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GALLIUM ARSENIDE QUANTUM WELL-BASED FAR INFRARED ARRAY RADIOMETRIC IMAGER

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ABSTRACT

We have built an array-based camera (FIRARI) for thermal imaging (λ = 8 to 12 microns). FIRARI uses a square-format 128 x 128 element array of aluminum gallium arsenide (AlGaAs) quantum well detectors that are indium bump-bonded to a high-capacity silicon multiplexer (6 x 10^7 electrons full well). The quantum well detectors offer good responsivity ($D^* = 1 \times 10^{10}$ cm(Hz)$^{1/2}$/W at 60 K) along with high response- and noise-uniformity (U ~ 0.02-0.04), resulting in excellent thermal images without compensation for variation in pixel response. A noise equivalent temperature difference (NEΔT) of 0.02 K at a scene temperature of 290 K was achieved with the array operating at 60K. FIRARI demonstrated that AlGaAs quantum well detector technology can provide large-format arrays with superior performance to mercury cadmium telluride at far less cost.

INTRODUCTION

The thermal infrared, extending from 8 to 12 microns and beyond, is a band of great interest and utility to many of NASA's remote sensing applications. Studies of the atmosphere, ocean, biosphere and lithosphere in this band provide vital data for energy-balance models that can shed light on the issue of global warming, among other things.

There are many situations where the simplicity of a staring detector array is highly desirable, however, the technological challenge of producing high quality infrared detectors in the 8 to 12 micron waveband has made large-format two-dimensional arrays impractical and prohibitively expensive. Imaging in this band has until now mainly been done by mechanically scanning a scene of interest across a single-point detector (typically mercury cadmium telluride (HgCdTe) at 100 K or extrinsic germanium at 4 K), or by pushbroom scanning across a linear array[1]. Unreliability, high 1/f noise, and large spectral non-uniformities from pixel to pixel are among the problems that motivate the search for detector alternatives to HgCdTe for large-format square arrays[2], whereas the very low operating temperatures of extrinsic silicon and germanium (~25 K and 4 K respectively) make their use for long missions impractical.

The advent and development of molecular beam epitaxy (MBE) and metallorganic chemical vapor deposition (MOCVD) have made possible the growth of semiconductors such as aluminum gallium arsenide (AlGaAs) in very thin layers of precisely controlled thickness. Electrons and holes in these layered structures display quantum confinement effects such as discrete subbands in the conduction and valence bands[3]. These subbands have been exploited to make infrared-sensitive devices[4]. This is in contrast to HgCdTe, with a band-gap energy on the order of that of an infrared photon (~0.1 eV) and which absorbs infrared in interband transitions (shown below) between valence and conduction bands. Quantum well infrared detectors can absorb in intersubband transitions when their energy level spacing is of the same order as the infrared photon energy. Either photoconducting or photovoltaic devices can

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be made: to make a photovoltaic detector, the multiple quantum wells are inserted between p and n-doped GaAs layers.

AlGaAs single element quantum well IR detectors at $\lambda = 10$ microns typically have sensitivities on the order of 10^{10} cm(Hz)$^{1/2}$/W at 77 K [5]. Although this is significantly lower than for HgCdTe ($D^* > 5 \times 10^{10}$ at 10 microns and 100 K), AlGaAs quantum well detectors do not exhibit any significant 1/f noise, and their response is linear over a wide range of photon flux levels. This makes calibration and pixel compensation of large arrays a much simpler matter than for HgCdTe. The excellent quality of the GaAs substrates and high degree of process control during wafer growth result in layer thickness and compositional variations of much less than 1% across a a three-inch wafer. This uniformity means that large-format square arrays of AlGaAs quantum well detectors can easily be fabricated with uncorrected pixel response and noise uniformity of 2 to 5%. Again, this uniformity is superior to what is attainable in HgCdTe arrays by at least a factor of 2. AlGaAs quantum well photoconductors are high-impedance devices (~100 KΩ), dissipating much less heat than HgCdTe photoconducting detectors. Finally, because of the wider band-gap of AlGaAs (1.43 eV versus 0.12 eV for HgCdTe at 10 microns), these devices are much more radiation-hard than HgCdTe, an important consideration for long duration space flight applications and certain military uses.

Further development of AlGaAs quantum well arrays is now being supported by Defense Advanced Research Projects Agency (DARPA) at ATT-Bell Laboratories in Murray Hill, New Jersey, Rockwell Science Center in Thousand Oaks, California and at Martin Marietta in Catonsville, Maryland. Among the aims of this research are to raise the operating temperature, lower the dark current and evaluate the performance of imaging systems using 128x128 or larger AlGaAs quantum well arrays.

RESULTS

As of May 1990 AlGaAs quantum well detectors had not yet been made in large arrays and successfully integrated with silicon multiplexers, and no performance data existed with which performance predictions could be validated. Under the auspices of the Goddard 1991 Director's Discretionary Fund and with additional support from the EOS project, we designed, built and tested an imaging radiometer based on a 128 x 128 element AlGaAs quantum well detector array. Since this was a Far IR Array Radiometric Imager, the acronym FIRARI was adopted. FIRARI was test-flown in a NASA Skyvan over varied terrain near Wallops Flight Facility in Virginia as part of its performance evaluation.

