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Laser-Induced Metallization for Fabrication of Circuits on the 3D Surface of Devices

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With the rapid development of technology, the volume of electronic products is getting smaller and smaller, but the functions are gradually increasing. 3D structural electronics technology that can integrate electronic circuits onto structural components has become an inevitable trend. Laser direct structuring (LDS) is a quite mature 3D surface circuit process, but it is only suitable for special plastic injection molding materials. Therefore, it can not be applied to 3D printing materials or other non-injection molding materials, nor can it be used to make multi-layer circuits. A novel laser-induced metallization (LIM) technique has been developed to fabricate circuits directly on the 3D surface of most objects. The objects can be made of plastic, metal, glass or ceramic. A special laser-activatable solution is first sprayed on top of the surface of the object, followed by laser structuring and electroless copper plating. The LIM process can be repeated layer by layer to realize the idea of 3D multi-layer circuits. The minimum linewidth of the LIM-3D circuit is strongly dependent on the spot-size of the focused laser. When the spot size of the laser is 38 μm and the object is plastic, the minimum linewidth patterned by laser is about 40 um. After copper electrodeless plating, the line width will slightly widened. Relatively, when the focused spot size is 16 um, and the object material is ceramics such as alumina, perovskite, etc., the minimum linewidth is about 15 um. This study applies LIM-3D circuit technology to 3D ceramic circuit board for CMOS image sensor(CIS) probe card, tactile sensor on humanoid robot finger, 2G/3G/4G all-in-one compact antenna and multi-layer NFC antenna on mobile phone case. Unlike traditionally all circuits must be fabricated on a flat substrate, in the future, LIM-3D circuit technology combined with 3D component die-bonding technology can open up new opportunities for the development of 3D structured electronics.

NOMENCLATURE

LDS = Laser direct structuring
LIM = laser-induced metallization
CIS = CMOS image sensor
Nd:YVO4 = neodymium-doped yttrium orthovanadate
MIMO = Multiple Input Multiple output
NFC = Near Field Communication

1. Introduction

Most electromechanical systems require additional space to accommodate individual circuit boards. As the volume of electronic products is getting smaller and the functions are gradually increasing, it has become an inevitable trend to integrate electronic circuits into structural components to form structural electronics without additional circuit boards. Structural electronics have the advantages of reducing volume by 30%, reducing production costs, reducing energy consumption by more than 20%, and improving signal quality, so they have attracted extensive attention from the global industry.

One of the most critical issue of structure electronics is how to fabricate the circuit directly on the 3D surface of the structure; the other is how to bond passive and sensing elements to the circuit on th e 3D surface. Several fabrication techniques can be found in the literatures: microscopic integrated processing technology (MIPTEC) [1], laser direct structuring (LDS) [2], and aerosol jet process [3]. Laser direct structuring (LDS) is a quite mature 3D surface circuit process, but is only available for a very specific few injection molding materials. Therefore, it cannot be applied to 3D printing materials or most other materials, including non-injected polymers, metals, glass, ceramics, etc., nor can it be used to make multilayer circuits. This paper presents a novel laser-induced metallization (LIM) technique to fabricate circuits directly on the 3D surfaces of most objects.

2. Laser-induced metallization process

The laser induced metallization can be described as shown in Fig. 1. First, a newly developed, metal-free laser-activatable solution containing epoxy, PU, and 1-5% of trigger particles, was sprayed onto the surface of the substrate. The trigger particles may be a pigment, organometallic particles, or a chelation formed from a metal chelated by a chelating agent. The substrate can be plastic, metal, glass, or ceramic.

After the solution was cured at 80 ^oC to form an insulating polymer layer with a thickness of 50~100 μm, an Nd:YVO4 (neodymium-doped yttrium orthovanadate) end pumped pulse laser was used to directly write circuit patterns on the cured layer and activate the trigger particles. Its wavelength is 10.6 μm, and pulse width is about 10 ns. The focused spot size is about 38 μm, therefore, the minimum line width patterned by laser is about 40 μm. Change the laser power (P, watt), pulse frequency (f, kHz), and scanning speed (S, mm/sec) will influences the linewidth (W, μm) and linedepth (D, μm), as shown in following equations.

$$W = \frac{(-0.1619\times f^2+15.397\times f+475.39)\times P}{S} + \frac{(-0.0256\times f^2+2.3647\times f+63.194)}{S} + 25.55 \text{ ----------------------------(1)}$$

$$D = \frac{(-0.1041\times f^2+18.084\times f+135.41)\times P}{S} + \frac{(-0.6028\times f^2+20.471\times f+64.563)}{S} - 0.15 \text{ ------------------------------(2)}$$

