Microelectromechanical (MEMS) Optical Beam Control

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ABSTRACT

This experiment explores the manufacturability of controllable Micro-electromechanical (MEMS) mirrors to direct optical signals. Design includes four separate mirrors which independently control vertical displacement, horizontal displacement, vertical pitch and horizontal pitch. Such devices could be used for a variety of applications but were specifically intended for future use in communications between optical based circuits residing on separate chips. Prototype devices were built in PolyMUMPs to test the feasibility of this process for applications such as this, including a full outgoing beam path with mirror orientations and actuation designs to accomplish this. Several elements of this outgoing beam path were successful and those which needed improvement indicate a high probability of success with limited trials needed. Improvement recommendations on currently successful design elements which could still be improved within the scope of PolyMUMPs have been identified. Originally intended only to direct the outgoing beam, this design could be used on the incoming path as well. Such a design would ensure that the receiving device only requires a target location and not that a specific incoming vector be obtained. This would thus comprise all the elements needed for a prototype proof of concept device to be built. More sophisticated fabrication processes could provide drastic improvements to both transmission and reception beam paths and potentially allow for a variety of more sophisticated designs to improve compactness, controllability, tighten tolerances on moving parts, increase mirror quality, and improved productivity of large quantities of devices.

Keywords: MEMS, micro-mirrors, beam steering, VCSEL, Photodetector

1. INTRODUCTION

As advancements in microelectronics continue, the common challenges which continually present themselves require newer and more ingenious methods. To this end, the advantages of photonics-based alternatives become more and more appealing. When one considers the general advantages of photonic systems versus their electronic counterparts (in areas such as noise reduction, increased data transmission speeds, security, reliability, reduction in heat, computational speed increases, etc.), the importance of developing all areas of this technology become apparent. One such potential obstacle lies in the ability to direct optical signals from one device to another reliably, such that individual photonic components may one day be assembled as easily as their electronic counterparts are today, but without any limitations on their capabilities caused by poor interconnection.

The Defense Advanced Research Projects Agency (DARPA) sponsors several programs which address a variety of technological challenges.\textsuperscript{1} Among these programs is one called Chip to Chip Optical Interconnects (C2OI).\textsuperscript{1} The overall objective of this program is to ‘remove the chip boundary as a significant obstacle to data transport and demonstrate between-chip interconnects that have comparable performance to on-chip non-local electrical interconnects’.\textsuperscript{1} The limitations specifically cited with current electrical base technology include:\textsuperscript{1} achieving high packing density, reduction of cross-talk between channels, minimization of frequency-dependent losses, and lower power dissipation.

While current technologies are beginning to utilize optical communications, most of the state of the art components are designed for computer networking applications and do not specifically address the above issues.\textsuperscript{1}
2. MIRROR AND CONTROL DESIGN

With the exception of a few specific areas such as micro-mirror arrays, optical applications utilizing MEMS which are directly applicable to this kind of an experiment are still relatively rare. In research however, a great deal of work has been performed in not only MEMS structures but also many of the required components needed to realize an effective design. Basic methods to interface a single Vertical Cavity Surface Emitting Lasers (VCSELs) with the macroscopic world have been explored. These include the addition of a movable lens which alters the emission angle and coupling a VCSEL with a 45° mirror which guides it into a carefully positioned fiber. The first of these experiments is limited in a number of ways, including the fact that the change in angle is extremely small and introducing a lens drastically effects beam dispersion. The second approach requires the optical interfaces be made during assembly of the MEMS device (and can not change post-production), requires such a connection be made at both devices connected during production (limiting adaptability later in the assembly process) and only allows the VCSEL to be sent to one specific destination once assembly is complete. Other work has been done to design MEMS mirrors actuated through electrothermal, electrostatic, and piezoelectric means, but in most cases the range of motion and/or controllability is again extremely limited. While each may be suitable for very specific applications, they lack the versatility needed for a project such as this. More sophisticated MEMS devices such as adjustable focal length beam paths, lenses, or beam splitters may one day be integrated with a project such as this, but because of the flexibility proposed here could be simply added to this work without significant redesign.

