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Infrared Sensors, Devices, and Applications III

Paul D. LeVan
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Editors

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J. W. Pattison, U.S. Army Research Lab. (United States); N. Dhar, Defense Advanced
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Infrared Sensors, Devices, and Applications III

Conference Chairs

Paul D. LeVan, Air Force Research Lab. (United States)

Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States)

Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

Arvind I. D'Souza, DRS Sensors & Targeting Systems, Inc. (United States)

SESSION 1: Novel IR Detectors and Focal Plane Arrays

Session Chairs: Arvind I. D'Souza, DRS Sensors & Targeting Systems, Inc. (United States); Paul D. LeVan, Air Force Research Lab. (United States)

Advanced imaging systems programs at DARPA MTO (Invited Paper) [8868-24]

N. K. Dhar, Defense Advanced Research Projects Agency (United States);

L. A. Elizondo, System Planning Corp. (United States); R. Dat, Booz Allen Hamilton Inc. (United States); S. L. Elizondo, System Planning Corp. (United States)

Mr. Lee Elizondo provided a marvelous overview in Dr. Dhar's absence, describing the aggressive goals of the AWARE program in terms of both pixel number and frame rates. The overall portfolio was described in terms of goals of increased sensor FOV and resolution, small pitch IR capabilities, advanced IR architectures that include higher operating temperature, and lower cost and size-weight-power for soldier portability. Also mentioned were efforts for 3D (through VISA involving two major FPA suppliers). Various efforts to realize high resolution imaging over very large fields-of-view were mentioned, and examples provided. The resulting systems demonstrate outstanding imagery as viewed over the entire field-of-view, and remarkable capabilities for zooming into very tiny subsections of the overall image. Additional efforts include very small-pitch LWIR pixels, 'pillarized' pixels of nBn (a barrier detector with a barrier surrounded by n-type detector material) offer nearly-complete light absorption capability and reduced dark current generation area. A variety of applications were described; one of the overarching themes is to better equip the soldier in the field with light-weight, low power surveillance devices.

Isolated nanoinjection photo detectors for high-speed and high-sensitivity single-photon detection (Invited Paper) [8868-1]

V. Fathipour, O. G. Memis, S. J. Jang, F. Khalid, R. L. Brown, I. Hassaninia, R. Gelfand, H. Mohseni, Northwestern Univ. (United States)

This invited presentation began by first describing linear and avalanches modes of APD operation in the 1.5 to 2.5 micron region, but with current emphasis on the InGaAs cut-off wavelength, and reported on low DCR (dark count rate) results

from the French LETI group. She then described a Type II architecture that incorporates a p-type barrier, and noted its need for bias voltage levels compatible with typical ROICs. In this interesting device, one photon-generated hole carrier results in 1000s of electrons signal, by overcoming the barrier. Other attributes include a uni-polar architecture that provides immunity to photon re-emission, as well as very high response speeds. Dark current measurements verses bias were presented. To support this effort, an integrated ASIC has been developed, acting as a charge amplifier for APD test structures. A full ROIC design incorporates unit cell counters, and is based on knowledge gleaned with the ASIC. Current dark count rates are still higher than theory but a path for reduction has been identified.

Comparison of ultimate limits of interband cascade infrared photodetectors and single-absorber detectors [8868-2]

R. T. Hinkey, R. Q. Yang, The Univ. of Oklahoma (United States)

This novel IR detector, fabricated of InGa and GaSb, seems to behave as a photovoltaic (low or zero bias voltage), but is a "multi-stage" device with multiple photon absorptions needed for photocarriers (electrons) to "hop" between multiple contacts. Guidance on the ultimate sensitivity of this approach, taken from an earlier paper by the Polish group (Piotrowski et al.), was reviewed. In Q&A, it was revealed that even though there are multiple layers within the structure, the overall thickness of the detector is comparable to conventional bulk and super lattice devices, thereby posing no additional issues with fabrication and hybridization of a "commercialized" version.

