

Nano Mechanical and Electronic Investigations with Tokyo Institute of Technology

VIRGINIA M. AYRES¹

¹ *Michigan State University, Electronic and Biological Nanostructures Laboratory, East Lansing, MI 48824, USA. E-mail: ayresv@msu.edu;*

ABSTRACT:

Multidisciplinary research has become key to scientific success, especially in nanotechnology. Effective collaborative interactions are therefore of vital importance. In an increasingly global research arena, an optimum collaboration may involve international partnerships. Experience suggests that face-to-face communication at regular intervals contributes greatly to strong productive partnerships. Therefore, global research collaborations depend on effective personnel exchanges. This introduces new cultural and language considerations, in addition to research considerations. The IREE: Nano Mechanical and Electronic Investigations with Tokyo Institute of Technology is a collaborative research effort that combines the nanomaterials growth expertise at Tokyo Institute of Technology with the nano/atomic scale characterization expertise of the Electronic and Biological Nanostructures Laboratory group at Michigan State University. The IREE supported the exchange of two early career researchers for a 3 month period, with a supervisory visit from the Principal Investigator at the conclusion of their visit. The two early career researchers were, respectively, just finishing and just entering Graduate school, therefore this opportunity will have a powerful impact on their career development. The 3 month visit enabled the two IREE early career researchers to learn the skills of the nano-carbon onions growth group at Tokyo Institute of Technology and to directly and the knowledgably share characterization results obtained at both Tokyo Institute of Technology and at Michigan State University. The IREE also showcased the new capabilities of the foundation grant in Scanning Probe Recognition Microscopy within an international investigation of key mechanical and electronic properties of two important nanomaterials, carbon onions (nested fullerenes) and gallium nitride nanowires. The visit has been a technical success with one joint USA-Japan authorship archival journal publications submitted and two in preparation. The visit has been an international success as the early career researchers learned both Japanese language and culture, and developed valuable professional networks within Japan.

INTRODUCTION (LIMIT: 1 PAGE)

- Name of awardee institution for current NSF award: Michigan State University
- A Brief Summary of Work being Carried Out Under Current NSF Award
A new scanning probe microscope methodology has been developed under the current NSF award: DMI-0400298: Scanning Probe Recognition Microscopy. Scanning Probe Recognition Microscopy (SPRM) gives the scanning probe microscope system itself the ability to auto-track regions of interest through incorporation of recognition-based tip control. A low resolution scan to identify regions of interest is followed by auto-track high-resolution scans of just these areas. New and powerful investigative capabilities result from this approach.
- Reasons/Rationale for International Cooperation Carried Out Under IREE
Multidisciplinary research has become key to scientific success, especially in nanotechnology. The first reason for the international cooperation carried out under the IREE was to combine nanomaterial growth expertise of the Tokyo Institute of Technology group with nano/atomic scale characterization expertise of the Michigan State University group. The IREE supported the exchange of two early career researchers for a 3 month period, with a supervisory visit from the Principal Investigator at the conclusion of their visit. The two early career researchers were, respectively, just finishing and just entering Graduate school, therefore this opportunity will have a powerful impact on their careers. The 3 month visit was long enough for the two IREE early career researchers to learn the skills of the nano-carbons growth group at Tokyo Institute of Technology and to directly and the knowledgably share characterization results obtained at both Tokyo Institute of Technology and at Michigan State University. Another reason for the IREE was to use the new SPRM capabilities of the foundation grant within an international investigation of key mechanical and electronic properties of two important nanomaterials, carbon onions (nested fullerenes) and gallium nitride nanowires. The latter was substituted for 2D graphene as an electronic material. The visit has been a technical success with two joint USA-Japan authorship archival journal publications submitted and a third in preparation. The visit has been an international success as the early career researchers learned both Japanese language and culture, and developed valuable networks within Japan. The visit concluded with an oral presentation by the early career researchers at the New Diamond and Nano Carbons International Conference in Osaka Japan 28-31 May 2007, in which the new research results were presented in (official conference language) English while sub-titled throughout in Japanese.

