Bulk micromachined silicon comb-drive electrostatic actuators with diode isolation

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Abstract

A simple bulk-micromachining process for the fabrication of comb-drive electrostatic actuators in single-crystal silicon is described. A p+ etch-stop layer is first formed by boron ion implantation and diffusion into an n-type (100) Si wafer. This layer is then patterned by reactive ion etching, and anisotropic wet chemical etching is used to create an undercut structure that is free to move on a flexure suspension. In-plane mechanical motion is obtained by applying electrostatic forces through comb-drive electrodes, using electrode isolation provided by inbuilt diode structures. Single- and double-axis laterally driven resonant comb-drive actuators fabricated by this process are described. © 1997 Elsevier Science S.A.

Keywords: Bulk micromachining; Comb-drive electrostatic actuators; Diode isolation; Silicon

1. Introduction

Because electrostatic forces scale relatively advantageously with reducing size, electrostatic actuators are promising alternatives to electromagnetic devices in the microstructure size domain [1]. Silicon-based surface-micromachined comb-drive actuators have already been demonstrated [2–4], using a modified CMOS process involving the deposition of SiO2 and polysilicon, followed by lithography and dry etching of the polysilicon to form shallow (typically < 10 μm) features. The SiO2 is then removed from beneath the suspension system and electrodes to allow motion; however, SiO2 remaining beneath support pillars provides the insulation needed to allow application of voltages.

This process has several intrinsic advantages. First, it is potentially compatible with CMOS microelectronics. Secondly, because etch selectivity is achieved using different materials, there are no restrictions on feature shape. However, there are also some disadvantages. For example, because of the small thickness of the silica layer, freeze-drying must be used after any final wet etch step [5] to avoid structural collapse by surface tension forces [6]. Dry etch-release processes are now being developed to avoid this problem [7–9].

Bulk micromachining involves the removal of material from a single-crystal Si substrate by a wet etch, such as ethylene diamine pyrocatechol (EDP) or KOH [10–12]. Because the process is anisotropic, the features fabricated can be very deep, although there are severe restrictions on the range of feature shapes. However, an etch stop can easily be formed by boron diffusion, greatly extending the range of possibilities [13]. Many different bulk-micromachined devices involving electrostatic actuation have been demonstrated (for example, spatial light modulators [12]). Most have involved out-of-plane motion of simple cantilever beams, excited by parallel-plate capacitative drives.

The main problems associated with in-plane actuators lie in the fabrication of narrow-gap comb-drive electrodes (which cannot easily be formed by anisotropic wet chemical etching), and the provision of insulation between different parts of the structure (due to the conductive nature of the substrate).

Two bulk silicon processes that circumvent both difficulties have been demonstrated. In the first [14], wet etching is used to create mesas that will eventually act as support pillars. Reactive ion etching of a boron-diffused layer is then used to fabricate the electrodes and mechanical parts. The supports are then bonded to a glass substrate, and wet chemical etching is used to remove all remaining unwanted silicon. A very
similar process uses an oxidized Si wafer as the bonded insulating substrate [15].

In the second, known as SCREAM [16,17], a single substrate is used. Reactive ion etching is again used to define the electrodes. The exposed surfaces of any etched parts are then covered by thermal silica, and electrical conductivity is restored by a sputtered layer of Al (which is insulated from the substrate by the silica). Undercut is then performed using an isotropic dry etch. A similar approach has been used for the fabrication of cantilevers in undoped Si by wet chemical etching [18].

In this paper, we describe an alternative bulk silicon process that can be used to create monolithically integrated electrostatic devices without the need for oxide interlayers. Reactive ion etching is again used to define the electrodes and mechanical suspension, and boron doping to protect these parts from attack by a wet chemical undercut etch. This approach has been used for the fabrication of resonator sensors with a complicated suspended structure [19], and also for thermally driven cantilevers [20]. More recently, it has been used to define one set of electrodes in a sophisticated actuator with vertical motion [21]. The main difference here is that an n-type substrate is used, so that p-n junctions provide the isolation needed to apply voltages across the electrodes. Diodes have of course been incorporated in micromachined structures many times before (see, e.g., Ref. [22]). Here, we show that this type of isolation can allow the application of voltages high enough for significant motion in comb-drive devices. The process is very simple: only a single patterning step is involved, no thick-layer deposition is required, and freeze-drying is avoided. Single- and double-axis actuators fabricated by this process are described.

