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Corporation for National Research Initiatives (CNRI) is submitting this Final Report for work performed on an award from the Defense Advanced Research Projects Agency (DARPA) under Grant Number MDA972-03-1-0022. This Grant award supported the program entitled, "A Widely-Accessible Distributed MEMS Processing Environment," also known as the MEMS Exchange program, whereby CNRI established, operated, and advanced a distributed MEMS processing environment in which fabrication and testing of MEMS devices and systems is performed at multiple, geographically dispersed sites located around the country.

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**A WIDELY-ACCESSIBLE DISTRIBUTED MEMS
PROCESSING ENVIRONMENT**

The MEMS Exchange Program

Final Technical Report

Reporting Period:
30 June 2003 – 31 July 2012

Sponsored By:
Defense Advanced Research Projects Agency (DOD)
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I. Introduction

Corporation for National Research Initiatives (CNRI) is submitting this Final Report for work performed on an award from the Defense Advanced Research Projects Agency (DARPA) under Grant Number MDA972-03-1-0022. This Grant award supported the program entitled, "A Widely-Accessible Distributed MEMS Processing Environment," also known as the MEMS Exchange program, whereby CNRI established, operated, and advanced a distributed MEMS processing environment in which fabrication and testing of MEMS devices and systems is performed at multiple, geographically dispersed sites located around the country.

The MEMS Exchange has dramatically increased rapid, flexible, and affordable access to MEMS technology, as well as made a broader variety of MEMS technologies available to the domestic community in a convenient, efficient, and cost-effective manner. The MEMS Exchange program has significantly increased access to conventional processing techniques, highly unique and hard to find processes, and new and promising MEMS fabrication technologies as well. A major research goal of the MEMS Exchange program has been to demonstrate that the fabrication of micromechanical devices, in particular MEMS devices, can be performed at separate and geographically distributed fabrication facilities without degradation in either quality or yield.   This capability was successfully demonstrated numerous times by the MEMS Exchange and the practice of using multiple foundries for MEMS fabrication has now become routine in the industry.

Although there are many benefits of this research, perhaps the most important is that a distributed fabrication network will significantly advance MEMS fabrication and manufacturing such that a diversity of product types can be developed quickly and inexpensively.   This has extremely important implications for the insertion of this technology into defense applications.   Another critical outcome is that the MEMS Exchange conducts a key role in diffusing MEMS technology throughout the DoD and non-DoD communities by providing high-quality implementation services to the various DoD laboratories and contractors. To establish a distributed MEMS processing environment, the MEMS Exchange utilized advanced communication and information technologies, including very high-speed networks, high-performance computing, and advanced web-based software, so as to link together dozens of fabrication and testing resources located around the country. This linkage, combined with the development of advanced MEMS fabrication techniques, remote access tools, and sophisticated operational methods is enabling a truly virtual MEMS fabrication environment to be realized and made readily accessible to the U.S. community.

This Final Report for the MEMS Exchange program being submitted by CNRI to the United States Government covers the entire program, spanning the time period from approximately June 30, 2003 to July 31, 2012. Within the program, there were specific goals and milestones as outlined in our proposal, the most important of which is the

transition of the program from being fully supported by the Government to achieving partial or full self-sufficiency.

The MEMS Exchange program contract had a five-year timetable running from approximately 2003 to the end of March 2008. A proposal was submitted to DARPA to extend the program out to July 31, 2011, as well as request support for the base activities for 2009, 2010, and half of 2011. Also included in this proposal was a request for funding for community outreach activities to help in achieving program self-sufficiency. This proposal was selected by DARPA and subsequently the program extension and additional funding instrument was executed by CNRI and the Government. More recently, CNRI requested and received a no-cost extension that extended the expiration date of the Grant from July 31, 2011 to July 31, 2012. The program is now expired.

II.   Program Overview

II.A.   Enlisted Fabrication Sites

More than 70 individual fabrication sites were enlisted to participate as service providers in the MEMS Exchange program. Most of these fabrication sites are commercial organizations and about 10 are academic sites. We also have one Government laboratory in the network, which is the Army Research Laboratory in Adelphi, Maryland. Our network represents the largest and most comprehensive collection of implementation capabilities that can be found. Currently, most of the processing work for the MEMS Exchange customers is performed at the Government lab by MEMS Exchange staff and in the MEMS Exchange's in-house facility. A small amount of fabrication is outsourced to selected foundries. This is a radical departure from early in the program when nearly all of the MEMS Exchange processing work was done at distributed academic fabrication sites. There are several reasons for this change, which include: the pricing is typically better and we have found that our customers are frequently very price sensitive; the quality of the work is usually better and our customers are extremely sensitive to the quality of the fabrication services provided; and, the turn around times are in general considerably better and customers are demanding quicker and quicker cycle times from the MEMS Exchange. Despite these limitations, it is important to note that the academic sites will likely always have an important role in the MEMS Exchange due to the fact that they frequently have unique and specialized processing technologies. More importantly, our new operational model utilizes in-house core competencies for fabrication and leverages existing fabrication capabilities at other foundries to provide our customers with greater design and processing freedom, but at a lower operational cost.

II.B.   User Registrations and Business Accounts

The number of registered users has continued to increase during the duration of the program and at the end of July 2012 stood at 7,497 (Figure 1). The number of business accounts set up by organizations using the MEMS Exchange service also continued to

increase throughout the program and stood at 971 separate individual accounts (Figure 2) at the end of July 2012. It should be pointed out that the business accounts are only derived from domestic organizations due to the restrictions placed on the MEMS Exchange by DARPA. It is reasonable to expect that if this restriction were lifted, the number of business accounts would have increased dramatically.
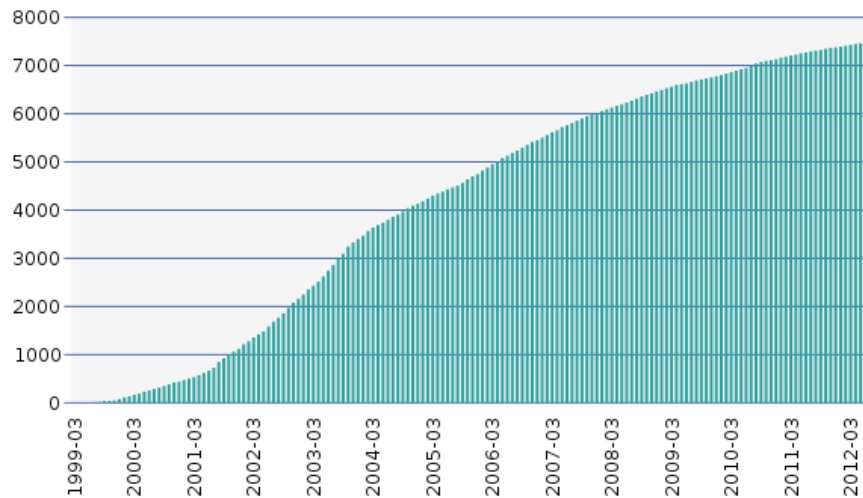

Figure 1: Chart showing the growth in the number of users registered with the MEMS Exchange for each month starting in March 1999 and ending July 31, 2012.
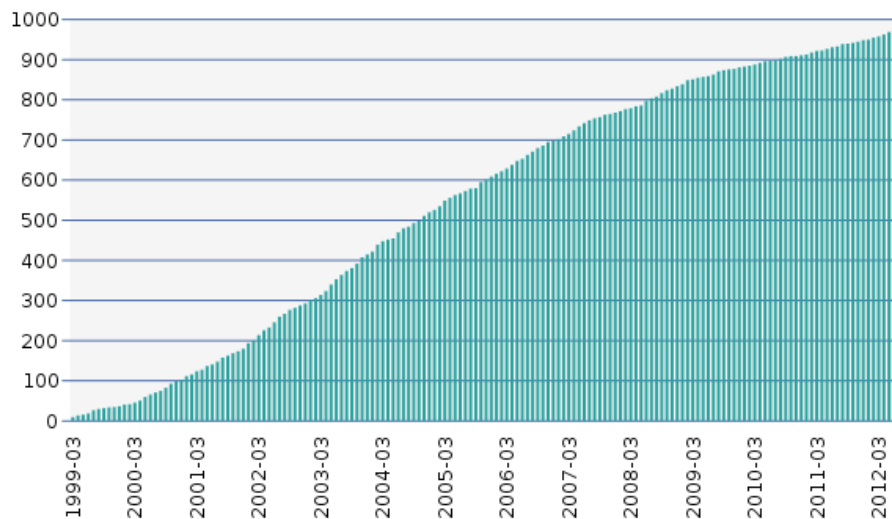

Figure 2: Chart showing the growth in the number of customer organization business accounts established with the MEMS Exchange for each month starting in March 1999 and ending July 31, 2012.

II.C.   MEMS Exchange Price Increases

A major goal of the current effort was to strive to make the MEMS Exchange service a self-sufficient operation.   Self-sufficiency requires the MEMS Exchange to charge users for the services delivered in an amount where total revenue equals or exceeds total expenses. Preferably we would want total revenue to exceed total expenses since this would allow a buffer or cushion to our cash flow. The expenses of the MEMS Exchange include: the cost of staff to run the service; the cost of staff to improve the service; fringe and overhead costs on the staffing costs; the cost of fabrication work performed in order to make quality control measurements on the fab sites; etc.   Importantly, the costs of running the MEMS Exchange are somewhat fixed and any scaling back of the services in one area may have a negative impact on services in other areas.

As we have explained in our previous reports, there are a number of ways that the MEMS Exchange can charge for the services it offers, but the most straightforward and simple approach is to charge a service fee as a percentage on each process run submitted from a user.   That is, the total cost of the process run is multiplied by a percentage markup, which is called a service fee.   This service fee is retained by the MEMS Exchange and treated as program income.   The application of a service fee has been the approach taken by the MEMS Exchange to derive program income to date.   However, it is worth noting that we have had sufficient flexibility to experiment with other pricing approaches.

The first application of a service fee by the MEMS Exchange was on September 1, 2001. At that time, a service fee in the amount of a 10% surcharge was placed on all process runs submitted to the MEMS Exchange for processing.   Subsequently, on September 1, 2002, the service fee on each process run was increased to 25%.   We believed at that time that a 25% service fee was nearing the limit that the service fee could be increased to before users would seek alternatives for their processing.   This is an important point and one confirmed through a customer satisfaction survey conducted in the summer of 2003, wherein we asked customers to estimate the monetary savings they achieved by using the MEMS Exchange service over any alternative sources.   The results of this survey were discussed in more detail in previous reports, but we found that customers estimated that they believed they saved between 25% and 50% (as a percentage of the cost of their process run) by using the MEMS Exchange.   This clearly indicates that there is a limit as to how much the MEMS Exchange can charge for the services offered before customers will seek alternative sources.

As part of the renewal, DARPA required the MEMS Exchange to conduct an experiment whereby the service fee would be radically increased to a level commensurate with the costs of running the program, assuming all other parameters, such as the number of process runs submitted and their size, remained unchanged. Although the previous service fees of 25% were considered significant from the perspective of our users, the service fees were not sufficient enough to determine the processing pricing elasticity. DARPA then directed us to further increase the service fees to a level commensurate with

what the MEMS Exchange would need to be nearly self-sufficient. One of the goals of this experiment is to attempt to measure the "price elasticity" of the MEMS community for processing services. That is, the pricing experiment is intended to measure the sensitivity of the community to the prices charged for processing services offered by the MEMS Exchange. One concern of this experiment is that it will cause undue hardship on some users, particularly those at smaller companies or academic institutions. Another concern is that these pricing experiments could potentially alienate the community toward the MEMS Exchange. Also, it would be expected that the number of runs will diminish as the price charged is escalated, and therefore the program revenue expected based on the number of runs could actually decrease rather than increase.

The MEMS Exchange was also required by DARPA to increase its fees another 50% at the beginning of 2006. Therefore on January 1, 2006, the effective multiplier placed on all new runs submitted (when the MEMS Exchange was not under a pre-existing pricing guarantee agreement with a customer) was increased by 50%. In 2008, after a program review with DARPA, prices were increased by an additional 10% across the board. This increase was in effect for nearly all of 2008, 2009, and 2010. Most recently, in the first quarter of 2011 we increased prices another 25% across the board. One concern with price increases is that during this economic downturn we have found that customers are even more price sensitive than they were in the past. For well more than half of the process runs we have provided pricing quotes for recently, the customers decided not to order from the MX based on their claim that our prices are too high. As part of our outreach efforts we performed a competitive analysis so as to calibrate what other fabrication sources are charging for prototyping work. This competitive analysis has been concluded and the results indicate that MX is less expensive than most other fabrication services around the US by an amount ranging from 25% to nearly 10X. In short, this analysis has shown that MX pricing is on the lower side of the range of prices quoted by commercial fabrication service providers. However, we are higher than the pricing of academic facilities.

II.D. Process Run Submissions and Completions

Figure 3 below presents the cumulative number of process runs submitted as work orders to the MEMS Exchange over time starting from the beginning of the program in 1999 to the end of July 2012. As can be seen the total number of process runs submitted since the start of the program was 2,621. We believe that the number of process runs that the MEMS Exchange has completed is a remarkable accomplishment. In comparison, the Microelectronics Center of North Carolina (MCNC) Multi-User MEMS Processing Service (MUMPS), which was established and supported by DARPA from 1992 to beyond 1998, performed approximately 24 process runs over a period of six years. In comparison, the MEMS Exchange has performed over 100 times as many process runs.

Work Orders Submitted
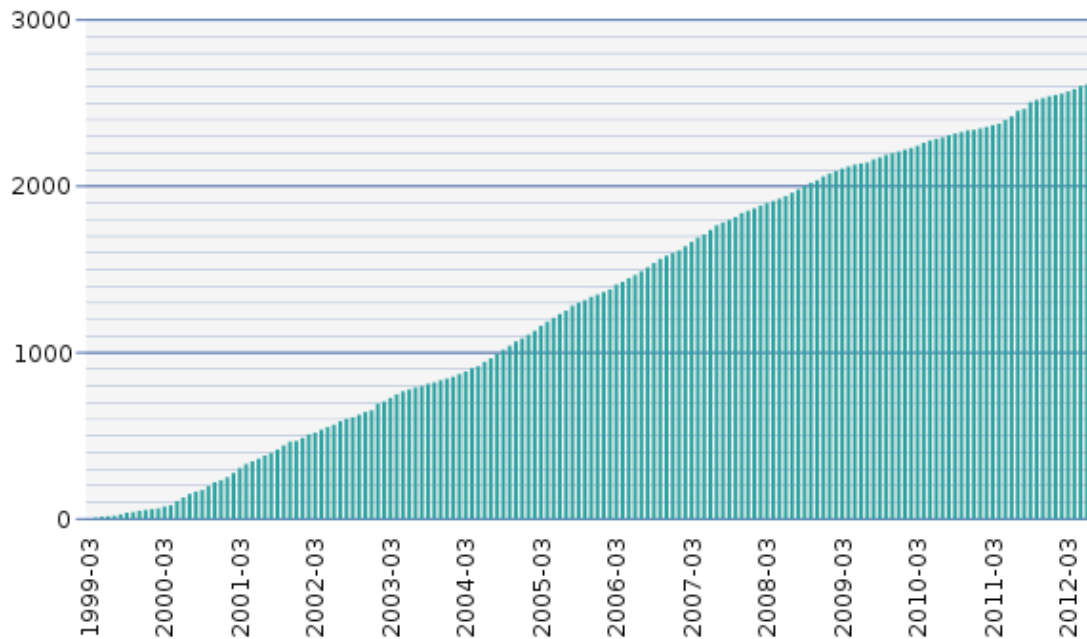
Figure 3: Chart showing the growth in the number of processing work orders submitted to the MEMS Exchange for each month starting in March 1999 and ending July 31, 2012.

