Front. Optoelectron. China 2009, 2(1): 86–91
DOI 10.1007/s12200-009-0008-x

RESEARCH ARTICLE

Laser micro-cladding electronic pastes for fabrication of MIM thick film capacitors

Yu CAO, Xiangyou LI, Xiaoyan ZENG (✉)

School of Optoelectronics and Engineering, Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract Two direct-write processing methods – direct material deposition by microPen and Nd:YAG laser micro-cladding – are integrated with computer-aided design/computer-aided manufacturing (CAD/CAM) technology for the fabrication of passive electronic components. A basic two-step procedure of the laser micro-cladding electronic paste (LMCEP) process for thick film pattern preparation is presented. In particular, metal-insulator-metal (MIM) type thick film capacitors are fabricated on ceramic substrates by the LMCEP process. Multilayer structures of the MIM thick film capacitors are demonstrated and discussed. Results of the frequency characteristics test show that the MIM thick film capacitors fabricated by the LMCEP process have excellent direct current (DC) voltage stability ($<2.48\%$), excellent frequency stability ($<2.6\%$) and low dissipation factor ($<0.6\%$), which are sufficient for many megahertz applications.

Keywords laser micro-cladding, electronic paste, microPen, thick film, capacitor

1 Introduction

The current trend in the field of electronic equipment production, from the product development stage to market launch, is characterized by extremely short innovation cycles. How to respond to market requests quickly, shorten the research and development (R&D) prototyping fabrication period, and reduce the cost of electronic devices have become challenging work. Thanks to new flexible manufacturing methods and technologies, this situation is being changed gradually. In the rapid prototype fabrication field, maskless mesoscale material deposition (M3D) technology, the direct-write syringe process (microPen, n-Scrypt), and the laser micro-cladding electronic paste (LMCEP) process are three typical alternative technologies for direct-write fabrication of thick film electronic devices besides screen printing and low temperature co-fired ceramic (LTCC) technologies [1–3]. The M3D technology created by Sandia National Laboratory is able to do conformal coating and three-dimensional builds, but requires material viscosity below 1 Pa·s. This limits its utilization of commercially available thick film pastes, since most of their viscosities are between 100 to 450 Pa·s. MicroPen and n-Scrypt are two material dispensing processes that can pattern electronic circuits with a wide variety of materials, including conductive inks and resistive compositions. This technique, however, currently has lower resolution rate.

The LMCEP process in this experiment includes two steps: first, depositing the electronic pastes on substrates by microPen, and then using the laser to irradiate the coatings. LMCEP has many advantages compared to the traditional screen printing and LTCC processes, including computer-aided design (CAD) direct-driven applicability, being maskless, fewer processing steps, and lower material cost. With the help of computer-aided design/computer-aided manufacturing (CAD/CAM) technologies, the LMCEP process can produce conductive lines and other passive components with complex patterns, and satisfy developing demands for rapid fabrication, low-cost and flexibility. The LMCEP process has been successfully applied for the flexible fabrication of conductive metal lines and various passive electronic components [3–6], which will significantly impact many industry segments such as electronics, aerospace and life sciences.

Metal-insulator-metal (MIM) structure thick film capacitors, which have been fabricated by screen printing and LTCC process for many years [7,8], are often the best choice for high frequency application because of their good performance at capacitance range, direct current

Received July 9, 2008; accepted October 5, 2008

E-mail: xyzeng@mail.hust.edu.cn

(DC) voltage dependency, surface mount device (SMD) compatibility and reliability, and other factors. In our study, the LMCEP process is used for the integrated fabrication of MIM thick film capacitors, which utilize commercially available thick film electronic pastes as the material system. Principles of Nd:YAG laser and microPen integrated fabrication of MIM thick film capacitors are also described in detail. Surface and interface bonding states of the multilayer structure are then characterized, and frequency characteristics up to 1 MHz are investigated.

