Innovative Magnetic, Biochemical, and Optical MEMS Devices for Intelligent Microsystems

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Abstract

In this paper, recent research activities at the Microsystems and BioMEMS Lab at the University of Cincinnati are presented. Magnetic, biochemical, and optical MEMS devices and microsystems have been demonstrated and explored focusing on UV-LIGA techniques, bi-directional magnetic micromirrors, magnetic bead-based microfluidic systems for biochemical detection, and capillary electrophoresis microchips for enzyme assays. The relevant issues to the design, fabrication, and characterization of the magnetic, biological and optical MEMS devices and microsystems have also been discussed for the realization of intelligent microsystems.

1. Introduction

Microelectromechanical systems (MEMS) have been a hot research topic since the middle of 1980s and numerous MEMS devices have been introduced and demonstrated in various applications. Although individual MEMS devices still have a great importance for sensor or actuator applications, much emphasis is currently being given on the microsystems which involve smart system concepts with several MEMS devices and system such as electrostatic, micromagnetic, microfluidic, optical, biochemical, biophotonic, and biomagnetic MEMS systems. In addition, recent demands on "lab-on-a-chip" and "micro total analysis system (μ-TAS)" require an intelligent microsystem instead of "microdevices".

To meet these growing demands, innovative magnetic, biochemical, and optical MEMS devices and systems have been developed at the Microsystems and BioMEMS Lab at the University of Cincinnati, pursuing numerous research projects funded from federal government and industry [1]. One of the examples is shown in Figure 1, which is a microfluidic system for portable biochemical detection system [2-3].

In this paper, MEMS devices and systems including novel magnetic devices using UV-LIGA techniques, optical devices/coupler, and microfluidic-based biochemical detection systems are much focused discussing relevant issues and recent achievements.

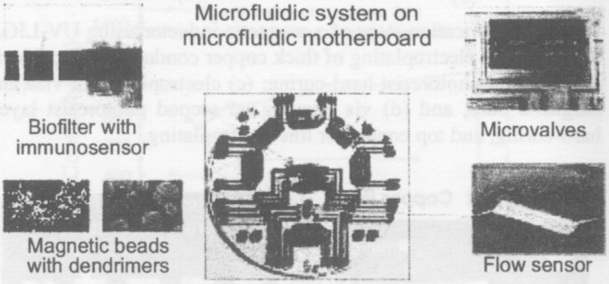


Figure 1. An example of the intelligent microsystems: "a microfluidic motherboard" with all microfluidic components for a biochemical detection system [2-3].

2. Magnetic MEMS Devices and Applications

Magnetic devices for use in the area of microelectromechanical systems (MEMS) are recently becoming a topic of great interest and growth. Recent work in this area includes the use of magnetic components and circuits as actuators, electronic components, and sensors. There are many advantages to the use of magnetic MEMS devices such as their ability to operate in harsh environments with CMOS compatible low driving voltages. For these advantages, large efforts have been given to development of magnetic MEMS devices at the University of Cincinnati including on-chip DC/DC power converters [4], microtransformers [5] magnetic fluxgate sensors [6], eddy current sensors [7], magnetically driven microvalves [8], universal magnetic actuators [9], and bi-directional magnetic mirrors [10-11] based on multi-layer UV-LIGA techniques [12]. Recently developed UV-LIGA techniques and its applications and bi-directional magnetic mirrors will be presented in the following sections.

2.1. UV-LIGA Techniques for Magnetic MEMS Devices

In order to generate a magnetic flux for actuators and to detect changes of a magnetic flux for sensors, UV-LIGA techniques have been adopted to realize inductive components. AZ-4000 series thick photoresist was used as both electroplating molds and insulators. Copper and Permalloy (Ni/Fe) were electroplated for conductive coils and magnetic cores, respectively. Simple fabrication steps are shown in Figure 2. Figure 3 shows realized magnetic MEMS devices for various applications using the developed UV-LIGA techniques.

