Award Title: PIRE: U.S.-Japan Cooperative Research and Education on Terahertz Dynamics in Nanostructures
Federal Award ID: 0968405
Report Submission Period: 09/01/2016 to 12/31/2016

Intellectual Merit: This U.S.-Japanese partnership explored terahertz (THz or 10^{12} Hz) dynamics in nanostructures. The electromagnetic spectrum from 0.1 to 10 THz offers many opportunities to study physical phenomena, with potential payoff in numerous technologies, such as security, communications, imaging, and spectroscopy. However, this regime is poorly developed compared to those of electronics (<100 GHz) and photonics (>10 THz). By a judicious combination of THz technology and nanotechnology ("TeraNano"), we significantly advanced our understanding of THz physics in nanomaterials and nanostructures, while improving existing, and developing new, THz devices. PI Kono has led and managed this international team of researchers and education experts, who, together, have published over 80 papers. Specifically, our successes include a demonstration of nearly perfect performance of carbon nanotube THz polarizers [1], the generation, detection, and analysis of coherent THz phonons in SWCNTs [2, 3, 4, 5, 6, 7], modulation of THz-wave transmission through gated graphene [8, 9], imaging molecular adsorption and desorption dynamics on graphene using THz emission microscopy [10], and detection of THz radiation using an in-plane *p-n* junction of aligned SWCNTs through the photothermoelectric effect [11]. These breakthroughs will lead to real-world applications, including airport and customs screening technology, next-generation wireless communication networks with ultrahigh data rates, and rapid and safe cancer detection methods. For more representative papers see http://nanojapan.rice.edu/research_teranano_publications.shtml.

Broader Impact: The key educational program of this PIRE grant was the **NanoJapan: International Research Experience for Undergraduates Program** [12, 13, 14]. Recognized as a model program for the expansion of international opportunities for engineering & science students by both the National Academy of Engineering [15] and the Institute of International Education [16], NanoJapan was a twelve-week summer program through which twelve freshman and sophomore physics & engineering students from U.S. universities complete research internships in Japanese laboratories in nanoscience, photonics, and condensed matter physics. By involving students with cutting-edge nanotechnology research projects, NanoJapan tightly integrated the international experience with students' academic program. NanoJapan aimed to increase the number of U.S. students who pursue graduate study in nanoscience and cultivate a generation of globally aware students who are prepared for international research collaboration [17, 18, 19, 20].

From 2006 to 2015, **144 students participated in the program, representing 49 different U.S. institutions**, including two Historically Black Colleges and Universities, five community colleges, liberal arts colleges, and a wide range of public and private research institutions. The program was particularly successful in recruiting underrepresented STEM students, particularly women. Female students represented 35.4% of NanoJapan participants overall, and 16.8% represented diverse ethnic groups in STEM fields. The representation of women is particularly impressive given that NSF data shows that, in 2010, the year our program began, female undergraduate students earned just 16.98% of engineering and 20.41% of conferred physics bachelor's degrees [21]. As a further testament to the impact on students' career development as

science & engineering researchers, to date, twelve NanoJapan students have been listed as co-authors in peer-reviewed journal articles published in prestigious journals including *Applied Physics Letters, Carbon,* the *Journal of Nanomaterials,* the *Journal of Physics D: Applied Physics, Physical Review B, NanoResearch, Nanoscale Research Letters,* and *Scientific Reports* [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, and 33].

In assessment of program outcomes [19], alumni identified three major impacts of participation in the NanoJapan: IREU Program:

- *Enhanced confidence:* Students report the experience conducting nanoscience research and living independently in Japan simply made them more confident in general. One student shared, "Relocating to a different lab in the U.S. will always pale in comparison to relocating to a lab on the other side of the world."
- *Training for graduate school:* Many students report that the NanoJapan experience provided a first exposure to the realities of graduate school. One shared, "...my NanoJapan lab gave me a realistic taste of graduate school life (the good and the bad) that many students lack when they apply for graduate school. I know more than a few people that have left their graduate programs because research was not what they expected."
- *Professional network:* Many alumni report remaining in contact with their Japanese research hosts. They also say that NanoJapan provided them with a network of motivated peers in their field to discuss graduate school and career options.

Our experience with the development and implementation of the TeraNano PIRE project and the related NanoJapan: IREU Program has shown that both graduate and undergraduate students see this program as combining the best aspects of intensive, cutting education research in an emerging field with integrated international experiences that build upon the best of a traditional study abroad program. This suggests that IREUs can be an important model for engaging STEM students in meaningful programs abroad and preparing them with the technical and research skills necessary to become future leaders in American's science & engineering workforce.