II.E.   MEMS Exchange Self-Sufficiency

The MEMS Exchange has had various milestones pertaining to percentages of self-sufficiency that were expected to be reached at the conclusion of each calendar year. At the end of calendar year 2008, the MEMS Exchange was required to reach self-sufficiency of 70% and by the end of the year we had reached a cumulative self-sufficiency over the proceeding 12 months of over 70%. Therefore the MEMS Exchange exceeded the metric for the self-sufficiency goal in 2008. The metrics for the end of 2009, 2010, 2011 and the mid-point of 2012 have not been specified.

In any case, achieving ever-increasing metrics of self-sufficiency is much more challenging due to the downturn in the economy unless additional help comes from DARPA. Additionally, the funding to support our planned outreach and business development activities was planned to start in early 2008, but this funding only partially arrived at the end of January of 2009, thereby significantly delaying these efforts. Also, a subsequent Phase of the program that was to begin at the beginning of 2009 was started on August 1, 2009 due to delays in receiving funding from DARPA until July 2009.

As part of the new proposal to DARPA, we worked with DARPA and the MEMS Exchange Expert Panel (see below) to devise a set of new capabilities for the MEMS

Exchange that would expand and broaden the business and thereby allow a higher level of self-sufficiency. The capabilities deemed by DARPA, MX, and the MX Expert Panel to potentially bring in the highest revenue did not begin until the end of 2009 or in some cases have not yet been funded, which obviously makes it difficult to increase the revenue over the previous years. Mostly due to the down economy, especially R&D work that is the bread and butter of the MEMS Exchange business, the MEMS Exchange was still running a deficit at the end of July 2012. Nevertheless, we are continuing to strive to increase our revenue and program income and work toward complete self-sufficiency.

II.F.   MEMS Exchange Quartz ICP Etcher Research Efforts

The MEMS Exchange was requested by DARPA to purchase, install, and facilitize for operation, an ULVAC NLD-6000 Inductively Coupled Plasma (ICP) Reactive Ion Etcher (RIE). This is a high-end production-worthy semiconductor processing tool that has shown promise for high-aspect and deep etching into fused silica. This process capability is important for a DARPA project called the Navigation-Grade Integrated MEMS Gyro (NGIMG) program. One of the NGIMG performer teams, composed of Boeing, HRL and JPL, previously had the ULVAC company perform etches on fused silica samples that appear to allow 2 to 1 aspect ratios in fused silica with a depth of etch of around 125 microns – a dramatic result in a very hard to etch material such as fused silica!

After receiving approval from DARPA, the MEMS Exchange purchased a previously-owned Ulvac etcher and installed the system in its lab in Reston Virginia. Figure 4 is a photograph of the installed tool in the Class 10 clean space of the MEMS Exchange laboratory.

The Purchase Agreement between CNRI/MEMS Exchange and Ulvac incorporated a few important criteria. First, the etcher must demonstrate the ability to etch fused silica with an aspect ratio of 8 to 1 to a depth of 125 um, with 1 um sidewall roughness and no nodules present in the etched features. Second, Ulvac would transfer ownership of the process recipe for this etch technology to the MEMS Exchange.

Initially we had several problems with the Ulvac etcher that needed to be addressed by Ulvac. These problems have now been corrected. To date, the etcher has provided excellent results. Figure 5 is a SEM of one of the wafers etched using a reduced amount of nickel on the masking layer. The mask had a 5 to 1 aspect ratio and the etch depth is approximately 135 um. As can be seen, there is some re-deposit of material (believed to be the metal-polymer etch residue) about 1/5 down into the trench. This polymer residue can be removed using subsequent chemical cleaning. This result is extremely promising and shows that the etch technology can provide extremely high aspect and deep features in a hard to etch material. Figure 6 is a SEM of a wafer having a mask with a 2 to 1 aspect ratio and shows extremely vertical sidewalls, which are important for the gyro performance.

Figure 4: Photograph of the Ulvac NLD-6000 ICP RIE etcher installed in the MEMS Exchange laboratory.
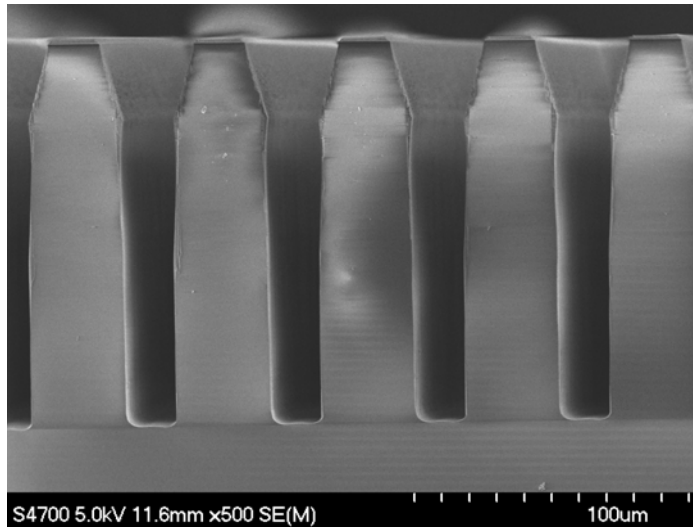
Figure 5: SEM of the cross section of a quartz wafer etched using the Ulvac NLD-6000 ICP RIE etcher installed in the MEMS Exchange laboratory. The aspect ratio of the etch is 5 to 1 and the etch depth is approximately 135 um.
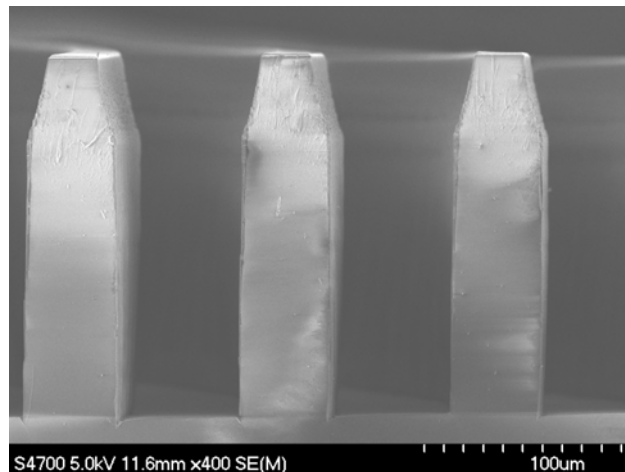
Figure 6: SEM of the cross section of a quartz wafer etched using the Ulvac NLD-6000 ICP RIE etcher installed in the MEMS Exchange laboratory. The aspect ratio of the etch is 2 to 1 and the etch depth is approximately 180 um.

The MNX has been supplying deep, high-aspect ratio etched wafers to the Boeing team on the NGIMG program until its completion at the end of September 2012. In the last Phase of the NGIMG project we etched a number of wafers for the Boeing team. Some of the initial wafers were part of a reproducibility study of the etch process. Extensive metrology was performed on the wafers both before and after the etch. The results indicated that the quartz etch process is very reproducible, having a wafer-to-wafer

uniformity of about 2.6%. Subsequent experiments were then performed to complete a Design of Experiments (DOE) study on the quartz etch process to find the optimal etch process for the NGIMG devices. The etching experiments as part of the DOE were completed and the collected data has been analyzed.

II.G.   MEMS Exchange Activity on DARPA BAA 04-10

The purpose of DARPA BAA 04-10 was to insert various processes into the MEMS Exchange catalog and make them available to the research and development community. To date there have been six efforts funded and these are: University of Colorado at Boulder for an Atomic Layer Deposition (ALD) of Alumina and Zinc Oxide; Rockwell Scientific for the aMEMS process; ISSYS for a high vacuum wafer level MEMS packaging; University of Michigan for a Silicon-On-Glass (SOG) and a Plastic MEMS process; University of California at Berkeley for a vapor deposited surface treatment; and Carnegie Mellon University for an Application Specific Integrated MEMS Process Sequence (ASIMPS). Currently, all of these processes have been developed, entered into the MEMS Exchange catalog, and beta runs have been completed for interested customers.

II.H.   MEMS Exchange Activity on DARPA BAA 05-12

The purpose of DARPA BAA 05-12 was to require performers to exercise the MEMS Exchange fabrication services as well as to insert new processes into the MEMS Exchange. The performers tasked with exercising the MEMS Exchange include: ARL; UC Davis; Tao Systems; University of Tenn.; University of Michigan; Science Research Laboratory; Rockwell Scientific; Quasar Corporation; University of California at Berkeley; Navy SpaWar Center; and Orbital Research, who received two contracts on this BAA. Most of these projects involved at least two full process runs. At this time the MEMS Exchange has completed all of the fabrication work on these projects.

Under this effort one performer was also funded to insert a process into the MEMS Exchange. This performer was SP3 of Mountain View California, for inserting a thin film diamond process. SP3 developed this process and has entered it into the MEMS Exchange catalog.

II.I.   MEMS Exchange Activity on Other DARPA BAAs

The MEMS Exchange is involved in the DARPA BAA 06-08 Analog Spectral Processor (ASP) program, performing fabrication work for Rockwell-Collins. We have received 8 fabrication runs and 6 draft runs on this effort. The first run was a 4 mask process for IF MEMS filters based on a design created by Cornell University. The MEMS Exchange completed this run in 21 days. The second run used 1 masking layer and was completed in about 7 days.

The MEMS Exchange provided proposals for several organizations on the DARPA BAA 06-25 Micro-Isotopes Power Systems (MIPS) including: Teledyne Energy Systems Corporation: Nonlinear Ion Dynamics; Research Triangle Institute; Sandia Laboratory; General Atomics; Cornell University; Hi-Z Corporation; and Executive Engineering. DARPA announced that awards were made to two of the organizations we provided proposals to including General Atomics and RTI. This program has expired.

The MEMS Exchange provided a proposal to Boyce Thompson Institute (BTI) on the DARPA BAA 06-22 Hybrid Insect MEMS or HI-MEMS program. We received 12 run submissions from BTI for this effort.

The MEMS Exchange worked with SRL on a proposal for using wafer bonding to attach solid-state laser diodes to heat sinks without the presence of a solder. This project has been completed.

The MEMS Exchange provided a seedling proposal to ITT on the development of a RF MEMS device and we were informed that this contract had been executed. However, we learned that DARPA cancelled this contract in early 2009.

The MEMS Exchange provided a quote to HRL on the DARPA IMPACT BAA 08-32 which involves performing deep high-aspect ratio etches on piezoelectric quartz materials. This program was not selected.

The MEMS Exchange provided a quote to GVS Inc. on the DARPA ITMARS BAA 08-74 which involves fabricating rotating MEMS devices. This effort was not selected.

The MEMS Exchange provided a proposal to DARPA to fabricate the Dynamic Pattern Generator (DPG) chip for the Nanowriter program. This program was selected and we have been developing a set of process technologies to fabricate the DPG device. This effort uses the Ulvac etch technology in order to make deep, high-aspect ratio cylindrical trenches into a multi-layer stack of thick dielectric films that alternate with metal film layers. We shipped the first device wafers to KLA-Tencor in June 2010 and we are awaiting news of their performance in the Nanowriter system. We were also awarded funding from DARPA to cover the development costs of the 5-layer DPG device. We sent completed 5-layer DPG device wafer to KLA for packaging and testing and we are awaiting results from these tests. We also sent a proposal to DARPA on the development of an advanced DPG device that would not require a charge-dissipating coating; this proposal is currently under review.

The MEMS Exchange submitted a proposal to DARPA-BAA-10-35 entitled, "High-aspect ratio, deep etching of Silicon Carbide (SiC) substrate material for emerging MEMS technologies." We received an award based on this proposal and completed negotiations for this contract. We began work on this effort in September 2011.

We sent in a proposal for the development of a piezoelectric Aluminum Nitride (AlN) technology for MEMS devices to DARPA-BAA-10-35. This proposal was recently rejected.

We also sent in a full proposal to the DARPA-BAA-12-16 DAHI program, which was recently rejected.

We also sent in a proposal abstract to the DARPA-BAA-12-43 LOCO program, which was rejected.

We also sent in a proposal to the DARPA-BAA-12-50 ICECool Fundamentals program, which is currently under review.

III.   Other Operational Changes

This section discusses other changes made in the MEMS Exchange operations in addition to the price changes, which were discussed previously in this report.

III.A.   Process Catalog and Bundled Pricing

In the past, when the service fees were increased over time from 0% to 10% and then to 25%, we saw increasing numbers of users going around the MEMS Exchange and directly contracting with the fabrication sites to get their processing work performed. This was relatively easy for the users to do since the MEMS Exchange web site had its supplier information accessible and open for the world to view. For example, the online MEMS Exchange catalog included the names of the fabrication sites, detailed information about the processes the fabrication sites were able to perform, and the cost that the fabrication sites charged. A user could go to the MEMS Exchange web site's online process catalog to determine what they wanted and where the processes they desired could be found. Not surprisingly, some customers would contact the fab site directly for the work, thereby not going through the MEMS Exchange to fulfill their processing needs. The user's motivation for taking this approach would be to avoid paying the service fees to the MEMS Exchange. This could allow a user to save 25% in the price of a run. For runs that were substantial in price, say a run costing $10,000, taking this round-about approach could save a customer $2,500. Of course, the problem with this is that the users were utilizing the extensive database, tools, and engineering resources that were developed by MEMS Exchange at significant cost to the Government without reimbursing or paying for these expenditures. Nevertheless, this action was easy for customers to accomplish since all the information was open and readily available. Evidence strongly suggested that this behavior increased in accordance with the service fee increases.

