Characterization of InGaAs Linear Array For Applications to Remote Sensing

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ABSTRACT

An Indium Gallium Arsenide linear photodiode array in the 1.1-2.5 µm spectral range was characterized. The array has 1024X1 pixels with a 25 µm pitch and was manufactured by Sensors Unlimited, Inc. Characterization and analysis of the electrical and optical properties of a camera system were carried out at room temperature to obtain detector performance parameters. The signal and noise were measured while the array was uniformly illuminated at varying exposure levels. A photon transfer curve was generated by plotting noise as a function of average signal to obtain the camera gain constant. The spectral responsivity was also measured, and the quantum efficiency, read noise and full-well capacity were determined. This paper describes the characterization procedure, analyzes the experimental results, and discusses the applications of the InGaAs linear array to future earth and planetary remote sensing mission.

1. INTRODUCTION

A focal plane array (FPA) is an array of individual photodiodes connected together in either a linear or two-dimensional arrangement. Whereas a single detector measures photon flux at a single area, a focal plane array measures it from many spatial areas or pixels. The implementation of such arrays by the conventional means of adding several individual detectors together is limited because of the large amount of wires and processing electronics it requires[1]. Therefore, the concept of charge-coupled device, where several devices performing charge generation, storage and transfer are integrated into a single device, is used for FPAs to facilitate the retrieval of signals generated by each detector with minimal amount of connecting wires and bonds[2]. An array of detector permits electronic versions of optical images to be formed[3]. The basic operation of an FPA begins with the generation of charge from incoming photons. Charge carriers are generated when the energy of the incident photon is greater than the bandgap of the material[1]. The generated charge is integrated in a capacitor during an assigned integration time. A shift register then transfers the collected charges from the individual capacitors, corresponding to each pixel element, in a serial form. The collected charges are then converted into voltage signals using amplifiers and digitized using analog to digital converters (ADC)[2].

In this paper, the characterization of an InGaAs linear FPA is presented. The characterized array is a hybrid linear FPA (Sensors Unlimited Inc. 1024 LE-2.2) composed of InGaAs photodiodes and silicon CMOS readouts. It has 1024 pixel elements in a linear arrangement, with each pixel having an active area of 20x250 μm^2. The array has an operating wavelength range of 1.1 to 2.2 µm. The architecture of each pixel of the array, shown in figure 1, is referred to as a capacitive transimpedance amplifier (CTIA)[4]. This includes an InGaAs photodiode at the input of an amplifier and a feedback capacitor for integrating the photogenerated charge carriers. When the capacitor is charged during a chosen integration time, the charge is sampled at both the beginning and the end of that time. These correspond to Video 1 and Video 2 outputs as indicated in the figure. The final video output is the difference between these two outputs. The InGaAs FPA, associated with its operating electronics, are integrated in a camera setup (Sensors Unlimited Analog Linescan Camera SUI1024LE-2.2T1-0250). The operating electronics provides the timing functions necessary to operate the device and a temperature control circuitry to stabilize the FPA temperature at 20°C.

2. EXPERIMENTAL SETUP AND PROCEDURE

The InGaAs FPA is characterized to quantify its performance parameters such as gain constant, spectral response, quantum efficiency, and linearity. The experimental setup and procedure were designed to determine these parameters by measuring the signal generated by the photodiode array in response to varying radiation intensities, radiation wavelengths, and exposure times.

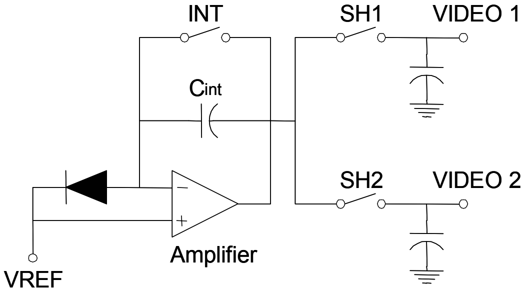

Fig. 1. Pixel Architecture for SUI 1024LE linear focal plane array[4].

