PROCEEDINGS OF SPIE

Infrared Technology and Applications XXXVII

Bjørn F. Andresen
Gabor F. Fulop
Paul R. Norton
Editors

25–29 April 2011
Orlando, Florida, United States

Sponsored and Published by
SPIE

Part One of Two Parts

Volume 8012

Proceedings of SPIE, 0277-786X, v. 8012

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:
Author(s), "Title of Paper," in *Infrared Technology and Applications XXXVII*, edited by Bjørn F. Andresen, Gabor F. Fulop, Paul R. Norton, Proceedings of SPIE Vol. 8012 (SPIE, Bellingham, WA, 2011) Article CID Number.

ISSN 0277-786X
ISBN 9780819485861

Published by
SPIE
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Printed in the United States of America.

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The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

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Introduction

The Thirty-Seventh conference on Infrared Technology and Applications was held the week of April 25-29, 2011 at the Orlando World Center Marriott Resort and Convention Center in Orlando, Florida. The agenda was divided into 23 sessions:

1. Target acquisition with today's leading imaging technologies
2. Threat identification I
3. Threat identification II
4. Smart imagining and signal processing
5. QWIP and QDIP
6. Type II Superlattice FPAs I
7. Type II Superlattice FPAs II
8. Emerging uncooled technologies
9. Uncooled FPAs and applications I
10. Keynote—Wide-area infrared surveillance: performance requirements and technology needs
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15. Cryocoolers for IR Focal Plane Arrays
16. HOT—High Operating Temperature FPAs
17. Active imaging I
18. Active imaging II
19. HgCdTe
20. IR optical materials
21. Application of selected technologies
22. Various uncooled detector technologies I
23. Various uncooled detector technologies II

In addition, there were thirty poster papers presented for discussion on Thursday evening—these have been added to the 23 sessions in the Proceedings. Highlights of six topical areas are summarized below:

- Target acquisition and threat identification
- Optics
- Smart image and signal processing
- Uncooled thermal detectors
- Photon detectors
- Cryocoolers

Target Acquisition / Threat Identification

Detection, recognition and identification of objects relevant to defense and security were discussed in sessions 1 - 3 and 21. The scenarios varied from faces at a few meters distance to Earth observation from satellites. Focus was put on demonstrating application of advanced technologies, techniques and design methods in new systems mounted on various platforms.

Integration of state-of-the art broadband InSb or HgCdTe FPAs in a compact long range target acquisition thermal imager was demonstrated. Cooled detectors having 1280 x 1024 pixels were used and target identification was predicted for ranges up to 7 km. While discussing the design of the imager, a "visualization tool" was described. The tool is a holistic simulation of the thermal imager which starts from using high resolution visible images.

These long-range imaging systems employ cryogenically cooled FPAs. Several uncooled microbolometer FPAs were presented and simulation was used to compare their performance in systems with that of state of the art 2nd generation, scanning, cooled LWIR arrays. It was shown that similar recognition ranges may be achieved for the two types of systems.

Fast spectral scans are frequently required for detection and identification of targets. This is the case when the target or sensor system moves fast, the signature changes rapidly, as during an explosion, or in the presence of turbulence. Several systems employing fast spectral imaging were outlined. One demonstrated the marriage of 3rd generation FPAs and micro-optical diffractive lens arrays. This system allows target ID via simultaneous spectral investigation.

Defense and security agencies are in constant search for new ways of detecting chemical and biological threats used by terrorist organizations. One research institute demonstrated their four-channel SWIR/MWIR radiometer for simultaneous four band measurements with a rise time of 6 μsec. The measured data may be used for identifying explosives and providing kill assessment.

While this system investigated explosions, another system was demonstrated which detects highly energetic materials (HEM) and homemade explosives (HME) prior to explosion at stand-off ranges as long as 60 meters. The high spectral resolution was provided by use of a MWIR Fourier Transform interferometer. Both passive and active modes of operation were demonstrated.

High reliability infrared detectors were discussed for space applications. These detectors cover various kinds of applications like Visible to VLWIR hyperspectral observation of the earth's atmosphere for meteorological or scientific purposes.

An airborne thermal infrared imaging spectrometer with 128 bands in the LWIR window was presented. Results from flight trials were shown.

It is known from measurements that the identification range advantage obtained by MWIR, as opposed to LWIR, may be wiped out in the presence of strong turbulence. Turbulence compensation is well known in astronomy. Can the same techniques be used in ground-to-ground scenarios? One laboratory suggested a method based on multiple time-separated images. It was demonstrated in simulations that the method has the potential of providing turbulence-free images and improved long range target identification—Fig. 1.

Recognition of human faces at public places like airports is a very important security-related means for apprehension of terrorists. Variation of illumination and lack of same hampers face recognition in the visible spectrum. Veins and tissues give rise to a unique thermal pattern which is different even for identical twins. Two universities have collaborated on the development and implementation of an affordable, robust and accurate security system based on facial thermograms. Presented experimental results showed an average recognition success rate of 94%.

