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TECHNICAL REPORT

Investigation of Basic Mechanisms of Radiation Effects in Carbon-Based Electronic Materials

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June 2017

HDTRA1-10-1-0016

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement *

U.S. Customary Units	Multiply by   Divide by[†]		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^3$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^3$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m ²)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m ³)
cubic foot (ft ³)	2.831 685	$\times 10^{-2}$	cubic meter (m ³)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
unified atomic mass unit (amu)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft ⁻³)	1.601 846	$\times 10^1$	kilogram per cubic meter (kg m ⁻³)
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electron volt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kt) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^3$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^5$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^3$	pascal (Pa)
Temperature			
degree Fahrenheit (°F)	[T(°F) – 32]/1.8		degree Celsius (°C)
degree Fahrenheit (°F)	[T(°F) + 459.67]/1.8		kelvin (K)
Radiation			
curie (Ci) [activity of radionuclides]	3.7	$\times 10^{10}$	per second (s ⁻¹) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg ⁻¹)
rad [absorbed dose]	1	$\times 10^{-2}$	joule per kilogram (J kg ⁻¹) [gray (Gy)]
rem [equivalent and effective dose]	1	$\times 10^{-2}$	joule per kilogram (J kg ⁻¹) [sievert (Sv)]

* Specific details regarding the implementation of SI units may be viewed at <http://www.bipm.org/en/si/>.

[†]Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

FINAL REPORT
Grant #: HDTRA1-10-1-0016

**Title: INVESTIGATION OF BASIC MECHANISMS OF RADIATION
EFFECTS IN CARBON-BASED ELECTRONIC MATERIALS**

PI Name: Michael Alles¹
Co-PIs: J. Davidson¹, S. Pantelides¹, Ji Ung Lee²

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Executive Summary:

This 4.5-year research project has applied experimental measurements and theoretical calculations to characterize the radiation response of carbon-inclusive materials systems (esp. graphene and carbon nanotubes) relevant to potential emerging technologies for electronic devices. Experiential radiation testing has included exposure to 10 keV X-rays, 4 MeV protons, heavy ions, and Ultra-Violet (UV) light. Test structures have included graphene on silicon dioxide, graphene on silicon nitride, graphene on boron nitride, suspended graphene, carbon nanotubes (CNTs) on silicon dioxide, and 2D molybdenum disulfide for comparison. Embodiments included simple layered structures for materials characterization, and carbon nanotube diodes, FET, and PZT-memory test device structures for electrical measurements. Pre- and post-irradiation characterization has included Rutherford backscattering (RBS) measurements, TEMs, and electrical measurements. Density functional theoretical (DFT) and Kinetic Monte Carlo (KMC) calculations have been applied to understand the observed effects.

The program has produced one Masters degree graduate, 2 Ph.D. graduates (one that continued for a follow on year as a post doc), and partially supported 1 additional Ph.D. student, 1 additional post doc, and multiple university faculty at two institutions. The program resulted in 38 publications and 31 conference presentations, and initiated relationship that resulted in multiple SBIR projects and other proposals and projects under the DTRA C-WMD basic research program. Overall, findings indicated that the very small volumes associated with the 2D materials such as graphene and CNTs result in minimal interaction of radiation with the 2D materials. The process integration and surrounding materials dominate the nominal electrical response as well as the radiation response. Specific scientific findings include:

- The radiation responses of devices that include a 2D active layer of graphene are dominated by the response of the thicker adjacent materials and substrate.
- Suspended graphene proved very resistance to x-ray and high-dose proton exposure.
- UV and X-ray exposure of graphene in the presence of oxygen results in ozone-enhanced defects formation and etching.
- Constant-voltage stress and 10-keV x-ray irradiation responses of encapsulated graphene-hBN devices both induce only modest shifts in the current and Dirac point of the graphene.
- UV ozone (UVO) irradiation of graphene-based NV (PZT) memory devices leads to shifts in the charge neutral point due to O doping, and a small reduction in memory window as a result of defect formation.
- Results of X-ray exposure on graphene structures which have no passivation can be strongly influenced by the atmospheric ambient (moisture, presence of oxygen, nitrogen, other contaminants, etc). This has become a major consideration in subsequent studies and projects where passivation should be used to be more representative of the eventual embodiment.
- Heavy-ion measurements resulted in transients that could be attributed to capacitive coupling from the substrate and not to direct effects in the graphene FET layer.
- Charge trapping measured at or near the graphene/BN interface due to x-ray irradiation suggests that net hole trapping occurs in the BN at low doses and net electron trapping occurs at higher doses.
- First-principles calculations demonstrate that hydrogenated substitutional carbon impurities at B/N sites at or near the graphene/BN interface can play an additional role in the radiation response of these structures.

