



WIMS WORLD

MichiganEngineering

A quarterly update from the Engineering Research Center for Wireless Integrated MicroSystems

Volume 2 No. 1 Winter-Spring 2002

MESSAGE FROM THE DIRECTOR



As I sit down to write this, I am looking out at beautiful Waikiki Beach in Honolulu. When I started my career, I really had no idea that engineers, and especially professors, traveled as much as they do. Frankly, I no longer enjoy traveling as much as

I once did, but for Hawaii I guess I can make an exception now and then. The week before last, I was at the Sensor, Actuator, and Microsystems Workshop on Hilton Head Island, S.C., where our WIMS ERC presented a number of important papers. It was great to see many old friends there, including many former Michigan people. We had 40 people at our Michigan dinner, and that was only a fraction of those at the meeting. And after two days back in Ann Arbor, it was time to come here to give a paper at the VLSI Circuits Symposium. My son recently advised me to forget about ever retiring. "You're doing too well 'working,'" he said. Maybe he's right at that.

A month or two ago, I probably wouldn't have agreed though. We were putting our ERC Annual Report together and getting ready for the annual Site Visit. The Annual Report ran to over 400 pages, and the handouts for our combined Site Visit/IAB meeting seemed nearly as big. I will always remember the long hours that our staff put in on those events. They worked days, evenings, and weekends, making sure that things got done right in spite of late hand-ins from faculty

and students alike. We're lucky to have such a dedicated group of people. It is one of the real strengths of the Center. It speaks to *commitment*, and I hope that is one of the things we are teaching our students. Doing it right, no matter what.

We learned a lot putting the Annual Report together. I was amazed that we now have a total of 97 doctoral students in the Center (56 supported under the ERC and 41 supported by associated grants and contracts) pursuing 91 projects spanning 12 departments in three universities. They represent some of the very best students in the world. They are part of the 227 people that have been involved in the Center during its second year of operation. Since the ERC began some twenty-one

aspect of microsystems is ignored. They also help us focus on the interdisciplinary intersections of different areas, where some of the greatest advances will likely come. But shared deadlines also tend to focus us on short-term goals, and too much of that can be counter productive. So as in most things, it's a balancing act. Many of the things we try are risky; some will fail. And yet out of all of the activity, we will also demonstrate new systems that go beyond anything ever realized before. Doing that in a university, and especially across three universities, takes balance and most importantly it takes *commitment*. It takes commitment to make it all work and to make it work synergistically with individual project goals, no matter what. I hope we never lose that commitment, because it is

INDUSTRIAL LIAISON



The next IAB Meeting will be held at the Crowne Plaza hotel in Ann Arbor on October 22-23, 2003. Members will hear about the latest research advances and meet with students and faculty to discuss projects in detail.

One purpose of these discussions is for the Center personnel to better understand the applications that our members are considering

for our technology. Another purpose is to discuss how the members may apply subsystems of our microsystems to their products. A strength of our testbed approach is that we need to address all the system issues (ie. sensors, actuators, packaging, electronics, architecture, power budget, thermal budget, software, assembly, etc). This systematic approach allows for faster development time as all the specific interface issues for these subsystems are defined and addressed.

We will spend the summer visiting many of our members' facilities to foster better collaboration between members and the ERC. We are soliciting member needs for 2003 interns. If your company is interested please contact me so that we can start planning in the Fall of 2002.

As always, I encourage you to visit the Center whenever possible so that we can discuss our latest research.

Joseph M. Giachino
Associate Director

months ago, its faculty and students have generated more than 22 disclosures and 145 technical papers, and we are still gathering momentum. Michigan continues to rank among the top contributors worldwide to the leading MEMS conferences, again testifying to our *commitment* to be the very best in this area. But it isn't the number of papers that is most important. It is their quality and the really new things they report.

Innovation is something we all seek — and not just new things, but new things that are useful. Michigan has always tended to emphasize microsystems, where it is probably harder to innovate than in processes or devices. In fact, one of the things that I worry most about is maintaining a balance between doing really new high-risk things and doing things that are more evolutionary. The testbeds that are part of the Center are important in building teamwork and in making sure no

what makes this Center the world focus for microsystems. It says we will do whatever it takes to achieve excellence, no matter how hard that may be. And things certainly do get a little frantic, especially right before deadlines.

I guess I'll go swimming. The trades are blowing and the surf is up.

