A JUMPING SILICON MICROROBOT WITH ELECTROSTATIC INCHWORM MOTORS AND ENERGY STORING SUBSTRATE SPRINGS

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ABSTRACT

We present the first demonstration of a silicon microrobot using electrostatic inchworm motors to store mechanical energy in springs etched into the silicon substrate. The microrobot is fabricated using a two mask silicon on insulator MEMS process with a 40μm device layer and 550μm substrate. The springs in the silicon substrate can store 100μJ of energy, more than 10X greater than what has been demonstrated previously using energy storing springs in the silicon on insulator layer.

KEYWORDS

microrobot, jump, electrostatic inchworm motor, substrate spring, silicon on insulator, SOI

INTRODUCTION

Recent progress on jumping [1,2], walking [3], and flying [4] microrobots suggests a promising future for autonomous microsystems. Microrobots of the future have been envisioned for use in search and rescue, space exploration, manufacturing, structural inspection, and medicine [5,6]. At small scales, jumping provides a mode of locomotion that can be used to traverse difficult and unknown terrain. Previous work on jumping microrobots using silicon includes a robot with a silicon skeleton and PDMS energy storing springs [1], and a robot made in a silicon on insulator (SOI) process with electrostatic inchworm motors and energy storing springs made in the SOI layer [2]. While the silicon and PDMS based robot was capable of storing 100μJ of energy, there were no motors integrated with the springs. On the other hand, the SOI based robot integrated motors, but the springs were capable of storing a maximum of 4μJ of energy.

The volumetric energy density of a material with Young's modulus E under strain ε is given in (1).

$$U_{volumetric,\max} = \frac{1}{2} E \varepsilon_{\max}^2 \tag{1}$$

Using the Young's modulus for [100] silicon, 169GPa, and a relatively conservative max strain of ε_{max} = 0.5%, results in a practical volumetric energy density of 2.1mJ/mm^3. An SOI wafer with a 40μm device layer and 550μm substrate has a maximum energy per unit area of layout of 85μJ/mm^2 and 1200μJ/mm^2 if making energy storing springs in the device layer and substrate, respectively.

Therefore, springs in the substrate can contain more than an order of magnitude more mechanical energy than in the device layer. Using conservation of energy and neglecting drag, the jump height of a robot with total mass m_t, spring mass m_s under strain ε with Young's modulus E, material density ρ, and gravitational acceleration g, is given in (2).

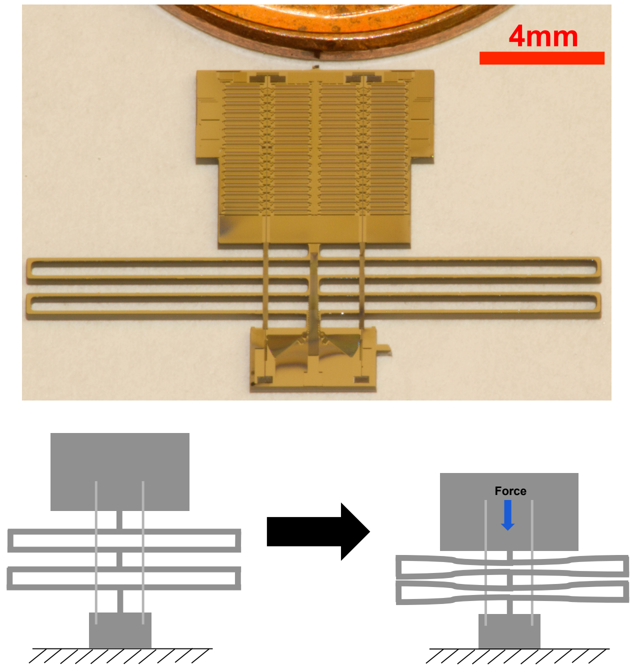

Figure 1: Top – The jumping silicon microrobot next to a US penny. Bottom – Cartoon of the robot's substrate springs being compressed and storing mechanical energy.

$$h = \frac{E\varepsilon^2}{2\rho g} \frac{m_s}{m_t} \tag{2}$$

In the theoretical limit when m_s and m_t are equal (and strained to 0.5%), a silicon robot can jump 94m high! When designing a jumping silicon microrobot, it is therefore beneficial to strain as much material as possible to the strain limit.

