Simulation of HgCdTe Double Layer Heterojunction Detector Devices

Glenn T. Hess[1], Thomas J. Sanders[2], Gwendolyn Newsome[3], and Theodore Fischer [4]

[1]AET Inc., 1900 S. Harbor City Blvd. Suite 115, Melbourne, FL 32901, (321) 727-0328 ext. 13,
ghess@aet-usa.com

[2]Florida Institute of Technology, 150 W. University Blvd., Melbourne, FL 32901(321) 768-8769,
tsanders@ee.fit.edu

[3]CECOM-NVESD,10221 Burbeck Rd, Ft. Belvoir, Virginia 22060, (703)-704-3877,
gnewsome@nvl.army.mil

[4]Army Research Lab, 2800 Powder Mill Rd, Adelphi, Maryland, (301) 394-4160,
tfischer@mail.arl.army.mil

ABSTRACT

Mercury-Cadmium-Telluride (HgCdTe) diodes are used as detectors of long wavelength photons by interaction of the infrared radiation with the atomic lattice of the material, creating hole-electron pairs and subsequent photocurrents. Models for these physical phenomena have been created and used to structure a new simulator for the HgCdTe device. Statistical simulation methods are being employed to implement optimization of the detector. Finally, data on specially built HgCdTe diodes has been compared with theoretical expectations derived from the HgCdTe detector simulator.

Keywords: Statistical simulation, HgCdTe detector, focal plane array, semiconductor modeling, infrared radiation.

1 INTRODUCTION

Compound semiconductor devices have been used for many years for the detection of infrared radiation but few adequate computer simulation models exist [1]. Focal plane array (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. This infrared radiation is called the SWIR-VLWIR region.

The material normally used for the FPA is HgCdTe (Mercury-Cadmium-Telluride, which is sometimes called MCT) compound semiconductor, because it has the proper band gap 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 [2].

HgCdTe has a bandgap 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 the mole fraction of Cd in the composite material. Other physical material parameters such as electron affinity, carrier diffusion constant, and carrier mobility are also of functions of composition.

2 DETECTOR MODELS

The object of this new MCT model is to provide for the engineer an improved simulation capability for HgCdTe focal plane array process, operation and performance. This model can be used for simulation and the design of commercial infrared detectors and can be used with existing FLIR (forward looking infrared) 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 processing requirements. The model generates a mathematical representation of the processes and device requirements necessary to fully simulate the operation and performance of a HgCdTe detector in the SWIR-VLWIR region. A cross-section of the HgCdTe model is shown in Figure 1.

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 $z = z_4$), as illustrated in Figure 1. This current can be calculated [3] as shown in equation 1.

$$I = qA \int_{0}^{z4} [U - G] dz \qquad (1)$$

Where U is the recombination rate and G is the generation rate. These parameters are functions of the detector design as well as the radiation on the detector and other factors. In the n-type HgCdTe material, U and G can be derived as given in equations 2 and 3.

$$U(z)=\frac{p_{n0}}{t}\left[e^{qV/kT}-1\right]e^{-z/L} \tag{2}$$

and

$$G(z)=\frac{\eta(1-r)\lambda}{hc}\cdot\frac{P}{A}\cdot\alpha\, e^{-\alpha\left(z3-z\right)} \tag{3}$$

Where p is the hole density, t is minority carrier lifetime, V is the applied voltage, z is the distance variable into the device, L is diffusion length, η is the quantum efficiency, λ is the wavelength of the radiation, P is the power of the radiation, A is the detector area, and α is the absorption coefficient.

The absorption coefficient is given by the expression in equation 4.

$$\alpha=\frac{\sqrt{2c}}{t}\sqrt{\left[1-\frac{\lambda}{\lambda_g}\right]\sqrt[3]{\frac{m\lambda}{h}}} \tag{4}$$

Where λ_g is the cutoff wavelength for the device. The cutoff wavelength is equal to Planck's constant (h) times the speed of light, divided by the value of the forbidden energy band gap of the semiconductor material. The band gap is calculated at each point in the device [4] by equation 5.

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

Where x is the Cd concentration at each point through the device

These models and many others were derived for the HgCdTe detector device and were incorporated into the simulator discussed in the next section.