Figure 2 shows the experimental setup employed for the characterization of the InGaAs FPA. The radiation source is a halogen lamp controlled by a constant current power supply. For spectral response measurements, the radiation is passed through a monochromator, which analyze the input radiation into its spectral components. A set of neutral density filters (NDF) is placed in front of the source, or the monochromator outlet, to allow variation of the intensity of the applied radiation. The radiation is then passed through a 6-inch diameter integrating sphere, providing an output with uniform intensity. The linear FPA in the camera is aligned to the integrating sphere outlet using a three-dimensional translation stage. An ADC (National Instrument PCI-6111) installed in a personal computer was used to process the FPA output signal (video output) and to convert it into a digital signal. The video signal, acquired through the ADC card, is processed with the camera's software provided by the manufacturer (Analog Linescan Camera Demo, Version 1). This software displays the voltage signal generated corresponding to a certain input, and allows control of exposure time, dynamic range, number of averages and number of samples. It also displays the voltage generated by each pixel both graphically and digitally. A save function allows writing the signal values of each pixel in a 1024 by 1 array format into a text file. The software was modified to enable saving multiple samples with only one save command. The resulting data file is a 1024 by *n* array, where *n* is the desired number of samples to be saved. It should be mentioned that the signals from the first and last 100 pixels of the FPA were not included in the data analysis. This is done to eliminate the effect of radiation non-uniformity near the integrating sphere outlet edges. Alternatively, the FPA could be placed further away from the integrating sphere outlet, which was impractical due to the intensity degradation.

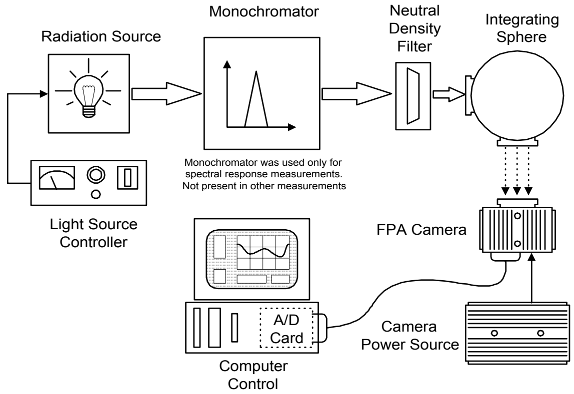

Fig. 2. General experimental setup for measurements made to the linear array.

3. DEVICE CHARACTERISTICS

The most important parameter of an FPA is the gain constant. It gives the number of generated electrons per digital number output of the ADC[2, 5]. The gain constant is obtained using the photon transfer technique, which is a study of the relation between the array noise and its mean signal. The spectral response is a measurement of the signal generated by the array per watts with respect to the wavelength of the incident light. Quantum efficiency gives the probability that a single incident photon generates a photocarrier pair that contributes to the detector current[3]. Linearity measures the relationship between the array and exposure time[2].

3.1 Photon Transfer Curve

The photon transfer curve (PTC) of an FPA is a plot of the signal noise, σ_S (in Digital Numbers, DN) with respect to the average output signal, S(DN)[2, 5]. The output signal is found by taking the average of the measured output of the illuminated pixels, after subtracting the background, whereas the noise is found by taking the standard deviation of the output. A PTC can be generated by uniformly illuminating the device at increasing radiation intensity or increasing exposure levels and by plotting the noise versus the average signal. To cover the large range of the FPA, a logarithmic scale is commonly used to plot the PTC. Figure 3 shows a typical PTC indicating the three main regions of interest (detailed discussion in ref 2 for Charge-Coupled Device). The first region is the read noise region, which is dominated by noise due to the readout circuitry of the array, signal processing, and ADC. Because read noise is independent of the signal level, the read noise dominated region produces a horizontal line on the PTC. As the signal increases, shot noise becomes dominant, as shown in the second region known as the shot noise region. Shot noise, which is characterized by a line with a slope of ½ as shown on the PTC, is due to the uncertainty in the arrival of photons as governed by Poisson's statistics[2]. The third region, known as the fixed-pattern noise region, is dominated by noise due to pixel nonuniformity due to the slight variations in the properties of each pixel. Pixel nonuniformity is primarily a result of fabrication imperfections. This region produces a characteristic slope of unity because pixel nonuniformity is proportional to signal[2, 5]. The fixed-pattern noise is normally removed using a simple mathematical technique described by Janesick[2,5] where noise is calculated from the difference of two adjacent frames. Another way of eliminating fixed pattern noise is by taking several shots or samples at each exposure level. The signal is found by averaging the signal from one pixel over the number of shots taken. The noise is found as the standard deviation of the pixel signal over the shots[6]. Thus, a PTC is generated for each pixel element of the FPA. The photodiode array reaches a saturation region, also called the full well capacity region, where the integrating capacitor becomes full with collected charge. The signal value corresponding to the maximum amount of electrons that can be collected in one pixel is defined as the full well capacity of the FPA[2].

