

Long Wavelength Infrared 128×128 $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ Quantum Well Infrared Camera and Imaging System

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Abstract—We discuss the development of a long wavelength (8–14 μm) 128×128 $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ multiquantum well infrared imaging system. Highly uniform, high-yield GaAs focal plane arrays, incorporating an integral grating structure for efficient optical coupling were hybridized to CMOS multiplexers. Excellent imagery, with low noise, a noise equivalent differential temperature (NEAT) of less than 10 mK, and a high image contrast signal-to-noise ratio has been achieved. We demonstrate that figures of merit concerning array uniformity, such as yield, NEAT, and maximum deliverable charge to the CMOS multiplexer are much more relevant variables that affect image quality than D^* .

INTRODUCTION

EXCEPTIONALLY rapid progress has been made recently in the fabrication and design of multiquantum well long wavelength infrared (LWIR) photodetectors based on intersubband transitions [1]–[7]. This progress is especially noteworthy in regard to LWIR imaging systems, where work on large scale 2-dimensional focal plane arrays has been reported [7]. For example, we have presented our recent work in some detail on a LWIR ($\lambda_c = 10.7 \mu\text{m}$) GaAs/AlGaAs multiquantum well scanned array imaging camera [6], with $D^*_\lambda = 2 \times 10^{10} \text{ cm} \sqrt{\text{Hz}}/\text{W}$ at $T = 77 \text{ K}$, and pixel-to-pixel uniformity of 2%. Since GaAs is an advanced material system and has a relatively mature growth and processing technology, we fabricated large scale uniform 128×128 GaAs/AlGaAs multiquantum well focus plane arrays. The new arrays were then incorporated into a newly developed real time infrared imaging system for testing.

ARCHITECTURE

Video images are obtained by focusing the intended target onto the back illuminated focal plane array using antireflection coated $f/2$ optics. The block diagram of the

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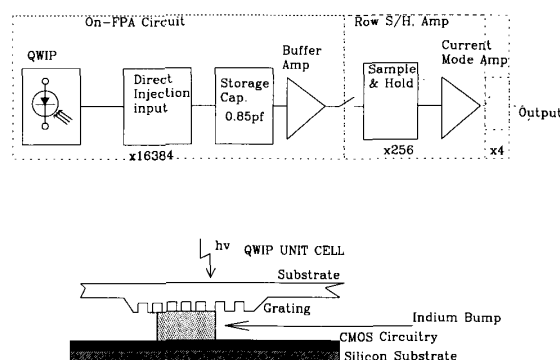


Fig. 1. Unit cell of the QWIP 128×128 focal plane array indium bumped to silicon CMOS multiplexer.

AT&T/Amber 128×128 QWIP/Multiplexer hybrid is shown in Fig. 1 [8]. The multiplexer has 16 384 input analog circuits organized as four intermeshed 64×64 arrays. Each input circuit has a common gate input amplifier, an integration capacitor, an integration time control switch, a source follower amplifier, and a selection switch to connect the source follower to the column bus.

Integration control, row selection, and row multiplexing are controlled by X and Y shift registers and associated logic gates outside of the main array. The column sample and hold amplifiers and current mode output amplifiers are in the periphery area of the hybrid.

The image processing system is shown in Fig. 2. Post video data acquisition is performed in both real time (bus rate of 10 MHz) and as a fully processed frame-grabbed image. The real time data acquisition mode makes use of the RS-170 video output from the AE/4128 A/D controller to the input of the real time image processing (A/D) system. The programmable ROM, which is part of the 4128 image processing software, is addressed directly over the RS-232 bus controlled by a Sun Sparc 330 host system. When operating the camera (we run at 60–217 frames per second) the host system simultaneously addresses the post image processing electronics through the VME bus, while interacting with the IR image through the 4128 controller. An image is frame-grabbed by the post processor in real time at the 10 MHz bus rate and

