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High Power Electret Motor and Generator on Shrouded Turbine

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Abstract

This paper describes the fabrication process of a shrouded turbine and surface modification using fluorinated silane coupling agents to stabilize the charges of a silicon-dioxide electret. The shrouded turbine was fabricated by cavity-through etching, which is deep reactive ion etching (DRIE) through a wafer having cavities made by DRIE and fusion bonding. By using this process, a shrouded turbine with little eccentricity was obtained without damaging the inner structures such as blades and flow ways. Charge stability of electrets was deteriorated by miniaturizing the size. The charge deterioration was caused by leak current through the surface. To decrease the surface conduction, the surface was terminated by fluorine with silane coupling agents. As a result, the charge stability of a silicon-dioxide electret was improved by 100 times compared with HMDS (hexamethyldisilazane) treatment.

Keywords: electret, micromotor, charge stability, gas turbine, shrouded turbine

1. INTRODUCTION

Lithium ion batteries are used as portable energy sources for electric devices, but their power and energy density are not enough for current and future devices. As high power portable power sources to replace the batteries, MEMS-based gas turbine generators are under development. By several groups, some technologies and components for the gas turbine, such as an air bearing for high rate rotation [1], electric generators [2, 3, 4], a combustor [5], etc, had been reported.

The topic of this paper is a high power motor/generator for the MEMS-based gas turbine. Figure 1 shows the schematic cross section of the motor. The motor has electrets on the rotor. Electrets are dielectric materials having quasipermanent polarization or charge, and generates a surface potential of several hundreds volts without using a voltage source. By using electrets, the rotor levitating from the stator can be excited to high voltage, and higher power than that of conventional electrostatic motor can be expected [2, 3].

To confirm the performance and the feasibility of integration on a turbine, a turbine-integrated motor is under fabrication. For the device, a shrouded turbine is chosen, because it is efficient in aerodynamics and a large area is available for a motor/generator or a bearing as shown in Fig. 2. MIT (Massachusetts Institute of Technology) group is also developing a high power motor integrated with a turbine. They achieved to generate 20 mW mechanical power at a rotational speed of 55,000 rpm [4], but the turbine is unshrouded type.

In this paper, we have developed practical fabrication processes for the electret motor/generator integrated on a shrouded turbine.

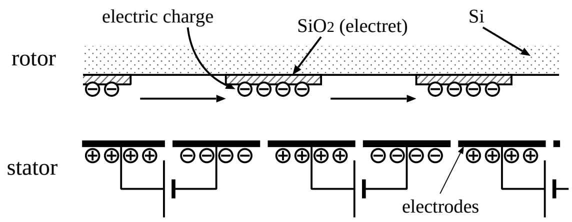

Figure 1: Schematic cross section of the electret motor

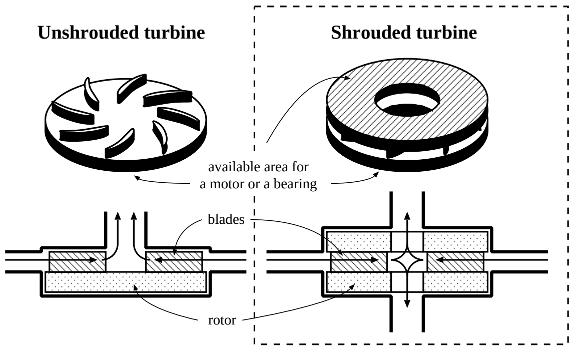

Figure 2: Schematic structure of a shrouded turbine

2. SHROUDED TURBINE

The efficiency of an unshrouded turbine is deteriorated by air leakage through the top of blades. Especially, the influence is significant in a MEMS turbine, because the gap between the top of the turbine and the stator is relatively large. To improve the efficiency, shrouding of the top of a turbine is effective. Furthermore, the shrouded turbine has large available area for

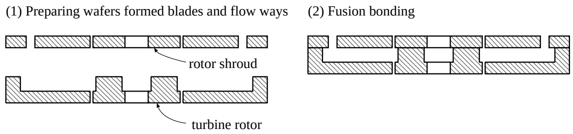

Figure 3: Fabrication process of a shrouded turbine without using cavity through etching

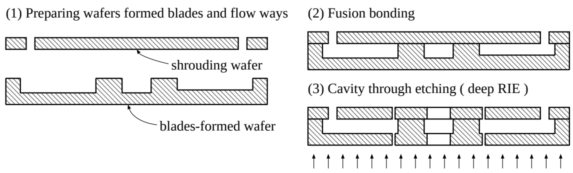

Figure 4: Fabrication process of a shrouded turbine with using cavity through etching

a motor/generator or a bearing. A shrouded turbine has these advantages to a unshrouded turbine.

