Electroplated Ni microcantilever probe with electrostatic actuation

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Abstract

Electrostatically-driven Ni curl-up microcantilever probes, which can be applied to new MEMS probe cards with contact-switching function, have been developed. MEMS probe cards are requisite to higher pad-density and smaller pad-pitch chips, and are effective in high frequency testing. If a probe card consists of an array of actuator-integrated microprobes, it could be applied to next-generation testing, for instance, a new wafer-level test/burn-in. This can be achieved as the microprobes can be used for the direct switching of the contact to reduce the number of the I/O lines of the probe card. We have designed arrays of Ni curl-up microcantilevers with a rolling-contact touch-mode electrostatic actuator and developed a micromachining process which includes the electroplating deposition of two layers having different internal stress and etching of the Al sacrifice layer. The fabricated cantilevers with a thickness of 1.0 μm and a width of 50 μm have successfully been driven at a pull-in voltage of approximately 100 V. From the disconnection force of the fritting contact between a Ni probe and an Al film, it is estimated that the fritting contact could be disconnected by applying voltages less than 100 V.

Keywords: MEMS probe card; Contact switching; Electrostatic actuator; Electroplated Ni

1. Introduction

Micro electro mechanical systems (MEMS) probe cards are now being put to practical use [1], because they can be fabricated with batch processing and have advantages over the conventional needle ones. Since the dimensions of micromachined structures can easily be smaller than a few hundred micrometers, they can be applied to higher pad-density and smaller pad-pitch chips, and are effective in a test using high-speed signals above 1 GHz. In addition, sensors and actuators can be built into MEMS probe cards with ease. If, for instance, a probe card consists of actuator-integrated microprobes, probe-pad contact force can be made uniform by compensating for the probe-pad distance deviation with probe self-deflection. Zhang et al. developed a probe card consisting of an array of thermally driven bimorph microcantilevers and pointed out that it could also be universally designed for several chip patterns [2]. Further, since contacts can directly be switched on and off, it could be suitable for a wafer-level test/burn-in probe card [3].

Recently, we have developed a new compliant MEMS probe card that comprises Ni microcantilevers with a simple and low-cost fabrication process [4]. The Ni microcantilevers having a curled-up compliant structure and protruding tips were fabricated by a process, which includes the electroplating deposition of two layers having different internal stress and etching of the Al sacrifice layer. We also found that the fritting process [5,6] using the microcantilevers could make a low resistance contact, smaller than 2 Ω, with a contact force of less than 10 μN [7]. In this paper, we discuss the development of curled-up Ni microcantilevers that can be electrically driven with a rolling-contact touch-mode to realize a MEMS probe card with a contact switching function.
2. Concept and design

Fig. 1 illustrates the schematic structure of the electrostatically actuated microcantilever probes. When applying probes of this type to testing, probes are brought into contact with the pads on the device under test (DUT) and then the fritting process is utilized to make low-resistance contact. After a test cycle, probes not in use are disconnected by probe actuation. We adopt a rolling-contact touch-mode electrostatic actuator, because an actuator of this type consumes less power and can generate a relatively large force with low voltage. In this mode, the application of a critical voltage pulls the probes into the counter electrode on the probe card substrate.

When the force necessary to disconnect the contact is $F_C$, the pull-in voltage $V_{Pi}$ of a curved cantilever is estimated by the equation:

$$ F_C + F_E (V_{Pi}) + F_R = 0. $$  (1)

Here, the electrostatic force $F_E (V)$ is expressed by:

$$ F_E (V) = \frac{1}{2} \varepsilon_r \varepsilon_0 b V^2 \int_0^l \left( d - w(x) \right)^2 \, dx $$  (2)

and the restoring force $F_R$ is given by:

$$ F_R = \frac{E b h}{12 (1 - \nu)} \left[ \frac{2q}{B^2} + \frac{8q}{B^2} + \frac{E b h^3}{4l^3} w(x) \right] $$  (3)

where, as shown in Fig. 2, $b$ is the width, $l$ the length, and $h$ the thickness of the cantilever; $w(x)$ the deflection curve; $q$ the deflection of the outer beam tip compared with the deflection of the beam tip in the central axis; $E$ the effective Young’s modulus of the beam; $\nu$ the Poisson ratio; $B$ is given by $E b h^3 (1 - \nu)$; $\varepsilon_0$ the dielectric constant of vacuum; and $\varepsilon_r$ the dielectric constant of SiO$_2$. On the basis of the expressions (1)-(3), we can establish that it is important that $q$ should be as small as possible to decrease the pull-in voltage.