Before making the large price increases mandated by DARPA, we believed it necessary to put into place a mechanism to prevent users from accessing the processing information

on the MEMS Exchange web site in order to then contact the fabrication site directly for the services they desired. Consequently, the MEMS Exchange made various changes in our software system including the process catalog, run builder, etc., so that the fabrication sites' names would no longer be visible to the user.

Additionally, in the past the MEMS Exchange had listed the costs charged for the processing steps and tallied these on the run cards for the users to see, with a line item for the service fee added to the total of the processing costs clearly delineated. The problem with this approach is that the mark-up applied by the MEMS Exchange on all process runs was clearly visible to the customer, with the result that customers would frequently complain about the service fee and attempt to negotiate the service fee to a lower level. To circumvent this problem, we made changes in the software so that the costs that the fabrication sites charge the MEMS Exchange are no longer visible to the users and instead the user only sees a bundled total price, which includes the service fee.

Nevertheless, we thought it prudent to retain many of the more desirable characteristics of our operational system and for this reason the new software system allows users to still see all the processing details, and they can select the processes that they desire from the listing of equivalent processes in the catalog.

Another feature we added is the ability for a customer to ask for an instant online quote for processing work.   There is a "get a quote" link on the MEMS Exchange home page that activates this capability. Since it has been operational, we have received several instant quote requests per day. This has resulted in increased business and submission of process runs.

III.B.   Generic System

In addition to the operational changes described above, the MEMS Exchange developed a new capability that we call a "generic operational system." What we mean by this is a system in which the users merely select a process from a generic listing, such as LPCVD polysilicon, and then enter any relevant process parameters.   The requested process sequence is then filled out with the specific processes from the MEMS Exchange catalog by the MEMS Exchange engineers. The advantages of this approach as opposed to the past operational methods are that this approach allows the MEMS Exchange to balance the workflow at the fabrication sites much better and it also allows the MEMS Exchange engineers to select those processes better suited for a particular user.   This can be an advantage for the customer, since the MEMS Exchange engineers usually have more detailed and extensive knowledge about the processes available at the sites than can be conveyed in the process catalog.

Additionally, we believe that this operational methodology is better suited to the more inexperienced users. The MEMS Exchange serves a very large diversity of users whose skill and knowledge levels range from the very basic to the expert level. In general, the

expert users typically require very little help or guidance while the inexperienced users require significant assistance. We believe that the generic system is more efficient and less confusing for inexperienced users.   A fully generic system is now operational.

III.C.   Quality Improvements

Over the course of the MEMS Exchange program a number of new quality improvements were implemented. Perhaps the most important is the evaluation of processing steps by the MEMS Exchange engineer in charge of managing the process run to determine whether the work was completed to specification or not.   Additionally, the MEMS Exchange engineers have been responsible for contacting every customer after their run is completed to make sure they are satisfied with the results of the work performed by the MEMS Exchange as well as by the fabrication sites.   Another quality issue that we track is the turn-around times, or cycle times, for each fabrication site for each process step they are performing. This allows us to identify where there are bottlenecks in getting the processing work completed and we have already identified where most of the delays are occurring. For the most part delays are caused by having to perform process diagnostics on the wafers as the processing work is being performed. The way this usually happens is that we discover a problem with a step in the process and then we are required to develop a solution to the problem. Sometimes these solutions are developed very quickly (e.g., less than a day) and sometimes it can take weeks to develop a viable solution. As expected, quality control and improvement in the type of work the MEMS Exchange performs is an ongoing process.

III.D.   Community Outreach Activities

The MEMS Exchange did not engage in any official marketing or advertising activity since its inception in 1999 until nearly 2008. However, with the new milestone goals of increasing self-sufficiency each year, we believed that it was necessary to begin marketing and advertising our services more aggressively.

DARPA approved the support of a more robust marketing program to get an outreach effort started, including hiring a person to help with this activity.   CNRI interviewed five extremely qualified candidates as part of our outreach activities, most having at least a technical PhD and several years of meaningful experience and some having both a PhD and MBA combined with significant technical and business experience. Based on the recommendations from DARPA, as well as some other notable persons in the MEMS community, CNRI hired a person named Mr. Joe Brown to develop and execute our marketing activity, as well as make sales for the MNX. Importantly, CNRI considered Mr. Brown to be the least qualified of all the applicants we interviewed, but based on the strong recommendations from DARPA, he was extended an offer, which he accepted. He started working in this capacity in August 2009. A summary of many of the specific tasks that have been completed or are being worked on is provided below:

Market Awareness: We launched "MEMS Express from MNX" MEMS news in March, 2010. This is an electronic news service about MEMS technology and business that is sent out daily to over 8,000 readers/subscribers. We perform a daily capture of the most recent, relevant and important news items and select among them for our readers. Therefore, the MNX is providing significant value to its readers on MEMS news and events to allow them to be well informed. Importantly, this venue also provides MNX with the opportunity to broadcast information to a wide cross-section of MEMS professionals working in the industry to bring market awareness to MNX. Since offering this service, we have received very favorable feedback from readers in the community. An example of a recent MEMS Express that was sent out to our readers is shown below in Figure 7.
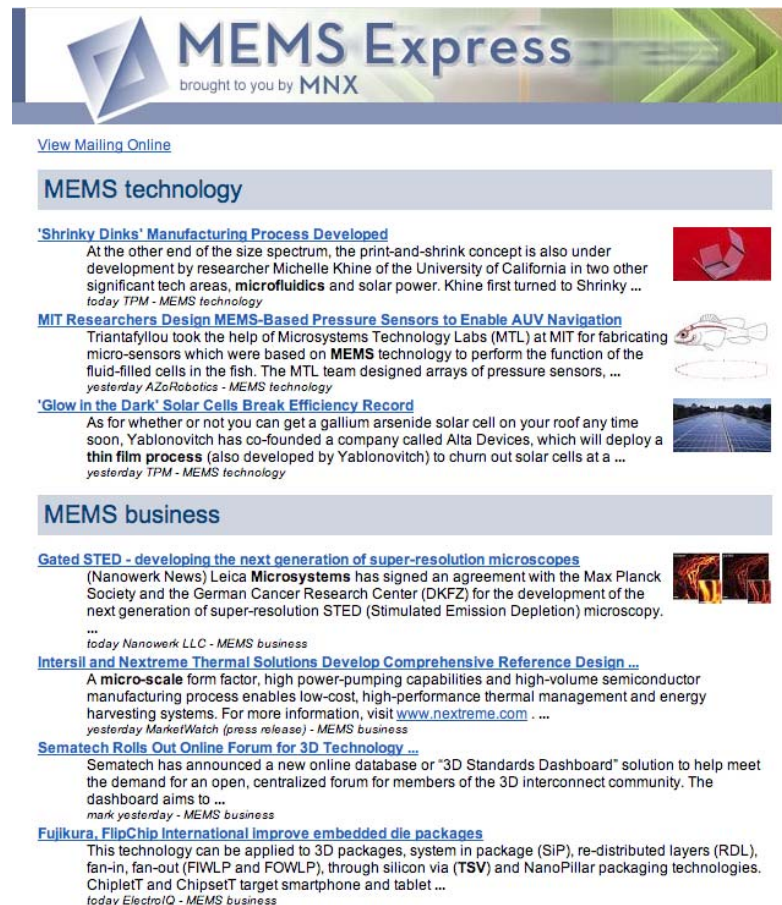

Figure 7: Screen shot of recent MEMS Express sent out to readers.

In addition, CNRI renovated its web sites, MNX and MEMSnet. We have engaged Jerry Gist of the Gist and Erdmann agency in the San Francisco bay area who is well known in this field to help us. An important goal for updating our web sites was to make them look

more professional and clarify what services MNX offers. An example of a newly released MNX home page is shown in Figure 8 below. It has a much cleaner and focused look and has an image of the inside of a foundry (not shown) that transitions into a diagram of the services we provide to our customers from Phase 1, concept development, to Phase 2, design and modeling, to Phase 3, prototype fabrication, and lastly to Phase 4, transition to manufacturing. We will also have a featured product or service that will vary periodically on the home page. The new web site required a large amount of work by the MNX staff to write new material, develop images, make decisions on style and format, and develop software for the more functional aspects of our site such as the process catalog, run cards, etc. Almost all pages of the MNX site are dynamically generated and therefore any design changes require that the underpinning of the software system be modified appropriately. The new web site was released in the summer of 2010. Jerry Gist also developed an E-beam advertisement for publication in print and electronic formats, and recently completed the MEMS Express newsletter template (see above). We also contracted Gist to re-design the MEMSnet Web site and this work was recently completed.

Figure 8: Screen shot of prototype MNX home page.

Additionally, CNRI presented MNX at various conferences (technical paper submissions & invited talks) such as: Sensors Expo (June, 2010); Microtech (June, 2010); 2 papers and presentations at the IEEE Sensors (November, 2010); 2 posters at the MFG2011 meeting in Napa, California (August, 2011); and a presentation at the NASA Sensors Tech Forum in Boston, MA (October 2011). At the IEEE Sensors event, MNX was selected for a dedicated session with six presentations about the MNX including one by

Dr. Huff on the basics of the MNX and five others from MNX customers. These meetings had very good attendance.

We also hired as a consultant a former employee of CNRI who worked as an engineer for the MNX to help us evaluate and understand the competitive landscape. This person left CNRI to pursue a MBA at MIT Sloan business school and is specializing in marketing. We crafted several representative projects and this person obtained pricing and service offerings from various foundry and development organizations. His final report is complete and he found that MNX was lower priced and more responsive to inquiries than nearly all of its competitors in the MEMS fabrication market.

Sales Activities: Sales leads from our outreach efforts resulted in our being asked to provide a number of device development quotes to customers. However, recently we have found that at present many potential customers are on very restricted budgets and while they claim to want to do work through the MNX, their funding and budgets are too restricted. Recently, we have also found that some customers have unrealistically low budgets for development (i.e. customer has only $5K to $10K to spend on a project that would nominally cost at least $50K or more).

We also began pursuing high-level business contacts with large companies such as IBM, Maxim, Freescale, Corning etc. This strategy has been based on working with larger companies to see if they would be interested in offloading their early stage development/prototyping activities to the MNX. The potential advantage for them to do this would be that these entities might be able to do development less expensively through the MNX while also getting access to more advanced fabrication technologies than would be available internally. Since the recession may be inducing larger companies to look for ways to reduce their internal costs, the timing of this strategy may be opportune. However, as yet, none of these relationships have fully developed.

Specific Events: The MNX attended a number of different meetings and trade shows in an attempt to increase our visibility and generate sales leads. In these events, we typically rented some booth space (usually a 10 foot by 10 foot space) on the exhibition floor and set up a display to inform the attendees about our services. The photograph in Figure 9 shows a typical booth set up at the MRS meeting that we attended and includes a large back poster; a looped slide show to explain our services; and a microscope to allow people to view some MEMS devices that we have fabricated. Brochures and other handouts were also provided.

A partial listing of the events that we have attended, set up, and manned a booth at is provided below.

Figure 9: Photograph of MNX booth at a recent meeting we attended.

Events Attended to Date:

DARPA PI Meeting, Aspen, Colorado (July, 2008)
MRS, Fall Meeting, Boston, Massachusetts (December, 2008)
Transducers '09 Denver, Colorado (June, 2009)
DARPA PI Meeting, Sun River Oregon (July, 2009)
IBM Trusted Foundry Meeting (September, 2009)
MIG Executive Congress (November, 2009)
Power MEMS (December, 2009)
3D Architectures and TSV Packaging Conference (January, 2010)
IMAPS MEMS packaging (March, 2010)
Integrated RF-CMOS MEMS Solutions for Mobile Terminals (March, 2010)
Micro and Nanomanufacturing (April, 2010)
MEPTEC – MIG METRIC 2010   (May, 2010)
International Microwave Symposium (May, 2010)
Hilton Head 2008 & 2010 Solid-State Sensors, Actuators and Microsystems Workshop (June, 2010)
Sensors Expo (June, 2010)
Microtech Conference and Expo 2010 (June, 2010)
DARPA PI Meeting, San Francisco, California (July, 2010)
COMS – Mancef (August, 2010)

Aerospace Measurement, Inspection & Analysis (October, 2010)
IEEE Sensors 2010 (November, 2010)
MEMS Executive Congress 2010 (November, 2010)
3D Architectures for Semiconductor Integration and Packaging (December, 2010)
SPIE Advanced Lithography (February, 2011)
Sensors Expo (June, 2011)
MFG2011 Conference (August, 2011)
COMS – Mancef (August, 2011)
MEMS in Motion (October, 2011)
Sensors Tech (October, 2011)
SPIE Photonics West (January, 2012)

MEMS Community Service:

I.   MEMS Clearinghouse

The MEMS Clearinghouse is a community service started by University of Southern California's Information Sciences Institute (ISI) back in 1994. The MEMS Clearinghouse consists of a website where relevant news items about MEMS technology and job announcements are posted, as well as a mailing list for group discussion of MEMS-related topics. Although the MEMS Clearinghouse was a vital resource to the MEMS community, it was no longer being actively enhanced or even maintained by ISI since support for this effort from DARPA ended several years ago.

In the summer of 2001 the MEMS Exchange took over maintenance of the MEMS Clearinghouse. In this transition, the software underlying the old site was replaced to make it easier to maintain. Our new site was launched on June 26, 2001, and is publicly visible at http://www.memsnet.org. More recently, the site was revised using assistance from a graphic artist to make it look more appealing and commercial-like. See Figure 10 below.

The most important features of the old Clearinghouse site were transitioned to memsnet.org, and new ones were added. In particular, memsnet.org now provides information about upcoming MEMS-related events such as conferences, news items, job postings, a directory of vendors for a variety of MEMS-related services and products, and a database of material properties. The back archives of the MEMS-Talk mailing list, extending back to 1994, have also been transferred to the new site. The traffic to memsnet.org remains fairly stable at around a few hundred-thousand hits per month.

Figure 10: The MEMS Clearinghouse Home Page.

II.   MEMS-Talk

One of the most visible parts of the MEMS Clearinghouse is probably the mailing list. Since taking over this function from ISI we have been able to improve the response time such that almost all messages are approved within a day of submission. If they arrive during work hours, messages will often be mailed within an hour. The electronic discussion group feature of the MEMS Clearinghouse is now called MEMS-Talk.

When we took over MEMS-Talk there were approximately 1500 subscribers. The subscriber list had not been kept up-to-date, thus about 60 (or 4%) of those addresses bounced or could not be delivered for various reasons (no such user, non-existent domain name, etc.). After the initial decline caused by removing these invalid users, membership began to increase and has now surpassed its starting point. The list now has around 3,000 subscribers from around the world, and it continues to increase daily.