A schematic of FIRARI is found in Figure 1; its salient features are listed below. FIRARI consists of a 128 x 128 element AlGaAs quantum well detector array with response peaked at 9 microns, indium bump-bonded to a high-capacity silicon multiplexer (full well = 6×10^7 electrons). The detector pitch is 60 microns. The array is housed in a continuous-feed liquid-helium dewar with a heater and temperature controller. Custom long focal-length f/2 zinc selenide and germanium optics with diffraction-limited performance are used without a filter to image a scene onto the array; the pass-band of the optics is approximately 8 to 12 microns. Drive and timing electronics for the array were designed and built inhouse; 12-bit digitization of the pixel signals was obtained via a standard A/D board for the MacII. MacII-based data acquisition, display and analysis software was written inhouse.

Instantaneous field of view (IFOV):	7.5 degrees full angle (131 m^2 foot-print @ 3000 ft alt.) 1 mrad/pixel resolution (1.0 m/pixel @ 3000 ft alt.)
ZnSe & Ge f2 fore-optics: (diffraction-limited)	MTF ~ 0.70 @ 10 line pairs/mm Transmission > 90% @ 9 μm

GaAs-AlGaAs quantum well detectors: (ATT-Bell Labs)	60 µm pitch $D^* = 1 \times 10^{10}$ cm (Hz)$^{1/2}$/W at 60 K 128 x 128 = 16,384 pixels Operating temp. = 50 K **NEΔT = 0.02 K @ 290 K**
High-capacity silicon multiplexer: (Rockwell Science Center)	Full well = 6×10^7 electrons

MacII-based data acquisition (12-bit digitization) and analysis software

Lakeshore dewar with continuous-feed liquid helium

FIRARI performed very well, producing high-quality images with little need for calibration other than subtraction of a reference frame at ambient temperature. Fewer than 2% of the pixels were bad, i.e. either hot or dark. Measurements in the laboratory of array performance indicated an average blackbody $D^* = (1 +/- 0.03) \times 10^{10}$ cm(Hz)$^{1/2}$/W at 60 K, yielding NEΔT = 0.020 +/- 0.004 K (values are the mean +/- standard deviation). The quantum efficiency averages 0.1%, which is much lower than anticipated; single, edge-illuminated detectors of the same type have quantum efficiencies of about 25%. Poor coupling at normal incidence into the quantum well structure lowers the quantum efficiency of the array; this is a weakness of this type of detector that needs to be addressed in future development. Furthermore, it is necessary to operate the array at 50 K instead of 77 K in order to reduce dark current to an acceptable level. Future work should be aimed at raising the operating temperature to 77 K in order for this detector technology to be strongly competitive with HgCdTe. This NEΔT is largely the result of very good pixel uniformity (the ratio of the standard deviations to the means of D*, NEDT and quantum efficiency are 2 to 4% before correction) which offsets the low quantum efficiency; likely future improvements in this detector technology should lower the NEΔT still further.

POTENTIAL COMMERCIAL APPLICATIONS

There are many practical applications of thermal imaging in atmospheric windows where there is little absorption by molecular water; these windows are from 3 to 5 µm and roughly 8 to 11 µm[1] . Up to the present time the 3 to 5 µm waveband has been heavily utilized mainly because of the limitations of detectors in the 8 to 12 µm band. Most of the radiance emitted by objects near room temperature falls in the 8 to 12 µm band; furthermore the spectral radiant contrast for near room temperature objects occurs there[6]. Hence the detection sensitivity of many thermal instruments can be improved by using detectors sensitive in the 8 to 12 µm band.

Thermal imagery has many applications in addition to NASA's own interests, including: forest-fire detection[7,8], industrial process monitoring[9,10], and non-destructive evaluation[11] to list a few. For instance, NASA Headquarters (Earth Observations Commercialization Applications Program, Office of Commercial Programs) very recently contributed $600,000 to a joint development effort between NASA Ames Research Center and Terra-Mar Resource Information Services to produce a system to provide ground crews with rapid access to information on forest fires gathered by reconnaissance aircraft bearing infrared sensors[8] As part of this effort, NASA has been called upon to improve its infrared sensors. The goal of this three-year program is "to develop and market a commercially viable real-time remote sensing system for monitoring such disasters as fires, oil-spills and floods." Quantum-well detector arrays such as the one used in FIRARI could in the future be a real asset to each of the applications described above: the square format and large number of pixels make detection more sensitive, data acquisition faster and simplify the detection system by eliminating the scan mechanism required for linear arrays and point detectors.