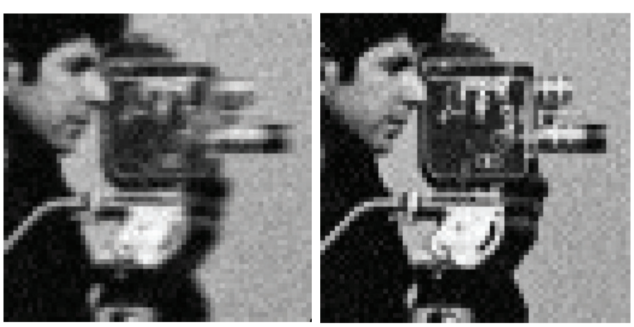

Fig. 1. Defocused input image (left) and processed image (right). Defocusing simulates turbulence.

Optics

Presentations in the three IR optics sessions, 13, 14 and 20, showed a strong effort by the optics community to answer the military's requirement for simultaneous operation in two or more of the spectral bands traditionally called "atmospheric windows". The use of multiple band operation facilitates target detection and identification. These systems are also required to be compact and light.

Which is the optimal type of a multiband optical system—refractive or reflective? Last year this conference heard a presentation of an essentially reflective multiband system which used folded optics in order to attain good compactness. This design concept was challenged in the present conference by a refractive system which was claimed to operate simultaneously over a large number of bands between visible and LWIR. The optimum combination of optical materials is determined by use of numerical methods to evaluate the dispersive properties of materials in terms of both instantaneous values and volatilities.

Several multiband optics designs were presented. One presentation discussed the design and development of a dual field of view, all-refractive, infrared optical system that images the MWIR radiation in one field of view and the SWIR in a narrower second field of view, both onto the same detector. Another walked the attendees through the selection of materials for a refractive system operating simultaneously in the SWIR and LWIR bands. A third presentation demonstrated a novel, all-reflective, off-axis optical systems for applications in space. Two designs are shown in Figure 2.

A group of laboratories reported on a cooperative effort to incorporate wide fov imaging functions, including compact and robust hyper– and multi-spectral imagers, inside a cooled detector dewar. This minia-

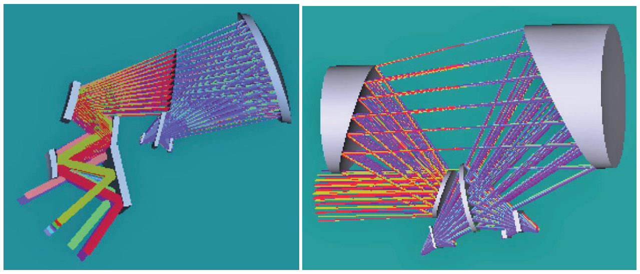

Fig. 2. Multi-band optical designs using three powered optical mirrors. The systems have two (left) and four (right) FPAs.

turization gives imaging capabilities to vehicles with small payload capacities. The stable low temperature improves the system sensitivity. First experimental results were presented from two spectral system architectures based on new optical designs. One of these is illustrated in Fig. 3.

The detector is often considered the "heart" of the system. To protect this vital component and its signal processor from intense blinding radiation from natural sources like the sun or from countermeasure sources, one paper presented a protection filter which operates on the exposed FPA pixels and returns to a neutral state when exposure is terminated.

Development of opto-mechanical systems requires strong communication between the various engineering and manufacturing functions. One company discussed their method and software for tightly integrating optical and mechanical design and fabrication and testing. Several examples were presented showing important gains in rapid and effective development.

One presentation focused on antireflection coatings for multi-lens systems with simultaneous operation in the MW- and LW-bands. A 10-element system with 95% AR transmittance per lens in each band will have an overall transmittance of about 60%. Design, coating, and characterization of high Dual Band Anti-Reflection, DBAR, films for a 3rd Gen set of lenses were demonstrated. Dual band and broadband transmittances were compared.

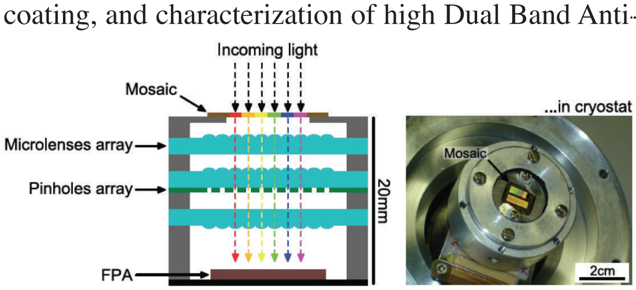

Fig. 3. (a) Compact multispectral camera integrated in cold shield. (b) Seen in opened laboratory dewar.

Smart image and signal processing

Session 4 on smart image and signal processing included papers featuring readouts with on-chip processing to enhance the functionality of the FPA. A variety of feature options were described in separate papers, including:

- multi-resolution and multi-scale imaging
- combining thermal imaging with laser range-finder functions
- designs to overcome reset noise in CTIA pixels
- calibration of polarimeter FPAs
- hexagonal pixel layout FPAs and related signal processing functions

Figure 4 illustrates the angular output before and after calibration of a four-pixel group that have polarizer grids (vertical, horizontal, and ± 45° orientation) over the pixels.

The difference of Gaussians was used to extract feature edges in an array of pixels from local contrast differences as illustrated in Fig. 5.

