FIRST JUMPS OF A SILICON MICROROBOT WITH AN ENERGY STORING SUBSTRATE SPRING

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ABSTRACT

We present the first-ever successful jumps of a microrobot fabricated in a silicon-on-insulator (SOI) process with an energy storing spring etched into the silicon substrate. The 0.08 gram silicon robot used its onboard electrostatic inchworm motor to store 8µJ of spring energy and vertically jump more than 3mm when powered and controlled with wire tethers. The robot's vertical jump height is more than 3X higher than what has been previously demonstrated by an SOI robot.

KEYWORDS

electrostatic, inchworm, motor, jumping, microrobot

INTRODUCTION

Jumping allows microrobots to traverse terrain that may not be possible by walking. Ideally, jumping microrobots should be mass-manufacturable, consume little power, store a lot of jumping energy, and easily integrate with CMOS for power (solar cells) and control (microprocessor, memory, and radio). Previous work on jumping microrobots [1, 2, 3] has fulfilled some of these requirements, but not all.

We present the first-ever successful jumps of a microrobot (Fig. 1) fabricated in a three-mask silicon-on-insulator (SOI) process with an energy storing spring etched into the silicon substrate [4]. The robot also has an electrostatic inchworm motor etched into the device layer used to stretch and store energy in the substrate spring. The fabrication process consists of e-beam evaporation of gold (500nm) for routing and wire bonding, deep reactive ion etching (DRIE) of the 40µm device layer, DRIE of the 550µm substrate, and a timed vapor phase hydrofluoric acid release of the 2µm buried oxide.

The areal energy density $U_{d,areal}$ (in units of J/m^2) of a material with Young's modulus E, thickness T, and strain ϵ is given by (1).

$$U_{d,areal} = \frac{1}{2} E \epsilon^2 T \quad (1)$$

As shown by (1), for a fixed layout area a substrate spring can store more energy than a device layer spring. Also, a substrate spring can provide mechanical support and rigidity to a robot that is not possible by a device layer spring. Using substrate silicon to store mechanical energy paves a way for future robots to vertically jump one meter high [4].

SYSTEM OVERVIEW

The robot's subsystems are shown in Figs. 1 and 2. The

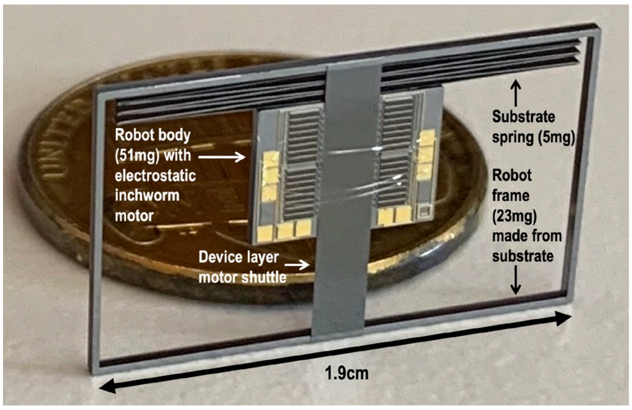

Figure 1: The 0.08 gram robot standing upright in front of a US Penny. The robot frame is 1.9cm wide and 1.2cm tall.

core of the microrobot is its electrostatic inchworm motor (capable of producing 15mN at 100V) and energy storing substrate spring, based on previous work in [5] and [6], respectively. The motor needs two high voltage signals and ground. Because the two halves of the motor on the robot are separated by the device layer motor shuttle, three wire bonds are needed to bridge the motor halves back together, which are shown in Figs. 1 and 2. Additionally, in order to interface the two high voltage signals and ground wire to the robot, a small, bare flex PCB with three 2 mil wires is wire bonded to the robot (Fig. 4). When the robot is standing upright the motor pushes on the device layer motor shuttle, thereby separating the robot body and robot frame and storing energy in the substrate spring (Fig. 5). When the substrate spring is fully displaced, its energy is quickly released causing the robot body to collide with the robot frame and the entire system jumps (Fig. 6).

DESIGN & JUMPING MODEL

A motor that produces force F_{mot} will displace a spring with stiffness k a distance $D = F_{mot}/k$. The energy U stored in the spring is given by (2).

$$U = \int_0^D F_{spring}(x)dx = \int_0^D kx dx = \frac{1}{2}kD^2 = \frac{1}{2}F_{mot}D \quad (2)$$

The motor used in the robot design can produce 15mN of force and provide up to 5mm of travel. Therefore, the maximum energy that can be stored is 38µJ. A spring made of 40µm wide fixed-guided beams etched into the 550µm thick silicon substrate was designed with a desired stiffness of 3N/m. A dynamics model was created in MATLAB to simulate jumps. A free body diagram of the model is shown in Fig. 3. The model consists of one ideal spring with stiffness k and two masses: frame mass m_f and body mass

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m_b. The position of the frame mass x_f and the position of the body mass x_b are described by (3) and (4). The initial displacement of the spring at time $t = 0$ is D, and the standard gravitational acceleration is g. The simulation begins with the initial conditions given by (5) and (6).