Analysis of the tribological properties and radiation resilience of carbon onions

カーボンオニオンのサイクロトロンレジリエンスと摩擦特性

Andrew D. Baczewski¹, Benjamin W. Jacobs¹, Kaylee McElroy¹, Dr. Virginia M. Ayres¹, Dr. Reg M. Ronningen², Dr. Al F. Zeller², Dr. Atsushi Hirata³, Ryouichi Yamada³

¹Michigan State University
Department of Electrical and Computer Engineering
(ミシガン州立大学)



²Michigan State University
National Superconducting Cyclotron Laboratory
(ナショナルスーパーコンダクティングサイクロトロン研究所)

³Tokyo Institute of Technology
Department of Mechanical Sciences and Engineering
(東京工業大学)




**Outline
アウトライン**

<ul style="list-style-type: none"> •Why Carbon Onions? •Experiments •Growth •Pre-radiation Results •Cyclotron Conditions •Post-radiation Results •Conclusions •Future Research 	<ul style="list-style-type: none"> •背景 •目的および測定方法 •成長過程 •分析結果 (照射前) •サイクロトロン測定条件 •分析結果 (照射後) •結論 •今後の課題
--	---

- Information about Host Laboratory
The primary host laboratory is the Tokura-Hirata Surface Engineering Laboratory of Professor Atsushi Hirata, specializing in self-assembly of carbon nanomaterials. The secondary host laboratory is the Enoki-Fukui laboratory of Professor Toshiaki Enoki, specializing in scanning probe microscopies of nanomaterials and nanocircuits. The two early career researchers also participated in the weekly seminar series of the secondary host laboratory.
- Names of Travelers: Mr. Benjamin W. Jacobs, Mr. Andrew D. Baczewski, Professor Virginia M. Ayres
- Dates of Travel:
Mr. Benjamin W. Jacobs, Mr. Andrew D. Baczewski: 3/5/2007 to 6/2/2007
Professor Virginia M. Ayres: 5/26/2007 to 6/2/2007

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION (LIMIT: 1.5 PAGES)

Please include information on:

- Program of research carried out during international research experience
This is a joint research endeavor between Michigan State University in the United States of America and Tokyo Institute of Technology in Japan. Growth, and macroscopic evaluation of the remarkable lubricant properties of nanoscale carbon onions, is the contribution of the group at Tokyo Institute of Technology while microscopic/atomic scale characterization is the contribution of the Michigan State University group. The best equipment resources from both institutions are utilized to promote the research. An infrared image furnace in the Surface Engineering Laboratory at Tokyo Institute of Technology is used for carbon onion production from various starting materials and included carbon black and nanocrystalline diamond and thermogravimetric analysis of the as grown carbon onions is used to test the thermal stability of the onions in air to determine onion structural quality are unique contributions of the Tokyo Institute of Technology group. Scanning probe microscopies, including the new Scanning Probe Recognition Microscopy capability of the foundation grant, and high resolution transmission electron microscopies are the unique contribution of the Electronic and Biological Nanostructures Laboratory at Michigan State University group. The collaborative research has resulted in a manuscript submission to Japanese Journal of Applied Physics with two more publications in preparation, and a strengthened and continuing research interaction. Discussions and interactions with Professor Toshiaki Enoki have opened potential future collaborative experiments on novel gallium nanowire structures discovered by the Michigan State University group. These experiments include nanowire electronic characterization in high magnetic fields using low temperature scanning tunneling microscopy (STM) to add to the knowledge obtained using Scanning Probe Recognition Microscopy (SPRM) described below.

- How the work on-site is related to the work of the current NSF award
Scanning probe recognition microscopy is being used to test highly localized elastic and friction properties of the carbon onions. Information from SPRM is combined with analytical high-resolution transmission electron microscopy used to test physical and chemical differences in carbon onions grown from different starting materials and growth temperatures. These investigations by the Michigan State University group provide a unique and very complete atomic scale perspective on the tribological properties of carbon onions. Too often such fundamental knowledge is decoupled from any practical impact due to the lack of scale-up. The contributions of the group at Tokyo Institute of Technology are therefore vital to complete the intellectual loop. The group at Tokyo Institute of Technology grows the carbon onions through a self-assembly process involving well-calibrated plasma parameters. The two early career researchers have participated in the growth experiments and clearly understand the parameters involved. The Michigan State group provides the atomistic friction information. Then both growth and atomistic friction information is correlated with macroscopic wear and friction experiments performed at Tokyo Institute of Technology. In this way, fundamental-level knowledge, obtained using SPRM and other atomic scale techniques, is efficiently coupled into both the nanoscale self-assembly and the macroscopic outcome.