2 Experiment

In the experiment, a $PbO\text{-}CaO\text{-}TiO_2\text{-}Al_2O_3\text{-}SiO_2$ neo-ceramic glass is used as the dielectric material, and a silver-palladium paste that can handle reflow or wave soldering is used as the top and bottom electrode material system. The multilayer structure design of the MIM thick film capacitors is shown in Fig. 1. The size of thick film capacitor is 4 mm×4 mm, while thickness of the dielectric layer is 55 μm. The substrate is 96% wt Al_2O_3 ceramic. All materials are available from Sino-Platinum Metals (SPM) Co. Ltd.

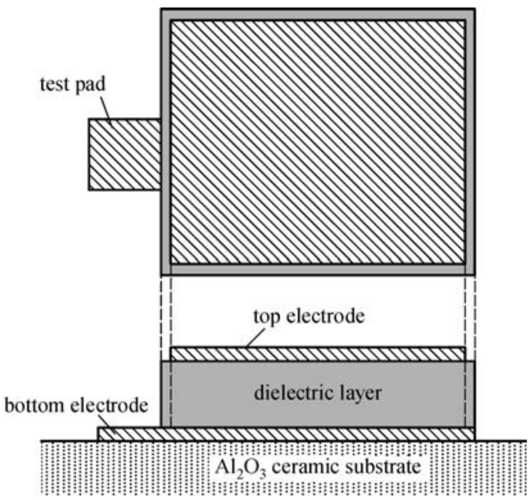

Fig. 1 Sandwich structure of MIM thick film capacitor

The laser micro-cladding fabrication system used is developed by our laboratory. Two direct-write material processing techniques – microPen and focused laser beam – are integrated by special LMCEP CAD/CAM software that can read CAD files directly and then transfer the data from the designed patterns to deposition paths. Figure 2 is the schematic diagram of the integrated laser micro-cladding fabrication system, which is composed of a three-axis working table, an Nd:YAG laser with maximum power of 50 W, and a microPen. The real equipment is shown in Fig. 3. The features of CAD direct-driven and multiple direct-writing techniques integration make the laser micro-cladding system an "art-to-part" processing platform, which eliminates expensive tooling and mask costs and hence leads to fewer manufacturing steps than other traditional methods.

The LMCEP process here is a basic two-step procedure in thick film preparation: deposit the material coatings directly by microPen, and then irradiate the deposition pattern by laser beam to solidify the coatings. For the fabrication of MIM thick film capacitors, three layers of coatings (i.e., MIM films) are deposited layer by layer and a laser irradiates each layer following each deposition layer. Following is the detailed procedure: first, an Ag-Pd paste layer is directly deposited onto the surface of the ceramic substrate as the bottom electrode by microPen, and then locally sintered by the focused Nd:YAG laser beam. The dielectric and top electrode layers are made through the same processing steps. Oven sintering post-processing is optional for decreasing pore defects in the dielectric film and increasing adhesion between the bottom electrode and substrate.

3 Results and discussion

3.1 Multilayer structure and properties

The surface and interface bonding states between the multilayer structures are a key feature of MIM thick film capacitors, which affect performance of the capacitor directly such as dissipation factor and capacitance stability. Figure 4 shows the interface bonding states of the multilayer structure of the MIM thick film capacitors fabricated by LMCEP, from which it can be known that the functional layers and the substrate are bonded strongly. Since the values of the MIM capacitors are in proportion to the area of the capacitors and in inverse proportion to the thickness of dielectric films, decreasing the thickness of the dielectric layer will increase the capacitance effectively. On the other hand, this method is difficult to control due to the existence of material defects such as pores when the thick film dielectric paste is only irradiated by a laser beam. Figure 5 shows the pore defects in the dielectric layer; the diameter of the pores ranges from 1 to 20 μm. The dielectric film should maintain minimum thickness of 50 μm to ensure good dielectric stability and limit dielectric losses in high frequencies. We designed a 55 μm thick dielectric layer in the experiment, by which a minimum 0.25% dissipation factor is achieved at 1 MHz frequency and 1.5 V applied bias voltage. Oven sintering post-processing is an effective way to decrease the porosity, but it will increase the overall manufacturing steps and bring the problem of compatibility in most IC processes.