Each time a collision occurs, the velocities $\dot{x_f}$ and $\dot{x_b}$ are reset according to conservation of momentum with coefficient of restitution C_R, given by (7) and (8). The frame mass and body mass velocities immediately after the collision, given by v_f and v_b, respectively, are functions of the frame mass and body mass velocities immediately before the collision, given by u_f and u_b, respectively. The net force on the frame mass m_f is forced equal to 0 until the first collision occurs, thereby simulating the ground providing a normal force.

$$k(x_b - x_f) - m_f g = m_f \ddot{x_f} \tag{3}$$

$$k(x_f - x_b) - m_b g = m_b \ddot{x_b} \tag{4}$$

$$x_f(t=0) = D\,, \dot{x_f}(t=0) = 0 \tag{5}$$

$$x_b(t=0) = 0\,, \dot{x_b}(t=0) = 0 \tag{6}$$

$$v_f = \frac{m_f u_f + m_b u_b + C_R m_b (u_b - u_f)}{m_f + m_b} \tag{7}$$

$$v_b = \frac{m_f u_f + m_b u_b + C_R m_f (u_f - u_b)}{m_f + m_b} \tag{8}$$

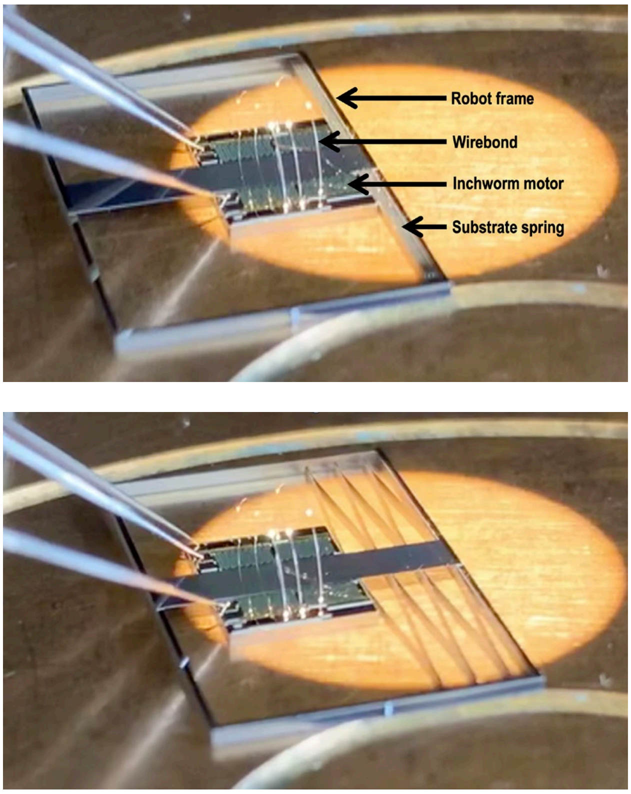

Figure 2: The robot lying flat on a probe station chuck having its motor tested. Top – The robot's motor has not yet displaced the substrate spring. Bottom – The robot's motor displaced the substrate spring approximately 3mm.

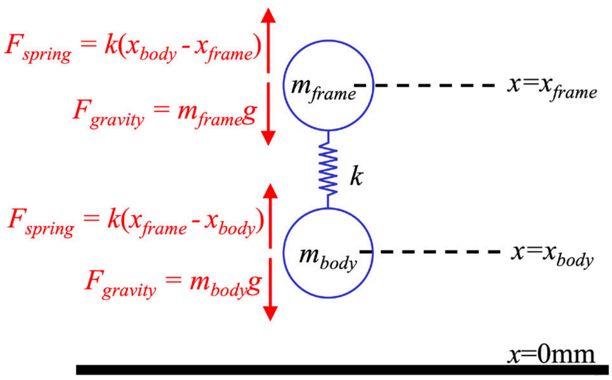

Figure 3: The free body diagram of the jumping model. The model consists of two masses (robot body and robot frame) connected by a spring (substrate spring).

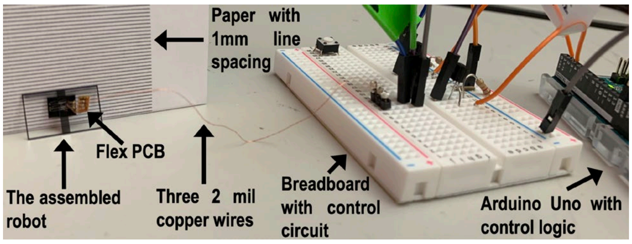

Figure 4: The test setup for conducting tethered jumps. A flex PCB is wire bonded to the robot's signal pads. Power is provided by the control circuit via the three 2 mil wires connected to the flex PCB. The robot is standing in front of a piece of paper with 1mm vertical line spacing.

