Inkjet Printing Approach to Fabrication of Non-sintered Dielectric Films and 3D Structures

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Abstract

With the current explosive growth of information communication technologies, it is required to realize 3D system integration of hetero-materials such as organic and inorganic materials with multi-functionality based on information-, nano-, bio, and energy technology. The direct-writing by the inkjet printing has significant attention since it is feasible to pattern and fabricate fine features directly from design or image file. In this presentation, we have formulated ceramic suspension inks (Al_2O_3 and $BaTiO_3$) and synthesized Ag conductive ink to print dielectric films and 3D circuitry such as metal-insulator-metal (MIM) capacitors and metal-via-metal interconnects. Inkjet-printed dielectric films were prepared without high temperature sintering process. Instead, a polymer resin was infiltrated through the inkjet-printed ceramic films and cured at 280℃. Since our goal is to fabricate non-sintered ceramic films, it is preferred that the inkjet-printed ceramic films should have a high packing density of more than 60%. High packing density leads to the inkjet-printed worth better electrical and mechanical properties. Roughly about 40% of micro-voids inside the inkjet-printed ceramic films were filled with the resin. The dielectric property measurement of the inkjet-printed Al_2O_3-resin hybrid films indicated that dielectric constant and dielectric loss are 6 and 0.003, respectively at 1 MHz In the case of inkjet-printed $BaTiO_3$-resin films, their dielectric constant and dielectric loss at 1MHz are 75 and 0.009, respectively. And we could fabricate all inkjet-printed embedded capacitor having MIM structure and daisy structure having metal-via-metal interconnection for 3D integration. The MIM capacitor consisted of 4 hybrid films that was placed Al_2O_3-Ag-$BaTiO_3$-Ag hybrid layers in order from below. In daisy structure case, the conductor patterns of lower and upper layer were built up each other with the Al_2O_3 films, and micro via was formed by laser drilling process then filled with Ag paste for interconnection between the conductor patterns.

Preparation of the Ceramic-resin Hybrid films

As advanced electrical ceramic device complexity increases, the need for alternate fabrication methods which offer a simple and rapid means of integrating multiple materials in three-dimensional (3D) structures is required. Fabrication of the ceramic devices is commonly achieved by a multilayer build sequence that utilizes thick film process such as low temperature co-fired ceramic (LTCC) technology, including tape casting and screen printing.[1] However, LTCC process commonly carries out a low-temperature sintering at below 900℃ and the sintering process involves shrinkage of the ceramic body for 3D structures. As a result, it is difficult to maintaining their interconnection of via to via in the structures.[2]

Therefore, we were trying to resolve the issue of the shrinkage from convergence of non-sintered process and inkjet-printing technology. Inkjet printing is beneficial in terms of additive manufacturing process which discards disadvantages of the conventional process requiring expensive and complicated high-vacuum equipments.[3] And non-sintered process induces high performance of the 3D interconnection because, the shrinkage does not occur in the ceramic-resin hybrid films by inkjet-printing and non-sintering process. First, The ceramic (Al_2O_3 and $BaTiO_3$ achieved low and high K, respectively.)suspension was inkjet-printed on substrate and then a polymer resin was infiltrated through the inkjet-printed ceramic films and cured at 280℃. Thus, ceramic-resin hybrid films were prepared without high temperature sintering process (Figure 1.).

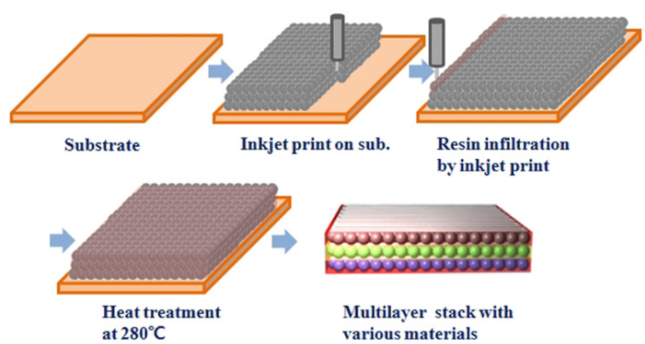

Figure 1. *Schematic diagrams of process of ceramic-resin hybrid filmsfabrication and it is possible to build up multilayer with various materials by these process.*

Dielectric Properties of the Hybrid films

Inkjet-printed ceramic films should have a high packing density of more than 50% for better electrical properties. Figure 2a indicates the inkjet-printed a typical dot, which was made by coffee ring effect, and we could observe this effect in a inkjet-printed line (figure 2b). As Figure 2d and 2e shown, a edge of the line had higher packing density than a central part of the line therefore, we successfully fabricated the ceramic films (Figure 2c) having a comparatively high packing density, it took advantage of overlapping the line edges that caused by coffee ring effect.