The surfaces of the multi-films of the MIM thick film capacitors fabricated by LMCEP are shown in Fig. 6. The electrode layer surface after laser sintering is shown in

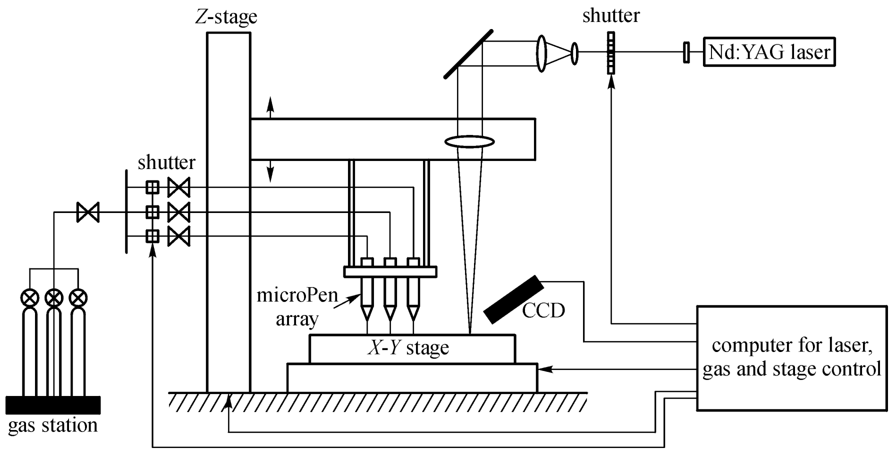

Fig. 2 Diagram of laser micro-cladding fabrication system

Fig. 3 Laser micro-cladding fabrication system

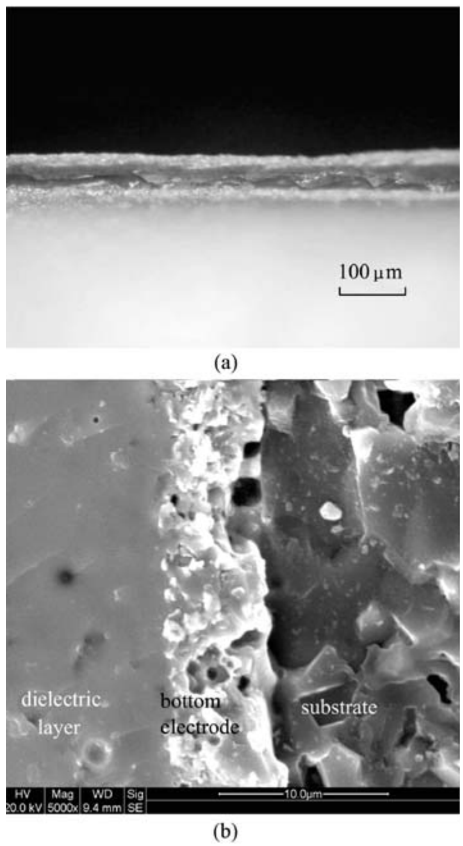

Fig. 4 Interface bonding states of multilayer structure of LMCEP fabricated MIM thick film capacitor. (a) Cross-section; (b) substrate, bottom electrode and dielectric layer bonding states

Fig. 6(a), in which the particles of Ag-Pd pastes are bonded very tightly and an interconnected network structure forms. Figure 6(b) shows the bottom electrode layer surface after both laser irradiation to form the patterns and 850°C oven sintering. Compared to Fig. 6(a), the particles of Ag-Pd pastes at the bottom surface are much more dense, interconnected and fluent. The porosity of the coatings has significantly decreased. It is confirmed that the resistivity of both surface and bottom electrodes are very low and are adequate as electrodes. Further experimental results demonstrate that the main effect of the oven sintering process will increase adhesion strength between the bottom electrode and substrate for MIM fabrication. Meanwhile, oven sintering processing is an effective step to decrease porosity in dielectric layer preparation. The surface morphology of the dielectric layer only irradiated by laser beam is shown in Fig. 6(c), while Fig. 6(d) shows the surface morphology of the dielectric layer irradiated by laser beam at first and then oven sintered at 550°C for 30 min. It can be observed that both surfaces of the dielectric layer are very smooth and their roughnesses are close to the level of the bulk ceramic material. Moreover, the arrows in Fig. 6(c) point out the pore defects at the

