Crosstalk Simulation in InSb Detector Arrays

Introduction

Crosstalk is one of the main parameters that critically affect the resolution of detector arrays. It results in a reduction in image clarity, thus degrading system performance. There are two type of crosstalk; optical crosstalk and electrical crosstalk. Optical crosstalk includes the effect of photon refraction, reflection at boundaries, and external and internal scattering in detector arrays. Electrical crosstalk is attributed to carriers that are photogenerated under one detector, diffusing and being collected by another detector in the array.

As the photodiode size and the pitch (distance between photodiodes) of the detector array get smaller, there is a greater probability of crosstalk influencing system performance since the probability of a generated carrier being collected by a neighboring junction increases. In Focal Plane Arrays (FPAs), a number of parameters will affect the amount of crosstalk. These include the photodiode size, pitch of the detector array, InSb buffer layer thickness, and the epilayer thickness.

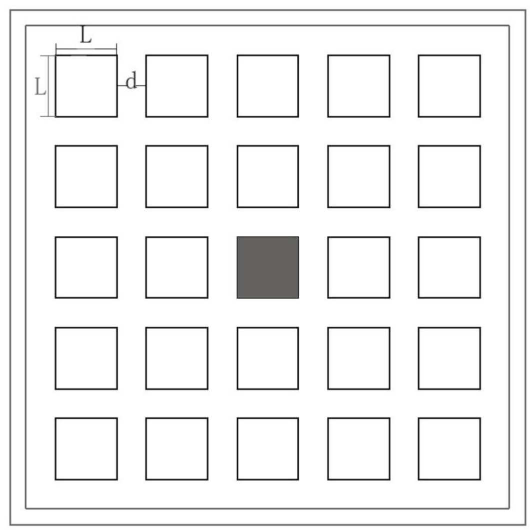
There are some published works which use mathematical approaches [1-2] or Monte Carlo simulation [3] to study the crosstalk in InSb array. Here, a commercial semiconductor device simulator, ATLAS, will be used to study the crosstalk and also the quantum efficiency of a 5 x 5 InSb detector arrays in the three dimensional domain. The software includes a comprehensive set of physical models such as drift-diffusion equations, heterojunctions, recombination models, light absorption and photogeneration models, etc. that can accurately predict the crosstalk and quantum efficiency of the InSb detector arrays.

In this work, we will study the dependency of the photodiode size, pitch of the detector array, epilayer thickness and InSb buffer layer thickness on the crosstalk, and quantum efficiency of the InSb detector array.

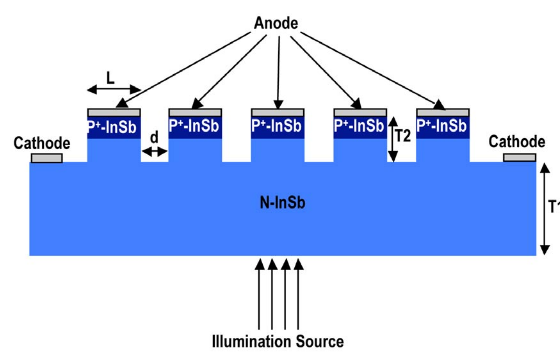
Simulation Structure

Figure 1 shows the simulation structure of the 5 x 5 InSb detector array. The structure consists of InSb photodiodes fabricated on top of the InSb buffer layer. The p+ regions were doped with acceptor concentration of 1 x 10^{19} cm^{-3} and the buffer layer was doped with donor concentration of 1 x 10^{15} cm^{-3}. The contacts on these photodiodes are ohmic and they are named as anode 1, anode 2, up to anode 25 in the simulation. For the cathode, it was formed on top of the buffer layer surrounding the photodiodes. In the figure, L is the size of the photodiode, d is the pitch of the array, T1 is the InSb buffer layer thickness, and T2 is the InSb epilayer thickness. These four parameters will be varied to study the crosstalk effect. The InSb material properties used in the simulation are as shown in Table 1.

