Advances of Computer Science Technology – Proposal of 3D-Electrode Structures Based on a Stereolithography-Based 3D-Printer –

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Abstract

We have succeeded for the first time in fabricating three-dimensional electrode structures by a stereolithography - based 3D-printer. 3D-printer technology is an innovative application brought by the computer science technology progress. In order to minimize the area taken by the electrical connections, we designed buried electrode structures. As a fundamental study, various shapes of mesa type electrodes have been designed, fabricated and characterized. For some structure shapes, the resistance between the electrode and the neighbor area was higher than 40MΩ, which reached the measurement limit of our resistance meter (multimeter). Thus, excellent electrical isolation has been obtained. Within four electrode structures, two of them performed a high electrical isolation.

Keywords: 3D-printer, sterereolithography, buried electrodes, SMEMS

1. INTRODUCTION

Recently, 3D printer machines are on the market from several companies [1]. The 3D printing technology is an innovative application brought by the advance of computer science technology, particularly rapid progress of 3D CAD (Computer Aided Design) / CAE (Computer Aided Engineering) / CAM (Computer Aided Manufacturing) [2]–[4] have a significant contribution. The authors have demonstrated for the first time that 3D-printed models can perform electromechanical functions such as in-plane lateral actuators and out-plane rotational actuators (torsional mirrors) [5]–[8]. For realization of these functions, the 3D-printed models must be suitably masked and metallized thereafter. Since the minimum possible fabrication size is in the order of sub-millimeters, these innovative models have been named by the authors as SMEMS (Sub-milli Electro-mechanical Systems) devices. In order to actuate one device, at least two electrodes are necessary. In the case of differential voltage driving, three electrodes must be formed on the device. Up to now, these electrodes are fabricated by masking polyimide tapes which are manually cut and taped up on desired places. The exposed and taped (masked) areas will turn out to electrode and isolation parts, respectively, after metallization process. This simple electrode formation method has been used up to now because the overall size of the device is relatively large. However, we are also conducting research for miniaturization and integration of several functions in one device and/or integration of several devices in a limited space. In this sense, we will no longer be able to manually fabricate electrode masks for electrical connections and isolations. In addition, since the device structures will become more three-dimensional and complex, even the use of stencil mask would be extremely difficult. In order to solve this problem, we have proposed several three-dimensional compact electrode structures that do not need any masking process. Furthermore, the electrical isolations of neighboring electrodes are surely kept though the structures are formed in batch metallizing process. These three-dimensional structures can be easily fabricated since 3D-printing technology is capable to create almost any kind of shape. In this paper, details of how these structures have been created, and design, fabrication and characterization are described.

2. STRUCTURE FORMATION

In this study, we have firstly considered structures having a mesa type shape and then extended to trace or line shapes which are usually used in electrode connections. The mesa type shape means that the structure stands up above a flat surface (substrate surface) having an image of a square table placed on a floor. If the mesa structures are consecutively connected, then a trace or line connection is obtained. The first electrode structure we have figured out is a T-shape cross-sectional structure which looks as a pedestal table as shown in Fig. 1.

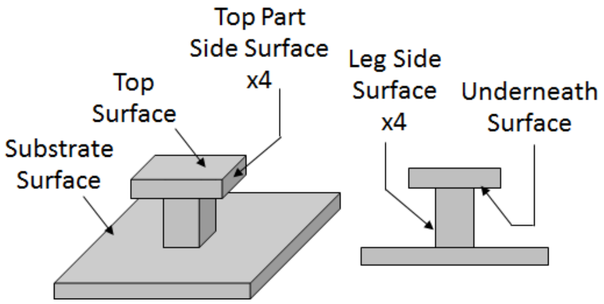

Figure 1 Basic electrode structure (naming of parts)

The name of each part of the structure is based on an image of pedestal table as follows: top surface (the top surface of a table top), four top part side surfaces (side surfaces of a square table top), four leg side surfaces (surfaces of a square leg), underneath surface (surface underneath the table top), substrate surface (surface or floor where the leg is supported). These names are used for other structures though there are few structural changes. In this study, the material used for these structures is a UV-curing resin which is an electrical insulator. Thus, the surfaces must be metallized in order to form an electrode. Usually, the substrate surface and top surface are connected to the ground and to a certain electric potential, respectively. In other words, these surfaces must be electrically isolated. The metallization process is conducted by an Au ion sputter (E-1020, Hitachi Co.) in batch process. Usually, this coater is used for preparing specimens coatings for observation in a scanning electron microscope (SEM) which lateral surfaces are also well coated. This kind of coater is very convenient for our SMEMS devices, since lateral sides must be coated such as in comb-drive actuator structures. For electrode formation, this feature is undesirable. Thus, a three dimensional structure must be devised in order to obtain a good electrical isolation. In order to accomplish such an electrical isolation, we have thought that shadowed area created by underneath surface would be effective. The T-shape cross-sectional structure would "automatically" isolate the mentioned surfaces. The designed 3D-CAD data is illustrated in Fig. 2.