Finally, the laser processed samples were subjected to the electroless plating process to deposit a copper layer in the laser-activated areas and realize the electrical circuit. The deposition rate of electroless copper is 5 μm/hr. The thickness of the metal circuit depends on the electroless plating time. The electrical property of the circuits would be more stabilized with a thickness over 3 μm. In particular, glyoxylic acid is used to replace formaldehyde to reduce the toxicity of the copper electroless plating solution and reduce the reaction temperature to 40~45 ^oC. After copper electroless plating, the line width will slightly widened.

Because the laser-activatable solution layer is metal-free, it's also a good electric insulator. The multilayer circuits can be fabricated by simply repeating the previous process on top of the original circuit. By the layer-by-layer processes, this method can be used to accomplish 3D circuits on almost any complex surface.

When the substrate material is ceramics, such as alumina, perovskite, etc., the first step of LIM process can be skipped because the trigger particles are already contained in these materials. However, due to the higher melting point of ceramics, higher laser power and smaller spot size must be used for laser activation. When the focused spot size of laser is 16 μm, the minimum linewidth is about 15 μm.

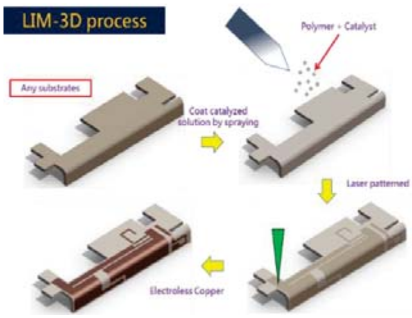


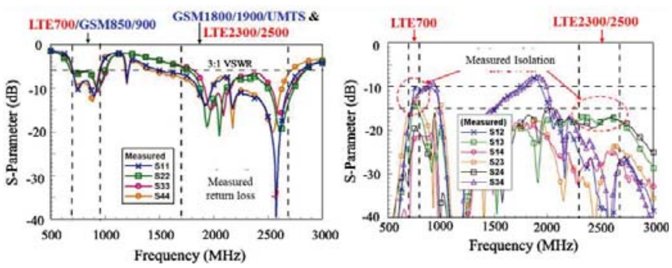
Fig. 1 Laser induced metallization process schematic

3. Applications and Results

3.1 2G/3G/4G LTE Multi-band 4 MIMO Antenna

By applying the LIM technology, a set of multi-band 4 MIMO antenna and an NFC antenna have been fabricated on the plastic or glass back cover of mobile phone, as shown in Fig. 2. In order to put more antennas in the same back cover, these antennas are designed as two-layer antennas to reduce their size, successfully reduce the consumption of space. The antenna was verified to cover LTE700 and LTE2300/2500 frequency bands and GSM850/900 and GSM1800/1900/UMTS operation, and achieve 2G/3G/4G full-frequency operation. The 2-layer NFC antenna had a compact size of 2.5 cm x 3 cm, reducing the area by 50%.

Fig. 2 A multi-band 4 MIMO antenna and a NFC antenna on plastic/ glass back cover of mobile phone.



(a) (b)

Fig. 3 Performance of the multi-band 4 MIMO antenna. (a) return loss and (b)isolation

3.2 Humanoid Robot Finger

This study attempts to design a new capacitive tactile sensor with a simple structure, as shown in Figure 4, which can theoretically be used as a tactile sensor to sense both normal force and shear force at the same time. A plurality of parallel strip copper electrodes placed on both of the polymer coating layers. The electrode strips on the upper layer positioned 90^o related to the electrode strips on the lower layer. Each electrode strip defines as a rectangle shape and connected with a narrow and short connection line. With the laser-induced metallization (LIM) technology, the tactile sensor has been successfully directly fabricated onto the curved surface as a humanoid robot finger as shown in Figure 5. This study was also verified that the capacitance of this sensing structure respond to downward normal forces on the finger. Initial capacitance of each sensing elements range from 0.67 to 0.77 pF, and the capacitance change purely caused by normal force of 29.4 N is 0.132 pF.

