Building Micro-Robots: A path to sub-mm^3 autonomous systems

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ABSTRACT

A process for realizing sub-cubic millimeter micro-robots is detailed. To date, the process has been used to produce spherical structures ranging from 0.5 mm to 3.0 mm in diameter. A model of a 0.7 mm diameter spherical robot has been developed and an estimated power budget is provided. In addition, a model of the electrostatic actuators that will be used for the robot is covered. This model has been verified through experiments using external actuators.

Keywords: MEMS, Robotics, Self Assembly, Silicon-on-insulator

1 Introduction

While the realization of micro-robotics has been a goal of researchers for several decades [1], it has proven extremely difficult to build systems that combine power collection, power storage, computation, sensing, and actuation in a compact package. Traditional MEMS approaches have tried to do this by first achieving the required functionality and then combining the pieces together to form a robot [2] and systems for the automated assembly of MEMS devices have been demonstrated [3]. In this work, we take the opposite approach and focus on realizing the structure first and then adding the functionality into this structure. We have initiated this work by developing a CMOS compatible process for fabricating sub-cubic millimeter structures. This process has been used to fabricate spherical structures that will eventually integrate electrostatic electrodes and enclose a photovoltaic cell, capacitor, and processor.

2 MICRO-ROBOT ARCHITECTURE

The end goal of this work is to develop a spherical micro-robot with a diameter under 0.7 mm that could serve as the basic unit for programmable matter [4]. However, the fabrication approach being developed is suitable to the realization of a wide range of micro-robotic systems. Fig. 1 provides an artist's rendering of a spherical micro-robot. The robot is formed from an outer shell surrounding an inner core. The outer shell consists primarily of electrodes formed from a thin ($\approx$ 0.25 μm) silicon layer enclosed in silicon dioxide. Also embedded in the oxide, a limited number of transistors ($< 2\%$ of the surface area) will be used to control the bias voltage applied to the electrodes. A short connector composed of oxide enclosed metal wires connects the outer shell to the circuit region of the inner core. This circuit region contains the electrical control and driver circuits for the robot. Finally, a capacitor for energy storage and a photovoltaic cell for energy collection will be located on top of the circuit region.

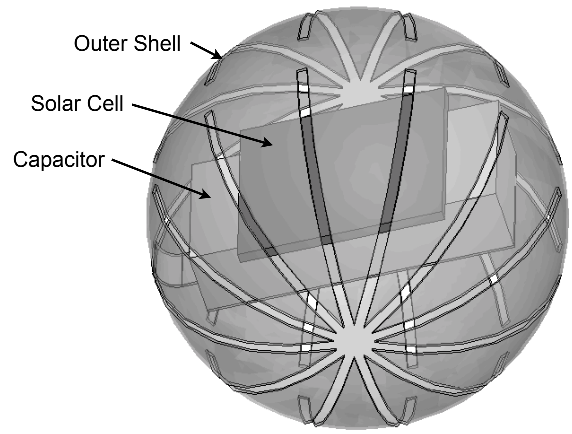

Figure 1: Artist's rendering of a spherical micro-robot. The robot consists of an outer shell containing transparent electrodes for actuation and an inner core containing the electrical circuits, a capacitor, and photovoltaic (solar) cell.

2.1 Power Collection and Storage

Photovoltaic cells provide a compelling power source for micro-robots since they use a readily available energy source (light), are fabricated using widely available processes, and provide relatively high energy density. In addition to this, high voltage photovoltaic sources can be realized by connecting multiple cells in series. In 2003, Bellew, *et. al*, presented a photovoltaic source with groups of up to 200 individual cells, each sized 400 μm by 400 μm, connected in series to get open circuit output voltages as high as 88.5 V [5]. The maximum power output of 2.01 mW (62.8 μW/mm) with a solar illumination air mass of 1.71 corresponds to an

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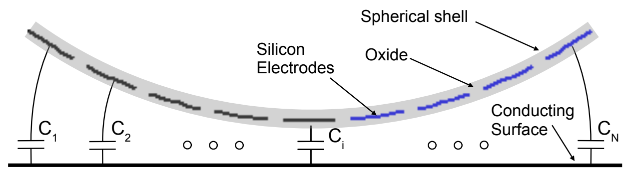


Figure 2: Schematic representation showing the oxide enclosed electrodes. A capacitor is formed between each electrode and the surface that the sphere is located on.

efficiency of 8.3%. This is fairly low compared to efficiencies over 20% commonly achieved with commercial photovoltaic cells, but is reasonable for a research effort. For a spherical micro-robot with a diameter of 0.7 mm, the photovoltaic cell will have a cross section of approximately 0.25 mm^2. Approximately 10% of the energy is lost due to reflection and absorption in the shell. Using an efficiency of 7%, a 0.25 mm^2 photovoltaic cell would provide 13.2 μW. Based on this, the robot is being designed to operate with a power budget below 10 μW.