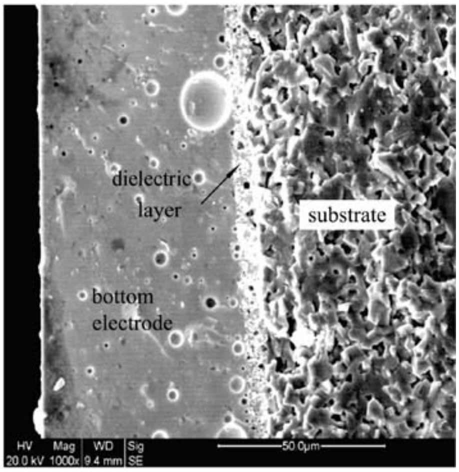

Fig. 5 Pore defects in dielectric layer

surface of the dielectric layer only irradiated by laser beam, but after oven sintering at 550°C for 30 min, no apparent pores can be observed, as shown in Fig. 6(d).

3.2 Electrical properties

The capacitance, insulation resistance and dissipation factor of the MIM thick film capacitors fabricated by LMCEP are characterized by an inductance-capacitance-resistance (LCR) meter (TH-2818) at 9 frequency sampling points with applied voltage of 1.5 V.

The capacitance of an MIM type thick film capacitor was given by [9]

$$C = 8.86 \times 10^{-3}\ \varepsilon_r A/d, \tag{1}$$

where C is the capacitance value, ε_r is the relative dielectric constant of the material, A is the common electrode area, and d is the thickness of dielectric material. Thus, the theoretical value of C is 23.6 pF in this study when ε_r, A and d are 10, 16 mm^2 and 0.06 mm, respectively.

Capacitance reduction as the operating frequency increases is one design consideration for wireless applications. Figure 7 shows the curve of the capacitance changed with the frequency, which demonstrates that the capacitance of the fabricated capacitor is very close to the theoretical value according to Eq. (1). The decline of the capacitance is only 2.6% (from 23.3 to 22.7 pF) as the frequency increases from 100 Hz to 1 MHz, and particularly 1.47% between 100 kHz and 1 MHz, which shows good frequency independent property.

Good capacitance DC stability, or the ability to maintain capacitance under DC bias, is required for analog circuit applications. Figure 8 gives the relationship between the

