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GRANT NUMBER DAMD17-96-1-6278

TITLE: Integrated Force Arrays for Specialized Robotics

PRINCIPAL INVESTIGATOR: Scott Goodwin-Johansson, Ph.D.

CONTRACTING ORGANIZATION: MCNC, Electronic Technologies Division
Research Triangle Park,
North Carolina 27709

REPORT DATE: July 1997

TYPE OF REPORT: Final

PREPARED FOR: Commander
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for public release;
distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE July 1997	3. REPORT TYPE AND DATES COVERED Final (1 Sep 96 - 15 Jun 97)

4. TITLE AND SUBTITLE
Integrated Force Arrays for Specialized Robotics

5. FUNDING NUMBERS
DAMD17-96-1-6278

6. AUTHOR(S)
Goodwin-Johansson, Scott, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MCNC, Electronic Technologies Division
Research Triangle Park, North Carolina 27709

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

19980729 106

13. ABSTRACT *(Maximum 200 words)*

The Integrated Force Array (IFA) is a powerful microelectromechanical actuator that can be thought of as artificial muscle. The work in this program focused on the verification of the performance of the IFA, the creation of longer IFAs, and initial studies on the formation of a monolithically fabricated polyimide frame around the IFA. Earlier fabricated IFAs were tested, and a new set of IFAs were fabricated and tested. Similar mechanical performance was measured compared to prior fabrication runs. Consistent performance was measured from test to test of a single IFA, from die to die on a wafer, and from wafer to wafer within the last fabrication run. IFAs were tested with lifetimes greater than 9.2×10^8 contractions and contraction rates of up to 24,000 contractions per second. Longer IFAs, 63 mm long, were successfully fabricated using overlapping exposures on an i-line stepper. Polyimide framed membranes were successfully fabricated verifying the robustness of the polyimide frame and the formation of gold feedthroughs.

14. SUBJECT TERMS
MEMS, actuators, electrostatic, artificial muscle, polyimide, large area actuators, mechanical performance

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

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7-14-97

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Introduction

This is the final report for the program entitled "Integrated Force Arrays for Specialized Robotics". This program concluded June 30, 1997 and was performed mainly at MCNC. There exists in the military a need for small, powerful actuators that can be used in ways that augment the skills and capabilities of humans, and on tasks that present great risk for bodily harm to soldiers. The integrated force array (IFA) provides several unique advantages in comparison to other microactuators for these tasks. The objective of this program was to more fully characterize and evaluate the performance of the IFA for actuator applications. Following a background description of the IFA, results from the three tasks of the program will be described. These tasks are the performance testing of the IFA, the fabrication of larger area IFAs, and studies on the formation of a polyimide frame around the IFA.

The Integrated Force Array

The integrated force array is a microelectromechanical (MEMS) device which consists of an array of deformable capacitors. Each capacitor in an IFA is made of metallized polyimide, a very strong and flexible dielectric commonly used in semiconductor manufacturing. The IFA provides large displacements and forces, the largest measured work per unit volume of any MEMS device reported in the literature. These arrays are highly electrically efficient, and can be thought of as artificial muscle with contractions of up to 20% in length and with forces comparable to muscle tissue when equal volumes are compared. Figure 1 shows a drawing of the IFA in the relaxed and compressed configurations. Since IFAs contract in response to an applied voltage, they can be used as actuators or, specifically, electrical-to-mechanical transducers. In addition, the IFA can also be connected as a sensor or mechanical-to-electrical transducer to sense movement and position. The initial development work, supported by a three-year Advanced Technology Program from the National Institute of Standards and Technology (NIST), was focused on the fabrication of an IFA structure in which only the direct application of current VLSI fabrication methods is needed. That work came to a successful completion with the demonstration of working prototypes, with a figure of merit of work per unit volume of 15 ergs/mm^3.

The IFA produces motion on a practical scale by adding the responses of many microscopic elements acting under an electrostatic force. The basic IFA force element is a small, deformable capacitor constructed from a pair of metallized polyimide plates. Polyimide spacers separate the plates and transmit the electrostatic force. Air gaps between the capacitor plates provide room for closure and, hence, compression of the entire IFA. As a voltage is applied between the capacitor plates, there is an electrostatic force generated between the plates that is, to first order, proportional to the square of the voltage on the plates and inversely proportional to the square of the separation between the plates. The electrostatic force bends the plates toward each other resulting in a contraction in the length of the IFA. Because the force generated by a single cell is independent of the scale of the x, y, and z dimensions of the cell, small cells are used to maximize the number of cells in a membrane and hence the force available from the membrane. The typical dimensions of the current generation of unit cells are a plate pitch of 1.7 μm, a plate thickness of 0.3 μm, a plate height of 2 μm, and spacing between the polyimide spacers or plate length of 25 μm. There are two approaches to increasing the force available from an IFA: decreasing the spacing between the capacitor plates, and increasing the thickness of the IFA membrane. Our experience indicates that the latter approach is more likely to result in a low cost, easily manufacturable device. The increase in the thickness of the IFA can be achieved either with

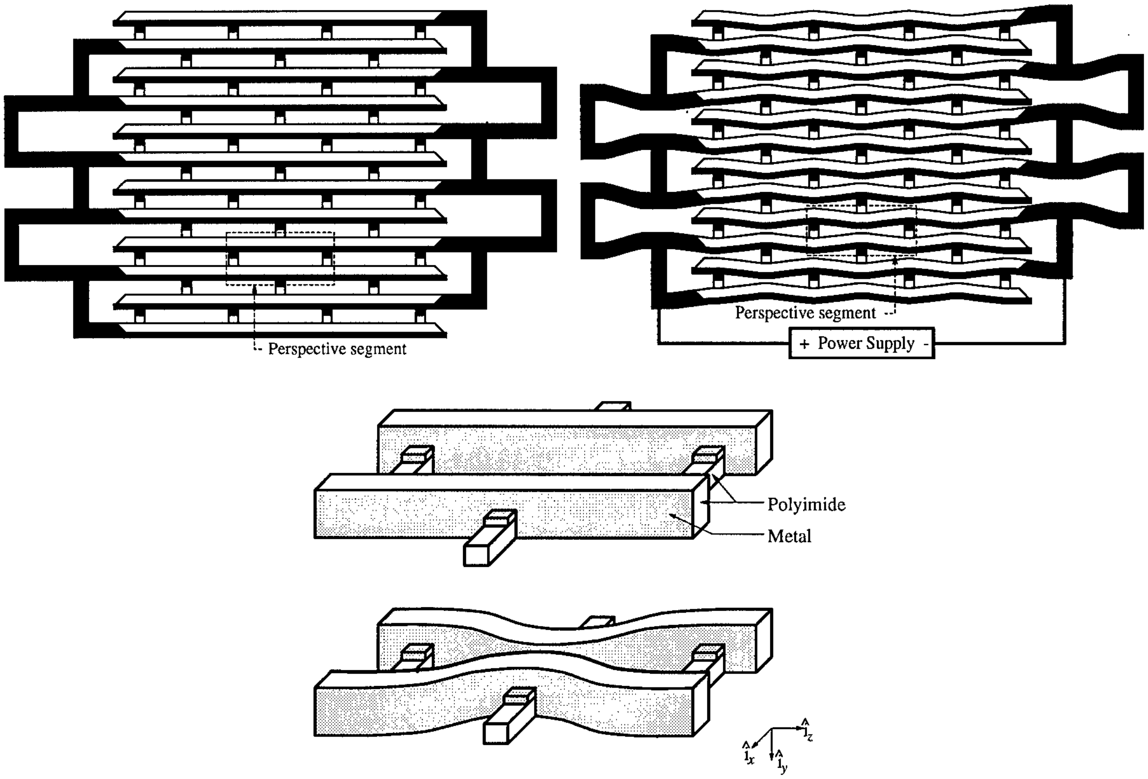

Figure 1. An IFA in a relaxed position on the left, compressed on the right, and unit cell shown below.

a single thicker membrane or by the combination of multiple membranes. Future work done in subsequent proposals will focus on increasing the thickness of single membrane IFAs.