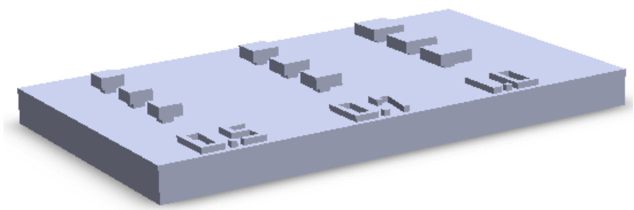

Figure 2 3D-CAD data of designed electrode structures

Fig. 3 shows the photograph of fabricated sample by a stereolithography-based 3D-printer (MiiCraft^{TM}). The photograph of the sample after Au ion sputtered is shown in Fig. 4. On the substrate surface, samples have been numbered as "0.5", "0.7" and "1.0". These numbers means the dimensions of each set (3 samples per set: #1, #2, and #3) as illustrated in Fig. 4 (d=0.5mm, 0.7mm, 1.0mm). Fig. 5 shows the detailed dimensions of the pedestal table structure in function of value "d". The leg height is set at 0.5mm for all samples.

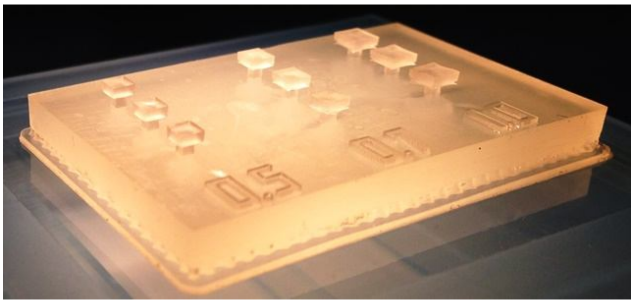

Figure 3 Fabricated electrode structures

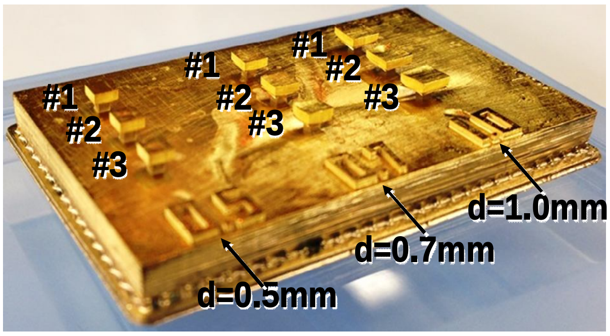

Figure 4 Au ion sputtered electrode structures

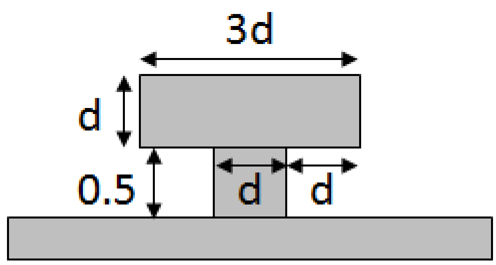

Figure 5 Detailed dimension of pedestal table structure

The resistance has been measured for each sample by a multimeter (U1231A, Agilent) and the results are shown in Table 1.

Table 1: Measured resistances

Sample No.	d=0.5mm	d=0.7mm	d=1.0mm
#1	5.0Ω	37.5Ω	O.L.
#2	5.3Ω	13.2Ω	O.L.
#3	5.6Ω	7.70Ω	51.2Ω

These resistances have been measured between the top and substrate surfaces. From these results, we obtained a very low resistance for 78% of the samples, thus we concluded that T-shape cross-sectional structures are not effective. At the same time, we have designed a spiral trace electrodes for d=0.5mm and d=1.0mm as shown in Fig. 6 (separation gap of 0.5mm). As in the mesa type structure results, electrical isolation between the top and substrate surfaces has not been achieved. However, we have noticed that the Au sputtered layer were lacking in uniformity in between the traces by more detailed observation. Thus, we have presumed that in such an area an electrical isolation has been obtained. In order to confirm this hypothesis, we cut out the outer traces where the lateral sides have been directly Au sputtered as shown in Fig. 7. Then, we measured the resistance between the center and the spiral end for each spiral. For both spirals, we obtained an O.L (over load) value, i.e., values higher than the measurable limit (>40MΩ). From these results, we have concluded that the point is to surround the electrode structure by an outer wall.

