VOL. 11, NO. 2 · DECEMBER 2000

Special Issue: ***Optical MEMs***
Edited by ***Matthew Hart and Hugo Thienpont***

SPIE's International Technical Group Newsletter

Optics & Information Systems

(formerly Optical Processing and Computing)

Silicon micromachines for lightwave networks: the little machines that will make it big

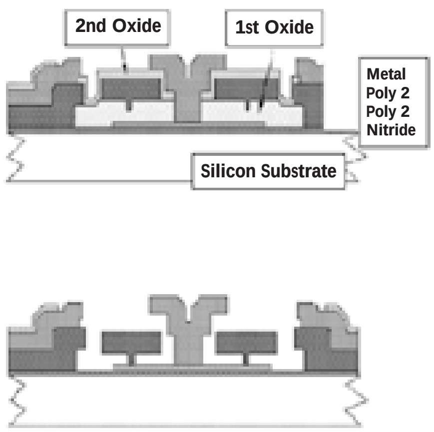

Figure 1. Schematic MEMS device.

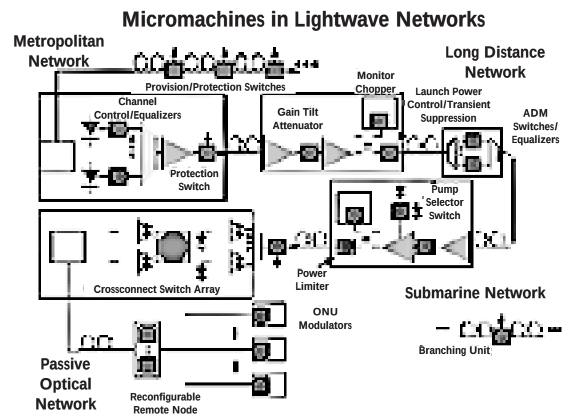

Figure 2. Schematic of lightwave network with MEMS applications shown as red dots.

Silicon micromechanics is an emerging field that is beginning to impact almost every area of science and technology. In areas as diverse as the chemical, automotive, aeronautical, cellular and optical-communications industries, silicon micromachines are becoming the solution of choice for many problems. Here we will describe what they are, how they are built and show how they have the potential to revolutionize lightwave systems. Devices such as optical switches, variable attenuators, active equalizers, add/drop multiplexers, optical crossconnects, gain-tilt equalizers, data transmitters and many others are beginning to find ubiquitous application in advanced lightwave systems. We will show examples of these devices and describe some of the challenges in attacking the billions of dollars in addressable markets for this technology.

What is a MEMS device?

MEMS research is an outgrowth of the vast capabilities developed by the semiconductor industry, including deposition, etching, and lithography, as well as an array of chemical processes such as anisotropic and highly selective etches having different etch rates for different crystallographic orientations and materials. These processes, which were originally developed to build microelectronics, are also capable of building micromechanical devices (structures capable of motion on a microscopic scale). MEMS are built in much the same way as a silicon integrated circuit (see Figure 1). Various films such as polysilicon, silicon nitride, silicon dioxide, and gold are deposited and patterned to produce complicated, multilayer three-dimensional structures. However, the major difference is a release step at the end. In a MEMS device, some of the layer materials are removed using a selective etch, leaving a device with elements that can move.

MEMS devices offer a number of advantages to designers. They are made using integrated circuit (IC) batch-processing techniques, so although fabrication may consist of a complicated, multistep process, the devices are economical to produce because many are made simultaneously. In addition, designers and manufacturers can exploit the extensive capabilities of the IC fabrication industry and can profitably use previous-generation equipment. In an era in which an IC factory costs a billion dollars and is obsolete in less than five years, the ability to reuse the equipment for a new class of cutting-edge products is very appealing.

IC fabrication techniques also allow designers to integrate micromechanical, analog, and digital microelectronic devices on the same chip, producing multi-functional integrated systems. Contrary to intuition, MEMS devices

(continued on p. 7)

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Steered agile laser transmitter

Exciting developments in sensor technology over the last couple of decades now allow co-integration of almost any type of known physical and chemical sensor using some combination of micromachining and integrated circuit (IC) technology. Combining these miniature sensors with appropriate mixed-signal electronics, as well as appropriate actuators, allows one to build a complete autonomous sensor platform smaller than a sugar cube. With wireless communication capabilities, data can be collected from hundreds or thousands of sensors simultaneously. Unfortunately, in millimeter scale, antennas at commonly used radio frequencies are very inefficient. The use of optical wavelengths for communication, however, enables the construction of efficient high-gain antennas, allowing small systems to emit narrow beams that can be aimed towards a potential receiver. With much of the transmitted power actually arriving at the receiver, long-range, low power, high bandwidth communication becomes practical.

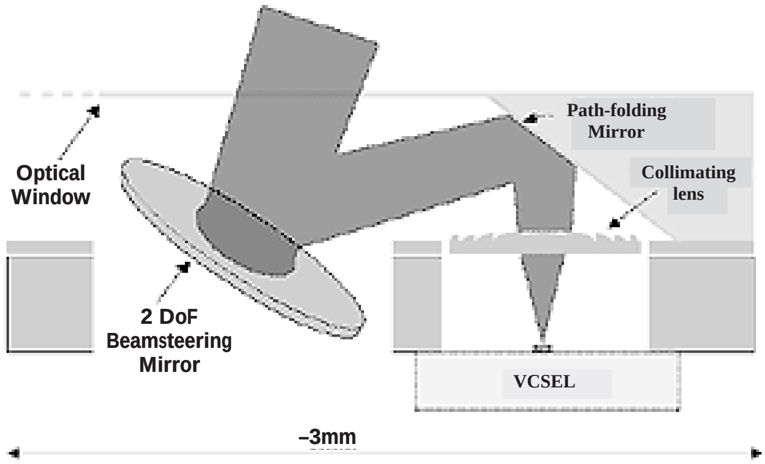

Figure 1. Proposed SALT schematic diagram. A vertical cavity surface-emitting laser (VCSEL) has a circular output beam, allowing better beamshaping using available spherical optics. A micromachined silicon Fresnel lens is used to collimate the beam. The path-folding mirror redirects the beam onto the beamsteering mirror, which aims at the intended target, scanning as much of the upper hemisphere as possible.