To fabricate the shrouded turbine, a process shown in Fig. 3 could be considered. In the process, a shroud and a turbine are released, and then bonded together. However, this process has some difficulties. First, the process needs to align a shroud and a turbine after released. Second, large eccentricity can be generated by miss-alignment between the shroud and turbine. To escape from these difficulties, a practical fabrication process of a shrouded turbine is proposed in this paper. The process is shown in Fig. 4. The key point of the process is “cavity-through etching”, which is deep reactive ion etching (DRIE) through a wafer having cavities made by DRIE and fusion bonding. Using the cavity-through etching, the alignment and bonding of released structures are not needed and eccentricity due to miss-alignment can be avoid. The SEM photograph of a shrouded turbine and a stator fabricated by the process is shown in Fig. 5 and 6. They were etched through from the bottom side in the figures. As the photograph shows, inner structures, such as turbine blades and flow ways, were not damaged by the cavity-through etching. The radial stripes on the shroud are silicon-dioxide electrets for the motor/generator.

3. CHARGE STABILIZING TREATMENT

To realize the electret motor/generator, how to charge the electrets is a challenging problem. If the electrets are successfully charged before assembly, high-temperature annealing for fusion bonding results in the disappearance of charges. We had reported a novel charging method using contact electrification [6]. Contact electrification is the electron transfer phenomena which is occurred when different materials are contacted. The phenomena are derived from Fermi level difference between different materials as shown in Fig.

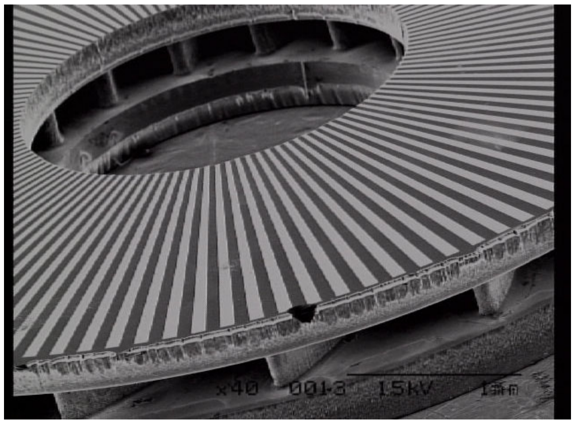

Figure 5: SEM photograph of a shrouded turbine

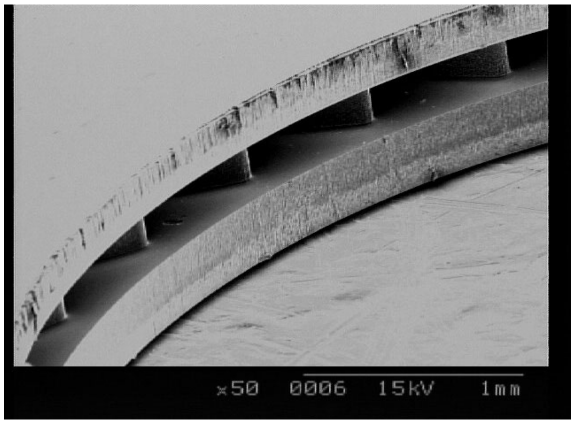

Figure 6: SEM photograph of a stator

7, and occurs just by making a contact between different material basically without any special equipments. In this study, mercury is selected as a contacting material. Mercury is liquid at room temperature, thus charging can be performed by dipping electrets into mercury. In addition, mercury has low wettability to silicon and silicon dioxide, thus mercury can be removed by just taking out the dipped electrets. In case of charging micropatterned electrets, however, pressurizing mercury is needed to improve the poor contact due to the low wettability, as shown in Fig. 8. By using this method, the electrets can be charged after assembly, and charge disappearance by annealing for bonding can be avoided.