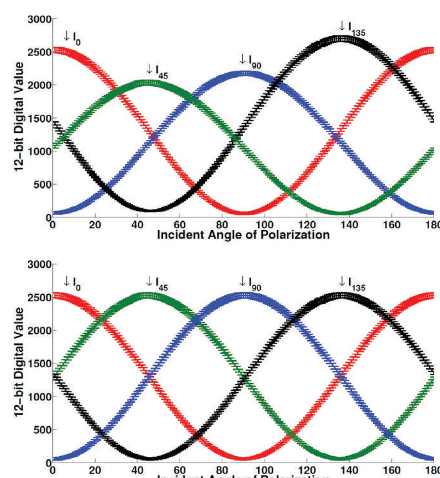

Figure 4. Average response of four polarization filter orientations before (top) and after (bottom) calibration.

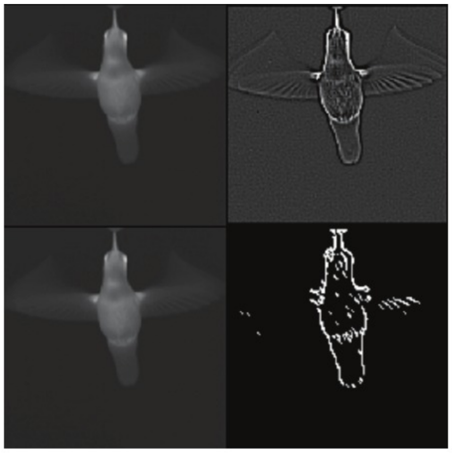

Fig. 5 The difference of Gaussian response of a hummingbird shows enhanced edge contrast as shown in the upper-right panel (input scene is in the upper-left). The zero-crossing image as shown in the lower-right image preserves the essential geometries in the scene, but conveys the information in a 1-bit representation. (Infrared imagery courtesy of the SE-IR Corporation, Goleta, CA)

Uncooled thermal detectors

Sessions 8, 9, and 11, 22, and 23 discussed uncooled detectors. The two leading uncooled technologies -- vanadium oxide (VO_x) and amorphous silicon microbolometers are continuing to be rapidly improved. Development of 17 μm pixel pitch FPAs is being extended to both smaller arrays—320 x 240—and arrays larger than 3 Mpixel—2048 x 1536. Currently, the largest such array - made by a U.S. company - is shown on a wafer in Fig. 6.

In addition, development of sub-17 μm pixel FPAs is continuing in the U.S., France, Japan and Sweden.

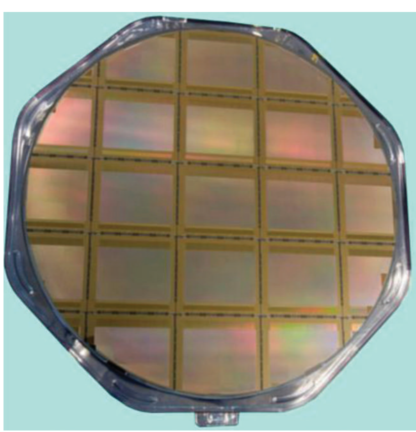

Fig. 6. 2048 x 1536 uncooled VO_x microbolometers with 17 μm pixel pitch on a 200 mm wafer.

Two Japanese companies have made advances in uncooled SOI (silicon-on-insulator) technology in which change in the forward bias voltage of silicon diodes with temperature is used to sense the incident infrared radiation. One company showed that the technology could be pushed to pixel sizes as small as 12 μm. Another company improved its SOI process by using 0.13 μm CMOS design rules and by placing micro-holes in the active cell that reduce the thermal capacity (but which do not decrease the absorption since they are smaller than the infrared wavelengths). This process is now believed ready for volume production. Figure 7 shows an image formed with this 320 x 240 SOI FPA with 22 μm pixels.

Sub-17 μm pixel FPA design has also been included in the analysis of ultra-low-cost PIR sensors for home security by an Australian company

The development of novel uncooled detectors is also continuing. The following novel uncooled technologies were reported on in this conference:

- A photomechanical imager (an array of bi-material microcantilevers that are read out optically) which was demonstrated as a Hostile Fire Indicator in the MWIR.
- A microbolometer based on single-crystal Si/SiGe quantum wells in which 17 μm pixel structures were demonstrated.
- A novel read-out for thermopile focal plane arrays that modeling shows can compete with 25 μm, 17 μm and 12 μm pitch microbolometers in both NEΔT and thermal response time.

Fig. 7 Low-cost 320 x 240 SOI FPA.

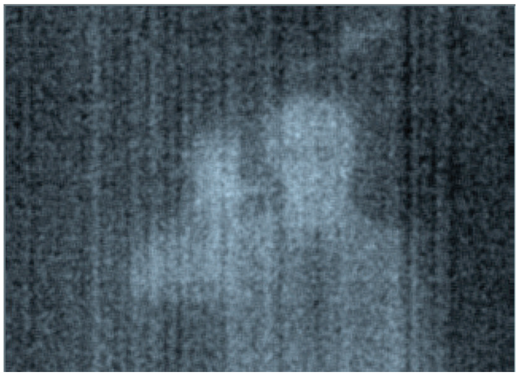

Fig. 8 Passive Terahertz image taken with an altered 320 x 240 VO_x microbolometer-based “Handy THz camera”.

In a related area, researchers in Japan demonstrated improved passive and active Terahertz imaging by altering a 320 x 240 VO_x microbolometer for use as a Terahertz sensor. Figure 8 shows a passive Terahertz image that has been integrated over 64 frames and a subarray of 3 x 3 pixels.

Photon detectors

Photon detector presentations continued to report good progress across the spectrum of device technologies in sessions 5-7, 10, 12, and 16-19.