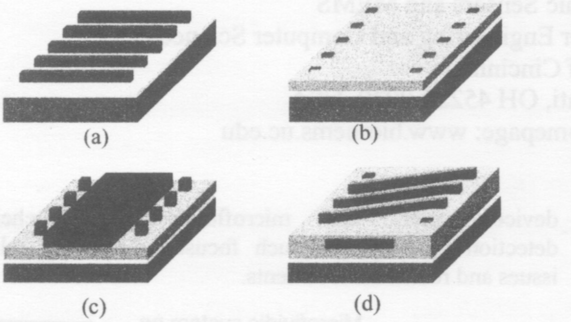


Figure 2. Fabrication steps of a magnetic inductor using UV-LIGA technique:(a) electroplating of thick copper conductor lines; (b) via opening and photoresist hard-curing; (c) electroplating of vias and magnetic core; and (d) via opening on second photoresist layer, hard-curing, and top conductor line electroplating.

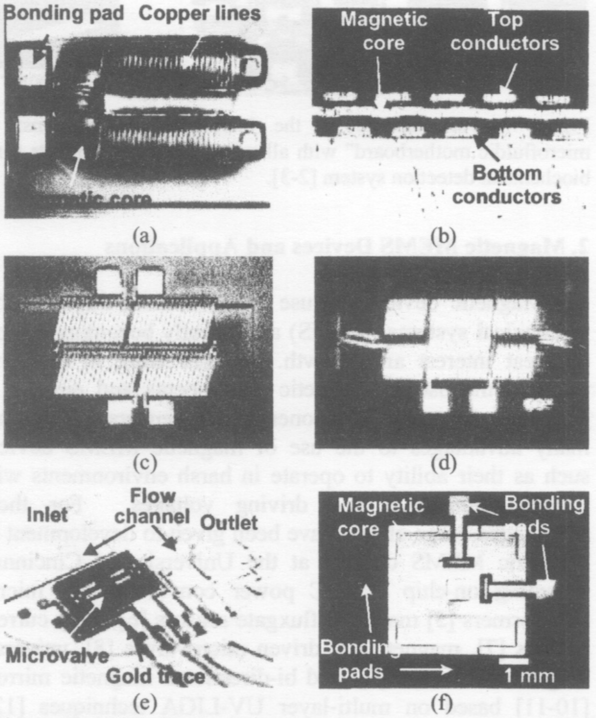
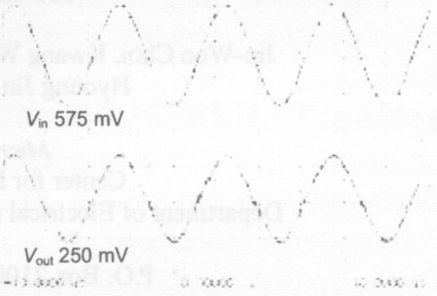
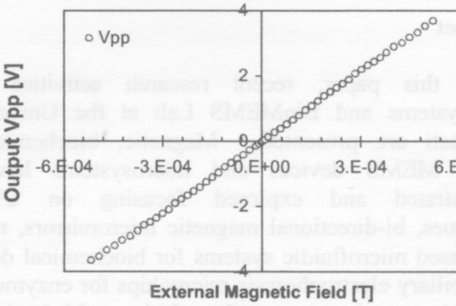


Figure 3. UV-LIGA techniques and various magnetic MEMS devices: (a) top-view of horseshoe-shaped inductor consisting of copper lines wrapped around a Ni/Fe magnetic core; (b) cross-sectional photograph of the device shown in (a); (c) magnetic transformer; (d) fluxgate sensor; (e) magnetically driven microvalve; and (f) eddy current sensor.

