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Robert E. Peale

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**14. ABSTRACT**

Plasmonic-electronic integrated circuits have been suggested, but input and output continue to rely on bulky free space optics and inefficient couplers such as prisms. The objective of this project was to study direct electronic generation and detection of plasmons. Since plasmonic-electronic interactions are known in the long-wave IR and THz frequency domains, but not in the optical range usual for plasmonic applications, it was necessary to first develop plasmonic materials and devices for the longer wavelengths. Then, interactions between plasmons and electronics were studied with the long range goal of developing electronic-plasmonic transducers. The work was strongly leveraged by collaborative interactions between the PI, his students, and the AFRL at Hanscom AFB. Research accomplishments are well described in publications that acknowledge this award, including 7 refereed journal papers, 29 conference publications, 3 dissertations and thesis, and one book chapter. The specific accomplishments and topics studied include tunable THz detectors based on plasmon resonances in two dimensional electron gases, new materials for infrared plasmonics, cathodoluminescence study of plasmons on metal gratings, and plasmonic properties of Gold Black nanoparticles.

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**Reason for work**

Plasmonic-electronic integrated circuits have been suggested, but input and output continue to rely on bulky free space optics and inefficient couplers such as prisms. The objective of this project was to study direct electronic generation and detection of plasmons. Since plasmonic-electronic interactions are known in the long-wave IR and THz frequency domains, but not in the optical range usual for plasmonic applications, it was necessary to first develop plasmonic materials and devices for the longer wavelengths. Then, interactions between plasmons and electronics were studied with the long range goal of developing electronic-plasmonic transducers. The work was strongly leveraged by strong collaborative interactions between the PI, his students, and the AFRL at Hanscom AFB.

**Summary of work done**

Research accomplishments are well described in publications that acknowledge this award. These include 7 refereed journal papers, 29 conference publications, 3 dissertations and thesis, and one book chapter. The work done may be summarized as follows.

Tunable THz detectors based on plasmon resonances in two dimensional electron gases.

Tunable plasmon absorption resonances were observed and studied in InP-based and GaN-based HEMTs. The former were manufactured at AFRL Hanscom. The latter were studied at UCF in collaboration with RPI. Initial observations of plasmons in large area CVD graphene devices fabricated at UCF were also observed. Work continues in collaboration with AFRL WPAFB on the transduction of the plasmon absorption to a useful electronic signal.

Materials for infrared plasmonics

To achieve the subwavelength confinement of electromagnetic surfaces waves known at visible wavelengths on nobel metal surfaces requires new materials with IR plasma frequencies. A number of materials were investigated, including metal silicides (Pt-, Pd-, Ni-, W-silicides), semimetals (Sb, Bi, graphite), doped-semiconductors (Si, CuInSe), and conducting polymers (polyaniline and polyaniline-graphite mixtures). These were evaluated theoretically and experimentally for their potential in IR plasmonic waveguides and IR surface plasmon resonance biosensors.

Cathodoluminescence study of metal gratings

The purpose of this study was to investigate electron beam excitation of surface plasmons, and their propagation, at nano-meter length scales. Micromachined grating structures fabricated in various materials at AFRL Hanscom were used to out-couple e-beam excited surface plasmons to a spectrometer for analysis. A number of systematic but puzzling effects were observed. Explanation of these effects has been constrained by numerous experiments with different materials, grating periods, grating amplitudes, grating orientation, grating size, e-beam energy, and e-beam current, and e-beam positioning. These clear and repeatable effects are not in agreement with the results and interpretations of similar experiments performed by other groups. A complete understanding, including the role of surface plasmons, for the observations is still under development, guided by additional constraining experiments and theory.

Plasmonic properties of Gold Black

Gold black consists of nano-structured filaments of gold which has been used for decades as an ultrablack broad-band coating for IR bolometers. We investigated the potential of sparse gold-black coatings as plasmonic scattering centers for enhancement of thin-film solar cell efficiency. Significant improvements were observed experimentally. Additionally, the plasmon resonance

excitation spectrum and spatial distribution was investigated via Photoemission Electron Microscopy during two visits to the Environmental Molecular Sciences Lab in Richland WA.