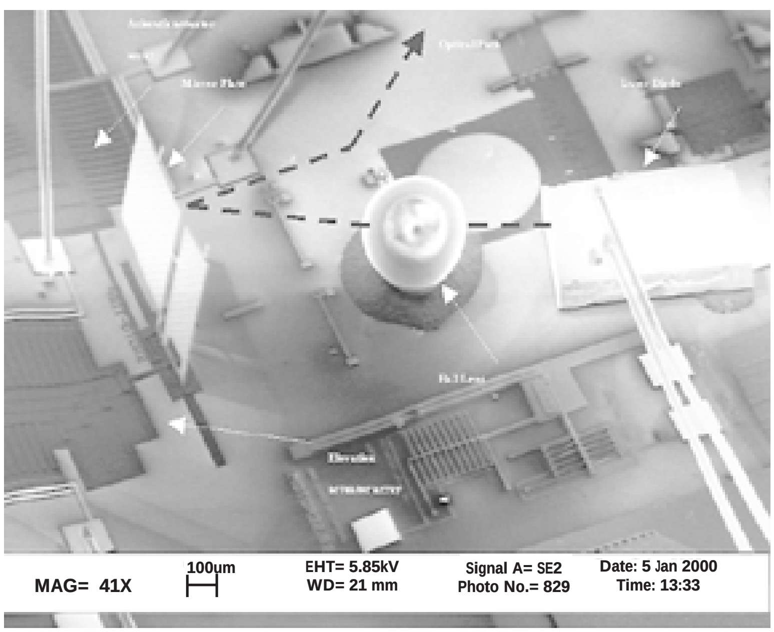

Figure 2. SEM micrograph of first generation SALT.

The steered agile laser transmitter (SALT) is a microelectromechanical system (MEMS) that functions as a steered laser beam transmitter for use in free-space communication. Measuring only a few millimeters on a side, this system utilizes the most recent developments in microfabrication and packaging technology to create a tightly-collimated and steered laser beam. SALT consists of a semiconductor diode laser coupled with a collimating lens and MEMS beam-steering optics based on a 2-degree-of-freedom (DoF) silicon micromirror, as shown schematically in Figure 1. The micromirror must possess many features that are difficult to achieve simultaneously: an atomically smooth and flat optical surface, very high speed, accurate position control over a large scanning range, and ultra-low operating power.

In the first attempts at SALT integration, we fabricated a 2DoF hinged-polysilicon micromirror through the Cronos Microsystems' Multi-User MEMS Process (MUMPS), and manually assembled a laser diode and collimating optics onto the substrate (Figure 2).[1] The mirror was actuated using two 4-bit mechanical digital-to-analog converters[2] (DACs) driven by arrays of thermal actuators. We demonstrated beam-steering over an optical range of 10˚ (azimuth) by 6˚ (elevation), with step response of 3.7 ms. A sapphire ball lens was used to collimate the output of the edge-emitting semiconductor laser.

This system had many shortcomings. The collimation of the laser beam was poor, and the mirror was relatively slow, limited in its range of motion, and excessively power hungry: we are aiming for sub-millisecond step response times over +/– 45˚ (optical) using microwatts of power. Additionally, due to the presence of residual stress gradients, our polysilicon mirror's radius of curvature was too small.

The proposed second-generation system is shown in Figure 1. It uses a novel micromachining and bonding technology that combines lateral high-aspect ratio MEMS linear actuators and position sensors with rotating mirrors suspended by torsion springs. The micromirror concept is seen in Figure 3. A high aspect-ratio gimbal is micromachined in a silicon-on-insulator (SOI) wafer, using torsion beams to allow 2DoF motion of the flat and ultra-smooth micromirror. A timed deep-reactive-ion etch (DRIE) forms the torsion beam. These are much lower in height than the overall structure and so lowering the axis of rotation of the gimbal. Another set of thin beams is bonded to the mirror several dozen microns above the torsion-beam axis of rotation. This lever-arm enables laterally-moving SOI actuators elsewhere on the same wafer to rotate the mirror. It is therefore possible to integrate any actuator and position sensing structure adjacent to the mirror.

In addition, it is straightforward to significantly reduce mass (and therefore increase resonant frequency), while not sacrificing structural rigidity and mirror flatness, by etching a waffle pattern into the silicon structure of the mirror, as also shown in Figure 3. A thin, single-crystal-silicon face sheet, bonded

(continued on p. 8)

Integrated 2D scanners with single-crystalline silicon micromirrors

Scanning micromirrors are critical components of the numerous and varied optical MEMS systems used for scanning, switching, and imaging applications. A key challenge in the design and fabrication of a scanning micromirror system is the requirement for simultaneous optimization of an optically smooth, flat surface and an electrically fast, low-voltage actuator with a large scan angle. Single-crystalline silicon, derived from bulk micromachining methods, is a suitable mirror material with characteristically smooth, flat surfaces. Surface micromachining provides more design flexibility for the actuators and is a readily available (e.g., Cronos' Multi-User MEMS Process or MUMPs), technique. However, micromirrors formed with the standard polysilicon structural layers may be degraded due to curvature from the released thin film's residual stresses.

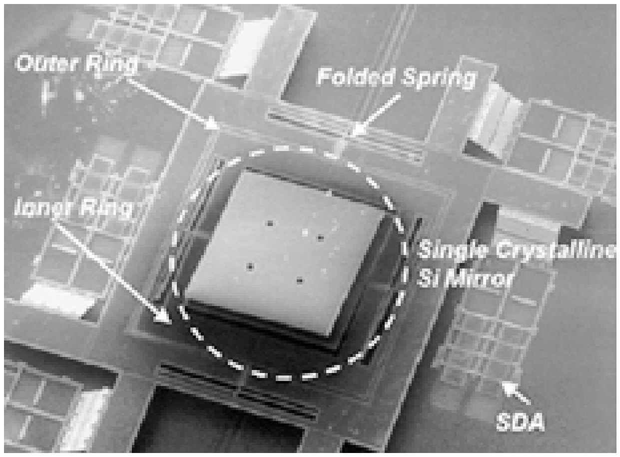

Figure 1. SEM micrograph of an assembled 2D scanner with a bonded single-crystalline silicon mirror.

