Selective Electrodeposition Technology for Organic Insulator Films on Microelectromechanical-System Structures

Tomomi Sakata Non-member (sakata@aecl.ntt.co.jp)
Hiromu Ishii Member (jihii@aecl.ntt.co.jp)
Yuichi Okabe Non-member (okabe@aecl.ntt.co.jp)
Norio Sato Non-member (nsato@aecl.ntt.co.jp)
Masao Nagase Non-member (nagase@aecl.ntt.co.jp)
Toshikazu Kamei Non-member (kamei@atsugi.ntt-at.co.jp)
Kazuhisa Kudou Non-member (kudou@atsugi.ntt-at.co.jp)
Masaki Yano Non-member (yano@atsugi.ntt-at.co.jp)
Katsuyuki Machida Non-member (machii@aecl.ntt.co.jp)

**Keywords:** selective, electrodeposition, insulator, MEMS, self-limiting, reliability, electrical short

This paper describes the electrodeposition characteristics of an organic insulator film on a gold surface. In the electrodeposition, there are two reaction patterns depending on the solution temperature, as shown in Fig. 1. Below around 30°C, the film thickness saturates regardless of deposition time after it rapidly increases. On the other hand, above around 30°C, the film thickness gradually increases with time and does not saturate.

![Floating pad](image1)

**Fig. 2.** Top view of the fabricated MEMS structure obtained with an optical microscope.

The fabricated structures with coated electrodes protected from the electrical shorts between the actuator and the gold electrode even though the pull-in occurred, as shown in Fig. 3.

![Pull-in](image2)

**Fig. 3.** 1-V characteristics of MEMS structures (a) with uncoated electrode and (b) with coated electrode.

Using the solution temperature of 30°C, the organic dielectric was deposited to coat microelectromechanical-system structures. The deposition was confirmed to occur only on the gold electrode to which a voltage was applied. Fig. 2 shows the top view of the fabricated MEMS structure. The film was deposited only on the electrode to which a negative voltage was applied.
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Tomomi Sakata* Non-member Hiromu Ishii* Member
Yuichi Okabe* Non-member Norio Sato* Non-member
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This paper describes the electrodeposition characteristics of an organic insulator film on a gold surface. In the electrodeposition, there are two reaction patterns depending on the solution temperature. Below around 30°C, the film thickness saturates regardless of deposition time after it rapidly increases. On the other hand, above around 30°C, the film thickness gradually increases with time and does not saturate. Using the solution temperature of 30°C, the organic dielectric was deposited to coat microelectromechanical-system structures. The deposition was confirmed to occur only on the gold electrode to which a voltage was applied. The fabricated structures with the coated electrodes were protected from the electrical shorts between the actuator and the gold electrode, even though pull-in occurred.

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1. Introduction

Microelectromechanical-systems (MEMS) technology is attracting a great deal of interest because of its potential to provide highly integrated devices with much functionality\(^\text{(6)}\). Unlike conventional microelectronic devices, MEMS devices contain movable parts that are actuated by electrostatic force. The reliability of these movable parts has to be improved in order for MEMS devices to be put into practical use. One of the key reliability issues is how to prevent electrical shorts, even when the pull-in occurs between the actuator and electrode\(^\text{(6)}\). Electrical shorts can be avoided by coating three-dimensional (3D) structures such as movable actuators and electrodes with an organic dielectric\(^\text{(6)}\). On the other hand, once an organic dielectric is coated over the entire surface of these complicated 3D structures, subsequent processes such as photolithography can no longer be applied to them. Therefore, any 3D coating technique for such structures must have good selectivity.

This paper describes a 3D organic-dielectric coating technique based on electrodeposition. The application of this technique to MEMS devices constituting a silicon actuator and gold electrode is examined and its effectiveness in protecting them from electrical shorts is confirmed.

2. Experimental

Electrodeposition occurs by means of an electrochemical reaction on the surface of any conductive material to which a voltage is applied. Figure 1 illustrates the technique.

![Schematic of the electrodeposition setup](image)

Fig. 1. Schematic of the electrodeposition setup

Electrodeposition was tried on gold evaporated on silicon dioxide (SiO\(_2\)) film because gold is a promising material for interconnections in MEMS devices, such as fingerprint sensors, optical MEMS micromirrors, and radio frequency inductors\(^\text{(4-5)}\). The adhesive was titanium (Au/Ti/SiO\(_2\)). The gold surface was pretreated with a hydrogen fluoride solution to investigate the electrodeposition characteristics. The substrate was the cathode, and the anode was stainless steel (SUS) 304. Sulfonium cations, \(S^+(R_1)(R_2)(R_3)\), were used as source material because sulfur bonds even with gold, which is relatively inert\(^\text{(7-8)}\). \(R_1\) and \(R_2\) are functional groups for hydration, and \(R_3\) is an epoxy group\(^\text{(9)}\). After deposition, the film was annealed at 230°C in a nitrogen ambient.

