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The objective of this program is to develop sensor and actuator array technologies based on microelectromechanical systems (MEMS) for distributed measurement and actuation in harsh environments. Currently MEMS devices are fabricated primarily from silicon, which limits application areas to temperatures below 250C. We are developing silicon carbide (SiC) as a material for MEMS in harsh temperature, corrosive, and erosive environments. To this end, we have focussed a major part of this program on the development of materials and processing techniques required to fabricate SiC-based MEMS structures. This document serves as the final progress report for this program

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A MULTIDISCIPLINARY RESEARCH PROPOSAL FOR MEMS-BASED SMART GAS TURBINE ENGINES

ARO MURI Contract Number DAAH04-95-10097

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Section 1: Scientific Progress and Accomplishments

Introduction

We have completed a five-year program to develop technologies for MEMS-based systems for harsh environment applications. This program leverages MEMS as an enabling technology for providing efficient, high performance systems that have inherent simplicity and reliability. Our primary aim was the deployment of these systems in a gas turbine engine. However, the results of our research, in general, apply to intelligent control of a wide variety of systems unrelated to gas turbines by using integrated a distributed sensor and actuator array schemes. A thrust area of this program was the development of fabrication and control technologies for arrayed MEMS sensors and actuators. To meet the requirements related to harsh environments, we have concentrated a significant portion of time, effort, and resources into the development of process and materials characterization of SiC as a MEMS material. This report will summarize these efforts for the period between July 1, 1995 and June 30, 2000, the termination date of the grant.

Proposed Research

The overall theme of the proposed research was the development of highly integrated and distributed sensor/actuator arrays (also referred to as microelectromechanical systems or simply MEMS) for intelligent control of systems. In general, we proposed to use microfabricated sensor arrays to obtain information on the condition of a system. Sensor interface electronics would be needed to obtain the data to then be reduced by the signal processing electronics. The results would then be communicated to the logic that controls the drive electronics, and therefore, the actuators. The actuators then manipulate the system for a desired purpose. Depending on the application, there would be a number of feedback levels, ranging from the lowest level where actuators are controlled by the adjacent sensors, to a high level of feedback requiring an intelligent controller for the entire system. The degree of integration would also depend on the application in mind. At least the sensor interface and the actuator drive electronics would have to be integrated on the same chip with the sensors and the actuators, respectively. In the most aggressive form, all the blocks would be integrated on the same chip.

The aforementioned control concept required the development of appropriate enabling technologies. These include sensor and actuator fabrication, integration of sensors, actuators and electronics, real-time signal processing related to large density arrays, wireless communication of the distributed sensor and actuator arrays, fault detection, and intelligent control of large degree-of-freedom systems. The proposed research was basic with respect to these enabling technologies. At the same time, the research was application driven toward a gas turbine engine. Our choice of a gas turbine engine was motivated by the significant technical challenges and potential benefits. The former required advanced technology development, for example, high-temperature silicon carbide (SiC) MEMS. Given the significant challenges in working with gas turbine instrumentation, extension of the proposed work to technologically less challenging applications was thought to be straightforward. The potential direct benefit would be a smart engine that offers higher performance and fuel efficiency compared with conventional designs.

A "smart" gas-turbine engine that integrates MEMS arrays with the appropriate control schemes was proposed. The concepts were to operate on both static and transient phenomenon and incorporate a broad intelligence to produce enhanced performance with increased reliability, durability, and maintainability. The concept was to integrate microfabricated sensors, actuators, and control circuits into materials which can be used as structural elements. Since these systems were to be built into the structural components of the engine, they would not disrupt other systems; they would be inherently simple; they would not increase engine size or weight; and they would operate without pilot control.