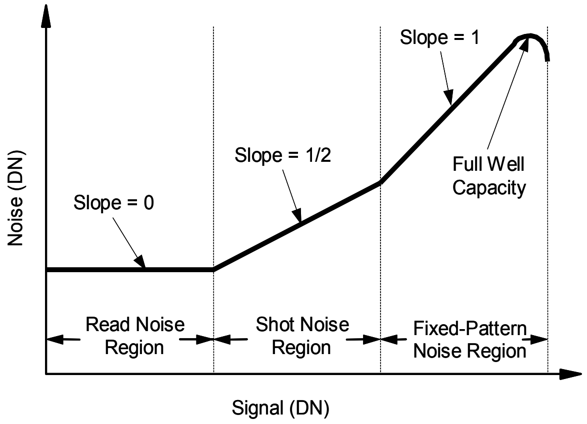

Fig. 3. Classic photon curve in logarithmic scale showing three noise regions and full well capacity[2].

For photon transfer measurements, the intensity of the applied radiation was varied by changing the neutral density filters at each exposure level. For each level, 250 shots were recorded. The number of shots was optimized to minimize the required acquisition time while maintaining reasonable accuracy. The exposure time was chosen at a typical value of 0.1012 ms, and the dynamic range of the ADC card was set to ±2V. The number of averages was set to 10, making each recorded shot equal to the average of 10 successive measurements. At each exposure level, the average output signal of each pixel was calculated by averaging the signal generated by each pixel over the 250 shots (minus the average dark signal of the pixel). The signal noise of each pixel is the standard deviation of the output signal for the 250 shots. A photon transfer curve with no fixed pattern noise was therefore generated for each pixel element of the array.

The ADC card used for the setup (NI PCI-6111) is a 12 bit bipolar multifunction I/O card. The converter produces a resolution of $4/2^{12}$ equal to 0.976 mV/DN in the ±2V voltage range setting. It was observed, however, that this resolution is insufficient because the noise being measured is less than 1 LSB. The ADC card produces a dither signal, which is approximately 0.5 LSB of white Gaussian noise added to the signal to be converted. The dither is inherent with the ADC card and could not be removed. Therefore, it contribute to the read noise of the FPA. The PTC generated by the array is shown in figure 4. This PTC has no fixed pattern noise because the average signal and noise were calculated per pixel over the 250 shots. The read noise region is observed up to about 500 DN signal level and the slope begins to increase until the maximum signal corresponding to +2V is reached.

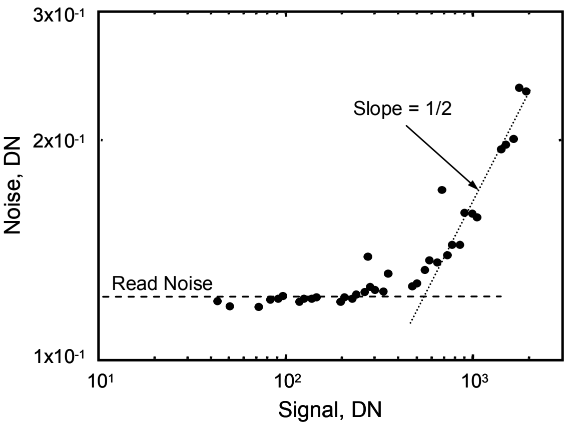

Fig. 4. Photon transfer curve for each pixel of SUI 1024LE.