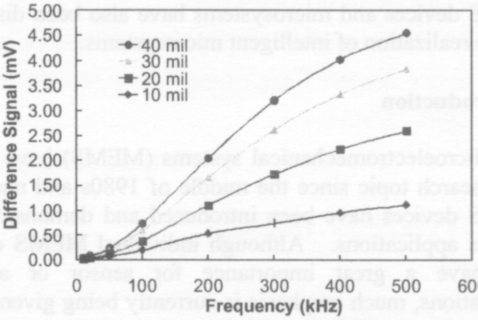
Representative experimental results are shown in Figure 4 for the microtransformer, the fluxgate sensor, and the magnetic microvalve.



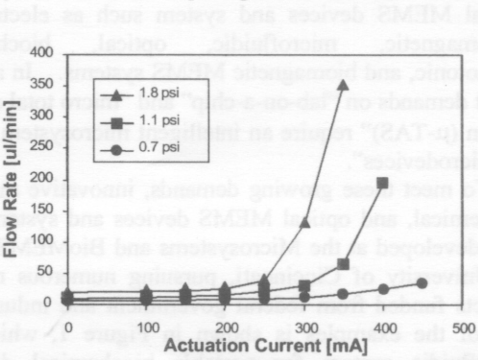
(a) Micro transformer: input voltage vs. output voltage



(b) Fluxgate sensor: output voltage vs. external magnetic field



(c) Eddy current sensor: output signals for different cracks on metal



(d) Microvalve: flow rate vs. driving current

Figure 4. Representative results of the magnetic MEMS devices: (a) the micro transformer [5]; (b) the fluxgate sensor [6]; (c) the eddy current sensor [7], (d) the microvalve [8].

The UV-LIGA techniques allow for the formation of thick conductor lines, thus resulting in a low resistance device at low cost compare to actual LIGA processing.

2.2. Optical Application of Magnetic MEMS Devices: Bi-directionally Movable Magnetic Micromirror

There has been growing interest in the fabrication of magnetic micromirrors and optical switching devices which make it possible to actuate the mirrors with millimeter size by low driving voltage. There have been technical difficulties in realizing bi-directional motion in magnetic MOEMS devices due to the lack of a suitable on-chip permanent magnet component. Recently, we have realized thick permanent magnet (CoNiMnP) alloy films and arrays [12-13] using UV-LIGA techniques. Based on this new fabrication technique, hard magnetic films or arrays are directly electroplated on silicon cantilever beams in order to compose moving mirror parts. A micromirror is constructed by combining the beam with an electromagnet. According to the change of current in electromagnets, the micromirrors are deflected either upward (repulsion mode) or downward (attraction mode) depending on the direction of magnetic field generated by the electromagnets.

A scanning silicon mirror was designed to have a size of 5 mm × 5 mm. The schematic diagram of the mirror shape is shown in Figure 5.

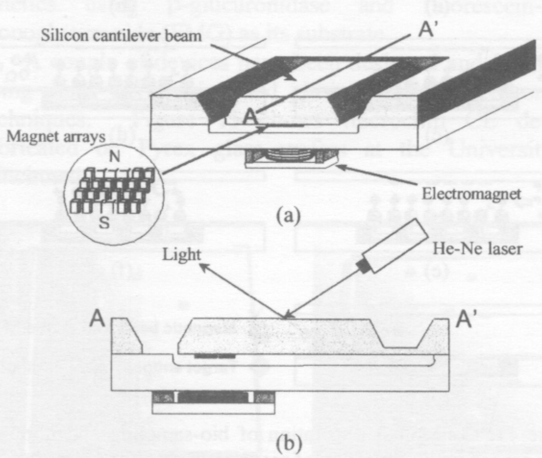


Figure 5. Scanning micromirrors using bi-directionally movable magnetic microactuators: (a) schematic view and (b) cut view.

