Analog Micro-Clock Driven by Scratch-Drive Actuators

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Introduction

Scratch drive actuators (SDAs) have been used in a wide variety of MEMS applications. Generally speaking, SDAs are convenient because the entire SDA structure is displaced during actuation, which is useful for motion over long distances. SDAs are capable of producing 100 µN of force [1] and have a typical step size on the order of 10 nm, so that a driving signal modulating at a frequency of 100 kHz corresponds to a velocity on the order of 1 mm/s. Finally, the step size and force output of an SDA can, to a degree, be tuned simply through the selected geometry. These attractive features of the SDA make it one possible mechanism for actuating an analog micro-clock.

SDAs have been researched extensively but certainly not exhaustively, with several papers published in the field of dimension optimization by Akiyama, Fujita, and others [1][2][3]. Additionally, SDAs have been used extensively as actuating mechanisms for rotating movement [4] as well as linear positioning [5].

Design and Fabrication

The Sandia SUMMiT process will be used for fabrication of the analog micro-clock. Referring to the processes flow shown below, polysilicon structural layers Poly1 and Poly2 will be used to define the clock hands, and a pin joint around which the hands rotate will be created using the Poly0 and Poly3 layers. A more detailed process flow follows.
A pin contact will be created using the Poly0 layer, and then in the SacOx1 layer we will begin to define the shape of the hands of the clock. Specifically, the Dimple1_Cut mask and etch (1.5 µm out of the 2 µm film) will be used to define a "mold" for the bushing of the SDA which will drive the hour hand. The SacOx1_Cut etch will be used to begin the definition of the eventual mold for the bushing of the minute-hand SDA. In addition, a Dimple1_Cut region will be etched surrounding the Poly0 pin contact to promote an electrically conductive path between the hour hand (and consequently, the minute hand which will rest on the hour hand) and the pin upon release

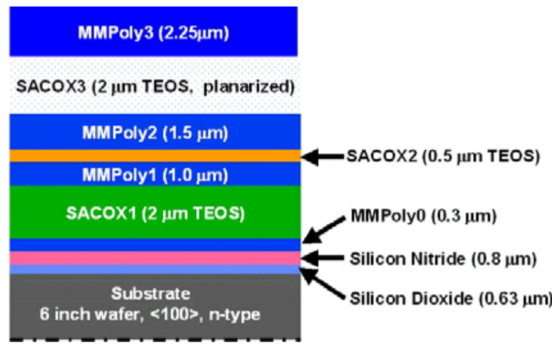

Fig. 1. Sandia SUMMiT process layer stack.

etch. The subsequent Poly1 deposition and Poly1_Cut steps will define the hour hand and its attached SDA. Next, the 0.5 µm TEOS SacOx2 deposition will serve to separate the Poly1 and Poly2 hands of the clock as well as to finish defining the mold for the SDA of the minute hand (now the bushing of this SDA will not contact the nitride insulating layer, ensuring correct release during sacrificial oxide etch). The Poly2 deposition and Poly2_Cut steps define the minute hand and accompanying SDA. Worth mentioning here is the crucial consideration that the minute hand should be aligned directly on top of the hour hand (being careful to straddle the bushing dimple of the hour hand with the minute hand) to ensure clearance such that the minute hand can pass over the hour hand as will be required. Finally, the SacOx3_Cut, Poly4 deposition, and Poly4_cut steps will be used to create a pin restraining the clock hands but allowing them to freely rotate. Since both the hour and minute hand SDAs sit 0.5 µm above the insulating nitride plane, we know that upon release etch of the sacrificial oxides, both SDAs will contact the wafer surface and each component of the entire structure will be electrical contact, allowing actuation of both hands using a single input signal.

Powering the device is relatively straightforward; a contact to the substrate can be cut through the insulating layer outside the radius of the clock, and since the Poly3 layer is deposited above the planarized SacOx3 layer, a contact to the structure can be fabricated by simply extending a "wire" which is suspended above the clock from the pin joint to a point outside the radius of the clock, where the wire can be connected to a second Poly0 pad and metallized.

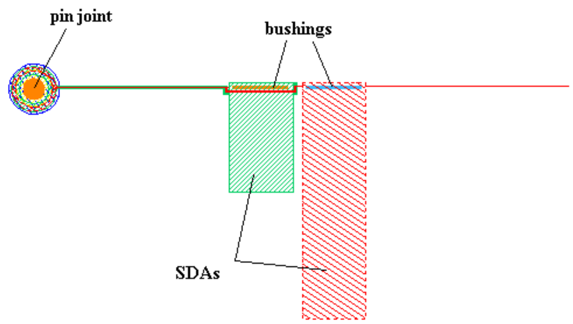

Fig. 2. Cadence layout of an analog clock. For illustrative purposes, the SDAs were drawn much larger (~5x) than scale to show the structure more clearly.

Following release etch, the minute hand will drop onto the hour hand, fitting snugly but still being able to pass over the hour hand entirely.