Interband cascade infrared photodetectors with InAs/GaSb superlattice absorbers [8868-3]

R. T. Hinkey, H. Lotfi, L. Li, H. Ye, L. Lei, R. Q. Yang, J. C. Keay, T. D. Mishima, M. B. Santos, M. B. Johnson, The Univ. of Oklahoma (United States)

The results of multistage detector growths in the LWIR (with impressive wavelength cut-offs near 11.9 and 12.8 μm), allowed photoresponse and D^* to be compared with other detector types. Results on dark current vs. temperature indicate excitation energy of about half the bandgap and non-diffusion limited behavior in the temperature range that was probed. Results were compared with Bill Tennant's "Rule 07" for HgCdTe, and to analytic expressions for the photocurrent and noise.

High-performance SWIR sensing from colloidal quantum dot photodiode arrays [8868-4]

E. Klem, J. Lewis, C. Gregory, G. Cunningham, D. Temple, RTI International (United States); A. D'Souza, E. Robinson, DRS Sensors and Targeting Systems (United States); P. S. Wijewarnasuriya, U.S. Army Research Lab. (United States); N. Dhar, Defense Advanced Research Projects Agency (United States)

In this approach, a solution of quantum-dots was prepared and shown to have favorable properties (e.g., I-V curves) for use as photodetectors. Both spectral absorption and external quantum efficiency measurements were described. The electrical properties were shown to be strongly influenced by the organic ligands present in the material. The speaker began by justifying the effort for colloidal quantum dot photodiode arrays in view of the mature InGaAs FPA technology, noting the high costs of the later, and its current limitation to relatively large pixel sizes and to wavelengths shortward of 1.7 microns. The dot diameter was shown to determine the response wavelength in this colloidal approach, and a distribution in dot sizes can be employed to tailor a spectral response for flatness, as needed. In test structures, less than 3 nanoAmp per square cm current density was measured at room temperature, and quantum efficiencies of 21% were measured near one micron. Sensitivity uniformity of 2-D arrays is in the upper 90 percentile. The photodiode quality of this approach was noted to be compatible with a broad range of ROICs; in this case a p-on-n unit cell with a CTIA amplifier was used.

SESSION 2: Novel IR Detectors and Performance Modeling I

Session Chairs: Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States); Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States)

The paper, **Effect of electrical contacts on quantum efficiency of near-infrared InGaAs detectors**, [8868-5] was canceled.

Photonic and plasmonic carbon nanohybrids for advanced optoelectronics applications (Invited Paper) [8868-30]

J. Z. Wu, The Univ. of Kansas (United States)

On-line proceedings only Prof. Wu described carbon-based nanostructures, including nanotubes (CNTs) and graphene that have superior electronic, optoelectronic and mechanical properties, for designs of novel infrared detectors. Discussions included CNT/graphene heterojunction infrared detectors, aligned ZnO nanowire/graphene hybrid ultraviolet detectors, and an ionic-liquid gated plasmonic nanoparticle/graphene hybrid that exploits localized surface plasmonic resonance frequency of nanoparticles decorated on graphene. Issues affecting photon absorption, exciton dissociation and phonon transport at nanoscale levels were described in detail. Promising approaches for bolometers based on the extremely broad-waveband absorption properties of these materials, and methods of achieving response times faster than

commercially available. Higher performance, uncooled bolometers seem possible by exploiting the “natural suspension” of some of the nanotube structures.

Embedded plasmonic quantum well infrared photodetector [8868-6]

R. L. Brown, A. Bonakdar, O. G. Memis, V. Fathipour, S. J. Jang, H. Mohseni, Northwestern Univ. (United States)

The author described an “embedded surface-plasmonic structure” that achieves impressive absorption over limited thickness, and is compatible with indium bump hybridization. Examples of exquisite pillar etching results (with each QWIP pixel comprising multiple pillars) were shown and seem to enable near theoretical levels of responsivity (~7 Amps per Watt near 8 microns wavelength). Unfortunately, the nearly finished device was damaged by spurious sputtering of a metal layer. Hopefully a future fabrication will make for a complete device that allows for detailed performance evaluation.

Improvement in the sensitivity of methane detection using a double fast Fourier transform-based filter [8868-31]

S. Mahdi, Univ. of Arkansas at Little Rock (United States); E. Wilson, Harding Univ. (United States); Y. Chen, G. Anderson, Univ. of Arkansas at Little Rock (United States)

The speaker began by describing a tunable diode laser spectrometer, with emphasis on variations of its output wavelength (near 1.6 microns) with injection current and temperature. This included a description on the control issues associated with these variations. Extensive signal processing was described, including the “flattening” of the 1/f distribution. The overall sensitivity for the detection of methane gas has been improved, with detection levels quantified in units of parts per billion methane molecules.