Perhaps more importantly, the message posting on MEMS-Talk has increased significantly since being transferred to the MEMS Exchange. Initially the message posting traffic was about four messages per day, but it is now about 20 messages per day and increasing. The discussion primarily consists of questions and answers about fabrication. For example:

"Does anyone have some experience doing Si-Si bonding with LPCVD nitride & anneal process? Normally we know we can do the fusion bonding by oxide layer, but how about nitride? If we want to do this process, can we do the LPCVD nitride on both wafers?"

"Does anyone know of a wet etch for tantalum nitride? We are using it for an underbump metalization at a subcontractor who does not have a dry etch capability."

The list has attracted a core group of regular posters who often provide helpful answers, and most questions get at least one response. Occasionally there are higher-level questions about device design.

More recently, we've created two smaller satellite lists. MEMS-Announce is a low-volume moderated list through which readers can receive news, job, and event postings from MEMSnet.org. MEMS-Business is a new unmoderated list for business-related discussion.

Summary of Progress to Date on Outreach Activities: On the question of the impact of our marketing efforts, specifically the impact on growing the MNX revenue, we have no evidence that these activities have increased our sales directly. After steadily rising for several years, our revenue began to drop in 2009, we think mostly due to the bad economy. In years past we would normally see a fair amount of business from small early-stage start-ups, but in 2009 and 2010 we stopped seeing much business coming from these types of customers. Also the revenue coming in from external DARPA sponsored projects has been lower compared to years past. Therefore, while we have not seen an increase in revenue since we began the marketing activity, it is possible that we might have seen an even larger drop in revenue if not for the marketing efforts.

In our discussions with Joe Brown, he asserted that it would take 16 to 18 months from the start of the marketing effort before we will see any significant impact on our sales revenue. After over 18 months since we initiated our marketing efforts and with no sales that can be directly attributed to these activities combined with that fact that no impending sales were on the near horizon, we decided to terminate the contract with Mr. Brown and to mostly pursue the sales and marketing activities using our own staff. We offered Mr. Brown a purely commission-based arrangement whereby CNRI would not pay a monthly stipend to him, but instead provide him with a sales commission for any sales that actually resulted from his work. However, he has not accepted this offer.

III.E.   Business Development and Improvement Activity

CNRI was instructed by DARPA to conduct a comprehensive review and evaluation of the MEMS Exchange operation in order to make recommendations as to how to increase revenue and lower expenses and thereby become self-sufficient. Despite the funding having arrived later than expected, we started this activity and selected a panel of experts, composed of world-known MEMS and business professionals, who were charged with reviewing the MEMS Exchange. The selected members of the panel met at our location

in Reston Virginia on April 3rd and 4th 2009. We were able to review the MX activities with them and get their feedback, as well as define a set of new capabilities that would help to expand and broaden the fabrication offerings of the MX and thereby better serve the research community and bring in higher levels of revenue. The members of the panel included: Dr. Kurt Petersen; Prof. Roger Howe; Prof. Al Pisano; Dr. Howard Frank; and Dr. Harvey Nathanson. The capabilities the Panel recommended included: a new e-beam lithographic service whereby state-of-the-art photolithography service could be offered and provided in a commercial-like manner; a flexible process technology that integrated MEMS with CMOS; and a well executed marketing program. The e-beam capability was supported by DARPA and is now operational. The integrated MEMS/CMOS process technology development has not as yet been supported.

IV.   Software Advances

Since the start of the program, the software system has been invaluable. It allows the productivity of MEMS Exchange operations to be significantly increased, enables better customer services, and increases the visibility of the MEMS Exchange services on the Internet. Importantly, the MEMS Exchange software system is a web-based system and therefore avoids any problems with interoperability.

The activities of the MEMS Exchange generate a substantial flow of information describing resources, tasks to be completed, tasks accomplished, revisions, and records. When the MEMS Exchange first started accepting process runs, the information was tracked using paper. It was very clear from the start that the MEMS Exchange operations could only scale up with the support of an advanced and comprehensive software system. It was determined at that time that a commercially available workflow management system would not be satisfactory for the information technology needs of this sort of operational system and would have severely restricted the growth in the service and processing capability of the MEMS Exchange. Commercial systems match the needs of businesses for which the data models are simple and stable, but they don't match the needs of the MEMS Exchange, which is extremely complex. In particular, the data managed by the MEMS Exchange must be integrated with existing and emerging tools for the design and analysis of process sequences, and this integration requires data that is highly detailed and carefully structured. Moreover, we must design and adapt the data structures as we develop new tools and as we learn from operational experience. For these reasons, the MEMS Exchange developed a customized software system. We believe that this was clearly the correct decision and one that is verified by our successes and satisfaction of our users.

The CNRI proposal to DARPA made a number of specific commitments of accomplishments related to software development to be completed during the period of performance. All of those commitments were satisfied and many were greatly exceeded. Furthermore, the software development activities have played an essential role in our being able to meet or exceed the objectives of our other commitments related to

successfully demonstrating distributed and remote MEMS fabrication as well as offering the MEMS Exchange operation as a service to the MEMS community for prototyping purposes. The remainder of this section will account for how these commitments have been met or exceeded during the period of this program.

The primary task of the MEMS Exchange is the provision of fabrication services through a distributed network of fabrication centers. To facilitate this task, the MEMS Exchange develops and operates a web server at www.mems-exchange.org. The web server delivers a variety of functions that include:

- The web server provides secure access tailored to the specific needs of users. Users log in to the secure server with a user name and a password. They are given access to the data they need, and confidential information is protected.

- The web server provides for the construction, maintenance, searching, and browsing of a library of detailed descriptions of available processes and equipment. The descriptions of these fabrication resources include specific process parameters, equipment information, materials, and cost models.

- The web server provides for the construction, maintenance, and management of process runs, including wafer descriptions, mask files and descriptions, and process sequences. It provides a prototype process sequence simulator and a prototype process sequence rule checker to make it easier to detect errors. The web server also provides a mechanism for the collection of detailed records of processing, including images, email, and metrology data.

- The web server provides some important business support functions, including contact information, shipping information, cost estimation, and payment tracking. It also provides an interface for using and managing our inventory of wafers.

- The web server provides educational materials that help people learn about MEMS processing generally and also about the specific services offered by the MEMS Exchange.

The MEMS Exchange web site includes a variety of advanced and specialized software tools and capabilities that are also described in detail in the sections to follow. We have developed tools to help us maintain web pages with proper form and spelling, and to maintain the integrity of the records in our database. We also have developed a specialized high performance system for delivering dynamic web pages. The MEMS Exchange also develops software required to foster communication within the MEMS community. We also provide educational materials about MEMS processing in general and about services provided by the MEMS Exchange. The details of most of the software capabilities developed are described below.

Access Control

In order to protect intellectual property belonging to MEMS designers and fabrication sites we have developed an access control system for our website. The model combines the traditional user/group model with the idea of privileges and roles. This system allows fine-grained access control. Each user belongs to one or more groups, and has zero or more privileges within the context of each group. Each customer account has a corresponding group, as does each fabrication provider, and a special group represents MEMS Exchange staff in the supervisory/administrative role.

When access to any particular resource or action is requested, the software uses the model to decide if access should be granted. Objects implement their own access control rules. For example, you can view a process run if any of the following conditions is true:

- you are the run's owner, or member of the run's group
- you are a member of a fab group and have the privilege to review runs for that group, the run has some processing steps at that fab site, and the run is under review or is in progress
- you are a member of the MEMS Exchange administration group.

More recently, we implemented and now utilize a system for fine-grain access control, wherein specific privileges may be granted to individual users. Certain actions on the web site, such as changing descriptions of equipment or processes, are restricted to users with the appropriate privileges.

A growing number of runs continue the processing of wafers produced by other runs. The fabs reviewing the subsequent run must have access to information about the previous processing of the wafers, even if they did not participate in the preceding run. In response to this need, we have added the capability for MEMS Exchange staff members to grant to specific fabs the ability to view preceding runs.

Business Support

There are a number of core business objects defined within the virtual fab system developed to manage MEMS Exchange business operations. The next several sub-sections describe the nature of MEMS Exchange business and the elements used to maintain information about business transactions and the principals involved.

I.   Account Management

As an e-commerce business, customer relationships with the MEMS Exchange are established online. All required information for accessing services through the MEMS Exchange is offered online and must be used to the extent possible. Occasionally it is

necessary for a customer to call with technical questions about special processes that may not be listed on the system or other matters such as wafer availability. However, most of these inquiries can be handled by email directed to the engineers through various links located on our website. Most business and administrative forms and functions are available online. If the customer has questions that are not answered in the FAQ he can submit an email inquiry to business@mems-exchange.org or call the Business Manager directly.

Once a customer has browsed our website for basic information about our services and processes and has decided they want to create and submit a run for processing, they must create their own user ID and password. This is essential to using the MEMS Exchange. The main page has a sign-in link so the user can complete this necessary first step. This ID and password enables the user to access all of the functions offered by MEMS Exchange through his personal page, while protecting his privacy and keeping his runs confidential and inaccessible to other users. After the customer has created his user ID and password, an account application must be filled out so he can establish a business account. It is necessary to have a business account in place before a run can be submitted for work and before any billable consulting takes place.

II.   Users

When a user signs up for a user ID and password, an individual User object is created and maintained on their behalf. Users are distinct entities that contain contact information and are granted certain access privileges based on their role in the system.
There are three main roles:

- Ordinary User. The user role represents the customers of the MEMS Exchange service.

- Fab Staff. The Fab Staff role is assigned to workers at individual fabrication sites. These users are granted fine-grained management access to process steps being performed at their facilities but not to runs or steps for which their fabrication site does not participate.

- MEMS Exchange Staff. MEMS Exchange staff are the expert users of the virtual fab. They typically have all of the access of ordinary and fab staff users plus access to all of the underpinnings as well. MEMS Exchange staff have access to materials, equipment, processes, inventory, and business functions. MEMS Exchange staff can also temporarily assume the identity of other users in the system to see exactly what they see and to perform functions on their behalf.

In addition to these three primary roles, users without a user ID and password can visit our website without identifying themselves so as to read information about the MEMS Exchange and browse our process catalog.

III.   Fab Provider Information

Each fabrication facility that we work with has an associated "Fab Provider" object in the system.   Each process in the process library is made available through a single fab provider.   Fab providers contain contact and address information so that when fab sites ship materials to other fab sites, the list of shippable destinations can be displayed.   A fab provider becomes a shippable destination for a particular run if they have at least one process step they are contributing to the sequence.

Each fab provider has an access group.   Fabrication staff, for which privileged access pertaining to the fab is granted, will be present in this access group.   As a component of the access control model, the group is examined to determine access information to control certain behavior of the website.   Fab providers also contain fab-specific cost information used in cost estimation for process steps that are performed at that fab site.

IV.   Business Accounts

Before a user can submit a request for work to be performed on a process run, they must have a business account.   Business accounts contain billing and contact information, credit and payment notes, as well as the terms of the signed MEMS Exchange Customer Agreement corresponding to the account.

It's not unusual for several users from the same organization to refer to the same business account for billing purposes.   However, each of these users may maintain their own set of process runs.   Even though most users have a single account, some users have two or more accounts. This allows customers to bill individual process runs to different accounts.

V.   Payments

Once a process run has been completed and the MEMS Exchange has received all related charges from the fab sites involved, an invoice is generated and mailed to the customer. If the customer wishes to make pre-payment (e.g. to make sure this run is paid for out of the current budget), the MEMS Exchange will prepare an estimated invoice based on cost estimates shown on the run card.

Payment is expected for the amount of the invoice with payment terms of net 30. Payments contain information about the method of payment (e.g. purchase order, credit card, etc.).   The chosen payment method may depend on the amount of the invoice.   For example, if a run is above a certain cost threshold, the customer organization might require a purchase order; where smaller payments, like those for wafers, might be more easily handled with a credit card.

A payment transaction is recorded when some form of payment is processed against a business account. This typically occurs when a user wishes to pay for work performed for a process run or to purchase wafers from inventory.

VI.   Wafer Inventory Management

The MEMS Exchange has an on-site inventory of wafers that are available to customers for their process runs.   We have designed a management system that maintains information about our on-site inventory of wafers. The inventory is made available to customers for their process runs. In addition to being able to add new and edit existing boxes in the inventory, there are several ways to view the inventory. Some of these views are made available to users while they are creating a process run, which allows them to create wafer descriptions based on wafers in our inventory.

VII.   Wafer Payments

If a user has selected wafers from the MEMS Exchange inventory to create a wafer description, a payment for these wafers must be received before processing can begin. We created a payment infrastructure for selling wafers that the customer has chosen from our inventory.   On the run card, the customer is instructed to contact our business manager to make payment for any wafers the MEMS Exchange has been asked to provide and for which the specified wafers are in the inventory. Arrangements for payment are made and in the system a payment object is created. The payment is then associated with the wafers being purchased and boxes in inventory that match the wafer type specified in the wafer description are debited the appropriate amount. The wafer inventory system maintains a history for every box of wafers in the system that shows which wafers went to which runs and when.

VIII. Fab Invoices

We deployed a system that generates a monthly invoice page for each fab. The intent is to generate an invoice page directly from our records that a fab can submit to us as the actual invoice for the steps they completed for the MEMS Exchange in that month. The system offers the method of simplifying record management for fabs and providing automatic reconciliation between the billing records at fabs and at the MEMS Exchange.

Fab Resources

Fab resources are the data models used to represent the equipment and process capabilities of fabrication providers in the MEMS Exchange network. Initially both equipment and processes were classified in a strict hierarchy, but this proved to be too restrictive. Resources are now associated with one or more resource groups which are nodes in a partial ordering. This allows for flexible classification of fab resources. For example, an LPCVD process is a member of the CVD group, which is a subgroup of the

deposition group. Another example is a process for gold lift-off, which is assigned to the lithography group, and also to the deposition group.

In order to maintain fab resource data, several user interfaces were developed: the Process Editor, the Equipment Editor, and the Fab Resource Group Editor. The Process Editor is an interface for maintaining the library of process descriptions. It allows the entry and editing of process descriptions and maintains a complete history of all changes. It allows processes to be assigned to resource groups. It also provides mechanisms for the review and management of changes to process information. The Process Editor also includes the tools for defining various pricing policies that may rely on input parameters provided by the customer. Cost information can be entered and edited for each of the account types, so different prices can be provided for an academic, commercial, or government customer. Similarly, the Equipment Editor is an interface for maintaining the library of equipment descriptions. Equipment descriptions are similar to process descriptions but less complicated, as there are no dependencies between equipment and no cost modeling at the equipment level.

There are several equipment resource groups: "standard wafer-handling", "wafer piece-handling", "pattern generation", etc. A given piece of equipment can be assigned to multiple equipment resource groups; for example, a tool that handles both wafers and wafer pieces would belong to the "standard wafer-handling" and "wafer piece-handling" equipment resource groups. Finally, the Fab Resource Group Editor was added to maintain the ordering of resource groups and the entry and editing of group information.