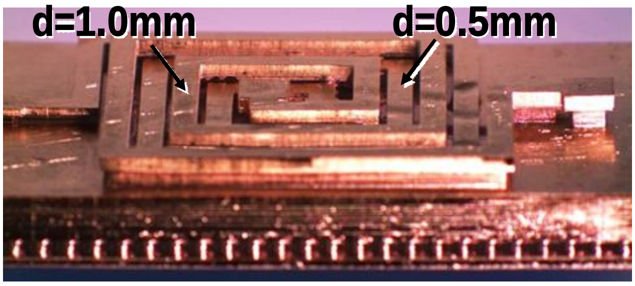

Figure 6 Spiral trace electrodes

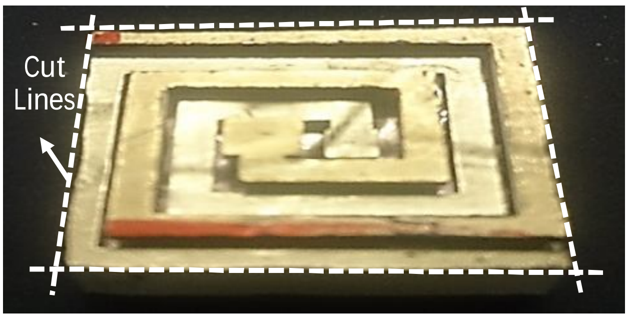

Figure 7 Spiral trace after cutting out the outer parts

6 Buried Three Dimensional Electrode Structures

Based on the considerations discussed in the previous section, we have designed four structures. Instead of surrounding the electrodes by outer walls, we have considered buried structures that are created inside the substrate which leads to the same result and further enhanced use of space. Moreover, when 3D-printer features are taken into account, buried structures can be easily fabricated. Since the cross-sectional view of each structure is similar to the alphabetical letter shapes as in the previous section, the naming has been given by the authors as follows:

1) Buried structure 1 (hereinafter referred to as "BS1"): I-shape electrode surrounded by a half T-shape side wall;
2) Buried structure 2 (hereinafter referred to as "BS2"): T-shape electrode surrounded by a half T-shape side wall;
3) Buried structure 3 (hereinafter referred to as "BS3"): I-shape electrode surrounded by a flat side wall;
4) Buried structure 4 (hereinafter referred to as "BS4"): T-shape electrode surrounded by a flat side wall;

The cross-sectional view of each BS and its dimension is shown in Fig. 8 (bilaterally symmetric structure). For all BSs the value of "d" has been set at 0.5mm.

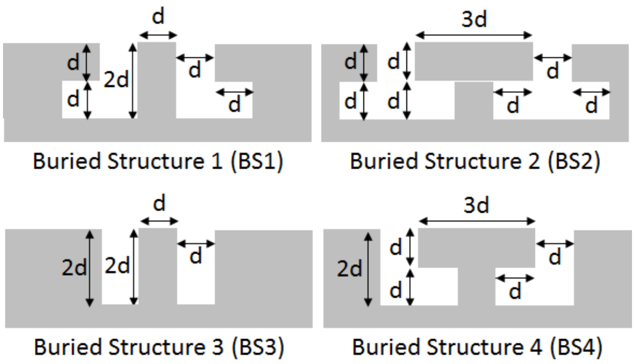

Figure 8 Designed buried electrode structures

BS1 and BS2 have been designed and fabricated on the same substrate. For each BS, four samples with same dimensions have been designed on the substrate in order to observe the uniformity. The same applies to BS3 and BS4. The fabricated BSs before and after Au ion sputtering are shown in Fig. 9 and Fig. 10, respectively.

