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# Movable Micromachined Silicon Plates with Integrated Position Sensing

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## Abstract

A process for fabricating large silicon plates of varying thicknesses suspended by thin, flexible polyimide beams has been developed. The plates have been integrated with an on-chip ring oscillator which provides a read-out of the plate position. The silicon plates can be moved electrostatically and the position of the plate determined by the frequency shift of the ring oscillator. Initial testing of the device yields a full-scale frequency modulation of approximately 2%, corresponding to a full-scale frequency shift of 13 kHz from a zero-deflection frequency of 680 kHz.

## Introduction

The technique of micromachining has been used to make a host of movable and flexible structures for sensing and actuation purposes (see, e.g. refs. 1–3). Recently, miniature deflectable reflecting plates for use as mirrors in fiber optic switching and display applications have been fabricated [4–7]. As many of these structures are micromachined from silicon, and as silicon is a stiff material, relatively large driving voltages may be required for large motions. In this work we have used silicon plates supported by flexible polyimide beams in the hope of reducing the driving forces required for large-scale deflection.

Structures using polyimide-supported plates as thermally isolated structures for gas sensors have been described by Stemme [8]. In that structure, polyimide was chosen for its thermal, not mechanical, properties. Recently, the mechanical properties of polyimide have been studied with the ultimate goal of using this material for structural members in microsensors and microactuators [9, 10]. Quantitative knowledge of the Young's modulus, residual stress and debond energy (adhesion) has now permitted the design and fabrication of polyimide-based microsensors and microactuators. Other desirable properties of polyimide are its mechanical flexibility (relative to silicon), its planarization properties, and its compatibility with integrated circuit processing. This paper describes the design, fabrication and testing of square silicon plates suspended by polyimide beams. A read-out scheme which allows on-chip sensing of the plate position is also reported. Possible applications for this device currently under investigation include feedback-stabilized electrostatically positionable mirrors (as described above) as well as a dynamically rebalanced accelerometer using the silicon plate as a proof mass.

## Implementation

The polyimide-supported silicon plates described below are square, 2 mm on a side, 10 $\mu$m in thickness, and supported at one end by a polyimide beam loaded in a torsional configuration (see Fig. 1). The mechanical response of these structures has been described previously [11]. A schematic of the structure with integrated read-out is shown in Fig. 2. Two metal pads can be seen on the movable plate: a drive electrode for electrostatic positioning and a sense electrode for position sensing. The silicon plate is attracted electrostatically by application of a voltage between the drive electrode on the movable plate and a second plate underneath the device. Variation of this voltage causes a change in the electrostatic attraction force and therefore a change in the angle of deflection of the movable plate. The plate position is determined using a capacitive read-out scheme. A variable capacitor is formed by the series connection of two capacitors, one variable and one fixed. The first capacitor (variable) is formed by the sense electrode on the movable plate and an overhead conducting plate at floating potential. The second

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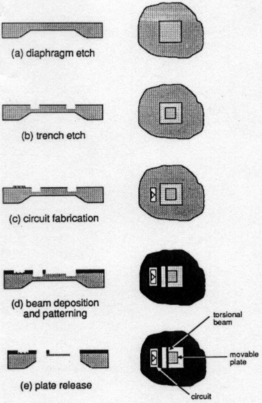


Fig. 1. Process sequence for device fabrication.

capacitor is formed between this same overhead plate and a fixed U-shaped electrode on the chip surface. The total coupling capacitance between the sense electrode on the movable plate and the fixed electrode on the chip surface is therefore given by the series connection of these two capacitors. It should be noted that it is not necessary to make electrical contact to the overhead conducting plate. As the drive voltage is increased, the movable plate is deflected downward and the total coupling capacitance between the sense electrode and the fixed U-shaped electrode decreases. This capacitance change is sensed by an on-chip ring oscillator (Fig. 3), which contains this variable capacitor in its feedback circuit. Changes in the plate position can therefore be detected by changes in the ring oscillator frequency.