In designing the components which make up this experiment there are several considerations. The first of these is the realization that this design must fall within additional constraints of available capabilities, materials, and time. As both resources and time are limited, a proof of concept will be the primary goal of this experiment within the capabilities currently available. The initial designs will attempt to prove that PolyMUMPs can be used to build the basic structures capable of performing these two tasks (directing signals from outside the device to the substrate and directing signals from the substrate in a specific, controllable direction). It is expected however that due to the limitations of PolyMUMPs, additional postprocessing will be needed and will be discussed in more detail.

Second, this design was intended to address the possibility that no electrical components or signals may be needed. Specifically thermal actuation will be used as much as possible as these devices can, in theory be replaced with a photonics-actuated version of the same basic technology (through controlled surface coatings which effect reflectivity, simple focused beams, etc.). If the assumption is that such chips would operate entirely on photonics, then some elements would for now require an electronic equivalent as these technologies either do not yet exist or are too new to be considered at this time, but at some point in the future would hopefully transition well if enough flexibility is included in this design. Some examples of these areas include symmetric ratioing of beam power geometrically to determine beam alignment, transferring beam alignment data to outgoing signal, and beam control algorithms from incoming data. As current technology does not yet support performing these tasks optically, approaches which utilize conventional electronics will need to be used for any testing and characterization performed on these devices. Because of this interim measure, some design limitations (such as the minimum beam size producible, data transfer rates, physical control parameters of mirrors, etc.) may also need to be limited. As supporting technological advancements are made, this design can adapt to better suit the overall objective of using all optical devices.

The most basic design which can accomplish this kind of beam steering will need to perform three tasks. First, the beam emitted from below the MEMS structure (as that produced by a VCSEL) must be re-oriented to a horizontal beam as presumably the two devices which are attempting to communicate will be located alongside each other. Second, this horizontal beam will need to be directed along some azimuth and elevation to the second device. The third task is to join these two functions which presumable may require some centerline adjustment from the axis of the original signal to the optimal axis prior to beam steering. These three tasks can in theory be performed by an arrangement of four mirrors outlined in Figure 1.

These four mirrors when configured in specific layout can in theory be used to accomplish the desired beam steering. Figure 2 shows the first two mirrors with the conceptual beam path (from the VCSEL beneath mirror 1 to the resulting beam path downward from mirror 2) which then continues to the tilting mirrors shown in Figure 3, which takes this beam and tilts it horizontally using mirror 3 and vertically using mirror 4.
Figure 1. Four mirrors required for beam steering (a) vertical beam is redirected by 90° at an adjustable height above the substrate, (b) beam path is then adjusted horizontally, (c) horizontal tilt is adjusted through rotating mirror and (d) vertical tilt is adjusted through second tilt-able mirror.

Figure 2. Layout of mirror pairs showing images of unassembled, fabricated devices on the top, alongside CAD drawing of assembled devices on the bottom for both vertical (mirror 1) and horizontal (mirror 2) positioning.
A variation of this not yet designed or tested, but in certain applications may be worth advancement introduces the possibility of multiple beam paths depending on mirror positioning. As shown in Figure 4, mirror 1 could potentially be modified such that the same linear motion can direct the output beam along two independent paths but still perform height adjustments for either path. While not shown, this same principle could be applied to the second mirror (provided its direction of travel is not parallel to the incoming beam) and further direct these along two other paths. By correctly sizing and positioning the turning mirrors (mirrors 3 and 4 in Figure 3), it's conceivable that nearly a full hemisphere of coverage could be achieved for applications in which transitioning between the four 'zones' was not critical. For those applications where this hand-off is critical, it is likely that at least two VCSELs (each with their own system of mirrors), would need to be implemented such that the two paths can be synchronized prior to switching from one VCSEL to the other.
2.1 Fabrication

The single most important constraint on this project is that all initial testing will occur using the PolyMUMPs process. As shown in Figure 5, this process involves repeated masks, depositions and etchings which occur in such a way that predefined patterned layers of doped polysilicon and silicon dioxide are sandwiched together. The final deposition is patterned gold which allows for a good connection for electrical contacts, and the unreleased structure is then coated in a layer of protected photoresist and delivered to the user. Typically the user will remove the protective layer with acetone then expose the structure to hydrofluoric acid (HF) which removes all exposed silicon dioxide but leaves any exposed polysilicon, nitride, and gold intact thus ‘releasing’ the polysilicon structures designed through careful patterning.