Ken D. Wise

Director
Engineering Research Center for Wireless Integrated Microsystems

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WINTER-SPRING 1



RECENT EVENTS

NSF SITE VISIT/IAB MEETING

May 21-22 - Welcoming in our second year, our combined NSF Site Visit and IAB Meeting was a tremendous help. The IAB provided us with direction and assistance in our research. The NSF's report helped to point out some of our blind spots, but also reinforced our confidence in what we've been achieving over the

last year, and where we see ourselves moving in the future.

Constructive critiques in mind, we are ready to tackle the next year's issues and implement recommendations generated from discussions at our annual retreat.

Special thanks go to all of our IAB Members and NSF representatives who have helped to make our Center as successful as it is.

~LL

SLC REPORT

Industrial Chair ~Pamela Bhatti
Efforts to expand the WIMS alumni network are underway. This will provide an excellent opportunity to keep alumni informed of center activities, and promote greater involvement at the IAB membership level. An active focus of the Industrial Advisory Committee is to increase industry internships through projects such as an internship recruitment/job opportunity session to be held during the October IAB meeting. Interested IAB members are encouraged to contact Joseph Giachino or Pamela Bhatti - pamelat@umich.edu.

Education Chair ~Joe Potkay
During winter semester, the SLC Education and Outreach Committee helped organize and acted as student teachers for the DAP-CEP program in WIMS. Detroit-area middle school students were introduced to wireless systems, sensors, programming, and problem solving through sessions on the UM campus every Saturday for six weeks. The program was a huge success with the students, both male and female, noting an increase in their interest in WIMS and in their confidence in dealing with such systems. Due to its success, a similar program is now being pursued for Ann Arbor students.

Social Chair ~Brian Stark
UM intramural teams captured the All-Sports Championship trophy for intramural sports during the 01-02 academic year! UM alumni/faculty/students dinners were hosted at MEMS '02 and at the Hilton Head '02 Sensors and Actuator Workshop, helping to reunite friends with common backgrounds.

MTU-SLC Report ~Ben Arcand
The MTU-SLC has begun facilitating social interactions among their newer students this summer with barbecues and an international cuisine night, featuring Indian, Cajun, Korean, and Chinese foods. MTU-SLC members are also trying to facilitate the First Regional, Upper Peninsula Lego League consisting of 25 teams - aged 9-14, to be held in November 2002.

MSU-SLC Report ~Angela Choi
During the spring semester, the MSU-SLC began our own seminar series, featuring Danielle M. Merriam (UM, Ph.D. Candidate) as our first speaker. Danielle spoke about cochlear prosthesis basics - covering the human auditory system - and presented the basics of cochlear implant systems with a focus on the technological advances needed for the cochlear electrode arrays. The MSU-SLC is continuing the series throughout the summer. Interested parties can contact Angela Choi at choijun4@msu.edu.



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Top: Director Ken Wise and Deputy Director Khalil Najafi accepting the All-Sports Champions Trophy from the SLC
Right: Infrared photograph of the graduate student mentor group taken after the discussion on IR communication with the DAPCEP students.



EDUCATION HIGHLIGHTS

During March and April, the WIMS ERC offered a Saturday morning program to nineteen seventh and eighth grade students enrolled in the Detroit Area Pre-College Engineering Program (DAPCEP). This program has been providing engineering, science, and math opportunities for motivated underrepresented youth in the Detroit area since 1976. The students were brought to campus through a program administered by the Minority Engineering Program Office (MEPO) of the UM College of Engineering. The WIMS ERC course introduced the DAPCEP students to the concept of WIMS devices and microsystems, associated science concepts, and engineering applications, including environmental monitoring and cochlear implants. Over the course of the five Saturdays, students received instructions in an environment

that was a carefully-paced mix of design activities supplemented by inquiry about recognition of science and math concepts. The mix helped provide relevance to the science and math associated with the design and function of the robots. The program revolved around a 3-tier Challenge: Master, Star and Superstar, with each level representing a higher degree of difficulty and comprehension. Students were grouped into teams of two DAPCEP students, with a graduate student facilitator from the Student Leadership Council (SLC), serving as a “third team member”. Each team was given special manuals and checklists. The manuals included special insights beyond the Lego docu-



Two of the WIMS DAPCEP Superstar Challenge certificate recipients.