SESSION 3: Characterization of Novel IR Detectors

Session Chairs: Priyalal S. Wijewarnasuriya, U.S. Army Research Lab. (United States); Arvind I. D'Souza, DRS Sensors & Targeting Systems, Inc. (United States)

ZnMgO solar blind detectors: from material to systems (Invited Paper) [8868-25]

M. F. Anwar, A. Rivera, A. Mazady, H. C. Chou, Univ. of Connecticut (United States); J. W. Zeller, A. K. Sood, Magnolia Optical Technologies, Inc. (United States)

This presentation, given by Dr. Sood, began by motivating the need of high performance, UV sensitive detectors and focal plane arrays. Attributes of this approach include the forgiving nature of nanowires to lattice mismatch; issues include the unknown amounts of Mg needed for the requisite UV spectral response. Results to date (for silicon substrates) indicate a typical photodiode-like current-voltage curve. Very high peak quantum efficiency (~80%) was found

near 280 nm. Hysteresis has been observed on a seconds timescale. This presentation also described the effects of catalysts in the formation of the material, with low pressure MOCVD growths and a variety of substrates also considered – SiO₂, GaN on sapphire, and p-type Si. In Q&A, the question was asked of how the relative maturity previously demonstrated for AlGaIn detector relates. In response, it was noted that detector gain is needed to detect many weak UV signals.

Optimisation of performance for platinum nanowires as sub-wavelength bolometers [8868-7]

P. Renoux, Univ. of Iceland (Iceland); D. Charpentier, S. Augé, INSA Toulouse (France); S. Ingvarsson, Univ. of Iceland (Iceland)

In this bolometer architecture, detector areas are a small fraction of the wavelength of detection (approximately 0.3 x1 micron), as motivated by the observation that efficient infrared emission continues as the area of the pedestal is reduced, in an emitter configuration. The author reported on the results of characterizations that included resistance and the thermal coefficient of resistance, finding values ranging from 10 to 1000 ohms for the former, and ~0.002 per Kelvin for the latter. Responsivities were measured and also reported, with most all the devices responding well with Platinum thicknesses in the range of 40 nm. Noise calculations indicate a predominate 1/f contribution, and techniques for mitigating this noise source were described. Questions included one on measured values of surface resistivity, and another on expected levels of sensitivity in terms of D*.

Research on multi-alkali cathode photoemission mechanism [8868-9]

X. Li, Q. Guo, Q. Lu, North Night Vision Technology Co., Ltd. (China)

This presentation emphasized a novel image intensifier conceived for ease of production. The materials are evaporated on a glass substrate, and work functions (in eV) were communicated for the bulk material and surface film. Interesting properties include the Fermi levels in the p- and n-type films, the associated levels of band bending, and the fluorescence spectrum. Responsivities were communicated in the units of milliAmps per lumen of incident light.

Measurement of the dielectric, conductance, and pyroelectric properties of MWCNT:PVDF nanocomposite thin films for application in infrared technologies [8868-10]

M. Edwards, P. Guggilla, J. Corda, S. Egarievwe, Alabama A&M Univ. (United States)

The author described the pyroelectric detection properties of polymer films that incorporate carbon nanotubes and nano-composite thin films. Layer flexibility is a key desired attribute and is a characteristic of these detectors. The popular

Triglycine Sulfate material was used as a comparison for performance figures of merit.

CMOS compatible IR sensors by cytochrome c protein [8868-11]

C.-J. Liao, G.-D. Su, National Taiwan Univ. (Taiwan)

The author announced phenomenal values of TCR (~20% per Kelvin) for this bolometer architecture, fabricated with a dramatically simplified approach that avoids epitaxial growth. The protein, acting as a sensing layer, can be deposited with inkjet printing techniques. He described the imaging analysis of the inkjet drops used to optimize the device performance. Responsivity was noted to have some interesting variations with temperature, and long-term device stability is also under investigation. The bolometer structure (with requisite thermal isolation and electrical contacts) employs*** an effective *** insulation structure.

