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Large Format Long-Wavelength Infrared Multi-Band and Broad-Band QWIP Focal Plane Arrays

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Abstract—A 640x512 pixel, long-wavelength multi-band and a broad-band ($\Delta\lambda/\lambda$~42%) quantum well infrared photodetector (QWIP) focal plane array (FPA) having a 15.4 μm cutoff have been demonstrated.

The QWIPs discussed in this article utilize the photoexcitation of electrons between the ground state and the first excited state in the conduction band quantum well (QW) [1]. There has been much interest lately [1] in large format QWIP FPAs. In this presentation we discuss the design, fabrication, and test results of a 640x512 pixel four-band, and broad-band QWIP FPAs. These large format FPAs will be useful for many applications such as the in-situ and remote sensing of gas molecules, thermal imaging, global atmospheric temperature profiles monitoring, cloud characteristic measurements, astronomy, tracking and identification of missiles, etc.

The unique feature of the spatially separated four-band FPA is that the four infrared bands are independently and simultaneously readable on a single imaging array. The multi-band FPAs based on narrow-band QWIP detector structures have the advantage over other broad-band detectors such as HgCdTe in that the spectral responses of QWIP are relatively narrow so that a detector designed for a specific spectral band only detects radiation in that band with little or no spectral crosstalk. Thus, pixel co-located multi-band QWIP FPAs can operate in simultaneous read mode compared to the alternate frame read mode of multi-band FPAs based on other detector technologies. These advantages lead to a reduction in instrument size, weight, mechanical complexity, optical complexity and power requirements since no moving parts are needed. Furthermore, a single optical train can be employed, and the whole focal plane can operate at a single temperature.

This four-band vertically integrated device structure was achieved by the growth of multi-stack QWIP structures separated by heavily doped n^+ contact layers, on a GaAs substrate. Device parameters of each QWIP stack were designed to respond in different wavelength bands. A typical QWIP stack consists of a multi-quantum-well (MQW) structure of GaAs QWs separated by $Al_xGa_{1-x}As$ barriers. The actual device structure consists of a 15 period stack of 4-6 μm QWIP structure, a 25 period stack of 8.5-10 μm QWIP structure, a 25 period stack of 10-12 μm QWIP structure and a 30 period stack of 13-15 μm QWIP structure. Each photosensitive MQW stack was separated by a heavily doped n^+ (thickness 0.2 to 0.8 μm) intermediate GaAs contact layer. Since the dark current of this device structure is dominated by the longest wavelength portion of the device structure, the very long-wavelength infrared (VLWIR) QWIP structure has been designed to have a bound-to-quasibound intersubband absorption peak at 14.0 μm. Other QWIP device structures have been designed to have a bound-to-continuum intersubband absorption process because the photo current and dark current of these devices are relatively small compared to the VLWIR device. This whole four-band QWIP device structure was then sandwiched between 0.5 μm GaAs top and bottom contact layers doped with $n = 5 \times 10^{17}$ cm^{-3} and was grown on a semi-insulating GaAs substrate by MBE.

The individual pixels of the four-color FPA were defined by photolithographic processing techniques. Four separate detector bands were defined by a deep trench etch process and the unwanted spectral bands were eliminated by a detector short-circuiting process. The unwanted top detectors were electrically shorted by gold-coated reflective two-dimensional etched gratings. In addition to shorting, these gratings serve as light couplers for active QWIP stack in each detector pixel [1]. Design and optimization of these two-dimensional gratings to maximize QWIP light coupling are extensively discussed elsewhere [1]. The unwanted bottom QWIP stacks were electrically shorted at the end of each detector pixel row.