HDTRA1-10-1-0016: INVESTIGATION OF BASIC MECHANISMS OF RADIATION EFFECTS IN CARBON-BASED ELECTRONIC MATERIALS

- Electrical stress and 10-keV x-ray irradiation and annealing responses of back-gate MoS₂ transistors demonstrated relative stability for constant-voltage stress. The drain current was found to decrease significantly after both positive and negative bias irradiation. DFT calculations and ozone exposure experiments suggest that O atoms adsorbed on the MoS surface during 10-keV x-ray irradiation function as electron traps, causing mobility degradation and voltage shifts.

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Goal:

The goal was to characterize the radiation response of carbon-inclusive materials systems relevant to potential emerging technologies through the application of experimental measurements and theoretical calculations in order to advance the understanding of the effects of radiation on these materials and test device structures. The project did accomplish the goal, delivering specific characterization and theoretical results, and advanced the understanding of the impact of radiation in the target material systems.

Accomplishments:

1) Major activities:

Task 1) The grantee shall perform the design of experiments including:

- Identification of test structures
- Acquisition or fabrication
- Test definition (Radiation exposure)

Task 2) The grantee shall perform testing to include:

- Radiation testing. May be multiple types.
- Pre and post-rad characterization
Characterization may include Raman, TEM, etc.), electrical (IV, CV, etc.) and radiation testing (X-ray, proton) of structures from Task 1.

Task 3) The grantee shall interpret results including:

- Perform data analysis and
- First-principles modeling to include theoretical modeling (DFT, KMC) to interpret response mechanisms

2) Specific Objectives:

1) Study structures that provide unique insight for materials and configurations of interest for candidate device technologies. Several structures were studied based on the state of the technology during the period of performance. Tested structures leveraged internal capabilities, or leveraged multiple new collaborative relationships that were established during the period of the project.

2) Pursue experiments and analyses to delineate of the impact of radiation on the carbon material from that on the surrounding materials and process integration. Examples include use of suspended vs. non-suspended graphene, graphene on silicon dioxide vs. on silicon nitride vs. on boron nitride.

3) Apply theoretical modeling Density Functional Theory and Kinetic Monte Carlo modeling to materials and structures that were tested in order to elucidate and quantify mechanisms associated with the experimentally observed effects.

3) Significant Results

The detailed results of this program have been reported in three annual review presentations and reports, and detailed in numerous publications.

Test structures have included graphene on silicon dioxide, graphene on silicon nitride, graphene on boron nitride, suspended graphene, carbon nanotubes (CNTs) on silicon dioxide, and 2D molybdenum disulfide for comparison. Embodiments included simple layered structures for materials characterization, and nanotube diodes, FET and PZT-memory test device structures for electrical measurements.

Key scientific findings include:

- The radiation responses of devices that include a 2D active layer of graphene are dominated by the response of the thicker adjacent materials and substrate.
- Suspended graphene proved very resistance to x-ray and high-dose proton exposure.
- UV and X-ray exposure of graphene in the presence of oxygen results in ozone-enhanced defects formation and etching.
- Constant-voltage stress and 10-keV x-ray irradiation responses of encapsulated graphene-hBN devices both induce only modest shifts in the current and Dirac point of the graphene.
- UV ozone (UVO) irradiation of graphene-based NV (PZT) memory devices leads to shifts in the charge neutral point due to O doping, and a small reduction in memory window as a result of defect formation.
- Results of X-ray exposure on graphene structures which have no passivation can be strongly influenced by the atmospheric ambient (moisture, presence of oxygen, nitrogen, other contaminants, etc). This has become a major consideration in subsequent studies and projects where passivation should be used to be more representative of the eventual embodiment.
- Heavy-ion measurements resulted in transients that could be attributed to capacitive coupling from the substrate and not to direct effects in the graphene FET layer.
- Charge trapping measured at or near the graphene/BN interface due to x-ray irradiation suggests that net hole trapping occurs in the BN at low doses and net electron trapping occurs at higher doses.
- First-principles calculations demonstrate that hydrogenated substitutional carbon impurities at B/N sites at or near the graphene/BN interface can play an additional role in the radiation response of these structures.
- Electrical stress and 10-keV x-ray irradiation and annealing responses of back-gate MoS transistors demonstrated relative stability for constant-voltage stress. The drain current was found to decrease significantly after both positive and negative bias irradiation. DFT calculations and ozone exposure experiments suggest that O atoms adsorbed on the MoS surface during 10-keV x-ray irradiation function as electron traps, causing mobility degradation and voltage shifts.

