Modeling and test of pixel cross-talk in HgCdTe focal plane arrays

Thomas J. Sanders
E. Lee Caraway
Glenn T. Hess
Gwendolyn W. Newsome
Theodore Fischer

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Thomas J. Sanders and E. Lee Caraway
Florida Institute of Technology, 150 W. University Blvd., Melbourne, FL 32901
tsanders@ee.fit.edu

Glenn T. Hess
AET Inc., 1900 S. Harbor City Blvd. Suite 115, Melbourne, FL 32901

Gwendolyn Newsome and Theodore Fischer
US Army, CECOM-NVESD, 10221 Burbeck Rd, Ft. Belvoir, Virginia, 22060

Abstract

Mercury Cadmium Telluride focal plane arrays with well over 1000 pixels have been fabricated for a number of years. These FPA's have been built as large two-dimensional arrays of HgCdTe p-n junction diodes on a single CdTe or CdZnTe substrate. Sensitivity of each pixel to impinging radiation is one of the most important quality factors for these devices. However, material parameters, which give diode high sensitivity, are the same as those that cause cross talk between adjacent diodes in the array. This cross talk causes a blurred image and in general is a detrimental factor for the FPA system.

The cross talk modeling is done in a two-dimensional simulation format to achieve high accuracy. In addition, the output information can be generated as a statistical function of the material and design parameter variations. Actual heterojunction FPA devices have been fabricated and tested for cross talk. In the paper, this data is compared to the simulation results. This design method and its algorithms are encapsulated in a software program called IRSIM. This physics-based simulator allows the engineer to use versatile geometries and material concentrations.

KEY WORDS: Cross talk, FPA design, modeling, system design, optimized performance, STADIUM

Introduction

Compound Semiconductor devices have been used for many years for the focal plane array (FPA) detection of infrared radiation but few adequate computer models exist. FPA detectors are semiconductor devices that detect long wave photons (1 to 20 microns) by interaction of the radiation with the atomic lattice of the material creating hole-electron pairs. The 1 micron wavelength region of the radiation spectrum is called the Short Wavelength Infrared (SWIR) region while the 20 microns region is called the Very Long Wavelength Infrared (VLWIR) region. Thus, 1 to 20 microns is referred to as the SWIR-VLWIR region. We have developed a robust simulation methodology to predict the results of these devices [1,2].

AET has employed advanced statistical techniques to improve the understanding of the FPA detector model developed in this program. Specifically, we utilize the statistical technique known as design of experiments (DoE) [3]. This technique is embodied in a software technology called STADIUM which has been developed by Florida Institute of Technology under funding from SEMATECH. The use of STADIUM leads to a comprehensive understanding of the relationship between the input parameters and the output of the detector. This is called "design for manufacturing." In addition, the statistical design of experiments methodology leads to fabrication process optimization through the use of Taguchi techniques.

The following sections begin with a discussion of modeling methodologies used in this project. AET has used MCT device physics analysis in modeling the performance of double layer heterojunction MCT devices. Traditional semiconductor device physics are coupled with a variety of material models to accurately simulate the electrical characteristics of devices. AET used this approach as a basis in developing an overall model. Actual heterojunction FPA devices have been fabricated and tested for cross talk, and this data is compared to the simulation results.

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Device Description

The material normally used for the IRFPA is a HgCdTe (Mercury-Cadmium-Telluride or MCT) compound semiconductor, which has the proper composition to detect the radiation of interest. In order to detect the long wave radiation, the semiconductor must have a very narrow forbidden bandgap. This narrow bandgap causes a significant problem in that a large number of intrinsic hole-electron pairs are thermally generated when the device is operated at room temperature. To overcome this problem, the FPA detector device is normally operated at temperatures as low as 77°K .

To model the cross talk of the focal plane array, we must examine the two dimensional array of diodes that make up the imaging device. This two dimensional array is illustrated in Figure 1.