The gas-turbine engine has been the focus of intense research since the first Whittle design in 1937. Although it has evolved into a very efficient source of power, many areas remain open for advances. Instead of continuing along the evolutionary track where more highly engineered and complex systems provide higher performance, the MEMS-based, smart-engine concept that we

proposed took a revolutionary path by potentially providing efficient, high-performance systems that have inherent simplicity and reliability.
A typical "smart" gas turbine engine requires MEMS with the following capabilities:

(1) bimetallic microvalves for turbine and combustor cooling:
-ambient pressure, 50 to 200 psi; -ambient temperature, 500°C to 800°C, -air flow rate, 1.5x 10-4 kg/sec/cm^2.
(2) bimetallic microvalves for combustor fuel/air control:
-ambient pressure, 100 to 200 psi; -ambient temperature, 500°C to 800°C, -air flow rate, 6x10-3 kg/sec/cm^2.
(3) ice detection sensors and actuators:
-ambient pressure, atmospheric to 50 psi, -ambient temperature, -20°C to 5°C, -hot gas temperature, 0°C to 300°C.
(4) pressure sensors and actuators for surge/stall and tip clearance control:
-ambient pressure, atmospheric to 200 psi, -pressure resolution, 0.02 psi, -ambient temperature, 50°C to 500°C, actuator motion, up to 0.7mm.
-compressor bleed flow, actual numbers cannot be quoted since the phenomenon is poorly understood.
(5) chemical sensors and actuators for combustion product and exhaust gas control:
-ambient pressure, atmospheric to 200 psi, -ambient temperature, 500°C to 1200°C.

At the onset of this program, the requisite silicon-based device technologies existed to address the needs outlined above, although not to the operational specifications required for gas turbine engines. As such, we proposed to develop and demonstrate the proposed sensor and actuator arrays in silicon, including the support electronics, signal processing and control during the first three years of the program. During the two option years we proposed to transfer this technology to SiC in order to achieve device structures that can meet the harsh environment operational specifications listed above.

It is appropriate to re-emphasize that while our work used a gas turbine engine as a vehicle for the development of the required enabling technologies discussed, this focus was not limiting. For example, we proposed to develop chemical sensor arrays for combustion monitoring. The device architectures have potential uses in monitoring chemical agents that may be released into a battlefield. Our control concept would then alert appropriate actuators for action. Such action could be the closing of microvalves blended into normally porous fabrics of suits to seal a soldier from the environment until the hazard was eliminated. Alternatively, the action could be a miniature MEMS-based drug delivery system that injects the soldier with the appropriate antidote. In another application, the sensors may be accelerometers to monitor vibrations in a system (e.g., helicopter rotor blades). The control system would then utilize the information in conjunction with macro- or microactuators for vibration suppression. Yet other application areas could be sensor and actuator arrays for adaptive optics, noise suppression and skin drag reduction for aerospace vehicles. Clearly, there are many civilian applications that parallel those described above. For example, automotive engine control for performance and fuel efficiency, and efficient environment/building air conditioning would be a direct civilian impact of the proposed research.

The sensors, actuators, and control circuits proposed for the gas turbine application required that the devices operate in high pressure and temperature environments as compared with more pedestrian applications. The microvalve actuators must also be capable of supplying and/or regulating relatively high fluid flow rates in these applications. When fluid flow rates exceed those available with microvalves, we proposed to incorporate fluid regulators and amplifiers to achieve the desired flow. At the time, this was a primary concern of many of the end users of MEMS. As such, we proposed to incorporate fluid amplifiers (e.g., in the variable geometry combustor where it is desirable to regulate a significant quantity of air) when necessary.

Review of Accomplishments

In terms of materials issues, the program was divided into two distinct subsets, the silicon subset, and the silicon carbide subset. At the onset of the program, development of SiC as a MEMS material was in its infancy, so a main thrust was to make devices from silicon. We recognized that many of the Si-based devices would not meet the operational specifications required for most gas turbine applications. However, we believed that the Si fabrication technologies were mature enough to allow for the fabrication of Si-based microsensor and microactuator arrays that could be used in the development of the control electronics and control methodologies for the program.