QWIP and QDIP technologies reported new milestones in development. QWIP activities are inspired by NASA’s plans to launch the LANDSAT Data Continuity Mission with QWIP detectors providing the LWIR sensors—see Fig. 9. This has focused development on large format—512 x 640—broadband QWIPs in the spectral range of 10- to -13 μm. The spectral collection efficiency—product of quantum efficiency x photoconductive gain—for three of NASA’s QWIP vendors are illustrated in Fig. 10 at a temperature a few degrees below the planned operating temperature of 43 K. The QWIP arrays all were measured to have NEΔT values between 15 and 17 mK with the f/1.64 instrument.

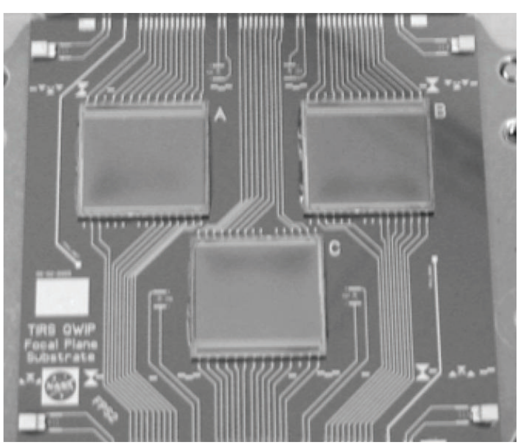

Fig. 9 The Thermal Infrared Sensor (TIRS) focal plane showing three QWIP sensor-chip assemblies.

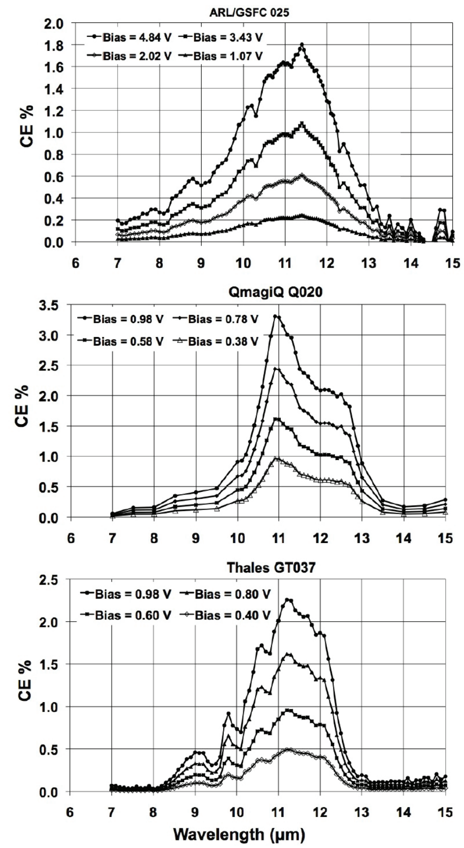

Fig. 10 Collection efficiency (CE) of QWIP FPAs from three NASA vendors as a function of wavelength for several bias values.

Type II superlattice FPAs provided an update on this rapidly advancing detector technology. Typical Type II superlattice FPAs have about 6x higher leakage (or dark) current compared to HgCdTe (Rule 7). The separation between the two detector materials performance has been reduced in recent years from a significantly wider margin however. Improvements in Type II materials are partly responsible for narrowing the performance gap, as illustrated in Fig. 11 that shows how the lattice quality has been improved, as X-ray rocking curve measurements show.

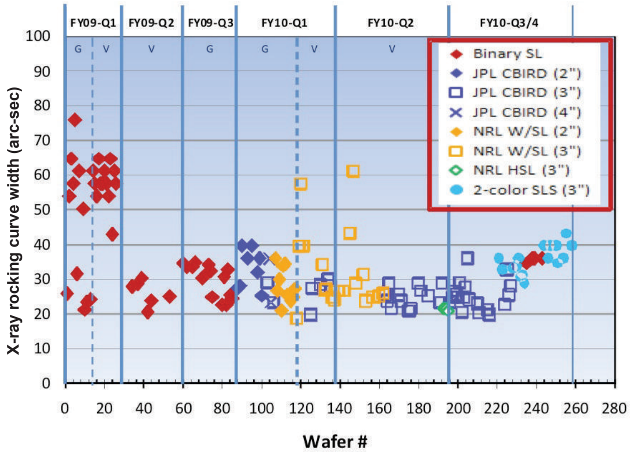

Fig. 11 X-ray crystal rocking curve data shows significant crystal quality improvement as experience is gained in growing Type II SLS material

Arrays of Type II superlattices of 1K x 1K have been demonstrated—see Fig. 12 for one from this conference—and a variety of barrier structures have been used to balance optical absorption and recombination mechanisms and for control of leakage currents.

Other Type II superlattice development efforts were described on precise inductively-coupled plasma (ICP) etching, dual band devices with reduced pixel size—see Fig. 13—growth on alternative substrates (GaAs), and the development of large, 4-inch GaSb substrates. Techniques for backside removal of the GaSb to eliminate parasitic absorption were reported as well.

A major issue in Type II materials has been the minority-carrier lifetime—typically measured in the range

Fig. 12 Image taken with a 1K x 1K Type II superlattice FPA.