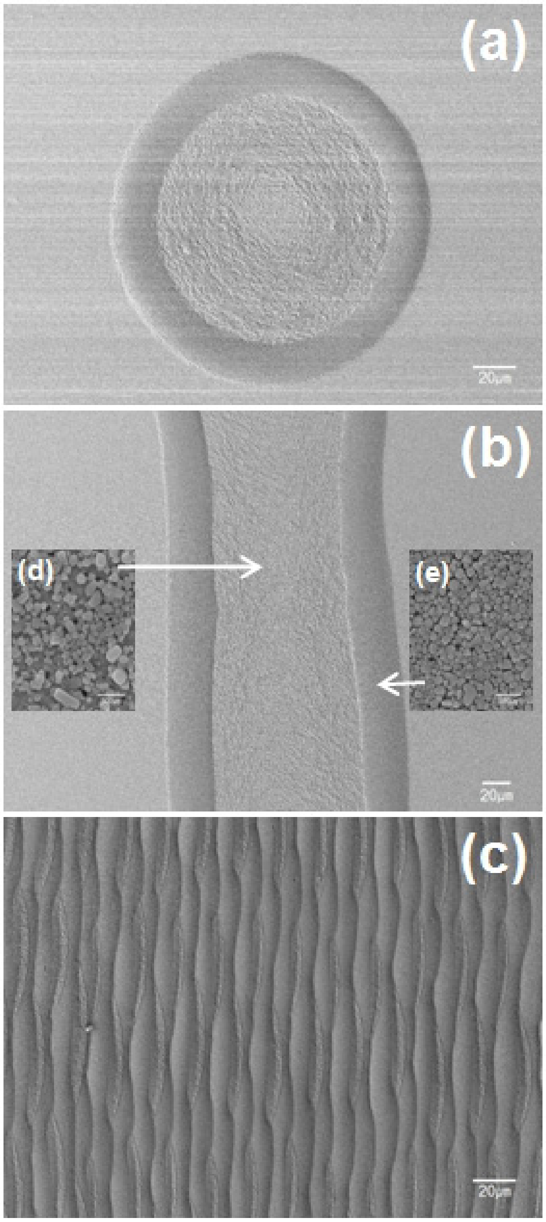

Figure 2. *SEM Images of (a) dot, (b) line and (c) film. $BaTiO_3$ films were fabricated by overlapping rabbit ears, because the part is very dense (d~e).*

The packing densities of the films were calculated by following equation with the measurement of the film weight, total volume, their thickness and the area.

$$Packing\ \ density\ (\%) = \frac{W}{\rho} \times \frac{1}{A \times T} \times 100, \quad (1)$$

where W is film weight, ρ if the density of solid material, A is the printed area and T is thickness of the film. The thickness of the films was measured by surface profiler (Dektak 150, Veeco) and dielectric properties of the films were measured at 1MHz by impedance analyzer (4294A precision impedance analyzer, Agilent). Al_2O_3 films had packing density of nearby 55% then the dielectric permittivity and loss was about 6 and below 0.003, respectively (Figure 3a).

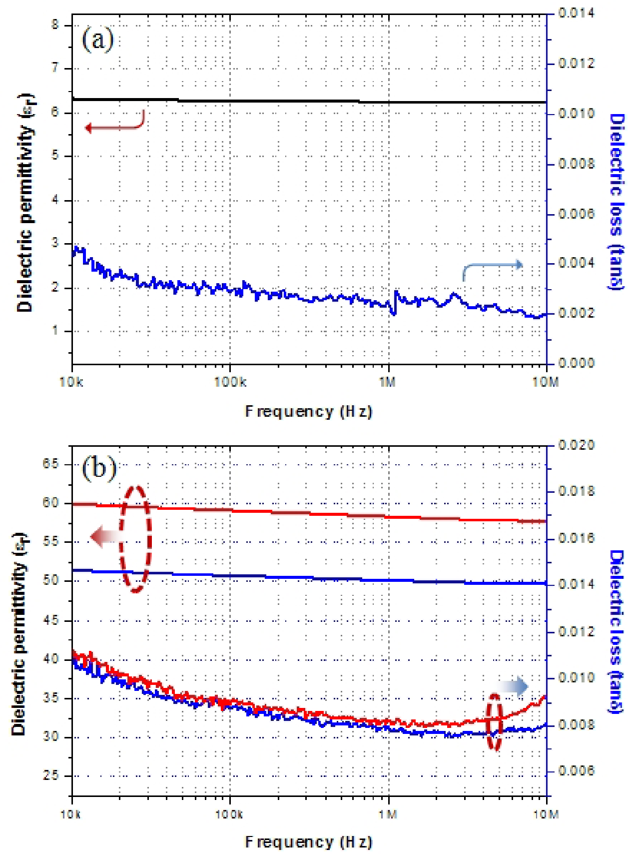

Figure 3. *Dielectric properties of the ceramic-resin hybrid films .(a) Al_2O_3 hybrid films, and (b) $BaTiO_3$ films.*