mentation for building and operating the robots; the insights gave step-by-step instructions that, if followed, would lead to meeting the robot design objectives, with minimal frustration. The checklists provided students a roadmap to achieve their goals. DAPCEP students recorded their observations about science and math concepts in individual and team journals. During lighter moments, the students toured the Chemistry Building on Central Campus, saw a demonstration on a light-bulb pickle, and enjoyed samples of nitrogen ice cream. In the end, eighteen of the nineteen students achieved Superstar Challenge Level certificates. More importantly, all students

reported significant changes in the way they viewed working with technology. By all accounts the WIMS DAPCEP course was a resounding success. At the end of the course, almost all students felt more encouraged to be able to solve engineering problems, and more students included engineering in their choice of possible careers. Students presented their work during a closing ceremony for both parents and family members. A significant factor in the success of the program was the support of the SLC and several undergraduate engineering students. Students from engineering, biomedical and chemistry departments, provided guidance, responded to questions, and had the pleasure of awarding certificates of achievement. The pairing of middle school, undergraduate and graduate students gave everyone involved a truly unique experience.

~ AT & LCM

EECS 425 (Integrated Microsystems Laboratory) was offered in expanded form for the first time last term. A total of forty two students (twenty six at UM and sixteen at MSU) representing seven departments were enrolled. Projects included pressure sensors, analog mirror displays, a thermal flowmeter, g-switches, digital micromirrors, tactile imagers, visible imagers, microphones (pictured), and an integrated Pirani gauge (pictured). The lecture and laboratory format allowed students to guide their two-chip microsystems through design, fabrication, and test. MSU students were able to participate through the use of high-speed telecommunication links. Live video links connected both campuses, providing video and audio capabilities.

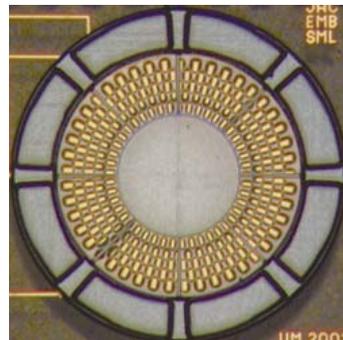
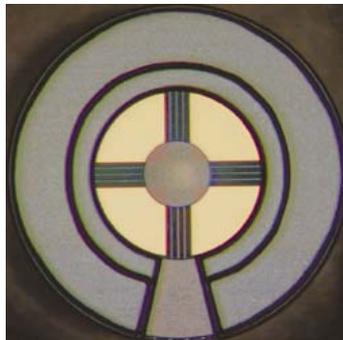
several courses that have been offered through MSU for some time now, the increasingly common use of video conferencing in the classroom allows for collaborative projects not commonly seen in the engineering fields.

Next year, the course will be made available to industrial members of the Center, as part of the MEng program. For more information regarding EECS 425 for Industrial members or the MEng Degree pro-

gram, please contact Michael Flynn at mpflynn@umich.edu. MEng program requirements and applications can also be found on our Web site at, www.wimserc.org.

~LL

Clockwise: Pirani gauge. Microphone. EECS 425 - MSU students. EECS 425 - UM students.



Though this method is not new to the faculty of either campus and, in fact, has been practiced for

RESEARCH HIGHLIGHTS

SENSORS

MICROPACKAGING

During the past quarter several new technologies were developed in the micropackaging thrust. Two wafer bonding techniques for both hermetic and vacuum packaging were developed and characterized, and a new wafer-level packaging technology using electroplated nickel was demonstrated for the first time. A summary of the latest results in these areas is illustrated in the photographs shown at right.