**Participants**

Nearly all of the work was performed in close collaboration with AFRL Hanscom AFB, particularly fabrication and simulations efforts. Since the closing of this facility in 2011, the entire wafer fab and many characterization tools was transferred to a new cleanroom facility at UCF, who paid for the move and installation fees. This unanticipated windfall and opportunity for continuity in fabrication required significant efforts that were supported by the grant during its last few months. The supported students provided the labor for the move and installation, so that the project could continue. One of the project participants, Justin Cleary, received his PhD and took a position at AFRL Hanscom. He has since moved with Walter Buchwald's THz lab to AFRL WPAFB, where he continues to collaborate with us. Indeed, one of the PIs current students Nima Nader is spending a year working with Dr. Cleary in Dayton.

UCF: Senior personnel: Prof. Robert E. Peale, Chris Fredricksen. Students: Himanshu Saxena, Justin Cleary, Gautam Medhi, Nima Nader, Janardan Nath, Deep Panjwani, Farnood Rezaie.

AFRL Hanscom: Senior personnel: Dr. Walter Buchwald, Dr. Richard Soref, Dr. Justin Cleary

Other: A number of other researchers contributed to the published research without direct or in-kind support from this award. See publication list for their names.

**Journal publications resulting from this project.**


**1.** "*Tunable two-dimensional plasmon resonances in an InGaAs/InP high electron mobility transistor,*" H. Saxena, R. E. Peale, W. R. Buchwald, J. Appl. Phys. 105, 113101 (2009).

**2.** "*IR permittivities for silicides and doped silicon,*" J. W. Cleary, R. E. Peale, D. J. Shelton, G. D. Boreman, C. W. Smith, M. Ishigami, R. Soref, A. Drehman, W.R. Buchwald, JOSA B 27, 730 (2010).

**3.** "*Long-wave infrared surface plasmon grating coupler,*" J. W. Cleary, G. Medhi, R. E. Peale, and W. R. Buchwald, Appl. Optics 49, 3102 (2010).

**4.** "*Temperature dependence of plasmonic terahertz absorption in grating-gate gallium-nitride transistor structures,*" A. V. Muravjov, D. B. Veksler, V. V. Popov, O. V. Polischuk, N. Pala, X. Hu, R. Gaska, H. Saxena, R. E. Peale, and M. S. Shur, Appl. Phys. Lett. 96, 042105 (2010)

**5.** "Effects of Polymer Infusion and Characteristic Length Scale on Gold-Black Long-Wave and Far-Infrared Absorbance," Justin W. Cleary, Robert E. Peale, Masahiro Ishigami, Christian W. Smith, Kevin Baillie, Josh E. Colwell, Oliver Edwards, and Chris J. Fredricksen, J. Materials Science and Engineering 5, 171-176 (2011).

**6.** "Infrared surface plasmons on heavily doped silicon," Monas Shahzad, Gautam Medhi, Robert E. Peale,Walter R. Buchwald, Justin W. Cleary, Richard Soref, Glenn D. Boreman, and Oliver Edwards, J. Appl. Phys. Published online (2011).

**7.** "*Infrared surface polaritons on antimony,* Justin W. Cleary, Gautam Medhi, Monas Shahzad, Imen Rezadad, Doug Maukonen, in press, Optics Express 2012.


**<u>Conference publications</u>**


1. "*Resonant terahertz absorption by plasmons in grating-gate GaN HEMT structures,*" A. V. Muravjov, D. B. Veksler, X. Hu, R. Gaska, N. Pala, H. Saxena, R. E. Peale, M. S. Shur, in <u>Terahertz Physics, Devices, and Systems III: Advanced Applications in Industry and Defense</u>, edited by Mehdi Anwar, Nibir K. Dhar, Thomas W. Crowe, Proc SPIE **7311**, 73110D (2009).