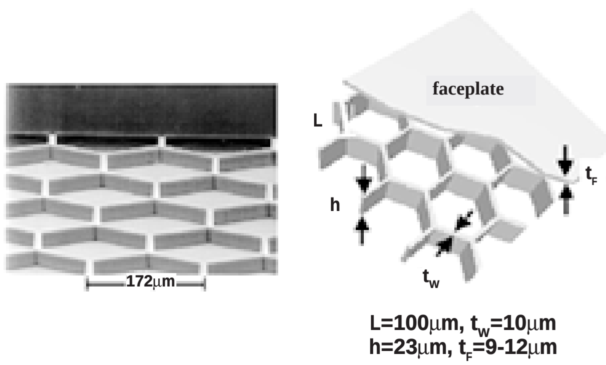

Figure 2. SEM micrograph and schematic showing dimensions of silicon micro-honeycomb structures.

Figure 3. 3D images from a Wyco RTS 500 surface profiler with radius of curvature for both polysilicon and bonded silicon 2D scanners.

We have developed an integrated design and fabrication process that combines the advantages of surface and bulk micromachining while effectively canceling the disadvantages of each technique. With our integrated process, the electrostatic actuator consists of a polysilicon 2D scanner raised above the substrate by a MESA (Micro Elevation by Self Assembly[1]) structure and is fabricated with the planar MUMPs process. The micromirror is fabricated independently using singlecrystalline silicon derived from the top layer of silicon on insulator (SOI) wafers. The component parts are subsequently bonded with a polymer layer and then heat cured; both photoresist and photosensitive benzocyclobutene (photo-BCB) have been utilized. After bonding the single-crystalline silicon plate to the actuator, the mirror is aligned, patterned, and etched to the size of the underlying polysilicon platform. The structure is then released in HF, and the MESA structure with bonded mirror is assembled with scratch drive actuators to a height of over 50µm above the substrate.

Bonded scanners with solid single-crystalline micromirrors, 450×450µm square and 23µm thick, have been made and tested.[2] An SEM micrograph of an integrated 2D scanner with a bonded single-crystalline silicon micromirror is shown in Figure 1. The added mass from a bonded single-crystalline mirror affects the scan speed of the device, since the resonant frequency of the device is inversely proportional to the square root of the effective mirror mass. To reduce the mass of scanning micromirrors, a polysilicon membrane structure with a single-crystalline silicon support ring has been reported.[3] In our work, to reduce mass, we have developed structures consisting of a honeycomb core and a solid faceplate as shown in Figure 2, again derived from the top layers of SOI wafers. Micro-honeycombs have been used previously as molds for MEMS structures[4,5] and, more recently, a polysilicon hexagonal torsional mirror with polysilicon cross support ribs has been reported.[6]

Our honeycomb pattern consists of single-crystalline silicon hexagonal cells with sides of 100µm and walls of 10µm: various thicknesses for the faceplate have been evaluated and we are currently focusing on ~10µm as this ensures a smooth optical surface. We have fabricated silicon honeycombs using two methods: one uses a single SOI wafer and timed deep reactive-ion-etching of the silicon such that a thin layer remains to form the faceplate. A second fabrication technique employs two SOI wafers and silicon fusion bonding. Bonded scanners with single-crystalline honeycomb micromirrors of the same area as the solid bonded mirrors (450×450µm square) have been made and tested.[7]

Both the solid and honeycomb bonded mirrors offer orders of magnitude improvement in optical flatness as indicated by radius of curvature measurements shown in Figure 3. These images of mirror deflection were obtained using optical interferometry (a Wyko RTS 500 surface profiler). Transfer characteristics for a bonded honeycomb 2D scanner as measured with a Polytech single-point-displacement laser doppler vibrometer show a mechanical scan angle of 6˚ at 50V. The cutoff frequencies of a solid bonded mirror and a polysilicon mirror alone have been measured at 230Hz and 280Hz, respectively. No resonant oscillation has been observed due to squeeze-film damping of air.

In summary, we have successfully developed an integrated bonding process that allows design flexibility and independent optimization of mir-

(continued on p. 8)

Self-aligned mirror and v-grooves in free-space micromachined optical cross connects

Free-space micromachined optical switching technology has emerged as a promising means of building the large scale optical cross-connects that will be needed in future optical networks.[1-5] Work in this area has revealed the intrinsically good optical quality of free-space interconnects, particularly in the areas of crosstalk, polarization- and wavelength-independence, and bit-rate transparency. However, the issue of tight optical alignment tolerances in free-space optics—in particular the angular alignment of the optical beam relative to the receiving fiber and the quality of mirror—are the major bottlenecks for large-scale matrix switches. A self-aligned structure between the mirror and fiber is required to make sure that the system is sufficiently close to the optical axis. Also, passive alignment of optical fibers is necessary to keep the cost of production low. Here we report a method of creating a low-cost optical structure with a high quality, self-aligned mirror and v-grooves for passive fiber alignment. This structure is fabricated using a one-level mask in (100) silicon wafer.

Principle of fabrication

The etching principle for a 2×2 elementary cell is described in Figure 1. This uses bulk micromachining and takes advantage of three properties of the silicon lattice:

1. The natural 45˚ angle between the <100> and <110> directions is exploited to make the self-aligned vertical mirror and V-grooves. In the <100> direction, underetched vertical walls act as the mirror, while at the same time the v-grooves are fabricated in the <110> direction for optical fiber alignment.
2. The surface of the mirror is strictly perpendicular to the optical axes, again because of the crystalline nature of silicon and the orientation of the (100) plane.
3. The etching selectivity against the (111) planes is used to perform two levels of structural depth. Due to the fact that these planes stop the etching, the width of the v-grooves in the design fixes the height of the optical axis. The etching of the (100) planes is still controlled by time. This defines the mirror and also the thickness of the supporting cantilever, which is defined from the back for mirror actuation.

The process is robust. Indeed, if a slight misalignment occurs with respect to crystallographic direction during alignment, then the resulting mirror will stay at 45˚ degree to the v-grooves thanks to the wet-etching process. Figure 2 shows an example of 2×2 optical switch using this etching principle. As the bottom and sidewall planes are all from the same {100} family, the lateral underetch rate is equal to the vertical etch rate. So, it is possible to define a vertical mirror with a thickness down to very few microns.The mirror is 185µm high, 100µm long at the top and 5µm thick.