In order to smooth out power variations and deliver high instantaneous power when needed, a capacitor will be used as a power buffer. Commercial surface mount capacitors are available down to EIA size 0201 with dimensions of 0.6 × 0.3 × 0.2 mm. One such part from Presidio Components provides 0.1 nF of capacitance for voltages up to 125V. Charging this capacitor with the 80 V output of a photovoltaic cell would result in stored power of 0.32 μJ, sufficient to provide nominal operation (10 μW) of the robot for 32 ms.

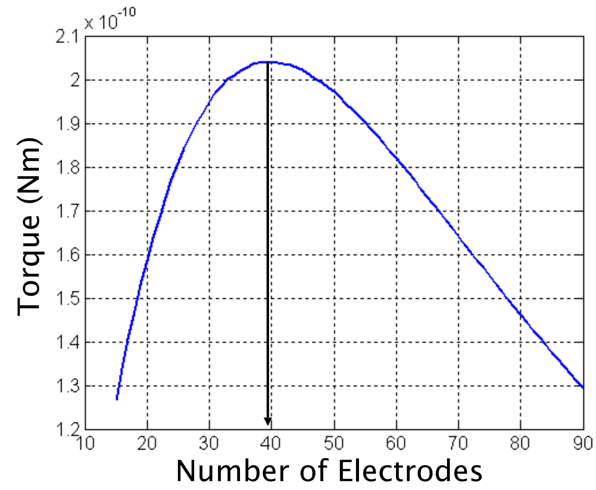
2.2 Actuation

The spherical micro-robot will be actuated using electrostatic actuators on the exterior shell. Biasing the electrodes relative to each other creates a charge separation that will induce corresponding surface charge on any conducting surface and thus provide an attractive force. Modeling this process is done by evaluating a series of capacitors over a conducting surface as shown in Fig. 2. Without loss of generality, we can arbitrary choose the ground of the robot to have a potential of 0 V. The potential of all of the electrodes is then well defined. The potential of the conducting surface (relative to the robot ground) is calculated as

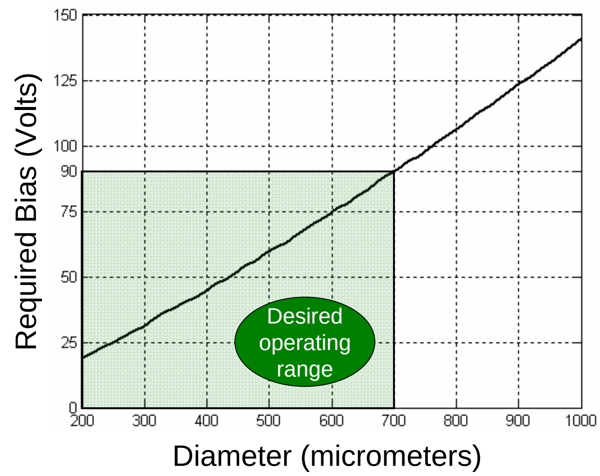
$$V_{plate} = \frac{\sum_{i=1}^{N_{el}} C_i V_i}{\sum_{i=1}^{N_{el}} C_i} \tag{1}$$

where N_{el} is the number of electrodes and V_{plate} is the voltage induced on the conductive plate when the each electrode is biased with voltage V_i. With all of the voltages defined, the force between each plate and the conducting surface can be calculated by subdividing each electrode into smaller segments and applying the familiar electrostatic force calculation $F_{es} = \epsilon A V_{bias}^2 / g^2$ to each segment. Multiplying the force of each segment by the moment arm from the point of contact and summing all of these values gives the total torque applied to the sphere. For equally spaced electrodes with a fixed pattern of bias voltages, the total torque generated can then be plotted as a function of the number of electrodes. As seen in Fig. 3 (a), for a 0.7 mm diameter sphere, the optimal number of electrodes in 39-40 which corresponds to electrodes covering 9 degrees.

After determining the optimum number of electrodes for a given diameter, it is straight forward to calculate the total torque as a function of voltage. Since it is desired that the robot can move up a vertical surface, it is necessary to calculate the voltage required to overcome the torque that gravity applies to a sphere on a vertical surface. This voltage is plotted as a function of spherical diameter in Fig. 3 (b). The plot shows that limiting the voltage used to 90 V requires that the robot have a diameter under 0.7 mm.