The IFA is a scalable technology capable of very small displacements of a few micrometers to large displacements of several centimeters. Since it is removed from the substrate on which it is fabricated, and due to the flexibility of its constituent materials, the IFA can be configured in many conformal applications. Because it is an electrical-to-mechanical transducer, the IFA is connected to the power source only through wires, which can be made small, thin, and flexible, thus, it can be located remotely from its power and control units. In comparison to mechanical systems which use cable interconnections or hydraulics to transmit mechanical force, the IFA's connections must only be electrically continuous, which simplifies the construction of robotic arms with multiple degrees of freedom. The IFA allows for much more freedom in how the mechanical tool is configured since the arrays which are used for actuation are small, lightweight, and have low power consumption.

IFA technology can provide great advances in the capabilities of robotics, where actuators are used to move the various limbs and grippers through the translation and rotation of the different joints. In surgery, there is a need for a mechanical gripper with seven degrees of freedom which can be inserted through a 1 cm opening in the patient. Another surgical need is the ability to do remote surgery on a patient at the battlefront with a mechanical tool which mimics the surgeon's motions. In the area of ordinance handling there is an obvious motive for developing mechanical robots that can remotely detect, handle, and defuse a shell or mine. These applications either require small actuators, or efficient, low-power actuators, such as the IFA. The scaling up of the IFA to form such actuators could result in revolutionary devices which would be used in robotics and to perform microsurgery. The interconnection of actuators and sensors in the same device allows for the simultaneous sensing of position as force is applied, thus giving feedback to the operator about the amount of resistance to the movement. Although each IFA moves in only one direction, arrays of IFAs can be connected to different lever arms to provide actuation with nearly any degree of freedom. The large amount of force available in such a small volume makes such an arrangement feasible.

Performance Testing of the IFA

In order to verify the performance of the IFA, a new set of IFAs was fabricated. This new fabrication run was not only to provide more devices for testing but also to verify the repeatability of the fabrication process. The fabrication sequence used was as identical as possible to one of the last NIST fabrication runs with no fabrication splits except for a few splits to use different thicknesses of the sidewall metallization, which is the final fabrication step. The NIST run that this run was patterned after had good results although there had been a high incidence of shorted structures. Prior to the fabrication of the new run, efforts were made to identify the source of the shorting.

Testing for short formation. Identifying the source of shorts in the IFA structure is a very difficult problem. Given the large number of identical cells within IFA (several hundreds of thousands), locating an error with a manual optical scanning is not possible unless the error was so pervasive that the required scanning area prior to finding an error was very small. Automated scanning equipment would find the non-planarity of a released IFA and the slight distortions of the arrays, cause of enough variations that the generation of false positives would be overwhelming to the operator. In addition, the electrical short may very well be occurring at a site that does not have an optical defect associated with it. For these reasons it was quickly decided that alternative techniques would need to be used. Voltage contrast imaging in an SEM which can be used to identify the presence and location of opens in a metallization of an IFA can not be used to find a short. This is because the voltage drops associated with the resistances of the planned metalization and the short are not necessarily large enough to be identified in the SEM.

One of the attributes of the IFA is its ability to be released from the substrate, and its small dimensions of the beams and connecting structures. This combined with the power loss due to the resistive, conductive path of the short leads to a heating of the IFA above the ambient temperature. Since the mass of the structure is small, and the heat loss though air is inefficient, the amount of current required for forming hot spots is only a few milliamps. Since the heat conduction along the structure is also minimal, the localization of the heating should be well defined. If the conductive path can be thus identified, a more detailed investigation with an SEM should identify the location of the short. With this in mind an infrared microscope was located at MCNC and configured to view the IFA while it was being internally heated. Unfortunately that microscope, which was designed for through wafer viewing, could only see temperatures down to approximately 600°C. Since the polyimide decomposes at approximately 450°C, that microscope was not sensitive enough for this task. During the process of multiple phone calls to other facilities in the area in search of a more sensitive microscope, an employee at IBM suggested the use of a temperature sensitive liquid similar to LCD materials, that goes through a change in polarization at approximately 30°C. Efforts to use this did not prove successful. Since the material stays in a liquid form during testing, the thermal isolation of the IFA is lost and the IFA could not be heated enough to localize the problem spots. In January an infrared microscope was located at the University of Maryland, and samples were delivered for testing. Unfortunately, shortly before the samples were delivered, the microscope went down due to multiple difficulties and was not repaired before the middle of June. Thus, we were unable during this program to locate the cause of the shorting.

Design of the IFA mask. To complete the larger area IFA task of the program, the mask set used for the IFA fabrication needed to be redesigned. The pads of one of the IFAs was extended past the other structures on the die so that they could be overlapped during the fabrication process.

In an effort to prevent a possible shorting mechanism through the half height features, some of the structures were redesigned. During the NIST program, it was observed that the embedded hard mask process could result in structures where the silicon half height hard mask features could be misaligned to full height features and the silicon features could extend all the way through the full height beam. In the embedded hard mask process the bottom half of the polyimide is deposited and then a thin silicon layer is deposited and patterned with the half height mask. The remaining polyimide is deposited and an evaporated oxide layer is deposited on top of the polyimide. The oxide layer is then patterned with the full height mask which is aligned to the lower embedded half height features. At this point the wafers are etched in a oxygen plasma which anisotropically etches away all the exposed polyimide and stops etching at the oxide layer on the silicon substrate, the silicon half height features, and the full height oxide features. A slight amount of undercut occurs at the oxide hard masks which allows an angled metal evaporation to coat the sidewalls of the polyimide with a discontinuity in the coating at the oxide hard mask. This discontinuity allows the metal on top of the oxide to be separated from the IFA when the wafer is inserted into HF which first dissolves the evaporated oxide and then removes the thermal oxide layer under the IFA. Figure 2 shows the fabrication sequence. The difference in heights between the oxide hard mask and the silicon hard mask can make the alignment difficult. In addition, the subsequent etching of the polyimide reduces the thickness of the polyimide features to approximately 0.3 μm, which is a narrow feature to align the edge of the silicon hard mask in without it penetrating all the way through. Figure 3 shows an SEM photograph of a silicon hard mask that pokes through the polyimide beam from an earlier NIST fabrication run. Although the silicon is undoped, it will be slightly conductive and could cause a short in the structure.

The change in the structure to reduce this shorting possibility was to increase the thickness of the full height beams by 0.1 μm in the immediate vicinity of the half height features, while leaving the beam pitch unchanged. This would significantly increase the final thickness of the polyimide there and ease the alignment problem. There would be a slight decrease in the amount of the possible IFA contraction due to the decrease in gap between the beams at their point of closure and also a decrease in the maximum force possible. Since the beam thickness is only altered right around the half height feature, the mechanical stiffness of the beam is not significantly altered.

