NSF EPSCoR RESEARCH INFRASTRUCTURE IMPROVEMENT

Idea Paper

Piezoelectric Vibrational Energy Harvester (PVEH) Power System Development for Wireless Sensor Network Applications

Principal Investigator:	**Dr. Junru Wu, Professor of Physics, UVM – CTO, MicroGen Systems LLC** *Acoustics, vibration and ultrasound researcher*
Co-Principal Investigator:	**Dr. Jeff Frolik, Associate Professor EE, UVM** *Wireless Sensor Network (WSN) researcher*
Graduate student:	**Robert Andosca, Ph.D. Candidate Materials Science – CEO MicroGen Systems LLC** *Microsystems design and manufacturing, scientist and entrepreneur (20 years)*
VT-based affiliations:	**MicroGen Systems LLC** – ***Micro-energy harvester product developer*** 31 Whiteface Lane, South Burlington, VT 05403
	MicroStrain, Inc. (www.microstrain.com) – ***WSN and meso-scale PVEH product developer*** 310 Hurricane Lane, Unit 4, Williston, VT 05495
	Suss MicroTech (www.suss.com) – ***Microsystems equipment manufacturer*** Route 100, Waterbury, VT 05676
	Bennington Microtechnology Center (www.benningtonmicro.org) – ***Micro-packaging foundry*** 441 Water Street, North Bennington, VT 05257
Other affiliations:	**Infotonics Technology Center, Inc.** (www.itcmems.com) – ***Microsystems foundry*** 5450 Campus Drive, Canandaigua, NY 14424

Current situation

Since January 2007 Dr. Junru Wu and his Ph.D. graduate student, Mr. Robert Andosca, have been developing a microsystems-based piezoelectric vibrational energy harvester (PVEH). The main idea is to make use of ambient vibrational energy which otherwise is wasted to generate electricity. The electrical energy generated via a parametric bending mode in a microscopic piezoelectric beam is sufficient to power wireless sensors in various applications. The team filed a patent disclosure on a novel PVEH device design that has led to an international patent application that was filed in March 2008. The patent is entitled "Piezoelectric Vibrational Energy Harvesting Systems Incorporating Parametric Bending Mode Energy Harvesting." The team has also spun-out a company called MicroGen Systems LLC. MicroGen has exclusively licensed this technology from UVM and will be commercializing the PVEH Power Unit Product when prototyping has been completed. Prototyping is currently being done at the Infotonics Technology Center (ITC) located near Rochester, NY, and packaging can be done through the Bennington Microtechnology Center located in North Bennington, VT (*Letters of Support* on file).

Dr. Wu and Mr. Andosca were awarded through MicroGen a modest amount of funding from a NASA EPSCoR Phase (0) SBIR grant. Subsequently, the researchers developed a theoretical model that describes the non-linear "parametric mode" phenomenon that allows the PVEH to efficiently produce more power or widen its bandwidth as compared to standard PVEH designs. This theoretical and computational research is being prepared for submission to *The Journal of the Acoustical Society of America*, and should be submitted in August 2008. In addition, as stated previously the microsystems based parametric mode enabled (PME) PVEH devices are being fabricated at ITC. ITC has provided these development services at no cost to date yet will need to be compensated for future development. Once the initial prototypes are completed, then the experimental testing will commence.

The investigators have since been awarded funds from the UVM Ventures' Pre-seed and Innovations Funds, and from the NY State Energy Research and Development Authority (NYSERDA). The latter is part of an alliance with ITC and Ember Corporation in Boston, MA. ITC has been awarded a Army Research Laboratory (ARL) grant, which is providing matching funds for the effort. Ember is a leading WSN component manufacturer. Both have provided *Letters of Support* for the partnership. Yet, even with these initial awards the researchers will need more funding to proceed forward and investigate energy harvesters more thoroughly over the next several years.

Dr. Jeff Frolik an Associate Professor of Electrical Engineering at UVM who works in the areas of sensor networks and wireless communications. Dr. Frolik's focus is on methods to extend the operational life of energy constrained wireless sensor systems operating under severe conditions. Work in this area has been sponsored by the Goodrich Corporation of Vergennes, VT. In addition, three of his recent graduate students now work for MicroStrain, Inc. a wireless sensor manufacturer located in Williston, VT. MicroStrain is a manufacturer of meso-scale non-microsystems-based PVEH devices as well. MicroStrain could become a customer of MicroGen.