The micromirror consists of a movable silicon cantilever beam, a glass spacer and an electromagnet. Underneath the cantilever beam, permanent magnet arrays are placed along the axis of the electromagnet. Vertical magnetic polarity of the magnet arrays enables bi-directional motion of the mirror when current is applied. The array design was adopted to suppress the residual stress between the hard magnetic CoNiMnP alloy and the silicon substrate, where the size of an array is 60 µm × 60 µm × 40 µm. To prevent the deformation in beam structure, only the thick portion of silicon beam structure was used for electroplating. The permanent magnet patterns were fabricated at a free end of the silicon cantilever beam within an area of 1.5 mm × 1.5 mm. A specially designed electroplating system was used for electroplating permanent magnet arrays. Fabricated permanent magnet arrays are shown in Figure 6 and the measured magnetic characteristics are shown in Figure 7.

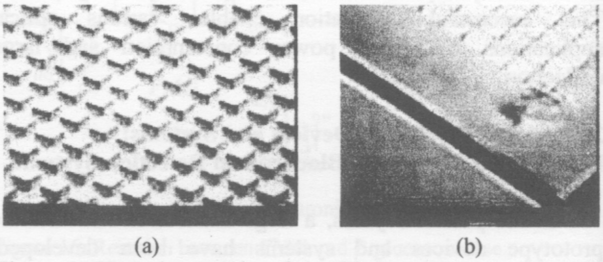

(a) (b)

Figure 6. SEM photographs of the fabricated permanent magnet arrays: (a) CoNiMnP alloy-based permanent magnet arrays fabricated by the UV-LIGA technique and (b) on-chip integration of permanent magnet arrays at the tip of a silicon cantilever beam.

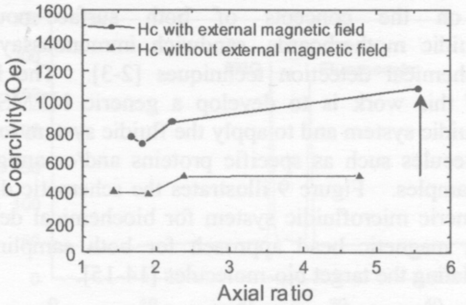


Figure 7. Magnetic characteristics of electroplated magnet arrays.

Optical properties of the scanning mirrors are measured by a He-Ne laser beam source with the wavelength of 632.8 nm and an optical power detector. A prototype scanning micromirror shows ±60 µm deflections at the current of ±100 mA. The Gaussian profile of the laser beam is well preserved. The reflectance is above 98% for the mirrors coated with aluminum films. Figure 8 shows the variation of deflection in fabricated micromirrors, where mirror plane size is 5 mm × 5 mm and thickness is 6 µm at the anchored point.

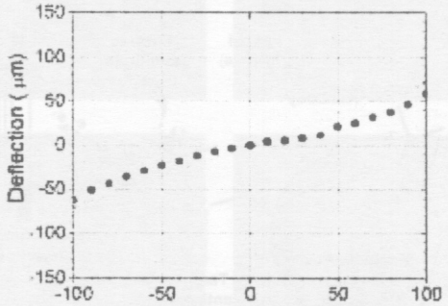


Figure 8. Experimental results of bi-directional deflection as a function of current in electromagnet (● experiment; – FEM).

Newly developed electroplating technique improved magnetic properties of permanent magnet arrays enough for actuator applications in MOEMS devices. Unique bi-directional actuation of magnetic microactuators with electroplated permanent magnets allows scanning micromirrors to have a bi-directional scanning capability, which is very important for several optical scanning systems. This successful integration enables various optical applications with low power consumption and large deflection.

3. Magnetic BioMEMS Devices and Systems: Integrated Microfluidic Biochemical Detection Systems

In the past few years, a large number of microfluidic prototype devices and systems have been developed, specifically for biochemical warfare detection systems and portable diagnostic applications. The BioMEMS team at the University of Cincinnati has been working on the development of a remotely accessible generic microfluidic system for biochemical detection and biomedical analysis, based on the concepts of both surface-mountable microfluidic motherboards, sandwich immunoassays, and electrochemical detection techniques [2-3]. The limited goal of this work is to develop a generic MEMS-based microfluidic system and to apply the fluidic system to detect bio-molecules such as specific proteins and/or antigens in liquid samples. Figure 9 illustrates the schematic diagram of a generic microfluidic system for biochemical detection using a magnetic bead approach for both sampling and manipulating the target bio-molecules [14-15].