4) Key Outcomes and Other Achievements:

The program resulted in 38 publications (including 9 since the last annual report) and 31 conference presentations as listed below. In addition, the program initiated new collaborations between Vanderbilt and the University of Minnesota (which has resulted in a new funded DTRA C-WMD project) and with UCLA and an associated spin-off small business (Aneeeve), which resulted in multiple basic research proposals and multiple funded SBIR projects, and joint publications. The program also initiated collaboration and a joint publication between Vanderbilt and the University of Manchester (England), who are also supported on a C-WMD program. The project facilitated and advanced new internal collaborative research relationship among different schools at Vanderbilt, specifically engineering and physics, which has resulted in another funded DTRA C-WMD research program to combine 2D materials with more traditional MEMs.

Publications

1. C. X. Zhang et al., "Total Ionizing Dose Effects on h-BN Encapsulated Graphene Devices," *IEEE Trans. Nucl. Sci.*, in press, Dec. (2014)
2. C. X. Zhang et al., "Electrical Stress and Total Ionizing Dose Effects on MoS₂ Transistors," *IEEE Trans. Nucl. Sci.*, in press, Dec. (2014)
3. C. X. Zhang et al., "Total-ionizing-dose effects and reliability of carbon nanotube FET Devices," *Microelectronics Reliability*, 54, pp. 2355–2359 (2014)
4. L. Tsetseris et al., "Doping, Functionalization, and Permeability of Graphene: Insights from First-Principles Studies", invited, *ECS Transactions* 64 (8), 121-125 (2014)
5. L. Tsetseris and S. T. Pantelides, "Graphene: an impermeable or selectively permeable membrane for atomic species," *Carbon* 67, 58-63 (2014)
6. L. Tsetseris et al., "Substitutional doping of graphene: The role of carbon divacancies", *Phys. Rev. B* 89, 035411 (2014)
7. J. Zeynab et al., "Enhanced photoresponse in curled graphene ribbons", *Nanoscale* 5(24):12206-11, 12 Dec. (2013)
8. B. Wang et al., "Enhanced chemical reactions of oxygen at grain boundaries in polycrystalline graphene," *Polyhedron*, 64, pp. 158-162, Nov. (2013)
9. H. J. Conley et al., "Bandgap Engineering of Strained Monolayer and Bilayer MoS₂," *Nano Letters*, vol. 13, pp. 3626-3630, Aug. (2013)
10. C. X. Zhang et al., "Total Ionizing Dose Effects and Reliability of Graphene-Based Non-Volatile Memory Devices," *proceedings of 2013 IEEE Aerospace Conference*, Mar. (2013)
11. B. Wang et al., "Introduction of nitrogen with controllable configuration into graphene via vacancies and edges," *Journal of Materials Chemistry A*, 1, 14927-14934 (2013)
12. B. Wang and S. T. Pantelides "Magnetic moment of a single vacancy in graphene and semiconducting nanoribbons" *Phys. Rev. B* 86, 165438 (2012).
13. S. T. Pantelides et al., "Defects and doping and their role in functionalizing graphene" *MRS Bulletin* (invited review), 37, 1187 (2012)
14. Y. S. Puzyrev et al., "Surface reactions and defect formation in irradiated graphene devices" *IEEE Trans. Nucl. Sci.*, 59, 3039 (2012)