There is strong synergy within the greater Burlington, VT area to develop WSNs powered by energy harvesting devices. The integration of the researcher's PVEH Power Units into WSNs and subsequent field testing will need further funding. Energy harvester and WSN technology will

provide a strong foundation for further research and development, and the education of other graduate students and post-doctoral study at UVM for years to come.

Vision

The researchers' vision is to have a strong microsystems program in the State of Vermont after 5-years R &D at UVM. A basis for such work would be built upon the work done on the PVEH device for WSN applications, and previous work done by the researchers on a microsystems-based Bio-sensor called a Lamb-wave acoustic micro-sensor. There are other micro-systems-based devices being researched within UVM's Engineering School as well. This long-term microsystems vision would create strong interdisciplinary research efforts between engineering (EE, CE, ME, Materials Science), science (agriculture, biology, chemistry, genetics, physics, etc.) and Medical programs at UVM.

Specific obstacles

At this point, the only obstacle is the need for more funding into this important research area. Long-term the researchers believe there is a strong need for UVM to have a modest clean-room facility and microsystems and micro-packaging equipment (see Plan for sustainability section within this document).

Intellectual merit

There is strong intellectual merit for a research program on a meso-scale and microsystems based PVEH devices. This is exemplified by the fact that there is a large amount of Federal proposal solicitations from the Federal government (NIST TIP, NSF, Army, Navy, etc.; see DEPSCoR – ARL BAA W911NF-07-R-0001 as a prime example – there are four (4) sub-topics that request energy harvesting and integration with WSNs). The PVEH researchers have also submitted two SBIR Phase (1) proposals in June 2008 on this subject to the NSF and Army. NSF seeks "DARPA-hard" or technologically "risky" projects that also have a strong commercial future. The NSF technical point of contact requested the investigators to submit a proposal after their PVEH white-paper was reviewed.

Plan for sustainability

Beyond the 5 years of NSF EPSCoR funding the plan for sustainability is to enhance microsystems research infrastructure at UVM. This can be done with the addition of a small clean-room and microsystems equipment to build micro-devices like the PVEH prototypes. This would require a sizable amount of funding and/or donations from industry. A company in Waterbury, VT and Germany called *Suss MicroTech* is a leading global provider of microsystems and micro-packaging equipment. Mr. Andosca has strong contacts within Suss MicroTech, and believes he can leverage his relationship to have equipment either donated to UVM or obtain an appreciable discount. This is especially if Suss MicroTech could utilize the equipment for customer demonstrations.

References related to PVEH development

- R.G. Andosca and J. Wu, "Efficient vibrational power harvesting with a microfabricated piezoelectric device – analytical solutions and device design concepts", **Journal Acoustical Society of America**, to be submitted Aug-08 (research using NASA EPSCoR Phase (0) SBIR grant).
- "Piezoelectric Vibrational Energy Harvester Development", NYSERDA, $300K awarded to MicroGen, equivalent matching funds from ITC- ARL grant and UVM Innovations fund (Jun-08).
- "Infotonics Technology Center and MicroGen Systems Partnership developing PVEH devices", (2007 and 2008).
- International Patent Application Serial No. PCT/US08/57865, filed by UVM through DRM PLLC on March 21, 2008, entitled "Piezoelectric Vibrational Energy Harvesting Systems Incorporating Parametric Bending Mode Energy Harvesting."
- "Piezoelectric Vibrational Energy Harvester Development", UVM Ventures Pre-seed and Innovations Funds, $20K and $100K awarded to MicroGen (Jul-07 and Jan-08).
- "Analytical and computational modeling of a non-linear piezoelectric vibrational energy harvester", NASA EPSCoR Phase (0) SBIR awarded to MicroGen, $10K (Jun-07).
- U.S. Provisional Patent Application Serial No. 60/896,077, filed by UVM on March 21, 2007, entitled "MEMS-Based Vibrational Power Scavenger."