The disconnection force $F_C$ is the sum of the contact and adhesion forces between the probe and pad surface. A critical problem of MEMS probe cards is that each probe cannot endure or produce the force required to break the oxide on the metal pad surface. Usually, a force over 100 mN is necessary to make a low-resistance contact with the Al electrodes mechanically. Therefore, a contact method with a low contact force is key to realize the MEMS probe cards. An electric breakdown of thin oxide film on metal contact, which is referred to as fritting, is a candidate for the low-force contact method. Beiley et al. showed that fritting under the contact force of 0.7 mN guaranteed a low resistance of approximately 1.5 $\Omega$ between a tungsten probe and an Al pad [5]. In recent years, the authors have been focusing on these phenomena and have investigated the characteristics of fritting contacts [6,10,11]. In our previous work [4], we studied the influences of the contact force on the contact resistance in the fritting process. We found that Ni-coated probes had a lower contact resistance than the probes made of other metals when utilizing the fritting process and a resistance as low as 1 $\Omega$ could be obtained with a contact force of less than 10 $\mu$N. In this study, the adhesion forces between Ni probes and Al films have been measured. Fig. 3 shows the forces required to separate the contact between an Al film and a Ni-coated probe that was realized by fritting with a contact force of 10 $\mu$N. Although the contact resistance decreases with an increase in the fritting current, the adhesion forces appear to be independent of the fritting current. The maximum adhesion force is $\text{SiO}_2$, $d$ is given by $d_{air} + h_{SiO2}/\varepsilon_{SiO2}$, where $d_{air}$ the gap of the fixed end, $h_{SiO2}$ the layer thickness of SiO$_2$, and $\varepsilon_{SiO2}$ the dielectric constant of SiO$_2$. On the basis of the expressions (1)-(3), we can establish that it is important that $q$ should be as small as possible to decrease the pull-in voltage.

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under low-resistance contact with a current limit of 100 mA is approximately 10 $\mu$N. As a result, we can estimate that minimum $F_C$ is approximately 20 $\mu$N.

If the curl-up cantilever probes are realized utilizing the Ni electroplating deposition of two layers having different internal stress, the heights of the probes with the same layer structure are proportional to the square of their length. It can then be calculated that the pull-in voltages gradually decrease with increasing lever length but are regarded as being almost independent of it. For instance, 50 $\mu$m wide curl-up cantilevers with $w(t) = t^2/1000$, $d_{SiO_2} = 0.5$ $\mu$m, and $d_{air} = 0.5$ $\mu$m can generate approximately 90 $\mu$N by applying 100 V. The force of 90 $\mu$N is sufficiently large for contact disconnection, although in some cases it is not sufficiently large to overcome the restoring force $F_R$.

3. Fabrication

We have developed a fabrication process for the electrostatically actuated microprobes illustrated in Fig. 4. Fabrication procedures to form an isolated counter electrode were included in the process for making the curl-up Ni microcantilevers, to integrate the actuator with them. As shown in Fig. 4, the process starts with the deposition of Au counter electrodes. After sputter deposition of 0.4 $\mu$m thick SiO$_2$ isolation layer, a 0.5 $\mu$m thick Al sacrificial layer is deposited by sputtering. Subsequently, first low-stress and then high-stress Ni is electroplated continuously after the sputter deposition of 0.1 $\mu$m thick Ni/Ti film. The different internal stresses of these two Ni layers are derived from different electroplating baths, sulfamic acid and Watts baths. The details of bath conditions are described elsewhere [4]. Finally, the Ni microcantilevers are released and then curled-up from the substrate by etching out the sacrificial Al layer using a 20% KOH solution at room temperature. Since the etching rate of SiO$_2$ in the 20% KOH at 333 K is approximately 47 nm/h [12], the thickness decrease of the SiO$_2$ isolation layer due to 1 min over-etching can be smaller than 1 nm. As shown in Table 1, we have structured two types of Ni layers. The lever lengths were designed to be 100, 150, 200, 250, 300 and 400 $\mu$m, and the width was set to be 50 $\mu$m.