15. C. X. Zhang et al., "Electrical stress and total ionizing dose effects on Graphene-based non-volatile memory devices," *IEEE Transactions on Nuclear Science*, 59, 2974 (2012)
16. E. X. Zhang et al., "Ozone-exposure and annealing effects on graphene-on-SiO₂ Transistors" *Appl. Phys. Lett.* 101, 121601 (2012)
17. L. Tsetseris and S. T. Pantelides "Hydrogen uptake by graphene and nucleation of graphane" *J. Mater. Sci.* 47, 7571 (2012)
18. S. Bubin et al., "Simulation of high-energy ion collisions with graphene fragments" *Phys. Rev. B* 85, 235435 (2012)
19. AKM Newaz, et al., "Probing charge scattering mechanisms in suspended graphene by varying its dielectric environment," *Nature Commun.* 3, 734 (2012)
20. L. Tsetseris and S.T. Pantelides "Molecular doping of graphene with ammonium groups," *Phys. Rev. B* 85, 155446 (2012)
21. Y.S. Puzyrev et al. "Surface reactions and defect formation in irradiated graphene devices" *IEEE Trans. Nucl. Sci.* (2012)
22. S. T. Pantelides, Y.S. Puzyrev, L. Tsetseris, B. Wang "Defects and doping and their role in functionalizing graphene," *MRS Bulletin* invited review (2012).
23. E. X. Zhang et al., "Low-energy x-ray and ozone-exposure induced defect formation in graphene materials and devices," *IEEE Trans. Nucl. Sci.* 58, 2961-2967 (2011).
24. B. Wang and S.T. Pantelides "Controllable healing of defects and nitrogen doping of graphene by CO and NO molecules," *Phys. Rev. B* 83, 245403 (2011).
25. B. Wang et al., "Strain enhanced defect reactivity at grain boundaries in polycrystalline graphene" *Carbon* 49, 3983 (2011).
26. L. Tsetseris and S.T. Pantelides "Defect formation and hysteretic inter-tube displacement in multi-wall carbon nanotubes," *Carbon* 49, 581 (2011).
27. L. Tsetseris and S.T. Pantelides "Intermolecular bridges and carrier traps in defective C-60 crystals," *Phys. Rev. B* 84, 195202 (2011).
28. L. Tsetseris and S.T. Pantelides "Defect-related hysteresis in nanotube-based nano-electromechanical systems," *Nanoscale Research Letters* 6, 245 (2011)
29. L. Tsetseris and S.T. Pantelides "Graphene nano-ribbon formation through hydrogen-induced unzipping of carbon nanotubes," *Appl. Phys. Lett.* 99, 143119 (2011)
30. L. Tsetseris, S.T. Pantelides, "Oxygen and water-related impurities in C-60 crystals: A density-functional theory study" *Phys. Rev. B* 82, 045201 (2010).
31. R. D. Schrimpf et al., "Radiation effects in new materials for nano-devices," *Microelectron. Eng.* 88, 1259-1264 (2011). **[Invited.]**
32. M. L. Alles et al., "Radiation effects in carbon devices: It's all about the substrate," GOMAC Proceedings, Orlando, FL, March 21-24 (2011)
33. B. Wang et al., "Strain enhanced defect reactivity at grain boundaries in polycrystalline graphene", *Carbon*, vol. 49, pp. 3983-3988 (2011)
34. B. Wang et al., "Controllable healing of defects and nitrogen doping of graphene by CO and NO molecules," *Phys. Rev. B*, vol. 83, no. 24, article no. 245403, June (2011)
35. E. Comfort et al., "Creation of individual defects at extremely high proton fluences in carbon nanotube p-n diodes", *IEEE Trans. Nucl. Sci.*, 59, 3039 (2011)
36. A. Malapanis et al., "Current-Induced Cleaning of Adsorbates in Single-Walled Carbon Nanotube Diodes", *Appl. Phys. Lett.*, 98, 263108 (2011)
37. A. Malapanis et al., "Measuring Carbon Nanotube Band Gaps through Leakage Current and Excitonic Transitions of Nanotube Diodes", *NanoLett.*, 11, 1946 (2011)

38. E. Comfort et al., “Spectroscopy of strongly localized excitons and band gap states in semiconducting single-walled carbon nanotubes”, *Phys. Rev. B (Rapid Communications)*, 83, 081401(R), 2011; Featured in *Virtual Journal of Nanoscale Science and Technology*, 23, 7, Feb. 21 (2011)

