applied to improve them.

3. LTCC CERAMICS

One of the most fast-growing and most popular technologies today is the technology of low-temperature co-fired ceramics (LTCC). It has been used successfully for different purposes such as broadcasting, telecommunications, mobile communications, portable computers, production of RF and microwave circuits with low and medium degree of integration, etc. In addition the LTCC-technology has been in demand in the field of power electronics. Primarily this is due to its limit operating parameters and characteristics. Ceramic has several advantages including the following indicators: very good electrical characteristics, excellent mechanical stability and the preservation of the linear dimensions, low CTE, good thermal conductivity, the possibility of 3D integration, integrity and capability with high temperature soldering [3, 4].

The production of ceramics begins with the preparation and casting of the slurry in a special form. The slurry is usually made by mixing ceramic powder, organic binders, solvents and additives. After the casting process ceramic sheets are formed and cut to the required size. The next step is the formation of the vias, filling them with conductive paste, and creation of the required topology (screen-printing) using special conductive and resistive pastes. The finished sheets are combined into an assembly which is then laminated and undergoes the curing at the temperature of 850°C. This process ensures the stability of the structure of ceramics in a wide temperature range. The final stage of production is the installation of the electronic elements in the stack. It should be noted that the curing temperature allows the use of metals with low resistivity (gold, silver).

It is necessary to highlight the following advantages of the LTCC technology:

- Dense structure of the LTCC ceramic doesn't let the moisture to pass, so the ceramic bodies can be used in a highly humid atmosphere without additional protection;

- Low CTE which is close to that ratio most of the electronic semiconductor materials (Si, GaAs, InP). It allows the mounting of the semiconductor crystals directly on the base of the board;
- Good thermal conductivity (2-4 W/mK), which is much higher than that of printed circuit boards based on organic materials (0.1–0.5 W/mK). The thermal conductivity of the LTCC can also be enhanced to 20 W/mK through the creation of metallized thermal drains.

In turn, the disadvantages are:

- The problem of obtaining high-quality ceramic slurry, which parameters can vary from batch to batch;
- The problem of the shrinkage of ceramics after the curing;
- Limited possibility of electronic components integration. Yet only passive electronic components such as resistors, inductors, created by coating the surface of the ceramic sheet of specialized pastes, were successfully integrated inside the ceramic structure. All other components are installed by standard mount techniques on the surface of the finished ceramic structure.
- The cost of raw materials and the cost of the entire production cycle. As a rule, each LTCC system is a unique solution, so the replacement of individual components is impossible. In case of necessary rework of a component of the ceramic structure, the entire production cycle has to start over. Also all special pastes for metallization are based on precious metals such as Au, Ag and Pt.

Taking into account all these features of LTCC technology realization, it becomes clear why the main area of application is the military-industrial complex, and at the moment LTCC is not widespread.

4. THREE-DIMENSIONAL INTEGRATION TECHNOLOGY BASED ON FLEXIBLE PRINTED CIRCUIT BOARDS

Flexible printed circuit boards, one way or another, find their application for miniaturization and integration of electronic devices. There are many options of use of flexible printed circuit boards, including miniaturization of power electronics products.

For example one of the most interesting miniaturisation technologies for power electronics is SKIN technology developed by Semikron. This company has been developing and manufacturing compact power modules for a long time and has a whole line of products based on this technology. The idea of SKIN technology is to create a power module with modified output connections based on flexible printed circuit boards (PCBs).

SKIN technology uses one flexible film with copper conductors applied on it instead of a large number of conductors connecting the contact areas of the crystal and the board by ultrasonic welding. Skin-film is a three-layer flexible PCB, in which the upper layer contains the conductors responsible for high currents, and the lower ones have metallization for the control and processing circuits. In general, the upper conductive thick layer is made of aluminium, and the lower one is a copper layer of standard thickness (35 μm), the inner polyamide layer serves as an insulator [5].

Power chips are connected to the lower Skin layer of the board by low-temperature silver diffused sintering (Sinter Joint) [6]. In this case surface mount components can be installed on the top side using standard mounting techniques, for example, using the flip-chip or by soldering (Figure 2, 3). As a result, it is possible to increase the contact area, as well as to provide an improved heat distribution due to the thick metallization layer.