References related to WSN development

- L. Bakir and J. Frolik, "Diversity gains in two-ray fading channels", in press, **IEEE Trans. Wireless Communications**, accepted Jul-08.
- J. Frolik, "On appropriate models for characterizing hyper-Rayleigh fading", in press, **IEEE Trans. Wireless Communications**, accepted: Mar-08.
- "The use of autonomous agents in dynamic, complex and robust sensor networks", Vermont EPSCoR, $45K (Jan-08 – Jun-09).
- J. Kay and J. Frolik, "An expedient wireless sensor automation with system scalability and efficiency benefits", accepted pending revisions, **IEEE Trans. Systems, Man and Cybernetics, Part A**, revised: Jan-08.
- "A wireless sensor network research test bed", CEMS Next Generation Initiative, $11.5K (2007).
- "Wireless sensor networks for aircraft support systems", Goodrich Fuel and Utility Systems, $158K (Jan-06 – Dec-07).
- B. Liang, J. Frolik and X. Wang, "Energy-efficient dynamic spatial resolution control for wireless sensor clusters", in press, Int. **Journal of Distributed Sensor Networks**, accepted: Aug-07.

Jun-ru Wu

University of Vermont, Physics Department, 82 University Place, A405 Cook Hall, Burlington VT, 05405
(802)6568357, fax (802)656-0817, Jun-ru.wu@uvm.edu

Professional Preparation

University of California, Los Angeles, M. S., 1981, Physics
University of California, Los Angeles, Ph. D., 1985, Physics
University of California, Los Angeles, Postdoc., 1985-87, Physics

Appointments

1998-2008	Chair of Department of Physics
1996-Present	Professor, Department of Physics, Department of Mechanical Engineering and Program of Biomedical Engineering, University of Vermont
1993-1996	Associate Professor, University of Vermont
1987-1993	Assistant Professor, University of Vermont
1985-1987	Postdoctoral Research Associate and Adjunct Assistant Professor, UCLA
1980-1985	Research Assistant and Teaching Assistant, UCLA

Awards and Honors:

Member of Sigma Xi Society
Outstanding Teaching Assistant Award, UCLA, 1983
National Scientific Progress Award (China), First Prize, 1986
Fellow of Acoustical Society of America (1991-present)
Fellow of The American Institute of Ultrasound in Medicine (1996-present)
Elected Full Member of Vermont Academy of Science and Engineering, 2001.

Synergistic Activities:

Reviewed *Introductory College Physics* for McGraw-Hill Book Company.
Reviewer for *The Physics of Fluids, Journal of the Acoustical Society of America,* and *Ultrasound in Medicine and Biology.*
Served as a reviewer for proposals submitted to NSF and DOE; Served as a member of a proposal review panel for NSF.

Selected Relevant Publications

1. Z. Zhu and J. Wu, *A General Dispersion Relation for Lamb-Wave Sensors With Liquid-Layer Loading*, Sensors and Actuators A **49**, 79-84 (1995).
2. J. Wu and Z. Zhu, *Sensitivity of Lamb Wave Sensors in Liquid Sensing*, IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control **43**, 71-72 (1996).
3. D. Fischer, W. Varhue, J. Wu, and C. Whiting, *Lamb-Wave Microdevices Fabricated on Monolithic Single Crystal Silicon Wafers*, IEEE Journal of Microelectromechanical Systems, **9**, 88-93 (2000).
4. J. Wu, C. Layman and J. Liu, Wave Equations, Dispersion Relations and van Hove Singularities for Applications of Doublet Mechanics to Ultrasound Propagations in Bio- and Nano- Materials, J. Acoust. Soc. Am. 115, 893-900 (2004); it was selected and

published by *Virtual Journal of Nanoscale Science & Technology* and *Virtual Journal of Biological Physics Research,* Feb. (2004).

5. C. Layman and J. Wu, *Theoretical Study* in *Applications of Doublet Mechanics to Detect Tissue Pathological Change in Elastic Properties Using Ultrasound*, J. Acous. Soc. Am. 116, 1244-1253 (2004); it was selected and published by *Virtual Journal of Biological Physics Research*--August 15, (2004).
6. D. J. D'Amco, T. M. Silk, J. Wu, M. R. Guo, Inactivation of Microorganisms in Milk and apple Cider Treated with Ultrasound, J. Food Protection 69, 556-563 (2006).
7. J. Wu, Shear Stress in Cells Generated by Ultrasound, Progress in Biophysics & Molecular Biology 93, 363-373 (2006).
8. J. Wu, J. Pepe, M. Ricon, Sonoporation, anticancer drug and antibody delivery using Ultrasounsd, Ultrasonics 44, e21-e25 (2006).
9. H. M. Langevin, D. M. Rizzo, J. R. Fox, G. J. Badger, J. Wu, E. E. Konofagou, D. Stevens-Tuttle, N. A. Bouffard, M. H. Krag, Dynamic morphometric characterization of local connective tissue network structure in human using ultrasound, BMC System Biology, 1:25 (2007).
10. J. Wu, Editor and author, *Emerging therapeutic ultrasound,* World Scientific Publishing Co., Singapore, August, 2006.