I.   Physical Values

Specifications of processes and equipment always include physical quantities. For example, a deposition may be available for thicknesses from 1 to 2 microns, or at a rate of 5 nanometers per minute. Because units vary from one context to another, the MNX has developed a flexible, reliable, and accurate data type for representing units, allowing conversions of values between compatible units and arithmetic operations. The software includes the capability to represent ranges or sets of values as well as individual values. The representations of physical units are shared, so that there is minimal duplication, and the display of physical units is always consistent.

II.   Parameters

The Process Catalog includes detailed specifications of processes and equipment. These specifications include lists of known parameters, such as the range of depths available for an etch process or the diameter of a furnace tube. To enable the use of these parameters in simulation and rule checking, and to facilitate their consistent usage and display, the MEMS Exchange has developed software for the specification and maintenance of parameters.

To maintain consistency among parameters, we maintain in the database a set (currently about 240) of master templates for parameters. Every parameter in the database is connected to a master template, which governs the name and the type of values allowed for that particular parameter. For example, we have a master template with the name "resistivity" that is connected to every resistivity value in the database. The master template for resistivity records the fact that every resistivity is a physical value whose unit must be Ohm*cm or a unit that is convertible to Ohm*cm. Other master templates may specify different types such as materials, selectivity tables, or strings. Whenever a parameter's value is entered into the database, the value is checked against the master template to make sure that it has the correct type. To maintain the set of master templates, the MEMS Exchange staff use a facility called the Master Template Editor.

Consistency of types is essential for parameters, but we also use parameters for obtaining values from users. For example, parameters are used to record the customer's wishes about the depth of an etch as well as the fab staff member's measurement of the thickness of a film. In these cases, we may also want to limit the range of choices to make sure that they make sense in a particular context. For example, if an etch process is available for depths up to 2 microns, we would want to have a way to notice when a customer asks for 10 microns.

Process specifications include some parameters that are fixed values provided by the fab staff, but other parameters are constraints on the values that may be selected by the customer. These parameters with constraints are used to guide customers as they add processing steps to their runs. In addition to their usage in process specifications, parameters are also used in specifications of equipment and wafer types.

III.   Materials

References to materials appear in many places in the Process Catalog. In particular, process descriptions, equipment descriptions, and wafer descriptions all refer to materials. Until late 2001, the material references were not restricted in any way. As a result, the database developed inconsistent material names; for example, one process description might use the name "polysilicon" and another might use "poly" to refer to the same material. Consequently, the process sequence simulator had no systematic means to classify materials. The simulator needs this capability in order to model certain processing steps. For example, varieties of photoresist need to be identified in order to model processing steps involving exposure, development, or stripping.

We reviewed every material reference in our database, identified a consistent nomenclature, populated a Material Database with standard materials, and updated the process database to standardize every material reference. In addition, we organized these standard materials into categories that are now used by the Process Sequence Simulator and in other parts of our software. As a result, the simulator is more reliable and the descriptions of processes, equipment, and wafer lots are more consistent and accurate.

When users need to name a material, they are presented with a list of appropriate choices. For example, a user identifies the material of a wafer by selecting from a short list of materials that are used as substrates.

We also wrote a Material Editor interface that MEMS Exchange engineers can use to add or modify material standards as needed. Note that some materials, such as aluminum oxide, are associated with certain sub-materials, which may indicate synonymous names or variants. At the bottom of the list where "ambient" appears, a list of sub-materials for the gases that act as ambients in fabrication processes are also displayed. When a fab provider is describing a process, the choice can be made from this list of ambient materials.

The software modules for the representation of materials were revised and improved to clarify the semantics of material categories. This change eliminated the ambiguity between collections of materials (e.g. variants of silicon dioxide) and specific materials (e.g. plain silicon dioxide). This change in the underlying representation also required a revision of the (prototype) Material Editor.

IV.   Cost Models

Several different pricing models have been developed to more accurately estimate the cost of different processing and fabrication services. Cost estimation turned out to be surprisingly challenging to model as the variability in options provided to customers has resulted in high variation in the costs of processing. The costing framework allows us to estimate the cost based on the physical parameters supplied by the customer; for example, a deposition might cost $200 per micron of material deposited, so a step calling for 1.5 microns of material will be estimated to cost $300. Other cost models may depend on the time required to perform the step, the number of batches to be processed, wafer size, or any other step characteristics. The system also allows fab providers to price a process differently based on the type of customer. For example, some academic fab providers offer discounts to academic customers, while other fab providers offer discounts to government accounts. Another challenge is how to convey to the customer how changes in the process parameters affect the price of a process. In order to accomplish this in the Process Catalog, we display graphs showing the range of costs for each process.

More recently, we introduced a radically new and powerful type of cost model. Working with an ever-growing number of fabrication centers, and with a growing variety of processes, we have experienced the need for a wide variety of cost estimation patterns. Rather than attempt to predict all of these patterns in advance, we made a new cost model, called the Python Code cost model, which utilizes the power of a high level programming language to provide for an unlimited variety of cost computation patterns.

In particular, an engineer defining a process can select the Python Code cost model, and enter an arbitrary formula that should be used to calculate costs.   The formula

automatically derives inputs from the parameters of the process and the run and calculates costs that are displayed in the catalog and on the run card. For example, the formula might calculate the cost as a function of the thickness of a deposition and the number of wafers that the user intends to process. To make sure that the values of these variables are uniform across all similar cost models, they are always converted to use the standard units that are defined by the master template for each parameter. For example, "depth" in a Python Code cost model formula is always provided in microns, even if the value stored on a particular process step is stored using Angstroms as the unit.

One of the exciting new capabilities provided by the Python Code cost models is the ability to define sophisticated cost estimates for process modules, and even for flexible process modules. To facilitate this, the environment within which the formula is evaluated includes a function that allows it to calculate the cost of process components with specified inputs. This allows the cost model to evaluate the cost of alternative components in a flexible module automatically, and derive the cost estimate using the most economical choice dynamically. For example, a module might include two alternative deposition components, where one is less expensive for smaller batch sizes, but only when the thickness of the deposition is below a certain limit. The cost model can evaluate the alternatives and produce an estimate using the best of the two deposition components.

V.   Process Catalog

The MEMS Exchange maintains detailed representations of all processes offered at the various fabrication sites in a collection called the Process Library. The Process Catalog is a user interface for browsing through this collection. It allows users to select categories of processes and view the available process capabilities and the details of the equipment used. The pages generated by the Catalog are customized based on the type of user accessing it. When MEMS Exchange staff and fab users with the privilege to edit resources navigate through the Catalog, they see the Process Editor interface for adding new or editing existing process capabilities. Customers only see available processes with cost information customized for their account type.

Run Card

The Run Card organizes the descriptions of wafers, masks, processing steps, and business information associated with a processing run. It provides an interface for building and editing this information and managing workflow.

I.   Creating and Editing Runs

In order to submit a process run, a user must tell us four things: the sequence of steps they want us to perform; specified parameters for the processing steps to be performed (i.e., the thickness of a deposition of a thin film); the type of wafers to be used as the

starting point; and the photolithography masks to be used. The interface used for assembling and displaying process runs is called the Run Card.

In previous reports, there were two separate interfaces for dealing with runs. The Run Builder was used to assemble and edit runs, and a separate Run Tracker was used to view existing runs and to mark steps as being completed. More recently, we merged the two subsystems into a single interface for viewing and editing. This was done because we wished to make the presentation of runs more consistent in the two interfaces, but that would mean that users would easily become confused about which interface they were using. Instead, we decided to remove the distinction between the two interfaces.

When assembling a process run, users can browse through our Process Catalog, select a particular process, and enter any required parameters. For example, the user could select a "Silicon nitride PECVD" process to deposit silicon nitride onto their wafer and then enter the desired thickness of the nitride layer. This value is usually limited to a particular range of values; for example, at the University of Michigan the thickness must be between 0 and 2 microns.

The process sequence can also be modified by copying or moving steps already in the sequence into new positions. Users can also view output from the Process Sequence Simulator and Process Rule Checker, so they can spot potential problems as soon as possible. Once the user is happy with their process run, they can save it and submit it to staff at the MEMS Exchange for review. If the run looks feasible, then our staff will approve it and send it on to the fabs for manufacturing.

II.   Wafer Tracking

Certain wafer processing equipment requires the wafers to be processed to be MOS clean. If a wafer is contaminated with a material that adversely affects the manufacturing of metal oxide semiconductors it is not MOS clean and cannot be processed on MOS clean equipment. Certain types of wafers, such as Pyrex wafers, are inherently not MOS clean as they contain sodium ions. However, any type of wafer can become contaminated if processed with equipment that is contaminated. In order for our fabrication providers to know if a particular set of wafers can be processed with a certain piece of equipment, we integrated a wafer tracking system into the Run Card. In addition to tracking the MOS clean state of wafers it also tracks when wafers are broken during shipment or processing. The tracking system relies on a combination of knowledge within the database about the MOS clean status of materials, equipment, and processes, as well as input from fab staff who provide additional information on the state of wafers as they are processed.

We have greatly improved our capabilities for geographic tracking of wafers as well as masks and other materials associated with runs. This capability was enabled by the now widespread use of our packing slip generation system that is integrated with the FedEx tracking system. Each time the MEMS Exchange or a fab makes a shipment the packing

slip software module records the contents and the FedEx tracking number and status. This information is used to inquire about the locations of individual items. Every mask and wafer description on the run card includes the geographic location if it is known, and identifies wafers that are in transit between fabs.

III.   Wafer Descriptions

Wafer description objects describe the characteristics of a group of wafers. One of the side effects of the material database work, described elsewhere in this document, was the identification and specification of over twenty different wafer materials. Each wafer material has its own list of properties. Properties that apply to certain materials (e.g., 'silicon' and 'doping-type') do not apply to others (e.g., Pyrex (Corning 7740)). To address this problem, we parameterized wafer descriptions. This moved the specification of the set of attributes associated with a particular wafer description object to another object in the system called a wafer template. A wafer template object exists for each wafer material and specifies the list of properties relevant for that material.

We extended the data model for wafer descriptions to allow the specification of wafer sources other than the customer and the MEMS Exchange. The motivation for this change came when we handled some runs that started with wafers that were provided directly from inventory of the fab responsible for the first step of the run.

A more sweeping revision of the wafer descriptions stored in the database was the recent standardization of wafer diameter measurements. Until then, the MEMS Exchange database specified wafer diameters using either inches or millimeters, reflecting the ambiguous, but common, usage. Now 100-millimeter wafers are always accurately described. Equipment specifications were similarly updated, so that the set of acceptable wafer diameters is accurate.

IV.   Wafer Descriptions created from Inventory

Users can select wafers from the inventory and associate them with their process run. Users can then modify the name of the wafer description or the number of wafers they are requesting without affecting the wafer type information. Alternatively, users can replace an existing wafer description by selecting a completely different type of wafer from the inventory. Wafer descriptions derived from our inventory can be edited in the same way as wafer descriptions created from scratch. If the user changes parameters in the wafer description corresponding to the physical properties of wafer materials, the resulting wafer description may not match wafers that are in the inventory (e.g. the MEMS Exchange does not maintain a large inventory of 6 inch wafers). To assist users in matching their wafer descriptions to wafers that are present in the MEMS Exchange inventory, the user interface can list wafers similar but not identical to the ones specified in the wafer description.

V.   Wafer Types

We developed an object called "wafer type" that describes the physical properties of a particular collection of wafers. Material, resistivity, thickness and orientation are all examples of properties that could be contained within a wafer type. Wafer types provide three important functions in the virtual fab system:

- Wafer types are used in the Wafer Inventory to describe wafers present in one or more boxes. The distinction of wafer type from boxes allows the MEMS Exchange to easily determine the number of wafers of a particular type that we have in stock versus how many are left in a particular box.

- Wafer types allow the MEMS Exchange to insulate the details of box management within our inventory from the user. The fact that a user's request for wafers was fulfilled by taking 3 wafers from box 1 and 2 wafers from box 2 is information that is critical to managing a wafer inventory but not important to the user.

- Wafer types can be easily compared. Because each wafer type is unique, wafer descriptions are always associated with one and only one wafer type.

Along with the wafer type object we created a 'wafer type search' user interface that can be used by users when they want to create wafer descriptions by choosing wafers from our inventory. The user interface allows the user to select the wafer material and to view the matching wafer types.

VI.   Mask Management

Mask layout files are sent to the MEMS Exchange site using the file upload capabilities. Users then enter a corresponding mask description in the Run Card. A mask description contains information such as the mask's materials, the type of equipment with which it can be used, and the alignment marks. When editing a step in which a mask or multiple masks are used, users are prompted to specify the mask, the alignment method, and the relevant alignment marks.

The system for editing and storing alignment information is designed to be flexible. It is possible to use multiple masks in a step as process modules may have multiple components that require alignment, or a user may require different masks for different wafers processed in a step. We have also improved the run card by including alignment marks in the display of mask descriptions.

VII.   Recording Process Step Results

The step update interface is where fab users record their progress during processing. This tool allows the fabrication site staff to enter equipment time, personnel time, or notes about the processing.

Some process steps include metrology and inspection components. For example, most deposition modules include a metrology component that measures the thickness of the deposited layer. Results are entered by fabrication staff using the web site. Multiple properties can be measured and recorded for multiple locations on multiple wafers. Metrology and inspection results are permanently stored in our database in a form suitable for display and for later quality control analysis. The results are immediately made visible to MEMS Exchange staff and the owner of the run.

More recently, the interface provided for fab staff to enter metrology data has been vastly improved. In particular, the entry of large numbers of measurements is much more convenient and efficient.

A critical innovation developed is the capability to upload and associate files with process steps, process runs, as well as process and equipment descriptions. With respect to process steps, the attached files are typically images collected at fabs, used for quality control, but they may also be layout files, notes about alignment marks, or other files, in any file format. The same capability applied to processes or equipment allows for the attachment of, for example, the manufacturer's equipment specifications in PDF format.

We also developed a reusable user interface for uploading and managing file attachments. The interface allows for reliable file uploads using the browser, management of meta-data such as the content type and descriptive comments. The file attachment system implements a clipboard mechanism that allows attachments to be copied and pasted when necessary.

The file upload mechanism automatically determines the content type, so that, for instance, JPEG images are always recognized properly. This is important because browsers require this information to determine how to display or download files. For example, a browser usually downloads a DXF file for display using a CAD program, but image files are usually displayed directly.

Another feature of the new file attachment system is that it provides for the automatic display of thumbnail images as links to the full images. This capability is a tremendous improvement in the run card's ability to convey critical information. For example, many images of resolution structures are attached to steps involving lithography. The thumbnails make it possible for engineers to quickly find the images with the information they seek.