3.2 Gain Constant, K

One of the parameters that can be derived from the PTC is the gain constant, K. The gain, with units of e^-/DN, is a conversion factor, which allows conversion of the measured signal level from units of digital numbers (DN) to absolute units of electrons (e^-). This factor also converts such parameters as read noise, full-well capacity and linearity from units involving DN into units involving e^-. The total noise, σ, of the system is given by the relation[2,5]

$$\sigma^2(e^-) = \sigma_R^2(e^-) + \sigma_S^2(e^-) + \sigma_F^2(e^-)\,, \tag{1}$$

where σ_R is the read noise, σ_S, is the shot noise, and σ_F is the fixed pattern noise, all expressed in number of electrons. The fixed pattern noise is eliminated by measuring noise and average signal of each pixel over several shots or frames. Moreover, photon noise obey the laws of Poissonian statistics, which means that the uncertainty in the amount of charge collected in a pixel (noise) is proportional to the square root of the number of incident photons or $\sigma_s^2 = S$, where S is the FPA signal[2, 5]. Converting all the terms of equation 1 from number of electrons into DN, by multiplying by K, and replacing the shot noise term with the signal expression we get

$$K^2\sigma^2(DN) = K^2\sigma_R^2(DN) + KS(DN)\,, \tag{2}$$

where σ^2, σ_R^2, and S are now in DN. It should be noted that this transformation is important since it is easier to handle the accessible digital data, rather than the number of electrons internally generated with in the FPA.

Now, dividing both sides of equation 2 by K, we get

$$\sigma^2(DN) = \sigma_R^2(DN) + \frac{1}{K}S(DN)\,, \tag{3}$$

For the shot noise limited region of the PTC, the read noise is negligible, simplifying equation 3 by eliminating the first term[2]. A graphical method for determining the gain constant known as the photon transfer method can be used if shot noise limited data is available[2,5]. When this method was applied to this device, it was found that read noise is not negligible even up to the saturation of the photodiode array. When read noise is not negligible, an alternate method using minimization of mean square error can be used to determine the value of K[7]. In this method equation 3 is converted into a linear relation with variables Y and X, slope of 1/K, and a y-intercept of L by making the substitutions

$$\sigma_i^2 = Y_i\,, \quad S_i = X_i\,, \ \text{ and } \sigma_{R,i}^2 = L, \tag{4}$$

where σ_i^2 is the dependent variable Y_i, S_i is the independent variable X_i, and $\sigma_{R,i}^2$ is the y-intercept L, and $i = 1,\ldots, M$ where M is the number of measured noise and signal pairs at varying exposure levels. Substituting equations 4 into 3 we obtain the M line equations

$$Y_i = (1/K) * X_i + L, \tag{5}$$

By minimization of mean square error of equation 5[7]

$$J(K,L) = \sum_{i=1}^{M} [Y_i - (1/K) * X_i - L]^2, \tag{6}$$

the values of K and L can be determined. By setting $\partial J/\partial K = 0$ and $\partial J/\partial L = 0$, the estimated values are obtained as[7]

$$(1/K) = \frac{MF - XY}{MG - X^2}\,, \ \text{ and } \ L = \frac{GY - XF}{MG - X^2} \tag{7}$$

with the quantities X, Y, F and G given by

$$X = \sum_{i=1}^{M} X_i \qquad Y = \sum_{i=1}^{M} Y_i$$

$$F = \sum_{i=1}^{M} X_i Y_i \qquad G = \sum_{i=1}^{M} X_i^2\ . \tag{8}$$

The gain constant was determined for each pixel element of the array. To analyze the accuracy of the gain constant, the K values for all the pixels were plotted in a histogram. 824 different K-values from pixel numbers 101 to 924 were used to generate the histogram as shown in figure 5, with 5000 e^-/DN bin size. The resulted distribution of the K values follow a normal distribution, therefore a Gaussian fitting was applied to the data as indicated in the same figure. The resulting normal curve has a mean of 52402 e^-/DN and a standard deviation of 6203 e^-/DN. Table 1 gives the values of the FPA parameters found from the PTC, including the read noise and full well capacity, which were converted into absolute units of electrons using the mean of the obtained gain constant.