The mask set contained four 3 mm wide and 8 mm long active areas IFAs. Three had normal length pad ends and the fourth had pads that extended past all other structures on the mask. All four IFAs were organized into three 1 mm wide columns with four pads at each end of the IFA. The long pad IFA had an IFA design from earlier NIST mask sets. Those IFAs were 20μm long cells arranged in subarrays of seven rows. A second IFA had cells 30 μm long arranged in subarrays of seven rows and also includes mechanical arch diodes to limit the weak cell effect. The third IFA has the 20 μm long cells in seven row subarrays but also includes the modified half height structures described above. The final

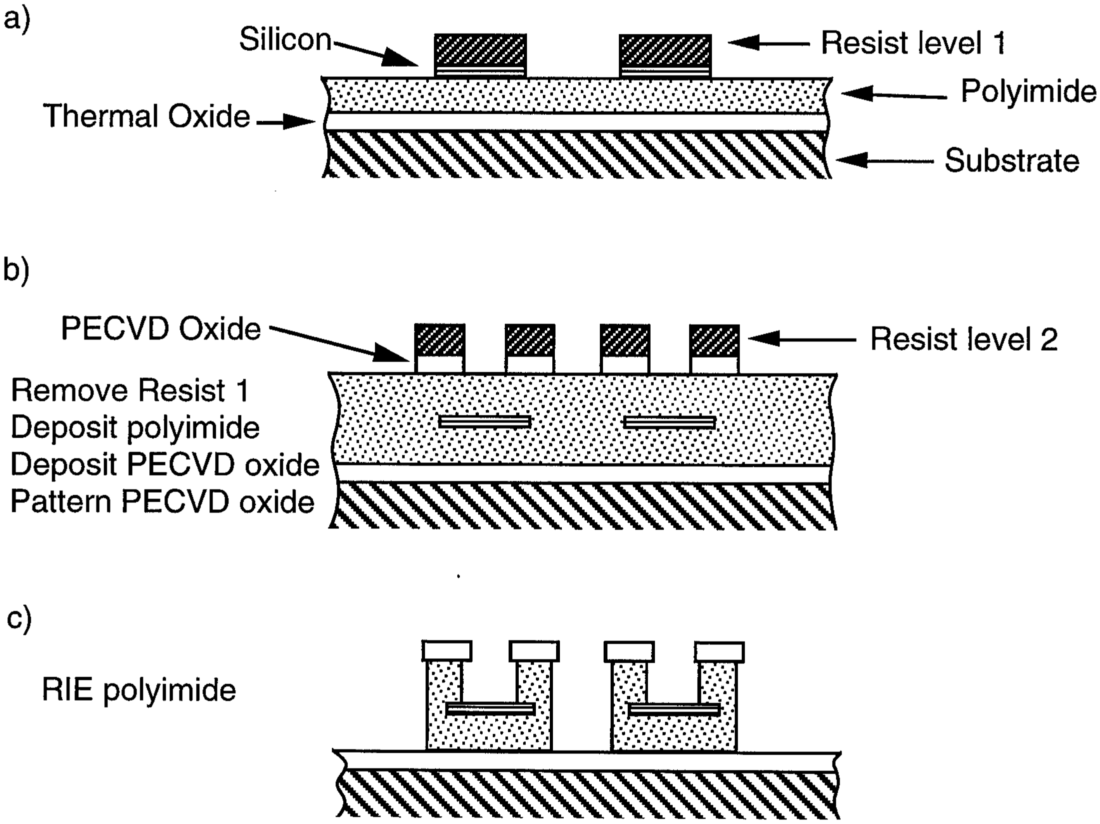

Figure 2. Process sequence with half height hard mask embedded in the polyimide film.

IFA has cells 25 μm long arranged in 3 row subarrays with the top half of the IFA including the modified half height structure. Also included in each die is a diagnostic test site used in previous mask sets. Figure 4 shows a photograph of the completed IFA die on the wafer.

IFA Fabrication. The fabrication of the IFAs used the embedded hard mask described above. The fabrication process is robust enough that the year gap since the last fabrication run did not affect the completion of the run. The fabrication process went smoothly except for the i-line stepper alignment procedure at the full height lithography step. At that point there was apparently a magnification error in the stepping of the images across the wafer. At the alignment die, good alignment was obtained but away from that die larger and larger alignment errors occurred. The cause of the problem was not fully identified and a work around solution was obtained to allow the lot to progress. The processing slowed down in the metalization sector due to personnel turnover combined with a heavy workload of metallizations. As a result the wafers were completed only a few weeks before the end of the contract.

NIST fabricated wafer testing. During the time of the fabrication run, additional testing was done of selected wafers that had been fabricated during the prior NIST contract. Part of the purpose of this testing was an attempt to identify the cause of the previously described shorting. Since there were different process splits used in the NIST contract, some processing distinction might be identified as a clue to the source of the shorting. In

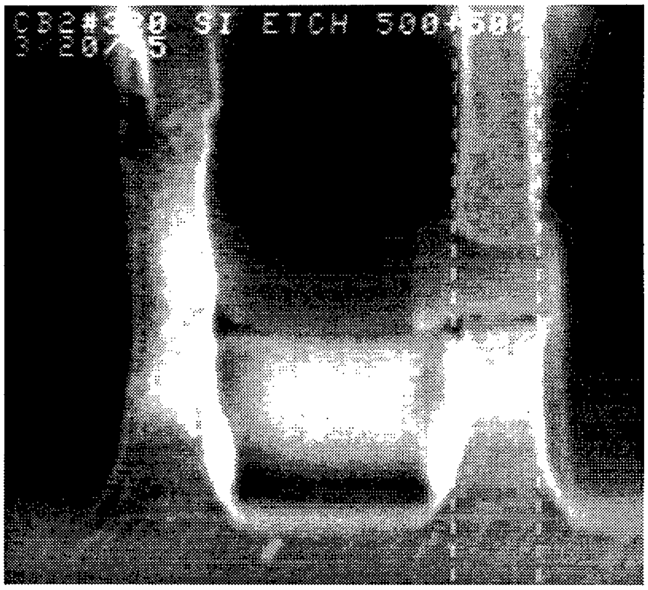

Figure 3. SEM micrograph of an embedded hard mask structure showing the misalignment of the hard mask through the right polyimide beam.

addition, the testing was used to identify the consistency of the IFA performance and to work on the release process. As before, the IFAs were removed from the final water rinse bath, face down, on pieces of aluminum foil. Earlier testing had used artist's tape to build a frame all the way around the IFA for ease in subsequent handling. The center portion of the foil was then cut and separated from the IFA, leaving the IFA suspended in the frame. The two drawbacks of this technique are the small size of the removed center foil portion which is more difficult to manipulate, and the thicker side pieces of the frame. When the framed IFA is tested for force measurements, the IFA is placed in a miniature, mechanical swing (see figure 5). As the IFA pulls the swing toward a fixed pedestal, the change in the swing's center of gravity can be calculated, based on the mass of the swing and the displacement of the swing. From this the required force pulling on the swing can be calculated. The swing can be used to measure displacements as small as 5 μm and forces as small as 0.1 dynes. The IFA is stuck to the pedestal and the swing with double-sided tape while the frame is still surrounding the IFA. Then the side pieces of the frame are cut with scissors which frees the swing to move in response to the applied voltage. The cutting action with the scissors can cause a sudden motion in the IFA that can potentially damage the IFA. The thickness of the frame side piece has a direct impact on the likelihood of causing enough motion for damage. For these two reasons a new framing technique was developed that uses paper for the side pieces. A paper frame is cut out that completely surrounds the IFA and is placed over the IFA. Then two pieces of artist's tape are placed across the ends of the IFA, spanning from side piece to side piece of the paper frame and attaching the IFA to the paper frame. By primarily applying pressure to the paper ends of the tape, the tape only weakly attaches to the foil and the foil can be removed from the paper and tape frame. The paper is considerably easier to cut smoothly and the larger piece of foil is removed more easily. Care must be taken in this framing process to not move the paper with respect to the foil, for that can tear the IFA.

The testing was primarily done with the IFAs constrained by the frame, which was sufficient to determine if there was motion in the IFA and at what voltages it occurred.