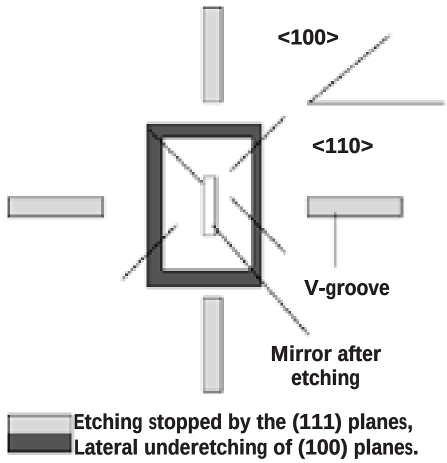

Figure 1. Principle of etching a 2×2 cell.

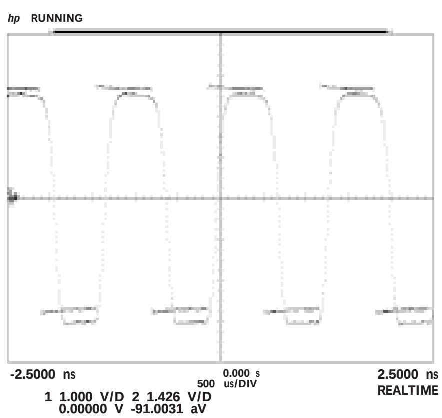

Figure 3. Switching time for a 2×2 bypass switch.

Characterization of the 2×2 optical switch

The switch is driven with an electromagnetic actuation that includes a permalloy layer (on the bottom of the cantilever) and an electromagnet. A displacement of 100µm is obtained with 30mA at 5V: this is high enough to perform the switch operation correctly. Insertion losses have been measured with an infrared wavelength at 1.55µm using single mode fibers with a gradient index lens.

The optical insertion losses are 0.3dB in the transmission state, and 0.58dB and 0.7dB for each path in the reflection state. The crosstalk is less than –40dB.

The dynamic response of 2×2 optical switch is plotted in Figure 3. The rise time and fall time are 300µs for each state. This principle of etching is easily scalable to larger optical cross connects. Figure 4 shows an example of a 1×8 optical matrix switch.

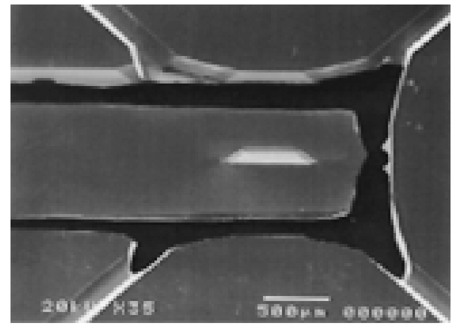

Figure 2. A 2×2 optical bypass switch.

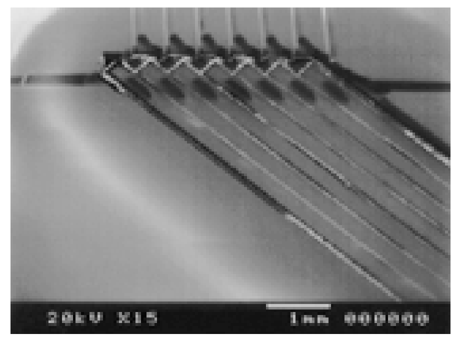

Figure 4. 1×8 optical crossconnect.

Philippe Helin, Tarik Bourouina, Makoto Mita, Gilbert Reyne, and **Hiroyuki Fujita**
LIMMS / CNRS – IIS
University of Tokyo, Japan
E-mail: philippe_helin@hotmail.com

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Micro-optical elements integrated with microfabricated fluidic devices for cellular assays

Today, one can justifiably talk about a revolution in the development and commercialization of miniaturized chemical and biomedical analysis systems. Taking advantage of micromachining processes mainly developed for the microelectronics industry, biochemical devices can be made in the form of “lab-on-a-chip” or Micro Total Analysis Systems (μTAS).[1-3] Chip-based microsystems that have been demonstrated include applications such as capillary electrophoresis,[4] flow cytometry[5] and polymerase chain reaction.[6] By reducing the size of a biochemical laboratory down to a microchip, advantages in reduced reagent volumes, automation of material manipulation, reduced footprint, increased parallel processing and higher throughput can be achieved. One area of particular interest is the analysis of cells and cell populations: used, for instance, in drug screening.

A new approach for such miniaturized biochemical analysis has been taken by Amic AB, a Swedish company specializing in high volume production of replicated microstructures, together with Gyros Microlab AB, a spin-off company from Amersham Pharmacia Biotech. The two companies are jointly developing a microfabricated disposable compact disc (CD) device for integrated cell-based assays, shown in Figure 1. The CD contains a number of cell-growth chambers, as well as distribution channels, that are realized by a combination of silicon micromachining and CD manufacturing methods. First, a silicon master is fabricated using micromachining techniques such as photolithography, and wet and dry etching. Then, a nickel mould can be formed from the master element by electroplating. This mould is finally inserted into an injection-molding machine that produces plastic devices in a CD format, allowing large numbers of components to be produced while still retaining the structural detail of the etched master.

To form enclosed structures and provide cultured cells with a means for obtaining oxygen for metabolism, the CD is covered with a thin silicone sheet. All liquid transfers are achieved by centripetal force through rotation of CDs at 200-6000rpm. A number of different cells have been cultured and analyzed by a CCD-based fluorescence imaging system. The results show that cells may be cultured within such CD devices and appear to have the same morphology as cells grown under standard conditions.[7]

In parallel with the paradigm shift in biochemical analysis, there has been an equal development for optical systems. Laser diodes, lenses, etc., can now be produced on the micron scale. The common CD-player, for instance, contains a mm-sized laser diode as well as a micro-optical lens. Micro-optical elements that make use of the wave nature of light can generate complex wavefronts, which may reduce the number of elements in optical systems and/or enhance system performance.[8] This emerging field has matured to the point where several industrial micro-optical systems are now in use.[9] Since optical elements of various kinds play an important role in many biochemical systems, it is worthwhile to see how the two fields can merge on a miniaturized scale.

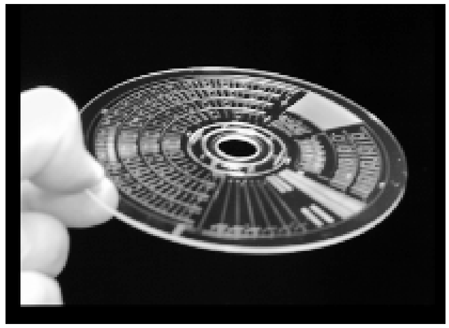

Figure 1. Microfabricated cell-culture CD.