2. Device design

A simple design of a single-axis electrostatic actuator, based largely on previously published layouts [2–4], was used to demonstrate the process. Fig. 1(a) shows a plan view. Here a small central table is moved by electrostatic forces provided by two sets of comb-drive electrodes, which act against the restoring force of a cantilever suspension. The static, dynamic and electrostatic operation of this type of device is well known, and so will be covered only briefly here.

The suspension has a stiffness $k = 4 \times 12EI/L^3$, where $E$ is Young's modulus, $L$ is the length of the suspension arms, $I = rw^3/12$ is their second moment of area, $w$ their width and $t$ their thickness. Assuming that there are $N + 1$ outer and $N$ inner fingers in each comb, and neglecting fringing fields, the force provided by each drive is $F = N\varepsilon_0 V^2/g$, where $\varepsilon_0$ is the dielectric constant of free space, $V$ is the voltage and $g$ the electrode gap. The static displacement is $\Delta_0 = F/k$. Mechanical oscillation can be induced by a sinusoidal voltage; how-

![Fig. 1. (a) Plan view and (b) section of laterally driven resonant comb-drive electrostatic actuator.](image-url)
Table 1
Electrical resonance frequencies for the four different suspension systems, (a) as originally predicted, (b) as measured, and (c) as calculated, based on assumption of lateral overtech and a best-fit value of Young's modulus

<table>
<thead>
<tr>
<th>Design</th>
<th>Suspension length (µm)</th>
<th>Suspension width (µm)</th>
<th>(a) Predicted resonance (Hz)</th>
<th>(b) Measured resonance (Hz)</th>
<th>(c) Corrected resonance (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900/2</td>
<td>8</td>
<td>666</td>
<td>409</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>900/2</td>
<td>12</td>
<td>1223</td>
<td>847</td>
<td>889</td>
</tr>
<tr>
<td>3</td>
<td>600/2</td>
<td>8</td>
<td>1223</td>
<td>751</td>
<td>736</td>
</tr>
<tr>
<td>4</td>
<td>600/2</td>
<td>12</td>
<td>2247</td>
<td>1593</td>
<td>1634</td>
</tr>
</tbody>
</table>

however, owing to the quadratic dependence of $F$ on $V$, the oscillation frequency $f_m$ is twice the electrical frequency $f_e$. There will be a mechanical resonance at a frequency $f_m = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$, where $m$ is the mass of the moving parts. The electrical frequency required to excite this resonance is then $f_e = f_m/2$.

The moving table consists of a 50/2 µm × 50/2 µm square plate, carried on two beams of length 1750/2 µm and width 10 µm, which are in turn attached to a rectangular frame. The frame beams are 20 µm wide, apart from those carrying the distributed load of the electrostatic drive, which are 30 µm wide. The moving part of each electrode consists of 132 fingers of length 100/2 µm and width 8 µm; the fixed part contains 133 similar fingers. The finger gap is 2.61 µm, and the overall width of each electrode structure is 2000/2 µm. These data were used to calculate the mass of the moving parts, based on an assumed thickness of 7 µm and a density of 2.33 × 10^3 kg m⁻³ for Si.

The frame is mounted on four suspension arms. Four arm designs were investigated, using different combinations of two lengths (900/2 and 600/2 µm, respectively) and two widths (8 and 12 µm). For each design, the suspension stiffness and the corresponding electrical resonance frequency were calculated. Figures for Young's modulus reported in the literature vary quite widely [12,23]; in our initial estimates we used the value 1.3 × 10^11 N m⁻². The resulting values of $f_e$ are shown in the fourth column of Table 1. Two designs have identical suspension stiffness, and hence equal resonance frequency. However, the largest static deflection was expected for Design #1, which has the weakest suspension. In this case, the predicted value of $\Delta_0$ was 0.35 µm with a 10 V drive.

3. Device fabrication

The devices were fabricated on 4" diameter (100)-oriented n-type wafers, with a resistivity of 4–7 Ω cm. The electrodes and suspension system were aligned at 45° to the intersections of (111) planes with the wafer surface (the x- and y-axes), to increase the undercut rate in the final wet etch step. Large lands, which were not fully undercut, provided supports for the fixed parts of the structure.

The fabrication process is shown in Fig. 2. The wafer was first doped with boron to form a p⁺ etch-stop layer (1), using a two-step method based on an initial B⁺ ion implantation followed by a drive-in diffusion. The implantation was carried out to a surface charge dose of 10¹⁷ C cm⁻², using a
1 mA beam current and 200 keV acceleration voltage. The diffusion was performed at a relatively high temperature (1250°C) to reduce residual stress gradients [24]. Using a 1 h diffusion, we have found that the boron concentration can exceed $7 \times 10^{19} \text{cm}^{-3}$ (the concentration needed to form an etch stop for EDP [12]) at a depth of at least 7 μm, while avoiding significant boron outdiffusion. Surface pitting during anisotropic etching is therefore minimized. The wafer was then deglazed in buffered HF.

