Fine-Sized Etching of Flexible Substrates Using Nano Particle Deposition System (NPDS)

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Nano Particle Deposition System (NPDS) was used to etch flexible substrates, such as SU-8 and indium tin oxide (ITO) substrates using nickel powders using micronozzles. The stand-off distance (SoD) was changed in order to find out the optimal distance on etching behavior. The results showed that the etching capability was influenced by the SoD and the types of substrate. Especially, the etching depth of the substrate was the largest when the SoD was 500μm. This phenomenon related to the variation of SoD can be explained by the flow behavior at which the powder-gas mixture injected from the nozzle where the particles are most highly accelerated at that point. The etching capability is also affected by the types of substrates. Especially, the hardness of the substrate mainly determines the etching depth. The result suggests that the NPDS gives an alternative way of micromachining suitable for fine-sized etching on flexible substrates. [doi:10.2320/matertrans.M2010221]

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1. Introduction

Patterning on a flexible substrate is an important issue in microelectronic devices. They have unique bending characteristics that are not possible in conventionally used hard materials. The flexible substrates’ mechanical flexibility and its density compared to other materials allow us to make new type microelectronic flexible devices so that there have been a number of studies about micro patterning on flexible substrates.¹,²) These substrates, however, also have some drawbacks. They are soft so that they are vulnerable to tear. As they also have relatively low glass transition temperature or melting temperature compared to that of metals and ceramics, chemical vapor deposition which requires high temperature processing, cannot be used on flexible substrate. Therefore, patterning at low temperature is a crucial step for flexible substrate and nano-particle deposition system (NPDS) is one system that can make patterning at low temperature possible.

NPDS is a new technique where highly accelerated powders were utilized to deposit on substrate at room temperature. Conventional powder deposition technologies include aerosol deposition method (ADM)³,⁴) and cold gas dynamic spray (CGDS) process,⁵,⁶) but they were limited in powder selection for deposition. In order to resolve this drawback, NPDS was originally developed to offer an alternative way to deposit powders on the substrate. As these conventional powder deposition processes share the common area shown in Fig. 1(a), NPDS was designed to use the intermediate region to use both types of powders.

Since the powders are blasted at the nozzle in this system, the NPDS can also show etching performances. The etching mechanism of this system has similar characteristics with powder blasting process. The structural similarities between NPDS and powder blasting are shown in Fig. 1(b). Powder blasting, or micro abrasive jet machining, is a mechanical etching technology where powders having several micrometers in diameter are accelerated and then collided to the substrate. The substrate is then etched by the accumulation of micro scratches induced by the particle-substrate collision.⁷–⁹)

Previously, the powder blasting process has been frequently used on ceramic substrate machining. Conventional studies in powder blasting process were carried out with brittle materials such as glass and silicon wafer coated with a protective mask in order to gain desired width. On the other hand, flexible substrate erosion by high-speed particle velocity was also discovered in cold gas dynamic spray coating technology. However, there has been no report on micro patterning of flexible substrate using micro nozzles that were fabricated by semiconductor processing techniques.

Micro nozzles, in this study, are fabricated using deep reactive ion etching (DRIE) techniques. Conventionally, micro nozzles have been fabricated using micromachining. As conventional mechanical machining, however, does not guarantee the micron-sized feature size, a number of studies have been conducted to replace conventional mechanical machining.¹⁰,¹¹) Figure 1 shows Scanning Electron Microscopy (SEM) image of micro nozzle that has been fabricated using DRIE techniques for this study.

In this study, micron-sized etching phenomenon was explored using NPDS. Two types of flexible substrates, indium tin oxide (ITO) film and SU-8 resin, were used to investigate the substrate dependence on etching capability since ITO is widely used as a conductive electrode and SU-8 is widely used as a flexible substrates. The stand-off distance (SoD) effect on etching behavior was also examined. Here SoD is defined as the distance between the substrate surface and the end of micro nozzle as shown in Fig. 1.