3 DETECTOR SIMULATION

The theoretical models developed for this program have been incorporated in a simulator called IR-SIM. This simulator is very user friendly, such that a novice in computer simulation can easily operate it and get valid simulation results.

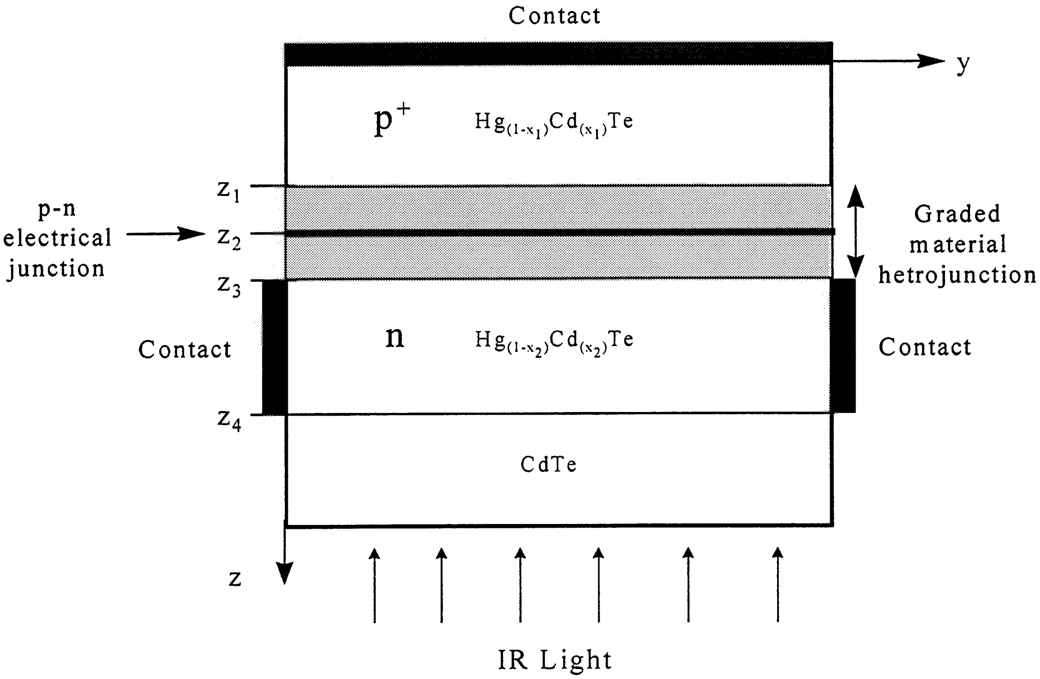
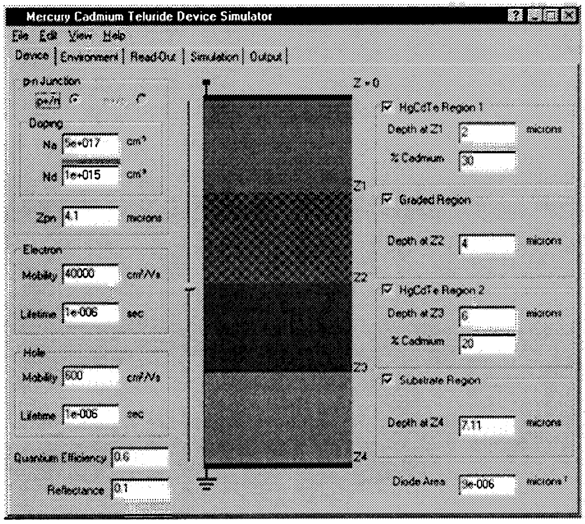


Figure 1: Cross-section of the HgCdTe heterojunction device

The first step in the developing the simulator of the MCT device is to divide the area of the structure into many smaller areas. This is referred to the "simulation grid". This will assure that all the material parameters that vary as a function of distance through the device will be calculated in each small area and thus produce accurate results. The device is further divided into regions of different Cd concentrations so that the proper physical models can be utilized in the device simulation.