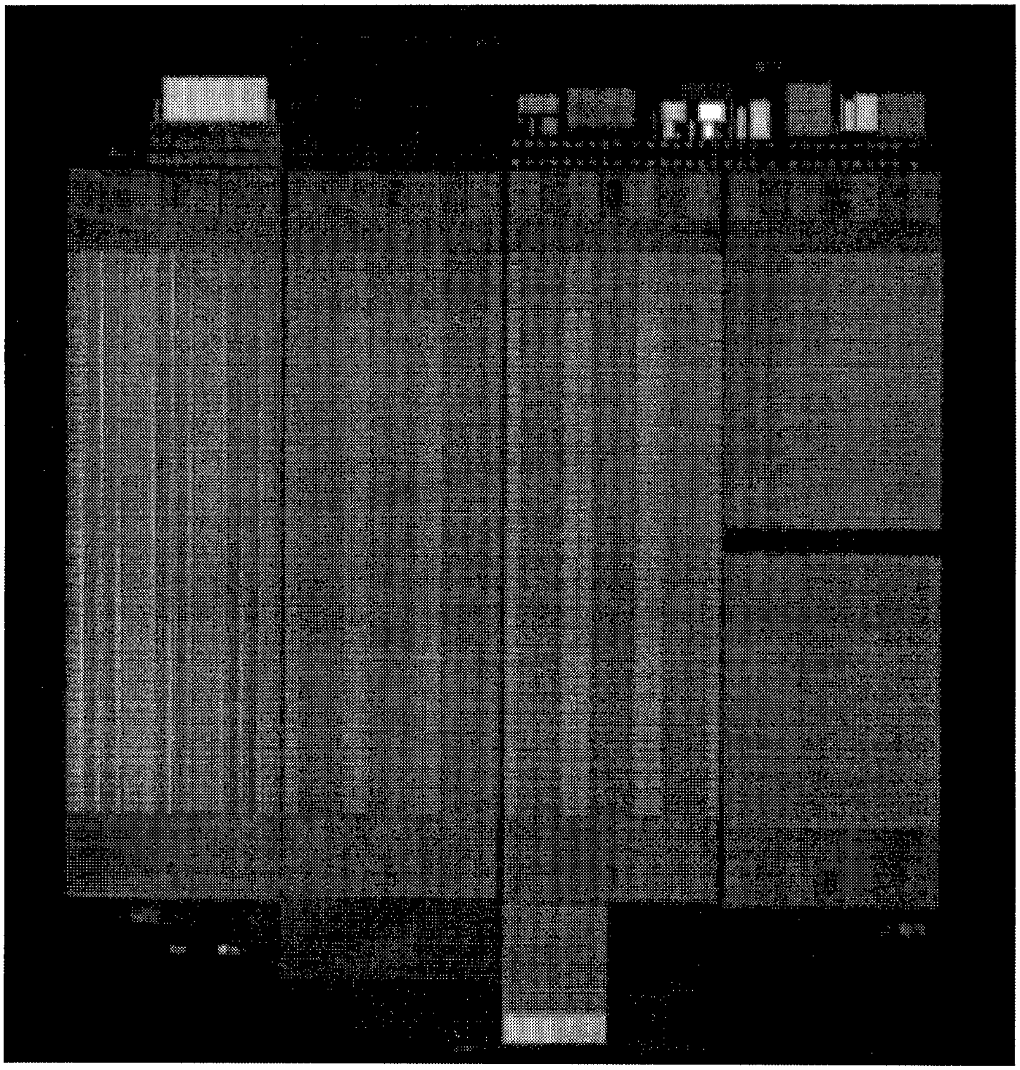

Figure 4. A photograph of a single die with the four IFA structures. The left has the mechanical diodes, the next one to the right has the long pads, the next has the modified half height structures and the last on has the subarrays with three rows of cells.

IFAs from 11 different wafers were tested. Those fabricated with the more similar process sequence to the current fabrication run tended to work better than those with different processing. One IFA was tested over a weekend to determine the lifetime of the IFA. The device was operated at 4000 contractions per second while the IFA was still in the frame. These conditions limited the amount of motion produced by the IFA while allowing the testing to be done in a reasonable amount of time. The testing was completed by turning the testing signal off while the IFA was still successfully operating. The IFA performed 921,000,000 contractions. A few IFAs were mounted on the test swing described below and exhibited motion, unfortunately these early measurements were not videotaped and cannot be quantitatively analyzed.

Performance results from this fabrication run. Die from four different wafers were tested after the conclusion of the fabrication run. Two were from the standard

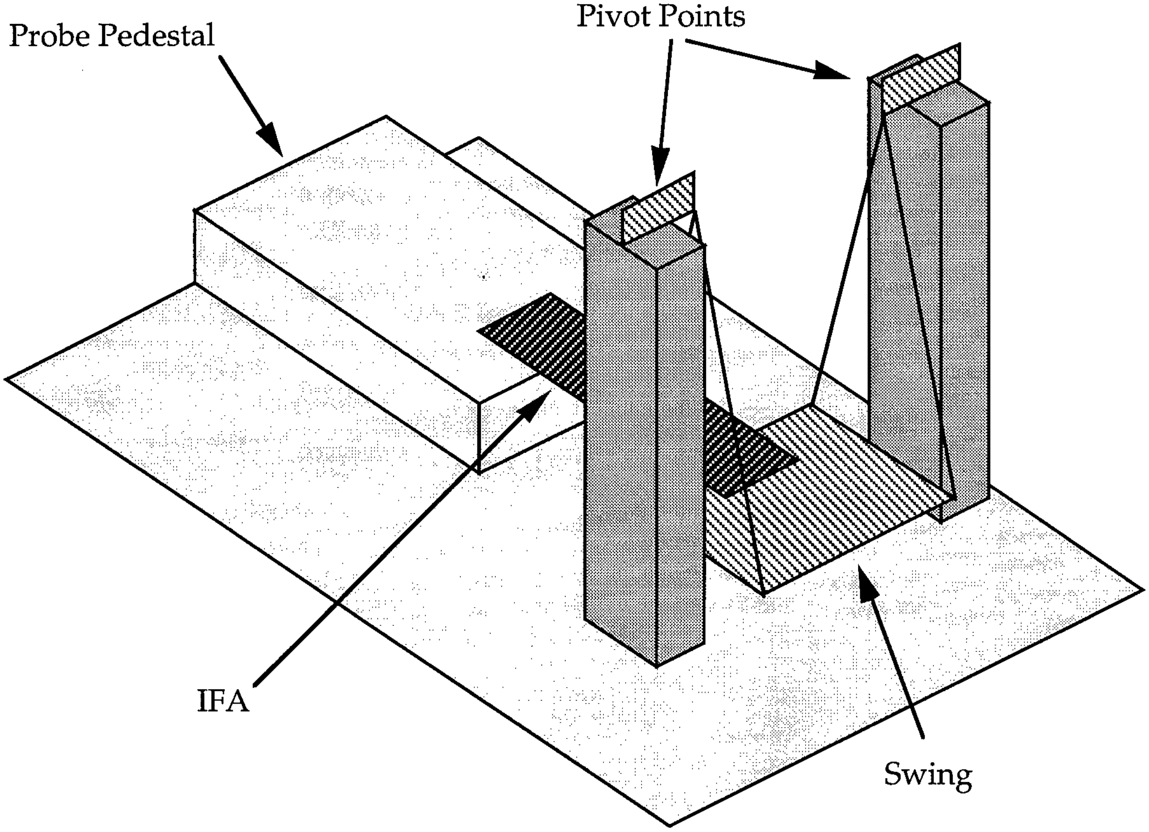

Figure 5. A perspective drawing of the test fixture for IFAs. The IFA is suspended between the pedestal and the swing.