SESSION 4: Detector Read-out Circuitry and Signal Processing

Session Chairs: Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Paul D. LeVan, Air Force Research Lab. (United States)

The presentation, **Si photonic components for mid-infrared sensing and chemical imaging [8868-12]**, was formally canceled.

On-line nonuniformity and temperature compensation of uncooled IRFPAs using embedded digital hardware [8868-13]

A. Wolf, R. Redlich, M. Figueroa, J. E. Pezoa, Univ. de Concepción (Chile)

The "ARMA" model was described; it models the response hysteresis seen over increasing and decreasing temperatures for the microbolometer sensor arrays that were studied. Incorporation of the model into a real-time calibration protocol, contained in a FPGA, allows for highly accurate correction of the signal non-uniformities, resulting in linear and stable response to incident levels of infrared radiation. Relevant operating parameters over which performance was assessed include frame rates up to 60 Hz, temperature changes on the order of a Kelvin per minute and operating temperatures up to 40 C.

Radiation hardness by design for mixed signal infrared readout circuit applications [8868-14]

S. Gaalema, J. Gates, D. Dobyms, G. Pauls, B. Wall, Black Forest Engineering (United States)

Steve Gaalema began with a discussion of the thermopile-based detector arrays that will be hybridized with the read-out circuitry developed to survive the harsh radiation environments of NASA planetary probes. The results with FPAs await future hybridization efforts. The author then described the CTIA-based ROICs that have been designed and fabricated for radiation exposure for typical long life,

Air Force space-based sensing applications. Noteworthy for the ROICs is the high level of flexibility that can be controlled with serial commands.

Wavelength stabilization of electrostatically actuated micromechanical infrared Fabry-Pérot filters [8868-15]

J. R. Schröter, S. Lehmann, M. Ebermann, N. Neumann, InfraTec GmbH (Germany)

In these electrostatically actuated Fabry-Pérot filters, the wavelength of transmitted infrared radiation is proportional to tiny changes in filter thickness. The author described a clever use of capacitance sensing (also related to the filter thickness) as a means of generating a feedback signal, by characterizing changes in capacitance along with changes in thickness and in transmitted wavelength. Then, a controller could be optimized for selection and stability of the output wavelength (to ~ 1 nm rms accuracy) in the presence of environmental variations. The approach allows for use of the device with a pyroelectric detector for spectral measurements in the 3.9 to 5 micron wavelength region for in-situ gas analysis. Future plans include implementation of a fast scan mode.

SESSION 5: Infrared Applications

Session Chairs: Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Arvind I. D'Souza, DRS Sensors & Targeting Systems, Inc. (United States)

Split-manufacturing of safe and secure integrated circuits (Invited Paper) [8868-16]

D. L. Polla, Defense Advanced Research Projects Agency (United States)

Presentation Only Dr. Polla described a 5-year program in its second year. Background information included information on the overseas foundries, and the large percentage of business they enjoy. He outlined several trends: Foundries doing "More than Moore", including providing additional value-added in the form of specialty layers (alternate materials, custom tailoring, etc.); the move to 3D transistors ("FinFETs", which resemble a shark fin in the height dimension). Mention was also made of the Apple iPhone and its present 7 or so chips (each having a "more than Moore" flavor) that replace the approximately 50 chips of the initial iPhones. He then described his program for split manufacturing: an overseas foundry does the transistor layers; wafers are sent to a US foundry for many layers of metallization and metallization etching for interconnects. Cost impact (relative to doing all overseas) is estimated at 15%. Participants in the test wafer fabs include Bell Labs (SiGe photodetectors), Raytheon Vision Systems ("new imaging modalities" & looking at the cryogenic operations issues), Cornell Univ. ("acoustic chip-to-chip interconnects"), Stanford Univ. (improved memory), and Carnegie Mellon (analog SAR circuitry). Design rule extents seem to start at 130 and move to 65 by the end of this calendar year. The number of questions following this presentation is indicative of one that was a valuable addition to the conference.