Heat Flux Sensors:

During the first year of the program (1995), work began on the development of Si-based ice detection and heat flux sensors. These sensor types were selected as the first to be developed since we had concurrent to this MURI, a DARPA-funded program to develop TiNi shape memory alloys for microactuator applications. It was hoped that the results of the DARPA program would yield a suitable processing technology to produce microvalve arrays for this MURI program. The heat flux sensor was based on four resistive temperature sensors configured in a Wheatstone Bridge configuration. The heat flux was measured by simply taking differential temperature measurements. The sensors consisted of microfabricated aluminum temperature sensing elements on a polyimide substrate. Heat fluxes of up to 2000 W/m^2 were measured. Details concerning the fabrication, calibration, and operation of these sensors can be found in the 1995, 1996, and 1997 Interim Progress Reports.

Ice Sensors:

Development of ice detection sensors also began in 1995. Two sensor designs were developed. The first design utilized a micromachined resonant membrane as the sensing element. The sensor was fabricated using a combination of Si bulk micromachining, Si-to-pyrex wafer bonding, and Si etchback techniques to produce a sealed-cavity membrane structure. The membrane, fabricated from heavily boron doped Si, was excited into resonance by applying an AC voltage to Al electrodes deposited and patterned into the micromachined substrate. The resonant frequency of the membrane was dependent on its stiffness and mass, therefore the formation of ice on the membrane surface effectively increased the mass of the vibrating structure and its stiffness. An increase in stiffness produces a smaller deflection than the ice-free membrane. Since the sensor is essentially a variable capacitor, such changes could be detected with the appropriate circuitry. This sensor design was able to discern the onset of freezing, as well as the difference in thickness between 0.6 and 0.8 mm-thick ice, thicknesses that are well below dangerous levels for many aerospace applications.

A second ice sensor prototype based on piezoelectric actuation was developed and reported in the 1997 Interim Progress Report. This sensor was constructed from commercial-off-the-shelf components and consisted of a piezoelectric transducer excited at its resonant frequency. As ice accumulated on the transducer, the resonant frequency changed in accordance with an increase in mass and stiffness. Such changes were detectable, and the sensor could be calibrated to correlate with observable formation of ice on the sensor surface. A resonant frequency shift of nearly 15 kHz was observed for a 04 mm increase in ice thickness. Details regarding both ice sensor prototypes can be found in the 1995, 1996, and 1997 Interim Progress Reports.

Control Electronics:

Research activities in the area of control electronics were performed throughout the entire program. Since initial emphasis was placed in the development of microsensor technologies, activity in control electronics was focussed on the development of capacitive sensing techniques. This proved to be a significant challenge, since the capacitances of many MEMS structures are quite small, in the femto-ferad range. Early work (1996) in capacitive sensing concentrated on the development of a Delta modulator. The performance of the early prototypes was deemed inadequate for harsh environment applications, so the design of a Sigma-Delta modulator was initiated in 1997. The Sigma-Delta modulator was designed to provide better resolution than the Delta modulator, as well as a digital output. The Sigma-Delta modulator was designed, but never fabricated. We believed that the digital output signals of the Sigma-Delta modulator could be transmitted over a wireless power/data interface, thus allowing for sensors to be located in the harsh environment with the critical Si-based control electronics located remotely. It was found that this goal was too ambitious; therefore, work in the remaining years of the program was dedicated to the development of a suitable microchip-based Delta modulator for capacitive sensing. IC versions of the Delta modulator were fabricated by MOSIS and tested in 1998 and 1999. During 2000, a package was developed to couple a MOSIS chip with a SiC surface micromachined lateral resonant structure in order to permit electronic sensing of the resonant frequency. Using this setup, the resonant frequency for this resonator was characterized as a function of ambient pressure, and as expected, the mechanical quality factor, Q, increased as the pressure decreased. Details concerning this experiment can be found in the 2000 Interim Progress Report. Details concerning development of the capacitive sensing cicuitry are presented in all Interim Progress Reports.