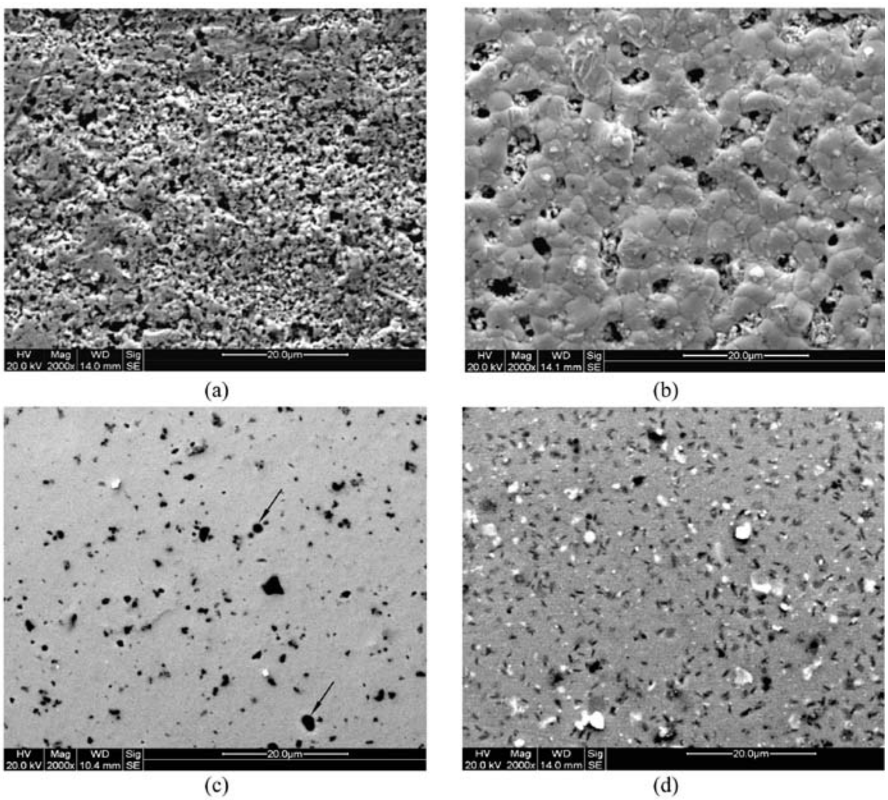

Fig. 6 Surface morphology of multilayer structures of MIM thick film capacitor fabricated by LMCEP. (a) Electrode layer after laser sintering; (b) bottom electrode layer after 850°C sintering; (c) dielectric layer after laser micro-cladding; (d) dielectric layer after laser micro-cladding and oven sintering at 550°C for 30 min

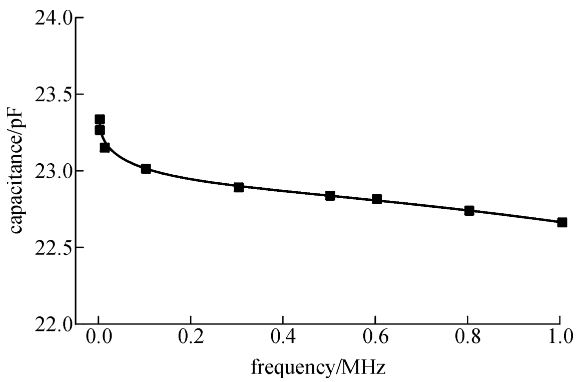

Fig. 7 Frequency evolution of capacitance of MIM thick film capacitor

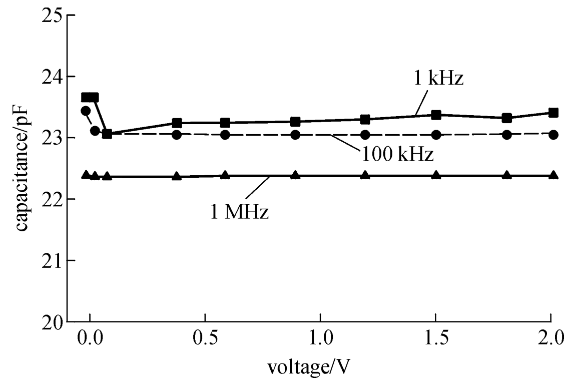

Fig. 8 Voltage evolution of capacitance of MIM thick film capacitor (1 kHz, 100 kHz and 1 MHz)

capacitance of the MIM thick film capacitor and the applied voltage, which demonstrates that the fabricated capacitors by LMCEP have excellent DC stability in the measured ranges.

To characterize the tuning performances of the capacitors in a given frequency, we define the parameter T as the tuning efficiency, as noted by

$$T = \Delta C / C_{\max},$$

where $C_{\max}$ is the maximum capacitance with the variation of the applied DC bias voltage, and $\Delta C = |C - C_{\max}|$. The tuning efficiency of the MIM thick film capacitors at different frequencies is given in Table 1. The smaller the value of T, the better the capacitance DC stability.

Table 1 Tuning efficiency of MIM thick film capacitors

frequency	T
1 kHz	< 2.48%
100 kHz	< 1.71%
1 MHz	< 0.13%

The frequency evolutions of the equivalent parallel resistance R_p and the dissipation factor of the MIM thick film capacitor are characterized and the results are shown in Figs. 9 and 10, respectively. These results demonstrate that the thick film capacitor shows a dielectric insulation characteristic when working at very low frequencies, and its equivalent parallel resistance R_p declines rapidly when the frequency increases. When the frequency is below 0.1 MHz, R_p is far beyond 18 MΩ, which rapidly declines to 2 MΩ as the frequency goes up to 1 MHz. The dissipation factor of the MIM thick film capacitor declines with the frequency increase, and the maximum dissipation factor of 0.6% occurs at the very low frequency of 100 Hz. The dielectric losses of the MIM capacitors are low enough up to the MHz regions.