Hetero-engineering infrared detectors with type-II superlattices (Invited Paper) [8868-26]

Z.-B. Tian, The Univ. of New Mexico (United States); E. A. DeCuir Jr., U.S. Army Research Lab. (United States); N. Gautam, S. Krishna, Ctr. for High Technology Materials, The Univ. of New Mexico (United States); P. S. Wijewarnasuriya, J. W. Pattison, U.S. Army Research Lab. (United States); N. Dhar, Defense Advanced Research Projects Agency (United States); R. E. Welsler, A. K. Sood, Magnolia Optical Technologies, Inc. (United States)

Prof. Krishna showed how Type II superlattices in the InAs/GaSb system provide considerable band engineering flexibility, including the incorporation of a variety of unipolar barriers. As part of a Phase II DARPA SBIR effort, a pBiBn (PIN device with two barriers) was shown to have photovoltaic-like behavior with only a small bias voltage (~0.25 V) needed for “turn on” of responsivity. Later, a similar structure having a cut-off wavelength near 13 microns was described, having appreciable responsivity at even smaller bias voltages. (A correspondence to published laser architectures was noted as a motivation for some of this work.) The author then described a “fourth generation” capability which would include phase sensitive detection, intelligent imaging, retinal-like motion detection, all operating at or near room temperature.

MWIR type-II InAs/GaSb superlattice interband cascade photodetectors (Invited Paper) [8868-29]

W. Pusz, A. Kowalewski, W. Gawron, Military Univ. of Technology (Poland); E. Plis, S. Krishna, Ctr. for High Technology Materials, The Univ. of New Mexico (United States); A. Rogalski, Military Univ. of Technology (Poland)

Dr. Rogalski described interesting cascade architecture as part of new approaches used to achieve high operation temperature (HOT) operation, comparing its performance with interband HgCdTe and intersubband QWIP, both alternatives to the stacked multi-junction detectors. For this effort, detector growth and characterization revealed SRH levels of dark current (excitation energy corresponding to approximately half the bandgap), very good values of RoA, and a quantum efficiency – photoconductive gain product of almost 3%. The components of the overall detector time constant were described in terms of drift, diffusion, and RC contributions; it was noted that the observed behavior in time constant with temperature (over the range of 220 – 400 K) is not easily explained. A compelling strategy for reducing the volume of detector material and enabling efficient photon trapping for high absorption was also described.

Modelling of MG-Y laser tuning characteristics [8868-18]

J. Poliak, Hochschule Pforzheim (Germany); H. Heining, F. Mohr, Brno Univ. of Technology (Czech Republic); O. Wilfert, Hochschule Pforzheim (Germany)

A laser architecture involving a multiple grating (MG) approach was shown to exhibit tuning on the scale of 40 nm at wavelengths near 1.55 microns. Detailed

characterization with control current variations allow for definition of a precise control loop to stabilize the output wavelength. An approach for miniaturization is underway, and should allow for transition to a potential user community.

Mechanically induced long period fiber gratings in Er³⁺ fiber for structural health monitoring [8868-19]

M. G. Pulido-Navarro, J. A. Alvarez-Chavez, Instituto Politécnico Nacional (Mexico); D. E. Ceballos-Herrera, Univ. Autónoma de Nuevo León (Mexico); P. J. Escamilla-Ambrosio, Instituto Politécnico Nacional (Mexico)

Structural health monitoring (SHM) in the context of road bridges and other public infrastructure was shown possible with embedded fibers, for which levels of stress can be sensitively measured through the variations in light propagation modes. The fiber core incorporates a Bragg grating that results in varying spectral transmissivity with stress; a probe through the fiber with discrete wavelengths is then indicative of the level of stress in the material in which the fiber is embedded. Wavelengths in the 1.5 micron region of are identified as promising for this approach. Doping the fiber was shown to enable transmission over the longer fiber lengths that could be required by an application.

Development of large area nanostructured AR coatings for EO/IR sensor applications [8868-27]

A. K. Sood, G. Pethuraja, A. W. Sood, R. E. Welser, Y. R. Puri, Magnolia Optical Technologies, Inc. (United States); P. Haldar, SUNY College of Nanoscale Science & Engineering (United States); E. F. Schubert, Rensselaer Polytechnic Institute (United States); N. K. Dhar, Defense Advanced Research Projects Agency (United States); P. S. Wijewarnasuriya, U.S. Army Research Lab. (United States)

The presenter described large-area nanostructured anti-reflection (AR) coatings that achieve the ambitious goal of 1% reflection loss at high angles of incidence, over a broad range of wavelengths (UV through MWIR). These properties are made possible with layers of nano-structures oriented along a preferred axis. Characterization exhibits low reflection out to angles of +/-60 degrees, in agreement with theory. Substrate flexibility further extends the range of applications of the technology, with relatively large substrates enabling larger diameter optical applications. Future plans include extension to very large wafer diameters (~ 6") and testing to levels of military standards. In response to audience questions, any levels of polarization selectivity also remain to be quantified.