Signal Processing and Control:

The effort to develop signal processing and control techniques was not delayed by the lack of fabricated sensors and actuators. Beginning in 1995, models that embodied sensors, actuators, local controllers and global controllers for feedback-based systems were being developed. The models were developed for large-scale systems with numerous inputs and outputs. Two approaches for the controller were developed. The first uses computer synthesis tools for linear plants with known dynamics and many failure-prone sensors and actuators. The second uses estimation to accommodate plants with unknown nonlinear dynamics. In both cases, algorithms were developed to accommodate MEMS-based systems, which are likely to have tens to hundreds of sensors and equally as many actuators due to the potential low cost of each MEMS unit. Such systems are likely to be subjected to numerous failures creating a situation that would require the controller to maintain system stability while maintaining feedback control. Algorithms were developed to meet this requirement. Due to issues related to the fabrication of arrays and control electronics, actual hardware testing of control schemes could not be performed. However, they are developed to a point that when the fabricated arrays and associated control electronics are fully developed, the control methods developed during this program could be tested. Details concerning developments in this area can be found in all Interim Progress Reports.

Silicon Carbide MEMS

As stated previously, the intent of this program was to develop "smart" microfabricated sensor and actuator arrays for gas turbine engines. It was known from the onset that although Si-based devices could be fabricated, the material properties of Si would prohibit their use in the gas turbine environment. Therefore, silicon carbide (SiC) was proposed as the material to be used for the sensor and actuator structures. Unfortunately, the fabrication technologies for SiC were immature at the start of this program, so we proposed to first develop Si-based prototype arrays in order to aid in the development of the necessary electronics and signal processing and control schemes. Ultimately the sensor and actuator arrays would be fabricated from SiC so as to make them suitable for harsh environment applications, but this was to occur during the option years (Years 4 and 5). It was presumed that the necessary fabrication technologies for SiC processing would be available at that time. This assumption was reasonable since our research group had a well-established research program in SiC MEMS that was producing early successes in surface and bulk micromachining of SiC. These accomplishments were, however, limited to the fabrication of rather simple device structures, such as bulk micromachined SiC diaphragms and single layer surface micromachined lateral resonant structures. The fabrication of more complex SiC structures, namely 3D bulk micromachined devices and multilayer surface micromachined structures proved to be much more difficult owing to difficulties in patterning and etching of SiC. Therefore, considerable effort during the first three years was focussed on developing SiC processing techniques with an eye towards creating processes that could be used for the fabrication of the proposed device array structures. The following is a summary of this development effort.

A. SiC Growth and Characterization

The cornerstone of this effort was a vertical-geometry, rf induction heated, atmospheric pressure chemical vapor deposition (APCVD) reactor constructed using funds from DARPA and NASA sources. This reactor is capable of depositing single and polycrystalline SiC films on large-area (4-inch diameter) Si wafers using silane and propane precursors and a hydrogen carrier gas. Two wafers can be coated with SiC in each run. Although the throughput of this reactor is low relative to silicon standards, the ability to deposit on large area substrates enabled full use of the processing tools in our Si microfabrication facility, which are also tooled for 4-inch wafers. The reactor, in essence, provided a test bed for the feasibility of using SiC as a MEMS material.

The benchmark process initially developed for this reactor was a heteroepitaxial growth recipe. The standard recipe was a three step process involving an in-situ surface cleaning, a carbonization step converting surface Si to 3C-SiC, and a film growth step to produce a heteroepitaxial film on the converted surface. This process is very effective at producing single crystal coatings on Si wafers. However, use of these films is limited to protective coatings and single SiC layer device structural layers because single crystal silicon is required as the substrate material. Therefore, one of the first SiC-related projects was to develop deposition procedures using suitable sacrificial substrates (1996). We began this effort by using polysilicon as a sacrificial material. Polysilicon was attractive for the following reasons: (1) SiC grows on Si substrates, (2) polysilicon films could be deposited on electrically-insulating SiO_2 and Si_3N_4 sublayers, (3) and sacrificial etching could be performed using KOH without damaging the other layers. Using this material system, we were able to develop the first single layer SiC surface micromachining process. During the development phase of this project, we observed that the polysilicon substrate exhibited a strong influence on the microstructure of the as-deposited SiC films. In fact, under proper conditions, the polysilicon served as a template for the SiC film, thus suggesting that grain-to-grain epitaxy was controlling the nucleation process. Further investigations verified our initial observations. The results of this study showed that the microstructure of the as-deposited SiC films is polycrystalline, with an orientation that is nearly identical to the polysilicon underlayer. A subsequent investigation of these films (2000) showed variations in Young's modulus and residual stress with respect to film texture, indicating that the performance of micromechanical structures can be "tuned" by simply selecting the proper microstructure of the substrate. Details regarding developments in this area can be found in the 1996 and 2000 Interim Progress Reports.