Typically, quarter-wavelength deep ($h = \lambda_p/4n_{GaAs}$) grating grooves are used for efficient light coupling in single-band QWIP FPAs. However, in this case, the height of the quarter-wavelength deep grating grooves is not deep enough to short circuit the top three MQW QWIP stacks. Thus, three-quarter-wavelength groove depth two-dimensional gratings ($h = 3\lambda_p/4n_{GaAs}$) were used to short the top unwanted detectors over the 10-12 and 13-15 μm bands. This technique optimized the light coupling to each QWIP stack at corresponding bands while keeping the pixel (or mesa) height at the same level which is essential for the indium bump-bonding process used for detector array and readout multiplexer hybridization. Figure 1 shows the normalized spectral responsivities of all four spectral bands of this four-band FPA. Spectral band widths of the four detectors from shorter wavelength to longer wavelength in increasing order are $\Delta\lambda/\lambda_p$ ~ 26%, 15%, 17%, and 11%, respectively. The typical spectral width of a MWIR QWIP is about 0.5 μm. The MWIR detector in this FPA is specifically designed to cover a 4-6 μm wavelength range with $\Delta\lambda/\lambda_p$ ~ 26% broader responsivity by utilizing three coupled QWs in each period of the MQW stack [1]. Also, the shorter wavelength response in this detector is achieved by using deeper $In_{0.33}Ga_{0.67}As$ QWs with lattice mismatched $Al_{0.3}Ga_{0.7}As$ barriers [1]. A high Al ratio is less desirable in these detectors because of the high defect density and the near crossing of the Γ and X valleys [1].

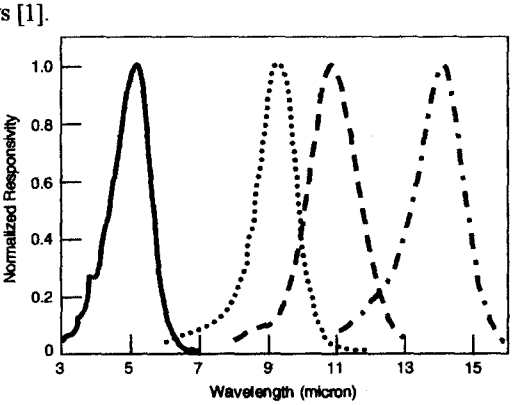

Fig. 1. Normalized spectral response of the four-band QWIP FPA.

A few QWIP FPAs were chosen and hybridized to a 640x512 pixel silicon CMOS ROIC and biased at $V_B = -1.5$ V. At temperatures below 83 K, the signal to noise ratio of the 4-6 μm spectral band is limited by array nonuniformity, multiplexer readout noise, and photo current (photon flux) noise. At temperatures above 45 K, temporal noise due to the 13-15 μm QWIP's higher dark current becomes the limitation. The 8.5-10 and 10-12 μm spectral bands have shown BLIP performance at temperatures between 45 and 83 K. This initial array gave excellent images with 99.9% operability (number of dead pixels ≈ 250).

Video images were taken at a frame rate of 30 Hz at temperatures as high as T = 45 K, using a ROIC capacitor having a charge capacity of 11×10^6 electrons. Based on single element test detector data, the 4-6, 8.5-10, 10-12, and 13-15 μm spectral bands show BLIP at temperatures 40, 50, 60 and 120 K, respectively, for a 300 K background with a f/5 cold stop. As expected (due to BLIP), the estimated and experimentally obtained NEDT values of all spectral-bands do not change significantly below their BLIP temperatures. The experimentally measured NEDT of 4-6, 8.5-10, 10-12, and 13-15 μm detectors at 40 K are 21, 45, 14, and 44 mK, respectively.

The broadband QWIP device structure was designed by repeating a unit of several QWs with slightly different parameters such as well width and barrier height. The positions of ground and excited states of the QW are determined by the QW width (L_w) and the barrier height, i.e. the Al mole fraction (x) of the barrier. Since each single set of parameters for a bound-to-quasibound QW [1] corresponds to a spectral band pass of about 1.5 μm, three different sets of values are sufficient to cover a 10-16 μm spectral region. The MQW structure consists of many periods of these three-quantum-well units separated by thick barriers [1].

The device structure reported here involved 33 repeated layers of GaAs three-quantum-well units separated by $L_B \sim 575$ Å thick $Al_xGa_{1-x}As$ barriers. The well thickness of the QWs of the three-quantum-well units are designed to respond at peak wavelengths around 13, 14, and 15μm, respectively. These wells are separated by $L_u \sim 75$ Å thick $Al_xGa_{1-x}As$ barriers. The Al mole fraction (x) of barriers throughout the structure was chosen such that the $\lambda_p = 13$ μm QW operates under bound-to-quasibound conditions. The excited state energy level broadening has been further enhanced due to the overlap of the wavefunctions associated with excited states of QWs separated by thin barriers [1]. Energy band calculations based on a two band model show excited state energy levels spreading about 28 meV.