3. Electrodeposition characteristics

Figure 2 shows the electrodeposition time dependence of film thickness at the applied voltage of 7 V. The film thickness was measured with a stylus profiler. The variation of the thickness was within 10% on the 6-inch wafer. There are two reaction patterns, depending on the solution temperature. Below around 30°C, the film thickness rapidly increases and then stays almost constant.
regardless of deposition time, which means that there is a self-limiting mechanism at work. At the solution temperature higher than around 30°C, on the other hand, the film thickness gradually increases with time and does not saturate, which means that there is not a self-limiting mechanism at work. It should be noted that at the solution temperatures higher than around 30°C, the deposition rate increases with solution temperature. On the other hand, below around 30°C, it decreases with increasing solution temperature. The opposite behavior of these temperature dependences suggests that each reaction pattern has an activation energy with different parity. At the solution temperature higher than around 30°C, the parity is positive, meaning that there is an elementary reaction that becomes a barrier to the deposition reaction. Below around 30°C, it is negative, meaning that there is no such elementary reaction. Although the details of the reaction are not clear at present, the difference in the reaction patterns might be related to the existence of the elementary reaction as a barrier to the deposition reaction.

Figure 3 shows the applied voltage dependence of the saturated film thickness at a solution temperature of 22.5°C, where the deposition’s self-limiting nature appears. The data indicate that the saturated film thickness tends to saturate towards the constant value after it rapidly increases with the applied voltage. This suggests that the exchange of the electrons, or the red-ox reaction, on the surface is disturbed by increasing the thickness of the organic film.

The surface morphology was further observed with an atomic force microscope (AFM). Figure 4 shows AFM images of the films deposited in the self-limiting and non-self-limiting regions. In the self-limiting region of the solution temperature of 22.5°C (a), the root mean square (r.m.s.) roughness of the film was about 9 nm.

![Image](image1.png)

Fig. 2. Relationship between film thickness and electrodeposition time for applied voltage of 7 V at the solution temperature of (a) 22.5, (b) 26, (c) 30 and (d) 35°C

![Image](image2.png)

Fig. 3. Relationship between saturated film thickness and applied voltage

![Image](image3.png)

Fig. 4. AFM images of the film surfaces deposited at 7 V for 5 minutes at the solution temperature of (a) 22.5 and (b) 30°C. Both films are about 2-μm thick, and their r.m.s roughness is about 9 nm

![Image](image4.png)

Fig. 5. XPS spectra of the (a) surface of the film and (b) interface between the gold and film, which was deposited at 5 V for 20 minutes at the solution temperature of 30°C
9 nm and the grain size was about 500 nm. In the non-self-limiting region of the solution temperature of 30°C (b), they were about 9 nm and about 300 nm, respectively. There is no difference in the roughness of these surfaces, indicating that the surfaces are almost the same regardless of the reaction patterns. On the other hand, the grain sizes of the deposited films differ depending on the reaction patterns. The grains in the self-limiting region, where the deposition rate is fast, are bigger than those in the non-self-limiting region, where the deposition rate is slow. This difference in grain size might be related to the difference in the activation energy.

To confirm that the deposited film adheres to the evaporated gold substrate, the surface and interface of the deposited film were analyzed by x-ray photoelectron spectroscopy (XPS). XPS spectra for the S\textsubscript{2p} region are shown in Fig. 5, where spectrum (a) is for the surface of the deposited film and spectrum (b) for the film-gold interface. The sulfur peak from the interface shifted towards lower binding energy, compared with one from the film surface. This means that electrons are back-donated to the sulfur from the gold, which is evident that a strong bond forms between them. In addition, Scotch\textsuperscript{TM} tape tests confirmed that the electrodeposition film had enough adhesivity on the gold surface.

4. Evaluation of Selective Deposition on MEMS Structure

To observe the selective deposition obtained by electrodeposition, the MEMS structure shown in Fig. 6 was fabricated.\textsuperscript{10} It consists of a 3-μm-wide and 2-μm-deep actuator made from n-type silicon (100) surface whose resistivity was 2-4 Ωcm, an anchor on which gold for a floating pad was formed, and a gold electrode. The electrodes were made by electroplating with Na\textsubscript{2}Au(SO\textsubscript{4})\textsubscript{2} solution.\textsuperscript{11} The gap between the actuator and the electrode was set at 2 μm to absolutely operate the actuator below the driving voltage of 100 V. Organic film was deposited at the solution temperature of 30°C to obtain the film thickness of 0.2 μm. The applied voltage was 5 V, and the electrodeposition time was 20 minutes.