SYSTEM DESIGN

We present a 90mg robot (Fig. 1) made in a two mask SOI process with a 40μm device layer, 2μm buried oxide, and 550μm silicon substrate. First, deep reactive ion etching (DRIE) is used to make structures in the device layer. Second, DRIE is used to make structures in the substrate, as well as singulate the robots so that they can be removed from the wafer. Finally, an anhydrous vapor HF etch is used to release structures in the device layer.

The robot's various subsystems can be seen in Fig. 2. Two electrostatic inchworm motors [3,7], two 10:1

mechanical advantage lever mechanisms [2], and a central shuttle are made in the device layer. Energy storing springs designed to be compressed are made in the substrate. Each motor shuttle is coupled to a 10:1 mechanical advantage lever mechanism to increase the force used to compress the substrate springs. Each motor is designed to move its shuttle 900µm in total before resetting. The motors are designed to operate as follows: The first motor displaces its shuttle 500µm, at which point the beak on the lever it is coupled to contacts the central shuttle (which is anchored to the robot above the substrate springs, and released below them). The first motor continues to displace its shuttle another 400µm. Because the lever provides a 10:1 mechanical advantage, the central shuttle has displaced 40µm. The second motor now begins to actuate, and when the lever it is coupled to contacts the central shuttle, the first motor resets. This process continues, and these 40µm displacements are accumulated; this accumulation of steps using electrostatic inchworm motors is called an "inchworm of inchworms."

The force generated by an electrostatic gap closing actuator (GCA), the building block of an electrostatic inchworm motor, is given in (3), where V is the applied voltage, ε is the dielectric permittivity, $A_{overlap}$ is the total capacitive finger overlap area, and d is the capacitive finger separation distance which is limited by the minimum feature size of the fabrication process.

$$F_{electrostatic} = \frac{1}{2} V^2 \varepsilon \frac{A_{overlap}}{d^2} \tag{3}$$

A useful force density metric of the motors is the dimensionless ratio of $A_{overlap}$ to the layout area needed to make the motors. The value of this metric for the robot in this paper is 0.69, which is 82% more than the value of this metric from the previous SOI based jumper [2], which is 0.38. The two mass one spring jump model shown in Fig. 3 is used with (4) [8] to determine the theoretical jump height of the robot, where h is the vertical jump height, m_u is the upper mass, m_l is the lower mass, k is the spring constant, g is gravitational acceleration, D is equal to the spring displacement, and d is equal to $m_l g / k$.

$$h = \left(\frac{m_u}{m_u + m_l} \right) \left(1 + \frac{d}{D} \right)^2 \left[\frac{kD^2}{(m_u + m_l)(2g)} \right] \tag{4}$$

This model neglects drag, and is a good approximation assuming the mass of the displaced air column is less than 100 times the mass of the robot. The motors on the robot were designed to produce 15mN of force at 80V. The robot should be able to jump vertically 3mm, 11mm, and 25mm, with 5mN, 10mN, and 15mN of motor force, respectively.

EXPERIMENTAL RESULTS

Substrate Springs

Force vs. displacement of the silicon substrate springs was measured using a Dage 4000 wirebond tester. A plot