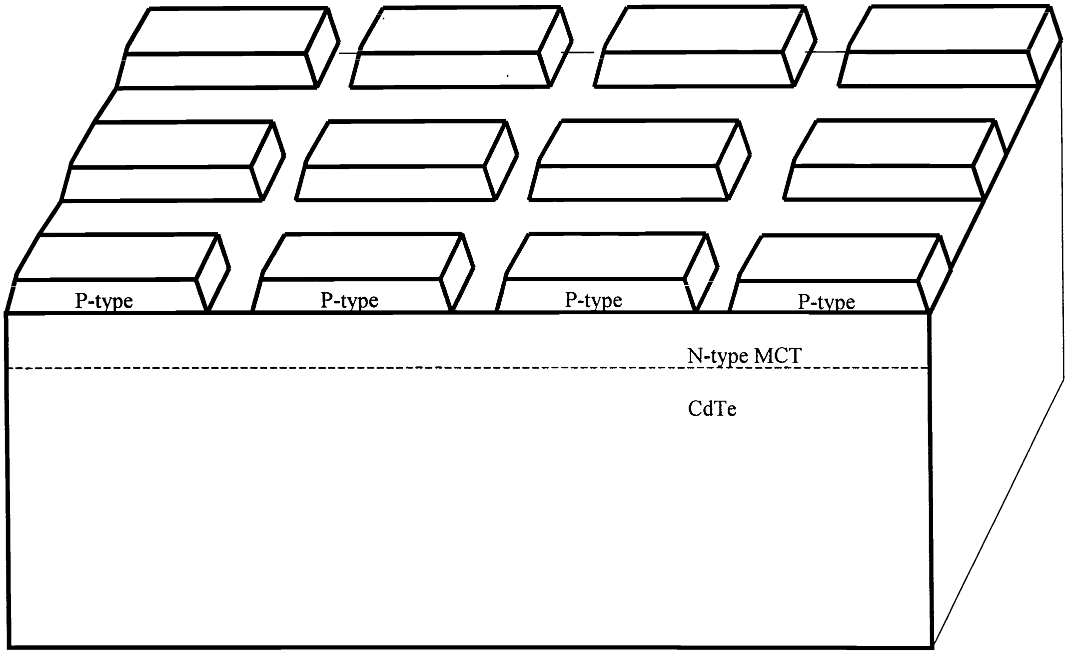

Figure 1. Structure of the MCT Focal Plane Array

In these narrow bandgap semiconductors, a problem arises when the thermally generated current becomes comparable to the photogenerated current. To solve this problem, one can use a double layer heterojunction. Such devices are built with a wide bandgap semiconductor on top of a narrow bandgap semiconductor. Figure 2 shows the band structure of such a device. With the highly doped p material at the surface, this device makes contacting the diode with interconnect material very easy.

HgCdTe has a energy band gap that varies from -0.3 to 1.6 eV, depending on its composition and temperature. The bandgap can be controlled by adjusting the proportion of HgTe and CdTe. Various empirical expressions for the bandgap energy have been developed which depend on composition mole fraction of Cd (*x*). Other physical material parameters such as electron affinity, carrier diffusion constant, and carrier mobility are also functions of composition.

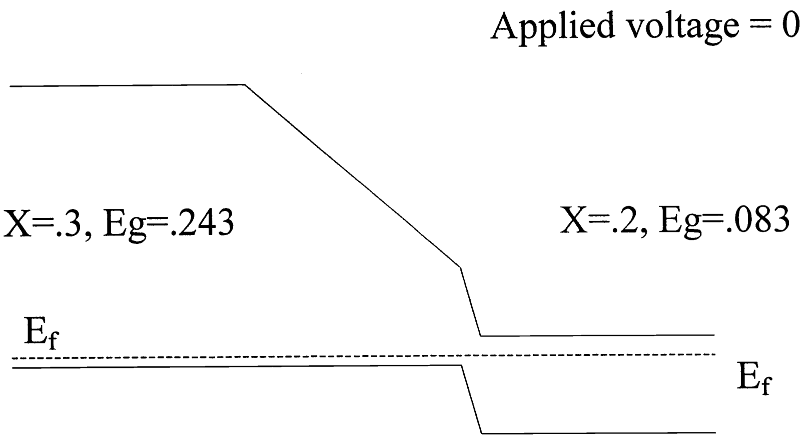

Figure 2. Heterojunction energy band diagram for the p-n junction.