Presentations

1. C. X. Zhang, B. Wang, G. X. Duan, E. X. Zhang, D. M. Fleetwood, M. L. Alles, R. D. Schrimpf, A. P. Rooney, E. Khestanova, G. Auton, R. V. Gorbachev, S. J. Haigh, and S. T. Pantelides, “Total Ionizing Dose Effects on h-BN Encapsulated Graphene Devices,” IEEE NSREC, Paris, France, July (2014)
2. C. X. Zhang, A. K. M. Newaz, B. Wang, E. X. Zhang, G. X. Duan, D. M. Fleetwood, M. L. Alles, R. D. Schrimpf, K. I. Bolotin, and S. T. Pantelides, “Electrical Stress and Total Ionizing Dose Effects on MoS₂ Transistors,” IEEE NSREC, Paris, France, July (2014)
3. (Invited) L. Tsetseris, B. Wang and S. T. Pantelides, "Doping, Functionalization, and Permeability of Graphene: Insights from First-Principles Studies", 226th Meeting of the Electrochemical Society, Cancun, Mexico, October 5-10 (2014)
4. Bin Wang, “Atomic-Level Engineering of Graphene and Transition Metal Oxides in Catalysis, Devices and Molecular Sensors”, School of Chemical, Biological, and Materials Engineering, The University of Oklahoma, Feb. 3, 2014.
5. Bin Wang, “Functionalization of graphene and MoS₂ for electronic and optical applications”, Quantum Dynamics Research Meeting, Nashville, March 10-12, 2014
6. Bin Wang, “Tunable electronic and optical properties of two-dimensional materials and transition metal oxides”, Condensed Matter Physics Seminar, Department of Physics and Astronomy, The University of Oklahoma, Sept. 5, 2014
7. Bin Wang, "Computational Simulations of Electronic and Optical Properties of Nanomaterials", Oklahoma Supercomputing Symposium, Norman, Sept. 24, 2014
8. C. X. Zhang, E. X. Zhang, D. M. Fleetwood, M. L. Alles, R. D. Schrimpf, E. B. Song, S. Kim, K. Galatsis, A.K.M. Newaz, K. I. Bolotin, “Total Ionizing Dose Effects and Reliability of Graphene-Based Non-Volatile Memory Devices,”, 2013 IEEE Aerospace Conference, Big Sky, MT, Mar. (2013)
9. E. X. Zhang, C. X. Zhang, D. M. Fleetwood, M. L. Alles, R. D. Schrimpf, E. B. Song, S. Kim, K. Galatsis, and K. L. Wang, "UV Ozone Irradiation Induced Defect Formation in Graphene/PZT devices", American Vacuum Society (AVS) conference 59, Tampa, FL, Oct. (2012)
10. (Invited) S. T. Pantelides, "Grain boundaries in graphene -- theory and microscopy", Materials Research Society Fall Meeting, Boston, MA December 26-30, 2012.
11. (Invited) S. T. Pantelides et al. “Probing graphene excitation with a combination of transmission electron microscopy and density-functional theory” CECAM-Workshop Graphene: from band structure to many-body physics, Bremen, Germany, September 3-7, (2012)
12. (Invited) Bin Wang, “Tunable Properties of Two-Dimensional Materials and Transition Metal Oxides via Surfaces and Interfaces”, symposium "Selected topics in science and technology", Institute of advanced studies, Technical University of Munich, May 13, (2013)