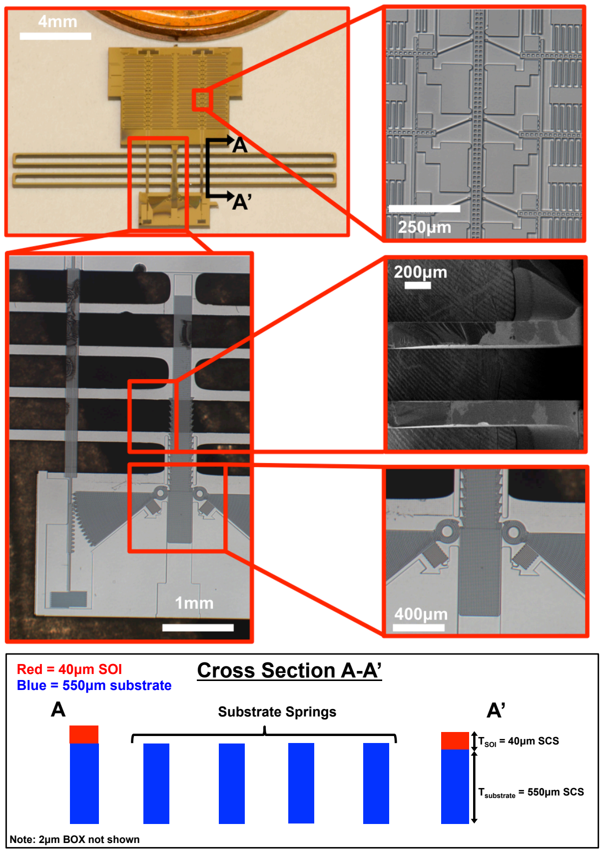

Figure 2: Counterclockwise starting from the top left. (1) The robot beneath a US penny. (2) The robot's left motor shuttle, both 10:1 mechanical advantage levers, central shuttle, and substrate springs are shown. (3) Cross section of A-A'. (4) Close-up of the two 10:1 mechanical advantage levers and the central shuttle. (5) SEM of a portion of the substrate springs. (6) The high density electrostatic inchworm motors used to compress the substrate springs.

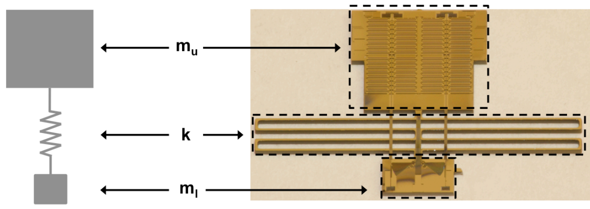

Figure 3: The jump model described by (4).

of force vs. displacement for three fabricated substrate springs is shown in Fig. 4. The maximum deflection of the springs was designed to be 800µm, theoretically resulting in 110µJ of stored energy. The mean value of the measured spring constants, 330N/m, agrees to within 6% with the theoretical spring constant, 350N/m.

Electrostatic Inchworm Motors

The force output of the motors was measured using spring vernier test structures whose spring constant was also calibrated using the Dage 4000 wirebond tester. The maximum measured force output of the motors was

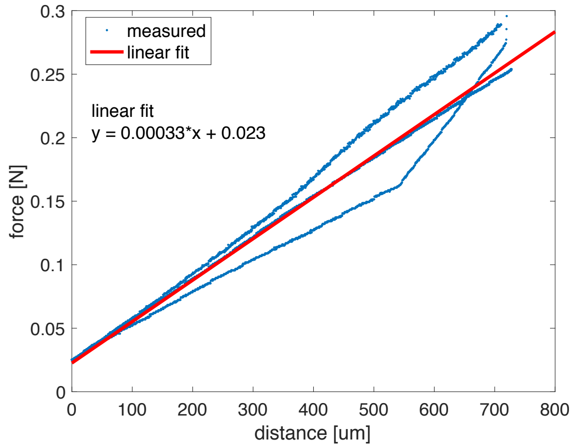

Figure 4: Force vs. displacement data for three measured substrate springs.