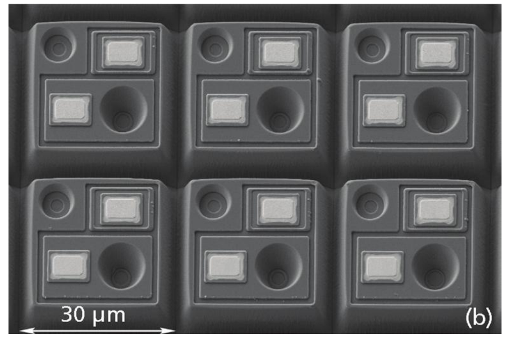

Fig. 13 Dual-band MWIR/MWIR Type II superlattice pixels with reduced—30 μm—pixel size.

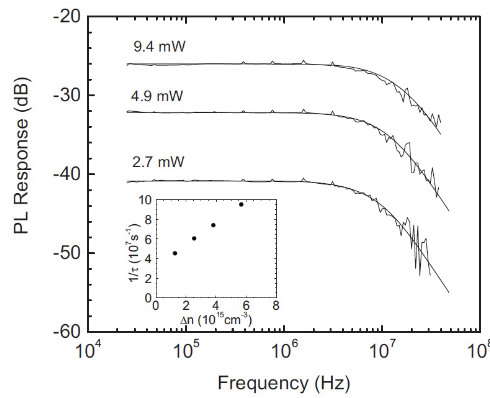

Fig. 14 Photoluminescence-decay measurements made on an LWIR Type II superlattice sample showing a lifetime of 31 nsec for the low-flux limit of photo-excitation.

of about 75 nsec for MWIR materials and 20 nsec for LWIR-effective bandgaps—see Fig. 14—compared with 10 μsec/2 μsec for MWIR/LWIR HgCdTe materials. A possible explanation related to the higher LO phonon energy in InAs and GaSb— ~30 meV— compared to HgCdTe with ~17 meV was presented.

Short wavelength infrared (SWIR) sensors continue to be under active development—see Fig. 15. A program to combine a SWIR array with 10 μm pixels together with an uncooled LWIR array with 20 μm pixels was presented. Such a combination would allow sensor fusion of reflected and emitted light to cover a wide variety of situations that soldiers may encounter, including the ability to see laser beams and thermal signatures combined.

Wide SWIR dynamic range—120 db—is available with InGaAs arrays by operating the array in forward bias like a solar cell—the open-circuit voltage being generated by the photon flux. The open-circuit voltage

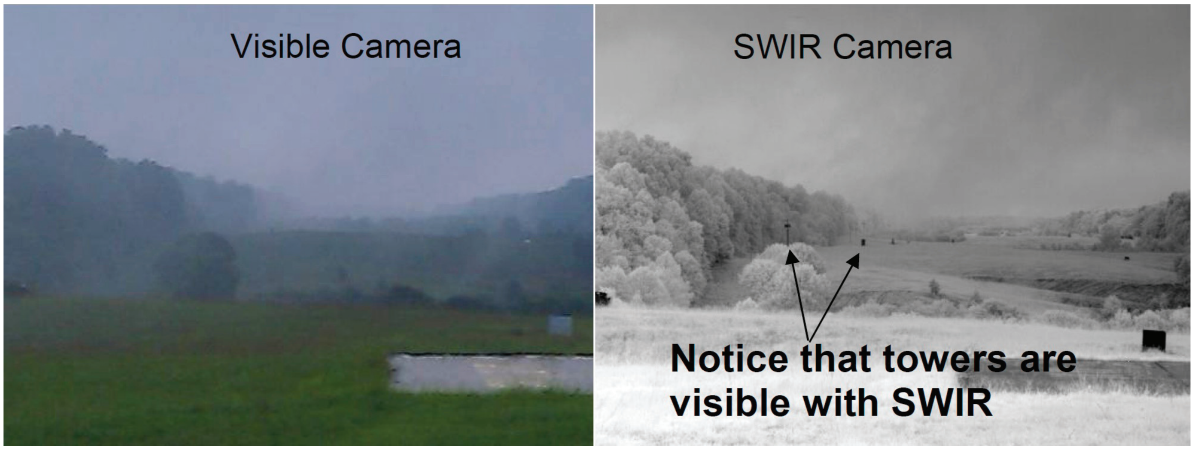

Fig. 15 Comparison of visible and SWIR imagery in atmospheric fog.

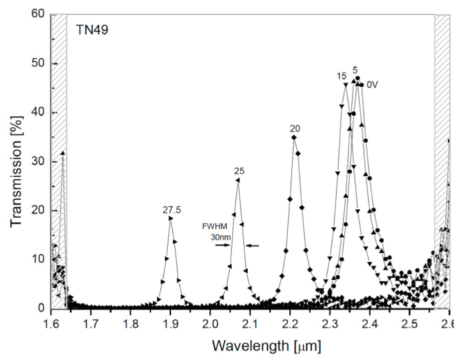

Fig. 16 Tuning range of a MEMs Fabry-Perot structure from 1.9 to 2.4 μm with applied voltage noted above peaks.

increases only logarithmically with the photocurrent. Such sensors are being proposed as an alternative to uncooled arrays for automotive applications such as extending the visibility range.

Pixel-level MEMs Fabry-Perot arrays were described with tuning in the SWIR band as illustrated in Fig. 16.