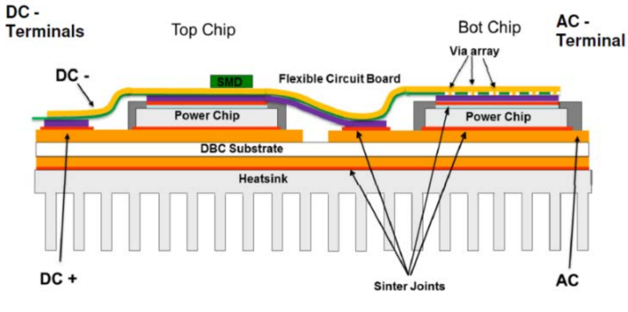

Figure 2. Semikron's 3D SKiN device with multi layer power routing

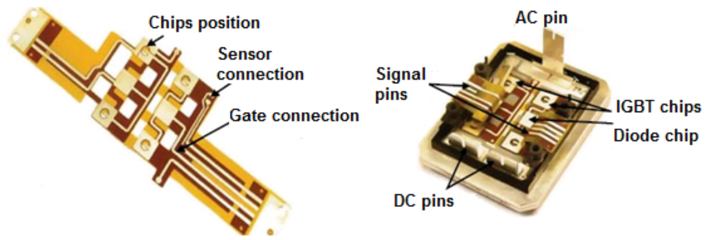

Figure 3. Semikron's miniature power modules

The disadvantages of this technology are the use of a rather complex process of silver diffuse sintering, which requires very careful technology elaborating. Also the development of multi-layer flexible boards with thermal conductive holes requires a special approach. Nevertheless, this technology has proved its effectiveness for the integration of open-frame semiconductor crystals in power micro-assemblies. Skin technology developers produce a whole line of highly integrated power modules like Semitop, MiniSKiiP, SkiM, SEMiX, Semitrans and others [7].

5. WIRELAID TECHNOLOGY

Wirelaid technology is used to create compact products of power electronics based on printed circuit boards. Problems of high currents and strict requirements for product miniaturization were solved using the thicker copper lines impeded in the design of printed circuit boards, which leads to a reduction in the size and number of layers of the printed circuit board. For large currents applications silver-coated copper conductors are used which are fixed on the metal foil by spot welding. After that the production of printed circuit boards is continued according to the standard technical process. Currently, the company operates with conductors of 1.4 mm and 0.8 mm thickness which are placed on the inner and outer layers of printed circuit boards. The implementation of the whole technological process is presented in Figure 4. The developed technology results in overall product dimensions reduction, heat dissipation decrease, the elimination of the connectors from the design, lessening the number of layers of printed circuit boards, and the usage of a more technological soldering process compared to traditional technology based on thick copper, etc. [8].

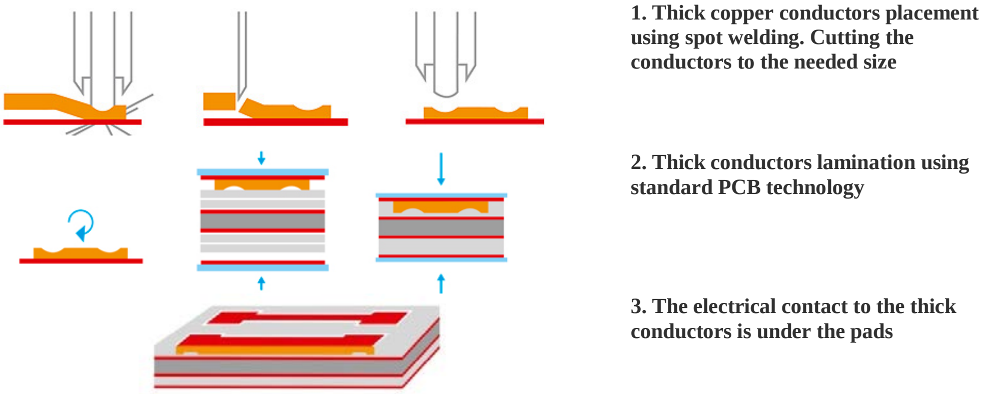

Figure 4. Process steps of Wirelaid technology

The described technology allows us to reduce some extent in the product dimensions due to the reduction of the occupied area of current-carrying tracks, to increase the heat sink efficiency, to increase the current density.