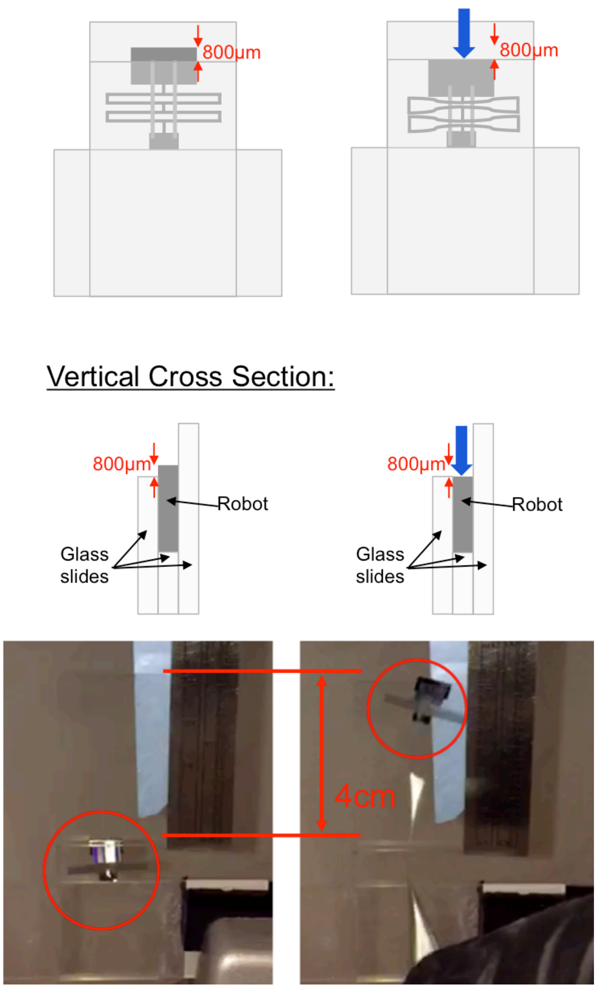

Figure 5: Top – Cartoon of manually compressing the robot's substrate springs with tweezers. The setup is perpendicular to the tabletop. Bottom – A fabricated robot's substrate springs are manually compressed 800µm, storing 100µJ of mechanical energy. The robot jumps 4cm.

4mN at 80V. A mechanical redesign of the motors using a more accurate analytical model [3] taking into account DRIE undercuts should allow the motors to operate significantly better and generate 10mN of force at 80V. Additionally, metalizing electrical traces and the motors' GCAs should prevent asymmetric voltage charge up times, possibly resulting in force loss of the current motors.

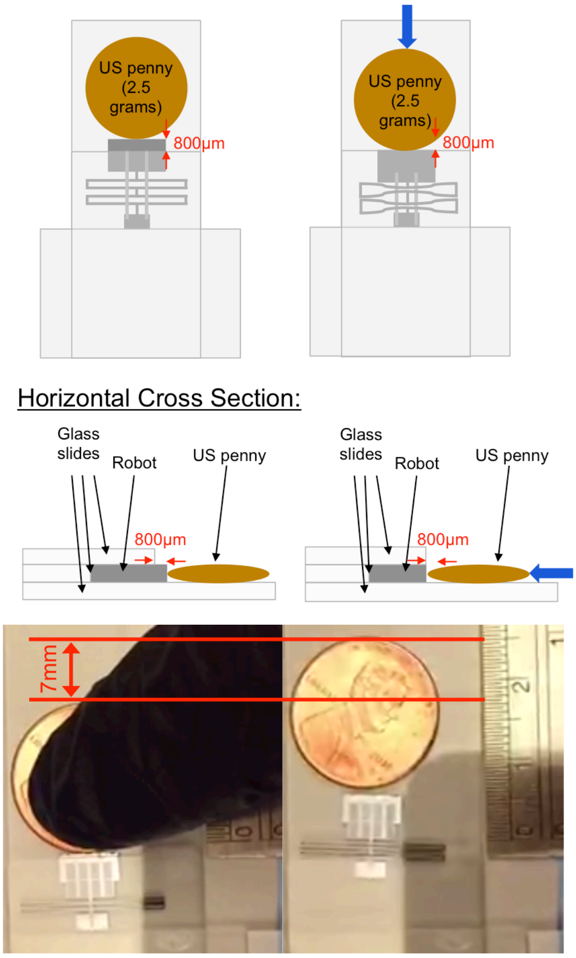

Figure 6: Top – Cartoon of manually compressing the robot's substrate springs with a US penny (2.5g). The setup is parallel to the tabletop. Bottom – The robot's substrate springs are manually compressed 800µm using a penny, storing 100µJ of mechanical energy. The robot kicks the penny 7mm.