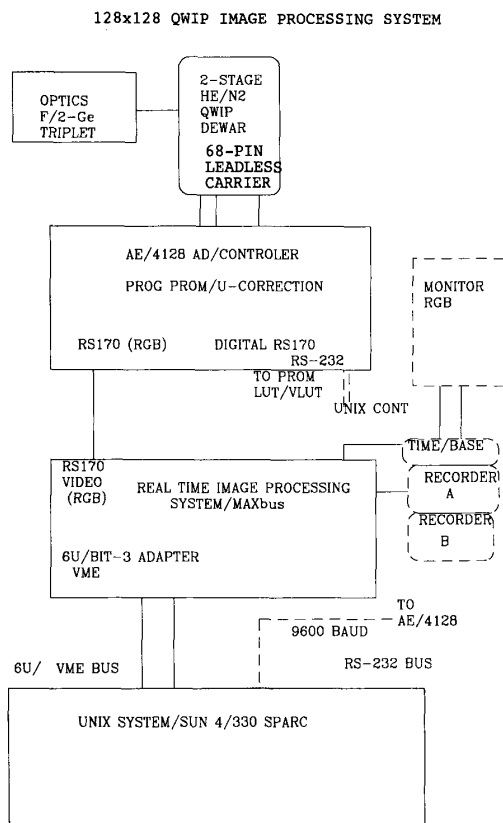


Fig. 2. Block diagram of LWIR camera and real time image processing system.

downloaded to the host computer by way of the VME bus. In this way image processing is not interrupted and we can continuously record an experiment, while simultaneously analyzing a still frame.

HYBRID QUANTUM WELL/MULTIPLEXER

Quantum-well infrared photodetectors (QWIP's) with individual integral GaAs optical gratings [11] ($50\text{ }(\mu\text{m})^2$) pixels for optical coupling were fabricated and hybridized to silicon CMOS read-out multiplexers (mux) made by Amber Engineering Inc. (see Fig. 1). These particular CMOS circuits were selected because of their near ideal input impedance match to our QWIP focal plane arrays. This impedance match is due to the direct charge injection technique the circuit employs to the MOSFET drain. It was also the most cost effective way to test for the first time our quantum well devices on large 2-dimensional focal plane arrays.

The QWIP active structure consists of fifty one $\text{Al}_x\text{Ga}_{1-x}\text{As}$ 500 Å thick barriers alternated with fifty 40 Å wide GaAs quantum wells [1]. The latter are n-type doped with silicon ($n = 10^{18}\text{ cm}^{-3}$). By varying the AlAs concentration in the barriers and the width of the quantum wells, operation at wavelengths in the 6–14 μm range can

Photo Response of QWIP Array

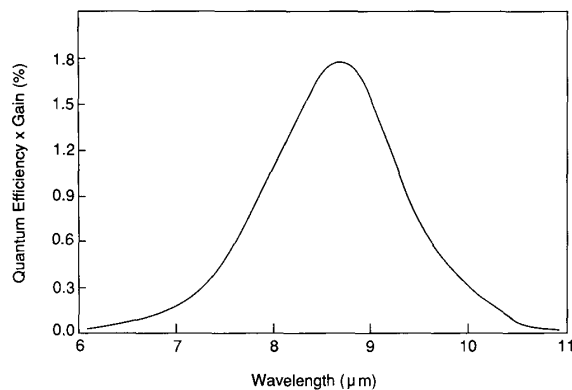


Fig. 3. The photoresponsivity curve at -1 V reversed bias for a single pixel is shown.

be achieved. For one of the devices tested, we show a typical responsivity curve in Fig. 3.

Briefly, it was previously shown that GaAs quantum well devices based on bound-to-extended state absorption make excellent LWIR photodetectors [1]. Cutoff wavelengths, λ_c , could extend out to 14 μm [10]. It was also shown that this can be achieved by decreasing the size of the dual state quantum well. As a result the excited bound state is pushed up into the continuum. The absorption between the single, localized bound state in the quantum well and the extended excited state in the continuum remains strong and D^* increases. Furthermore, we reduced the noise and the dark current associated with electron tunneling and demonstrated that the long collection mean free path for electron transport in the extended states above the barriers is crucial for achieving a high quantum efficiency and D^* [1].

These photodetectors have very high differential impedance and this leads to high voltage responsivity in the order of 10^5 V/W . The typical shot noise associated with the QWIP's dark current is approximately $10^{-14}\text{ A/Hz}^{1/2}$ ($T = 77\text{ K}$, at -1 V bias). D^* is comparable to that of HgCdTe at 10 μm . For the same detector area, the QWIP has been measured to be more than two orders of magnitude faster than HgCdTe or InSb; thus they are ideal for ultra high video frame rates $> 10^3\text{ Hz}$ [9].