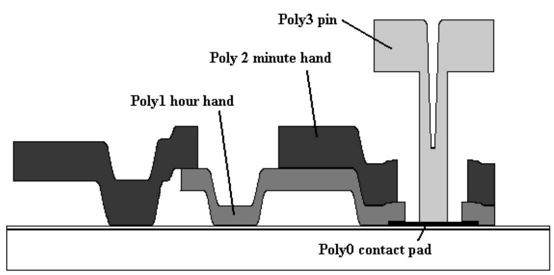

Fig. 3. Cross-section of device following release etch. The minute hand is in one mechanical piece, but must avoid running over the bushing of the hour hand.

SDA Motion Mechanism

The SDA consists of two simple components, which can be fabricated in a single process step. Shown below, these components are a rectangular plate (dimensions L_P*W_P) and a bushing (height H_B) which elevates the plate above the substrate.

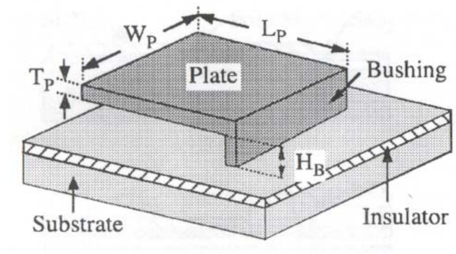

Fig. 4. Standard SDA, from [3].

As a voltage is applied between the plate and the substrate, the plate is drawn into contact with the insulated substrate and the bushing is jutted out slightly. When the voltage is reversed, the plate is restored to its original position and the new location of the bushing acts as a pivot point around which the SDA "scratches" forward.

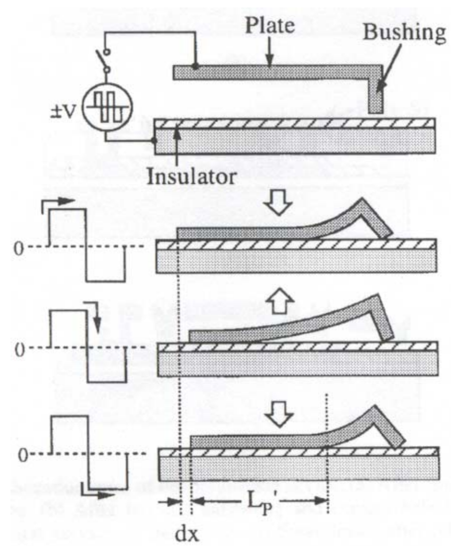

Fig. 5. Scratch drive actuation, from [3].

Akiyama and Shono [2] showed that the simple geometric relation

$$\Delta x = H_B^2 / 2(L_P - L_P') \qquad (1)$$

gives the step size of the SDA, where H_B is the height of the bushing and L_P' is the cross-sectional length of the SDA that is drawn into contact with the insulator film. Unfortunately, further research has shown that the step of the SDA won't follow this equation strictly [1,2]. As L_P' increases, the static friction between the section of the plate contacting the insulating plane increases correspondingly, and the SDA might "grab" slightly, so that the step does not increase as much as expected, or might even decrease. Therefore, this relation should be used only as a rough guideline from which to choose some nominal values of the SDA geometry. Of course, L_P' depends on both L_P and H_B, as well as the applied voltage and thickness of the SDA plate—therefore, with the right geometrical configuration we should be able to tailor the dimensions of the SDA to generate the desired ratio between step sizes for the hands of the clock (specifically minute:hour = 12:1, since the minute hand must make 12 revolutions for each single revolution of the hour hand). Then, the frequency of the applied signal simply needs to be adjusted so that the hands rotate at proper rates to correctly tell time. (For a typical step size of about 10 nm, a driving frequency in the neighborhood of 50 Hz will be required to tell time accurately.)

One might wonder whether the minute hand will require a larger force from its SDA in order to compensate for its extra mass. However, SDAs offer the luxury of not having to worry about this issue; considering the typical force produced by an SDA lies in the range of tens of µN, while the weight of a clock hand (including SDA) lies in the range of nN, the weight of the clock hand is clearly negligible and won't play a role in determining the motion of the device. However, the 12:1 ratio will have to be adjusted slightly—depending on exact geometry of the structure—to account for the fact that the radius of the circle around which the minute hand travels slightly exceeds that of the hour hand.

Test Structures

Finding the proper SDA dimensions will then depend heavily on a thorough search of test structures. The bushing heights of the SDAs driving the minute and hour hands are fixed at 2.0 and 1.5 µm, since these values are process parameters. Akiyama and Shono found that for bushing height 2.0 µm, the plate length should fall between 44 and 100 µm in order to achieve step motion at all. Therefore, test structures covering a slightly larger range in plate lengths than this will be fabricated to determine the step sizes of our two varieties of SDA for various plate widths and applied voltages.