2. Experimental Procedures

2.1 Structure of NPDS

The schematic of NPDS is described in Fig. 1(c). Originally it was invented to spray diverse nano-sized powders, but it is still able to accelerate micron-sized...
particles. Powder itself cannot gain speed, so a compressed carrier gas, mainly air, is used to transfer the physical momentum to particles. The high pressure air is supplied and it goes to the powder feeder to convert to air-powder mixture called an aerosol. The pressure inside the chamber was \(\frac{1}{C_0} = 0.8\) MPa, and the pressure for the injection of carrier gas and powders was set to 0.6 MPa at room temperature. In this system, nickel powders are given, and this air-nickel powder mixture is sprayed at the micronozzle as demonstrated in Fig. 1(d). The micronozzle has convergence-divergence profile to effectively accelerate the mixture, and then finally the accelerated particles are collided with the substrate at supersonic speed. The computational fluid dynamics (CFD) results under the conditions used in the experiments, as shown in Fig. 2, shows that the velocity reaches a supersonic speed at a SOD ranging from 300 to 500 µm.\(^{13}\)

### 2.2 Mechanical etching process

The process parameter settings are listed in Table 1. The negative-type SU-8 resin was spin-coated on the surface of silicon wafer using photolithographic process. The SU-8 resin was prebaked at 90°C for 1 h and then exposed to ultraviolet light (G-line) for 2 min to ensure that the molecular structure was cross-linked together. The thickness of SU-8 was approximately 30 µm. On the other hand, the ITO film was sputtered on the PET film. The thickness of the ITO layer and PET film are 200 nm and 189 µm, respectively. The mechanical surface hardness (Vickers Hardness) values of polymer substrates are listed in Table 2. Nickel powders having 1 µm in diameter was used as a substrate etchant. The compressed air was flown along the path with flow rate of 10 L/min and it transported nickel powders to the micro nozzle. Here, the nozzle throat is approximately 150 µm with its length being 640 µm as shown in Fig. 1(d). The nickel

<table>
<thead>
<tr>
<th>No.</th>
<th>Powder</th>
<th>Substrate</th>
<th>Size of micronozzle (µm)</th>
<th>SOD (µm)</th>
<th>Carrier gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>ITO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Nickel</td>
<td>Nickel</td>
<td>150</td>
<td>1000</td>
<td>Air (0.6 MPa)</td>
</tr>
<tr>
<td>4</td>
<td>Nickel</td>
<td>Nickel</td>
<td>150</td>
<td>300</td>
<td>Air (0.6 MPa)</td>
</tr>
<tr>
<td>5</td>
<td>SU-8</td>
<td>SU-8</td>
<td>300</td>
<td>500</td>
<td>Air (0.6 MPa)</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 CFD analysis results based on the experimental conditions shown in Table 1.\(^{13}\)
powders were injected from the micro nozzle to the substrate with high velocity as the mixture is accelerated. The SoD was changed in order to find out the effect of distance on etching behavior. The chamber pressure was held constant at 13.33 kPa. After the powder spray was finished, SU-8 and ITO surfaces were observed using an optical microscope (OM) and alpha-step machine to measure the surface morphology.

3. Results and Discussion

3.1 Surface observation

The surface image and profile image results are shown in Fig. 3. The optical images of etched surface show that the size of the etched area gradually increases as the SoD increases as shown in Fig. 4. This linear relationship was consistently observed in both ITO and SU-8 surface. This trend can be simply stated by the fact that the sprayed air-particle jet flow tends to be dispersed as it gets out of the nozzle. This dispersion is induced by the pressure difference between air-particle flow and inside atmosphere of the chamber.

The depth of the etched area was the highest at SoD being 500 μm for both types of flexible substrate as shown in Fig. 3(b), (c), (f) and (g). Figures 3(c) and (g) show the alpha step measuring results where the maximum etching depths at SoD of 500 μm were approximately 6.5 μm for both ITO and SU-8 substrates. In the case where SoD is other than 500 μm, the etching capability decreased as shown in Fig. 4. This nonlinear etching behavior can be explained by the particle acceleration.