A surface mask was then formed from 6000 Å of sputtered Cr metal, which was patterned by photolithography and wet etching (2). The exposed areas of boron-doped Si were then etched in a plasma containing CHF₃, Ar and O₂ to a depth of greater than 10 μm, using an Oxford Plasma Technology RIE80 fitted with a 6.5° table (3). The pressure, power and d.c. bias were 50 mtorr, 160 W and 420 V, respectively. These conditions gave an etch rate of $\approx 2 \text{μm} \text{h}^{-1}$, with a selectivity of $\approx 20:1$ to the Cr mask and an anisotropy of $\approx 20:1$.

The Cr mask was then removed, and residual oxide was stripped in buffered HF. The substrate was then etched in EDP at 112°C to a depth of 120 μm (4). At this depth, all suspended parts were fully undercut. The wafer was then rinsed, cleaned in fuming nitric acid, and rinsed again. Because of the relatively deep undercut etch, structural collapse was mostly avoided (so that a freeze-dry release was not required) and samples could be blown dry. However, it was found that some collapsed structures could be released from stick-down using a thermal shock in a rapid thermal annealer.

Evaporation of 700 Å Al metal was then used to form ohmic contacts to the p* layer (5); the large clearance between the contact pads and the substrate made it trivial to avoid a short circuit to the substrate. Finally, contact wires were attached (6). Because there is a p–n junction at every point of contact between the suspended parts and the substrate, as shown in Fig. 1, the two halves of each comb drive were isolated from each other by a pair of back-to-back diodes. Voltages could therefore be applied between the electrodes, to the limit of reverse breakdown of the diodes.

4. Device performance

Fig. 3(a) shows a completed actuator, in which the large clearance between the suspended parts and the substrate may clearly be seen. The exposed substrate is levelled flat, even below the electrodes. Boron diffusion is well known to cause tensile stress, due to shrinkage of the silicon lattice caused by substitution of smaller boron atoms. Stress gradients caused by non-uniform distribution of dopant may also arise, resulting in warping of long structural members. However, Fig. 3(b) shows a detail near the centre of one set of electrodes, where good alignment between the two halves of the comb drive may clearly be seen despite the large extent of the shuttle ($\approx 2.5 \text{mm} \times 2.8 \text{mm}$). This result may be attributed to the use of a folded flexure design, which is well known to release much of the built-in residual stress in the suspension [2], and the use of a short, high-temperature diffusion [24]. Near-vertical features are obtained during reactive ion etching, but optical measurements showed that feature widths are typically reduced by $\approx 2.3 \text{μm}$ by lateral etching. Half of this reduction can be attributed to the wet etch step used to pattern the Cr mask.

The performance of the electrical isolation was determined by measuring the $I$–$V$ characteristics of back-to-back diode pairs. Reverse breakdown occurred at relatively low voltages, in the range 5–25 V, presumably because of the heavy doping of the p-side of the junction. Fig. 4(a) shows a typical variation, in which the current rises abruptly at a voltage near 15 V. Just before breakdown, the leakage current is $\approx 1.5 \text{μA}$, indicating reasonably effective isolation. Irreversible damage generally occurred at higher voltages, after which one or both of the diodes became permanently conducting.

The observation of large variations in the breakdown voltage, together with frequent electrical failure, suggested that breakdown was occurring across the many exposed edges of the diodes rather than in the bulk. The fabrication process was therefore modified to protect the p–n junction edges with a thin oxide layer. This was done by thermally oxidizing the

![Fig. 3. SEM view of (a) completed actuator and (b) electrode detail.](image-url)
The entire device to a depth of 1000 Å after the undercut etch step, and then removing the silica from the upper surface before Al metallization by reactive ion etching in CHF$_3$ and Ar alone (as shown by the dashed-line path in Fig. 2). Immediate improvements in electrical stability were obtained.

The mechanical performance of the devices was tested by applying a variable frequency a.c. voltage to one of the comb drives, and measuring the resulting deflection in air using an optical microscope fitted with a video camera. Fig. 5 shows stills of the centre of one electrode pair during typical operation. In Fig. 5(a), the device is undriven and both electrodes are static. In Fig. 5(b), the device is driven at resonance, and the motion blur of the right-hand electrode is clearly visible.