2. "*Tunable THz Plasmon resonances in InGaAs/InP HEMT,*" R. E. Peale, H. Saxena, W. R. Buchwald, G. C. Dyer, and S. J. Allen, Jr., in <u>Terahertz Physics, Devices, and Systems III:</u>

Advanced Applications in Industry and Defense, edited by Mehdi Anwar, Nibir K. Dhar, Thomas W. Crowe, Proc SPIE **7311**, 73110I (2009).

3. *"Gold-black optimization and characterization,"* Justin W. Cleary, Robert E. Peale, Kenneth M. Beck, Alan G. Joly, and Wayne P. Hess, Chris J. Fredricksen and Oliver Edwards, in 10th Intl. Conf. on Laser Ablation, Nov. 2009, Singapore.

4. *"Terahertz Plasmons in Grating-Gate AlGaN/GaN HEMTs,"* A.V. Muravjov, D.B. Veksler, V.V. Popov, M.S. Shur, N. Pala, X. Hu, R. Gaska, H. Saxena, R.E. Peale, in Conf. Lasers and ElectroOptics (2009).

5. *"Grating-gate tunable plasmon absorption in InP and GaN based HEMTs,"* R. E. Peale; H. Saxena; W. R. Buchwald; G. Aizin; A. V. Muravjov; D. B. Veksler; N. Pala; X. Hu; R. Gaska; M. S. Shur, in Nanophotonics and Macrophotonics for Space Environments III, Edward W. Taylor; David A. Cardimona, Editors, Proc. SPIE **7467**, 74670Q (2009), **INVITED**.

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7. *"Gold-black as IR absorber and solar cell enhancer,"* R. E. Peale, J. W. Cleary, M. Ishigami, C. W. Smith, K. Baillie, J. E. Colwell, K. M. Beck, A. G. Joly, O. Edwards, C. J. Fredricksen, in Mat. Res. Soc. Symp. Proc. Ser. Vol. 1208E (Fall Meeting, Boston MA, 2009).

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10. *"Silicon Plasmonic Waveguides for Infrared and Terahertz Applications,"* R. Soref, S. Y. Cho, W. Buchwald, and R. E. Peale, Proc. SPIE (2009).

11. *"Infrared Surface Plasmon Resonance Biosensor,"* R. E. Peale, J. W. Cleary, W.R. Buchwald, O. Edwards, in OSA Biomedical Optics (BIOMED) and 3-D Imaging Congress and Exhibition Technical Digest, Paper BTuD104 (ISBN 978-1-55752-887-2, Optical Society of America, 2010).

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13. *"Multi-layer far-infrared component technology,"* Robert E. Peale, Justin W. Cleary, W. R. Buchwald, A. Davis, S. Wentzell, B. Stacy, O. Edwards, Proc. SPIE 7817-12 (2010) **Invited**.

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16. *"Surface plasmon resonance biosensor based on characteristic biomolecular vibrations,"* G. Medhi, J. W. Cleary, R. E. Peale, G. D. Boreman, I. Oladeji, R. Soref, S. Wentzell, W.R. Buchwald, 13th Intl. Conf. Vibrations at Surfaces (VAS13) March 10-13, 2010 Orlando, Florida, USA

17. *"Electronic-Plasmonic Transduction,"* R. E. Peale, in AFOSR Nanophotonics Program Review,Cambridge MA 1-3 Dec 2010, **INVITED**.

18. "INFRARED SURFACE PLASMON RESONANCE HOSTS FOR SENSORS," Gautam Medhi, Justin W. Cleary, Robert E. Peale, Glenn Boreman, Walter R. Buchwald, Sandy Wentzell, Oliver Edwards, and Isaiah Oladeji, Photonics 2010: International Conference on Fiber Optics and Photonics held at Indian Institute of Technology Guwahati India, from 11-15th Dec 2010