(a)



(b)

Figure 3: (a) Torque generated by a 0.7 mm diameter robot. (b) Voltage required to move a sphere vertically up a conductive surface.

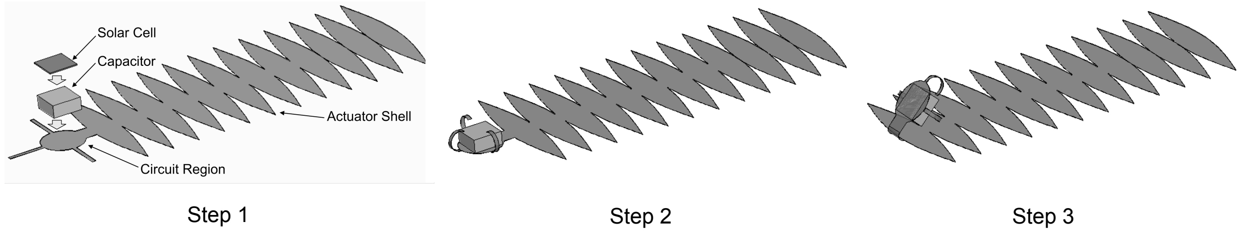


Figure 4: Fabrication of the robot begins with a foundry SOI BiCMOS process. Step 1: The die are post processed to form oxide enclosed circuits of the desired shape and additional devices are flip chip mounted. Step 2 and 3: The die is released by etching away the silicon from under the buried oxide layer causing the released device to roll up into a spherical shell around the bonded devices.

The power required to move the robot can be estimated by the voltage required to charge the drive electrodes. This capacitance is dominated by the inter-electrode capacitance, and therefore can not be known until the design is complete. We estimate that moving one step will require charging a capacitor of ≈0.5 pF. To charge to 90 V then requires 2.02 nJ. To move at rate of 5 revolutions per second (1.2 cm/sec) would then require making 200 steps per second, or 0.41 μW. Adding in a safety margin of 10x to account for leakage results in a power requirement of ≈4.1 μW.

2.3 Computation

In the first versions of the robot, a small finite state machine will be fabricated in the circuit region. In the long run, an ARM7-TDMI-S can be separately fabricated using a 90 nm CMOS process and bonded onto the circuit region. The ARM7-TDMI-S with 4 kB DRAM and 4 kB flash RAM can be fabricated in 0.16 mm^2. Clocking the core at 20 kHz would require under 2 μW of power. Using more recent 45 nm processes, both the size and power requirements can be reduced.

3 FABRICATION PROCESS

The process for fabricating the robots is the key to realizing highly functional units in a compact size. This process must provide low cost mass production in a highly repeatable manner with tightly packed functionality. Therefore, the process we are developing is based around commercial CMOS processing. These processes are ideal for producing large numbers of repeatable, compact, highly integrated circuits. Adding bonding and micro-machining processes after the CMOS process provides the added functionality required for the cells.

Fabrication begins with the submission of circuit and actuator designs to a commercial foundry with an established silicon on insulator (SOI) bi-polar complementary metal oxide semiconductor (BiCMOS) process. Many SOI processes also include the ability to co-fabricate high voltage circuits that are required for the actuators. In an SOI process, all of the circuits are fabricated on top of a buried oxide (BOX) layer. Further, after the transistors are defined, additional layers of metal and oxide are added on top of the transistor layer. The result is an integrated circuit that is embedded in silicon oxide on both the top and bottom.

Using a process developed in-house at the Air Force Research Laboratory (AFRL), the oxide layers, including the BOX layer, will be patterned and etched down to the silicon handle wafer. This process enables us to create a patterned two dimensional shape on top of a silicon handle wafer as shown in Step 1 of Fig. 4. At this point, individual devices such as a processor, a capacitor, and a photovoltaic cell can be mounted to the circuit region of the device using commercially available flip chip attachment. Next, the silicon layer under the BOX layer is etched out causing the patterned structure to release from the substrate. Since the BOX layer is a highly stressed thermal oxide, and the silicon layers have very low stress, a bending moment is created in the released circuit causing the structure to curl up into a spherical shape. Through the placement of etch access holes, the folding process can be controlled so that initially (Fig. 4: Step 2) small structures are released, then larger structures (Fig. 4: Step 3). The end result is that the structure will roll up into a sphere resulting in the final device illustrated in Fig. 1.