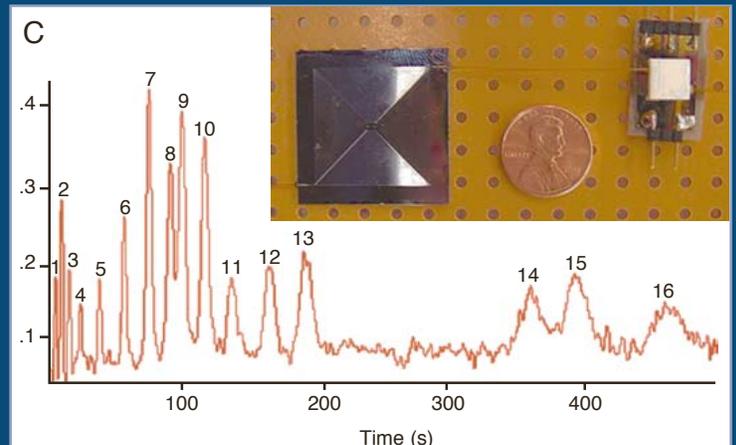
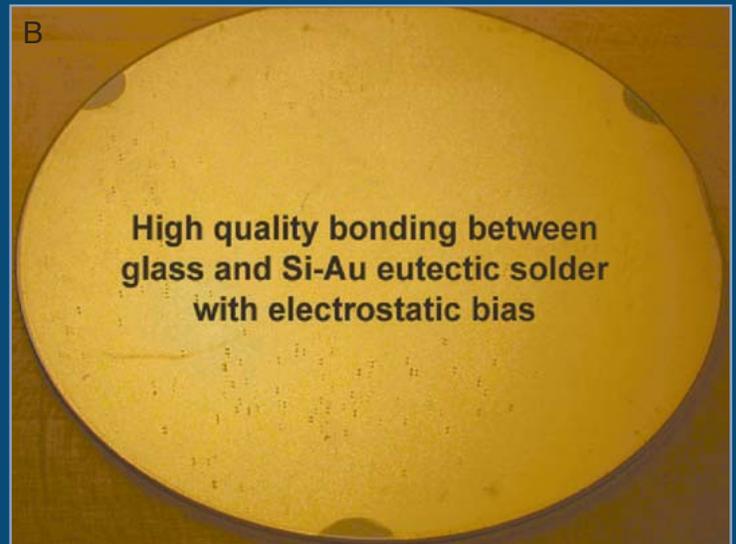
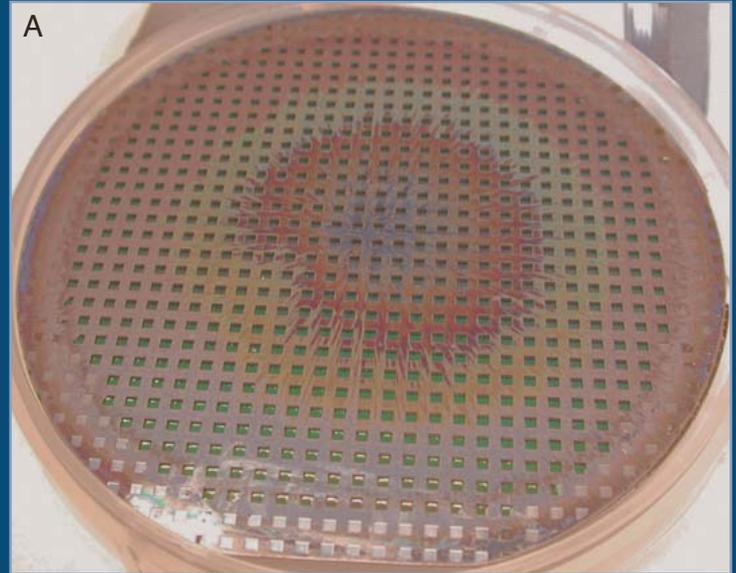
Photograph A shows two bonded Si wafers with vacuum cavities covered by thin diaphragms. The wafers are bonded together using a silicon-gold eutectic layer at a temperature of 400°C. Appropriate preparation of the bonding surfaces and a suitable bonding process sequence in vacuum result in wafer-level bonds with uniformity of >95%. This process is reproducible and has been used to produce vacuum cavities that have maintained a low pressure for more than 7 months.

Photograph B shows a bonded glass and silicon wafer (looking through the glass wafer on top). The wafers were bonded together using a new bonding technology referred to as field-assisted silicon-gold eutectic bonding. A silicon-gold eutectic is formed between the wafers when the temperature is raised above 380°C, the wafers are brought together in vacuum, and a voltage is applied between the wafers (similar to standard glass-silicon anodic bonding), the wafers are then cooled until they are bonded. The use of the electrostatic bias significantly increases the bond uniformity and reproducibility. In addition, the use of the soft silicon-gold eutectic allows feedthroughs to be formed for packaging applications.