Progress in reducing the dark current and noise in dense arrays was reported. The trade-off in power requirements for TE cooling vs. using SWIR illuminators was also discussed. In addition to InGaAs SWIR detectors, other approaches were described based on MOVPE Type II materials and “black” silicon.

The conference keynote session described the requirements and technology needs for wide-area persistent surveillance sensors.

A half-day session was devoted to High-Operating Temperature (HOT) detectors—a hot topic for the past couple of years. Papers presented in this section covered a variety of detector material candidates, including:

- MWIR Type II superlattices
- MWIR InAsSb xBn structures
- InAsSb alloys with special absorber structures
- Interband cascade photodetectors
- HgCdTe photodiodes
- Quantum dot (Qdot or QDIP) photodetectors
- InSb

Progress with detectors having majority-carrier barriers is extremely active—see Fig. 17. The paper on Type II superlattices in this session reported designs that included such a barrier, as did other papers more specific to this approach. Barrier detectors have a po-

Fig. 17 Image taken at 150 K with an nBn 640 x 512 array showing an NEΔT of 20 mK. The dark spots on the hill are cows.

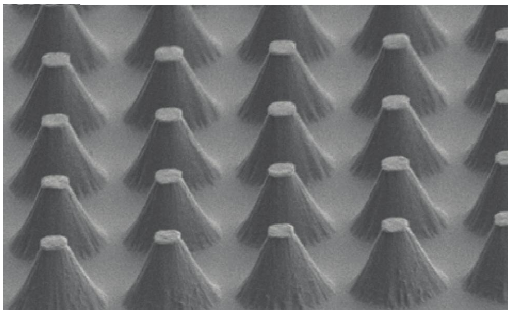

Fig. 18 Pyramidal absorbers on an InAsSb layer were structured to increase photon absorption.

tential advantage if the operating temperature is below the cross-over between diffusion- and generation-recombination-limited regimes. That cross-over point may vary from one material system to another, and within each material system as well, dependent upon the material quality and purity, minority-carrier lifetime, control of doping and bandgap gradients, etc.

The winners in this category will need to be sorted out by investment, time, and experiments. The answer may also depend upon the specific details of the application. Lattice matching to standard substrates may preclude barrier detectors from some applications if the wavelength response is limited to the shorter region of the MWIR band. Novel ideas including pyramid absorbers—see Fig. 18—to enhance absorption in thin layers was discussed. The detector community has less experience with technologies that have prospered in the laser field, such as cascade quantum structures. We shall see in future years how the current results improve over time.

HOT results for traditional detectors—HgCdTe and InSb—were presented. Fig. 19 illustrates how NEΔT increases for a HgCdTe detector with increasing temperature for two spectral MWIR bands. It was noted

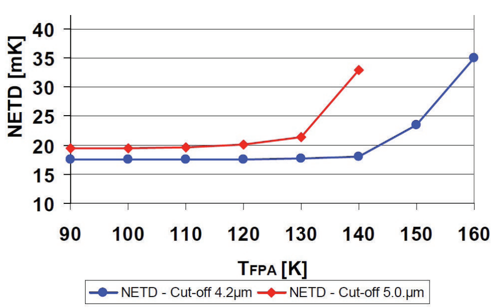

Fig. 19 NEΔT for two MWIR spectral bands—noted—as a function of operating temperature.

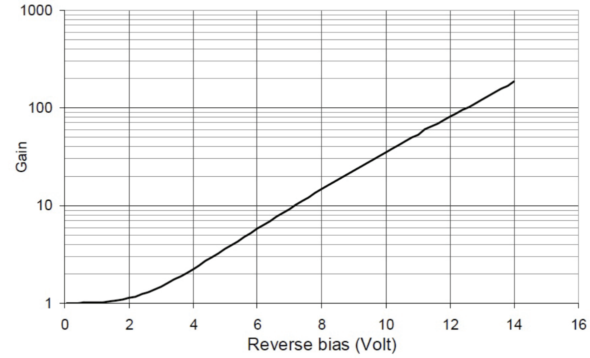

Fig. 20 Gain as a function of bias for a HgCdTe e-APD having a spectral cutoff of 3.1 μm at 200 K.

that small-pixel arrays can generally be cooled more quickly and will operate with lower power than large-pixel arrays in the same format. Additional HOT data is part of two papers in the HgCdTe detector session.

Active imaging technology presentations covered three materials capabable of producing avalanche photodiode (APD) devices:

- InSb
- InGaAs
- HgCdTe
    - hole-avalanche devices
    - electron-avalanche devices

The electron avalanche gain of a HgCdTe detector having a 3.1 μm cutoff as a function of bias is shown in Figure 20. The gain exceeds 100 at a bias of 12 V. Here the use of shorter cutoff material, compared with earlier results means that such an electron-avalanche detector would need less cooling than one with a cutoff in the range of 4-5 μm. On the other hand, the longer cutoff material is better able to provide passive

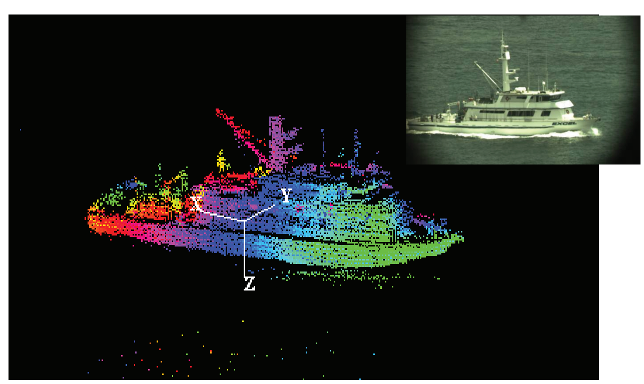

Fig. 21 3D image of a ship (visible insert) made with a scanned linear array of hole-avalanche HgCdTe detectors.

thermal imaging in addition to APD operation.