Polysilicon proved to be an adequate sacrificial material for SiC surface micromachining, but its use required an additional electrical insulator in order to achieve electrostatic actuation. In order to reduce the number of films needed in a process, we also engaged in a study investigating SiC growth on amorphous SiO_2 and Si_3N_4 substrates (1999). This study involved the deposition of SiC films using silane and propane precursors over a temperature range from 950°C to 1300°C. In general, we found that the SiC films were randomly oriented polycrystalline films with good adhesion to the substrates. The only exception was SiC depositions on SiO_2 at temperatures near 1300°C, which yielded films with very poor adhesion. The grain size of the films increased with increasing temperature, and films grown on SiO_2 had larger grains than films grown on Si_3N_4 for the same temperature. The results of this study led to the development of a lift-off patterning process for SiC films. The process involves use of Si_3N_4-coated Si wafers as substrates, thick (2 micron) and SiO_2 films as lift-off molds. The surface kinetics of this material system yield SiC films that adhere well to the nitride substrate but do not coat the sidewalls of the patterned SiO_2 mold, thus making lift-off with HF relatively simple. We have implemented this process in a number of applications, including the patterning of piezoresistors and shield layers for lateral resonant structures. Details in this area of research can be found in the 1999 Interim Progress Report.

Epitaxial 3C-SiC films, while difficult to surface micromachine, are relatively easy to bulk micromachine, since SiC is arguably nature's best etch stop in silicon micromachining. To this end, we conducted a thorough investigation into the mechanical properties of 3C-SiC films grown on Si substrates (1999). We used the load-deflection technique to characterize the Young's modulus and residual stress of the films. Our standard test specimen consisted of a 2 micron-thick epitaxial film that was fabricated into free standing, yet fully supported, membranes using standard Si bulk micromachining techniques. Each membrane was supported on a 4x4 mm^2 silicon chip that was mounted on a pressure chuck and associated hardware. Pressure was applied to each membrane and the resulting deflection was recorded. The deflection-versus-pressure curves were fitted to a polynomial equation, from which the Young's modulus and residual stress were extracted. We found vary little fluctuation in Young's modulus regardless of film growth conditions. In contrast, the residual stress was highly dependent on the growth conditions. Likewise, the Young's modulus varied little across a 4-inch diameter wafer, whereas the residual stress was low and uniform only near the center of each wafer. This data suggest that while film stiffness (i.e., Young's modulus) is well behaved, residual stress variations can be high and control is not straightforward. This finding will most certainly affect the fabrication of piezoresistive pressure sensors, which tend to be sensitive to high stresses in the sensor membranes. Details concerning this investigation can be found in the 1999 Interim Progress Report.

Epitaxial 3C-SiC films are not only attractive for membranes in pressure sensors and other actuators, but also as substrates for growth of GaN, as well as for nanoelectromechanical systems. Such uses require relatively thin films (< 0.5 microns), therefore we investigated the early stages of 3C-SiC growth, namely the carbonization stage. It is during carbonization that crystalline defect formation is highest, and voids tend to form at the SiC/Si interface. Our reactor has the unique property of producing void-free films for reasons unclear to us. We therefore conducted a simple study looking at the formation of the carbonization layer as a function of time. The outcome of that study was somewhat predictable, the carbonization layer growth rate is parabolic, because the process is self-limiting. We did however, identify that voids tend to form by hydrogen etching during the cool down step after carbonization. This phenomenon could be suppressed by simply cooling down the wafer in argon. Thus, we believe we have uncovered a process route for the preparation of uniform, submicron 3C-SiC films.