Figure 7 shows an optical microscope image of a fabricated MEMS structure, when a negative voltage was applied to the gold electrode and the gold pad was floating. We observed the light pad and dark electrode, which shows that the film was selectively deposited only on the electrode to which the negative voltage was applied; it was not deposited on the gold floating pad. The film thickness measured with stylus profiler was about 0.2 μm. The measurements confirmed that there was no deposition on the silicon dioxide as well, which is probably due to there being no electrodeposition on an insulator surface.

To further confirm the selective deposition on the gold surfaces, the surfaces of the floating pad and the electrode were analyzed by Auger electron spectroscopy (AES). AES spectra of the surfaces are shown in Fig. 8, where spectrum (a) is for the floating pad and spectrum (b) for the electrode. For the floating pad, there are peaks attributed to only the gold. On the other hand, there are two kinds of peaks for the electrode. The peak at the lower Auger electron energy is for carbon in the film, and the one at the higher Auger electron energy is for oxygen in the film. This clearly shows that no organic film was deposited on the floating pad and that the electrode, which is connected with the cathode, was completely coated. This indicates that the selectivity operates even on the metal surfaces depending on whether a voltage is applied or

![Fig. 6. Schematic view of the MEMS structure. The gap between the actuator and the electrode is 2 μm](image1)

![Fig. 7. Top view of the fabricated MEMS structure, obtained with an optical microscope. The deposited film thickness is 0.2 μm](image2)

![Fig. 8. AES spectra of the surfaces of the (a) floating pad and (b) electrode](image3)
not. In addition, the obtained film was hydrophobic. This would help us prevent in-process sticking, which might improve the yield even in wet-processes after the release of 3D structures, although further study is necessary.

To assess the protection from electrical shorts, the current-voltage (I-V) characteristics between the actuator and electrode were measured using two MEMS structures. For one structure, an organic dielectric film was selectively deposited on the electrode. For the other, the electrode was not coated. Figure 9 shows their I-V characteristics. As the applied voltage increased, pull-in occurred at 71 V. However, in the structure with the coated electrode (b), there was no current flow, even after pull-in. This means that even after pull-in occurs, the organic film acts as an excellent insulator that prevents electrical shorts. This also shows that the electrodeposition is capable of depositing the organic film on side walls of 3D structures. From this I-V measurement in Fig. 9, dielectric breakdown voltage is estimated to be over 4.5 MV/cm (>90 V @ 0.2 µm thick). This value is comparable with that of thermally oxidized SiO₂.(12)

5. Summary

The electrodeposition characteristics of organic films were investigated. Depending on the solution temperature, the electrodeposition showed either a self-limiting nature, in which the film formation automatically stops after the film thickness rapidly increases, or a non-self-limiting nature, in which the film thickness gradually increases and does not saturate. Selective deposition was also confirmed on the surface of MEMS structures. The electrodeposition provided excellent selectivity even on the metal surfaces, and the organic dielectric electrodeposited on the gold electrode in MEMS devices demonstrated excellent insulation.

We can thus conclude that the selective coating by electrodeposition is a very promising way to protect MEMS devices from electrical shorts.

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References


Tomomi Sakata (Non-member) was born in Okayama, Japan, in 1965. He received the B.S., and M.S. degrees in Chemistry from Tohoku University, Miyagi, Japan, in 1989 and 1991, respectively. In 1991, he joined the NTT Applied Electronics Laboratories, Nippon Telegraph and Telephone Corp., Musashino, Tokyo, Japan. He has been engaged in the research and development of optical waveguides and optical switches. He is now with NTT Microsystem Integration Laboratories, Atsugi, Kanagawa, Japan. He is currently working on the improvement of the reliability of MEMS devices. He is a member of the Japan Society of Applied Physics.
Hiromu Ishii (Member) was born in Tochigi, Japan, in 1956. He received the B.S., M.S., and Dr. Sc. degrees in Chemistry from the University of Tokyo, Tokyo, Japan, in 1982, 1984, and 1996, respectively. He joined the Atsugi Electrical Communications Laboratories, Nippon Telegraph and Telephone Public Corp. (NTT), Kanagawa, Japan, in 1984. He has been engaged in the research and development of atomic layer epitaxy, CVD, and multilevel interconnection processes for ULSIs. He is now a Senior Research Engineer, Supervisor, at the NTT Microsystem Integration Laboratories, Atsugi, Kanagawa, Japan. He is currently working on the development of new device integration technologies using MEMS. He is a member of the Japan Society of Applied Physics, Physical Society of Japan, the Chemical Society of Japan, the Electrochemical Society (ECS), and the Institute of Electrical and Electronics Engineers (IEEE). He is also an associate editor of the Japanese Journal of Applied Physics.