We have experimented with different access control models for file attachments. In the current model, the object to which a file is attached governs access to the file. For

example, access to a file attached to a process step is granted to any user that is allowed access to the step itself.

VIII.   Process Rule Checking

To address the requirement for process rule checking, the MEMS Exchange has developed and deployed a prototype version of a process sequence simulator and a process sequence rule checker.   The following two sub-sections provide detailed explanations of the operation of these two capabilities.

VIII.a. Process Sequence Simulator

MEMS Exchange customers use the website to construct process runs. A process run describes the wafers that will be used, the steps of the sequence, the subsets and sides of the wafers for each step, and the values of other parameters (e.g. depth, thickness, or material) that depend on the type of process. With all of these variables in play, there is some probability that the user will fail to produce a specification that matches his or her intent.

Unfortunately, these specification errors are difficult for customers to identify due to the number of details that must be considered.   Furthermore, because MEMS process sequences vary so widely, errors of specification may not always be caught when the process sequence is reviewed by MEMS Exchange engineers or by fabrication center staff.

The MEMS Exchange developed a Process Sequence Simulator to help to mitigate the problem of specification errors. The Process Sequence Simulator models the process sequence as each step applies to different sides of different wafers, and it constructs a schematic view of the cross sections that may be present on the wafers at each point in the sequence. These schematic views, called cross section diagrams, are a visual representation of the layers of materials, and as such, they create an extra opportunity for the user to identify and correct specification errors. For example, the following cross section diagram (Figure 11) shows the layers present after a deposition of 2 microns of silicon dioxide on the front side of a batch of 525-micron thick wafers:
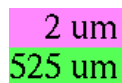
Figure 11: Cross Section Diagram after a Deposition.

The user can distinguish materials by the different colors shown, and the exact materials and other details of each layer are presented when the user moves the mouse over the particular layers in the diagram. A photolithography step that leaves 0.75 microns of photoresist on selected areas of the wafers would cause the simulator to generate this next cross section diagram (Figure 12):
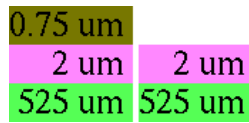
Figure 12: Cross Section Diagram after Lithography

If the user had intended for the photolithography step to apply to the back of the wafers instead of the front, a quick look at the diagram above would tell them that their sequence specification does not match their intent. This example shows the type of problem that would be difficult for a MEMS Exchange engineer to catch because he may not know the customer's intent.

The Process Sequence Simulator was implemented and deployed on the MEMS Exchange website and it has been made available to all users. The Run Card includes a link at the top of the page that can be selected to give a page that shows the cross section diagrams after each process step. Because the number of cross sections doubles with each lithography step, the Process Sequence Simulator only constructs cross section diagrams for runs with fewer than seven lithography steps. Most runs in the MEMS Exchange database have fewer than seven lithography steps, so the cross section diagrams are almost always constructed.

The Process Sequence Simulator is a useful tool that facilitates examination of the process sequence by all interested parties. However, there is considerable improvement that needs to be made in the system to make it extremely useful. In particular, the current system does not reference the mask or design information and therefore can only show all possible permutations of how the layers stack up on the surface of the substrates. We plan to interface the process simulator with the output from the mask layout editor to display a more accurate cross section of the substrate. Furthermore, we also developed an advanced system that allows the user to view the cross section in 3-D form and automatically mesh the structure for subsequent finite element analyses.

VIII.b. Process Sequence Rule Checker

While the Process Sequence Simulator is useful in identifying sequence specifications that differ from the customer's intent, there are a variety of other types of specification errors for which the Process Sequence Simulator alone offers no solution. The simulator produces a model of the processing, but it makes no attempt to make sure that the sequence is safe and sensible.

When customers submit process sequences, they are reviewed by MEMS Exchange engineers. The MEMS Exchange engineers check the sequences to make sure that they are sensible and safe for the equipment. This review process is tedious and time consuming, and it represents an expensive bottleneck in the work of the virtual fab. In an attempt to reduce the time and expense of the initial sequence review, we have developed the Process Sequence Rule Checker. The Process Sequence Rule Checker studies the run and looks for patterns that violate a set of rules.

Here are some examples of process rules:

- The wafers involved in each processing step must have dimensions that are compatible with the equipment that will be used in that step.

- Steps that have operating temperatures above 450°C should not follow steps that deposit aluminum.

- Photoresist should be removed between lithography steps.

- If a run includes an LPCVD step performed at Stanford, then it should be preceded by an appropriate cleaning step performed at the same fabrication center.

The output of the Process Sequence Rule Checker appears as a list of warnings that describe any rule violations that are detected.

The current version of the Process Rule Checker demonstrated the feasibility of this tool for the intended application. As we add new processes to our library and as we have more experience reviewing runs, we continue to develop and refine the set of rules. The Process Rule Checker has become a mainstay tool in the operation of the MEMS Exchange. Many of the rules are derived through interacting with the fabrication sites since we require the fabrication sites to provide reasons when they reject a run. These are then used to construct more rules and over time the fidelity of the Process Rule Checker continually improves.

The Process Sequence Simulator and the Process Sequence Rule Checker are available to all users. The system we have developed has successfully demonstrated the enormous opportunity of this technology.

IX. Run Life Cycle

Each process run begins as a draft, and may proceed through a sequence of states before it is completed. For example, a draft may be submitted by the customer for review by the MEMS Exchange, and from that state it may be circulated among the fabs involved for their review and approval, and so on. In each state, different people have different responsibilities with respect to the run. Fab staff have no responsibilities with respect to drafts, so the personal pages of fab staff don't show runs that are drafts. The personal pages of fab staff do, however, show runs that require their review or actual processing. The run life cycle governs workflow throughout the MEMS Exchange fabrication network.

As the run moves from one state to another, the actions available for the run change. For example, it is not until the Work Order Approval Agreement is accepted by the customer

and all of the fabs that actual processing can begin. Also, some changes from one state to another can only be initiated by certain users. For example, the transition to the Work Order state can only be initiated by the owner of the run, since that transition corresponds to the acceptance of the Work Order Approval Agreement. The MEMS Exchange software makes sure that the necessary requirements are met for each state transition.

More recently, the software modules that automate the run life cycle operations have been improved. First, we developed a new life cycle model with fewer states, thereby simplifying the basic operations of run management. Many of the software changes involved refining the conditions under which state transitions are available. The system now guarantees, for example, that cost information is complete and up-to-date before a run can be accepted by a fab. This improvement gives us a new level of support for process steps that require customized price quotes from fab staff. Other changes in the life cycle system guarantee that addresses are acceptable for FedEx, and that run cards and wafer descriptions are complete and consistent.

Previously, the life cycle management had an automatic notification system to inform (by email) the appropriate parties when certain transitions occurred. This notification system has been expanded to allow for notifications when certain transitions are attempted, even if they are not completed. For example, MEMS Exchange engineers now receive notification when a customer attempts to submit a run for review, even if some inconsistency of the run prevents the submission from going forward.   This provides a way for engineers to know when assistance may be needed.

X.   Personal Pages

The MEMS Exchange program included tasks describing the development of an electronic notebook capability. The electronic notebook provides each user with a convenient way to record and locate processing records, including images. The MEMS Exchange website maintains these records and images and links them to the associated runs. Convenient access to these records is provided through the user's personal page. After a user logs in on the MEMS Exchange website, the personal page is the first page seen. The personal page presents a view of the website tailored specifically for that user, including links to all of the user's runs. Because the personal page is dynamically generated, the page is always up-to-date and accurate.

The information presented on the personal page is organized in channels: one channel for the user's current runs, one for news items, and other similar channels. The channels included on the page vary from one user to another.

Fab users see channels that present processing steps that they need to perform and runs they need to review.   MEMS Exchange staff members see channels listing new account applications, process descriptions that are under development, internal reports, and site administration links.

The personal page for customers includes a link to a page for example runs. These runs cannot be modified, but they can be copied, to serve as a starting point for a new run. Even if they are not used directly to define new runs, the example runs give new users a model to help them understand the components of a complete run card.

Another feature on the personal page is the addition of a search field for FedEx shipments. A user can enter a FedEx tracking number to get the current status of the package.

XII.   Legal Agreements

The MEMS Exchange website supports the execution of a number of legal agreements which are necessary to protect the customers, the fabrication sites and the MEMS Exchange itself. Customers are required to review and agree to (by clicking acceptance) a copy of the MEMS Exchange Customer Agreement, which specifies the terms and conditions for engaging the services offered through the MEMS Exchange. In addition, every time a user logs in to the site, he or she sees and must agree to the MEMS Exchange Confidentiality Agreement, which describes MEMS Exchange policy with respect to confidential and proprietary information.

As a process run is reviewed by the staff at participating fabrication sites, they each are presented with the Work Order Approval Agreement for that run, which they may either accept or reject. Once all of the participating fabs accept the Work Order Approval Agreement, the customer is presented with the Work Order Approval Agreement, which he or she may either accept or reject. If the Work Order Approval Agreement is accepted by the parties involved and a method of payment is received, then processing can begin.

One interesting aspect of the Work Order Approval Agreement is that we now have some fabs that require extra terms in the Work Order Approval Agreement. For example, one academic facility requires language stating that the wafers "are to be used solely for non-commercial research purposes." When a run uses processes from this fab site, the Work Order Approval Agreement includes these extra terms and conditions.

Similarly, we also have at least one customer account now that requires its own special terms and conditions as part of Work Order Approval Agreement. This was for work completed for a Government organization. When this customer orders a run, the page presenting the Work Order Approval Agreement to fabs includes the customer-specific terms and conditions.

More recently, the run card as shown to MEMS Exchange staff includes a link to a separate web page that shows the contractual components of the Work Order Agreement so that we can more easily review the specific terms presented to customers and fabs.

XIII.   Shipping

The MEMS Exchange regularly ships wafers and masks to fabrication sites. Fabrication sites regularly ship wafers and masks to the MEMS Exchange and other fabrication sites. When processing is complete, fabrication sites or the MEMS Exchange ship wafers and masks to the paying customer. Keeping address information used for shipping up-to-date is critical to ensuring packages of wafers and masks do not get lost. Within the virtual fab database, accurate contact names, phone numbers, and address information for both senders and recipients is maintained.

When the MEMS Exchange began, the shipping of materials was accomplished via FedEx. Around the same time the virtual fab became our production management system, we established a shipping infrastructure using the FedEx website. There were a number of limitations to this approach. The FedEx website does not have access to the up-to-date address or run information stored within the virtual fab database. Instead, each fabrication site had its own FedEx login identity and its own set of addresses that was not necessarily the same as the other Fabrication sites. Due to a limitation in the FedEx web interface, the address book maintained for fabs tended to become inaccurate. As staffing changes occur at a fab, for example, staff at the MEMS Exchange would have to update every fab site's address book through the FedEx website. With the growing number of fabrication sites, this task was quickly becoming unmanageable. Another limitation of the FedEx website is that tracking information is only available for 45 days after a package is delivered. Often we need to check when a package was delivered after the 45 day period. Finally, because the FedEx website has no information about process runs, it was a manual procedure to associate shipments with runs.

To address these problems, we integrated FedEx shipping capabilities within the virtual fab system in order to centralize contact and address management, to store delivery information indefinitely, and to more closely integrate shipments with process runs. FedEx offers a software interface to ship, delete, and track packages called the FedExAPI. We developed a software interface to the FedExAPI and had FedEx certify it for production operation. From the Run Card, a MNX or fab user can create a FedEx shipping label by choosing from a centrally maintained address book. Only the addresses that are relevant sources and destinations for each run appear as choices for the sender. FedEx shipping labels and packing slips are created on demand and are printed out on a standard laser printer for use. Once a label is created a FedEx tracking number is assigned to the shipment and tracking of the package automatically begins. At any point in time, a MEMS Exchange or fab user can go to the shipping page of a particular run to see where the package is or if it has been delivered. Once a package has been delivered, the delivery date and signer are permanently added to our database so that the information can be recalled at any point in the future. If a shipping label was created by mistake, the shipment can be cancelled with a single click.

Periodically, we have improved the estimates of shipping and packaging costs that are shown on the run card. In particular, we now calculate the specific type and number of wafer containers needed and their associated costs. We also use the FedEx tracking data to display, on the run card, the geographical location of wafers and masks. Similarly, this information was used to enhance the Work-In-Progress report so that it includes more information about where wafers are currently located. This feature helps improve the efficiency of the regular conference calls between fabs and the MEMS Exchange staff.

Another change made provides for automatic email notification to MEMS Exchange staff when packing slips are created or changed. Also, the run number now appears directly on the shipping label and the bill, so that packages are easier to identify and reconcile with the shipping bills we receive from FedEx.

In response to requests from fab staff, the software system was changed to add support for scheduling and canceling FedEx courier pickups. This makes it possible for fabs to get all shipping operations completed entirely through the MEMS Exchange web site.

Record Keeping

I.   Mail Archive

The regular operation of the MEMS Exchange includes a great deal of email correspondence between MEMS Exchange staff, fabrication staff and customers. In order to manage this volume of email we have developed a highly scalable mail archive system. Email added to the archive is permanently stored. The archive currently contains about 16 thousand messages using about 340 MB of space but it should easily scale to hold many times that size in messages. Since many email messages relate to process runs, the web pages for runs allow for easy access to mail.

II.   Page Archive

The MEMS Exchange website undergoes continuous change. The majority of the web pages on the site are dynamically generated using data from an object database. New information is added to the database and existing information is updated. The MEMS Exchange software developers also make regular improvements to the website software; sometimes changing the way data is stored and displayed.

It is desirable to have a permanent, immutable record of the web pages displayed by the MEMS Exchange website. We have developed an archive system to automatically save nightly "snapshots" of web pages. The web pages are stored in a revision control system to minimize storage requirements. We have also developed an interface that allows the website to be viewed as it existed on past dates.

Fabrication Support

I.   Process Run Reports

With over 1000 runs in the system, the logistics of managing them could become a daunting task. To make this task easier we have written a number of report generators. The "Work Request" report summarizes the runs that have been submitted for review by customers.   The report lists useful information such as the customer and MEMS Exchange contacts for the run and what must happen in order for the review to be completed.

The "Work in Progress" report summarizes the runs that have been approved and are currently being processed at fabs. It gives an overview of the process steps being worked on at each fab and the progress of runs in the past week. In order to assist business operations, there are reports that summarize completed and cancelled runs along with their payment status. Other report generators include many charts that plot trends in the number of runs submitted and completed, the number of registered users, and the number of business accounts.