Table 1. Summary of obtained FPA parameters.

FPA Parameter	**Value**
Gain constant, K	52402 ± 6203 e^-/DN
Read noise, σ_R	0.1211 DN (6346 e^-)
Full well capacity	2433 DN (127.49 x 10^6 e^-)

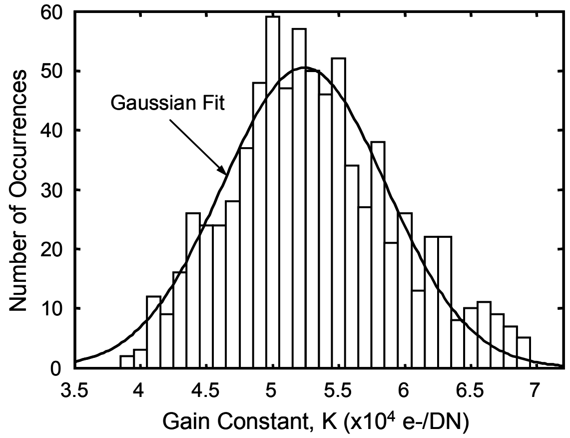

Fig. 5. Histogram of the K value of SUI 1024LE.

3.3 Spectral Response

The responsivity, $\Re_{array}$, of the photodiode array in V/W can be found using the equation[2]

$$\Re_{array} = \frac{S}{P} = \frac{S}{I_n A_{array}}, \tag{9}$$

where S is the average signal output per pixel of the array in volts, and P is input optical power in watts. The power can also be expressed as the product of intensity of the applied radiation $I_{n,}$ in watts/m^2 and the active area, A_{array}, of a pixel in m^2, resulting to an alternative equation for $\Re_{array}$. The intensity was found using a calibrated reference detector (Hamamatsu G5853-01). By placing the detector at the same location of the photodiode array in the setup and recording the signal output of the detector at each wavelength setting, the intensity was calculated using the responsivity versus wavelength data of the reference detector. The spectral response was measured by illuminating the photodiode array with varying wavelengths of radiation using a monochromator. The wavelength of the applied signal was from 1000 nm to 2400nm in 40 nm increments. The spectral response of the array is shown in figure 6. The maximum responsivity is reached around 1.8-2.1 μm corresponding to the InGaAs bandgap energy. Lower responsivity at shorter wavelengths is due to the domination of the surface recombination effects. At longer wavelengths, the responsivity is limited by the falling edge of the InGaAs absorption coefficient. The quantum efficiency, QE, of a linear array as a function of wavelength is given by the equation[2]

$$QE(\lambda)_{array} = \frac{A_{diode} S_{array} QE_{diode}}{A_{pixel} S_{diode}}, \tag{10}$$

where A_{diode} is the active area of the diode in m^2, S_{array} is the average signal generated by the array, QE_{diode} is the quantum efficiency of the reference diode supplied by the manufacturer, A_{pixel} is the active area of each pixel of the array in m^2, and S_{diode} is the signal generated by the reference detector. By expressing the variable with known quantities, the quantum efficiency can also be expressed as

$$QE(\lambda)_{array} = \frac{12390 q S(DN) K}{A_{pixel} t_{\exp} I_n \lambda}, \tag{11}$$

where q is the electron charge in Coulombs, t_{exp} is the exposure time in seconds and λ is the wavelength of the input radiation (Å). The quantum efficiency of the photodiode array was calculated using equation 11 and shown in figure 7.