Fig. 5 shows the fabricated type-A cantilevers. The cantilevers with an etching slit pattern and an effective width of 40 $\mu$m, as shown in Figs. 5(a) and (b), have curl-up shapes. However, the cantilevers without the etching slit, shown in Fig. 5(c), have large $q$ and a straight shape instead of a curved one.

![Fig. 4. Fabrication process: (a) deposit and pattern Au as ground electrode on SiO$_2$/Si; (b) sputter SiO$_2$ and make a connection hole by RIBE; (c) sputter and pattern the Al sacrificial layer; (d) sputter Ti/Ni as the seed for Ni electroplating and pattern photore sist; (e) electroplate low-stress Ni; (f) electroplate high-stress Ni; (g) remove resist and Ti/Ni seed layer; (h) etch Al sacrificial layer using KOH solution.](image)
shape. In this case, since the sacrificial layer etching progresses from the edges to the center in the y-direction, the difference in the internal stress of Ni layers could result in a large $q$. Subsequently, the effective flexural rigidity of the lever in $x$-direction can increase due to the large $q$, although further study is necessary to explain the cause. As a result, the introduction of an etching slit is effective for decreasing the pull-in voltage. The measured tip-heights of both types of cantilevers with an etching slit are shown in Fig. 6. The tip-heights are actually proportional to the square of the lever length. It was observed that the tip-height could easily be altered by controlling the thickness ratio of the high-stress layer to low-stress layer.

4. Characterization

4.1. Mechanical properties

Figs. 7(a) and (b) show the relationships between the load and the displacement of the lever-end for type-A and -B levers, respectively. These relationships were measured utilizing a surface profiler. The stylus of the surface profiler tracks the surface of the cantilever from its fixed end to its free end at a load. Subsequently, the tip-height of the cantilever at the load is measured and the displacement of the lever end can be given by the difference between the loaded tip-height and unloaded one. The load-displacement relationships of all

<table>
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<tr>
<th>Type</th>
<th>Thickness of lower layer (μm)</th>
<th>Thickness of upper layer (μm)</th>
<th>Total thickness (μm)</th>
<th>Thickness ratio (low-stress/high-stress)</th>
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</thead>
<tbody>
<tr>
<td>Type A</td>
<td>0.67</td>
<td>0.23</td>
<td>0.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Type B</td>
<td>0.72</td>
<td>0.18</td>
<td>0.9</td>
<td>4.1</td>
</tr>
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</table>

Fig. 5. SEM images of fabricated electrostatically-drivable curl-up Ni microcantilevers with etching slit (a), (b) and without etching slit (c). The lengths of the cantilevers with etching slit are: (a) 100, 150 and 200 μm; (b) 250, 300 and 400 μm.
the long cantilevers are basically non-linear, because the cantilevers are curled-up. From the slopes between the loads of 2 and 3 μN, we estimated that the effective Young’s moduli of the type-A and -B levers are 140 and 200 GPa, respectively. These calculated Young’s modulus values are comparable to the reported values but can largely be altered by the values of the lever thickness. Although the Ni layer thickness was controlled by electroplating time, it appeared to be difficult to control the thickness with an error of less than ±10%. Since the Young’s moduli are calculated using the relation $E = \frac{4kl^3}{bh^3}$, where $k$ is a measured spring constant, their error can be in a range of approximately ±30%. The Young’s moduli of electroplated Ni are dependent on the electroplating bath – conditions, and additives – and can be changed in the range of the calculated values. However, the difference in the calculated Young’s moduli is very large and cannot be due to the small difference of the thickness ratio. The difference is most probably caused primarily by the difference in thickness. If the type-A and -B levers are 0.94 μm thick and 1.06 μm thick, respectively, both the effective Young’s moduli can be estimated as 170 GPa. In the following, these thicknesses and the Young’s modulus of 170 GPa are used for the estimations related to Figs. 8–10.

4.2. Actuation

Pull-in voltages of type-A and -B cantilevers with various lengths were measured by gradually increasing the voltage between the lever and the counter electrode. Fig. 8 shows the measured dependence of the pull-in voltage on the lever length. The pull-in voltages of the type-A and -B levers decreased from 140 to 130 V and from 80 to 70 V, respectively, with increasing lever-length from 100 to 400 μm. As expected from the theoretical equations, it was found that the pull-in voltages gradually decrease with increasing lever length but are regarded as being almost independent of it. These indicate that the force-displacement characteristics of
tip-heights of the cantilever probes can be widely controlled by altering only the lever length and keeping the pull-in voltage almost constant. Using the estimated effective Young’s moduli and measured tip-heights, the measured pull-in voltages approximately agree with the theoretical ones when \( q = -1.1 \) \( \mu m \) for type-A levers and \( q = -0.3 \) \( \mu m \) for type-B levers. These \( q \) values are too small for direct observation by scanning electron microscopy.