However, this technology is more focused on the task of increasing the current density and the implementation of the heat sink. But the reduction of the overall dimensions of the device is only partially resolved. In addition, the use of thick copper structures embedded in the printed circuit board can possibly affect the reliability of the assembly in conditions of low and high temperatures because of the materials CTE difference. Also, this technology implies only one-level integration.

6. EMBEDDED DIE TECHNOLOGY

A very promising 3D integration technology is Embedded Die Packages. Despite the large number of technological solutions and patents held by different firms [9-10], the basic idea is the integration of crystal or packaged component directly to the printed circuit board prior to pressing of the layers (Figure 5).

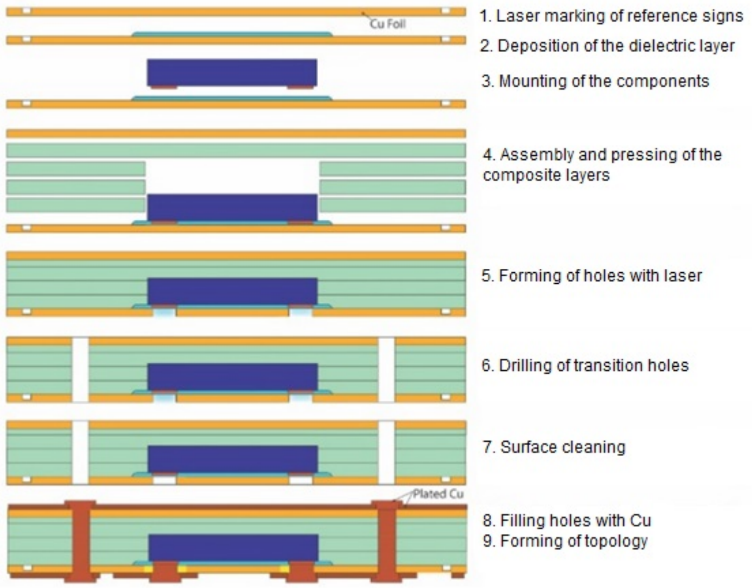

Figure 5. Embedded Die Packages technological route

As for the field of power electronics, there are a number of studies aimed to develop the methods for creating power modules using embedding technology. For example, the article [11] presents the results of using the embedded die technology to create a cased power key. The MOS transistor was installed in the prepared grooves in the prepreg, the resin coated copper layer was applied from above, and then the micro-assembly was laminated and cured in vacuum. The conductive via and topology of the board was formed by direct laser structuring. Since the die of the power transistor was installed directly on the copper conductors by soldering, this provides a good thermal contact, and therefore a good heat dissipation. Figure 6 shows a power MOSFET transistor encased in the embedded die technology.

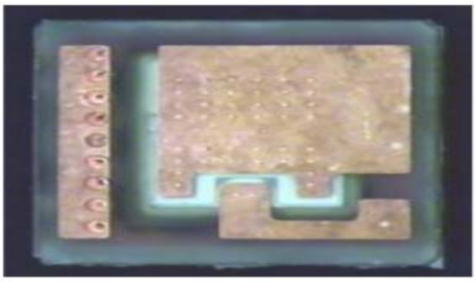

Figure 6. The picture of the embedded MOS-transistor

The Embedded Die Packages technology is very prospective from the point of view of further miniaturization of electronics devices. It allows the maximum use of standard printed circuit boards capabilities for reducing the size of the produced device. However, the possibilities of the technology are highly dependent on the type of embedded components. When using embedded electronic components in packages it is necessary to ensure the tightness of the assembly with different types of pastes and compounds. The main problem is the selection of the required materials ensuring mechanical strength and the reduction of the stresses in the multilayer structure under conditions of operating temperatures. Obviously there are the limitations of the application of embedding technology for power electronics products, which depend on the maximum output power of the elements.

7. CONCLUSION

Technologies of three-dimensional integration are actively developing and extend fields of applications. These innovations do not displace standard technologies as their use for the design of the whole device is impractical from the point of view of financial and time costs. However, the use of integration technologies for individual items, as well as combining different approaches in a single product, enables to achieve a substantial gain in size and key characteristics of the final product.

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