As stated previously, surface micromachining of epitaxial 3C-SiC films is not straightforward, due to the lack of a suitable sacrificial substrate layer. During this program, we have developed a wafer bonding technique that is useful in transferring 3C-SiC films from their original growth substrate to an oxidized silicon wafer. The transfer process uses wafer bonding in conjunction with etchback to produce a 3C-SiC-on-Insulator structure. The process is not simple to execute, due to the high residual stresses in the 3C-SiC films. Despite these difficulties, we are able to achieve transfer yields up to 80% on a 4-inch diameter wafer. The fact that oxidized silicon wafers are used in the process results in a substrate that is, in essence, the single crystal equivalent to the poly-SiC on SiO_2 substrate useful in "conventional" SiC surface micromachining. In fact, we fabricated and tested single crystalline 3C-SiC resonator structures in order to show the utility of the 3C-SiC-on-Insulator substrate. In addition, we developed a homoepitaxial growth process that can be used to produce low defect density 3C-SiC films. Details regarding developments in this area can be found in the 1996 Interim Progress Report.

B. Finite Element Modeling

Several finite element modeling (FEM) efforts were performed at various stages throughout the program in order to directly support the research efforts in the area of SiC MEMS. These include load-deflection modeling of single crystal (1999) and polycrystalline (2000) SiC membranes, operational performance of SiC lateral resonant structures (1998), and flow dynamics of the APCVD reactor (1997). Details concerning the models and their applications can be found in the associated Interim Progress Reports.

C. SiC Devices and Fabrication Processes

The aforementioned activities either directly or indirectly supported the main thrust area in the SiC subset of this program, namely SiC device fabrication and process development. It was clear from the start that early development in these areas would involve limited use of SiC, since the patterning and etch processes were unavailable. We know from experience, however that given the proper substrate, 3C-SiC should provide an excellent protective coating material for Si devices, due to its chemical inertness, wear resistance, and good adhesion to Si. To validate this hypothesis, we selected a bulk micromachined Si fuel atomizer as a test vehicle. The atomizer was an ideal choice for a number of reasons. First, deep reactive ion etching (DRIE) could be used to fabricate Si structures with a high degree of dimensional complexity. Second, fuel atomizers are a vital component in a gas turbine engine. Third, test protocols for erosion resistance already exist. In another program, we developed and optimized the geometry for Si-based fuel atomizers. The structures actually outperformed conventional metal atomizers in terms of spray solid angle and droplet size, but failed the erosion test. To see if our deposition process was effective in applying a durable SiC coating the complex atomizer geometries, we coated a number of atomizers with a 1.5 micron-thick 3C-SiC film and subjected them to the complete battery of tests. The results showed that the SiC-coated atomizers performed on par with conventional and Si atomizers in terms of atomization and spray angle. Moreover, the SiC coating showed no signs of degradation upon completion of the erosion tests. By comparison, atomizers coated with Si_3N_4, SiO_2, and diamond-like carbon failed the erosion tests. Details concerning this work can be found in the 1996 and 1997 Interim Progress Reports.

Concern over the long-term adhesion of the 3C-SiC coating on the Si atomizer surfaces when subjected to a high number of thermal cycles led us to develop a fabrication process for a solid SiC atomizer. The process is fundamentally different from the methods used to fabricate Si atomizers in that DRIE could not be used on SiC. Instead, we developed a molding-based process, involving the fabrication of Si molds using DRIE, filling the molds with SiC, planarizing the molds using mechanical polishing, and dissolving the molds in a silicon etchant. The resultant structures are "bulk micromachined" SiC components made without having to etch the SiC. The structures are hundreds of microns in thickness, with multiple intermediate levels, thus having the 3D characteristics of Si components. This was the first process to produce micromachined SiC components with a true 3D quality. Like the aforementioned SiC-coated Si atomizers, the solid SiC atomizers passed all qualification tests. Issues related to the cost of production currently prohibit wide-scale commercialization of these and related structures. Details concerning this research topic can be found in the 1998 Interim Process Report.