Yuichi Okabe (Non-member) was born in Gunma, Japan, in 1977. He received the B.E. degree in Chemical Engineering from Doshisha University, Kyoto, Japan, in 2001 and the M.E. degree in Applied Chemistry from the University of Tokyo, Tokyo, Japan, in 2003. In 2003, he joined Nippon Telegraph and Telephone Corp. (NTT), Tokyo, Japan. He is now with the NTT Microsystem Integration Laboratories, Atsugi, Kanagawa, Japan. He is currently engaged in the research and development of manufacturing technologies for MEMS. He is a member of the Japan Society of Applied Physics.

Toshikazu Kamei (Non-member) was born in Kanagawa, Japan, in 1975. He received the B.E. degree in Chemical Technology from Kanagawa Institute of Technology, Kanagawa, Japan, in 1998. In 2002, he joined the NTT Advanced Technology Corp., Atsugi, Kanagawa, Japan. His current work involves the development of thick film technology and deep Si etching using inductively coupled plasma reactive ion etching for MEMS. He is a member of the Japan Society of Applied Physics.

Kazuhisa Kudou (Non-member) was born in Miyazaki, Japan, in 1968. He received the B.E. degree in Electronics Engineering from the North Shore College, Kanagawa, Japan, in 1989. In 1989, he joined Nippon Telegraph and Telephone Technology Transfer Corp. (NTEC), Atsugi, Kanagawa, Japan, where he was engaged in the development of plasma etching and LSI fabrication processes. His current work is the development of thick film patterning technology for MEMS. He is now an Engineer with NTT Advanced Technology Corp., Atsugi, Kanagawa, Japan. He is a member of the Japan Society of Applied Physics.

Masaki Yano (Non-member) was born in Kanagawa, Japan, in 1967. He received the B.E. degree in Electronics Engineering from the North Shore College, Kanagawa, Japan, in 1987. In 1987, he joined Nippon Telegraph and Telephone Technology Transfer Corp. (NTEC), Atsugi, Kanagawa, Japan, where he was engaged in the development of CVD and LSI fabrication processes. His current interests are electroplating and thick film technologies. He is now a Staff Engineer at NTT Advanced Technology Corp., Atsugi, Kanagawa, Japan.

Norio Sato (Non-member) was born in Tokyo, Japan, in 1974. He received the B.S. and M.S. degrees in Physics from the University of Tokyo, Tokyo, Japan, in 1997 and 1999, respectively. In 1999, he joined Nippon Telegraph and Telephone Corp. (NTT), Tokyo, Japan. He is now with the NTT Microsystem Integration Laboratories, Atsugi, Kanagawa, Japan, where he is engaged in the research and development of semiconductor fabrication processes and MEMS. He is a member of the Japan Society of Applied Physics, the Physical Society of Japan, and the Institute of Electrical and Electronics Engineers (IEEE).

Katsuyuki Machida (Non-member) was born in Nagasaki, Japan, in 1954. He received the B.E., M.E., and Dr. Eng. degrees in Electronics Engineering from Kyushu Institute of Technology, Fukuoka, Japan, in 1979, 1981, and 1995, respectively. In 1981, he joined the Musashino Electrical Communications Laboratory, Nippon Telegraph and Telephone Public Corp. (NTT), Musashino, Tokyo, Japan, where he was engaged in the research of ECR plasma CVD and the development of LSI processes and manufacturing technologies. He is now a Senior Research Engineer, Supervisor, at the NTT Microsystem Integration Laboratories, Atsugi, Kanagawa, Japan. He is currently engaged in research and development on material and manufacturing technologies for MEMS. He is a member of the Japan Society of Applied Physics and the Institute of Electrical and Electronics Engineers (IEEE).

Masao Nagase (Non-member) was born in Tokyo, Japan, in 1959. He received the B.E., M.E. and Dr. Eng. degrees from Waseda University, Tokyo, Japan, in 1982, 1984, and 1997, respectively. In 1984, he joined the Atsugi Electrical Communications Laboratories, Nippon Telegraph and Telephone Public Corp. (NTT), Kanagawa, Japan, where he was engaged in the research and development of fabrication processes for sub-micrometer VLSIs. He is now with NTT Basic Research Laboratories, Atsugi, Kanagawa, Japan. He is currently researching fabrication processes for mesoscopic devices, in particular, the characterization of the nanometer-scale structures. He is a member of the Japan Society of Applied Physics.

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