Progress toward the WIMS- μ GC continues and the layout of the "Gen-0" prototype is complete, with a target delivery date of May '03. Fabrication has begun on one component of the planned particulate-removing inlet module, which employs porous silicon. The first on-board calibration sources are being tested with second generation devices nearly assembled. Tests of the single-stage, high-aspect-ratio preconcentrator/focuser have been very encouraging (> 5,000-fold preconcentration factors) and 3-D finite element modeling has provided guidance in further optimizing the design for more power efficient operation. The 3-stage preconcentrator/focuser will require less than 6 mg of adsorbent. Tests of novel alternative adsorbent materials, including a conformal, CVD-deposited graphitic material and a metal-organic framework material have shown very promising early results. Anodically-bonded, pyrex-Si etched-channel separation columns have been used to achieve separations of 16-component vapor mixtures in under 2.5 minutes with temperature programming. An alternative column fabrication strategy that promises much lower power consumption is in early trials. Integrated 4-sensor arrays employing transduction layers of different Au-thiolate nanoclusters, sealed with a micro-milled ceramic coverplate have been interfaced to a 3-m separation column and a single-stage concentrator/focuser, and the ensemble successfully tested. Progress is also being made on the sensor-array temperature controller, valves, and micropump, with first devices expected later this year.

Figure C shows a chromatogram obtained with the column and sensor array (and a conventional injector) illustrating the isothermal separation of 16 volatile organic compounds (VOCs)

Figure A: Bonded Si wafers with vacuum cavities covered by thin diaphragms. **Figure B:** Glass and silicon wafers bonded using field-assisted silicon-gold eutectic bonding technique. **Figure C:** Chromatogram from a single sensor channel illustrating the isothermal (30°C) separation of 16 VOCs with the column and array shown in the inset.



PERSONNEL



Clark T.-C. Nguyen, leader of the WIMS ERC Wireless Inter-

faces Thrust, has taken a two-year leave of absence to join the Defense Advanced Research Projects Agency (DARPA) as Program Manager for MEMS. Clark joined the University of Michigan in 1995 and since that time has developed one of the world's premiere programs in RF MEMS. Among his many awards are the "1938E" Award from the College of Engineering (1998), the 1999 EECS Departmental Achievement Award, and the College's Ruth and Joel Spira Teaching Award for 2000. He received the 2002 Henry Russel Award from the University of Michigan. Along the way, he and his students have received best paper awards from conferences such as the MTT International Microwave Symposium and the International Electron Devices Meeting. At DARPA, Clark will have a major influence on the development of microsystems nationwide. He will continue to supervise his on-going WIMS students during his leave, albeit sometimes from a distance.



Michael P. Flynn, who recently joined the WIMS ERC as a faculty member in the circuits area at the University of Michigan, has

been appointed as Interim Leader of the Wireless Interfaces Thrust. As such, he is responsible for day-to-day activities in the wireless area of the ERC. Michael received his Ph.D. from Carnegie Mellon University in 1995. After two years at Texas Instrument's R&D Lab in Dallas, TX, he joined Parthus Technologies in Cork, Ireland. At Parthus, he was Fellow and Technical Director, with responsibilities in the areas of analog circuit design and gigabit

serial communication. Michael is an expert in RF circuits and high-speed data converters. We are grateful to have his expertise in the wireless area of the ERC.



Yogesh Gianchandani has joined the ERC in the sensor/microinstrument area. He received the B.S., M.S., and Ph.D.

degrees in electrical engineering from University of California, Irvine, University of California, Los Angeles, and University of Michigan, Ann Arbor in 1984, 1986, and 1994, respectively.

He held industrial positions with Xerox Corporation and Microchip Technology, Inc. from 1985 to 1989, working in the area of integrated circuit design. From 1994 to 2001, he held various positions first at the University of Michigan, Ann Arbor, and then at the University of Wisconsin, Madison. In 2002, he returned to the University of Michigan, where he is currently an Associate Professor in the EECS Department. His research interests include all aspects of design, fabrication, and packaging of micromachined sensors and actuators and their interface circuits. Prof. Gianchandani received a National Science Foundation Career Award in 2000. He serves on a number of editorial boards and steering/program committees, and served as the General Co-Chair for the IEEE International Conference on Micro Electro Mechanical Systems (MEMS) in January 2002.



Leo C. Kempel, a member of the WIMS ERC in the wireless area, is the recipient of the 2002 Michigan State University

Teacher-Scholar Award. This award is given annually to faculty early in their careers who have earned the respect of students

and colleagues for their devotion to and skill in teaching. Activities in research, teaching, and service are considered in the selection process. The award is one of the highest distinctions given to young faculty by Michigan State University.