This device structure was grown on a semi-insulating 3-inch GaAs substrate by using MBE growth technique. Test detectors were fabricated as described elsewhere for electrical and optical characterization of the detector material. In Fig. 2, the responsivity curve at $V_B = -2.5$ V bias voltage shows broadening of the spectral response up to $\Delta\lambda \sim 5.5$ μm, (i.e. the full-width at half-maximum from 10.5 – 16 μm). This broadening $\Delta\lambda/\lambda_p \sim 42$ % is about a 400% increase compared to a typical bound-to-quasibound QWIP. The responsivity of the detector peaks at 13.5 μm and the peak responsivity (R_p) of the detector is 250 mA/W at bias $V_B = -2.5$ V. The peak absorption quantum efficiency was 11% at bias $V_B = -2.5$ V for a 45° double pass.

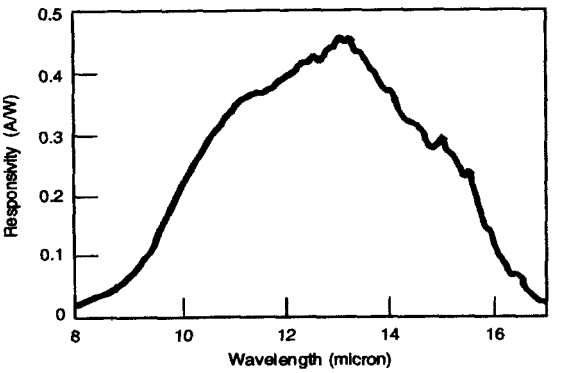

Fig. 2. Responsivity spectrum of a broadband QWIP test structure at temperature T = 55 K. The spectral response peak is at 13.5 μm and the long wavelength cutoff is at 15.4 μm.

Using experimental measurements of noise and responsivity, one can now calculate specific detectivity D^* [1]. The calculated D^* value for the present device ($\lambda = 15.4$ μm) at T = 55 K and $V_B = 2.5$ V is 3×10^{10} cm $\sqrt{Hz}$ /W. Even with broader response, this D^* is comparable to previously reported D^* of QWIPs with narrow spectral response. Though two-dimensional grating is an efficient light coupler, it is not suitable for broad-band QWIPs due to its inherent narrow band light coupling efficiency. Thus, we have implemented a wide-ranged random reflector for coupling normal incident radiation into broad-band QWIPs [1]. The broad-band 640x512 pixel QWIP FPAs were then fabricated using standard FPA fabrication techniques [1]. The pixel pitch of the FPA is 25 μm and the actual pixel size is 23x23 μm^2. These broad-band QWIP FPAs were hybridized via an indium bump-bonding process to a 640x512 pixel silicon CMOS ROIC and biased at $V_B = -2.5$ V. At temperatures below 48 K, the signal to noise ratio of the system is limited by array nonuniformity, multiplexer readout noise, and photo current (photon flux) noise. At temperatures above 48 K, temporal noise due to the dark current becomes the limitation. Due to the QWIP's high impedance, a charge injection coupling efficiency into the integration capacitor of the multiplexer $\eta_{inj} = 99.5\%$ was achieved at a frame rate of 30 Hz. This initial array gave very good images with 99.9% operability.

The mean value of the experimentally measured NEDT histogram of the FPA at an operating temperature of T = 40 K, bias $V_B = -2.5$ V at 300 K background with f/2 optics is 55 mK. This agrees reasonably well with our estimated value of 25 mK based on test structure data. The experimentally measured peak quantum efficiency of the FPA was 9.5%, which agrees well with the 11% absorption quantum efficiency estimated from the single element detector data. In summary, we have demonstrated the first 640x512 pixel spatially separated monolithic four-band detector array and the first 640x512 pixel broad-band FPA.

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Reference

[1] S. D. Gunapala and S. V. Bandara, "Quantum Well Infrared Photodetector (QWIP) Focal Plane Arrays," *Semicon. Semimet.*, vol. 62, H. C. Liu and F. Capasso, Ed. San Diego: Academic Press, 2000, pp. 197-282.