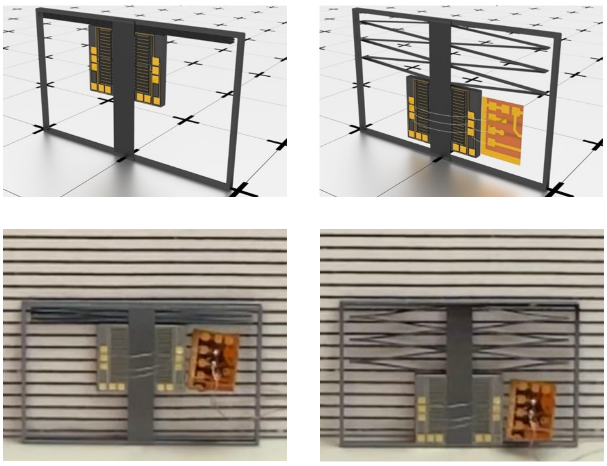

Figure 5: Top Left – A 3D model of the robot standing upright before it is wire bonded to a flex PCB. Top Right – A 3D model of the robot standing upright after it has been wire bonded to a flex PCB and the robot's on-board motor has displaced the substrate spring a distance of 5mm. Bottom Left – The fabricated robot has not yet used its on-board motor to stretch the substrate spring. Note that the substrate spring droops approximately 1mm due to the weight of the robot body, flex PCB, and three 2 mil wires. Bottom Right – The fabricated robot's on-board motor displaced the substrate spring a distance of 5mm from its fully relaxed position. The spring stored approximately 8μJ of energy.

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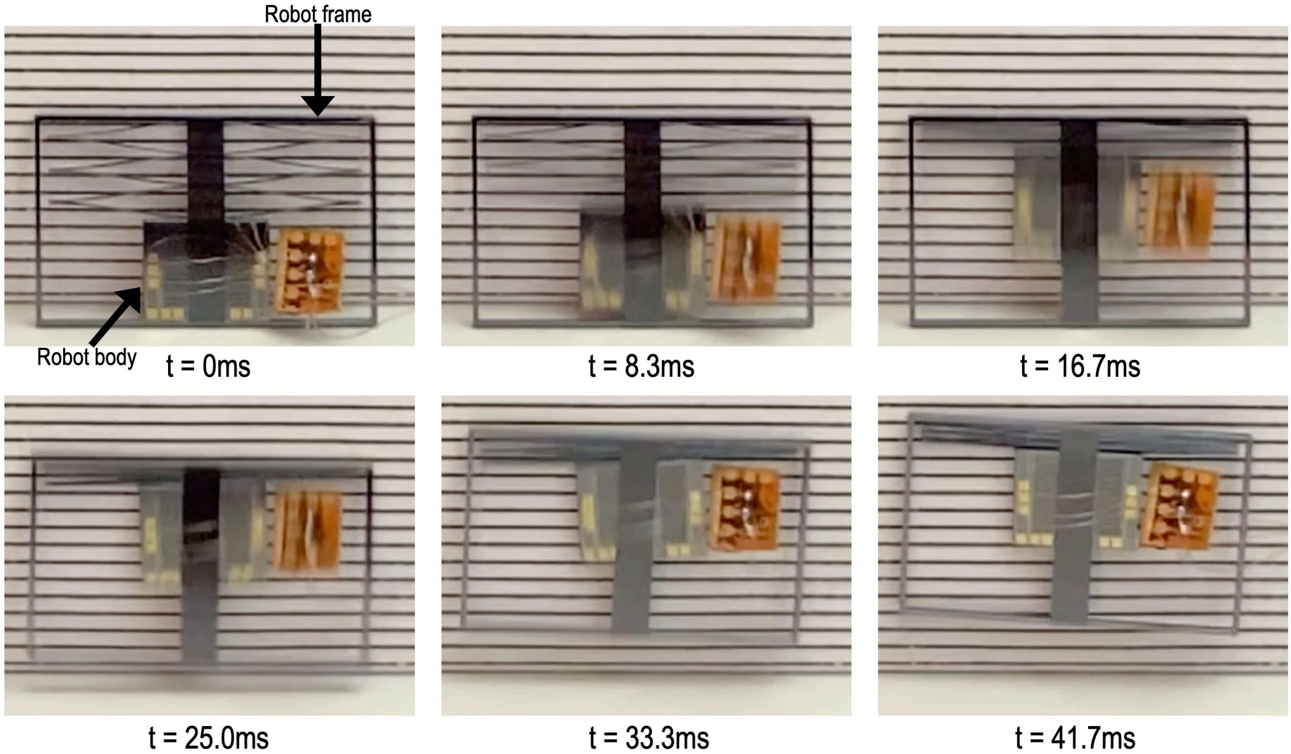