19. *"Metal-black scattering centers to enhance light harvesting by thin-film solar cells,"* Deep Panjwani, Robert E. Peale, Isaiah Oladeji, F. Khalilzadeh Rezaie, Kevin Baillie, Josh Colwell, and Christopher J. Fredricksen, Proc. SPIE 8035 - 25 V. 3 (2011).
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*21.* "*Infrared surface waves on semiconductor and conducting polymer,"* Monas Shahzad, Gautam Medhi, R. E. Peale, Ryuichi Tsuchikawa, Masahiro Ishigami, Walter Buchwald, Justin Cleary, Glenn D. Boreman, Oliver Edwards, D. J. Diaz, and Ted. A. Gorman, Proc. SPIE 8024 - 2 V. 7 (2011).
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*23.* "*Investigation of plasmonic resonances in the two-dimensional electron gas of an InGaAs/InP high electron mobility transistor,"* Justin W. Cleary, Robert E. Peale, Himanshu Saxena, and Walter R. Buchwald, Proc. SPIE 8023, 80230X (2011).
24. "*Electronic-Plasmonic Transduction,"* R. E. Peale, AFOSR 2011 Joint Electronics Program Review, 23-26 May 2011 Arlington VA **Invited.**
25. *"Plasmonic enhancement of thin-film solar cells using gold-black coatings,"* C.J. Fredricksen, D. R. Panjwani, J. P. Arnold, P. N. Figueiredo, F. K. Rezaie, J. Colwell, K. Baille, S. J. Peppernick, K. M. Beck, A. G. Joly, R. E. Peale, Proc. SPIE 8111 - 6 V. 2 (2011).
26. "*InP- and graphene-based grating-gated transistors for tunable THz and mm-wave detection,"* R. E. Peale, Nima Nader Esfahani, Christopher J. Fredricksen, Gautam Medhi, Justin W. Cleary, Walter R. Buchwald, Himanshu Saxena , Oliver J. Edwards, Ben D. Dawson, and M. Ishigami, Proc. SPIE 8164 – 7 (2011).
27. "*Planar integrated plasmonic mid-IR spectrometer,"* P. Figueiredo, J. Nath, G. Medhi, A. Muraviev, C. J. Fredricksen, W. R. Buchwald, J. W. Cleary, R. E. Peale, Proc. SPIE 8155A – 2 (2011), **Invited**.
28. "*Cathodoluminescence spectroscopy on lamellar metal and semiconductor gratings for nano-photonic devices,"* J. Nath, C. Schwarz, E. Smith, Chandana Ghosh, R. E. Peale, L. Chernyak, W. R. Buchwald, Proc. Intl. Conf. Advances in Materials and Materials Processing (ICAMMP-2011) Indian Institute of Technology, Kharagpur, 9-11 December, 2011.
29. "*Study of 'gold black' coating as potential thin film solar cell efficiency enhancer,"* Deep Panjwani, Christopher J. Fredricksen, Samuel J. Peppernick, Alan G. Joly, Kenneth M. Beck, Yauheni Rudzevich. Robert E. Peale, Proc. Intl. Conf. Advances in Materials and Materials Processing (ICAMMP-2011) Indian Institute of Technology, Kharagpur, 9-11 December, 2011.

**PhD Dissertations and MS Thesis**
1. Himanshu Saxena, "Tunable terahertz detectors based on plasmon excitation in two dimensional electron gases in InGaAs/InP and AlGaN/GaN HEMT, (2009), Subsequent Employer: Zyberwear Inc. Orlando FL
2. Justin Cleary, "Surface plasmon hosts for infrared waveguides and biosensors, and plasmons in gold-black nano-structured films," (2010), Subsequent Employer: Air Force Research Lab, WP AFB OH.
3. Deep Panjwani, "Gold-black coatings for enhancement of solar cell efficiency," (2011).

**Book Chapter**
"*Silicon Plasmonic Waveguides*", R. Soref, S. Y. Cho, W. Buchwald, R. E. Peale and J. Cleary, Chapter 2 in Silicon Photonics for Telecommunications and Biomedical Applications, S. Fathpour and B. Jalali eds. ( Taylor and Francis, UK, 2010).