By using the method, 0.5-μm-thick silicon-dioxide treated by HMDS (hexamethyldisilazane) was charged at a surface potential of -50 V, and micropatterned electrets having line-and-space feature was also charged to a surface potential similar to that of unpatterned electrets [6]. However, the charge stability of the micropatterned electrets was deteriorated, when the width decreased below several tens microns. Table 1 shows the surface potential decay of unpatterned and

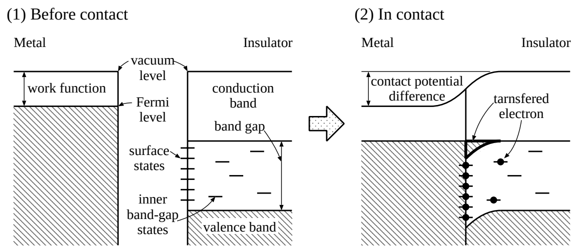

Figure 7: Band diagrams of metal and insulator before and in contact

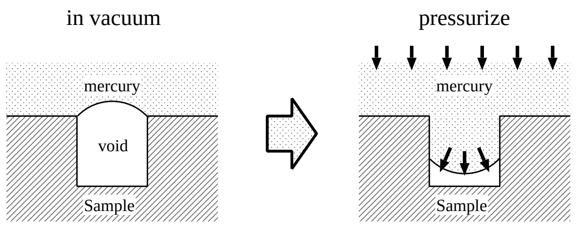

Figure 8: Pressurizing process to improve contact with mercury

micropatterned electrets. From the dependence of the charge stability on the electret width, we inferred that leak current through the electret surface was the dominant reason of the surface potential decay, as shown in Fig. 9. And, from some other results, we estimated that adsorbed water on the surface caused the leak current.

To decrease the adsorption of water and improve the charge stability, the surface of silicon-dioxide electrets was terminated fluorine by fluorinated silane coupling agents which reduce the surface energy. The structure of the silane coupling agent was

$$CF_3(CF_2)_9CH_2CH_2Si(OC_2H_5)_3.$$

Figure 10 shows the surface potential decay of micropatterned electrets treated by the fluorinated silane coupling agents. From the result, dramatic improvement (100 times of HMDS treatment) in charge stability was confirmed. Furthermore, the surface potential of the 0.5-μm-thick silicon-dioxide electret was increased to -83 V by the fluorinated silane coupling treatment. The silane coupling treatment can be also performed after assembly as well as electret charging. Therefore, the electret charging process does not restrict the fabrication and assembly process.

Table 1: Surface potential decay of micropatterned electrets treated by HMDS

electret width	just after charged	the next day
unpatterned	-44 V	-46 V
25 μm	-44 V	-14 V
10 μm	-40 V	0 V

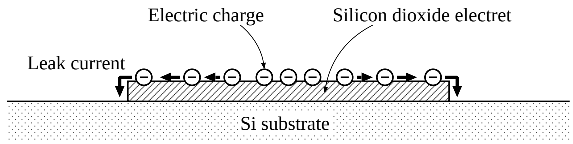

Figure 9: Charge disappearance by leak current through the surface

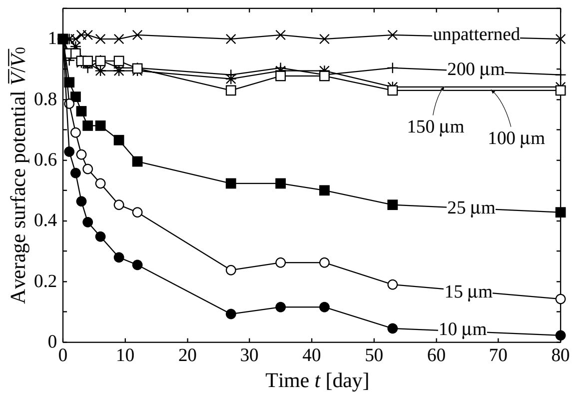

Figure 10: Surface potential decay of micropatterned electrets treated by fluorinated silane coupling agents (real time scale)

4. DISCUSSION

Charge stability was improved by the fluorinated silane coupling agents, but it is not enough. In the optimum design of the electret motor/generator, 5-μm-wide electrets are needed [2, 3]. And, for practical use, the lifetime should be several years or longer. Therefore, further improvement is essential.