Scanning probe recognition microscopy is further being used to investigate electron beam lithographically fabricated nanowire field effect transistor designs (NanoFETs). A NanoFET is an unconventional Schottky-barrier modulated device, in which a work function difference between the nanowire or nanotube and the metallic contact creates a Schottky energy barrier at the contacts. Indirect electrostatic modulation across an insulating layer thins or thickens this Schottky barrier, which allows or prohibits quantum tunnelling into and through the nanowire or nanotube, creating a closed or an open circuit. The Schottky barrier at the contact is therefore the vital control element in the NanoFET circuit architecture. There are few direct measurements available. Professor Ayres' group at Michigan Sate University is the first to use ballistic electron microscopy to directly probe the nature of the Schottky barrier at the contact interface while using SPRM to maintain reliable auto-focus on the region of interest. Low temperature high magnetic field STM of GaN nanowire cross sections will add a novel augmentation of understanding of electron transport properties within the nanowires.

- A substantive description of the general interaction between researcher and host laboratory during the international research experience
Mr. Jacobs and Mr. Baczewski conducted research through learning several new techniques, including thermogravimetric analysis, X-Ray photoelectron spectroscopy, and carbon onion growth procedures with a quartz tube furnace. Graduate student group members of the host laboratory trained Mr. Jacobs and Mr. Baczewski on these instruments and provided assistance after training was completed. Additionally, Mr. Jacobs and Mr. Baczewski were able to suggest improvements in existing experimental procedures within their host lab. Mr. Jacobs and Mr. Baczewski participated in productive discussions in completing a publication with the host professor and making suggestions for future experiments as well as future publication possibilities.
- Relevant schedule, if applicable

The 3 month on-site visit at Tokyo Institute of Technology, Tokyo, Japan by Mr. Jacobs and Mr. Baczewski, and the supervisory visit by Professor Ayres have been completed. The research and its dissemination are continuing.

- Any other information that relates to the Intellectual Merit of the research carried out abroad
 - Refereed publications resulting from IREE
 - 1. A. Hirata, R. Yamada, V. M. Ayres, B. W. Jacobs and A.D. Baczewski, "Correlation of Fundamental Properties with Tribological Performance of Carbon Onions with Oxidation Treatment", submitted to Japan J. Appl Phys.
 - 2. K. McElroy, B.W. Jacobs, X-D Fan, A.D. Baczewski, V.M. Ayres, R.M. Ronningen, A.F. Zeller, A. Hirata, M. Iwasaki "Analysis of the radiation resilience and tribological properties of carbon onions", manuscript in preparation for submission to Carbon
 - 3. B.W. Jacobs, K. McElroy, Q. Chen, Y. Fan, L. Udpa, A.F. Rice and V.M. Ayres, "Scanning probe recognition microscopy investigation of GaN nanowire nanocircuits", manuscript in preparation for submission to App. Phys. Lett.
 - 4. A.D. Baczewski, B.W. Jacobs, V.M. Ayres, A. Hirata, and R. Yamada, "Analysis of the tribological properties and radiation resilience of carbon onions", Abstract Book New Diamond and Nano Carbons 28-31 May2007, Osaka, Japan, p. 71 (2007)
- Be sure to include at least two graphics that highlight the progress of the research