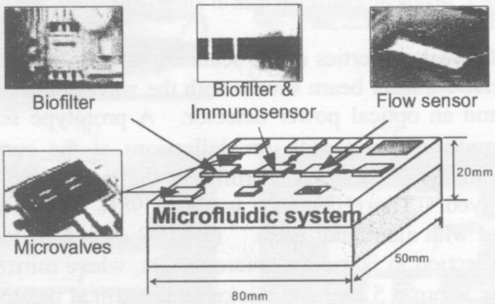


Figure 9. Schematic diagram of a generic microfluidic system for biochemical detection.

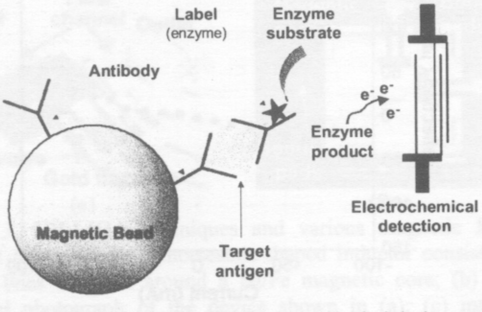


Figure 10. Analytical concept based on sandwich immunoassay and electrochemical detection.

The analytical concept is based on sandwich immunoassay and electrochemical detection [16] as illustrated in Figure 10.

Magnetic beads are used as both substrate of antibodies and carriers of target antigens. A simple concept of magnetic bead-based bio-sampling with electromagnet for the case of sandwich immunoassay is shown in Figure 11. Antibody coated beads are introduced on the electromagnet and separated by applying magnetic fields. While holding the antibody-coated beads, antigens are injected into the channel. Only target antigens are immobilized and thus, separated onto the magnetic bead surface due to antibody/antigen reaction. Other antigens get washed out with the flow. Next, enzyme-labeled secondary antibodies are introduced and incubated, with the immobilized antigens. The chamber is, then, rinsed to remove all unbound secondary antibodies. Substrate solution, which will react with enzyme, is injected into the channel and the electrochemical detection is performed. Finally the magnetic beads are released to waste chamber and the bio-separator is ready for another immunoassay.

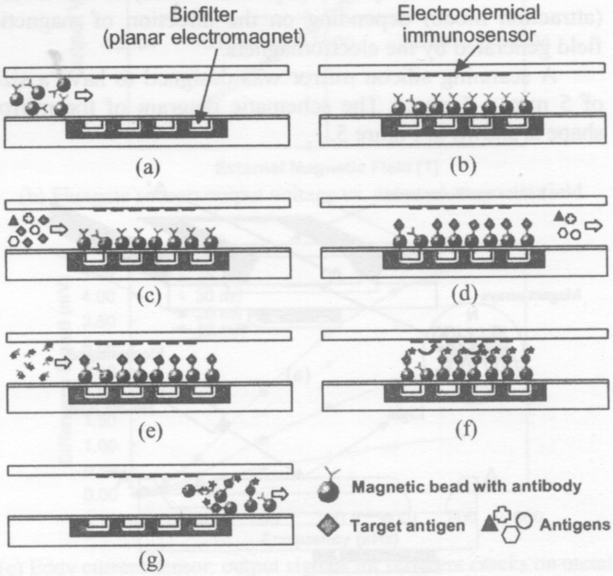


Figure 11. Conceptual illustration of bio-sampling and immuno-assay procedure: (a) injection of magnetic beads; (b) separation and holding of beads; (c) flowing samples; (d) immobilization of target antigen; (e) flowing labeled antibody; (f) electrochemical detection; and (g) washing out magnetic beads and ready for another immunoassay.