This concept is illustrated in Figure 2, where the initial window of the IR-SIM software is presented. In this window, the user can specify a number of material and device geometry parameters. These include thickness of each of the HgCdTe regions, doping concentrations of both sides of the junction, carrier mobility, carrier lifetime, quantum efficiency, surface reflectance, and detector area.



p-n Junction: p+/n ●

Doping
Na 5e+017 cm^3
Nd 1e+015 cm^3

Zpn 4.1 microns

Electron
Mobility 40000 cm^2/Vs
Lifetime 1e-006 sec

Hole
Mobility 600 cm^2/Vs
Lifetime 1e-006 sec

Quantum Efficiency 0.6
Reflectance 0.1

☑ HgCdTe Region 1
Depth at Z1 2 microns
% Cadmium 30

☑ Graded Region
Depth at Z2 4 microns

☑ HgCdTe Region 2
Depth at Z3 6 microns
% Cadmium 20

☑ Substrate Region
Depth at Z4 7.11 microns

Diode Area 9e-006 microns^2

Figure 2. Initial window of IR-SIM.

The simulation control window of IR-SIM is shown in Figure 3. In this window, the type of simulation, including design of experiments (see section 4) can be controlled.

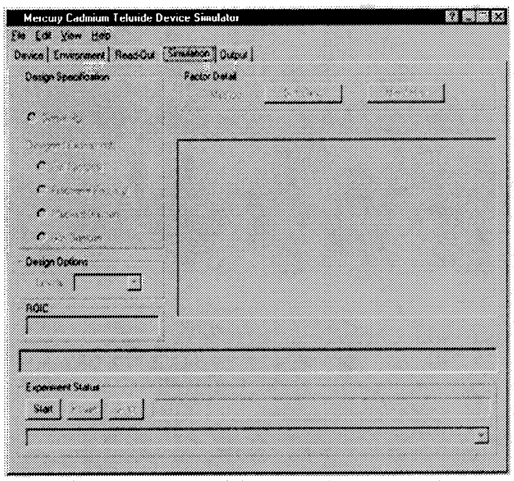


Figure 3. Simulation control window of IR-SIM.

4 STATISTICAL MODELING

We have employed advanced statistical techniques to improve the understanding of the MCT detector model developed in this program. Specifically, we utilize the statistical technique known as design of experiments (DoE), which is embodied in a software technology called STADIUM [5, 6, and 7].

In the STADIUM environment, a carefully planned approach to conduct a designed experiment results in valid answers to statistical questions while maintaining a low cost for the experiment (i.e., number of simulation runs). The DoE methodology has long been used in manufacturing process development as a systematic way of optimizing a process while minimizing the number of replications needed to achieve that optimization. STADIUM implements this design of experiments methodology in an easy to use computer program, which is incorporated into the IR-SIM software.

This DoE methodology supports a number of advantages not available with other statistical techniques, such as Monte Carlo where a much larger number of simulations are needed and less information is obtained. The system input includes variations from both the process being analyzed and its environment. These variations form part of the input deck to the simulator and using design of experiments, the simulator is run a multiple number of times with the variables automatically set to their appropriate levels. After the simulations are run, the STADIUM program extracts the specified results from each simulation run. Following this, STADIUM creates a regression model for each output characteristic. This regression model is a mathematical relationship that relates the output characteristic as a function of the input parameters. From this model, it is possible to estimate the mean and standard deviation as well as other statistical information.

5 EXPERIMENTAL RESULTS

To validate the simulation models, AET had fabricated heterojunction HgCdTe focal plane array devices with various cutoff wavelengths. These devices were tested for a variety of parameters including current-voltage characteristics, spectral responsivity, and capacitance-voltage characteristics.

As shown in Figures 4, 5 and 6, there is very good agreement between the simulation results and experimental data. The first of these figures shows the relative responsivity of a graded heterojunction for a detector with a cutoff wavelength of about 10 microns. The responsivity of the detector is the output current divided by the input optical power to the device. The typical curve of responsivity versus wavelength increases with wavelength until the cutoff wavelength is reached. At this point, the responsivity rapidly falls to zero because the energy of the input optical power is less that the material band gap.