GRATING COUPLING

The LWIR coupling of the target image is determined by the quantum mechanical selection rules of the inter-subband transition [10]. Absorption of the IR and hence photocarrier generation can only be achieved when the electric field of the incident IR signal has a component normal to the quantum-well layers. We therefore have made use of optical grating coupling to enhance the overall quantum efficiency of the array. Gratings with 3 μm periods were fabricated photolithographically on a gold alloyed contact layer [11].

Preliminary optical crosstalk measurements were made

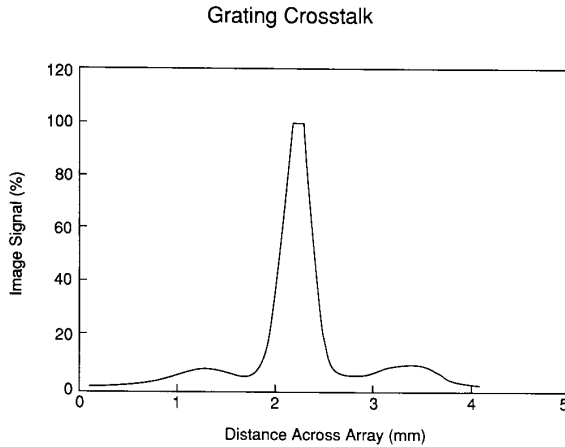


Fig. 4. Grating crosstalk of an image (peak saturated) versus the distance across the QWIP focal plane array.

using a small pinhole in front of a black body source and imaged in the far-field. A polarizer was also placed in front of the pinhole and rotated at various angles, to test signal-to-noise as a function of polarization. In Fig. 4 the first order maxima of the grating array is shown to be approximately 9% of the full charge collected on each pixel. This optical crosstalk signal is believed to originate from each grating by rays that are reflected and diffracted between the GaAs substrate and air interface. The image and the crosstalk were also observed to be highly sensitive to the polarization of the incident light, clearly indicating that they are due to the grating. By polishing the substrate down and coating the back side of the QWIP with an antireflection film, it may be possible to completely eliminate crosstalk, or at least bring it down a few orders of magnitude (optical crosstalk $< 0.1\%$).

QWIP/MUX INJECTION EFFICIENCY

The CMOS mux used has a maximum allowable input charge of 4×10^7 electrons [8]. Since it was designed for a photovoltaic InSb photodetector array operating near zero bias and not a photoconductive QWIP operating at a bias of $V_b > 1$ V, we are greatly encouraged by the excellent initial results from the imaging system. At temperatures below 60 K, the S/N ratio of the system is limited by array nonuniformity and multiplexer readout noise. At temperatures approaching 77 K, temporal noise due to the QWIP's higher dark current becomes the limitation, a result of thermionic emission which causes the readout circuitry to saturate [1], [10], [12]. This is due, in part, to the inability of the mux to handle the higher electron charge that is generated. Since the QWIP's are using the same readout architecture employed in Amber's photovoltaic InSb focal plane arrays, we are optimistic that a multiplexer design incorporating a higher injection charge capacity will allow us to operate at temperatures near 80 K. In fact Kozlowski *et al.* [7] have demonstrated 78 K operation with readout charge capacity of 8.5×10^7 elec-

trons, using QWIP's with $8.1 \mu\text{m}$ cutoffs. These arrays did not have the advantage of optical grating coupling, but nevertheless did demonstrate that QWIP array imagery can be very competitive with that achieved with higher quantum efficiency materials, i.e., InSb and HgCdTe.

The high impedance and high differential resistance of QWIP's, enables one to obtain a very high charge injection coupling efficiency into the multiplexer. At a temperature of 50 K the differential resistance R_{det} can be greater than $10^8 \Omega$. Charge injection efficiency can be obtained from [7]

$$\eta_{\text{in}}(\omega) = \frac{g_m R_{\text{det}}}{1 + g_m R_{\text{det}}} \times \frac{1}{1 + j\omega\tau} \quad (1)$$

where $\tau = R_{\text{det}} C_i / (1 + g_m R_{\text{det}})$ and $g_m = \partial I / \partial V_D|_{V_G}$ which is the source transconductance of a common gate.