![Figure 5. Cross section overview of the PolyMUMPs process showing sacrificial oxide (SacOx) locations and thicknesses, polysilicon (Poly) locations and thicknesses and dimple dimension.]

2.2 Backside Reflection

An important observation in this design is the fact that the reflective surface in all designs is actually the back side of the polysilicon structure and thus the mirroring material can not be simply deposited on the top of the finished design directly. If the wavelength being reflected is not absorbed by polysilicon, and the deposition process produces polysilicon of high enough quality then the MEMS structure itself can serve as the mirror. If however the situation requires another material be present to perform the reflection, then instead of entire mirrors being built in polysilicon, only the frame can be constructed using the PolyMUMPs process and postprocessing will accomplish the deposition of this other desired material.

2.3 Frame Structure

Applying this idea, there exists the possibility of building mirrors using PolyMUMPs with a backside reflecting surface. Figure 6 shows the method of depositing this mirror along with etching the through-hole for the VCSEL to transmit from beneath the substrate. The first part (a) shows the device as delivered from the foundry which still contains the protective photoresist layer which is deposited prior to shipping and will remain on for the first few steps. Next in part (b) the entire device is flipped over and using backside alignment, photoresist is patterned on the back which corresponds to the location of the hole to be etched with photoresist thick enough to protect the rest of the substrate. The third step, part (c) shows the device after the substrate, nitride and polysilicon layer 0 (if present) have been etched through using the first oxide layer as an etch stop layer. The fourth step, part (d) flips the entire device over again, removes all the old photoresist, then on the top a new layer of lift-off resist is patterned such that metal deposition can occur over areas within the frame of each mirror with sufficient overlap onto the polysilicon frame. Next in part (e), the mirror is deposited. While it is shown as a single layer of gold, if gold is not adequate to perform the reflection needed, another metal could possibly be used if it is encased in top and bottom layers of gold to allow it to survive the release process which uses hydrofluoric acid (HF). Part (f) details the structure after the lift off has been performed, leaving only the mirror structure. Following this step, part (g) details the application of a backing layer (such as SU-8 or some other material which is resistant to HF). Finally in part (h) the released structure is shown after being rotated up to an angle of 45°.
Figure 6. Postprocessing required to deposit a backside mirror on a polysilicon frame after initial foundry run, but prior to release a) starting structure b) flipped and patterned for through hole c) post etch through substrate d) all photoresist removed, flipped and re-patterned for mirror deposition e) post metal deposition f) post lift-off g) SU-8 backing layer patterned to support mirror surface and h) post release showing raised mirror structure and conceptual beam path.

2.4 Mirror Motion and Actuation

As was mentioned previously, thermal actuation was chosen as the method of choice as optical actuation may be possible directly. Conceptually, it is reasonable to assume that mirrors such as this would likely function better if an actuation method was devised which did not require constant power to maintain a set, adjusted position but instead, only required energy for corrections when needed. Additionally, actuation schemes which accomplish this have been used and characterized to some extent with promising results as shown in Figure 7. While speed response will likely be very much dependant on the load being driven, drives such as this carrying similar loads have been observed to cycle in the range of up to several kHz, thus millisecond response times or better are expected.

The details of the driving mechanism illustrated outline how both rotary and linear motion can be achieved. Banks of thermal actuators are used for all actuation in this design. A single thermal actuator operates by passing current through two parallel lengths of polysilicon, which are connected electrically in series. One of the two lengths has a greater cross-sectional area than the other and thus, these sections will have different resistances. As thermal expansion will occur in both sections, the amount of expansion will be different in the two sections and the result is a bending motion. Releasing the current allows the actuators to sink the heat accumulated to the substrate and return to their unbent position. In part (a), cycling the Push and Engage actuator banks using square wave pulse trains $90^\circ$ out of phase results in a rotational motion of the pawl which then turns the rotating mirror. By changing the relative phase of the two pulse trains, the opposite rotation can be achieved. As one direction uses actuating force to accomplish motion while the other relies on restoring force, the motion which puts the restoring force to work results in faster response times (thus the possibility of paired and opposing banks of drives might be worth pursuing if a more symmetric response is required).