fabrication run and two were from the large area, stitched image run described below. Similar results were obtained from all four wafers which indicates that the processing was uniform in the run. During the release step in the HF acid of the various die, it was discovered that the rate of insertion into the HF and the angle of insertion into the HF was playing a significant role in the quality of the released IFAs. If the angle was too steep and the rate of insertion too fast, there was a likelihood of the metal on the oxide caps not being separated from the IFAs. This was apparently due to the etching of the oxide caps not occurring fast enough for the surface tension of the acid to pull the excess metal to the surface away from the IFA. Die with poor release characteristics tended to have the excess metal lying on the IFA in the water rinse baths that could only be removed with a very fine loop of hair glued to a plastic stick. That removal process could stretch or tear the IFA and also very small pieces could be left behind on the IFA. Following the release and creation of the frames around the IFAs, the first testing was done on the IFAs in the frames. This testing was used to identify what columns in the IFA were functional (shorts, opens, and tears) and if there was motion, how many subarrays down from powered pads were working and a check to ensure the motion was not just electrostatic attraction to the chuck. Die released at the beginning of the testing that did not have the optimum release process were much more likely to be shorted when tested at this stage than those die released at the end of the testing. The later die tended to yield 3 out of the 4 devices with working IFAs. The IFAs released containing the mechanical arch diode did not function in this testing.

Apparently the additional scrap polyimide that is removed from that IFA, interferes with obtaining a clean release of the IFA. Additional work is needed to identify which scrap pieces are hindering the release process and how the design can be improved. At the end of the testing period approximately 10% of the IFAs were being damaged irretrievably by the framing process. Early framing efforts had a larger loss rate due to the paper frame shifting on the foil during the attachment of tape and also due to the foil being stuck too hard to the tape and not separating cleanly. These problems were overcome with increased framing experience.

Since the frames limit the amount of motion possible by the IFAs, only limited testing was done at this stage. With the IFAs surrounded by the frames, the testing was easily done with very little damage occurring to the IFAs (primarily gross mistakes in handling). An HP4145 was used as a voltage source during the testing. The 4145 allows for easy control of the maximum current supplied to the IFA to prevent unwanted damage due to shorts. A symmetric positive and negative voltage was supplied to the IFA to create an overall ground potential around the IFA to limit the attraction of the IFA to the chuck. The testing was done from the pads at each end. This was done for those cases where there was an apparent break in the metalization and to verify IFAs with motion all the way down the IFA. In addition to identifying which columns were operational, the minimum voltage that would result in motion was determined at this stage. This voltage was not a pure measure of the electrostatic/mechanical properties of the IFA since the behavior of the remainder of the IFA had a strong influence on this performance measure. If there was slack in the IFA between the tape ends of the frame, a lower minimum voltage was observed since there was less of a mechanical restoring force to work against. Also a larger number of subarrays functioning in the IFA would also decrease the minimum voltage. The minimum voltage observed in several IFAs for creating motion was 8V. Two IFAs from this fabrication run were tested over two different weekends to determine some lifetime information. Each device was operated at 4000 contractions per second while the IFA was still in the frame. These conditions limited the amount of motion produced by the IFA while allowing the testing to be done in a reasonable amount of time. In each case the testing was completed by turning the testing signal off while the IFA was still successfully operating. In one case 765,000,000 contractions were performed and in the other case 918,000,000 contractions.

Promising IFAs were then mounted on the miniature swing for further testing. A few IFAs were lost at this stage due to excess motion of the swing during the positioning of the swing on the probe station or during the cutting of the side pieces. A video camera was used to record the motion of the IFA on videotape for subsequent analysis. Only one end of the IFA can be powered when the IFA is mounted on the swing, so the best end was chosen for the swing testing. The applied voltage was ramped up in 1V steps for each power supply (a net increase of 2V per step) with a 150 msec additional delay at each step. This method was used to minimize the jerkiness and resultant resonant swinging by the swing in response and to produce a smooth motion that would allow easy measurements of the motion. Each ramp was repeated approximately 10 times without a break to allow a measure of the repeatability of the motion. A typical current consumed by the IFA was recorded for the peak applied voltage. During the testing the motion of the IFA and the current level was monitored to identify when a column in the IFA failed. A sudden reduction in the motion of the IFA or in the current level was indicative of a column opening up. This was verified by powering selected columns of the IFA and observing the behavior of the IFA. The testing would then be resumed with the appropriate columns powered. The maximum ramp voltage was increased by 5V (a net of 10V) after each sequence of contractions.

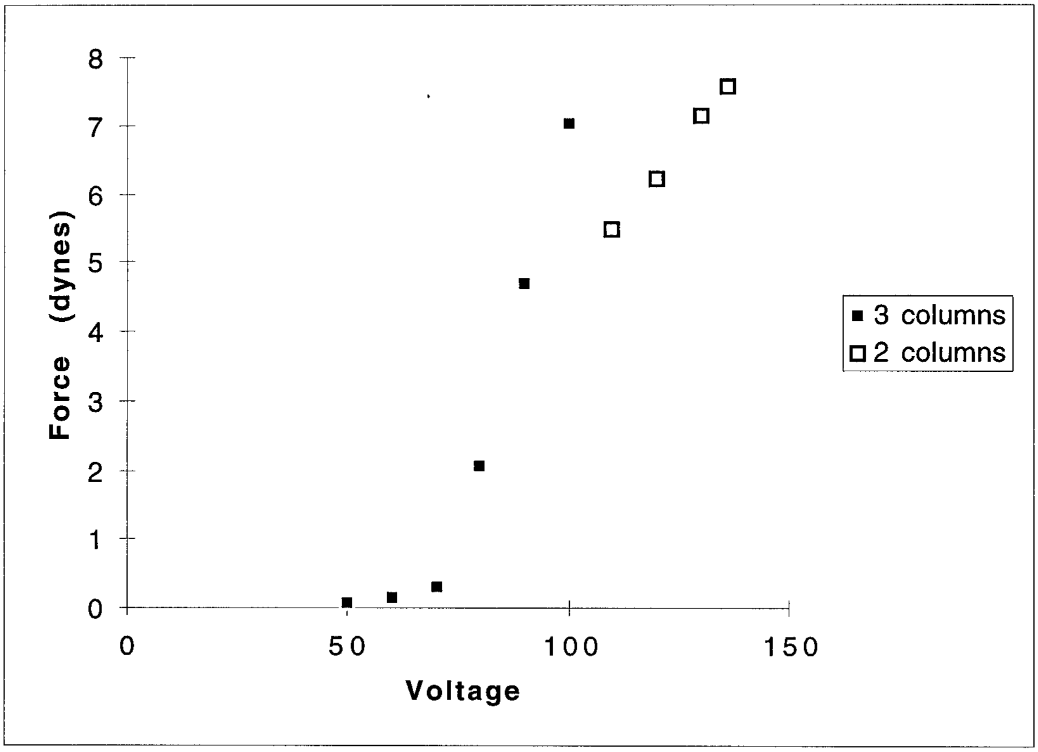

Figure 6. Measured force as a function of applied voltage for a single IFA.

Several IFAs were tested overnight while they were mounted on the swing to measure the lifetime of the IFA while undergoing large motions. The operating frequency was considerably lower than in the other lifetime testing in order to avoid the resonance frequency of the swing and to allow large motions of the IFA. One test at 4 contractions/second ran for 244,000 contractions before the testing signal was turned off while the IFA was still functioning. A second test at 2 contractions/second ran for 105,000 contractions. A third IFA was tested at 4000 contractions per second since the IFA was torn and the swing was not influencing the motion of the IFA. The tear was relatively close to the pad end, so the IFA was able to move that fast and still have a much larger motion than the earlier high speed lifetime testing. That IFA ran for 172,000,000 contractions before the testing signal was turned off. For that test the motion was somewhat smaller in extent at the end of the test than at the start of the test.