## Fabrication

The devices described above were fabricated using standard bulk micromachining techniques. The starting material was a single-side polished ⟨100⟩ n-type silicon wafer of 2 in diameter and $11 \pm 1$ mil thick. A 1.3-$\mu$m-thick masking oxide was grown at 1100 °C in steam for 3 h. The front of the wafer was protected with photoresist and the oxide on the backside of the wafer was patterned into a series of square holes 3 mm on a side using a buffered oxide etch (BOE) (see Fig. 1). The photoresist was stripped in 3:1 sulfuric acid: hydrogen peroxide solution and the wafers were etched in 20 wt.% potassium hydroxide (KOH) solution at 56 °C for 11 h. The etch rate of this solution was 20–21 $\mu$m/h, forming 3-mm square diaphragms approximately 40 $\mu$m in thickness (Fig. 1(a)). The front-side oxide was then patterned using an infrared aligner to align the front-side pattern to the diaphragms and the wafers were etched in the above KOH solution for 30 min to form trenches 10 $\mu$m deep. During this etch the diaphragms were also etched 10 $\mu$m from the back, resulting in a 30-$\mu$m-thick square 2 mm on a side surrounded by a 1-mm-wide trench 20 $\mu$m thick (Fig. 1(b)). All masking oxide was then

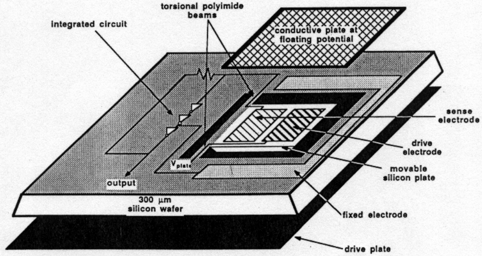


Fig. 2. Schematic of fabricated device.

stripped in BOE and the wafers were cleaned using a standard RCA cleaning procedure.

The three-stage ring oscillator circuit for read-out of the plate position was implemented at this point using a self-aligned polysilicon-gate PMOS process with 10 $\mu$m design rules (Fig. 1(c)). After the circuit process was completed (including sintering of patterned metal), the mechanical structure process was continued as follows. An adhesion promoter layer consisting of a 0.5% solution of $\gamma$-triethoxyaminopropylsilane in 95% methanol/5% water was spin-coated on the front of the wafer at 5000 rpm for 30 s. The polyimide (DuPont PI-2555) was then spun on the front side of the wafer as its polyamic acid precursor from solution in *N*-methylpyrrolidone at 2000 rpm for 120 s. The polyamic acid was baked at 120 °C for 10 min to drive off the solvent and induce partial imidization and reaction with the adhesion promoter. Photoresist (KTI 820-20) was then spin-coated at 2500 rpm for 30 s on top of the polyimide and baked at 90 °C for 25 min. The photoresist and partially imidized polyamic acid were simultaneously patterned by the resist developer (a solution of tetramethylammonium hydroxide in water) to form the supporting beams (Fig. 1(d)). The resist was then stripped using acetone and methanol, and the patterned polyamic acid beams were fully imidized by baking at 400 °C in nitrogen for 45 min. The thickness of the post-cured polyimide was approximately 4 $\mu$m. A second level of metal consisting of 100 Å of chromium and 1500 Å of gold was sputter-deposited and patterned using standard etchants to form the sense and drive electrodes and to connect these electrodes to the integrated circuit. Finally, the wafers were blanket-etched from the back using a sulfur hexafluoride plasma etch until the silicon in the trenches surrounding the plates was etched away, releasing the beams and center plates (Fig. 1(e)). Figure 4 shows a photomicrograph of a fabricated device.