In Figure 1(a), the center photodiode as indicated in black will be back illuminated by an illumination source. Under illumination, the incident photon will result in the generation of electron-hole pairs. Most of these electron-hole pairs will be "collected" at the center photodiode and contribute to an external current, while some will diffuse and will be "collected" by the nearby photodiodes in the detector array. The crosstalk at each neighboring diode is defined as the current collected at the neighboring diodes divided by the current collected at the center diode.



(a) Top view



(b) Side view

Figure 1. 5 x 5 InSb detector array.

Mobility of Electron ($cm^2\ v^{-1}\ s^{-1}$)	4.77x10^5
Mobility of hole ($cm^2\ v^{-1}\ s^{-1}$)	850
Carrier lifetime (s)	5x10^{-8}
Permittivity	16.8
Temperature (K)	77
Thermal conductivity (watt $cm^{-1}\ c^{-1}$)	0.18
Radiative recombination coefficient ($cm^3\ s^{-1}$)	5x10^{-11}
Electron effective mass	0.014 m_0
Hole effective mass	0.43 m_0

Table 1. InSb material properties.

In this simulation, a multi-spectral source will be used and the source will be a black-body radiator operating at a temperature of 2000 Kelvin. The spectral power distribution of a black-body radiator can be expressed in terms of wavelength λ (in meters) and temperature T (in Kelvin) as described by Planck's formula [4] below:

$$M_e = \frac{c_1}{\lambda^5\left(e^{c_2/T\lambda} - 1\right)} \qquad W \cdot m^{-3}$$

where

$$c_1 = 2\pi hc^2 \qquad W \cdot m^2$$

$$c_2 = \frac{hc}{k} \qquad m \cdot K$$

$$c = 2.99792458 \times 10^8\, m \cdot s^{-1} \quad \text{(Velocity of light)}$$

$$h = 6.626172 \times 10^{-34}\, J \cdot s \quad \text{(Planck constant)}$$

$$k = 1.380662 \times 10^{-23}\, J \cdot K^{-1} \quad \text{(Boltzmann constant)}$$

To define the black-body radiation in the simulation, we computed the spectral power density at 2000 Kelvin for different wavelengths in an external ASCII file. This is a text file that contains a list of pairs defining wavelength and spectral power density. This ASCII file is then specified in the "POWER.FILE" option in the BEAM statement.

Simulation Results and Discussion

Figure 2 shows the simulated current density contour plot of the 5 x 5 InSb photodiodes array back illuminated by a multi-spectral black-body radiator (2000 Kelvin) at the center photodiode. Each photodiode size is 40 x 40 μm^2 and the pitch of the array is 20μm. The thickness of the InSb buffer layer is 10μm and the InSb epilayer is 5μm.

From the contour plot, high current density is observed at the center photodiode and lower current density is found at the nearest neighboring photodiodes surrounding the center photodiode. Very low current density is observed at the second nearest neighboring photodiodes.

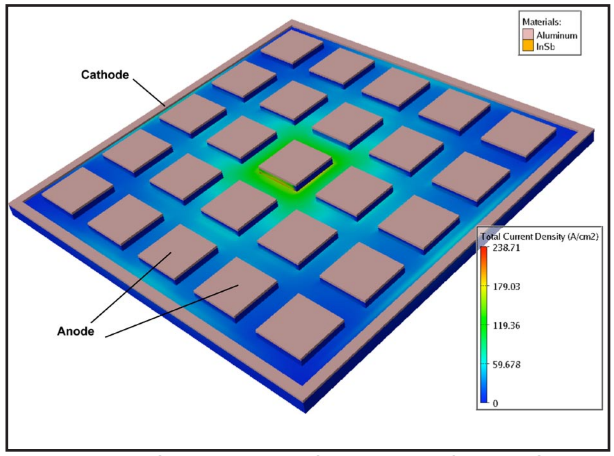


Figure 2. Total Current Density Contour Plot of 5 x 5 InSb photodiodes array.