The maximum speed of the IFA was also investigated while the IFAs were mounted on the swing. At the frequencies tested, the swing was unable to respond except in an averaging motion. A stroboscope was used to detect the motion of the IFA. Maximum contraction rates were measured from 16,000 to 24,000 contractions per second for different IFAs.

The maximum force measured during the testing was 7.59 dynes for two columns at 136V which corresponds to a compression of 297 μm at the swing. The maximum force from three columns was 7.03 dynes at 100V. Figure 6 shows the measured data for this device. For comparison the maximum force measured during the NIST program was 13.1 dynes at 130V for two columns. One difficulty in the swing measurements arises from the occurrence of slack in the suspended IFA. The initial contractions will first remove the slack before the swing will begin to move. For the 136V measurement, portions of the IFA moved 610 μm while the swing only moved 297 μm. A similar behavior happens

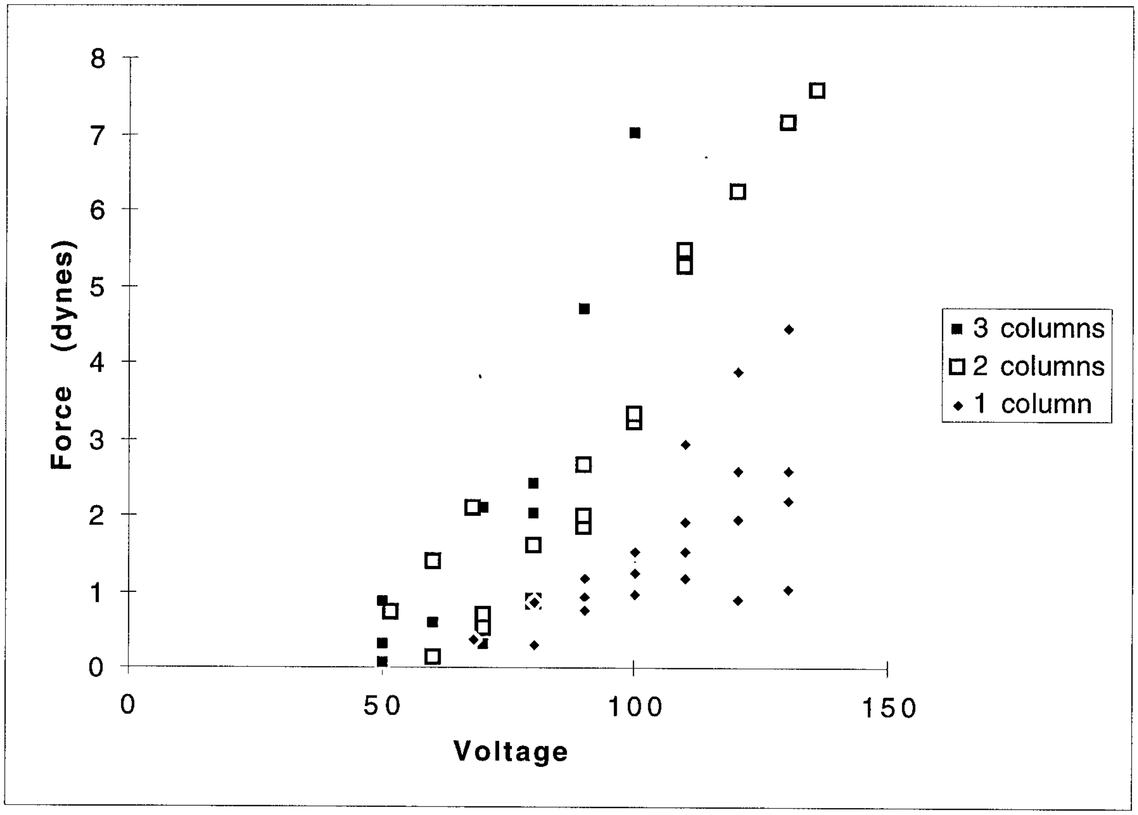

Figure 7. Measured force as a function of applied voltage for all tested IFAs.

when the IFA has a tear in it. During the NIST program the maximum measured movement of the IFA was 700 μm. All the IFAs tested from this run had maximum measured forces of at least 2.2 dynes. Figure 7 shows all the measured force data for all the devices. A general shape of the curves can be seen despite the variations in cell size and arrangements indicating the repeatability of the performance. Some of the outlying data can be attributed either to the occurrence of slack in the suspended IFA or to partial failures of a column. In general the die released at the end of the testing had better performance due to the better condition of the IFAs during testing.

The repeatability of the force and displacements during the repeated applications of the ramp voltage was quite good. For the earlier released die the total range was approximately 10% of the average value for a given voltage. Later die again had better performance with the total range of less than 4% of the average value for each voltage.

The hysteresis of the IFA was observed during a very low frequency sawtooth signal applied to an IFA. The closure of the IFA was much faster as a function of time than the opening of the IFA. This corresponds to the closing occurring during the voltages closer to the peak voltage and thus over a short period of time, and the opening occurring over lower voltages, hence the longer period of time. The hysteresis is due to the large increase in the available force when the capacitor plates fully close.