Figure 21 shows the 3D image of a ship taken with a linear array of HgCdTe hole-avalanche APDs in a 256 x 4 scanned sensor. These APDs operate up to 1.5 GHz in a linear mode with no after-pulsing effects providing sub-nanosecond time resolution. The sensor has a TE cooler for temperature stabilization. Both InGaAs and hole-avalanche HgCdTe can operate at room temperature in the eye-safe SWIR range of 1.5-1.7 μm, but cannot provide thermal imagery as well as APD operation.

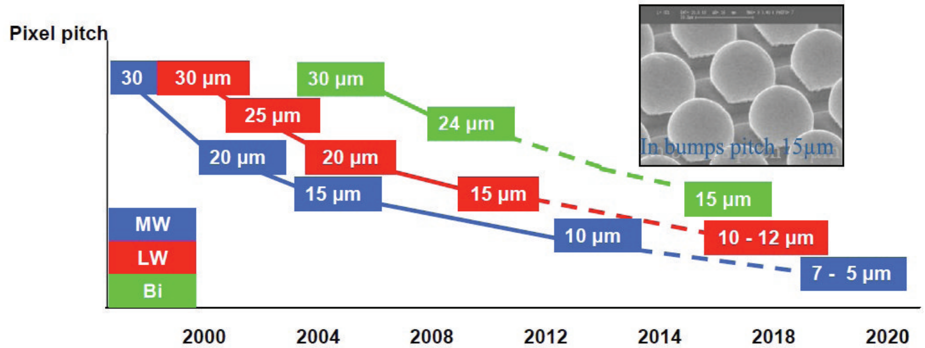

Fig. 24 Progress (solid line) and projections (dashed line) for reducing pixel size for MWIR (blue), LWIR (red), and dual-band FPA applications.


Fig. 22 Phillippe Tribolet

The session on HgCdTe detectors began with a memorial for colleague Phillippe Tribolet—Figure 22—who tragically died in the fall of 2010, much too young. He will be missed by our infrared community.

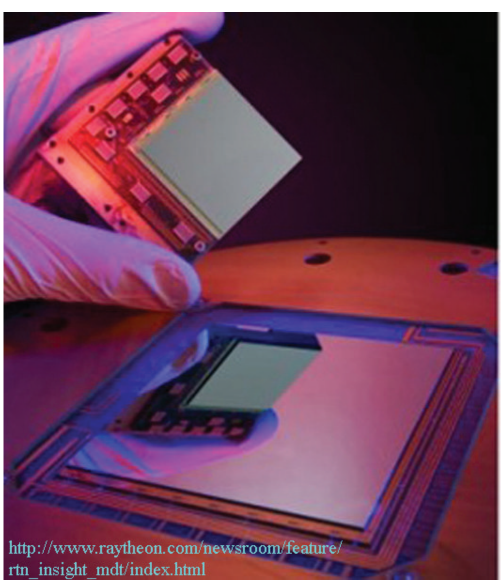

Fig. 23 Image of a 2K x 2K reflected in a 4K x 4K MWIR HgCdTe array grown on silicon.

Advances in HgCdTe detectors were reported in Session 19. Very large format SWIR and MWIR arrays built with HgCdTe grown on 6-inch silicon substrates were described—4K x 4K—with 20 μm pixels—see Fig. 23. Even larger formats—8K x 8K—are expected in the near future. HgCdTe grown on silicon wafers has made this possible, but currently not for LWIR material which is more sensitive to the lattice mismatch.

Progress and projections for reducing pixel size were presented—as shown in Fig. 24 above. This has led to large format MWIR FPAs with 15 μm pixels in a 1280 x 1024 tactical format. Excellent imagery results for single and dual MWIR bands were shown—the dual-band in a 640 x 512 format with 24 μm pixels and 20 and 25 mK NEΔT, respectively—see Fig. 25.

The combination of GaAs substrates and MOVPE growth has also produced high quality MW/LW results in a 640 x 512 format with 20 μm pixels. Figure 26 illustrates the NEΔT results for one of these FPAs. In Orlando, Selex demonstrated an extension of this technology to a larger format—860 x 480 with the same pixel pitch and NEΔT performance for 3rd Gen


Fig. 25 Imagery taken with a dual-band MW/MW array of HgCdTe on CdZnTe having 24 μm pitch in a 640 x 512 format.

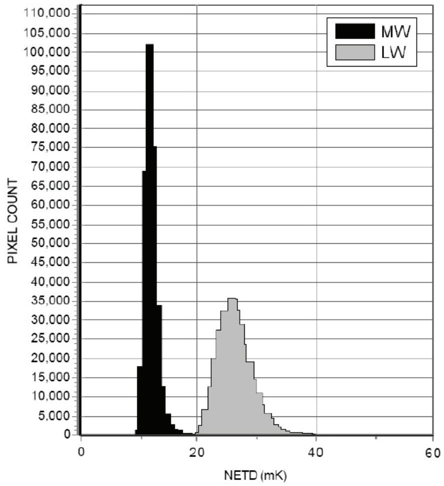

Fig. 26 Histograms of MW and LW band NEΔT measured on a HgCdTe-on-GaAs array with 20 μm pixels.