For the actuation experiments, the maximum applied voltage was 220 V. Subsequently, the breakdown of the SiO2 isolation layer or an abrupt increase in leakage current was then not observed. The breakdown field of the SiO2 layer is estimated to be more than 500 MV/m.

### 4.3. Contact

The fritting characteristics of the 400 \( \mu m \) long cantilever were measured. The probe tip was pressed into a sputtered 1.0 \( \mu m \) thick Al film sample with a lever displacement of approximately 200 \( \mu m \), prior to the application of the fritting voltage between the probe and the Al film. Subsequently, the contact force was estimated to be 3 \( \mu N \), as shown in Fig. 7. When the application voltage was 10 V, the maximum current at fritting was approximately 120 mA and then the mean, median, standard deviation, maximum and minimum of the contact resistance were 3.1, 2.0, 2.5, 9.4 and 1.0 \( \Omega \), respectively. Although these resistance values could be acceptable for usual testing, they are larger than those measured in our previous studies. This is because the contact force was as small as 3 \( \mu N \) in this case, while the forces were as large as 10 \( \mu N \) when a resistance of approximately 1 \( \Omega \) was obtained.

### 5. Discussions

When the probe tip of the 400 \( \mu m \) long cantilever is pressed into the pad with a lever displacement of 200 \( \mu m \), the tip-height is 60 \( \mu m \). When applying the probes to wafer testing, this tip-height can be referred to as compensation deflection, \( d_c \), which compensates the tip-pad distance deviation [10]. Fig. 9 shows the relationship obtained by calculation between the disconnection forces \( F_C \) and the pull-in voltages for type-A probes using \( q = -1.1 \) \( \mu m \). We find that the influence of the disconnection force required for the actuation is relatively small. Even when \( F_C = 50 \mu N \), which is much larger than the minimum \( F_C = 20 \mu N \), the increase in pull-in voltage is as small as 17 V.

In the experiments, since the longest and softest cantilever was used, the contact force was relatively small, and as a result the contact resistance was larger than the values obtained in the previous studies using the same types of curl-up micro-cantilevers. However, to increase the contact force, the shorter and harder cantilevers can be utilized for the probes without increasing the pull-in voltage. Here, we set \( d_c = 10 \mu m \) because \( d_c \) can be decreased to approximately 10 \( \mu m \) in the next generation IC test. Subsequently, we calculated the maximum contact forces by pressing the probe tips to the DUT, and allowing for a space of 10 \( \mu m \). As shown in Fig. 10, the contact force can be greater than 10 \( \mu N \), when using only the 150 \( \mu m \) long type-A cantilevers among the fabricated ones. In this case, the increase in pull-in voltages is approximately 7 V compared to the case when \( l = 400 \mu m \) and \( d_c = 60 \mu m \). As a result, we can obtain both a contact resistance of less than 1 \( \Omega \) and a switching voltage of less than 100 V.

For future study, in order to examine the applicability of these types of probes to next generation MEMS probe cards, reliability data, such as those of contact resistance, disconnection force, and pull-in voltage, should be experimentally obtained using probes with optimized dimensions.

### 6. Conclusions

We have proposed and fabricated the curled-up Ni micro-cantilevers for a new type of MEMS probe card that can
be electrically driven with a rolling-contact touch-mode. Investigating the characteristics of fritting contact between the electroplated Ni probes and Al electrodes, it has been observed that the adhesion forces of the contact made by the fritting process could be as small as $10^{-9}$ N. For the fabrication, we have successfully developed an array of curled-up Ni microcantilevers with counter electrodes for actuation. It was demonstrated that the developed probes could be successfully driven with a pull-in voltage of less than 150 V. We estimated that the fritting contact with a contact resistance of $1 \Omega$ can be disconnected by applying voltages of less than 100 V using one of the fabricated cantilevers. These types of probes will be applied to a next generation wafer probe card with a contact switching function.

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References


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