The electrical frequencies needed to excite resonance in the four different designs are shown in the fifth column of Table 1. The measured values differed markedly from the predicted ones; generally, the measured values are lower. A number of effects might account for the difference. First, lateral etching alters the mass of the moving parts and (more importantly) the suspension stiffness. Secondly, the partial amorphization caused by ion implantation followed by incomplete annealing might be expected to alter Young's modulus. Thirdly, incomplete release of stress caused by boron diffusion will result in the suspension arms being in compression. However, the large variation from the predicted value obtained for Design #1 (where the arms span almost the whole width of the comb drive) suggests that stress is not a major factor. Reasonable agreement with the measured values is obtained assuming only a dimensional reduction of 2.3 μm and a best-fit value for $E$ of $1.08 \times 10^{11}$ N m$^{-2}$, as shown in the final column of Table 1.

The small static deflections were hard to measure with precision. However, as expected, the largest values were obtained using Design #1, which has the weakest suspension. In this case, the deflection ($\approx 0.6$ μm with a 10 V drive) was
larger than predicted, once again mainly because of lateral etching. This decreases the suspension widths (thus reducing the stiffness) and increases the electrode gaps (decreasing the electrostatic force). For Design #1, the former effect outweighs the latter, so that the overall deflection increases. Further correction to the predicted deflection arises from the three-dimensional nature of the electrostatic field [25]. However, the difference from the approximate formula given in the previous section is small for the large finger engagement distances here. Good agreement with the theoretical model was therefore obtained simply by correcting relevant design dimensions by 2.3 μm and assuming a reduced Young's modulus.

The larger dynamic deflections were much easier to quantify. Fig. 4(b) shows the variation of resonant deflection with voltage for two devices of Design #1. Reasonable agreement with a quadratic variation is obtained; divergences from the expected response can be attributed to misalignment of the electrodes in the vertical plane (at low voltages) and diode breakdown (at high voltages). Similarly, Fig. 6 shows the frequency response of a device of Design #1, in which the deflection rises from a static value of 1.0 μm with a 15 V drive, to 17 μm at resonance. The data have been matched to a mass–spring–damper model, to allow the damping factor to be estimated as 0.025.

Deflections were still observed after damage had occurred to one of the isolation diodes, but only for one voltage polarity. For devices containing only a single operational diode, it was found that resonance could be excited at drive frequencies of \( f_{row} \) and \( 2f_{row} \), presumably because the voltage across the electrodes then consisted of a half-wave rectified signal, which contains a substantial d.c. component. The frequency response of a device with unipolar isolation is shown superimposed on Fig. 6 to illustrate this effect. Normal operation could be restored to devices damaged in this way by replacing the sinusoidal drive with a full-wave rectified drive derived from a precision rectifier.

The overall design was then modified to allow fabrication of \( x \)–\( y \) stages based on two orthogonal flexure suspensions [15]. The flexure parameters were similar to those of Design #1; however, portions of the internal lands in Fig. 1 were omitted to allow transverse motion, together with the outermost members linking opposing sets of electrodes. In addition, a lattice girder construction was used for the electrode support beams to reduce the mass of the moving electrodes. The overall performance was found to be very similar to that of the single-axis stages described earlier, with good matching between resonance frequencies for \( x \)- and \( y \)-motions. Fig. 7(a) shows a detail of the two orthogonal comb drives near one corner of an \( x \)–\( y \) microactuator, while Fig. 7(b) shows the movable table.

5. Conclusions

A simple bulk-micromachining process has been demonstrated, which may be used to fabricate monolithic silicon electrostatic devices involving comb-drive electrodes and in-plane motion. These have a mechanical performance similar to devices fabricated by surface micromachining. The process described here is clearly less flexible; however, it may offer a method of providing excitation in resonant sensors that are already based on bulk-micromachining technology, such as pressure sensors [19]. Alternatively, because it avoids the use of \( SiO_2 \) as a sacrificial material, it might be used to introduce electrostatic actuation to devices that retain silica as a functional material, such as silica-on-silicon integrated optic components; one possible application is an electromechanical waveguide switch [26]. In this case, the final wet etch step might also be used to fabricate fibre alignment grooves.

The electrical parameters of the isolation diodes have not yet been optimized. Although the doping level of the \( p^+ \) layer is essentially fixed by the requirement that it acts as an etch stop, there may be scope for increasing the reverse breakdown voltage by altering the doping level of the substrate. Similarly, the leakage current may be lowered considerably by
reducing the area of the supporting lands. These aspects are now being investigated.

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References