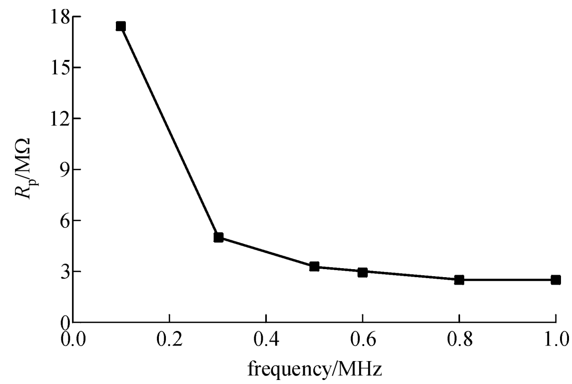

Fig. 9 Frequency evolution of equivalent parallel resistance

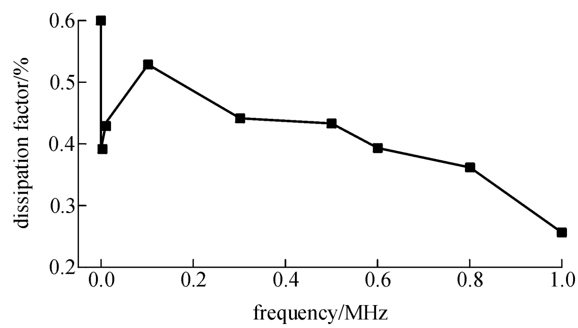

Fig. 10 Frequency evolution of dissipation factor at an applied bias voltage of 1.5 V

4 Conclusion

As a novel technology, the LMCEP process has been introduced to fabricate thick film conductive lines and passive components, especially the sandwich architecture MIM thick film capacitors. The surface morphology and interface bonding states analysis show that functional layers of the MIM thick film capacitors fabricated by the LMCEP process and the substrate are bonded strongly. The results of the frequency characteristics tests up to 1 MHz show good DC voltage stability, good frequency stability and low dissipation factor of the MIM thick film capacitors that may be applied to MHz regions. The LMCEP process for fabrication of MIM thick film capacitors should be further intensified by adapting high dielectric constant materials as the dielectric layer, such as tantalum oxide (Ta_2O_5).

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 50575086) and the National Hi-Tech Research and Development Program of China (Grant No. 2006AA04Z313).

References

1. King B. Maskless mesoscale materials deposition. Electronic Packaging and Production, 2003, 43(2): 18–20
2. Colvin J, Carter M, Puszynski J, Sears J. Laser sintering of silver nano-particle inks deposited by direct write technology. In: Proceedings of 24th International Congress on Applications of Lasers and Electro-Optics, Scottsdale, AZ, USA. 2005, 369–374
3. Zeng X Y, Li X Y, Liu J W, Qi X J. Direct fabrication of electric components on insulated boards by laser microcladding electronic pastes. IEEE Transactions on Advanced Packaging, 2006, 29(2): 291–294
4. Li H L, Zeng X Y, Li H F. Study on thick film resistor and electrode fabricated by laser micro-cladding electronic pastes. Surface and Coatings Technology, 2006, 200(24): 6832–6839
5. Li H L, Zeng X Y. Study on the structure and properties of thick-film capacitors fabricated by laser micro-cladding and rapid prototype. Journal of Materials Processing Technology, 2007, 184(1–3): 184–189
6. Zeng X Y, Dai Z G, Li X Y. Direct fabrication of thermosensors by laser micro-cladding functional materials. In: Proceedings of ICALEO 2006, Los Angeles, USA. 2006, 252–256
7. Kummel M L. A screenable high dielectric constant capacitor system for commercial circuit applications. In: Proceedings of 22nd Electronic Components Co. 1972, 124–133
8. Abe K, Ikegami A, Sugishita N, Taguchi N, Isogai T, Tsubokawa I, Ohtsu H. Development of the thick-film capacitor and its application for hybrid circuit modules. IEEE Transactions on Components, Hybrids, and Manufacturing Technology, 1979, 2(4): 434–441
9. Riad A A R, Stephenson F W. Thick film capacitor value. In: Proceedings of IEEE Southeastcon'81. 1981, 1–4