Since particles have a great mass compared to individual air molecules, particles needs optimal distance to be accelerated with high speed. The momentum transfer takes longer time even if air molecules are far faster than the heavy particles. Even though the flow rate or speed of the air exceeds supersonic speed when sprayed, the particles still have low flowing speed because of the small dimension of the micro nozzle where the powders are not sufficiently accelerated. When SoD is too small, particles cannot gain enough kinetic energy to induce cracks on the substrate. As the SoD increases up to some critical point, particles will gain more energy. Beyond the critical point where the speed of air flow becomes lower than that of particles, individual particles begin to lose its kinetic energy and to be dispersed, and fewer cracks would be propagated. To estimate the actual velocity of the particles, the computational fluid dynamics (CFD) analysis under the conditions used in the experiments were performed as shown in Fig. 2. From this analysis, the velocity of the particles reaches a supersonic speed at a SOD ranging from 300 to 500 μm, and then the particles decelerate afterwards. The measurement results in Fig. 4 show that this critical point stated above for mechanical etching using nickel powders with 1 μm in size is 500 μm and that agrees with the analysis results.

3.2 Etching depth difference

The surface profile measurement for both substrate at SoD = 500 μm showed that the etched depth on SU-8 substrate was deeper than that of ITO substrate as shown in Fig. 4. Surface hardness of the substrate is the main factor for the etching difference. Since SU-8 is a type of polymer materials, it is evident that the SU-8 substrate is more vulnerable to erosion. The result is consistent with the previous report where polymer materials were easily damaged or eroded by the particle-air mixture. In some cases, however, the powders were deposited on the surface. Nickel powders were deposited on the ITO film when the SoD = 300 μm, and SU-8 when the SoD = 1000 μm.

This can be explained by the kinetic energy of nickel powders. Nickel particles gain momentum from the rapidly flowing carrier gas and the velocity gradually increases because it has a mass. These factors cause that particles still gain speed even if the air flow speed reaches the highest level and starts to decrease, because there is a velocity discrepancy. This air-particle velocity behavior around the nozzle is frequently studied by numerical analysis. It can be suggested that nickel particles are the fastest right after the point where the air flow velocity reaches the maximum. Once the particles go beyond this point, the flow velocity drastically decreases and it acts as a dragging force for nickel particles so that they lose their kinetic energy. On the other hand, since the hardness of nickel is much stronger than that of substrate which is essentially polymer-based material (Table 2), the polymer substrate is easily eroded. As the powder bombardment would leave continuous tiny scratches on the surface, the erosion of polymer substrate is directly influenced by the kinetic energy of individual particles. Therefore, concerning the behavior of flow around the nozzle discussed above, it can be concluded that the particles will not etch the substrate if they do not have large kinetic energy. Once the velocity is not optimized, they show poor etching capability or they are even deposited. That effect is demonstrated in Fig. 4(a) where none etching region exists at SoD of 300 μm whereas the maximum etching is observed at SoD of 500 μm.

4. Conclusions

Several conclusions can be obtained based on those experimental results.

First, NPDS can be used in etching substrate due to its mechanism similar to the powder blast process. Therefore, NPDS can potentially be used in both particle deposition and substrate etching by slightly changing particle size, SoD and types of substrates.

Second, the SoD between micro nozzle and substrate determines the size of the impact area. There is a linear trend between the SoD and the impact area.
Fig. 3 Surface morphology measured by an optical microscope and alpha-step. (a) Optical image of etched pattern on ITO substrate at SoD = 300 μm (Run #1 in Table 1); (b) and (c) Optical image and the surface profile of etched pattern on ITO substrate at SoD = 500 μm (Run #2 in Table 1). Here, y-axis of alpha step being etching depth is in \times 1000 Å and x-axis being the etched diameter in μm. The thick lines indicate surface of the substrate before etching. (d) Optical image of etched pattern on ITO substrate at SoD = 1000 μm (Run #3 in Table 1); (e) Optical image of etched pattern on SU-8 substrate at SoD = 300 μm (Run #4 in Table 1); (f) and (g) Optical image and the surface profile of etched pattern on SU-8 substrate at SoD = 500 μm (Run #5 in Table 1). Here, y-axis of alpha step being etching depth, is in \times 1000 Å and x-axis being the etched diameter in μm. The thick lines indicate surface of the substrate before etching. (h) Optical image of etched pattern on SU-8 substrate at SoD = 1000 μm (Run #6 in Table 1).
Third, the etching capability is also affected by the types of substrate. Especially, the mechanical hardness of the substrate mainly determines the etching depth. The SU-8 substrate is more likely to be etched than the ITO film due to its low mechanical hardness compared to that of nickel.

Finally, NPDS shows the best etching performance at SoD being 500 µm. It is due to the fact that the particles are most highly accelerated at that point.

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