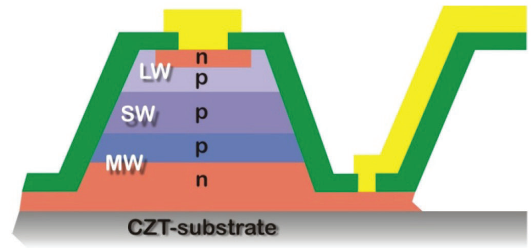

Fig. 28 Doping structure of a novel n-p-n dual-band HgCdTe pixel structure.

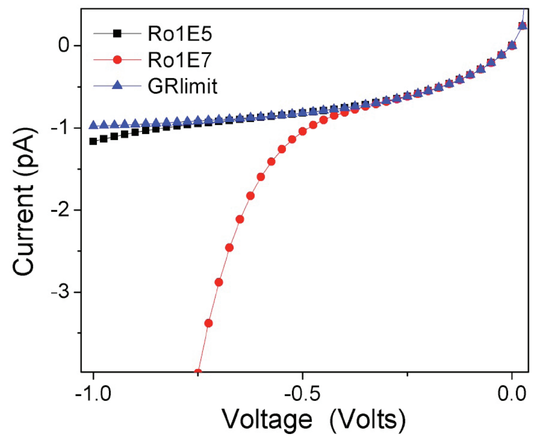

Fig. 29 Illustration of the impact of dislocation density on the reverse-bias characteristics of a HgCdTe diode.

imaging applications. The HgCdTe-on-GaAs technology also reported progress in MWIR HOT detectors, with impressive imagery shown in Fig. 27 at 160 K using a 640 x 512 format with 16 μm pixels. The NEΔT under these conditions was less than 18 mK.

Plans were outlined for dual-band 3rd Gen MW/LW technology development also using HgCdTe n-p-n diodes. Descriptions of a variant of the usual n-p-n structure were presented in two papers—see Fig. 28 for one example. Another novel description was that of a dual-band FPA with a fish-eye lens system partially integrated into the dewar.

Fig. 27 Image taken at 160 K with a HgCdTe-on-GaAs FPA with 16 μm pixels.

Elevated dislocation densities are typically encountered when growing HgCdTe on alternative substrates such as Si or GaAs. A theory was presented to explain this effect. An example of this calculation on the I-V characteristics is shown in Fig. 29.

Cryocoolers

Session 15 covered cryocoolers. A great effort has been made to miniaturize the detector cryocoolers while retaining or improving the Mean Time To Failure—MTTF. A MicroCryogenic Cooler, MCC, of the Joule-Thomson type was demonstrated for temperatures down to 200 K. MCCs using mixed refrigerants are very promising because they can require only a tenth of the input power of a corresponding TE cooler, and fill a tenth of the volume of a corresponding Stirling cooler, as illustrated in—Fig. 30.

While looking into the future, the MCC presenters envisaged "invisible" cryocoolers which may revolutionize future IR imaging systems. Potential additional size reductions of more than 10 times may be obtained by use of MEMS compressors.

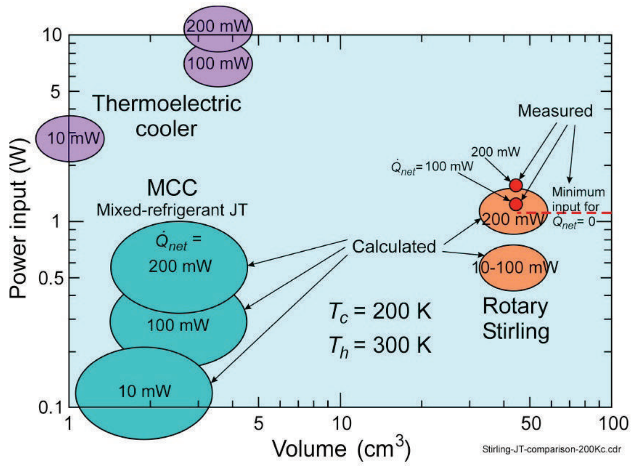

Fig. 30 MCC compared with thermoelectric and Stirling coolers for temperatures down to 200 K.

A novel miniature cryocooler was demonstrated. The reduction of its dimensions was achieved by using moving magnet technology and omitting flexure suspension in split Stirling linear coolers.

Recent trends in developing mini- and micro-satellites for relatively inexpensive missions have prompted attempts to adapt leading-edge tactical cryogenic coolers for suitability in the space environment. The primary emphasis has been on reducing cost, weight and size. Practical and theoretical aspects of adaptation of a microminiature tactical split Stirling cryogenic cooler to the space application were described. The operation of the cooler may give rise to vibrations which will degrade the IR imager's functionality. The authors outlined, in a companion paper, their techniques for reducing these vibrations.

Several coolers of the rotary type were presented. Among these were a sub-micro cooler with fast cooldown and low jitter, one that is particularly suited for intermediate temperatures of 90 to 150 K., and one with a redesigned bearing resulting in doubling of the MTTF.

Paul R. Norton

Bjørn F. Andresen

Gabor F. Fulop