Amic has recently investigated the use of a micro-optical element replicated at the back surface of a cell-assay CD device.[10] The purpose of the optical surface is to collect the luminescent light from the reaction chambers within the CD. Instead of using an externally-aligned light-collecting lens, the integrated micro-optical element can be produced at a low cost with a minimum of crosstalk between different cell chambers. Figure 2 shows a microscope photograph of a cell chamber with a Fresnel lens replicated on the opposite side of the CD. The preliminary results indicate the potential of this approach. Amic and Gyros Microlab intend to further investigate the use of other novel micro-optical elements such as subwavelength gratings (which can be used as artificial antireflective coatings or polarizing filters)[11] and photonic bandgap structures (e.g. for wavelength filtering).[12]

Fredrik Nikolajeff
Amic AB
Uppsala Science Park
SE-751 83 Uppsala, Sweden
Phone: +46-18-521640
Fax: +46-18-143250
E-mail: fredrik.nikolajeff@amic.se
http://www.amic.se

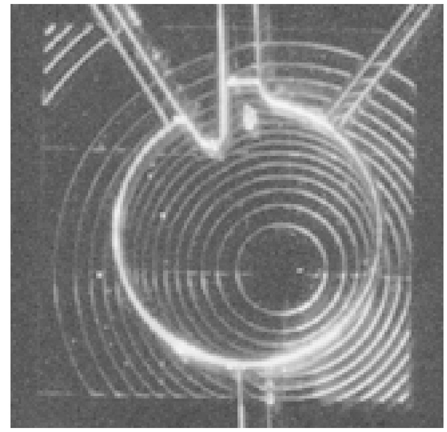

Figure 2. A cell-growth chamber with a Fresnel lens replicated on the back of the CD.

Per Andersson
Gyros AB
Uppsala Science Park
SE-751 83 Uppsala, Sweden
Phone: +46-18-566305
Fax: +46-18-566350
E-mail: per.andersson@gyrosmicro.com
htpp://www.gyrosmicro.com

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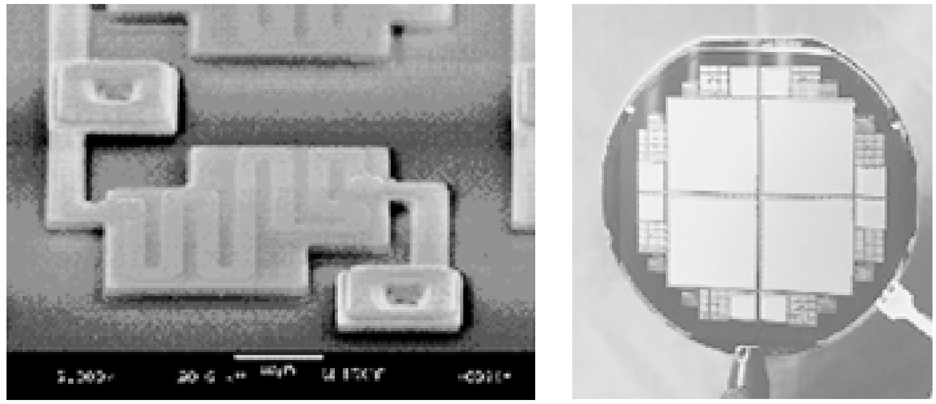
Advanced MEMS thermal emitters for infrared scene projection



(a) (b)

Figure 1. a) Honeywell micromachined infrared thermal-emitter pixel. This design uses a 30% fill factor to optimize thermal response time vs. radiative output. b) Wafer with fabricated 512×512 infrared display devices.

The availability of high-performance cooled and uncooled infrared focal-plane arrays (IRFPAs) has led to their widespread use in many types of military systems: these include those for security, surveillance, enhanced vision and target acquisition. The imaging performance of these IRFPA-based systems is typically evaluated statically using bar targets with black body sources and simulated scene images. It has long been realized that static imaging does not fully characterize an array but, without some way of performing it in the laboratory, dynamic testing could only be achieved in expensive field and aeronautical conditions or by artificially injecting “simulated” signals into the camera electronics. Hence, many approaches have been developed to allow dynamic scenes to be generated and projected in the laboratory. One approach to the generation of infrared scenes is the resistive emitter array. These systems are made up of joule-heated resistors that are individually controllable, and the matrix of these emitters can form an image.

Honeywell developed an implementation of these arrays in the early 1990s, based on the microstructures and MEMS fabrication processes developed for uncooled microbolometers. The Honeywell emitter array technology[1] consists of a 2D array of microstructures (see Figure 1) that are thermally isolated from the substrate by being operated in vacuum and by having low conductance supports. These pixels are formed on top of CMOS electronics that provide overall addressing. Typically analog signal inputs to the array are directed to the desired pixel by these integrated electronics. *Sample* and *hold* circuitry at the pixel cell is used to maintain the pixel radiance for reduced flicker while other pixels are being addressed.

These arrays have been fabricated in formats as large as 544×672, with active areas as large as 2"×2" and pixel yields as high as 99.99%. These arrays are in use in many US DOD test facilities, including the Redstone Technical Test Center, Air Force Research Lab, Army Aviation and Missile Command and Naval Air Weapons Center/China Lake. The arrays have utilized a 30% fill factor pixel design with a time constant of 5.5ms and an apparent temperature of 700K Mid Wave Infrared (MWIR). Projection frame rates up to 120Hz have been demonstrated. However, as the imaging rates of IRFPA-based systems increase, there is the need to dynamically project scenes at frame rates exceeding 200Hz. The thermal time constant of the pixel must be significantly reduced to faithfully reproduce IR scenes over a wide dynamic range. In addition, the desire to increase the spatial resolution of the array to formats of 1024×1024 or larger dictates that pixel efficiency must improve to minimize overall array power consumption.