Alkaline phosphatase (AP) and p-aminophenyl phosphate (PAPP) was chosen as enzyme and electrochemical substrate. Alkaline phosphatase makes PAPP turn into its electrochemical product, p-aminophenol (PAP). By applying potential, PAP gives electrons and turns into 4-quinoneimine (4QI), which is oxidant form of PAP. Figure 12 illustrates the electrochemical detection principle.

developed in this work, can be also applied to generic biomolecule detection and analysis systems by replacing antibody/antigen with appropriate bio receptors/reagents such as DNA fragments or oligonucleotides for the application to DNA analysis and/or high throughput protein analysis.

4. Capillary Electrophoresis (CE) Microchip for Enzyme Assays

In recent years, there has been a growing interest in microchip capillary electrophoresis (CE), which has the potential to simultaneously assay hundreds of samples in a matter of minutes or less. Recent applications of microchip CE devices for immunoassays, protein analyses, and DNA sequencing have employed a variety of signal detection techniques including UV-visible wavelength absorbance and laser-induced fluorescence (LIF). The main advantages of using microchip CE instead of conventional fused silica capillaries are reduction in fluid handling steps, electrokinetic switching, lower cost per unit from batch fabrication, compact size and durability, faster analysis times, and the possibility of multiple channel networks on a chip.

The objective presented in this section is to develop a CE microchip in glass substrate [18], to demonstrate the separation using fluorescent dyes, and to carry out enzyme kinetics using β-glucuronidase and fluorescein-β-D-monoglucuronide (FMG) as its substrate.

A couple of devices have been designed and fabricated using glass wet etching and glass-to-glass direct bonding techniques. Figure 15 shows microchip CE devices fabricated on Pyrex glass wafers at the University of Cincinnati.

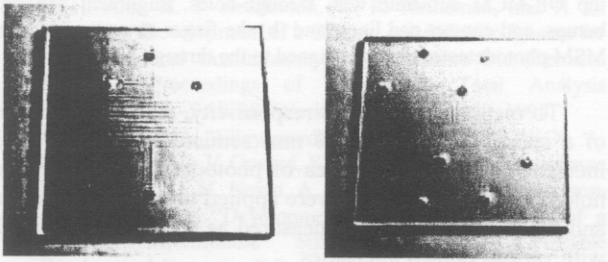

(a)
(b)

Figure 15. Photograph of the fabricated microchip CE devices: (a) long serpentine channel device and (b) double-T channel device and short serpentine channel device.

After sample injection test, enzyme assays have been tested on the developed microchip CE. A stable and simple enzyme substrate pair was sought with a fluorescence wavelength in the detection range of our experimental setup. β-glucuronidase was chosen as an enzyme. As a fluorescent substrate, fluorescein-β-D–monoglucuronide (FMG) was chosen. The β-glucuronidase enzyme hydrolyzes the FMG substrate to produce fluorescein and a sugar molecule. The substrate and product can be excited by 480 nm light and the emission can be detected by a PMT with a 520 nm band-pass filter attached in front of the PMT.

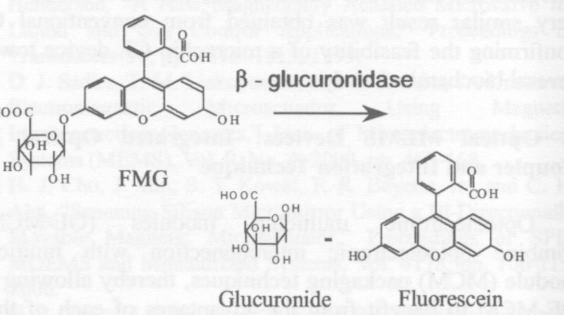


Figure 16. Reaction between FMG and β-glucuronidase.

Figure 16 shows the structures and reaction of the enzyme and substrate pair. Figure 17 also shows the electropherogram of this separation.