The total capacitance C_i is the series and parallel combination of all capacitances, such as the detector QWIP capacitance, the gate-source capacitance, and any stray capacitance effects. The source transconductance follows the theoretical weak inversion law [7], since we are biasing the QWIP/CMOS mux combination at currents less than 20 pA. We obtain the transconductance of the mux from

$$g_m = eI_{\text{det}}/kT. \quad (2)$$

Injection efficiencies approaching 90% are obtainable, corresponding to a total electron charge injection of 4×10^7 electrons at a frame rate of 109 Hz with integration times of about 9 ms.

FOCAL PLANE ARRAY IMAGING

There are numerous materials that are considered to be established technologies in the infrared, at $T = 77$ K. HgCdTe and InSb have the highest quantum efficiencies ($\sim 70\%$) [8] and detectivities ($D^* = 10^{12} \text{ cm}^2 \sqrt{\text{Hz}}/\text{W}$ for both HgCdTe and InSb at $5 \mu\text{m}$). Since AlGaAs/GaAs QWIPs used in focal plane arrays [10] have somewhat lower detectivities $D^* \sim 10^{10} \text{ cm}^2 \sqrt{\text{Hz}}/\text{W}$ (at $\lambda = 10 \mu\text{m}$) [1], with quantum efficiencies of about 5–10%, the question of relevant figure of merit for the best imaging array technology must be discussed [13]. In order to get some idea of the relevant figure of merit for a long wavelength 8–12 μm focal plane array, we have compared our QWIP camera to a high performance commercially available, InSb midwavelength $\lambda = 5 \mu\text{m}$ infrared camera employing this technology. In Table 1, we show a comparison between the high quantum efficiency InSb focal plane and that of our standard QWIP. It should be understood that we have not polished off the $500 \mu\text{m}$ substrate to reduce cross talk nor have we used an antireflection coating on the QWIP to reduce it further. Fig. 5 shows the histogram of the mean D^* of the QWIP focal plane and Fig. 6 gives a direct comparison of images taken with both focal plane array cameras. The high quality of these frame-grabbed and digitized pictures is clearly evident. In fact, the QWIP

QWIP DETECTIVITY

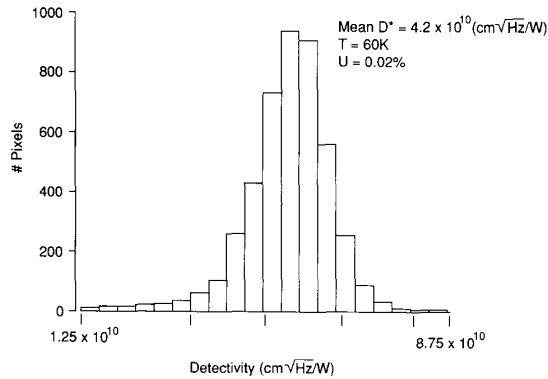


Fig. 5. The mean D^* histogram of the QWIP array at -1 V reversed bias for 1024 pixels.

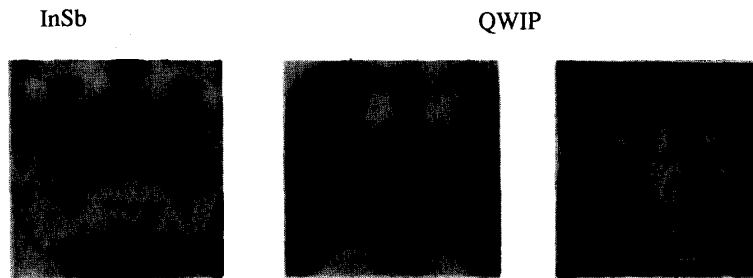


Fig. 6. Comparison of images (both digitized and frame grabbed) taken with both the InSb and QWIP cameras.