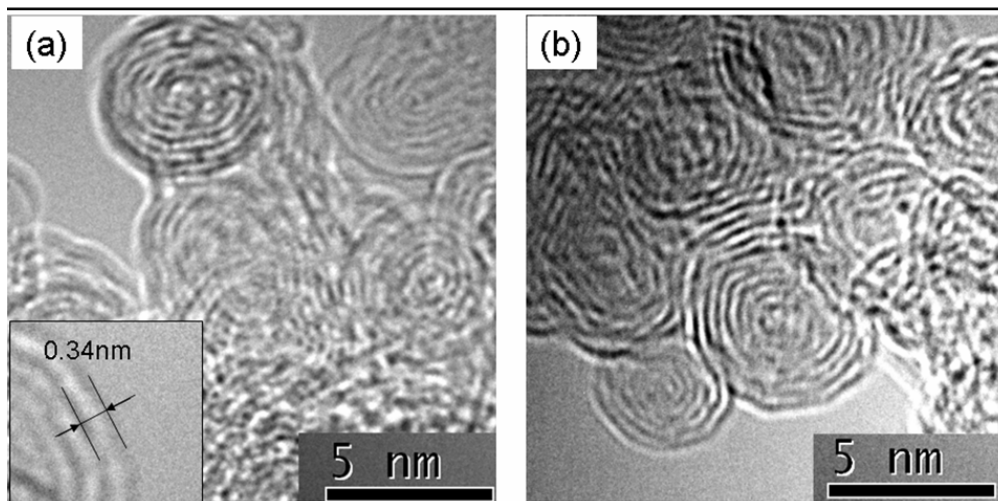
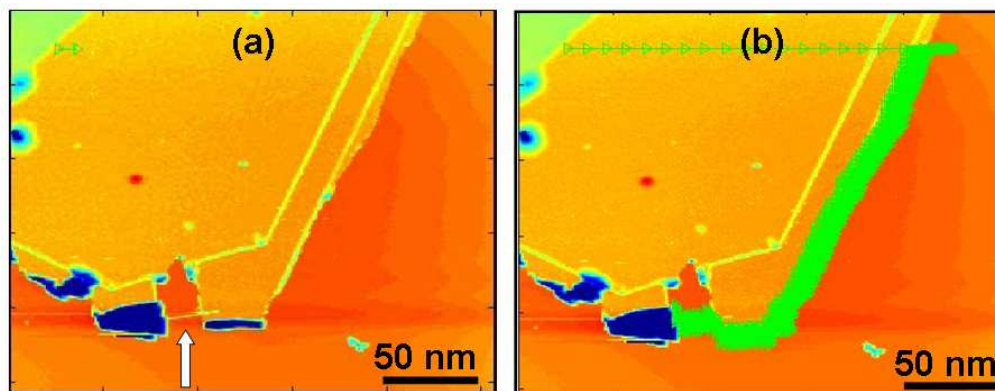


Figure 1 from A. Hirata, R. Yamada, V. M. Ayres, B. W. Jacobs and A.D. Baczewski, "Correlation of Fundamental Properties with Tribological Performance of Carbon Onions with Oxidation Treatment", submitted to Japan Journal of Applied Physics shows high resolution transmission electron microscopy of (a) untreated and (b) treated carbon onions.



(a) GaN nanowire (arrow) in electron beam lithographically fabricated nanocircuit. (b) The green trace shows Scanning Probe Recognition Microscopy tip motion along the edge of the contact and across the nanowire.

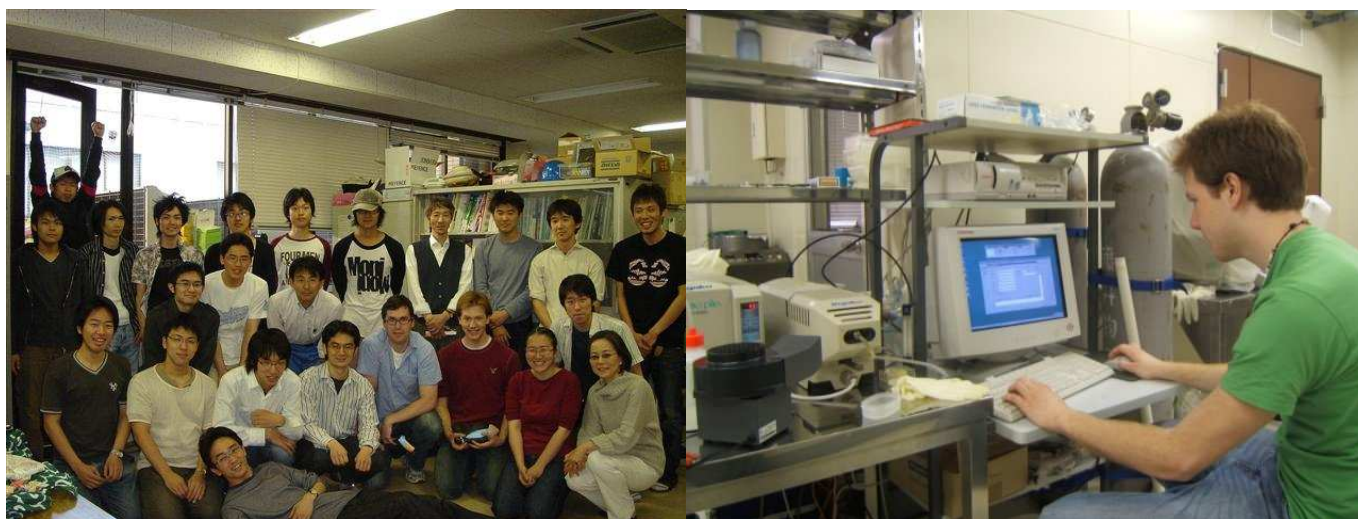
BROADER IMPACTS OF THE INTERNATIONAL TRAVEL (LIMIT: 1-1/2 PAGES)