II.   Remote Microscope

Since the MEMS Exchange has primarily been a vehicle for prototyping, customers often wish or need to play an active role throughout the process sequence development, by frequently inspecting, monitoring or testing the wafers after every critical process step. Giving MEMS designers this capability in a distributed fabrication environment dramatically increases the likelihood of a successful process run and builds the information database necessary to begin to establish MEMS design and process rules.

Wafer access during fabrication can be managed in several ways. One approach would be to send the wafers back to the designer's location for inspection or testing after each critical step (of course, this assumes the designer has the appropriate inspection or testing equipment). This capability can be easily enabled, but would dramatically increase the logistical complexity, cost and time of a process run. Furthermore, many of the designers do not have any in-house MEMS testing capability.

A better approach is to allow the designers to "feel" as though they are in the lab without ever passing through the entry of the fabrication facility, and allow them to inspect, monitor, or test the wafers as they would if they were in the lab themselves. In this approach, the wafers never leave the fabrication facility, but instead would be remotely accessed. One of the most critical pieces of laboratory equipment for characterizing the process sequence is the semiconductor inspection microscope. As a first step to making the designer part of the fabrication process at key decision points in the process sequence, the MNX has developed an Internet-connected, remotely accessible automated inspection microscope system.

A Leica INM 200 fully automated inspection microscope was purchased and received. This microscope was selected since it offered the best price and performance of the available systems on the market at that time. All microscope functionality is completely automated, which allows the user sitting in front of the system to scan over the surface of the wafer, change magnification, change from bright to dark-field or differential interference contrast, focus and defocus, and place filters in the optical path, all under electronic control. Since the automation is electronically controlled, commands to control the microscope can originate from any location. Combining this capability with the ability to capture and transmit microscope images via a digitizing camera enables the remote designer to obtain high quality, high-resolution images from any location. Further, images can be stored by the designer for later retrieval and analysis.

Remote control of an optical microscope requires software for both the server and the client sides. The server software accepts commands from client programs and controls the position of the microscope's stage and the settings of the microscope's optics; it must also be secure against eavesdropping and break-ins, limit access and control of the instrument to authorized users, and must protect the microscope from damage as might be caused by hitting the wafer with the microscope's objective. The client software is executed by the end-users, and displays an image showing a region of the wafer as seen through the microscope, along with controls to change the region displayed and the viewing settings (magnification, light intensity, focus, etc.). The separation between client and server—they need only implement the communication protocol—allows the production of multiple interfaces.

II.a.   Microscope Server

The server implementation runs as multiple processes: a network server process waits for new incoming connections and services them, a camera control process takes snapshots and passes them to the network server, and a microscope control process controls the X, Y, and theta coordinates of the microscope stage via the stage's RS-232 interface. Driver modules can be written to support different equipment, and the right driver selected by a configuration file. This is an important development since a more modular based architecture will allow us to develop software that can be reused for other metrology tools we intend to make remotely accessible over the Internet. Currently, we now support the following devices: the Polaroid DMC camera or the PXC-200 frame grabber, and the Leica INM200 or INS1000 microscopes.

II.b.   Microscope Protocol

The protocol used is fairly simple, and is ASCII-based and human-readable for ease of development. Some sample messages in the protocol are:

CHATDISPLAY id=gwb msg="The alignment marks are clear"

```
MOVE x=1000 y=2000
IMAGE x=320 y=200
```

The first word denotes the operation to perform, and the remainder of the line is an accompanying set of named parameters. The protocol is asynchronous, so client and server can both send messages at any time, not expecting an answering response. That is, if a client sends a message requesting moving the stage, the client doesn't have to wait for a status response from the server. The server will process the message, and may optionally generate new messages; for example, moving the microscope results in two messages being generated, containing the coordinates of the resulting position and the graphic data for the new visible image. A separate TCP connection is used to transport the image data.

II.c.   Microscope Client

A graphical user interface for controlling the microscope has been developed as a Java applet to execute in a web browser. The digital camera being used has several modes of differing resolutions; for the sake of speed, a fairly low-resolution display is more frequently used when maneuvering the microscope. It can be switched to request a much larger, higher-quality image at any time and can save the image to a file for later use. The person controlling the microscope may draw a rectangular area on the display, or measure distances, and other users will see the same selection or measurement on their screens. The interface also provides simple text-based chatting with other users of the server; this allows working groups, or a teacher and a group of students, to examine a wafer together and discuss what they're seeing. An example of the microscope client is shown in Figure 13.

More recently, we implemented and deployed a prototype version of the remote microscope that works without Java through an ordinary web browser. This change was motivated by the need to make a system that requires no special client-side installation. The web-page version provides the essential remote access and control capabilities of the Java-based client.   In addition to the advantage of reducing the client side installation requirements, the new microscope client/server is simpler and therefore more reliable and maintainable.
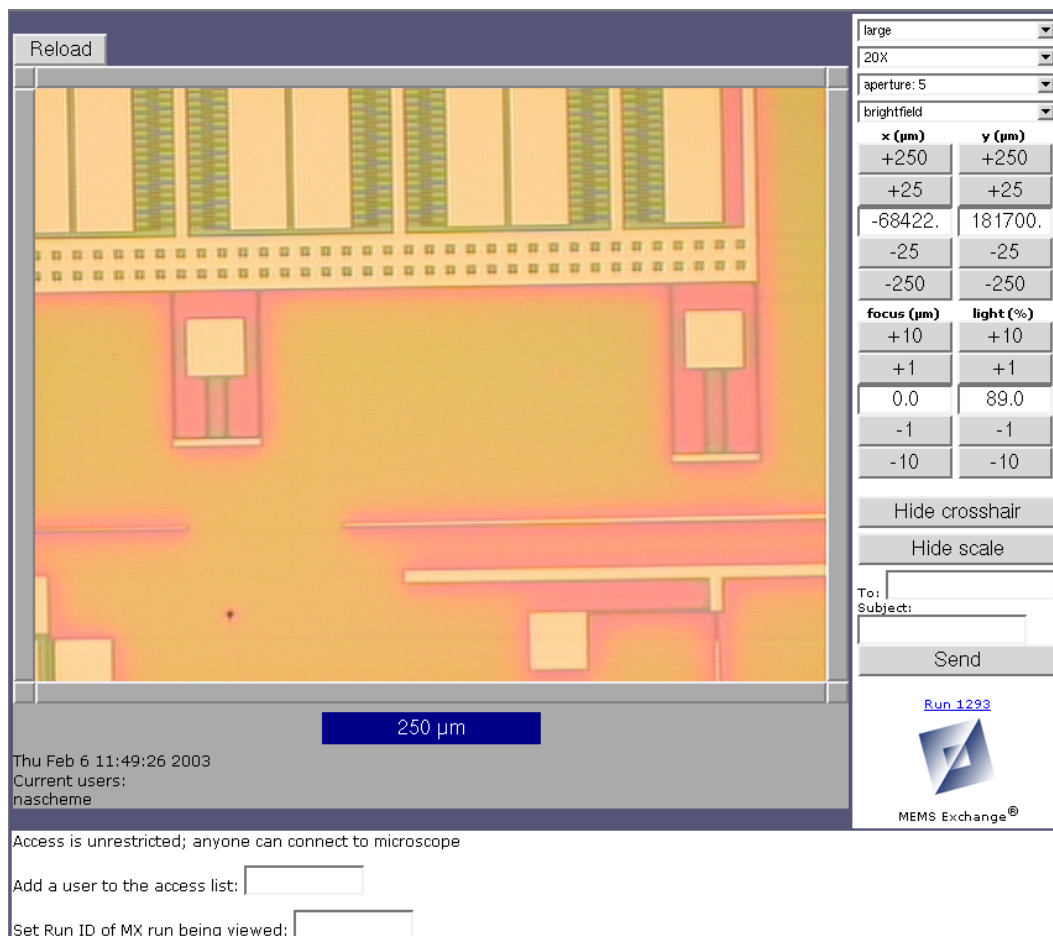
Figure 13: Screen Shot of Remotely Accessible Microscope Graphical User Interface Running on the Client Side Computer.

II.d.   Deployment

The MEMS Exchange deployed remotely accessible microscopes to several fabrication sites. The MEMS Exchange purchased four additional Leica microscopes and configured them as remotely operable microscope platforms. Completely functional remote microscope systems were set up in the microfabrication facilities at Berkeley, Stanford, Cornell, University of Michigan, and the MEMS Exchange. Each of these systems included a Leica semiconductor inspection microscope and a server computer with the accompanying remote microscope server software installed.

The remote microscopes have proven many times to be very useful tools in a distributed MEMS processing environment. These tools allow the users and the MEMS Exchange staff to view wafers at any time. Typically, the interaction is as follows: A problem or

question arises about a user's wafers. The staff loads the wafer onto the microscope stage and the user, the MEMS Exchange staff, and the fabrication site staff have a conference call while simultaneously viewing the substrate on their respective computers on their desks. The issue is usually successfully resolved within several minutes.

We also developed a faster version of the remote microscope by replacing the high-resolution digital camera with an analog camera combined with a frame grabber. The digital camera has an image size of 1400 pixels by 1200 pixels and 24 bit color, resulting in an image file size of over 40Mb. Due to limitations in the camera, the camera is only able to acquire a new image every second. We were interested in developing a system not constrained by the camera speed, but instead to the bandwidth of the network connection. The analog camera selected has a lower image size, in particular 480 by 640 and 24-bit color, resulting in a total image size of 7.4 Mb. When combined with the frame grabber it is able to push images of this size out at a rate of nearly 27 frames per second. Therefore the data transfer rate is around 200 Mb/s before compression. The current frame rate is close enough to the standard video rate of 30 frames/sec, that further optimization of the server seems unnecessary at this time. We configured this system on the microscope platform located at UCB and placed it on a very high-speed network, the Supernet.

More recently, we have found that capturing images and loading them into the run cards is typically more convenient and efficient for customers, fab sites, and MNX engineers.

III.   Handhelds

The PDA project began with the goal of giving fabrication site staff portable, up-to-date access to the MEMS Exchange process run database. The staff at the University of California Berkeley Microlab began using PDA devices as a primary means of accessing process run information and for reporting processing results. The feedback from the Berkeley staff was positive and we worked on deploying an improved system. The original interface required special client code and synchronization. We have experimented with the Compaq PDA platform using IEEE 802.11b wireless networking and an embedded web browser as a means of accessing the MEMS Exchange process run database. This platform allows full access to the MEMS Exchange website in real-time.

More recently with the increased technological capabilities of handhelds, the MEMS Exchange web is easily accessible using most any vendor product without any special software interfaces.

IV.A.   Software Releases

Over the course of this effort, CNRI released a number of different software packages as listed below:

- Durus, our object-database system,
- Qpy, our XML-generating system,
- QP, our web application framework,
- Dulcinea, our library of modules to use with QP, and
- Sancho, our unit test framework.

V.   Other Noteworthy Accomplishments of the Program

V.A.   Equipment

The MEMS Exchange purchased various items of equipment, some of which came from a MEMS fabrication site that had shut down. The equipment purchased included items supported under the new Grant such as an STS Advanced Silicon Etcher (ASE) Deep Reactive Ion Etch (DRIE) system, an STS Advanced Oxide Etcher (AOE), a Jenoptik HEX 03 Hot Embosser system, and an FEI Dual-Column Focused Ion Beam (FIB). Also, we purchased an Ulvac ICP RIE etcher. This equipment was made operational. The MEMS Exchange has also made several improvements to its clean room so as to install the new equipment. These improvements include: the installation of a new higher capacity air conditioning unit; installation of a Nitrogen delivery system; installation of a compressed air delivery system; and installation of a new process gas delivery system and a process gas exhaust system.

As part of the MEMS Exchange extension by DARPA, CNRI was provided funding to establish a new state-of-the-art electron-beam photolithography capability and make this capability available as a service to the community. Most of the funds for the tool purchase came from the Army and the tool is located in the Army's ARL Adelphi facility that the MEMS Exchange has access to.   DARPA contributed approximately $1M to ARL for the procurement of various upgrades on the e-beam tool that will allow it to be used as a production-oriented system. The new e-beam is now operational and two MEMS Exchange engineers have been trained and certified to use the tool.   The upgrades for the e-beam were installed in early 2010. The MEMS Exchange has been marketing and advertising this capability.

V.B.   MEMS Exchange Educational Initiatives

We have developed various educational documents and placed this instructional material on-line on our website to help provide information about MEMS technology, the MEMS Exchange, and how to use our site. For example, we placed a document entitled "The Beginners Guide to MEMS Processing" on the MEMSNet and MEMS Exchange

websites. This document contains an introduction to the methods used by MEMS processing engineers to fabricate and manufacture MEMS devices. We thought this document would be useful given the number of novice users who were unfamiliar with MEMS fabrication technology. This document has been reprinted in various archival journal publications in addition to the numerous downloads from our site. Therefore, we believe that this has reached a large number of people interested in MEMS. This document can be viewed at the following URL:

http://www.memsnet.org/mems/beginner/

Also, we have developed a guide to photolithography and mask making called "Mask Layout and Conventions", that is a general tutorial on photolithography as well as information about the resources available to users of the MEMS Exchange. Photolithography tends to be a process technology that can be difficult for inexperienced customers to fully understand. For example, a step and repeat system has a maximum die size and requires that fiducials be in specific locations. The purpose of this document is to explain the process of photolithography to users of the MEMS Exchange in general terms, but also to provide critical information such as where the alignment marks on the layout need to be located in order to do photolithography at the various facilities. This document is helpful to users as well as MEMS Exchange staff since it answers many of the questions that a user may have during the design phase of their project. This document can be viewed at:

http://www.mems-exchange.org/users/masks/

Another document, called the "Photolithographic Templates", provides specific mask making information and tools to successfully use the photolithography capabilities of the MEMS Exchange. One of the most important features of this document concerns the use of multiple photolithographic tools and at multiple fabrication sites. Obviously, for this to be successfully performed the alignment marks and fiducials must be located in the proper place on the mask and a large amount of coordination between the registration requirements for each tool must be accommodated. Also the document contains a variety of photolithographic alignment templates that can be immediately used for registration of masks to be performed at multiple fabrication sites and on multiple photo tools. This document is available at:

http://www.mems-exchange.org/users/litho-templates/

In addition to the information in the process catalog, the MEMS Exchange has developed and posted Frequently Asked Questions (FAQ's). Many of our new users contact MEMS Exchange with similar questions regarding signing up and getting started. While we will always be willing to walk users through the system, we would like this system to be as user friendly as possible. The more information provided on the web site, the easier it is

for the users, and the FAQ provides helpful information as well as consistency for our policies and procedures. The categories listed on the FAQ include:

* User Registration & Sign-in
* Establishing a MEMS Exchange Business Account
* MEMS Exchange Customer Agreement
* Pricing
* Payment
* Submitting Mask Designs
* Wafers
* Processes Available through MEMS Exchange
* Process Runs
* Miscellaneous Questions

The FAQ's are accessible from our main page and from various other links throughout the site.   The Frequently Asked Questions (FAQ) can be viewed at:

http://www.mems-exchange.org/exchange/faq/

In addition, we have been continuously adding new and updated content about MEMS technology and the MEMS Exchange to both the MEMSnet and MEMS Exchange web sites. Some of this information is quoted in widely distributed magazines such as *Forbes* and *Semiconductor*.