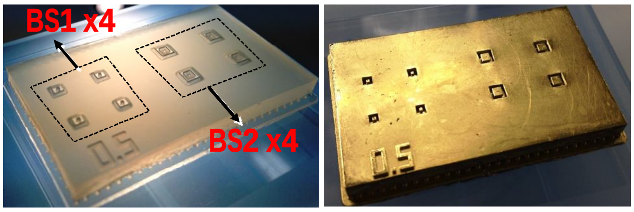

Figure 9 BS1 and BS2 before (left) and after (right) metallization process

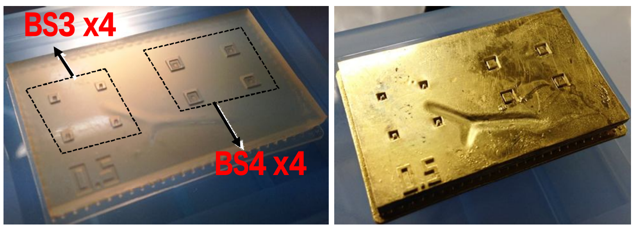

Figure 10 BS3 and BS4 before (left) and after (right) metallization process

7 Results and Discussions

The BSs have been Au ion sputtered and the resistance between the top electrode and substrate surface has been measured by the multimeter in function of the Au coating thickness. Based on the sputtering thickness ratio, which is 6nm/min (from data sheet), we have firstly coated 60nm and measured the resistance thereafter, and then adding the thickness in increments of 30nm (90nm, 120nm, …, 300nm). The resistances have been measured for each increment. The resistance in function of the thickness for BS1 and BS3 has been plotted as shown in Fig. 11. As expected, the resistance tends to decrease with the increment of thickness. BS2 and BS4 are not illustrated in the graph because their resistance values are over load (O.L) for all thicknesses. From these results, BS2 and BS4 are both excellent structures for electrode structures. On the other hand, the isolation of BS3 starts to degrade from 120nm. Usually for our devices, the electrode thickness is from 100nm to 200nm, thus BS3 is not suitable for electrode structure. BS1 starts to degrade from 240nm, thus taking into account the isolation tolerance, BS1 would be a good electrode structure for thickness less than 200nm. BS1, BS2 and BS4 have one point in common, i.e., they have an underneath surface on the electrode structure and/or on side-walls. Thus, we can assure that the combination of underneath surfaces and close side-walls are required conditions to achieve a good electrode structures.

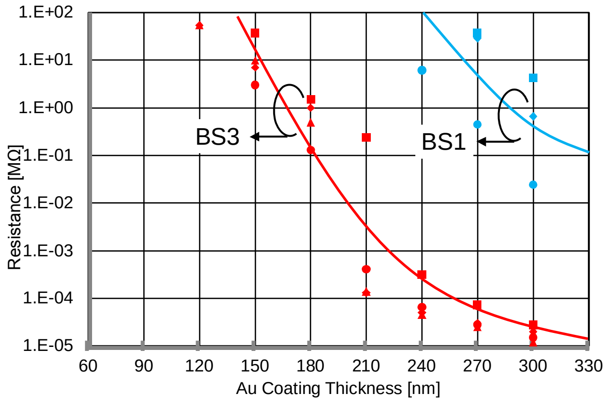

Figure 11 Resistance in function of thickness (mega-ohm)

8 CONCLUSION

We have designed, fabricated and characterized innovative three-dimensional buried electrode structures that do not require any masking process. Furthermore, they can be metallized by a batch process. These structures have been fabricated by a stereolithography- based 3D-printer and metallized by an Au ion sputter thereafter. Within four structures, two of them (T-shape electrode surrounded by a half T-shape side wall, and T-shape electrode surrounded by a flat side wall) performed excellent electrical isolation within thickness range from 60nm to 300nm. I-shape electrode surrounded by a half T-shape side wall demonstrated to have good isolation up until thickness of 200nm. We have revealed that underneath surfaces and close side-wall are the required conditions to achieve good electrode structures. This time, mesa type structures have been intensively investigated. Based on these good results, we can assure that these structures can be extended for line or trace type electrodes. These results are one of the key points towards the integration of SMEMS devices.

Acknowledgment

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References

[1] D. A. Roberson, D. Espalin, R. B. Wicker, "3D Printer Selection: A Decision-Making Evaluation and Ranking Model," Virtual and Physical Prototyping, VIII (3), pp. 201-212, 2013.

[2] C. Wu, Y. Xie, S. M. Mok, "Linking Product Design in CAD with Assembly Operations in CAM for Virtual Product Assembly," Assembly Automation, XXVII (4), pp. 309-323, 2007.

[3] G. Uzun, "An Overview of Dental CAD/CAM Systems," Biotechnology & Biotechnological Equipment," XXII (1), pp. 530-535, 2008.

[4] N. Prabhu, M. D. Anand, L. E. Ruban, "Structural Analysis of Scorbot-ER Vu Plus Industrial Robot Manipulator," Production & Manufacturing Research, II (1), pp. 309-325, 2014.

[5] J. Mizuno, S. Takahashi, "Characterization of an In-Plane Single-Sided Lateral Comb Actuator Fabricated by a 3D-Printer," The SIJ Transactions on Computer Science Engineering & its Applications, II (3), pp. 82-87, 2014.

[6] J. Mizuno, S. Takahashi, K. Suzuki, "Vertical Comb-Drive Actuated Torsional SMEMS Mirror Fabricated by a Plaster-Based 3D-Printer," In Proceedings of the International Congress on Natural Sciences and Engineering 2014 (ICNSE 2014), pp. 770-776, 2014.

[7] J. Mizuno, T. Kakizaki, S. Takahashi, S. Kudo, "A stereolithography-based 3D-printed torsional mirror scanner actuated by vertical comb-drive," International Journal of Application or Innovation in Engineering & Management, IV (6), pp. 153-160, 2015.

[8] J. Mizuno, S. Takahashi, "A Double-Sided In-Plane Lateral Comb-Drive Actuator Fabricated by a Plaster-Based 3D-Printer," Key Engineering Materials, DCLVI-DCLVII, pp. 594-599, 2015.

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