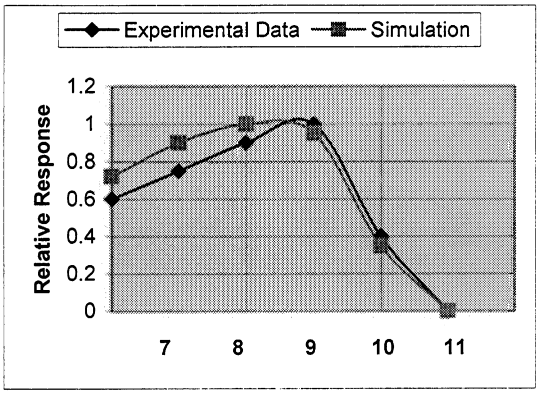


Figure 4. Relative responsivity for the HgCdTe detector with cutoff wavelength of about 10 microns.

Figure 5 presents the I-V Characteristic of for the HgCdTe detector with cutoff wavelength of about 10 microns. Again good agreement is achieved between the simulation and the experiment.

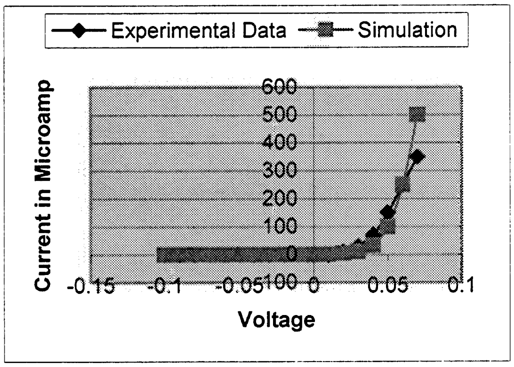


Figure 5. The I-V Characteristic of for the HgCdTe detector with cutoff wavelength of about 10 microns.

Figure 6 presents relative responsvity with a cutoff wavelength of about 4 microns with good agreement between the simulation and the experiment.

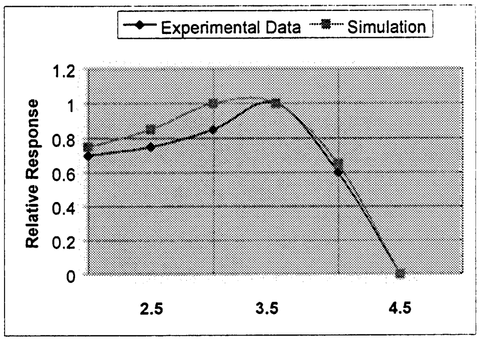


Figure 6. Relative responsivity for the HgCdTe detector with cutoff wavelength of about 4 microns.

6 CONCLUSIONS

This paper has presented the theoretical and experimental aspects of a program aimed at developing a superior simulation capability for HgCdTe heterojunction infrared radiation detectors. The simulation models are based on physical phenomena and the simulation is performed over a very fine grid to increase the accuracy of the result. Statistical simulation results can be achieved because of the inclusion of the STADIUM methodology in the software. Finally, the simulation results have been compared with experiments and show that good agreement is achieved.

The authors wish to thank the US Army Night Vision Laboratories, CECOM-NVESD, for their support of this project.

REFERENCES

1. Glenn T. Hess and Thomas J. Sanders, "Heterojunction Model for Focal Plane Array Detector Devices", 1997 IEEE University/Government/Industry Conference Proceedings, Rochester, NY, July 1997

2. T.J. Sanders, and G. Hess, "Focal Plane Array Detector Device Modeling and Simulation", 1998 Government Microcircuit Applications Conference, Digest of Papers, Washington, DC, March 1998.

3. K. Hess, Advanced Theory of Semiconductor Devices, p. 177, Prentice Hall

4. G. Hansen, et. al., "Energy Gap versus Alloy Composition and Temperature in HgCdTe", Journal of Applied Physics, Vol 53, 1982, p. 7099.

5. T. J. Sanders, K. Rekab, D. P. Means, and F. M. Rotella, "Integrated Circuit Design for Manufacturing through Statistical Simulation of Process Steps," *IEEE Transactions on Semiconductor Manufacturing*. November 1992.

6. T. J. Sanders, D.P. Means, and S.B. Johnson, "Statistical SPICE Circuit Simulation Using Design of Experiments ", *GOMAC Digest of Papers,* pp. 155-156, November, 1994.

7. T. J. Sanders, M. J. Phelps and G. T. Hess, "STADIUM-SOI: Statistical Design for Manufacturing Software for Low Power Silicon-on-Insulator MOSFETS", *IEEE SOI Conference Proceedings*, October 1995.