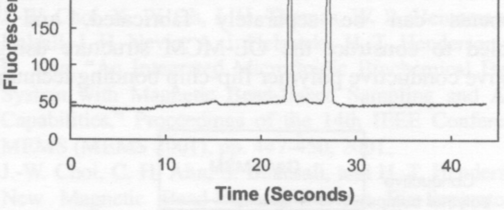


Figure 17. Reaction between FMG and β-glucuronidase.

The separation of fluorescein and FMG as seen through the CCD camera is shown in Figure 18. It can be observed that the sample injection plug, starting as one part, separates into two as it passes through the separation channel.

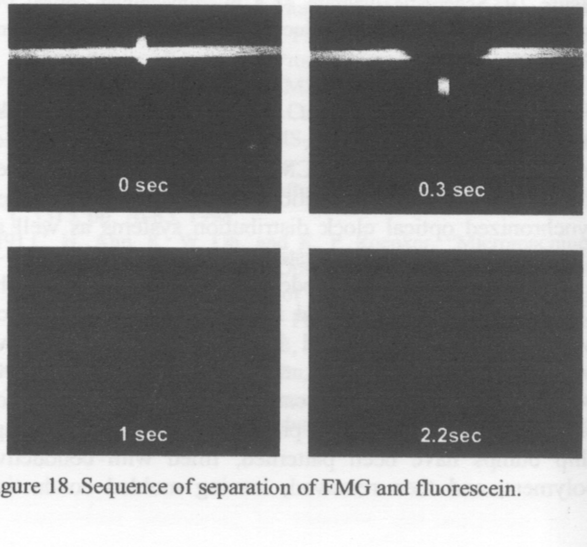


Figure 18. Sequence of separation of FMG and fluorescein.

Initial velocities were also measured at different substrate concentrations and the data analysed using a nonlinear best fit statistic software (SigmaPlot™) to calculate the K_m. The value for K_m was 21 ± 3.9 μM. A very similar result was obtained from conventional CE, confirming the feasibility of a microchip CE device toward several biochemical analyses.

5. Optical MEMS Devices: Integrated Optical I/O Coupler and Integration Technique

Optoelectronic multichip modules (OE-MCMs) combine optoelectronic interconnection with multichip module (MCM) packaging techniques, thereby allowing the OE-MCM to benefit from the advantages of each of these separate technologies. While traditional MCMs use metal transmission lines for chip-to-chip communication, optoelectronic interconnects can provide numerous benefits such as high speed, compact size, immunity to electromagnetic interference, and large bandwidth. Figure 19 shows the proposed OE-MCM structure with a GaAs metal-semiconductor-metal (MSM) photodetector [19]. The OE-MCM is a modular design consisting of three major components: a photodetector; an integrated electrical MCM and optical waveguide structure; and an optical I/O coupler using micromachined silicon mirrors. These three components can be separately fabricated, and then assembled to construct the OE-MCM structure using an innovative conductive polymer flip-chip bonding technique.

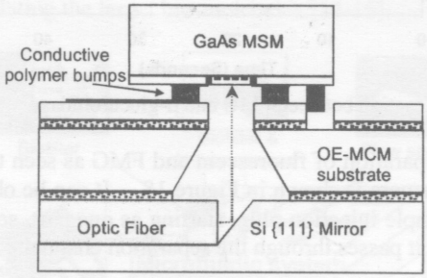
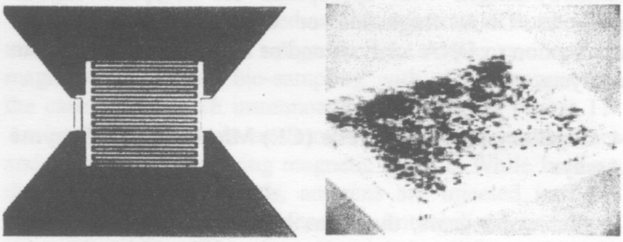


Figure 19. Schematic diagram of a micromachined optical I/O coupler by the use of a conductive polymer flip-chip bonding technique

By overcoming current communications bottlenecks associated with computer, communication, and other information systems, OE-MCMs promise to be widely used in a variety of applications including high speed synchronized optical clock distribution systems as well as distributed remote sensing systems.