Please describe traveler's activities in the foreign country that are relevant to highlighting the Broader Impacts of the international travel, which may include:

- How the supplement award promoted diversity

Mr. Jacobs' and Mr. Baczewski's interaction with the host laboratory gave them the opportunity to experience research methods and intellectual development different from that which they had experienced in the United States. Developing personal relationships with members of the host laboratory proved to be an important consideration when Mr. Jacobs and Mr. Baczewski first arrived. Access to important equipment required the trust of both Professor Hirata and his graduate students and was only granted after a prolonged period of personal interaction. At first, this approach was unfamiliar to Mr. Jacobs and Mr. Baczewski who were accustomed to simply training on an instrument for a short period of time before gaining access as is standard practice in the United States. Learning to cope with this more involved and personal method of training helped Mr. Jacobs and Mr. Baczewski understand the process of conducting experimental research in Japan.

- How the supplement award helps expand the original scope of the current award
The scope of the original award has been expanded to include the global opportunities resulting from Professor Ayres' Chair of International Cooperation sabbatical visit at Tokyo Institute of Technology 2005-06. A difficulty with many international collaborative activities is that they become personal links between a few individuals. To build a true international University research effort rather than a social partnership, an engaged student researcher component is essential, as it is in any successful domestic University research effort. This is, however, a very new paradigm in a newly emerging global research model, and few direct support mechanisms exist. The National Science Foundation International Research and Education in Engineering program addresses a timely and significant need.
- How the travel fosters closer future interaction between awardee institution and host institution
Mr. Jacobs and Mr. Baczewski were able to form a strong relationship with the host laboratory as well as a relationship with Professor Toshiaki Enoki's Laboratory in the Chemistry Department at Tokyo Institute of Technology. The connections to these laboratories, which Mr. Jacobs and Mr. Baczewski helped strengthen, will no doubt lead to future access to highly specialized instruments. Furthermore, their personal familiarity will facilitate future interactions with highly knowledgeable colleagues at Tokyo Institute of Technology, promoting a higher level of fundamental research.
- If researcher is citizen or permanent resident of the U.S., how the visit has helped to enhance international perspective for the researcher. Include information on activities that increased the researcher's familiarity with foreign languages, culture, and applicable technological trends and business practices
Mr. Jacobs and Mr. Baczewski used this opportunity to learn Japanese culture and language in a total immersion environment. They were able to find an excellent Japanese tutor, who taught them Japanese and answered many questions about the language, culture, politics, and current events. Furthermore, they were able to help many of their lab mates along in their study of the English language, particularly with regards to technical vocabulary and presentation.



Left: Mr. Jacobs and Mr. Baczewski with their host professor and graduate students. Right: Mr. Baczewski using the thermogravimetric analysis furnace at Tokyo Institute of Technology

DISCUSSION AND SUMMARY (LIMIT: 1 PAGE)

Highlights of the successes of the **IREE: Nano Mechanical and Electronic Investigations with Tokyo Institute of Technology** include the following:

- New research results that correlate atomic-scale surface and structural properties with tribological measurements and lubrication performance of nanoscale carbon onions have been achieved through this collaborative activity and have been reported. Manuscripts currently (September 2007) in preparation will report the results of additional experiments in heavy ion interactions in carbon onions, and in electronic transport in gallium nitride nanowire nanocircuits.
- The IREE showcased the new capabilities of the foundation grant in Scanning Probe Recognition Microscopy within an international investigation of key mechanical and electronic properties of two important nanomaterials, carbon onions (nested fullerenes) and gallium nitride nanowires.
- The visit has been a technical success with one joint USA-Japan authorship archival journal publications submitted and two in preparation. The visit has also been a technical success in that it greatly strengthened the collaborative interaction between the Tokyo Institute of Technology groups and Electronic and Biological Nanostructures Laboratory at Michigan State University group. This will lead to future significant research results and further international opportunities.
- The two early career researchers were, respectively, just finishing and just entering Graduate school. The IREE opportunity will have a powerful impact on their career development.
- The visit has been an international success as the early career researchers learned both Japanese language and culture, and developed valuable professional networks within Japan.
- Recommendation for “Best Practices” in future operation of the IREE Program:
NSF should consider working systematically with University Contracts and Grants offices to assist the development of funding mechanisms that are appropriate for the support of long term international travel. This is especially needed for travel that is long enough to require ordinary daily living accommodations but is carried out under “Visitor” legal status, with no ability to open a local bank account. It should also be noted that many societies are more conservative and more personal than the United States in their approach to foreigners. For example, Japan is a cash-based rather than credit-based society. It is also a society that requires sponsorship of international visitors at a fairly high level. The practical details of engaging apartments for the two early career researchers depended on Professor Hirata personally vouching for the students and Professor Ayres directly providing payment of the bills. Even Professor Ayres’ ability to pay bills was greatly facilitated by her having held Resident Alien status (and therefore a local bank account) in Japan during the previous year, thus developing both an official profile and a local record of financial good faith. Otherwise, payment responsibly might well have fallen upon Professor Hirata. The current model used at Michigan State University in which the students themselves would put large bills on their credit cards and be reimbursed 6-8 weeks later would simply not have worked. In Japan, they would be considered unacceptably junior aliens. In the United States, they could not possibly wait 6-8 weeks to be reimbursed for several thousand dollars worth of expenses. The result was that Professor Ayres personally advanced \$14,374.02 to support this IREE, of which \$10,764.02/\$14,374.02 has been reimbursed as of September 2007. An effective travel advance program would have been a better financial vehicle for the support of this work. In practice, this could be slowed by legitimate caution over legal risks. Resolving money matters with respect for other cultures by researching available methods and providing information to financial personnel in the United States when they are confronted with unfamiliar financial and legal situations can be an important contribution of the NSF IREE program.

ACKNOWLEDGEMENTS

- The support of National Science Foundation grants DMI-0400298 (foundation grant), DMI-0637134 (IREE) and DMI-0631978 (REU) is gratefully acknowledged. One participant (BWJ) also acknowledges the NASA Graduate Student Research Program Fellowship program. Professor A. Hirata acknowledges the support of the New Energy and Industrial Technology Development Organization, Japan.

BRIEF BIOGRAPHIES OF RESEARCHERS

Virginia M. Ayres, Ph.D. is an Associate Professor in the Department of Electrical and Computer Engineering at Michigan State University. She is the head of the Electronic and Biological Nanostructures Laboratory research group at Michigan State University, and is the Principal Investigator for DMI-0400298 Scanning Probe Recognition Microscopy. Her research interests include scanning probe microscope instrumentation development, investigation of the biomimetic properties of nanostructures, investigation of the electronic properties of nanostructures and nanodevices, and investigation of self-assembly mechanisms for nitride nanowires and carbon nanomaterials.

Benjamin W. Jacobs received his B.S. and B.A. degrees in Electrical Engineering and German Studies in 2001 and 2006, respectively, from Michigan State University. He is currently a Ph.D. candidate in Electrical Engineering at Michigan State University. His current research includes determining growth kinetics of novel gallium nitride nanowire homostructures, understanding nanowire based device electron transport characteristics and studying heavy ion radiation resiliency in nanomaterials including gallium nitride nanowires and nanowire based devices, and in carbon onions and carbon nanotubes. Mr. Jacobs is a member of the IEEE and MRS.

Andrew D. Baczewski received his B.S. with High Honors in Electrical Engineering from Michigan State University in May 2007. He is currently working on a dual Ph.D. in Electrical Engineering and Physics at Michigan State University. His current research is directed towards fast computational techniques for problems in Theoretical Condensed Matter Physics, particularly, crystal growth. Mr. Baczewski is a member of the IEEE, Tau Beta Pi, and Eta Kappa Nu.