With the current pixel design, the only practical way to reduce the time constant is to reduce the pixel mass, and this reduces radiative output and efficiency. To improve efficiency, or the maximum apparent temperature of the pixel, the fill factor must increase, thus increasing pixel mass. To overcome this undesirable tradeoff a new pixel has been developed by Honeywell utilizing advanced micromachining techniques.[2] This new pixel, dubbed the “gossamer,” reduces the mass of the pixel by 50%, thus enabling a larger area for improved radiance. The innovation in the gossamer pixel is that a significant amount of the emitter area is on an extremely thin membrane that adds very little thermal mass and yet retains all of the emissivity. This development makes use of the structural stability achieved with the baseline emitter process, and the improved ability to make higher resistivity, low-temperature coefficient of resistance (TCR) emitter resistor films. A SEM photograph of a recently fabricated gossamer pixel is shown in Figure 2.

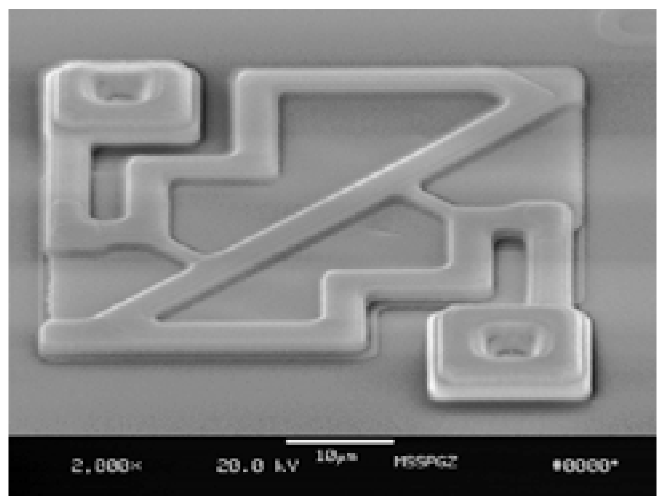


Figure 2. Honeywell’s new “gossamer” micromachined infrared thermal-emitter pixel. This pixel has a fill factor of 62% with the same mass as the previous generation’s 30% fill factor design.

This pixel has a 8000Å-thick, z-shaped resistor region and silicon nitride supports. The reduction in mass is achieved by utilizing a 500Å-thick emitter film that forms a web under the z-shaped resistor. The new gossamer pixel has a time constant of less than 2ms with a measured emissivity of >.85 (MWIR). Infrared projection arrays with a 512×512 matrix of gossamer pixels have achieved dynamic imagery with an apparent temperature of 740K

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Silicon micromachines

(continued from cover)

have proven to be robust and long-lived, especially those whose parts flex without microscopic wear points. Research in this area has been extremely active over the last decade, producing microscopic versions of most macro-machines. In particular, many of us believe that the size scale at which these machines work well make them a particularly good match to optics problems where the devices, structures, and relevant wavelengths range in size from one to several hundred microns.

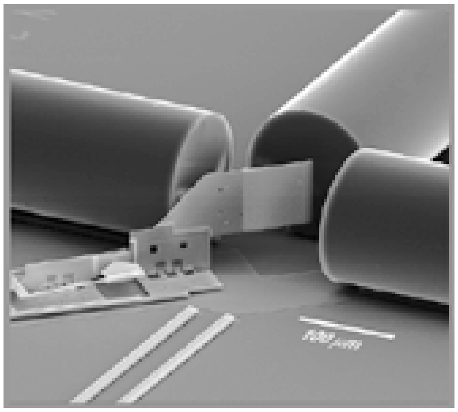

Figure 3. A 1×2 switch.

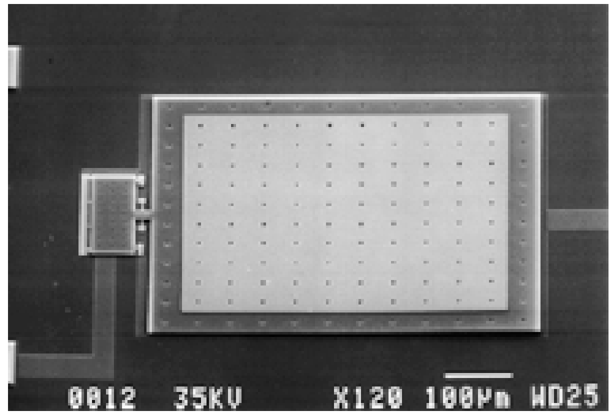

Figure 4. A variable attenuator.

Where in a lightwave network will they be applied?

Work at Bell Labs in Optical MEMS has focused on a number of devices such as optical modulators, variable attenuators, switches, add/drop multiplexers, active equalizers and optical cross-connects. Shown in Figure 2 is an overview of those places in light-wave networks where we see application for MEMS components. Each red dot is a place where MEMS can be the solution of choice. Clearly, there exist many opportunities.[1-4]

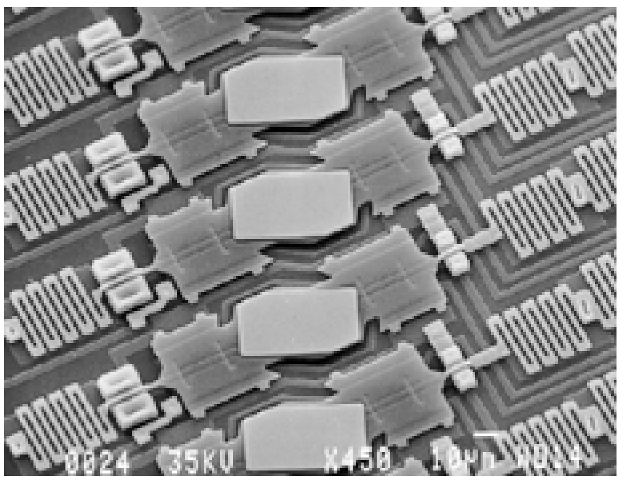

Figure 5. An array of micromirrors.

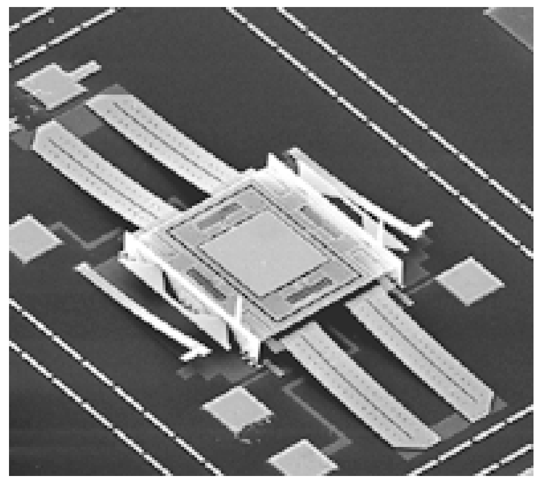

Figure 6. A two-axis micromirror for use in an all-optical crossconnect.