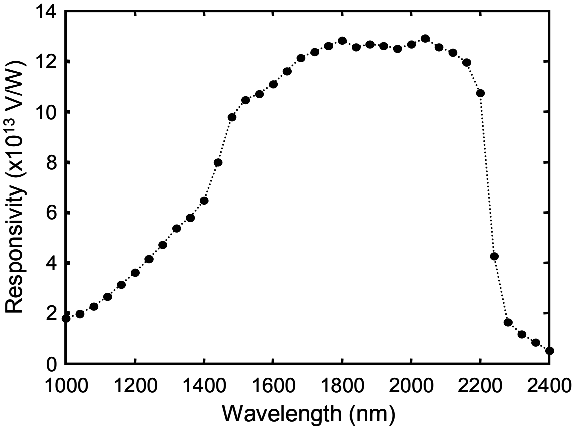

Fig. 6. Spectral response of SUI 1024LE.

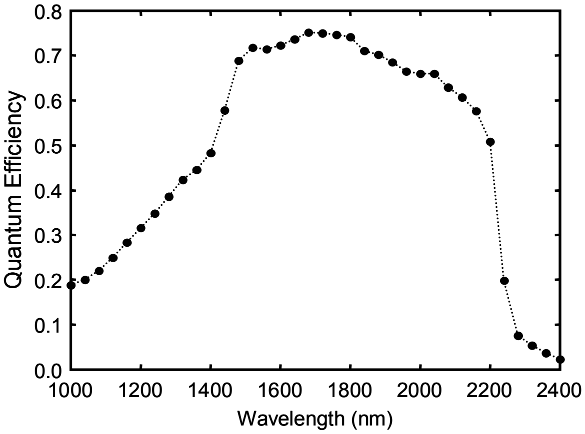

Fig. 7. Quantum efficiency of SUI 1024LE.

3.4 Linearity

Linearity of an FPA gives its ability to produce an output signal in proportion to the charge contained in the pixel[5]. It was measured by generating a linearity curve, which is a plot of the signal, S(DN), as a function of exposure time, t_{exp}. A straight line curve with a slope of unity indicates good linearity, which implies that the FPA output signal is proportional to exposure time[2]. The linearity of the photodiode array was measured by taking 2 sets of measurements. In the first set of measurements, the camera was covered with the lens cap to prevent light from entering the detector area. The exposure time was varied and 100 shots were taken for each exposure time. This data was used as a dark reference signal. For the second set of data, the detector array was exposed to a uniform white radiation source. The intensity of the source was chosen so that the array can saturate at higher exposure time (around tens of milliseconds), and kept constant for all measurements. The exposure time was varied and 100 shots were also taken each time. The average signal of the array for each exposure time was found by subtracting the average dark signal from the average exposed signal. The resulting signal in DN is plotted against exposure time as the linearity transfer curve in figure 8.

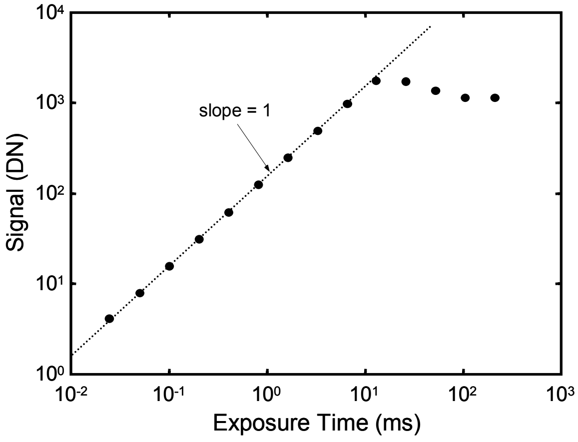

Fig. 8. Linearity transfer curve

4. SUMMARY AND CONCLUSION

Characterization was carried out for InGaAs focal plane array. We have measured the spectral response and calculated quantum efficiency in the 1.0 to 2.2 μm wavelength range. Photon transfer curve was generated for this InGaAs FPA. It was observed that read noise is dominant up to saturation, and the conventional photon transfer method could not be employed to find the gain constant of the FPA. An alternate method could determine the gain constant even when read noise is not negligible. It was found that the pixel has a relatively large full well capacity, which can be suitable for applications to higher dynamic range. Further measurements are underway to better understand the device properties for future applications to earth science and planetary mission.

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