TABLE I
QWIP vs. InSb 128×128 FOCAL PLANE ARRAY

Units	QWIP	InSb
Background Temperature (K)	300	300
D^* (cm $\sqrt{\text{Hz/W}}$)	4×10^{10}	5×10^{12}
T (K)	60	60
Integration Time (ms)	8.9	9
λ_c (μm)	9.5	5
Frames/Sec	109	109
NE ΔT (mK)	< 10	10
ηg (%)	1.65	54
Residual Non-Uniformity U (%)	0.02	0.03

image is quite comparable to that from our reference InSb camera. Although the QWIP image is taken at $\lambda_c = 9.5 \mu\text{m}$ and the InSb at $\lambda_c = 5 \mu\text{m}$, the higher D^* of the InSb detector does not result in a higher quality image. In this regard we again note that the QWIP mux is not optimized for the increased signal charge [8]. It is also not a fully optimized detector array. The high quality imagery from our QWIP is further exhibited in Fig. 7 where we show the capability of the QWIP to capture fast moving targets in real time. The photos are three still frames of a commercial jet in flight. The image was captured in the corner of our RGB monitor. It becomes clearly evident, that while one must recognize the importance of detectivity

and quantum efficiency, other significant factors that govern camera performance (image quality) are good wafer uniformity, wavelength controllability, reproducibility and device yield [13]. In particular, the individual pixel uniformity is directly related to NE ΔT . If we analyze an image in the limit of no spatial noise, NE ΔT can be shown to relate to the reciprocal of the contrast signal to noise ratio. As we will discuss later in this paper, it is the excellent uniformity of the QWIP, which results in a lower post-corrected residual non-uniformity that is responsible for low NE ΔT , and good image quality.

The measured NE ΔT of the QWIP focal plane array was 10 mK at $T = 60$ K. This agrees well with our calculated value of 12 mK. We have obtained this value from

$$\text{NE}\Delta T = \frac{\sqrt{AB}}{D_B^* (dP_B/dT)} \quad (3)$$

where D_B^* is the blackbody detectivity, A is the active area, B is the bandwidth, and dP_B/dT is the derivative of the integrated blackbody power (in the spectral range of the filters and detector) and respect to temperature. The detectivity is defined as $D_B^* = R_p \sqrt{A \cdot B / i_n}$, where i_n is the detector noise current, and R_p is the peak responsivity (A/W). Our calculated estimate at $T = 60$ K of $D^* = 4.5 \times 10^{10}$ cm $\sqrt{\text{Hz/W}}$ agrees with the measured value of

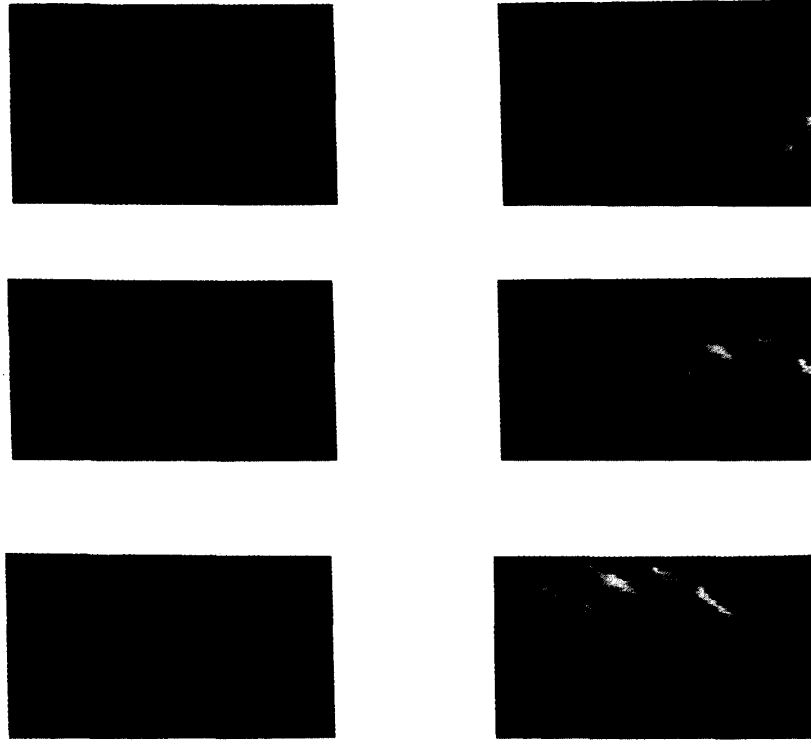


Fig. 7. Images of a passenger jet digitized and frame grabbed taken at 109 frames per second.