This shows that the nearest neighboring photodiodes act as guards, preventing carriers from diffusing past them to the second nearest neighboring photodiodes. To observe the crosstalk effect more clearly, Figure 3 shows the quantitative analysis of the 5 x 5 InSb photodiodes array. Here, the current collected by each photodiode is indicated as shown in Figure 3.

From Figure 3, it can be seen that a substantial current of 2.0mA is collected at the center photodiode from the illumination. The current collected at the nearest neighboring photodiodes (vertically and horizontally) is approximately 66mA, and current collected at the diagonally nearest neighboring photodiodes is about 7.5mA. Since crosstalk is defined as the ratio of collected current by the photodiode to the collected current by the center photodiode, this translates the crosstalk at nearest vertically and horizontally photodiodes to be 3.3% and 0.375% at nearest diagonal photodiodes. Outside the 3 x 3 nearest neighboring photodiodes, the crosstalk drops off to nearly zero.

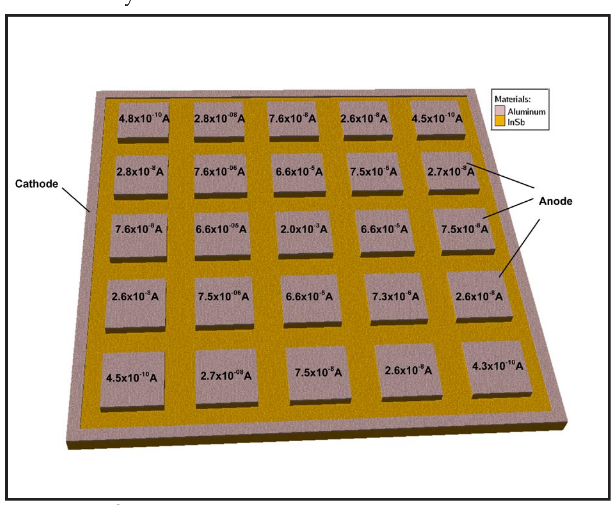


Figure 3. Simulated current at each cell. Photodiode size: 40μm; Pitch: 20μm; InSb thickness: 10μm; and InSb epilayer thickness: 5μm.

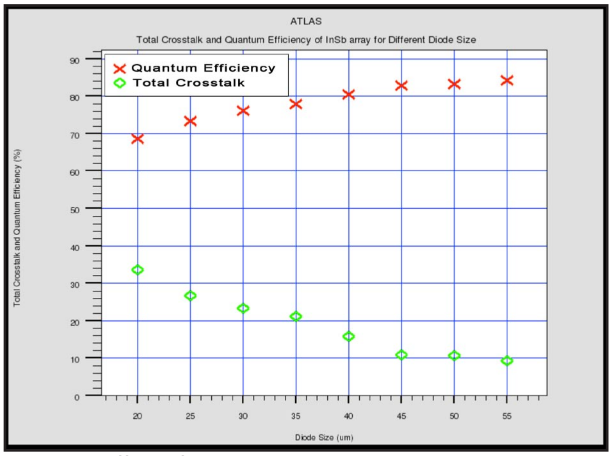


Figure 4. Effect of photodiode size on the total crosstalk and quantum efficiency of the InSb array. Pitch: 20μm; InSb thickness: 10μm; and InSb epilayer thickness: 5μm.

Thus, the total crosstalk for the 5 x 5 array (summation of all crosstalk values at the neighboring photodiodes) is 15%. In addition, the simulated available photocurrent is 2.7mA and the quantum efficiency (defined as the total current collected at all photodiodes divide by the available photocurrent) is 83%.

Next we will investigate the effect of photodiode size, pitch of the array, InSb buffer layer thickness, and InSb epilayer thickness on the total crosstalk and quantum efficiency of the InSb array.