In $BaTiO_3$ films case, the packing density dominate permittivity of $BaTiO_3$ films. There are many theoretical prediction models for the dielectric permittivity of ceramic-polymer hybrid films such as Lichtenecker, Maxwell-Wagner, Yamada, Jayasundere-Smith, etc. [4] McGeary et al. showed that the packing density increased when the ceramic films were prepared with the multimodal size distributed powders.[5] And when ceramic powders of bimodal distribution were mixed, the ratio of diameter of large particle to the small particle need to be larger than 6.5 for dense ceramic film. In our experiment, in order to improve the packing density of the $BaTiO_3$ films, bimodal $BaTiO_3$ ink was formulated by mixing 30nm $BaTiO_3$ powders into 300nm $BaTiO_3$ powders which system had the ratio of diameter of large particle to the small particle was 10. As a result, $BaTiO_3$ films had packing density of about 60%. Then the dielectric permittivity increased from 50 in the single modal film to 58 in the bimodal film, and dielectric loss of the bimodal film was below 0.009 (Figure 3b).

Fabrication of Daisy Structure and MIM Capacitor for 3D integration

We fabricated all inkjet-printed embedded capacitor having metal-insulator-metal (MIM) structure and daisy structure having metal-via-metal interconnection with above-mentioned two ceramic-resin hybrid films along with inkjet-printed conductors (with silver nano-powder dispersed ink). MIM capacitor consisted of four inkjet-printed hybrid films of Al_2O_3-Ag-$BaTiO_3$-Ag. Two Ag layers applied for top and bottom electrodes, the $BaTiO_3$ layer applied for insulator for high K and the Al_2O_3 layer act as bare substrate for embedded 3D structures (Figure 4a).

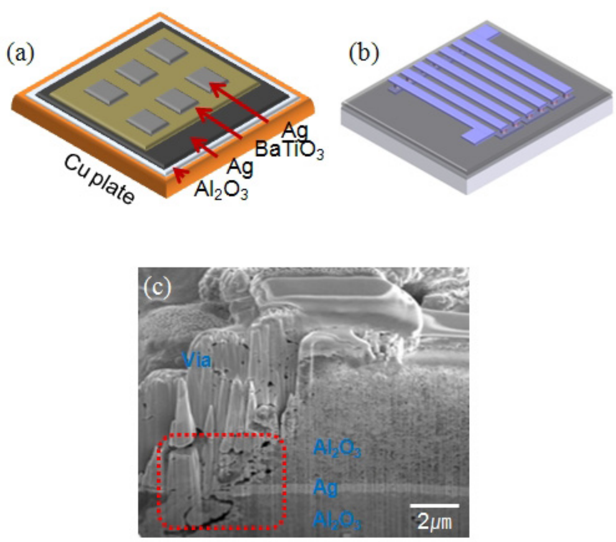

Figure 4. *(a) Schematic diagrams of MIM capacitor and (b) daisy structure, and (c) Cross-section image of via hole filled with Ag paste in daisy chain structure.*

In daisy structure case (Figure 4b), the conductor patterns of lower and upper layer were built up each other with the Al_2O_3 films, and micro via was formed by laser drilling process then filled with Ag paste for interconnection between the conductor patterns. However, it is very difficult for laser drilling to terminate accurately right in front of starting point of lower electrode layer after drilling upper conductor layer, because the inkjet-printed electrode is very thin. Eventually, the laser drilling penetrated lower electrode. Nevertheless, the lower ceramic hybrid layer was not seriously damaged in the drilling process, the interconnection could be maintained by filled silver paste (Figure 4c).

Summary

We fabricated ceramic-resin hybrid films by inkjet-printing technology and without high temperature sintering. Then, the dielectric permittivity and loss of Al_2O_3 films were nearby 6 and 0.003, respectively. In $BaTiO_3$ hybrid films case, the dielectric permittivity and loss were 58 and below 0.009, respectively. And we successfully could fabricate the embedded MIM capacitor and daisy structures for 3D interconnection.

Acknowledgement

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References

[1] R. E. Mistler, "Tape Casting: The Basic Process for Meeting the Needs of the Electronics Industry," Am. Ceram. Soc. Bull., 69, 6, 1022-26 (1990)
[2] Imanaka, Yoshihiko, "Multilayered LTCC Technology," Springer Verlag. (2004)
[3] J. Miettinen, V. Pekkanen, K. Kaija, P. Manasikkamaki, J. Mantysalo, M. Mantysalo, J. Nittynen, J. Pekkanen, T. Saviauk, and R. Ronkka: Microelectronics J. 39, 1740 (2008)
[4] T. Yamada, T. Ueda, and T. Kitayama, J. Appl. Phys. 53, 4328 (1982)
[5] R. K. McGeary, J. Am. Ceram. Soc 44, 513 (1961)