Eric Marsman, a UM EECS graduate student, has been selected to receive a University-wide Outstanding Graduate Student

Instructor Award for 2002. The award is based on the excellent work he's been doing as a GSI in EECS 427 for several semesters. Eric is an outstanding teacher, very knowledgeable about integrated circuit design, and totally dedicated to helping the student teams design their microprocessors.

To be awarded at a public ceremony this fall, Eric will receive a certificate and check for \$1,000. Eric's photo and citation of his achievements will be on display in the Rackham corridor leading to the Dean's office.

We are very proud of Eric for his excellent teaching and for bringing this honor to the College of Engineering, EECS, and WIMS.



Andrew Mason has joined the ERC in the micropower circuit area. He received the B.S.

in Physics with highest distinction from Western Kentucky University in 1991, the B.S. E.E. from Georgia Tech in 1992, and the M.S. and Ph.D. in Electrical Engineering from The University of Michigan in 1994 and 2000, respectively. From 1997 to 1999 he was an Electronic Systems Engineer at Canopus Systems and from 1999 to 2001 he was an Assistant Professor at the University of Kentucky. In 2001 he joined the Department of Electrical and

Computer Engineering at Michigan State University where he is currently an Assistant Professor and director of the Advanced Microsystems and Circuit Laboratory. His research focuses on low power microsystem networks, mixed-signal VLSI circuits for communications and sensor interfaces, and biosensor arrays.



Ken D. Wise, WIMS ERC director, was recently named the William Gould Dow Distinguished University Professor by the

Regents of the University of Michigan. This designation is one of the highest honors the University confers on its faculty. William Dow joined the University in 1926 as an instructor in the Department of Electrical Engineering. He obtained an M.S.E.E. from Michigan in 1929 and in 1937 published the first college textbook on electronics. From 1943 to 1945, he was with the Radio Research Laboratory at Harvard, pioneering advances in micro-wave vacuum tubes and radar countermeasures. In 1946 he established the Electron Physics Laboratory (now the Solid-State Electronics Laboratory) at UM, one of 13 research units he founded during his career. Professor Dow became Chair of the Department of Electrical Engineering at Michigan in 1957, holding that position until he formally retired in 1964. He remained very active continuing research in nuclear power production, and publishing and patenting new advances throughout the 1980s and 90s. He was still working on new ideas for power generation when he passed away in 1999 at the age of 103. "I'm very honored to hold a professorship named for Bill Dow," said Professor Wise. "Although he was nearly 80 when I came to Michigan, I knew him for over twenty years. He was a real dynamo."

**SEMINAR SERIES**

To view scheduled seminars go to www.wimserc.org.

April 2, 2002

Dr. Andrew Oliver
Sandia National Laboratories
Design And Packaging Of Surface Micromachined Mechanisms

April 2, 2002

Kumud Srinivasan
Intel Corporation
Deliver Automation Solutions Integrated With Process Technology Development And Volume Manufacturing

April 16, 2002

Prof. Amir Mortazawi
University of Michigan
Frequency Agile RF Circuits Based On Thin Film BST

April 30, 2002

Wei-Cheng Tian
University of Michigan
Micromachined Preconcentrators Using Thick And Thermally Isolated Microheaters For Micro Gas Chromatography

April 30, 2002

Dr. Yuhai Mei
University of Michigan
A Robust Gold-Silicon Eutectic Wafer Bonding Technology For Vacuum Packaging

May 3, 2002

Dr. Bishnu Gogoi
Motorola Sensors Product Division
MEMS Sensor Manufacturing In Motorola

May 21, 2002

Kenichi Takahata
University of Michigan
Micro-Electro-Discharge Machining As A Batch Fabrication Technology

May 28, 2002

Chester Wilson
University of Michigan
On-Chip Microplasma for Chemical Analysis And Other Applications

June 11, 2002

Prof. Dominique Durand
Case Western Reserve University
Interfacing With The Peripheral Nervous Systems

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PRESENTATIONS

Papers presented at the IEEE EMBS Conference on Microtechnology In Medicine and biology, Madison, WI May 2002

R. H. Olsson III, M. N. Gulari, K. D. Wise
Silicon Neural Recording Arrays With On-Chip Electronics For In-Vivo Data Acquisition