SESSION 6: Novel IR Detectors and Performance Modeling II

Session Chairs: Ashok K. Sood, Magnolia Optical Technologies, Inc. (United States); Arvind I. D'Souza, DRS Sensors & Targeting Systems, Inc. (United States)

Evolution of EO/IR technology and systems (Invited Paper) [8868-21]

K. Lewis, Sciovis Ltd. (United Kingdom)

This invited presentation had a biologically inspired sensing theme. Emphasized was the fact that many insect eyes track objects very well, despite the fact that they don't always image scenes. Another theme related to the exploitation of spectral variations occurring over a FOV -- "spectral diversity from angular diversity", one example of which being an angle-sensitive wavelength filter. Examples of AVIRIS scenes were spectrally enhanced to emphasize surface water content. This then motivated discussion for a detector architecture that, with an electrically switched pair of wavebands, could itself be sensitive to surface water content. The presentation also mentioned plasmonics examples and "Rayleigh anomalies".

Multiscale modeling of photon detectors from the infrared to the ultraviolet (Invited Paper) [8868-22]

E. Bellotti, J. H. Schuster, B. Pinkie, Boston Univ. (United States); F. Bertazzi, Boston Univ. (United States) and IEIT, CNR, Politecnico di Torino (Italy)

The motivations for this modeling effort were first reviewed, emphasizing that even HgCdTe photovoltaic detectors are not completely understood in terms of carrier transport (carrier-phonon; carrier-carrier interactions), Auger mechanisms, and radiative recombination rates. This "no fitting parameters" approach for modeling involves a diversity of theoretical methods. The empirical pseudo-potential method or density functional theory calculates the band structures of specific detector architectures. Monte Carlo methods are then employed to understand carrier transport in the presence of high electric fields, radiative recombination and Auger recombination rates. Finite element methods are used to perform drift-diffusion simulations, simultaneously solving the carrier continuity and Poisson equations in 3D. Applications to date include HgCdTe and InAsSb detectors, and a photon trapping structure that results in both efficient absorption and lowered values of spatial cross-talk.

Unleashing giant TCR from phase changes in carbon nanotube composites (Invited Paper) [8868-23]

G. E. Fernandes, J. H. Kim, J. Xu, Brown Univ. (United States); A. K. Sood, Magnolia Optical Technologies, Inc. (United States); N. K. Dhar, Defense Advanced Research Projects Agency (United States); M. Dubey, U.S. Army Research Lab. (United States)

In this presentation given by Dr. Sood, recent work on carbon nanotube nano-composites, involving a phase-change polymer, was reviewed. The relatively large temperature coefficient of resistances (TCR; $\approx -10\%/^{\circ}\text{C}$) that were measured are about an order of magnitude larger than the TCR observed in other carbon nanotube materials, and are thought to result from a volume-phase-transition that affects tunneling resistances between adjacent

carbon nanotubes. Other bolometric figures of merit, including responsivity and time constant, are also strongly affected by the phase transition.

Development of III-N UVAPDs for ultraviolet sensor applications [8868-28]

A. K. Sood, R. A. Richwine, R. E. Welsler, Y. R. Puri, Magnolia Optical Technologies, Inc. (United States); R. D. Dupuis, M.-H. Ji, J. Kim, T. Detchprohm, Georgia Institute of Technology (United States); N. K. Dhar, Defense Advanced Research Projects Agency (United States); R. L. Peters, U.S. Dept. of the Interior (United States)

Dr. Sood motivated the need for detector gain in applications involving small UV photon rates. These detector growths were by molecular beam epitaxy at Georgia Institute of Technology, and the fabrication resulted in a PIN detector architecture on sapphire substrates. Additional device growth and fabrication, as well as performance characterization, are expected in the future.