Figure 6: Six high speed (240 frames per second) images of a single tethered jump in front of a piece of paper with 1mm vertical line spacing. Top Left – The robot used its electrostatic inchworm motor to displace its substrate spring 5mm at a rate of 100µm/s. An estimated 8µJ of spring energy was stored. Top Center – The robot body began accelerating upwards towards the robot frame. Top Right – The robot body almost reached the robot frame. Bottom Left – The robot began jumping into the air. Bottom Center – The robot continued its jump upwards. Bottom Right – The robot frame vertically jumped more than 3mm.

The parameters used in the MATLAB model to simulate the design were m_b= 69mg, m_f = 26mg, k = 3N/m, and C_R = 1. The mass of the substrate spring was split in half and lumped into m_b and m_f. The mass m_b consisted of the robot body silicon (51mg), flex PCB (10mg), three 2 mil wires (5mg), and half of the substrate spring silicon (~3mg). The mass m_f consisted of the robot frame silicon (23mg) and half of the substrate spring silicon (~3mg). The simulated jump height was 3cm.

TETHERED JUMPING

A confocal microscope was used to measure the beam width of a fabricated substrate spring from both the device layer side and substrate side, measured to be 21µm and 30µm, respectively. The reduction in beam width was likely due to undercutting of the photoresist and a re-entrant etching profile during DRIE. With a trapezoidal cross-section and a Young's modulus of 130GPa (due to a wafer manufacturing error, the Young's modulus was smaller than intended because the spring was fabricated parallel to a {100} plane of a (100) wafer instead of a {110} plane), the spring stiffness was calculated to be 0.6N/m.

The test setup for conducting tethered jumps is shown in Fig. 4. High speed images of a single jump can be seen in Fig. 6. An experimentally measured trajectory as well as the simulated model using a spring stiffness of 0.6N/m and coefficient of restitution C_R = 0.3 (found by minimizing the squared error between experiment and simulation) are shown in Fig. 7. The measured data matches the simulation well, with discrepancy from the model possibly due to unmodeled friction between the robot and the paper used for measuring the jump height. This microrobot was the first to successfully jump using a substrate spring and jumped more than 3X higher than the best prior jumping silicon microrobot [3] which used energy storing springs etched into the device layer.

CONCLUSION

The robot has successfully jumped five times, proving itself to be resilient to the repeated impulse imparted to it, physically falling over, and operating for multiple hours outside of a cleanroom environment.

The immediate next step is to change the design and/or fabrication process to create a substrate spring with a stiffness of 3N/m so that a robot can jump 3cm.

Following a successful 3cm jump, the fabrication process will have an alumina atomic layer deposition step added [7] so that the electrostatic motor's capacitive fingers can be insulated. If the fingers are insulated, they will not short if touched. This change will allow the motor on the robot to be designed with much smaller gaps, increasing the force output by a factor of approximately 5. Additionally, because the fingers will not short, the actuation voltage can be increased from 100V to 200V, increasing the force output by a factor of 4. Combined, these two improvements will increase the force output of the motor by a factor of approximately 20.

Following the creation of a stronger motor, a stiffer

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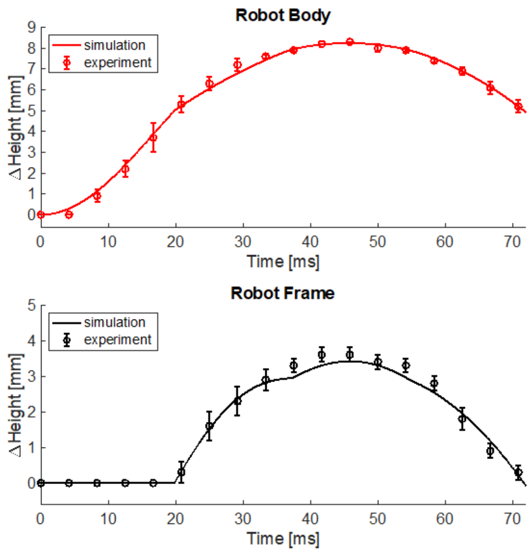

Figure 7: MATLAB simulated and experimentally measured height changes of the robot body and robot frame during the jump shown in Fig. 6. The error bars show position uncertainty ranges (measured with 0.1mm resolution) due to image blurring and the data points show the midpoints of the ranges.

substrate spring will be designed that is capable of storing enough energy so that a robot can vertically jump one meter. Finally, integrating the robot with a CMOS brain [8] and solar cells [9] for power will make it a truly autonomous system.

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