ROBERT G. ANDOSCA

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PROFESSIONAL EXPERIENCE

MicroGen Systems LLC, South Burlington, VT. www.microgen-systems.com 10/06 to present
President and CEO

- Founded company in 2006. Registered as a VT-Limited Liability Company (LLC) as of February 26, 2007.
- MEMS-based piezoelectric vibrational energy harvester (PVEH) product development for wireless sensor networks. Apps. include automobiles, aircraft, HVAC, industrial monitor, Homeland Security, and others.
- Technology partnerships with The University of Vermont (www.uvm.edu) and the Infotonics Technology Center (www.infotonics.org), Canandaigua, NY. Consulting for VEH prototype development at Infotonics.
- Several proposals written and submitted (four funded to date.) One patent application submitted.

R.G. Andosca and J. Wu, "Efficient vibrational power harvesting with a microfabricated piezoelectric device – analytical solutions and device design concepts", **Journal Acoustical Society of America**, to be submitted Aug-08 (research using NASA EPSCoR Phase (0) SBIR grant).

"Piezoelectric Vibrational Energy Harvester Development", NYSERDA, $300K awarded to MicroGen, equivalent matching funds from ITC- ARL grant and UVM Innovations fund (Jun-08).

"Infotonics Technology Center and MicroGen Systems Partnership developing PVEH devices", (2007 and 2008).

International Patent Application Serial No. PCT/US08/57865, filed by UVM through DRM PLLC on March 21, 2008, entitled "Piezoelectric Vibrational Energy Harvesting Systems Incorporating Parametric Bending Mode Energy Harvesting."

"Piezoelectric Vibrational Energy Harvester Development", UVM Ventures Pre-seed and Innovations Funds, $20K and $100K awarded to MicroGen (Jul-07 and Jan-08).

"Analytical and computational modeling of a non-linear piezoelectric vibrational energy harvester", NASA EPSCoR Phase (0) SBIR awarded to MicroGen, $10K (Jun-07).

U.S. Provisional Patent Application Serial No. 60/896,077, filed by UVM on March 21, 2007, entitled "MEMS-Based Vibrational Power Scavenger."

Infotonics Technology Ceneter, Canandaigua, NY. www.itcmems.com 3/07 to present
Manager / Senior MEMS Scientist and Consultant

- Managing several MEMS-based projects, including PVEH, large 3D-mirror array, micro-shutter, etc.

Lilliputian Systems Inc., Wilmington, MA 02/05 to 10/06
MEMS Process Development Manager – Reported to VP Chip Development

- Solid Oxide Fuel Cell (SOFC) chip – co-managed development/manufacturing team, including four (4) engineers and five (5) techs. Daily meetings, semi-weekly development reviews set short-term goals.
- Directed individual contributor process development, including DRIE, LPCVD LSN, IBE, metal lift-off, and plating. SMART performance goals set and reviewed quarterly. Corrective actions set as needed.
- Managed procurement and process development of equipment set, including STS Pegasus DRIE, EVG photo equipment, LPCVD, etc. Responsible for process integration of entire SOFC process flow.
- New MEMS fabrication facility, first SOFC lots started and completed ahead of schedule with high yield.
- Hands-on process development including DRIE, custom ion assisted e-beam evaporation and electro-plating.

Foundry Manager – Reported to VP Engineering

- Managed SOFC chip development activities at Advanced MicroSensors in Shrewsbury, MA.
- Directed individual contributor process development to improve yield from 0 to >95% membrane yield and 1st operational auto-thermal fuel cell.

IntelliSense and Corning IntelliSense www.intellisense.com 11/00 to 02/05
Director, Business Development and Hardware Engineering – IntelliSense, Woburn, MA (1/04 to 2/05)

- Joined former colleagues to re-build IntelliSense as fabless MEMS design house – Reported to VP Sales
- Managed design team. Led team on several projects, including a vibrational energy harvester.
- Formed strategic alliances with MEMS foundries, including Infotonics Technology Center (Rochester, NY) and Advanced MicroSensors (Shrewsbury, MA).
- Wrote commercial and government proposals (General Motors, Infotonics, Crossbow, SBIR, DARPA).
- MEMS FE modeling using Intellisuite® and process design. Hands-on design of an electromagnetic angle sensor for auto applications. Submitted to NineSigma, General Motors Corporation; finalist.
- International and domestic business travel to customers and conferences, including Canada, and Malaysia.