Manually Loaded Vertical Jump and Horizontal Mass Kick

Two experiments were conducted to test the energy storage of the robot's substrate springs: a manually loaded vertical jump, and a manually loaded horizontal penny kick (shown in Figs. 5 and 6, respectively). In both experiments the robot was constrained using glass slides to prevent out of plane motion. When compressed manually with tweezers in the vertical jump experiment, the robot jumped 4cm. Using the jumping model from (4), the robot should jump 8cm vertically. The discrepancy is likely due to frictional losses in the glass slide setup as well as the robot contacting the tweezers during release. When compressed manually in the horizontal experiment, the robot kicked a US penny (2.5g) 7mm. A 2.5g mass given 100µJ of kinetic energy slowing only due

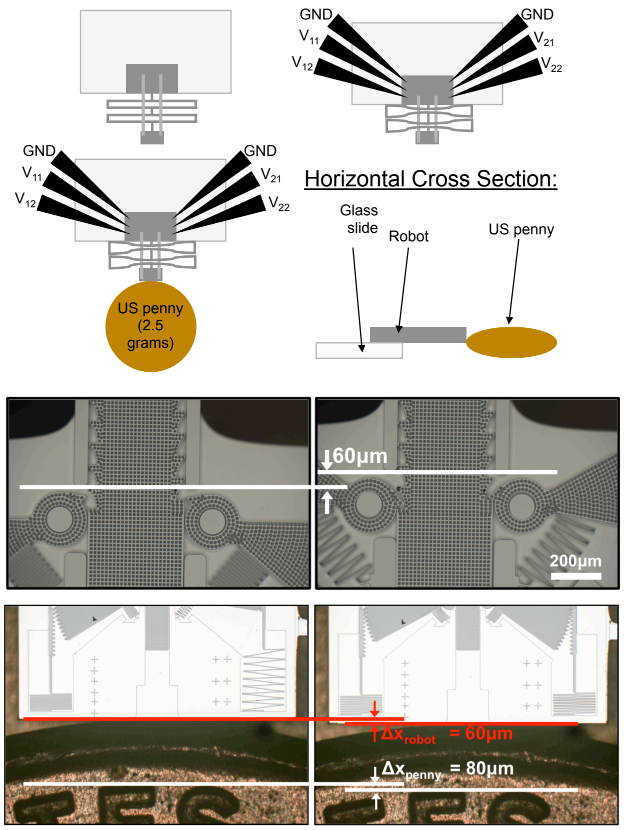

Figure 7: Top – Cartoon of the setup used to have the robot's electrostatic inchworm motors compress the substrate springs and kick a penny. The robot is glued to a glass slide with its substrate springs overhanging. The glass slide is put onto the probe station chuck, and micromanipulator probes apply control signals to actuate the inchworm motors. A penny is placed on the chuck next to the robot's foot. The control signals are removed, and the penny is kicked. Bottom – The robot's substrate springs are compressed 60µm. When the springs' energy is released the penny is kicked 80µm.

to friction ($\mu_{glass\text{-}penny}$ = 0.4, calculated by experimentally measuring the tilt angle at which the penny slides down the glass slide) should travel 10mm. The discrepancy is also likely due to frictional losses in the setup.

Electrostatically Loaded Substrate Springs and Horizontal Mass Kick

The first demonstration of displacing silicon substrate springs using SOI electrostatic inchworm motors was demonstrated, and is shown in Fig. 7. The left lever displaced the substrate springs a full 40µm, and the right lever displaced them an additional 20µm. The total displacement of 60µm resulted in 0.5µJ of stored mechanical energy. The robot was not able to compress its substrate springs any further because the left lever did not reset while the right lever was moving the central shuttle, thereby blocking it (middle bottom two images of Fig. 7). A US penny (which has more than 25 times the mass of the robot) was placed on the probe station chuck next to the robot's foot; when the actuating voltage on the motors was removed, the energy in the substrate springs was released, and the penny was kicked 80µm. This corresponds to a coefficient of friction of about 0.3.

CONCLUSION

We have designed and fabricated a microrobot in a silicon on insulator process with electrostatic inchworm motors, mechanical gain stage, and energy storing substrate springs. We characterized the motors and substrate springs, showed that the robot can store 100µJ of energy and jump 4cm vertically when loaded manually with tweezers, and can store 0.5µJ and kick a penny 80µm horizontally using its electrostatic motors. The robot should be able to jump 11mm with 10mN of electrostatic inchworm motor force. Increasing the mechanical advantage of the motors, improving lithography to make better springs that can be stretched to their strain limit, and designing a mechanism to harness the force output of all of the robot's GCAs simultaneously should allow future designs to jump more than 1m.

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