MCT Model Development

The object of this new MCT model is to provide the engineer an improved development capability for HgCdTe Focal Plane Array process, operation and performance. This model can be used for simulation of the design and manufacture of commercial infrared detectors and can be used with existing FLIR models to create a comprehensive simulation of an entire night vision system. One of the primary objectives of this model is to identify critical heterojunction fabrication steps and processes. The model developed generates a mathematical representation of the processes and devices necessary to fully simulate the operation and performance of an HgCdTe detector and an FPA in the 1 - 20 microns region. A cross-section of the HgCdTe device is shown in Figure 3.

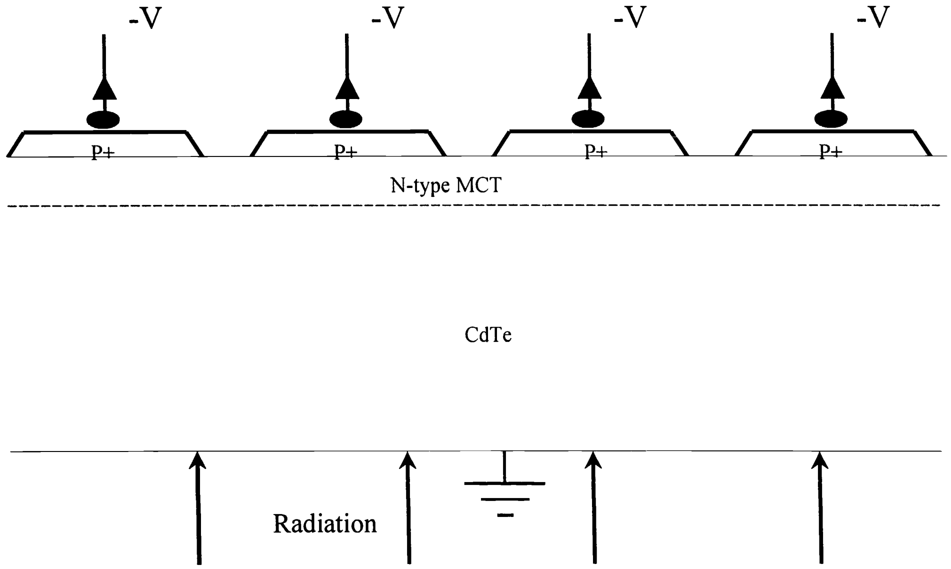

Figure 3. Cross-section of the HgCdTe heterojunction device.

To derive the output parameters of the MCT detector device, we solve the well known continuity equation [4].

$$\frac{\partial n}{\partial t} - \frac{1}{q}\nabla J = G(n) - U(n) \tag{1}$$

Poisson's equation [5] is also solved in all regions of the device .

$$\nabla^2 V = -\frac{1}{\varepsilon_0}\delta\rho \tag{2}$$

For a semiconductor device, the Poisson equation in one dimension in the depletion region of the p-n junction is approximated as follows [5].

$$\frac{dE}{dz} = \frac{q}{\varepsilon_0 \varepsilon(z)}\left[p - n + N_D^+ - N_A^-\right] \tag{3}$$

The first step in the modeling of the MCT device is to break up the device into many points. This will assure that all the material parameters that vary as a function of distance through the device will be calculated at each point and thus produce smooth and accurate curves. The device is broken up into regions or grid points where material parameters can vary and device calculations can be performed.

After the grid is determined, the material parameters can be assigned for each point on the grid. These parameters include the Cd concentration, impurity doping and other parameters such as carrier mobility and lifetime. The dielectric constant is calculated at each point through the device from the following [6],

$$\varepsilon = 20.5 - 15.5x + 5.7x^2 \tag{4}$$

where x is the Cd concentration at each point through the device.

The band gap is calculated at each point through the device from the following [7],

$$E_g = -0.302 + 1.93x + (5.35x10^{-4})T(1 - 2x) - 0.810x^2 + 0.832x^3 \tag{5}$$

where x is the Cd concentration at each point through the device and T is the temperature.

The material's intrinsic carrier concentration throughout the device is calculated from [6],

$$n_i = \left[5.585 - 3.820x + 1.753x10^{-3}T - 1.364x10^{-3}Tx\right]\left[1x10^{14} E_g^{0.75} T^{1.5}\right] e^{-E_g/2kT} \tag{6}$$

where x is the Cd concentration at each point through the device, E_g is the band gap at each point through the device, and T is the temperature.