Technical Leader – Emerging Business Unit, Corning IntelliSense, Wilmington, MA (11/00 to 11/02)
- RF MEMS focus. Team planning, proposal development, and marketing – Reported to VP Engineering
- Successful team implementation of joint RF MEMS project with Northrop Grumman Corporation.

MEMS Research & Development Manager / Engineer – Corning IntelliSense – Reported to VP Engineering
- Managed split shift research & development efforts, two (2) engineers and (3) technicians reporting.
- Project: 2D Optical Cross-Connect – internal Corning program.
  - Coordinated multi-site project/team (Corning FRC, Corning Sullivan Park, and Corning IntelliSense).
  - Led the implementation of SPC and manufacturing practices to improve manufacturability.
    - Directed the use of DOE methodology to develop robust processes. SPC practices instituted
    - Team fabricated first 8x8 2D switch to meet insertion loss criteria < 8 dB (company milestone).

Senior MEMS Development Engineer – Corning IntelliSense – Reported to VP Engineering
- Project: Bio-MEMS micro fluidic nozzle – external foundry customer – Advion BioSiences, Ithaca, NY.
  - Directed two (2) engineers & five (5) technicians. Process flow developed & integrated.
  - Developed several plasma DRIE (Alcatel) through-wafer & high-aspect-ratio etches.
  - LPCVD Si_xN_y stress and electric field breakdown strength tailoring. LPCVD oxides and nitrides.
  - Directed testing and packaging teams. Successfully transferred to volume manufacturing.

- Project: RF integrated filter / capacitively coupled switch – external foundry customer.
  - Design and process flow developed. Au electroplating & lift-off on quartz substrates.
  - Directed modeling team using Intellisuite® MEMS FE modeling. L-Edit used for CAD layout.

- Project: Spatial Light Modulator – external foundry customer.
  - Design and process flow developed. Combined bulk and surface micromachining.
  - Directed modeling team using Intellisuite® MEMS FE modeling. L-Edit used for CAD layout.

"RF MEMS Improvement Program," Air Force Research Laboratory / DARPA grant, 2003.

U.S. Patent 10,099,153 "Electrostatically Actuated Microelectromechanical Devices and Method of Manufacture," R.G. Andosca, filed December 2001.

"An Automated Nanoelectrospray Platform Based on BioMEMS Microchip Technology", T. Corso, S.J. Prosser, C. Fung, R. Andosca, *et al*, (SmallTalk 2002, The Microfludic, MicroArrays and BioMEMS Conference, San Diego, CA, July 28-31, 2002), p. 58.

U.S. Patent 10,053,844 "Tilting Mirror with Rapid Switching Time," R. Andosca, J. Bernstein, *et al*, filed January 2002.

Umicore Semiconductor Processing, Boston, MA – Umicore, Olen, Belgium www.umicore.com 01/03-12/03

Operations / General Manager – Reported to Business Line Manager
- General Manager responsible for P&L of custom semiconductor substrate manufacturer (Si & Ge).
- Managed 25 person company, including five (5) direct manager reports (sales, accounting, development, manufacturing, and quality control). Managed oversees Ge development department in Belgium.
- Developed five year business plan. Obtained internal funding to build thick, bonded SOI and GeOI product lines. Acquired EVG 850 production SOI bonder with plasma activation and other bonding tools.
- International and domestic business travel to customers, vendors and conferences (> 75% time).

- Reported to Olen, Belgium headquarters monthly. Managed 300mm Ge development effort in Belgium.

"Backgrind GeOI Substrates up to 200mm Diameter," G. Raskin, R. Andosca, M. Gabriel, M. Reiche, M. Firth, C. Franco, J. Dumas and P. Mijlemans, (Materials Research Society Proceedings, Symposium B, Spring Meeting 2004, San Francisco, CA).

Clare Corporation, Beverly, MA www.clare.com 11/97 to 11/00

Senior Process Development Engineer / Project Manager – Reported to Technology Director

- Project: Dielectric Isolated BiCDMOS IC chip and Photo-voltaic chip integration, $5 M project.
  - Managed and worked as engineer on project. Transferred to production with > 90% yield.
  - Directed and developed micromachined dielectric isolated SOI process module. Equipment acquisition.
  - Process integration with high voltage BiCDMOS and optically isolated switch circuits.
  - Directed or developed several unit step development efforts including DRIE (STS), CMP, LPCVD, etc.
  - Work instructions, SPC and manufacturing practices implemented.
  - Transferred to production with > 70% and 95% yield, respectively.