REFERENCES

1. See for example: *Remote Sensing and Image Interpretation,* Second Edition, T. M. Lillesand and R. W. Kiefer, John Wiley and Sons, 1987

2. Proceedings of IRIS Specialty Group on Infrared Detectors, August 1991

3. An excellent general reference on this subject is: *Quantum Phenomena,* S. Datta, Addison-Wesley Modular Series on Solid State Devices, 1989

4. "A new IR detector using electron emission from multiple quantum wells", J. S. Smith et alia, Journal of Vacuum Science and Technology, V B1, pp 376-378, 1983

5. "High sensitivity low dark current 10 μm GaAs quantum well infrared photodetectors", B. F. Levine et alia, Applied Physics Letters, V 56 - No. 9, pp 851 - 853, February 26, 1990

6. See for example: RCA Electro-Optics Handbook, 1974, pp 35 - 44

7. "Early warning detection of forest fire at high resolution by thermal scanner from high-flying aircraft", A. Rainhart, SPIE Proceedings Volume 1467, 1991

8. "Fighting Forest Fires with Remote Sensing", Photonics Spectra, inset p 66, August 1991

9. "Using IR thermography as a manufacturing tool to analyze and repair defects in printed circuit boards", D. K. Fike, SPIE Proceedings Volume 1467, 1991

10. "A cool box finds hot spots", A. Teich, Photonics Spectra, p 99, August 1991

11. "Real-time thermographic battle damage field inspection for rotary wing aircraft", C. G. Pergantis, SPIE Proceedings Volume 1467, 1991

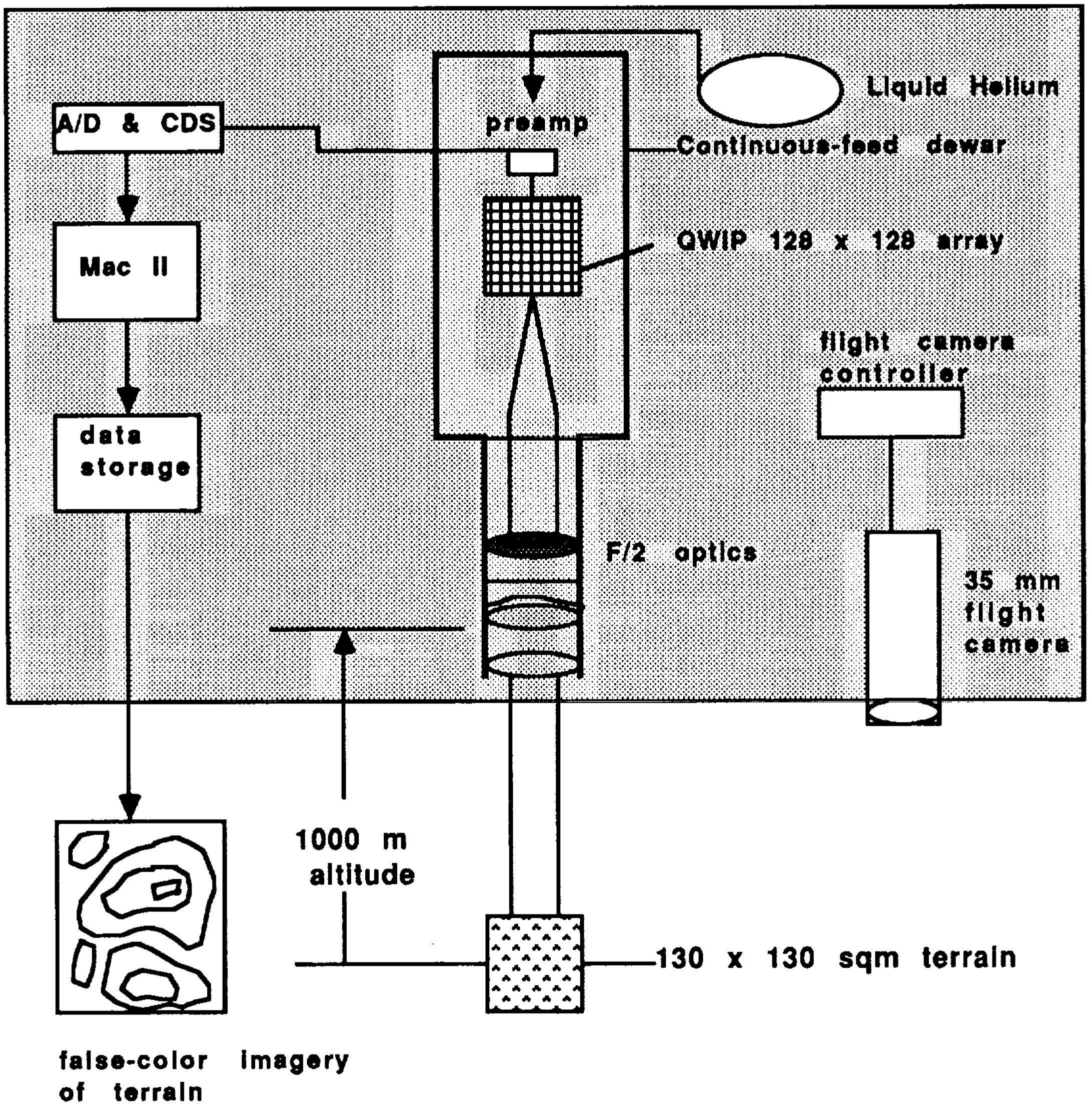

Figure 1. Schematic of FIRARI as flown in NASA Skyvan in vicinity of Wallops Flight Facility, 12:30 to 13:45 EST, May 23, 1991.