The MCT device current is calculated by integrating the one dimensional steady state continuity equation. The integration is performed over the entire device length ($z=0$ to $z=z_4$). This can be written as [4],

$$I = qA \int_{0}^{z4} [U - G]dz \tag{7}$$

where U is the recombination rate and G is the generation rate.

We have also developed models for the quantum efficiency and absorption coefficient of radiation for this device. The quantum efficiency [8] is given by equation 8.

$$\begin{aligned} &\eta = \eta_0 && \text{for} \quad \lambda < \lambda_p \\ &\eta = \eta_0 \sqrt{1 + \frac{3}{4}\left(\frac{\lambda - \lambda_p}{\lambda_g - \lambda_p}\right)^2} && \text{for} \quad \lambda_p < \lambda < \lambda_{test} \\ &\eta = 0 && \text{for} \quad \lambda_{test} < \lambda \end{aligned} \tag{8}$$

The absorption coefficient [9] is given by equation 9.

$$\begin{aligned} &\alpha = 0 && \text{for} \quad \lambda_g < \lambda \\ &\alpha = \frac{(2c)^{1/2}}{\tau_r}\left(\frac{m_r \lambda}{h}\right)^{3/2}\left(1 - \frac{\lambda}{\lambda_g}\right)^{1/2} && \text{for} \quad \lambda < \lambda_g \end{aligned} \tag{9}$$

Carrier generation [9] is due to the incident light. We assume that all the light passes through the CdTe region. This generation component is determined by the set of equations shown below.

$$G(z) = \frac{\eta(1-r)\lambda}{hc} \cdot \frac{P}{A} \cdot \alpha e^{-\alpha(z3 - z)}$$

and (10)

$$G = G(z) e^{\left(\frac{z - zd1}{Lp}\right)} \qquad \text{For } z < z_{d1}$$

$$G = G(z) e^{\left(\frac{zd2 - z}{Ln}\right)} \qquad \text{For } z_{d2} < z < z_3$$

Depending on which region of the device we are in, we calculate the carrier recombination rate for p+/n diodes as shown in equations 11.

$$\text{For } z_{d2} < z < z_3 \qquad p_{n0} = \frac{n_i^2}{N_2} \qquad D_p = \frac{kT}{q}\mu_p \qquad L_p = \sqrt{D_p \tau_p} \tag{11}$$

$$U = \frac{p_{n0}}{\tau_p}\left(e^{qV/kT} - 1\right)e^{\frac{z_{d2}-z}{L_p}}$$

Cross Talk Experiments and Modeling

To model the cross talk of the focal plane array, we must examine the two-dimensional array of diodes that make up the imaging device. This two-dimensional array used for the modeling is illustrated in Figure 1.

MCT focal plane arrays were tested at 77K in the laboratories of Florida Institute of Technology and the results are shown in Figure 5. Here we see the relative response to laser radiation of three MCT diodes as the laser is swept across the array. The focal plane array used for this experiment consists of diodes that are 200 microns square with a separation between diodes of 50 microns. Diodes 1 and 2 have two diodes between them and diodes 2 and 3 have two diodes between them. All three diodes (1,2and 3) are in a straight line. Note that the diodes response increases as the laser beams moves right.