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13. (Invited) Bin Wang, "Nanomaterials with tunable electrical and optical properties: case studies of two dimensional materials and transition metal oxides", colloquium "Simulation of nanosystems for energy conversion", Technical University of Munich, May 14 (2013)
14. (Invited) Bin Wang, "Tunable properties of two-dimensional materials: graphene, boron-nitride, and molybdenum disulfide" online workshop "frontiers of carbon related materials", Penn State Erie, The Behrend College, May 15 (2013)
15. J. H. Lin, B. Wang, S. T. Pantelides, "Enhanced catalytic reactivity of graphene and h-BN by selective substitution" APS March Meeting, Baltimore, March 18 (2013)
16. (Invited) S. T. Pantelides et al., "Topics in graphene" Workshop Toward Reality in Nanoscale materials V, Levi, Finland, February 19-23 (2012)
17. Colloquium, S. T. Pantelides "Graphene, the miraculous material", University of Cyprus, Nicosia, Cyprus, May 17 (2012)
18. (Invited) S. T. Pantelides et al. "Probing graphene excitation with a combination of transmission electron microscopy and density-functional theory" CECAM-Workshop Graphene: from band structure to many-body physics, Bremen, Germany, September 3-7 (2012)
19. L. Tsetseris and S. T. Pantelides, "Graphene On the Edge: Growth and Doping of Graphene Nanoribbons", 4th North America – Greece – Cyprus Workshop on Paramagnetic Materials (NAGC 2011), Patras, Greece, June 14-18 (2011)
20. L. Tsetseris and S. T. Pantelides, "Atomic-scale mechanisms of growth and doping of graphene nanoribbons", Presentation E4.1886, 220th Electrochemical Society Meeting, Boston, USA, October 9-14 (2011)
21. L. Tsetseris and S. T. Pantelides, "Effects of point defects in nanotube-based nano-electromechanical systems", Presentation H1.2413, 220th Electrochemical Society Meeting, Boston, USA, October 9-14 (2011)
22. Y. S. Puzyrev, B. Wang, and S. T. Pantelides, "Defect Interactions at Grain Boundaries in Polycrystalline Graphene", Oral presentation, AVS 58th International Symposium and Exhibition, Nov. 2, Nashville (2011)
23. B. Wang and S. T. Pantelides, "Controllable defect healing and N-doping of graphene by CO and NO molecules", Oral presentation, AVS 58th International Symposium and Exhibition, Nov. 3, Nashville (2011)
24. B. Wang and S. T. Pantelides, "Chemical reactions and thermal stability of oxygen impurities on graphene" Oral presentation, APS March Meeting, Boston, February 28, (2012)
25. Y. S. Puzyrev et al., "Scattering mechanisms in graphene suspended in liquids. II. Flexural phonons (Theory)", Oral presentation, APS March Meeting, Boston, February 27, (2012)
26. Y. S. Puzyrev et al., "Surface reactions and defect formation in irradiated graphene devices", 2012 IEEE Nuclear and Space Radiation Effects Conference, Miami, July 16-20 (2012)
27. E. X. Zhang, C. X. Zhang, D. M. Fleetwood, M. L. Alles, R. D. Schrimpf, E. B. Song, S. Kim, K. Galatsis, and K. L. Wang, "UV Ozone Irradiation Induced Defect Formation in Graphene/PZT devices", American Vacuum Society (AVS) conference 59, Tampa, FL, Oct. (2012)

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28. C. X. Zhang, E. X. Zhang, D. M. Fleetwood, M. L. Alles, R. D. Schrimpf, E. B. Song, S. M. Kim, K. Galatsis, and K. L. Wang, "Total ionizing dose effects on graphene-based non-volatile memory devices," oral presentation, IEEE NSREC, Miami, FL, July (2012)
29. E. X. Zhang, A. K. M. Newaz, S. Bhandaru, B. Wang, C. X. Zhang, M. L. Alles, D. M. Fleetwood, K. I. Bolotin, R. D. Schrimpf, S. T. Pantelides, S. M. Weiss, R. A. Reed, and R. A. Weller, "X-ray-induced defect formation in graphene," American Vacuum Society Symposium 58, Nashville, TN, Oct. 31-Nov. 4, (2011)
30. M. L. Alles et al., "Radiation effects in carbon devices: It's all about the substrate," presented at GOMAC Tech, Orlando, FL, March 21-24 (2011)
31. E. X. Zhang et al., "X-ray Induced Defect Formation in Graphene," presented at American Vacuum Society, 58th Meeting, Nashville, TN, November (2011)

Training and Professional Development

Cher Xuan Zhang completed her Ph.D. degree under this DTRA program, and joined Vanderbilt as a post-doc to continue her work on this project. As a post doc, she has also contributed to other DTRA C-WMD programs and SBIR projects.

Jason Greaving completed the M. S. degree in Material Science under this DTRA program.

Everett Comfort, completed Ph.D., CNSE, U at Albany, SUNY. Presently, he is a front-end process engineer with Intel.

Professor Dan Fleetwood (Vanderbilt) taught: EECE 304. Radiation Effects and Reliability of Microelectronics. Prof. Dan Fleetwood, VU

The students, post-docs, and professors on the team attended numerous international conferences, which not only supported dissemination of project results, but also served to advance their personal profession development.

Dissemination of Results

Dissemination of Results

The results have been disseminated to communities of interest through the numerous publications and presentations as listed previously in this report. These presentations and publications include venues beyond the typical radiation effects community. Results have also been shared directly with the partners who provided the results, providing seed information to University of Minnesota for a successful proposal and recently kicked-off C-WMD project on 2D material/high-k interfaces, as well as to Aneve Nanotehnologies to SBIR and commercial development efforts.

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