To accomplish linear motion as shown in part (b), the same driving mechanism is used but drives a set of gears which in turn drive a rack which moves linearly. This linear driving mechanism is used in mirrors 1, 2 and 4 as shown in Figure 2.

3. ASSEMBLED DEVICES

From this design work, a set of four mirrors was fabricated using the PolyMUMPs process as shown in Figure 8 and the first steps of evaluating these designs were taken. Fifteen devices were returned and from these devices,
an attempt was made at characterizing three areas of the design: actuation, backside mirror deposition and assembly.

Actuation of the devices was possible, but due to a combination of two related issues the results indicate that improvements need to be made to the design. Prior designs (from similar applications) used much larger banks of push actuators but due to layout constraints this number was reduced from 5 pair to 2. This resulted in a smaller push force in addition to a very long, thin and overly flexible push arm which did not produce sufficient force to move any of the mechanisms repeatably.

A number of attempts at producing backside reflecting mirrors was also attempted. While it is possible that
for some frequencies a solid sheet of polysilicon may be sufficient, in order to address those applications which required the ability to address other bands, this area was looked at in more detail. Given the time provided and the limited number of devices with which to work, limited but valuable observations were made in this area.

First of all, for mirrors of this size a single layer of gold does not have sufficient strength to survive the sacrificial release without additional structural support. While a mesh of polysilicon would correct this issue, backing the mirror with another material is a possibility which was also explored using a polymer which can survive solvent rinsing called SU-8. While a 2500 Angstrom layer of gold coated with 2 microns of SU-8 showed excellent adhesion between the metal and polymer throughout the release process, the backing material and gold layers did not adhere well to the polysilicon frame primarily because of insufficient overlap of the SU-8 and polysilicon and lack of an adhesion promoter. Both aluminum and chrome seed layers were attempted between the gold and polysilicon but even extremely thin layers were immediately dissolved during release.

With the few remaining devices, assembly of the mirror frames was performed with the results of one of the mirrors (in this case mirror 4) shown in Figure 9. In general, the smaller mirrors were extremely difficult to assemble without breaking due to large stresses in the catch arms but the larger mirrors with longer, more flexible arms were much more successful.

4. CONCLUSIONS AND RECOMMENDATIONS

As was mentioned previously more sophisticated MEMS processes could be implemented to improve several aspects of this design effort. The results of this initial fabrication attempt however proved successful enough to indicate that PolyMUMPs does show potential for use in an initial proof of concept design.

While the polysilicon which is used in the PolyMUMPs process may or may not be sufficient for reflection (depending on what kind of VCSEL is integrated with the design and the quality of the beam desired), backside mirror deposition is also still a possibility with some minor variations to the initial design. With the addition of an adhesion promoter along with larger surface overlap, an SU-8 backing should support the deposited gold layer well and as it is formed in a low temperature environment, additional stresses would lead to mirror curvature should be at a minimum. Should this become an issue however, various methods of gold deposition might be explored (sputtering vs. evaporative, rapid thermal annealing to reflow the deposited metal, etc.).
While the overall mirror geometry does require some amount of precision, the very nature of the adjustable mirrors allow for fabrication error to simply limit the overall range of motion and not prevent the design from functioning. The actuation method has proven successful in previous designs and once the areas of concern are corrected should be able to move the relatively lighter loads.

The extreme stresses present in the catch arms of the current design are definitely an issue with the current design. Which this excessive bending resulted in difficulties in assembly, the fact that assembly was still achievable indicates this is not an overwhelming obstacle. The most direct approach would be to develop hinges on these arms which would still allow for the required motion needed for assembly but eliminate any stresses in the final assembled structure.

While there are other areas which need to be addressed (such as auto vs. manual assembly, mirror curvatures, response times of final structures, etc.) this initial attempt appears to warrant some merit as a possible solution. Should the next steps using this process (PolyMUMPs) prove successful, this would certainly provide the justification for future work. If the design is then modified for more sophisticated processes, more complex designs may be warranted. Eventually, a custom process could then be developed for a device designed to be mass produced and one day bridge this gap between all optical devices and bring us one step closer to this next generation of photonic devices.

REFERENCES