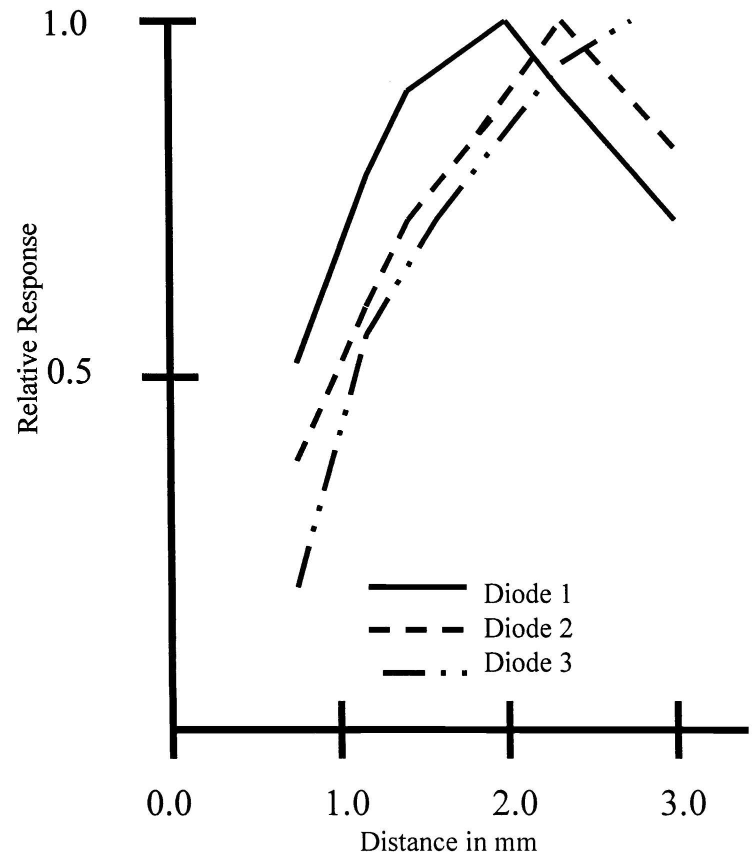

Figure 4. Relative response of three MCT diodes in a focal plane array as the laser beam moves left to right.

In the theoretical part of this work, we attempted to predict the focal plane response to the experimental conditions of the laser beam sweeping across the array. This was a difficult task because we did not have exact knowledge about the size and shape of the laser beam. We modeled the beam as a spot of diameter of 1.5 mm. Using this model for the laser radiation and the two dimensional model for the MCT diodes, we achieved the predicted the relative response for the three diodes as shown in Figure 5.

In the theoretical work, we were able to achieve the approximate shape of the relative response for the three diodes. The placement of the response in space is not exactly correct, but we attribute this to our lack of knowledge about the laser beam shape and size. Overall, we believe that our models do a good job of predicting the relative response of the experimental devices.

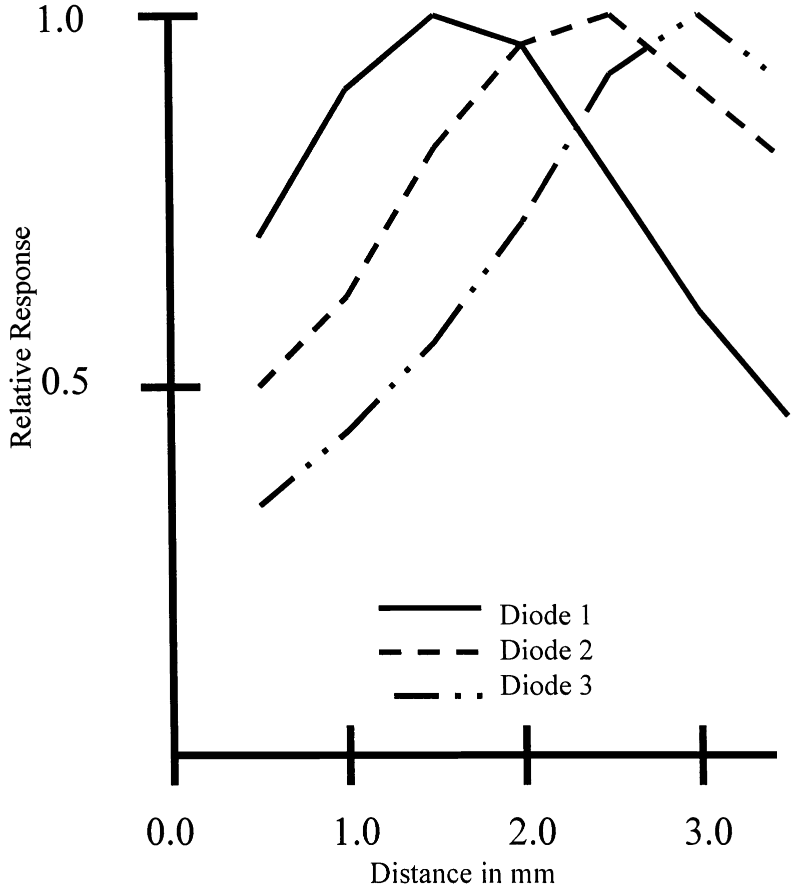

Figure 5. Predicted response of three MCT diodes in a focal plane array as the laser beam moves left to right.