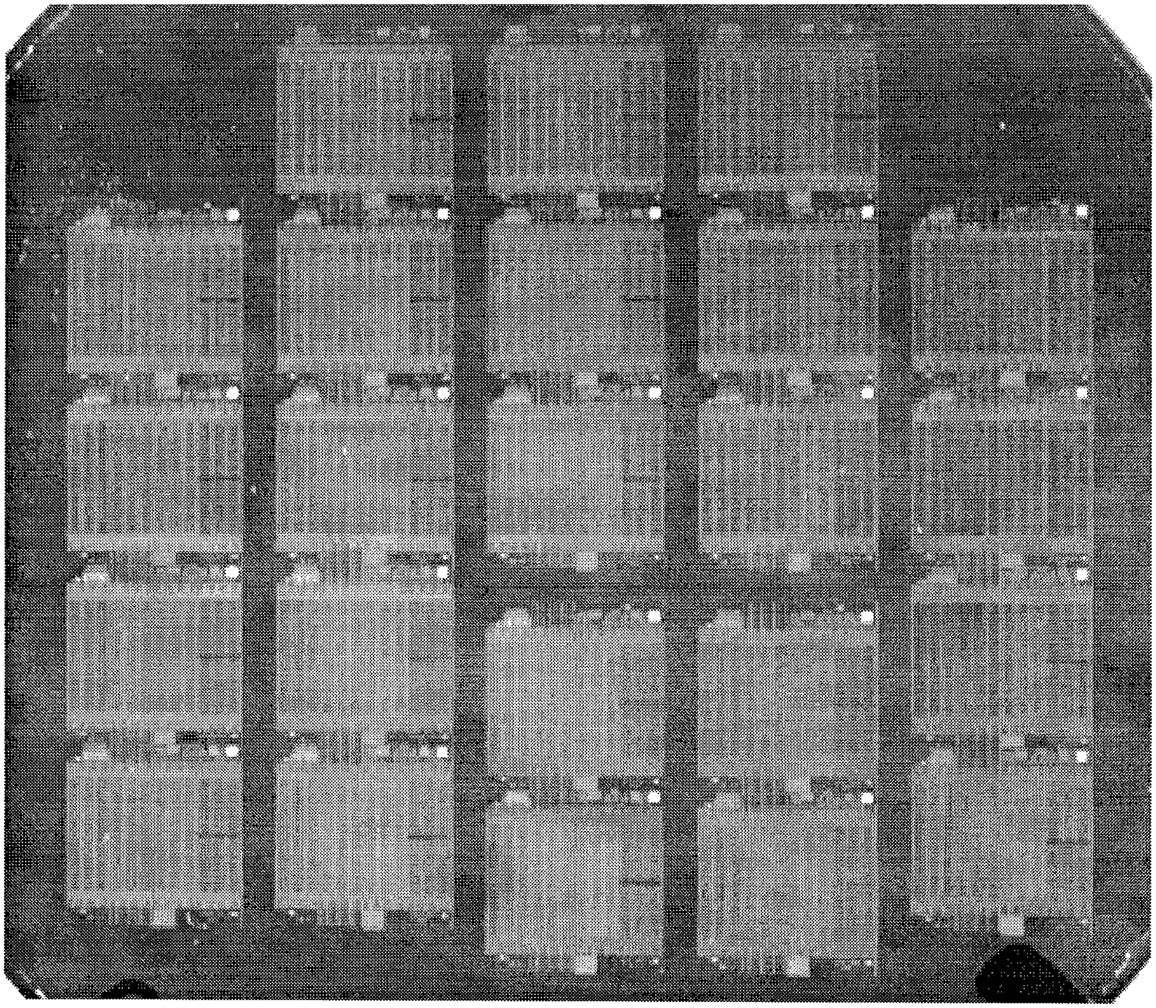

Figure 8. A photograph of a completed wafer showing two IFAs each of four, three, and two fields and one five field IFA.

Larger Area IFA Fabrication

The size of the current IFAs fabricated during the NIST program was limited by the field size of the step and repeat photolithographic stepper. This is the exposure area where it can maintain the focus and the dimensional control of the features. As was described above, the mask design was altered to permit the overlap of the edges of the exposure fields during the stepping process and allow the size of the IFA to increase without any major change in the fabrication technology. Because the alignment between adjacent fields is relatively poor, (on the order of several microns) and because there is some overexposure of the edge features, the size of the edge features cannot be made as small as the features in the middle of the field. Since the electrical pads and interconnections at the ends of the IFAs are relatively large, overlapping these features is possible. By extending the pads of the IFA and using the framing blades on the stepper, long IFAs were fabricated that have a continuous metallization path from one end to the other. Figure 8 is a photograph of a

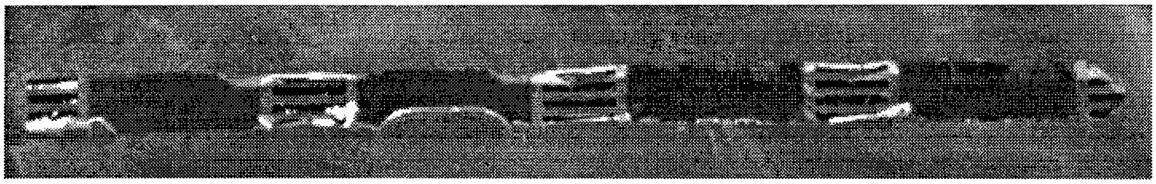

Figure 9. A photograph of a released four field IFA on foil.

completed wafer that contains the stitched or overlapped IFAs. By setting up the stepping program to make several passes on each wafer a variety of different length IFAs were fabricated. Long IFAs were successfully released from the wafers. Figure 9 is a photograph of a four field IFA, 51 mm long, on a piece of foil prior to the fabrication of a frame around it. The longest IFAs were 63 mm long, made from five fields as can be seen in Figure 8. With the use of a different stepping pattern than the five by five pattern we use, and with larger diameter wafers, even longer IFAs can be fabricated.

As was described earlier the angle and speed of the insertion of the IFA into the HF determines the amount of metal caps that are removed from the IFA. The longer IFA requires a deeper and larger volume container for the HF than what is used for the single die releases. This complicates the dilution process of the rinse baths since there is much more HF in the container. The overlapping of the field went smoothly except for one instance where the framing blades did not overlap enough of the reticle. The framing blades are used to control how much area of the reticle is imaged on the wafer in each flash. The positioning of the framing blades is measured in the hundreds of microns. Although the test exposures were perfect, when the actual wafers were shot with the half height reticle, the framing blades were approximately 10 μm beyond the end of the metalization pads at one end of the long IFAs. This was not seen until after the etching of the silicon film and deposition of the second polyimide film. As a result the topmost IFA in some of the long IFAs is electrically separated from the other IFAs. This is an easy problem to solve for future fabrication runs. For these fabricated devices, conductive epoxy can be used to bridge over the gap. Limited testing was done of these structures due to the increased difficulty in releasing the devices just described. A simple test to determine the ability of the overlapped fields to function properly was designed. The probes were placed in the long connecting pads between the IFAs, and the IFAs above and below the pads were examined for motion. The contracting motion was seen in those IFAs indicating that the electrical connection was continuous from one IFA to the next. The success of the fabrication of longer IFAs also indicates that the technique could also be applied to fabricate wider IFAs, or a single IFA that uses most of the wafer surface area. Increased precision in the placement of framing blades would increase the relative area of the active portions of the IFA and result in a more controllable process.

Polyimide frame for the IFA

The formation of the building block IFA actuator is based on the fabrication of a frame around the IFA. This allows the easy handling of the actuator during assembly. The use of a 25 μm thick polyimide frame will provide enough stiffness to significantly increase the ease of handling 2 μm thick IFAs. With this thickness, a large number of actuators can be stacked in a small volume, attached together, and mechanically freed by the removal of portions of the frame. In addition, the frame will provide an automatic spacing between adjacent IFAs. The combination of different modular IFA structures requires a simple and low cost method for making mechanical and electrical connections to the IFA. The electrical connections can be built into the frame by plating metal feed-throughs in the silicon trench before the polyimide deposition. A z-axis conductive tape can attach the frames together mechanically and electrically. An alternative method would be the use of fluxless soldering. With the capability to join the modules, customized IFA arrays can be created with the desired length and cross-sectional area for controlling the compression and force respectively.

A mask set was designed and fabricated to create a variety of polyimide frame test structures. Frames for 3 mm and 10 mm wide IFAs, and 10 mm and 20 mm long IFAs were designed with a variety of frame widths. The metal feed-throughs ranged from 400 μm by 600 μm to 100 μm by 100 μm in size. Several 3 mm by 5 mm frames were included with a center frame member to allow the formation of an actively driven, two direction IFA. Such a device could be used as a secondary actuator for magnetic disk drives. Because all the mask dimensions were relatively large, a contact mask was used.