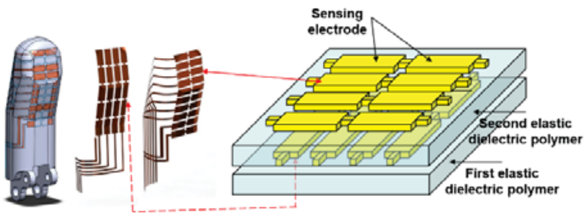
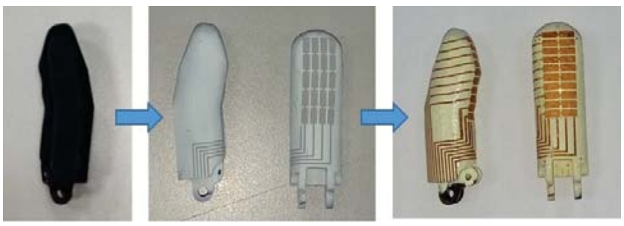
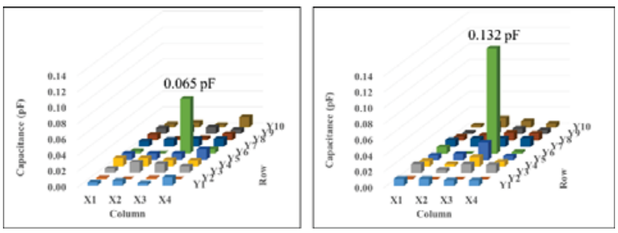


Fig. 4 Schematic of the tactile sensing structure in this study



(a) (b) (c)

Fig. 5 Humanoid robot fingers. (a) 3D printed finger (b) first polymer dielectric layer sprayed and patterned by laser. (c) Spraying of the second polymer dielectric layer and laser patterning and metallization



(a) (b)

Fig. 6 Capacitance change caused by downward normal force. (a) downward force of 14.7 N (b) downward force of 29.4 N

3.3 3D ceramic circuit board for CIS probe card

The probe card connects an electronic tester and a semiconductor wafer to validate the functionality of the circuits on the wafer. The probe card basically comprises a printed circuit board (PCB), a space transformer and probe needles, as shown in Fig. 7. Conventional space transformers are made of multilayer ceramic or multilayer organic. The space transformer not only transfers power and signals between the probe needles and the PCB but also expands the pad pitch from needle side to PCB side via dense and complexly routed metal circuits in multiple layers. Relatively dense and staggered metal traces are not conducive to the transmission of high-frequency high-speed signals. At the same time ceramic space transformers are always expensive and usually take a long time for manufacturing. This study used LIM technology to fabricate fan-out metal circuits on the surface of a 3D ceramic block to replace the conventional multilayer ceramic space transformers. Metal circuits have a minimum line width of 61 µm and space of 59 µm. 3D ceramic circuits board can be bonded with MEMS micro-cantilever probe needles to form a modular probe head, as shown in Fig. 8, one modular probe head for one die. It can be applied to high-speed testing of CIS wafers with tens of millions of pixel.

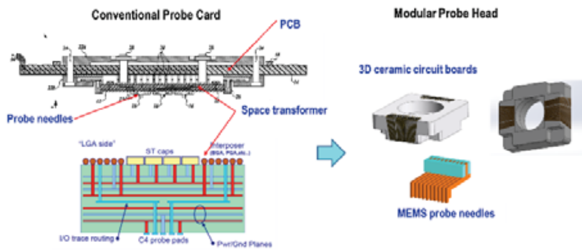


Fig. 7 Schematic of probe card (upper left), space transformer (lower left) and modular probe head (right)

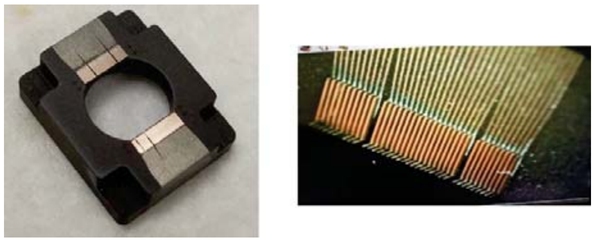


Fig. 8 3D ceramic circuit board bonded with MEMS probe needles

4. Conclusions

This study shows a new developed three-dimensional laser induced metallization (LIM) technology. LIM can be used to fabricate circuits directly on the 3D surface of most objects made of plastic, metal, glass or ceramic. Repeating the LIM process multiple times can realize 3D multi-layer circuits.

LIM technology has been verified in applications of 2G/3G/4G all-in-one compact antenna and multi-layer NFC antenna on mobile phone, tactile sensor on humanoid robot finger, and 3D ceramic circuit board for CIS probe card.

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