In Figure 3 is a micrograph of our 1×2 MEMS optical switch. The mirror is connected to a see-saw and either reflects the light from the optical fiber on the left to the fiber at right angles to it, or moves out of the way to allow the light to go straight into the other fiber. In Figure 4 is a micromirror for use in a variable attenuator. Light from a fiber at right angles to the mirror gets reflected to an output fiber, and the coupling between the two can be adjusted by applying a voltage to the electrode to the left of the large mirror. In Figure 5 is an array of micromirrors for use in an add/drop multiplexer. In operation, each wavelength of light in an optical fiber gets spatially demultiplexed by a grating and lands on its own mirror to be correctly routed to either the output port or the drop port. Finally, shown in Figure 6, is a two-axis micromirror for use in an all-optical crossconnect. The mirror is doubly-gimballed so that light can be routed in two directions to allow complex switching functions to be performed. Such mirrors have allowed Lucent to be the first to build and deliver to customers large, MEMS-based, optical crossconnects. Such switches have very large port counts, low losses, fast switching speed, and low costs. Clearly, the possibilities for novel optical devices and functions are endless.

With MEMS devices now being deployed in active lightwave networks, the wealth of new capabilities presented by MEMS optical devices places them as certain candidates for imminent commercial success. The optical MEMS industry is estimated to become a multi-billion dollar business in five years. Many companies, including Lucent Technologies, identify MEMS as a strategic technology they cannot afford to neglect, and we believe it will provide exciting technical challenges and business opportunities for many years to come.

David Bishop, Vladimir Aksyuk, Cris Bolle, Randy Giles, and **Flavio Pardo**
Micromechanics Research, Bell Laboratories
Lucent Technologies, Murray Hill, NJ 07974
E-mail: djb@lucent.com

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Steered agile laser

(continued from p. 2)

onto the waffle, provides a lightweight polished mirror surface.

A simpler version of this micromirror is shown in Figure 4. It was fabricated in an SOI wafer whose device layer is 50µm thick. The insulating layer serves as an etch stop for the deep etch. Holes etched through the backside of the wafer provide room for the mirrors to rotate. In this case, the low-height silicon beams are used to apply lateral force below the torsion beams' axis of rotation, and to connect to low-power electrostatic comb drives adjacent to the mirror. More detailed information about this process, and pictures of resulting devices, can be found at the URL below.

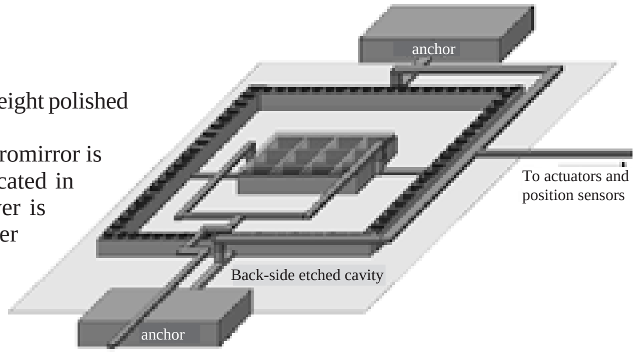

Figure 3. Second-generation mirror concept. A 2DoF single-crystal silicon mirror is suspended using torsion springs. Lateral actuators can rotate the mirror around two axes independently.

Matthew Last, Veljko Milanovic, and **Kris Pister**
Berkeley Sensor and Actuator Center
497 Cory Hall #1770
Berkeley, CA 94720-1770
E-mail: mattlast@eecs.berkeley.edu
http://www.eecs.berkeley.edu/~mattlast/research/

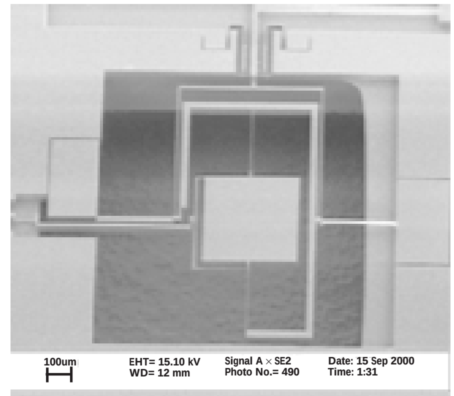

Figure 4. SEM micrograph of a second-generation mirror. The mirror measures 400µm across.

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Integrated 2D scanners

(continued from p. 3)

ror and actuator parameters. Bonded solid and reduced-mass honeycomb micromirrors, which are flat to a radius of curvature larger than 1m, have been demonstrated. An optical scan angle of 12˚ and a cutoff frequency of 230Hz have been achieved for the honeycomb and solid-bonded mirror, respectively.

Pamela R. Patterson, Guo-Dung John Su, and **Ming C. Wu**
Electrical Engineering Department
University of California, Los Angeles
CA 90095-1594, USA
Phone: 310/825-7338
E-mail: {pamela, johnsu}@icsl.ucla.edu, wu@ee.ucla.edu
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MEMS thermal emitters

(continued from p. 6)

(MWIR) at frame rates of 200 Hz. This innovative new emitter microstructure will allow 1024×1024 arrays to be fabricated with the same power requirements as the current 512×512 arrays.

Dr. Barry Cole and **Steve Weeres**
Honeywell Technology Center
12001 State Highway 55
Plymouth, MN 55441
Phone: 763-954-{2836, 2730}
E-mail: {barry.e.cole, steve.weeres}@honeywell.com

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MEMS-controllable microlens array

(continued from p. 12)

Beam steering results

The MEMS-controllable microlens array chip was actively aligned with the VCSEL array chip. The system has successfully demonstrated 2D beam steering with maximum angle of 70mrad (4˚) as shown in Figure 3, which is adequate for enhancing optical alignment in free-space optical interconnects. Measurement verifies insertion loss of less than 2dB. The system was demonstrated up to a rate of 1kHz of operation frequency, a result of the low inertia and small travel of the microlens components.