The next step in the investigation was to predict the cross talk that would be expected between adjacent diodes in a focal plane array. To derive the cross talk, we used a model for the focal plane array under radiation as shown in Figure 6. Here we see that only the diode on the left side of the figure is illuminated with the radiation, while the remaining three diodes in the picture are not illuminated. We then define the cross talk between two diodes as the ratio of the photocurrent of the diode not illuminated divided by the photocurrent of the diode that is illuminated. This can be expressed as:

$$\text{Cross Talk of diode } 2 = I_2 / I_1$$

Cross talk = I_n / I_1

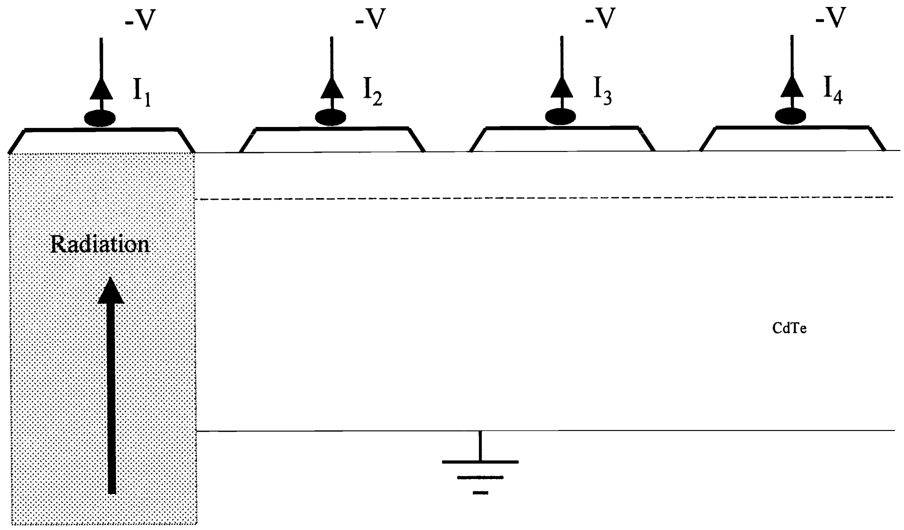

Figure 6. Model used for the focal plane array cross talk calculations.

The results of these cross talk calculations are shown in Table 1. The predicted cross talk of nearest neighbors by our analysis should be about 0.34. That is, about one third of the current that flows through the diode that is illuminated would flow through a nearest neighbor diode that is not illuminated. This would cause a blur effect in the output of the focal plane array. Of course as we move further away from the radiation, we would expect to see the cross talk diminish as is illustrated in Table 1.

Table 1. Cross talk simulation results

Cross talk node	**Current ratio**	**Cross talk value**
Node 2	I_2/I_1	0.34
Node 3	I_3/I_1	0.10
Node 4	I_4/I_1	0.03

4. CONCLUSIONS

This paper has described the new heterojunction MCT model methodology developed by AET, Inc. and Florida Institute of Technology for the US Army under an SBIR contract. This methodology uses basic physics to model this complex device. Initial results of the comparison of the simulation output with experimental data is very encouraging. The new MCT cross talk model is being used in conjunction with the AET IRSIM software to allow the engineer to accurately predict the photocurrent response for the focal plane array.

To improve the manufacturability and cost metrics associated with the focal plane array, AET has employed advanced statistical techniques to improve the FPA detector model developed in this program. Specifically, we utilize the statistical technique known as design of experiments (DoE). This technique is embodied in a software technology called STADIUM, which has been developed by Florida Institute of Technology under funding from SEMATECH. The use of STADIUM leads to a comprehensive understanding of the relationship between the input parameters and the output of the detector. This is called "design for manufacturing." In addition, the statistical design of experiments methodology leads to fabrication process optimization through the use of Taguchi techniques.

Acknowledgments

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