- Project: SOI wafer bonding development.
  - Wafer bonding using EVG 850. Acoustic void detection using Sonoscan C-SAM. Bond yield > 98%.
  - Grind (Okmoto) and chemical mechanical silicon polish (Westech 372).

- Project: MEMS Micro-relay – MIT, Microsystems Technologies Laboratory, Cambridge, MA.
  - Worked on Clare / MIT team designing MEMS micro-relay. Project directed by Dr. Martin Schmidt.
  - Patent disclosures internally submitted for novel Lateral Actuated Micro-relays (LAM).

"MEMS Based Micro-relay," N. Polce, R. Andosca, S. Jones, M. Schmidt, J. Lang and J. Wong, (Sensors Expo Proceedings, Chicago, Illinois, October 6-8, 1998) p. 397.

Lockheed Martin (now BAE Systems), Nashua, NH www.lockheedmartin.com 05/96 to 11/97

Group Leader / Senior Manufacturing Engineer – Reported to Fab Manager

- Dry Chemistry Group Leader, Plasma-etch and deposition processes. Two engineers and one technician.
- Lockheed Martin laboratory consolidation process transfer team member. GaAs / InP, PHEMT / MMIC.
- Developed GaAs high aspect ratio backside through-wafer plasma etch process. BCl_3 / Cl_2 RIE process.

Irvine Sensors Corp., IBM Microelectronics Division, Essex Junction, VT www.irvine-sensors.com 05/94-05/96

Group Leader / Process Engineer III – Reported to Fab Manager

- IBM partnership fabricating 3D "Cube" 80MB stacked DRAM CMOS technology. Development to volume manufacturing.

"Silicon Based Cap Chip for Stacked Memory," T.G. Ference, R.G. Andosca, *et al*, (IBM internal pub, 1996).

EDUCATION & PROFESSIONAL RESEARCH

Ph.D. (A.B.D.) Materials Science, The University of Vermont, Burlington, VT.

- Ph.D. comprehensive exams and coursework completed successfully. Electrical Engineering and Solid State Physics coursework concentration (3.7 / 4.0).
- Dissertation research re-starting in January 2007.
  - Design of MEMS vibrational, piezoelectric based energy harvester for wireless sensor networks.
  - Modeling using IntelliSuite *CAD for MEMS*® finite element analysis software.

Advisor: Dr. Jun-ru Wu and Dr. Walter Varhue.
Physical Acoustics and Semiconductor Processing Laboratories, Physics and EE Departments.

Graduate Research Fellow and Teaching Assistant. 05/92-05/96

Original Ph.D. research on Bio-MEMS acoustic Lamb-wave sensor. (latter 2 years part-time while working)

- Device design, modeling, and mirco-fabrication. Device fabricated on 2.0 μm thick Si membranes.
- Large 2.5 x 2.5 cm membranes fabricated using EDP boron etch-stop technique.
- Piezoelectric ZnO deposited by sputtering directly onto highly doped Si membrane.

"Lamb Wave Micro-sensor Development," SBIR, NSF / VT-EPSCoR Grant, $5000, 1994.

Materials Science Graduate Student Award, College of Engineering, University of Vermont, 1992-93.

M.S. in Materials Science May 1992

- Electrical Engineering and Solid State Physics concentration. (3.5 / 4.0)

The University of Vermont, Burlington, VT

Advisor: Dr. Walter J. Varhue.
Semiconductor Processing Laboratory, Electrical Engineering Department,

M.S. Thesis: "Bulk Properties of Silicon Dioxide Thin Films Prepared by Electron Cyclotron Resonance Plasma Enhanced Chemical Vapor Deposition".

"Silicon Dioxide Prepared by Electron Cyclotron Resonance Plasma Enhanced Chemical Vapor Deposition," R.G. Andosca, W.J. Varhue and E. Adams, **Journal of Applied Physics 72**, 1126-1132 (1992).