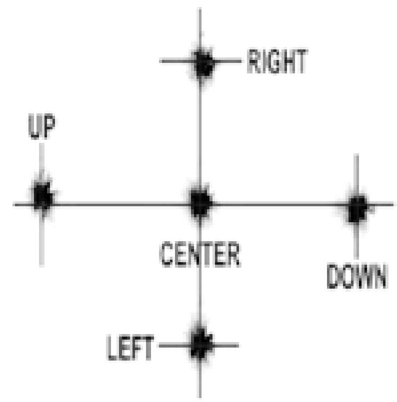

Figure 3. Demonstration of 70mrad 2D beam steering.

This work is supported by the U.S. Air Force Office of Scientific Research (AFOSR), Grant number F49620-98-1-0291.

Adisorn Tuantranont, Victor M. Bright, Jianglong Zhang, Wenge Zhang, John Neff, Y. C. Lee, and **Ganesh Subbarayan**
NSF Center for Advanced Manufacturing and Packaging of Microwave, Optical, and Digital Electronics (CAMPmode)
Department of Mechanical Engineering
University of Colorado, Boulder
CO 80309-0427, USA
Phone: 303/735-1734
Fax: 303/492-3498
E-mail:Adisorn.Tuantranont@colorado.edu
http://mems.colorado.edu

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MEMS-controllable microlens array for enhanced alignment in optical interconnect systems

Free-space optical interconnection is attractive for several applications including telecommunication switching networks and fine-grained parallel processing in computers. However, alignment challenges are inevitable in optical interconnect systems. Mechanical vibrations or thermal expansion can cause misalignment. We propose an enhanced alignment approach for free-space interconnects, without a demand for tighter assembly tolerances, using a MEMS-controllable microlens array. Figure 1 shows the use of such an array to enhance the alignment of smart pixel array on a board-to-board optical interconnect in a digital system. The microlens collimates an incident Vertical Cavity Surface Emitting Laser (VCSEL) beam and the microlens actuators steer the beam to a predefined position on a hologram array by laterally translating the microlens. The beam is then accurately aligned to the detector array.

MEMS-controllable microlens

The 2D MEMS-controllable microlens array was fabricated through commercially available surface micromachining technology (Multi-User MEMS Process, known as MUMPs).[1] Photo-bisbenzocyclobutene (BCB) electronic resin, a photo-sensitive polymer, was used in our own process to fabricate micro-hemispherical polymer lenses on MEMS. Each microlens was fabricated directly on a MEMS X-Y movable plate, with a circular aperture to let the light go through, using a photolithography and reflow technique.[2] Arrays of electro-thermal actuators are coupled with the 80μm×80μm polysilicon movable plate to translate the microlens in the X-Y plane. The microlens array is located at the focal plane in front of the VCSEL array and collimates the incident VCSEL beams. Via the concept of decentered microlens, if the microlens is decentered with respect to the beam axis, then the beam will propagate through the off-axis point of the microlens. The microlens still collimates the beam, but the beam is now directed to a nonzero field angle. The steering angle then depends on the lateral displacement *(Δd)* of the lens with respect to the beam axis, and the focal length *(f)* of the lens as shown in Figure 1. In this scheme, large steering angles are possible via large lens displacement, on the order of the lens radius, and short focal length.

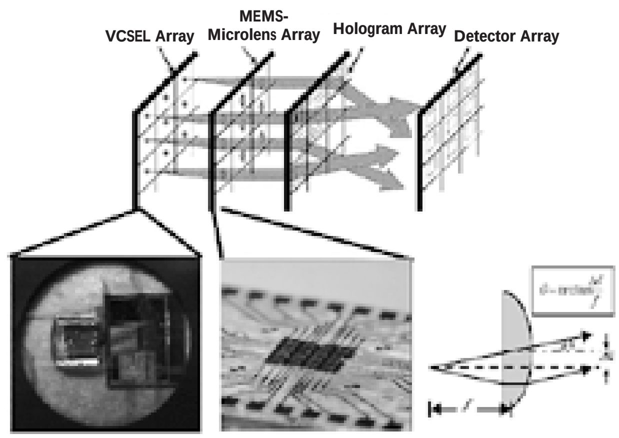

Figure 1. Concept and configuration of board-to-board optical interconnects using MEMS-controllable microlens array for enhanced alignment.

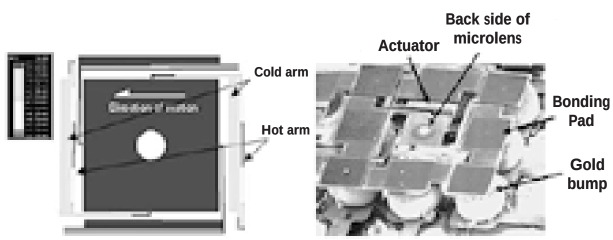

Figure 2. Configuration and scanning electron micrograph of MEMS-controllable microlens.

'U'-shaped lateral electro-thermal actuators, or 'heatuators,' used to drive the central plate in a lateral motion, consist of a single-material connected narrow arm and a wider arm. Current is passed through the polysilicon actuator, and the higher current density in the narrower or 'hot' arm causes it to heat and expand more than the wider or 'cold' arm. The arms are joined at the free end, which constrains the actuator tip to move laterally in an arcing motion towards the cold arm side. The tips of the actuators are coupled to the central plate by long thin flexures on opposite sides of the plate. The left actuator in Figure 2 pulls the plate, while the right actuator pushes the plate at the same time. Via this push/pull actuator mechanism, the motion of the plate is linearly proportional to the consumed power. The mechanical crosstalk in X and Y directions is minimized by using long, thin flexures.

The MEMS-controllable microlens array was flip-chip transferred onto a transparent substrate.[3] The MEMS structures are built upside-down on top of sacrificial oxide, so that the bonding pads fabricated on the MEMS are matched with bonding pads on the quartz target substrate. The quartz receiving substrate was patterned with gold wires, and with bonding pads for flip-chip bonding and wire bonding. A layer of photoresist is used to protect the quartz and gold interconnects when the assembly is released in hydrofluidic acid (HF). Gold bumps of 70μm in height are placed on the pads and used to bond and electrically connect the MEMS structure and wiring substrate. The MEMS-controllable microlens array is then flipped and bonded to the wiring quartz substrate using thermosonic bonding. The last step in this process is to release the bonded device in a HF bath and remove the silicon substrate. Finally, the MEMS device is flip-chip transferred to a quartz substrate as shown in Figure 2.

continued on p. 10