4 RESULTS

While our end goal is the realization of sub-cubic millimeter robots, our efforts to date have focused on developing the fabrication process for creating the spherical shells. Utilizing our in-house release process, a variety of two dimensional patterns have been used to generate spheres such as those shown in Fig. 5. The diameter of the shells as a function of the layers that compose the shell, the layer thicknesses, and the residual stress in the layer is calculated using a simple bending model. Fig. 6 shows the predicted diameter for shells with a 1.1 μm thick BOX layer and varying silicon layer thickness. Also plotted are results for three released shells.

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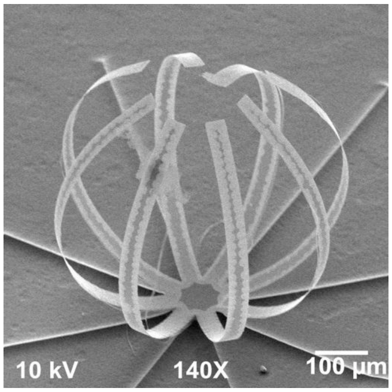

Figure 5: Scanning electron micrograph of a spherical shell formed from glass-silicon-glass layers. Shells with diameters ranging from 0.5-3.0 mm have been produced.

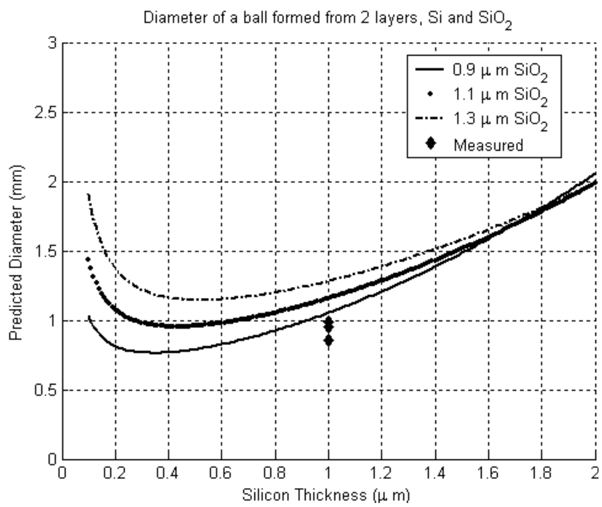

Figure 6: Plot of the predicted and measured sphere diameters.

The thickness of the silicon layer is nominally 1.0 microns, but could range from 0.8-1.05 microns. Generally, the measured values agree with the prediction. As more complex two dimensional patterns such as the layout in Fig. 4 are used, the models will require the use of finite element simulators to accurately predict the diameter.

Using the fabricated shells, we have also demonstrated actuation of the devices using voltages of 80-100 V. The shells are placed on an electrode array. The array has four independent voltages that are repeated. Fig. 7 shows four images of a shell on the external electrode array. As can be seen, the sphere is moving to the biased electrode.

5 CONCLUSIONS

We have developed a process for fabricating spherical shells composed of oxide enclosed silicon. This process is compatible with CMOS circuitry and can therefore be used in the fabrication of very compact micro-robots.

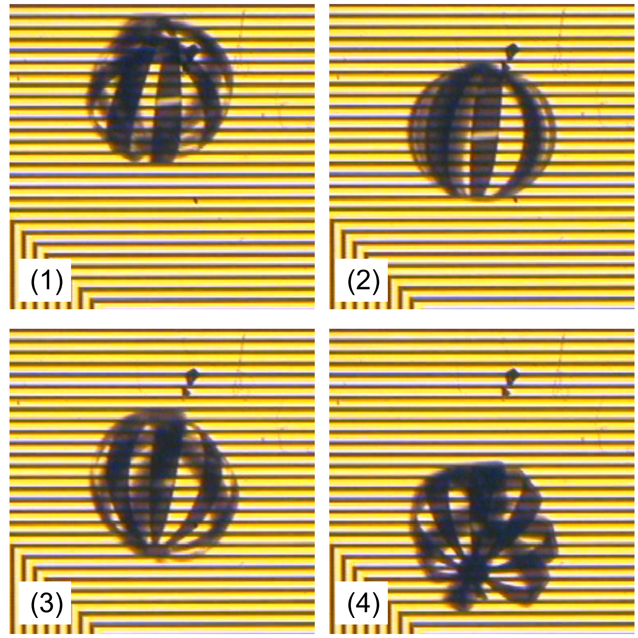

Figure 7: Still frames captured from a movie of a spherical shell rolling under the influence of external electrostatic actuator electrodes.

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