"Electrical and Chemical Characterization of SiO_2 Deposited by ECR-PECVD," R.G. Andosca, W.J. Varhue and S. Titcomb, in Chemical Perspectives of Microelectronic Materials II, edited by L.V. Interrante, K.F. Jensen, L.H. Dubois and M.E. Gross (Materials Research Society Proceedings **204**, Pittsburgh, PA 1990) pp. 489-494.

B.S. in Physics / Mathematics (3.2 / 4.0), Keene State College, Keene, NH May 1989

Research Advisor: Dr. J. Russell Harkay.
Thin-film Research Laboratory, Physics Department, USNH.

- Thin-film metallic film research completed under ultra-high vacuum.
- Deposited alkali earth metal films onto quartz slides. Determined optical constants as wavelength function.

"Observations of Bulk Plasmons and Determination of Optical Constants for Alkali and Other Metals," R.G. Andosca and J.R. Harkay, (American Physical Society Bulletin **34**, No. 8, 1989) p. 1855.

"Observations of Bulk Plasmons and Determination of Optical Constants for Alkali and Other Metals," R.G. Andosca and J.R. Harkay, (Forty Third Annual Eastern College Science Conference, West Point U.S. Military Academy, April 20-22, 1989) PH-12.

"High Resolution PREL using IGOR for Optical Constants and Carrier Concentrations in Thin Films," J.R. Harkay, R. Andosca, P. Chapman, P. Hornblad and J. Newcomb, (American Physical Society Bulletin **34**, No. 8, 1989) p.1857.

"Optically Stimulated Plasma Resonance in Bismuth and Thallium Films as a Function of Surface Contamination," J.R. Harkay and R. Andosca, (American Physical Society Bull. **33**, No. 8, 1988) p.1810.

SPECIAL COURSEWORK & TRAINING

- Tanner EDA / L-Edit training course (Infotonics Technology Center, 2007).
- Intellisuite® CAD Training Course (Corning IntelliSense, 2001 and IntelliSense, 2004)
- Microsystems: Mechanical, Chemical, Optical (MIT, Cambridge, MA, Senturia, Summer 1998)
- SixSigma SPC training course (IBM Microelectronics Division, 1995)
- Modern Materials Analysis Techniques (Materials Research Society, Fall 1990)

U.S. CITIZEN
References and transcripts available upon request

JEFF FROLIK

(I) PROFESSIONAL PREPARATION

Institution and Location	Major	Degree & Year
Univ. of South Alabama, Mobile	Electrical Engineering	BSEE - 1986
Univ. of Southern California, Los Angeles	Electrical Engineering	MSEE - 1988
Univ. of Michigan, Ann Arbor	Electrical Engineering-Systems	Ph.D. - 1995

(II) APPOINTMENTS

04/08-date	Associate Professor of Engineering, University of Vermont
09/02-04/08	Assistant Professor of Electrical Engineering, University of Vermont
09/98-08/02	Assistant Professor of Electrical Engineering, Tennessee Technological University
08/95-6/98	Independent Consultant for Shinawatra (Thailand), Hughes Aircraft Co. (California), and Binariang Sdn. (Malaysia)
06/93–7/95	Hughes Information Technology Co. (Troy, MI)
09/86-5/93	Hughes Aircraft Co. (Los Angeles, CA): Space and Communications Group

(III) PUBLICATIONS (mentored students underlined)

Most Related Publications

- J. Frolik, *Implementation of handheld, RF test equipment in the classroom and the field*, IEEE Trans. Education, Vol. 50, No. 3, August 2007.
- J. Frolik, *A case for considering hyper-Rayleigh fading channels*, in press, IEEE Trans. Wireless Communications, Vol. 6, No. 4, April 2007.
- J. Frolik and M. Fortney, *A low-cost wireless platform for first year, interdisciplinary projects*, IEEE Trans. Education, Vol. 49, No. 1, February 2006.
- J. Frolik and J.B. Zurn, *Evaluation of Tablet PCs for engineering instruction and content development*, ASEE Computers in Education Journal, Vol. 15, No. 3, July-September 2005.
- J. Frolik and T. Weller, *Wireless sensor system design: an approach for a multi-university design course offering*, IEEE Trans. Education, Vol. 45, No. 2, May 2002.