The MEMS Exchange has also addressed the general education goal by running the MEMS-Talk mailing list and managing the MEMS Clearinghouse.

Lastly, we have performed different presentations or workshops in each year of the program explaining to the community the services of the MEMS Exchange.   These presentations have been made at many academic institutions, commercial organizations, technical meetings, industrial meetings, and business forums.

Extraction of Processing Design Rules

A test feature set has been developed for direct optical measurement of design rules which is sufficiently generic so that it can be applied to just about any process sequence. The design rule test structures have been included in runs spanning a number of different process technologies. When the runs are completed the design rules may be read directly from the features. This information is being compiled into our database, which is then used to formulate design rules for custom process sequences. Additional runs are in progress to determine design rules for layering pairs of different materials and with varying thickness.   This information will continue to be collected as new processes are added.

<u>Merging Lithography</u>

A feature set has been developed to allow different lithography tools to be used on the same wafers. This is needed since we frequently have process runs where the photolithography is performed at multiple fabrication sites. Experiments have been completed to test the feature set to determine whether the alignment structures are adequate to allow a contact aligner mask to be successfully aligned to a stepper pattern and vice versa. We are now offering this capability to our customers so as to allow all lithography tools within the MEMS Exchange to be aligned to one another and thereby provide the customer with further flexibility. See Figure 14 below.
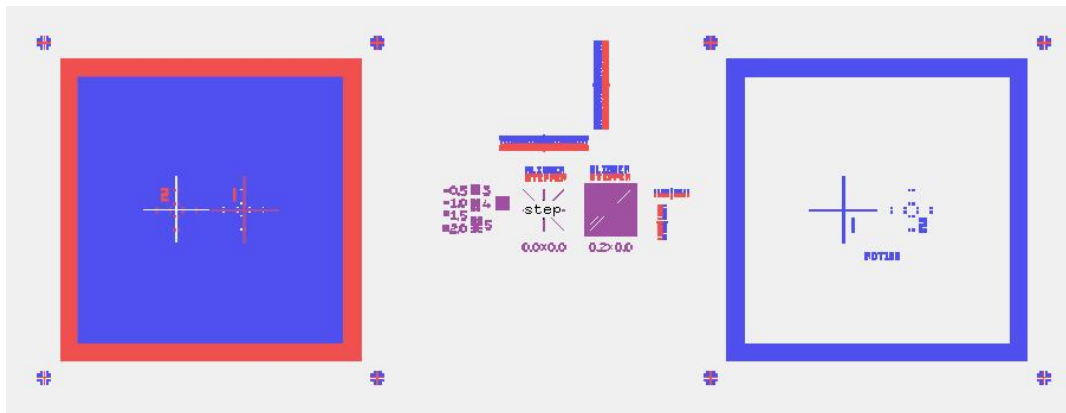

Figure 14: Mixed Lithography Alignment Features.

In tandem to the mixed lithography technology experiment set, continued work is also being done to measure layer to layer registration and the resolution limits of individual lithography tools. This is an important factor for the generation of speculative design rules for customized process sequences.

VI.   Presentations and Publications

VI.A.   Publications

<u>Presentations:</u>

A. Flusberg, S. Swartz, M. Huff and S. Gross, "Thermal-to-Visible Transducer (TVT) for Thermal-IR Imaging," Proc. SPIE 6940, Paper 6940-37, March 2008 (Orlando, FL).

A. Flusberg, S. Swartz, M. Huff, M. Pedersen, and P. Sunal, "Thermal IR Imager Utilizing a Thermal-to-Visible Transducer," Special Session on the MEMS Exchange, IEEE Sensors 2010 Conference, Sensors 2010, Waikoloa, HI, November 1-4, 2010.

D. Binger, M. Ozgur, M. Pedersen, P. Sunal, L. Oh, and M. Huff, "Advanced Sensor Development by MNX," Special Session on the MEMS Exchange, IEEE Sensors 2010 Conference, Sensors 2010, Waikoloa, HI, November 1-4, 2010.

Book Chapters:

[1] Fundamentals of Microelectromechanical Systems
Chapter 23 of the *Semiconductor Manufacturing Handbook*, editor Hwaiyu Geng, McGraw-Hill, New York, 2005.

[2] Process Integration
Chapter 14 of the *MEMS Materials and Processing Handbook*, editors R. Ghodssi and P. Lin, Springer Press, New York, 2011.

[3] BioMEMS and Biomaterials for Medical Applications
Biomaterials Science: An Integrated Clinical and Engineering Approach, edited by Yitzhak Rosen and Noel Elman, CRC Press, Boca Raton, FL, 2012.

VI.B.   Patents

The following patent applications were submitted and are in the pending state:

- "Variable Capacitor Tuned using Laser Micromachining"
- "Low-Temperature Wafer Bonding of Semiconductor Substrates to Metal Substrates"
- "Method of Reflecting Impinging Electromagnetic Radiation and Limiting Heating Caused by Absorbed Electromagnetic Radiation Using Engineered Surfaces on Macro-Scale Objects"
- "A Tailorable Titanium-Tungsten Alloy Material Thermally Matched to Semiconductor Substrates and Devices"
- "An Improved Method of Fabrication of MEMS, NEMS, Photonic, Micro- and Nano-Fabricated Devices and Systems"
- "Method for the Fabrication of Electron Emission Devices Including Carbon Nanotubes"
- "System and Method for Precision Fabrication of Micro- and Nano- Devices and Structures"
- "Method and System for Controlling the State of Stress in Deposited Thin Films"
- "Method and System for Integrated MEMS and NEMS using Deposited Thin Films having Pre-Determined Stress States"
- "A Versatile Communication System and Method of Implementation using Heterogeneous Integration"
- "A Self-Aligned Dynamic Pattern Generator Device and Method of Fabrication"
- "Means for Improved Implementation of Laser Diodes and Laser Diode Arrays"

The following patent applications were submitted and are in the issued state:

- "Radio Frequency Microelectromechanical Systems (MEMS) Devices on Low-Temperature Co-Fired Ceramic (LTCC) Substrates"
- "Integrated Electromechanical Switch and Tunable Capacitor and Method of Making the Same"
- "Miniature Condensor Microphone and Fabrication Method Therefor"
- "Optical Cross-Connect Switch"
- "Electro-optic Phase-only Spatial Light Modulator"
- "Micro-Mechanical Capacitive Inductive Sensor for Wireless Detection of Relative or Absolute Pressure"
- "Method of Fabricating Radio Frequency Microelectromechanical Systems (MEMS) Devices on Low-Temperature Co-Fired Ceramics (LTCC) Substrates"
- "Method of Making an Integrated Electromechanical Switch and Tunable Capacitor"
- "MEMS-Based Variable Capacitor"
- "Circuit for Direct Digital Delta-Sigma Conversion of Variable Electrical Capacitance"
- "Phased Array Antenna using MEMS Devices on Low-Temperature Co-Fired Ceramic (LTCC) Substrates"
- "Fabrication of Movable Micromechanical Components Employing Low-Cost, High-Resolution Replication Technology Method"
- "Miniature Acoustic Detector Based on Electron Surface Tunneling"
- "Method of Fabricating an Acoustic Transducer"
- "Fabrication of Transducer Structures"
- "Method of Fabricating Small Dimensioned Lens Elements and Lens Arrays using Surface Tension Effects"

VI.C.   Software Releases

For a description of software releases in the last period, see Section IV.A., above.

VII.   Plans for the Future

CNRI continues to operate the MEMS Exchange and is attempting to increase revenues and cut cost to become self-sufficient.

VIII.   Comments, Issues, and Concerns

Based on our successes to date in the delivery of high-quality and affordable processing services to the MEMS community, the MEMS Exchange has become an invaluable resource to the country. The MEMS Exchange team remains fully committed to continuing to build and improve our services for the benefit of our users and the community.

However, a major concern of the MEMS Exchange is how fast the program can become self-sufficient. While DARPA has directed the MEMS Exchange to dramatically

increase service fees and prices charged to users, it is known that many users are highly cost sensitive and may not be able to absorb the higher costs of obtaining process runs. Consequently, it is possible that the effect of the large price increases may have the unintended consequence of lowering program revenue rather than increasing it. It is also evident that the timing of these large price increases is not optimal since the high-tech economy, particularly the MEMS economy, is not performing well at present.

Self-sufficiency has always been a goal of the MEMS Exchange, but the approach we believed most prudent was to keep the fees or markups added by the MEMS Exchange to modest levels and to increase the number of runs over time so that the program revenue would be adequate to cover the costs of running the service.

We take lessons from the very successful MOSIS program that was supported by DARPA and which began over twenty years ago. Many technology experts agree that the MOSIS program has been one of the most important and successful programs in DARPA's history. MOSIS has provided training to countless graduate students in IC design, provided support to many silicon-valley startups that have become legendary (e.g., Sun Microsystems, Silicon Graphics, etc.), and also provided extensive technology support to the military and intelligence communities. Nevertheless, MOSIS needed support for nearly 20 years before it could become completely self-sufficient. Importantly, the state of the microelectronics technology when MOSIS was first established was very mature and vibrant and healthy IC manufacturers already existed.

Unfortunately, MEMS is not nearly as mature a technology and a healthy manufacturing base does not yet exist in the MEMS technology arena. Furthermore, it is clear that there exist some significant manufacturing issues in MEMS technology that did not arise in microelectronics. We believe that these manufacturing issues must be overcome in order to allow MEMS to flourish and provide the technological benefits to our economy and society. We also believe that the MEMS Exchange has demonstrated that it is a national resource and can be utilized in tackling many of these issues. Consequently, it is hoped that the Government will work with the MEMS Exchange so as to ensure that this resource is not lost and can serve the community well into the future. Perhaps the most important way for the Government to help MEMS technology is to continue to support a plan toward self-sufficiency wherein the service fees are kept at modest levels (e.g., approximately 25%) and the focus of the effort is on increasing the number of runs completed each year, advance the operational system so as to provide higher quality and predictable results, and improve the efficiencies of the services offered.

Furthermore, it is imperative that DARPA or the United States Government directly confront and solve the extremely serious manufacturing issues related to MEMS technology. If these manufacturing problems are not solved, it will severely limit the growth of the technology. Furthermore, these manufacturing problems will severely curtail the acceptability of MEMS in DoD products. These problems cannot be solved solely by business; leadership from the Government is absolutely necessary. As said

before, many in the community believe that the modular approach to process technology is the best and most cost effective approach to solving this issue. We strongly believe that this approach will ensure success for MEMS technology and DARPA. We also believe that the MEMS Exchange is the best environment in which to develop these process modules.

Although the past DARPA policy of mandating that performers use the MEMS Exchange helped to increase our revenue and program income, it did not do enough to substantially change our self-sufficiency. Specifically, the major problem was that many performers who indicated that they planned to use the MEMS Exchange actually submitted fewer runs than they indicated in their proposals. The consequence is that the actual income was far short of the expected income and we spent an enormous amount of time developing proposals (and ideas for the performers) that did not result in a commensurate revenue and program income. We had asked for an audience with the Agency Director to propose solutions to this problem and he decided on a plan whereby performers could access an additional $300K that could be spent at the MX for fabrication on each project. This would serve two purposes. First, it would allow the performers to try out ideas that they otherwise would not attempt and thereby increase innovation. Second, it would bring in a very sizable amount of new revenue into the MX. Unfortunately, the DARPA Director left before this plan was put into action and was abandoned.

Lastly, higher levels of self-sufficiency are becoming increasingly harder to achieve, particularly with the economy in its current condition. Consequently, we are very concerned that we may not make the self-sufficiency at the end of the effort. Moreover, the plan to get to self-sufficiency was contingent on the MEMS Exchange putting in place the community outreach and business improvement and development activities with sufficient time for these activities to have an effect on our revenues. However, the funding for some of these activities did not arrive until very late and funding for some important initiatives did not arrive at all. Therefore, given the late funding for these activities as well as the lack of compliance with the DARPA mandate to use the MEMS Exchange, we think that it would have been more reasonable for the MEMS Exchange to be held to less aggressive self sufficiency metrics until a new plan to ensure for self sufficiency can be formulated, tested and put into practice.

IX.   Technical Transfer Performed

The MEMS Exchange provided processing and design services to a variety of military applications including: the Army Research Laboratory's development of a MEMS-based magnetometer (Alan Edelstein); RDECOM-ARDEC's development of a MEMS safe and arm fuse (Charlie Robinson); and the micro-g accelerometer project at Spawar (Richard Waters), as well as many others.

In addition, the MEMS Exchange has provided services to a variety of DARPA-supported projects, many of which are working on direct military relevant applications.

One of the most important is the MEMS Exchange work to provide fabrication services to Boeing, HRL and NASA JPL under the DARPA NGIMG program. Another important project is the Nanowriter. MEMS Exchange has shipped working die to KLA-Tencor on this project.

The MEMS Exchange has also provided services to other Government users, particularly various groups in NASA and NIST at multiple locations. The MEMS Exchange has also worked with the Navy on several projects.

Lastly, the MEMS Exchange worked extensively with the fabrication site staff at ARL in Adelphi Maryland to make the microfabrication facility more broadly available to the community. A number of members of our staff were qualified to use the equipment in the ARL facility resulting in a substantial amount of processing work being performed there. Furthermore, we made some highly specialized and unique processes that the Army has developed, including sol-gel PZT, available to the research community. Additionally, a new advanced e-beam capability for performing the highest resolution photolithography in the world was established at ARL and this capability has been made available to the research community through the MEMS Exchange.

X.   Deliverables Delivered

The most important deliverable has been the enormous number of fabrication services performed by the MEMS Exchange for many MEMS researchers and developers which stood at over 2,600 individual runs at the end of the program. This has enabled these MEMS researchers and developers to better advance their specific projects as well as the entire field of MEMS technology, and for DARPA to directly benefit from an ever more vibrant and mature technology base.

Another important deliverable has been the continuation of the experiment of radically increasing the prices charged for processing services as required by DARPA.

Other deliverables over the program include: many new improvements to the software and operational system so as to meet the directives of DARPA to significantly increase the processing fees as well as to measure the effects of the price changes; the launching of new services so as to increase program revenue; and various improvements to our laboratory so as to better serve the community's processing needs. Lastly, we installed MEMS Exchange software at the Army Research Laboratory MEMS lab to help run and manage the facility.