First, standard SDA test structures will be fabricated using a design similar to that used by Akiyama, Collard, and Fujita [3]. Each structure consists of a single SDA supported by two 150 µm beams connected to contacts where a voltage may be applied between the SDA and the substrate (accessed elsewhere at a cut through the nitride insulating layer). Two arrays (one for Poly1 SDAs with H_B = 1.5 µm and the other for Poly2 SDAs with H_B = 2.0 µm) have structures ranging from 45 to 120 µm in length along one axis and ranging from 50 to 70 microns in width along the other axis. These structures will be used to develop an empirical understanding of the relationship between geometrical quantities and SDA step size.

However, the motion of the SDAs in this application is not linear but rather circular (as long as the circle is large enough, of course, then the motion is approximately linear, but this effect is still important to look into). Therefore, an additional array of analog clock structures will be fabricated, with similar ranges for plate length and width. In fact, these test structures will have the exact layout of the eventual clock structure, except that we will power the clock directly through the Poly3 pin holding the two clock hands in place rather than try to wire the structures to power externally, as would be done in the final product. These structures will not only yield additional diagnostic information about the SDAs, but will also serve to give an idea of the yield of production of the device, and possibly lead to beneficial design adjustments.

These test structures will be useful whether the analog clock design is successful or not, since we will in the worst case at least be able to derive some experimental relation between the variables under consideration, namely how L_P' depends on L_P, H_B, V, and SDA plate thickness.

Expected Results

Akiyama and Shono published results relating step size Δx to plate length and showed that the step size reaches a maximum at a single value for plate length given a fixed applied voltage and plate width [2]. Obviously, then, we expect to reproduce these results to some degree.

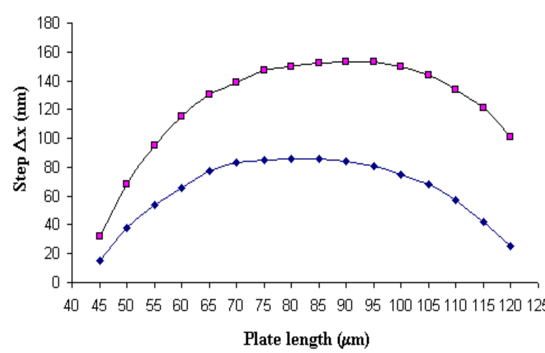

Fig. 6. Step size of the SDA versus plate length for a given applied voltage and plate width. The upper curve is for SDA with H_B = 2.0 µm; the lower curve corresponds to H_B = 1.5 µm.

In addition, a general relationship between the plate thickness and step size will be derived (it is expected that the step size will decrease with increasing plate thickness since L_P' should decrease for fixed L_P and H_B since the plate will be more difficult to bend with a given applied voltage.

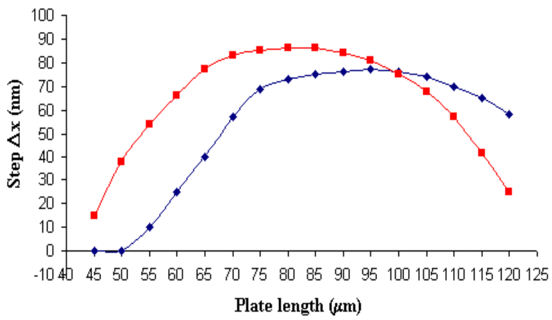

Fig. 7. Step size of the SDA versus plate length. The upper curve is for SDA with plate thickness 2.0 μm; the lower curve corresponds to plate thickness 1.5 μm.

Discussion

Using the empirical results of the test structures, the design of the analog clock can be completed simply by choosing two SDAs whose step size differs by a factor of 12. However, it is doubtful that the results of the test structures will be rigorous enough to allow for decisive certainty in finding such a pair of SDAs. In addition, there will certainly be some uncertainty in the processing such that the factor of 12 will never be precisely realized. We can moderate this problem by simply making the size of the structure large enough that process variation is negligible—unfortunately, this effect can only be studied through extensive fabrication.

One alternative to the concept of matching SDA step sizes in ratio as proposed here is to use a single driving mechanism and a gearing structure to set the precise ratio of rotation of the clock hands using the basic geometry of number of gear teeth. This is certainly possible if one has sufficient structural layers. However, it cannot be realized using the SUMMiT process, for example, because the gearing mechanism must lie on a different plane than the clock hands to allow the hands to completely rotate. (Teeth from neighboring gears must be in contact continuously, not allowing for a mechanical gap in the gear where a clock hand could protrude from either gear.) Of course, then additional structural layers are required.

Another interesting aspect for future consideration might be the effect of erosion of the SDA and insulating layer on step size. That is, it may be the case that the performance of the SDA deteriorates over time, and that the driving frequency must be continually adjusted to maintain correct calibration. Therefore, if we determine following fabrication that we cannot reliably generate ratio-matched pairs of SDAs and decide to switch to a single driving device, then we might consider using an alternative driving mechanism altogether—in particular, we might consider a standard resonant gap-closing or comb-drive actuator that won't degrade over time.

References

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