$4 \times 10^{10} \text{ cm } \sqrt{\text{Hz}}/\text{W}$. Operational temperatures of the present focal plane arrays were from 60°K down to 20°K .

Since the multiplexer limits the maximum charge which can be collected, it is important to discuss the various charge generation mechanisms. The total charge developed on a single pixel can be calculated by considering the total blackbody flux from the background temperature and the various optical components in the camera, such as windows, filters and any lens elements in the image plane. The total number of electrons accumulated on a pixel for one frame is given as [12]–[14]

$$N = N_d + R \int_{\lambda_1}^{\lambda_2} \eta(\lambda) [\epsilon(\lambda) L_p(\lambda) + (1 - \epsilon(\lambda)) L_b(\lambda)] d(\lambda) \quad (4)$$

where $\epsilon(\lambda)$ is the emissivity and $\eta(\lambda)$ denotes the quantum efficiency of a pixel. L is the photon radiance and the subscripts indicate the photosignal and background. The photon radiance of a target is defined as ($\text{Wm}^{-2} \text{sr}^{-1}$)

$$L(\lambda) = \frac{2c}{\lambda^4 (\exp(c_2/\lambda T) - 1)} \quad (5)$$

$c_2 = 1.439 \text{ cm K}$ and R describes the camera's optics and functional settings, and is given as

$$R = \frac{\pi A \eta_f \tau_0 t_i \cos^4 \theta \eta_c}{4 f^2} \quad (6)$$

where A is the active area of a pixel, τ_0 is the optical transmission, t_i is the integration time, η_f is the array fill factor, θ is the angular displacement from the optic axis, η_c is the cold shield efficiency and f is the f -number. The dark charge N_d with no photon flux is well below the multiplexer saturation charge at 60°K and was measured to be readout-noise-limited.

SPATIAL UNIFORMITY

The contrast signal-to-noise ratio for focal plane arrays has been described in detail and is given as [13]

$$\text{CSNR} \cong \frac{N_b}{\sqrt{N_f^2 + N_b + N_b^2 U^2}} \quad (7)$$

where N_b is the number of photogenerated carriers, N_f is the system noise, U is the nonuniformity (i.e., $N_b U$ defines the spatial noise in the image). Equation (7) can be approximated as [13]

$$\text{CSNR} \cong \frac{1.439}{T_b^2 \lambda_{\text{mean}} U} \quad (8)$$

where T_b is the background temperature, λ_{mean} is the mean spectral band-pass of the QWIP, and U is the residual nonuniformity after 2-point correction.

Nonuniformities in device photoresponsivity from pixel-to-pixel and nonuniform device dark currents across

the QWIP array, result in a spatial variation which may manifest itself as low contrast or a type of speckle pattern noise in the image. This spatial variation from device to device can be caused by factors such as growth nonuniformities, or device processing. As will be discussed below, the present initial QWIP arrays are extremely uniform ($< 10\%$).

In the usual case, individual IR detectors are operated near the background limit. In this region, the dominant detector noise is caused by statistical variations or fluctuations of the infrared background flux. It is known that, as the wavelength of operation is shifted toward a longer wavelength, 8–14 μm , most infrared imaging systems become pattern or spatially noise limited [13]. The origin of pattern noise generation in an image is due to the modulation of the incident infrared background signal by pixel-to-pixel variations in the responsivity of the focal plane array [14].