M. Ghovanloo, K. Beach, K. D. Wise, and K. Najafi
A BiCMOS Wireless Interface Chip For Micromachined Stimulating Microprobes

Papers presented at North American Solid-State Sensors, Actuators, and Microsystems Workshop, Hilton Head, S.C., June 2002

P. Chang-Chien and K. D. Wise
A Barometric Pressure Sensor With Integrated Reference Pressure Control Using Localized CVD

A. DeHennis and K. D. Wise
A Passive-Telemetry-Based Pressure Sensing System

Paper presented at Digest IEEE VLSI Circuit Symposium, Honolulu, pp. 106-109, June 2002

K. D. Wise
Wireless Implantable MicroSystems: Coming Breakthroughs In Health Care

For additional publications, see the Members Only section of our Web site at www.wimserc.org

PUBLICATIONS

T. J. Harpster, B. Stark, and K. Najafi
A Passive Wireless Integrated Humidity Sensor
Sensors and Actuators A: Physical, Volume 95, Issues 2-3, pp. 100-107, 1 January 2002

M. O. Müller, L. P. Bernal, P. D. Washabaugh, T-K A. Chou, And K. Najafi
Flow Field And Performance Of High Frequency Micromachined Synthetic Jets
40th AIAA Aerospace Sciences Meeting and Exhibit, paper # 2002-0974, Reno, NV, January 2002

J. Chae, H. Kulah, and K. Najafi
A Hybrid Silicon-On-Glass (Sog) Lateral Micro-Accelerometer With CMOS Readout Circuitry
Technical Digest, IEEE 2002 Int. Conference on Micro Electro Mechanical Systems (MEMS 2002), Las Vegas, pp. 623-626, January 2002

T-K A. Chou and K. Najafi
Fabrication Of Out-Of-Plane Curved Surfaces In Si By Utilizing RIE Lag
Technical Digest, IEEE 2002 Int. Conference on Micro Electro Mechanical Systems (MEMS 2002), Las Vegas, pp. 145-148, January 2002

G. He, and K. Najafi
A Single-Crystal Silicon Vibrating Ring Gyroscope
Technical Digest, IEEE 2002 Int. Conference on Micro Electro Mechanical Systems (MEMS 2002), Las Vegas, pp. 718-721, January 2002

T-K A. Chou, K. Najafi, M. O. Muller, L. P. Bernal, and P. D. Washabaugh
Characterization Of Micromachined Acoustic Ejector And Its Applications
Technical Digest, IEEE 2002 Int. Conference on Micro Electro Mechanical Systems (MEMS 2002), Las Vegas, pp. 264-267, January 2002

T. J. Harpster and K. Najafi
Long-Term Testing Of Hermetic Anodically Bonded Glass-Silicon Packages
Technical Digest, IEEE 2002 Int. Conference on Micro Electro Mechanical Systems (MEMS 2002), Las Vegas, pp. 423-426, January 2002

C. Zhang, and K. Najafi
Fabrication Of Thick Silicon Dioxide Layers Using DRIE, Oxidation And Trench Refill
Technical Digest, IEEE 2002 Int. Conference on Micro Electro Mechanical Systems (MEMS 2002), Las Vegas, pp. 160-163, January 2002

T-K A. Chou, K. Najafi, M. O. Muller, L. P. Bernal, P. D. Washabaugh, and B. Amirparviz
Micromachined E-Jet For IC Chip Cooling

Technical Digest, IEEE International Solid-State Circuits Conference, pp. 356-357, San Francisco, CA, February 2002

T. J. Harpster, S. Hauvespre, M. Dokmeci, and K. Najafi
A Passive Humidity Monitoring System For In-Situ Remote Wireless Testing Of Micropackages
IEEE/ASME J. Micro Electro Mechanical Systems (JMEMS), Vol. 11, no. 1, pp. 61-67, February 2002

COMPLETED DOCTORAL DISSERTATIONS 2002

Marcus D. Gingerich
Multi-Dimensional Microelectrode Arrays With On-Chip CMOS Circuitry For Neural Stimulation And Recording
The University of Michigan 2002
Advisor: Prof. Ken Wise

Patty Chang-Chien
Wafer-Level Packaging And Frequency Trimming Using Localized Mass Deposition
The University of Michigan 2002
Advisor: Prof. Ken Wise

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