To reveal the mechanism of the surface potential decay, the decay behavior was theoretically analyzed, assuming that the surface potential decay was dominated by surface conduction. In the analysis model shown in Fig. 11, the electret has width L and infinite. And, the uniform physical properties of the electret in depth direction is assumed. Under the condition, the surface potential $V(x,t)$ is governed by the differential equation represented as

$$\frac{\partial V(x,t)}{\partial t} = \frac{1}{rc}\frac{\partial^2 V(x,t)}{\partial x^2}, \tag{1}$$

where r and c are the sheet resistivity and capacitance per unit area of electrets, respectively. By solving the equation with a boundary condition as $V(0,t) = V(L,t) = 0$, it is revealed that the average surface potential $V_a(t) = \int_0^L V(x,t)/L\,dx$ has a time constant τ represented as

$$\tau = \frac{1}{rcL^2}. \tag{2}$$

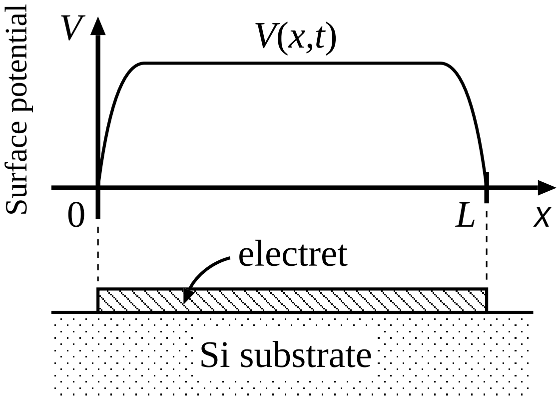

Figure 11: The electret model in the surface decay analysis

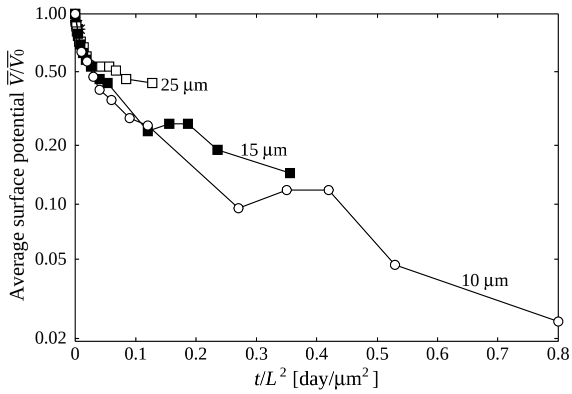

Figure 12: Surface potential decay of micropatterned electrets treated by fluorinated silane coupling agents (normalized time scale)

The time constant of charge decay is inversely proportional to the square of the electret width. To confirm if this relationship is shown on the results of Fig. 10, the abscissa was changed from t to t/L^2 as shown in Fig. 12. In this figure, each line is almost on the same curve without the dependence of electret width. From the result, it is revealed that the charge stability is dominated by the surface conduction of electrets. The result also indicated that the time constant τ is inversely proportional to sheet resistivity. Therefore, to satisfy the demands mentioned above, sheet resistivity should be improved by 1000 times.

5. CONCLUSION

This paper described the fabrication processes of a shrouded turbine and surface modification using fluorinated silane coupling agents to stabilize the charges of a silicon-dioxide electret. The shrouded turbine was fabricated by cavity-through etching, which is deep reactive ion etching (DRIE) through a wafer having cavities made by DRIE and fusion bonding. By using this process, a shrouded turbine rotor with little eccentricity was obtained without damaging the inner structures such as blades and flow ways.

Charge stability of electrets was deteriorated by miniaturizing the size. The charge deterioration was caused by leak current through the surface. To decrease the surface conduction, the surface was terminated by fluorine with silane coupling agents. As a result, the charge stability of a silicon-dioxide electret was improved by 100 times compared with HMDS treatment. But 1000 times further improvement is needed to satisfy for practical use.

Acknowledgments

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