In order to achieve the highest quality image in the 8–14 μm range these nonuniformities must be either eliminated or corrected prior to post image processing and display. This is achieved using the Amber 4128 A/D control system. The A/D nonuniformity correction algorithm requires two uniform sources as a reference. Initial calibration is achieved first with a uniform cold source using the camera itself and averaging from between two and 16 frames of data and then a hot source calibration is introduced over the same range of pixels. The nonuniformity correction is performed using two point correction gain and offset on each pixel of data. The correction coefficient RAM in the primary Data acquisition unit is initialized by a UNIX based SUN 330 Sparc System, which is the control host computer via the RS-232 interface bus. All elements of the camera may be addressed directly from the Sun work station keyboard, i.e., global gain, offset, frame rate etc. Corrected data is converted to a 12-bit data format and then sent to dual 16 K $\times$ 12-bit frame buffers. While one frame buffer is writing to the corrective circuit, the other frame buffer is being read by the display circuit at the display frame rate. The 4128 output frame buffer is addressed through a 16 K $\times$ 14-bit vector table, which provides the arbitrary spatial reformatting of the QWIP's pixel data. This same vector look up table may be used to replace any given number of bad pixels. The output frame buffer also feeds the RGB video display circuitry, which consists of pseudo-color lookup tables and triple digital-to-analog converters.

The nonuniformity algorithm is based on the 2-point correction of an image I_{ij} which is achieved by multiplying the pixel gain coefficient G_{ij} by the temporal signal charge T_{ij} and subtracting a pixel offset value $\bar{O}_{ij}$ [8]

$$I_{ij} = G_{ij}T_{ij} - \bar{O}_{ij}. \quad (9)$$

The accuracy in which the calibration for the 2-point correction is performed, will directly affect image quality and contrast. After correction the measured residual nonuniformity is about 0.02%. This is evident in the images of Figs. 6 and 7 [15].

POSTVIDEO ACQUISITION

The output of the 4128 A/D system is additionally processed through a series of real time, 10 MHz digitization and display electronics with $512 \times 512 \times 8$ -bit resolution. One of 8 input analog channels can be selected through software controls via the VME bus interface and control hardware and software. Phase-locked loop techniques are used for generation of master timing signals, such as for the sync signals and the incoming composite video. This provides a reliable and ultra-stable frequency lock to incoming RS-170 signals.

Programmable analog video prefilters are incorporated for low pass filtering, and hence clearer video images. In addition a programmable variable gain of up to 10 dB is used to condition the signal further. By combining a programmable offset to adjust the dc offset of the input video signal and combining the additional effect of gain, one can convert the analog signal to a full range of 256 digital values. The offset circuitry effectively causes a "windowing" of a portion of the amplified video signal. This permits a histogram function, which expands the image contrast. Once converted to a digital signal the video signal is sent to the input lookup Tables (ILUT) which consist of eight banks of 256×8 RAM. Software commands written in C are passed to the ILUT for reading and writing applications. The ILUT outputs directly to the video bus at 10 MHz for further processing.

POST-CONTRAST ENHANCEMENT

We take an RS-170 analog IR video signal pipelined at 10 MHz and perform feature list extraction and real time histogramming. The IR image has a dot resolution based on the symbology overlay of 512×480 . The features of the image are extracted as a pair of x, y coordinates of some specified characteristic feature within the image, while the histogram operation counts the number of times each data value occurs. In this way the contrast of the IR image can be enhanced in real time as a post processed image. Histogramming can actually count up to 10^6 occurrences for each pixel's value, while the feature list extraction mode can count up to 64×10^6 possible occurrences of image characteristics.

SUMMARY

The demonstrated imagery of our new QWIP focal plane arrays are excellent with better than 99% of the pixels operating. The high uniformity of the array and large dynamic range in linearity of the individual pixels, result in a low residual nonuniformity after correction of 0.02%. Low NE Δ T of 10 mK results in good image contrast in the LWIR. For future high speed applications, the imaging system will be able to operate well above 1000 frames per second. Although this reduces the integration time, the system S/N ratio at a temperature of 60 K is limited by the readout circuit noise. At 77 K the QWIP is still able to detect an IR target, but the excess charge from the

dark current saturates the CMOS mux circuitry. A mux design capable of handling a higher input charge will significantly raise the operating temperature of the QWIP/CMOS hybrid to temperatures near $T = 80$ K. Since the QWIP structure was far from optimum (gratings, coatings, doping of the quantum wells, etc.) the technology demonstrates the promise for LWIR imaging with large two dimensional focal planes arrays. We have further shown that figures of merit other than a high detectivity for a single pixel element must be considered, in regard to imaging applications. Increasing focal plane array size even further to 256×256 mandates excellent array uniformity, control of wafer parameters over the entire area, and reproducibility for high yield at a low cost.

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