Figure 4 shows the effect of the photodiode size on the total crosstalk and quantum efficiency. In this simulation, the pitch of the array is 20μm, thickness of the InSb buffer layer is 10μm and InSb epilayer thickness is 5μm.

Figure 4 shows that total crosstalk reduces with the increase in the photodiode sizes, and quantum efficiency increases with the increase of the photodiode sizes. For photodiode size of 20μm, the total crosstalk of the InSb array is 34%. When the photodiode size increases to 55μm, the total crosstalk reduces to 9%. The quantum efficiency increases from 69% to 84% when the photodiode size increases from 20μm to 55μm. This is because increasing the photodiode dimensions increases the junction sizes as well. This allows more excited charge carriers to be collected at the junction while reducing the number of carriers crossing to neighboring photodiodes. Therefore, the total crosstalk effect is reduced and the quantum efficiency of the InSb array is increased. This shows that photodiode size has a significant impact on the crosstalk and quantum efficiency of the InSb array, and should be considered when optimizing the dimensions of the photodiodes.

Figure 5 shows the effect of the pitch on the total crosstalk and quantum efficiency of the InSb array. In this simulation, the pitch varies between 10μm and 80μm with the photodiode size, InSb thickness, and InSb epilayer thickness is kept constant at 40μm, 10μm and 5μm respectively.

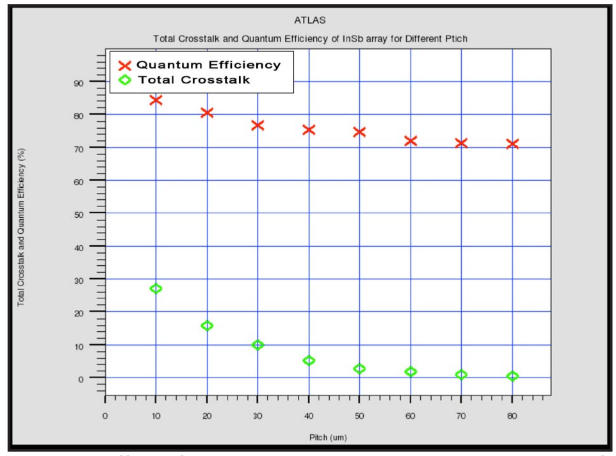


Figure 5. Effect of pitch on the total crosstalk and quantum efficiency of the InSb array. Photodiode size: 40μm; InSb thickness: 10μm; and InSb epilayer thickness: 5μm.

From the graph, the total crosstalk is 27% when the pitch is 10μm, and reduces to less than 2% for a pitch value greater than 60μm. The same trend is observed in the quantum efficiency curve, which starts from 84% (pitch = 10μm) and is reduced to 72% (pitch = 60μm). Above pitch value of 60μm, any increase in the pitch of the InSb array will have a negligible effect on both the total crosstalk and quantum efficiency.

The InSb buffer layer thickness may vary over the array, or from array to array, due to a non-uniform thinning process. It is also important to study the effect of the InSb buffer thickness on the crosstalk and quantum efficiency of the InSb array. Figure 6 shows the simulation of the InSb array with buffer thickness varying from 7μm to 14μm. Here, the photodiode size is 40μm, pitch is 20μm and InSb epilayer thickness is 5μm. The graph shows that both crosstalk and quantum efficiency are linearly proportional to the thickness of InSb buffer layer. As the buffer thickness increases from 7μm to 14μm, the quantum efficiency decreases from 87% to 71%, due to in-