## Testing and Results

The chip was packaged in a standard flat-pack carrier. A 3-mil-thick piece of polyimide (Kapton) adhesive tape was placed on the bottom of the flat-pack to provide insulation for the electrostatic drive, and the chip was mounted on the tape using a commercially available cyanoacrylate adhesive (Permabond 200). A front-side substrate contact was made by etching a small area of field oxide using concentrated hydrofluoric acid and bonding directly to the exposed silicon. A glass microscope cover slip approximately 5 × 5 mm on a side coated with sputtered indium–tin oxide was used as the external cover plate for capacitively coupling the ring oscillator signal from the movable plate to the fixed U-shaped electrode. This cover plate was positioned with the indium–tin oxide side facing the movable plate so as to cover the movable plate and U-shaped electrode except for the edge of the plate with the torsional polyimide beam. The outer edges of the cover plate were supported on the polyimide in the field regions of the chip; thus, the cover plate was separated from the movable plate by the thickness of the polyimide film (approximately 4 $\mu$m).

The feedback loop of the on-chip ring oscillator (Fig. 3) was completed using a 47K external resistor ($R_1$) and a 2 pf external capacitor ($C_0$) in parallel with the variable (movable plate) capacitor C. For the testing described below, the sense and drive pads on the movable plate were tied together electrically. The chip was bonded and packaged with cover plate as described above, and terminal voltages of $V_{DD} = -6$ V, $V_{GG} = -10$ V and $V_{SB}$ (substrate bias) = +5 V were applied. An off-chip comparator was used to buffer the oscillator signal and the frequency of oscillation was measured using a digital frequency counter. Under these conditions, a free-running (zero-deflection) ring oscillator frequency of approximately 682 kHz was observed. A positive voltage relative to the circuit ground was applied to the metal case of the flat-pack carrier which caused the movable plate (held near circuit ground by the on-chip oscillator) to deflect downward towards the case. This downward deflection decreased the coupling capacitance and increased the frequency of the ring oscillator, as expected. Figure 5 shows a plot of the ring oscillator frequency as a function of the applied deflecting voltage. A nonlinear relationship is observed due to the nonlinear force–voltage electrostatic relationship. A full-scale

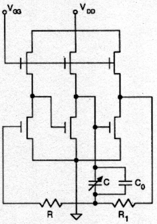


Fig. 3. Schematic of on-chip ring oscillator. R is an on-chip resistor; C is the variable capacitor formed between the movable plate and the fixed electrode as described in the text; $R_1$ and $C_0$ are external components used to set the oscillation period, as described in the text.

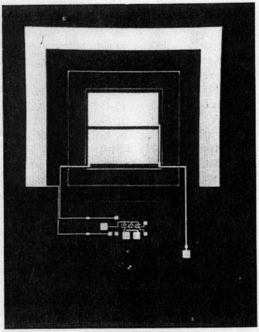

Fig. 4. Photomicrograph of fabricated device.

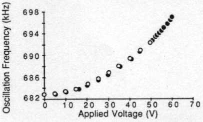


Fig. 5. Ring oscillator frequency as a function of attracting voltage on plate: (●) sweeping voltage from low to high; (○) sweeping voltage from high to low.

(approximately 70 $\mu$m) plate deflection corresponding to the maximum applied voltage of 60 V yields a full-scale frequency shift of 13 kHz, corresponding to a full-scale frequency modulation of approximately 2%. Application of drive voltage to the movable plate without the indium–tin oxide cover plate in place resulted in deflection of the plate with no corresponding change in oscillator frequency.

## Conclusions

A polyimide-supported electrostatically deflectable silicon plate with integrated sensing of the plate position has been demonstrated. The device has been implemented using standard bulk micromachining techniques and a self-aligned polysilicon-gate PMOS process. A full-scale deflection of the plate results in a frequency shift of approximately 2%, which is easily observable with an off-chip comparator/buffer and a digital frequency counter. Under current investigation is the use of the plate position read-out for feedback stabilization of the plate, and the closed-loop response of the feedback-stabilized device to applied acceleration.

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