Concurrent with the development of robust bulk micromachining processing techniques, we embarked on an aggressive development program for SiC surface micromachining. Our early work in the area of SiC reactive ion etching (RIE) indicated that although single layer devices such as simple cantilever beams and lateral resonant structures could be fabricated using RIE, the technical challenges associated with low etch rates, etch-field micromasking, and etch selectivity to sacrificial layers would require that an alternative patterning technique be used for multilayer devices. Our experience with the molding-based bulk micromachining process suggested that a similar technique could be developed for thin films. In fact, the process might just be simpler, since more materials could be used. We selected the SiC, SiO_2, polysilicon material system, since each of these materials have a unique etchant that can be used to selectively dissolve microfabricated masks and sacrificial layers. Our first "micromolding" process was a single layer process and was used to fabricate simple lateral resonant structures and micromotor shapes. In 1998, this process was extended into the world's first multilayer SiC surface micromachining process, as demonstrated by the fabrication and high temperature testing of micromotors. During the last 2 years of the program we extended this process further by implementing micromolding into a 4-layer SiC surface micromachining process. The process not only addresses key fabrication issues, but is also designed around the well-known MCNC MUMPs process used in polysilicon surface micromachining. We call our process MUSiC, short for <u>M</u>ulti-<u>U</u>ser <u>S</u>ilicon <u>C</u>arbide process. MUSiC is able to support device designs from a multitude of designers, as long as the designs comply with certain design rules. Our first "test" of the MUSiC process was initiated in 1999, using device structures designed by graduate students at CWRU. The fabrication run was successful in generating completed chips, however, issues related to the material properties of the SiC films, mainly in the areas of residual stress and residual stress gradient, prohibited successful testing of most devices. The micromolding process did, however, prove to be a viable patterning technique for SiC multilayer processing.

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Student Theses

Krishna Vinod, M.S., 1/97, "3C-SiC on Silicon, Oxidation, Wafer Bonding, and Schottky Diodes"

Kavita Chandra, M.S. 5/97, "Characterization of Residual Stress and Elastic Modulus of Silicon Carbide Films Grown on Silicon by APCVD"

Zhuo Fu, M.S. 8/97, "Sensor Array Signal Processing with Neural Networks"

Dejun Wang, M.S. 8/97, "Integrated Sensor Array Characteristics and Calibration"

Sumant Ranganathan, M.S. 5/97, "Interface Electronics for Capacitive Sensors and Arrays"

Sorin Stefanescu, M.S. 8/97, "Testing and Calibration of a Microfabricated Heat Flux Sensor"

N. Rajan, MS, 1/98, Erosion Resistant Coatings for Micromachined Fuel Atomizers".

V.B. Karnani, MS, 5/98, Frequency Powered Wireless Telemetry for Sensor Data Acquisition at 200C".

V.C. Arihilam, MS, 5/98, "RF Telemetry for Vibration Measurement in Rotating Machinery".

S.Y. Lei, MS, 5/98, "Data Acquisition Circuitry for Capacitive Sensors and Arrays".

C.C. Feng, PhD, 5/98, "Reliable Decentralized/Centralized Control Systems".

A.Yasseen, Ph.D., 5/99, “Micromachined Devices Using New Processes and Materials”.

X. Zhang, M.S., 5/99, “A MEMS Bar Code Scanner”.

J.Mitchell, B.S., 5/99, “Analysis of the Mechanical Properties of 3C-SiC Thin Films Using the Load Deflection Technique”.

Xiangyang Song, MS, 5/00, "Multi-User Silicon Carbide (MUSIC) Surface Micromachining Process".

J. Mitchell, MS, 1/01, "Characterization of Mechanical Properties of Thin Films of Cubic Silicon Carbide Deposited onto Silicon".

C-H. Wu, Ph.D., 1/01, "Growth and Characterization of SiC for MEMS Pressure Sensors".

S. Lei, Ph.D., 5/01, "Capacitive Sensor Interface Circuits for MEMS Transducers with Application to High Temperature Data Acquisition".

S. Roy, Ph.D., 1/01, “Microelectromechanical Systems for Extreme Environments”.

Journal Publications

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Report of Inventions

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