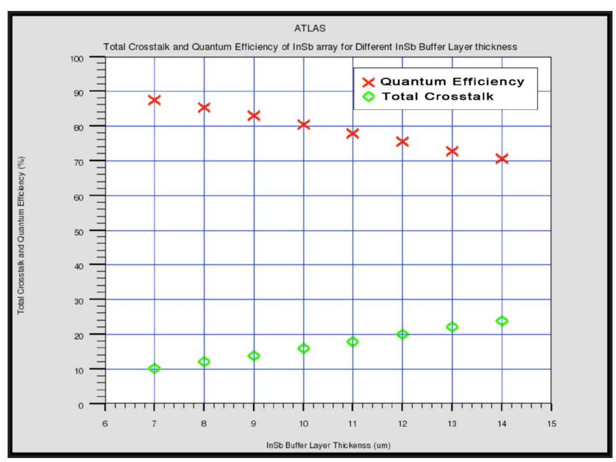


Figure 6. Effect of InSb buffer layer thickness on the total crosstalk and quantum efficiency of the InSb array. Photodiode size: 40μm; Pitch: 20μm; and InSb epilayer thickness: 5μm.

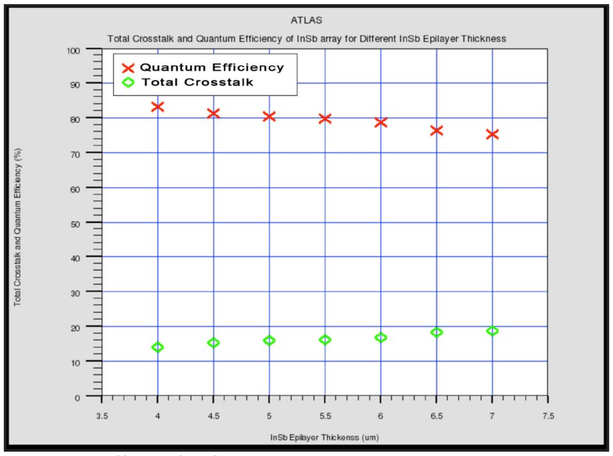


Figure 7. Effect of InSb epilayer thickness on the total crosstalk and quantum efficiency of the InSb array. Photodiode size: 40µm; Pitch: 20µm; and InSb buffer layer thickness: 10µm.

creased recombination in the bulk and the total crosstalk increases from 10% to 24%. Therefore, a non-uniformity thickness of ±1μm results in a non-uniformity response of about ±2%.

Finally, the effect of the InSb epilayer thickness on the total crosstalk and quantum efficiency is shown in Figure 7. It shows the same linear response as in Figure 6. The quantum efficiency decreases from 83% to 75% and total crosstalk increases from 14% to 19% when epilayer thickness increases from 4μm to 7μm. Therefore, a ±0.5μm difference in epilayer thickness will result in ±3% change in quantum efficiency and ±0.8% change in total crosstalk.

Conclusion

We have presented the use of a 3D semiconductor device simulator, ATLAS, to simulate the quantum efficiency and total crosstalk of a back-illuminated InSb detector array. Results from the simulation showed that the quantum efficiency and crosstalk have a strong dependency on the array dimensions such as the photodiode size, pitch of the array, InSb epilayer and buffer layer thickness. Thus, it is important to take care of these parameters when designing and optimizing the resolution of detectors arrays.

REFERENCES

[1] J. Shappir and A. Kolodny, “The Response of Small Photovoltaic Detectors to Uniform Radiation”, IEEE Trans. on Electron Devices, Vol. ED-24, No. 8, August 1977, Page 1093 – 1098.

[2] I. Bloom and Y. Nemirovsky, “Quantum Efficiency and Crosstalk of an Improved Backside-Illuminated Indium Antimonide Focal-Plane Array”, IEEE Trans. on Electron Devices, Vol. 38, No. 8, August 1991, Pages 1792 – 1796.

[3] R. Fastow and A. Strum, “Monte Carlo Simulations of the Cross Talk in InSb Matrices”, SPIE, Vol. 2274, 1994, Pages 136-146.

[4] Rybicki, G. B.; Lightman, A. P. (1979), Radiative Processes in Astrophysics, New York: John Wiley & Sons.