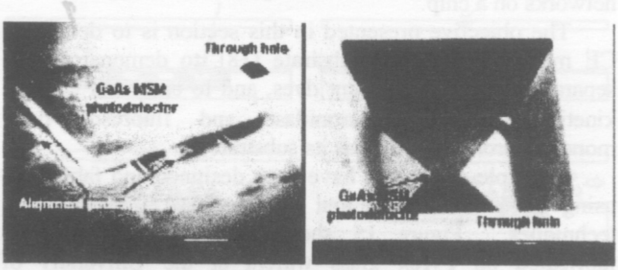
The GaAs MSM photodetector was fabricated at the University of Cincinnati and integrated on the top silicon wafer using the developed low temperature conductive polymer flip-chip bonding technique. The conductive polymer bumps was fabricated using UV-LIGA based photolithography with thick photoresist, molds for the flip-chip bumps have been patterned, filled with conductive polymers, and then removed, leaving molded conductive polymer bumps [20]. Figure 20 shows the fabricated GaAs MSM photodetector and the conductive polymer bumps.



(a) (b)

Figure 20. Microphotograph of (a) fabricated GaAs MSM photodiode and (b) conductive polymer bumps.

The fabricated photodetector was, then, precisely diced and aligned using the additional pedestal bumps on OE-MCM structure as shown in Figure 21. The passive-alignment between photodetectors and through holes is based on dicing accuracies of flip-chip photodetectors and precise formation of copper pedestal bumps. When completed, the photodetectors were aligned with the mirror within an accuracy of less than 5 μm.



(a) (b)

Figure 21. SEM photographs of: (a) the flip-chip packaging for the top OE-MCM substrate with through-holes, alignment pedestal bumps, and contact pad lines, and (b) the finger structure of GaAs MSM photodetector passive-aligned to the through hole.

To measure the optical responsivity, the optical output of a short wavelength (870 nm) semiconductor laser was incident onto a detector area of photodetector through the hole. The electrical biases were applied to the photodetector and the photocurrent was measured as shown in Figure 22 with various optical intensities.

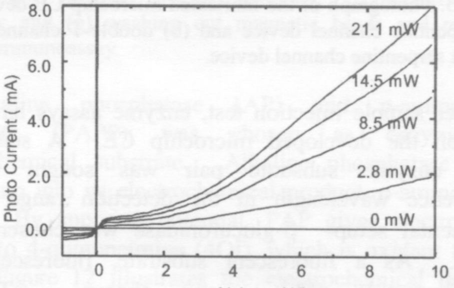


Figure 22. I-V optical characteristics for GaAs MSMs photodetectors flip-chip bonded over the through holes.

A prototype OE-MCM structure for optical I/O couplers realized using bulk-micromachining, conductive polymer flip-chip bonding, and passive pedestal alignment techniques. The conductive polymer flip-chip bonding technique developed in this work can be applicable to sensor and actuator systems, surface mounting microfluidic systems, optical MEMS, OE-MCMs, and electronic systems.

6. Conclusions

Several MEMS devices and microsystems realized at the Microsystems and BioMEMS Lab at the University of Cincinnati have been introduced and discussed in this paper. Using the UV-LIGA techniques developed at the University of Cincinnati, magnetic, biochemical, and optical MEMS devices have been successfully explored and realized for smart microsystem applications, which include bi-directional magnetic micromirrors, magnetic bead-based microfluidic systems for biochemical detection, capillary electrophoresis microchips for enzyme assays, and integrated optical I/O couplers. The relevant issues to the design, fabrication, and characterization of the realized devices and microsystems have also been discussed.

7. Acknowledgement

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