Other Significant Publications

- J. Galbreath and J. Frolik, *Channel allocation strategies for wireless sensors statically deployed in multipath environments*, Fifth International Conference on Information Processing in Sensor Networks (IPSN06), April 19-21, 2006, Nashville, TN.
- J. Kay and J. Frolik, *An expedient wireless sensor automation with system scalability and efficiency benefits*, accepted pending revisions, IEEE Trans. Systems, Man and Cybernetics, Part A, revised: January 2008.
- R. Ketcham, J. Frolik and J. Covell, *Propagation measurement and statistical modeling for wireless sensor systems aboard helicopters,* in press, IEEE Trans. Aerospace and Electronic Systems, accepted: February 2008.
- J. Frolik, *On appropriate models for characterizing hyper-Rayleigh fading*, in press, IEEE Trans. Wireless Communications, accepted: March 2008.
- L. Bakir and J. Frolik, *Diversity gains in two-ray fading channels*, in review, IEEE Trans. Wireless Communications, revised: May 2008.

(IV) SYNERGISTIC ACTIVITIES

Dr. Frolik and has over 20 years of industrial and academic experience in the areas of communication systems, signal processing and sensor networks. His industrial experience includes systems engineering and consulting on direct broadcast communication satellites. His academic experience began at Tennessee Technological University where he twice received the L. E. Sissom Innovation and Creativity Award for his curricular efforts. In 2002, he was named the ASEE Southeastern Section New Teacher Award. At the University of Vermont (UVM) he has received five internal grants along with external funds for curricular innovation. His research has resulted in an automaton based architecture for sensor networks which is highly robust to individual node failure and empirical results along with new theory for hyper-Rayleigh fading in wireless communication channels.

NSF-sponsored undergraduate education projects:

- DUE-0717326 (PI): *MUSE: A model for undergraduate learning of complex-engineered systems*, Collaborating PIs: T. Weller (Univ. South Florida), P. Flikkema (Northern Arizona Univ.) and W. Shiroma (Univ. Hawaii). 9/07-8/10
- DUE-0310150 (PI): *A comprehensive, laboratory-enhanced signals and communications curriculum*. 09/05- 10/08.

Corporate-sponsored undergraduate education projects:

- Microsoft Research (co-PI): *Educational Value and Validity - Student Adaptation to Tablet PC Technology in Business and Engineering Curriculums*, Collaborators at Univ. Vermont: J. Kraushaar (PI), T. Chitteden, and D. Novak. 06/06-05/08.
- Hewlett Packard (PI): *Implementation of Tablet PCs in engineering laboratory and design environments*. 07/03- 08/04.

Providing out-of-class and research experience for undergraduate students:

- Faculty advisor to UVM's Alternative Energy Racing Organization which received three design awards at the 2008 Formula Hybrid International Competition
- Faculty advisor to two underrepresented students sponsored by the McNair Scholars Summer Research Program and one student sponsored by UVM's Barrett Foundation for Summer Research
- Faculty advisor to five undergraduates sponsored through UVM's URECA! Program.
- Student Activity Coordinator, IEEE Green Mountain Section.

Transfer of knowledge (patent applications):

- *Method of making a decision on the status of a mechanical system using input and response data acquired in situ*, US Patent Application Serial No. 11/413,025 (Filed April 27, 2006).
- *Zero-order energy smart antenna and repeater*, w/ T. Weller. US Patent Application Serial No. 11/608,462 (Filed December 8, 2006).
- *Compact reconfigurable channel emulator*, w/ T. Weller. US Patent Application Serial No. 60/973,915 (Filed September 20, 2007).

(V) COLLABORATORS & OTHER AFFILIATIONS

(a) Collaborators and Co-Editors: Paul Flikkema, Northern Arizona Univ.; Jim Kraushaar, Univ. Vermont; Wayne Shiroma, Univ. Hawaii; Christian Skalka, Univ. of Vermont; Joe Tront, Virginia Tech; X. Sean Wang, Univ. Vermont; Tom Weller, Univ. South Florida; Beverley Wemple, Univ. Vermont.

(b) Ph.D. Advisor: Andrew Yagle, University of Michigan

(c) Graduate Student Advising (15 students in total graduating since 1998): Univ. of Vermont students: B. Liang (Ph.D., current), L. Bakir (Ph.D., current), S. DiStasi (MS, current), C. Chen (MS, current), J. Kay (Ph.D. – 2007), R. Ketcham (MS – 2007), M. Fortney (MS – 2007), B. Capsuto (MS – 2006), C. Fitzhugh (MS – 2006), J. Galbreath (MS – 2006), L. Mayer (MS – 2004), S. Maciejowski (MS – 2003), A. Fredman (MS – 2003).