Fabrication: The polyimide frame was fabricated by etching a trench into the silicon substrate using an oxide mask, stripping the oxide mask, and then re-oxidizing the wafer. The oxide layer is required to release the completed structure from the substrate. The trench depth was approximately 25 μm deep. A chrome/gold plating base was evaporated on the wafers, and an 8 μm thick photoresist film deposited and exposed to open the locations of the metal feed-throughs. Gold was then plated on the wafer with a thickness such that the top surface of the gold was a few microns above the top of the trench. Since the plating thickness was greater than the photoresist thickness, the plated metal mushroomed over the photoresist opening. This shape locks the feed-throughs into the polyimide frame. The photoresist was stripped, as well as the exposed plating base. Then a total of 40 μm of polyimide was deposited in multiple coating steps. At this point the wafers were ready for planarization and removal of the excess polyimide. Through the DARPA supported Tech-Net service, San Jose State University was identified as doing chemical mechanical polishing (CMP) of MEMS wafers. Although they had not done CMP of polyimide, they were willing and eager to add that capability to their service. The wafers were shipped to San Jose State University but the receiving department there mislaid the box, and the wafers were lost for over six weeks. Repeated phone calls to a number of staff members finally resulted in the wafers being delivered to the appropriate group at San Jose State University. During this time they were unable to obtain a polishing compound optimized for polyimide. Since so much time had been lost due the shipping problems, it was decided to polish a few wafers with the best polishing compound they had and to polish the remaining wafers later at their own expense when they obtained a more appropriate compound. Two wafers were shipped back to MCNC. Only about 10-15 μm of polyimide had been removed, leaving more than 25 μm of polyimide to be removed. The process had been designed for there to be 2-3 μm of polyimide remaining which would have been removed with an oxygen plasma etching step. To remove the 25 μm of polyimide with the oxygen plasma would have removed too much of the frame to continue processing. Instead it was decided to use a crude single wafer polishing tool at MCNC to remove more of the polyimide. One wafer arrived at MCNC broken and could not be polished. Some unidentified material had attached to the other wafer backside at San Jose State University which could not be removed. This resulted in a high spot on the top surface of the wafer after it was attached to a vacuum chuck. When the wafer was polished with a diamond impregnated disk, the polyimide was quickly removed off of the high spot resulting in a large variations in the polyimide thickness. This second wafer also broke while it was being removed from the wafer chuck which prevented further processing of the wafer in the clean room. The final steps in the processing have not been completed as a result of the broken wafers. These steps included the etching of the remaining polyimide

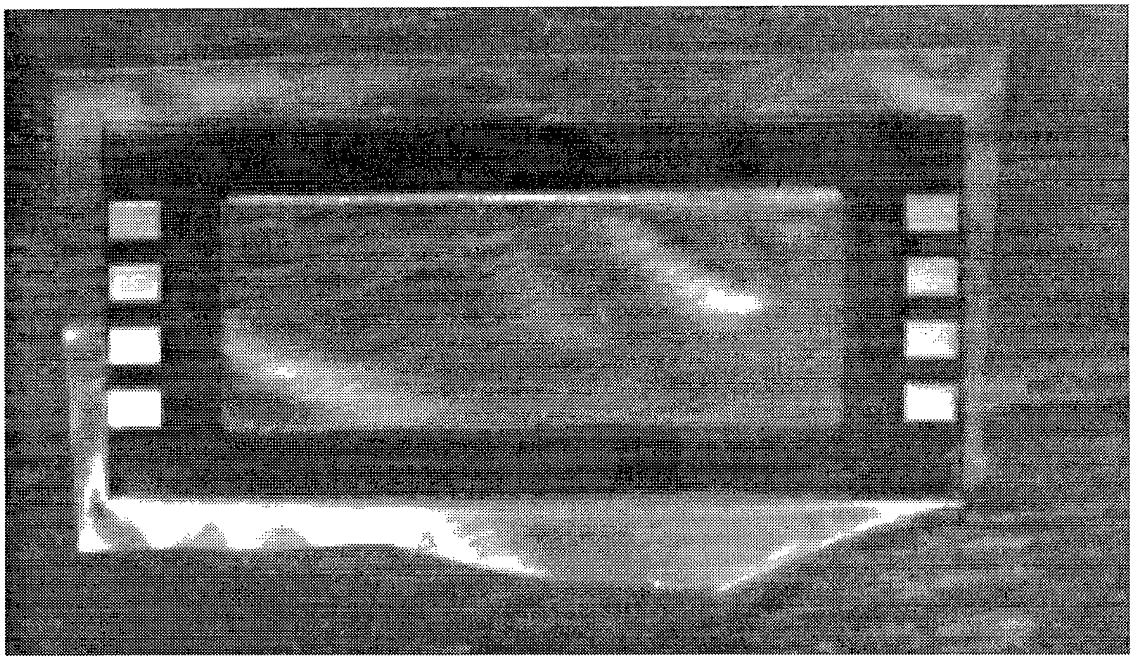

Figure 10. A photograph of a released polyimide framed membrane with gold feed-throughs.

film, the deposition of a new 2 μm thick polyimide film, and the patterning and etching of the polyimide over the gold feed-throughs.

Results: The broken wafers were immersed in HF to release the polyimide frames as they were. Figure 10 shows a photograph of one of the frames that has been separated from the other frames. As expected, the polyimide frames are very robust and easy to handle without any fear of damage. On the few frames where the polishing exposed the top of the gold feed-throughs some electrical testing was done. This involved the placing of the frame test structure on aluminum foil and probing the tops of the exposed feed-throughs to see if there was electrical continuity from the top of one feed-through, down to the foil and back up to the top of a second feed-through. These tests showed consistent electrical continuity where the gold was exposed.

Conclusions

The IFA has been shown to have repeatable performance results, not only from die to die and wafer to wafer, but also fabrication run to fabrication run. While the development process of the new release and framing techniques reduced the quantity of measured results from first die released during this program, the later IFAs showed promising results. Lifetimes of over 9×10^8 contractions were measured as well as contraction rates of up to 24,000 contractions per second. The maximum force measured was 7.59 dynes and the maximum observed motion was 610 μm. These measurements are consistent with measurements completed during the NIST program. New measurements were made of the consistency and repeatability of the performance with good results, and of lifetimes of large motion contractions. The robustness of the fabrication process was demonstrated by the quality of the fabrication processing and test results with no other IFAs having been fabricated during the previous year. IFAs five times longer than earlier devices were fabricated by the overlapping of adjacent exposures with the i-line stepper and released.

The overlapped pad regions provide electrical continuity as shown by the operation of IFAs above and below a probed overlapped pad region. The formation of monolithically fabricated polyimide frames around the IFAs appears promising despite the limited number of wafers processed with the test structures. The results provided by their second effort at the CMP of the test structures will be carefully examined and evaluated. As time permits, additional testing will be done on the fabricated IFAs using the improved release and framing techniques. These results will be communicated as they become available.

The results generated during this program supports the conclusion that the IFA is a powerful actuator and that further development work is warranted. The performance of the IFA is consistent and is primarily affected by the difficulties in handling the released IFA. With the creation of more robust IFAs, IFAs will be one of the very few MEMS devices that are totally released and separated from their fabrication substrate and then can be successfully interfaced to the macroscopic world. The formation of more robust IFAs is a crucial step in the widespread application of the IFA. This can be done through the fabrication of frames around the IFA, which will increase the yield of the released IFAs in the rinse bath, result in a simpler separation from the aluminum foil, and much easier handling of the IFA for testing and assembly into systems. The framed IFAs will allow the stacking of them for stronger actuators. Another approach to more robust IFAs is the fabrication of thicker structures. There are a number of approaches to achieve this. Molding of IFAs and IFA forms could greatly reduce the cost of the IFA in addition to the fabrication of more robust IFAs. A second approach is the use of conductive polymers which are etched with anisotropic reactive ion etching. Since there does not need to be a sidewall metallization, thicker structures can be fabricated. A third approach which moves from forming IFAs on a surface to forming them in volumes is to extrude an IFA through a metal mold formed by MEMS technology. This technique pushes extrusion technology into new dimensions not previously attempted and has the potential of forming IFAs measured in cubic centimeters instead of thicknesses of microns. Different applications will probably require different IFA fabrication techniques, so efforts in multiple fabrication techniques are necessary. The application of the IFA, a form of artificial muscle, in robotics can provide great advantages in power, weight, flexibility and force.

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Personnel Supported in This Program

Scott Goodwin-Johansson, Principle Investigator
Joseph Mancusi, Engineer
Florence Doutriaux, Design Engineer
Lindsey Yadon, Process Engineer
David Vellenga, Process Engineer