Infrared Detectors for Astronomical Applications

Design of a Near-Infrared Astronomical Grade Detector

Rafal Piersiak
Electrical Engineering Department
Stony Brook University
ESE 525: Modern Sensors
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Mark Drzymala
Electrical Engineering Department
Stony Brook University
ESE 325: Modern Sensors
Fall 2013

***Abstract*—Infrared radiation was first discovered by an astronomer measuring the heat transferred through a glass prism at different visible wavelengths. Since this discovery, infrared detection has developed to measure infrared light through a variety of means, including temperature-dependent materials, the thermoelectric effect, and pyroelectricity, utilizing solid state detectors. These detectors have exploded in use over the last few decades in countless fields, including astronomy. Astronomical detectors use different technologies and materials to analyze different portions of the infrared spectrum for purposes such as planet detection and viewing distant red-shifted galaxies. This paper is a review of the operation of infrared detectors, the different types of materials used, the limitations that need to be overcome, sensor implementation, and a discussion of current research and future prospects.**

Keywords—infrared detector; photovoltaic; HgCdTe; InSb; astronomical; telescope; near-infrared

I. Introduction

The astronomer William Herschel discovered the existence of infrared light in sunlight on February 11, 1800. Since then infrared sensors have been developed that allow us to peer into outer space and discover galaxies and celestial entities that were previously invisible. Since the universe is rapidly expanding, most objects in space are moving away from us. Due to the Doppler Effect the light that we see on Earth shows redshift; the light that reaches us has increased wavelength. This means that some light emitted by objects in space will shift from the visible spectrum into the infrared spectrum. Since all galaxies and stars radiate heat, they all emit infrared light. Light in the Visible spectrum will be obscured by dust and gasses, but light in the Infrared spectrum can pass through. Dust and gasses will also emit infrared light themselves. Without special detectors that can detect this light we would never be able to see many galaxies and stars that were previously undiscovered.

II. Operation

A. The Photovoltaic Effect

Most infrared detectors operate on the principle of the Photovoltaic Effect. A solar cell consists of a PN junction and conductors connected to the P-type and N-type sides. When a photon strikes the cell it excites an electron which jumps from the valence band into the conduction band. Due to the electric field formed by the depletion region the electron flows through the conductor connected to the n-doped side, through the read-out integrated circuit (ROIC), and into the p-doped semiconductor.

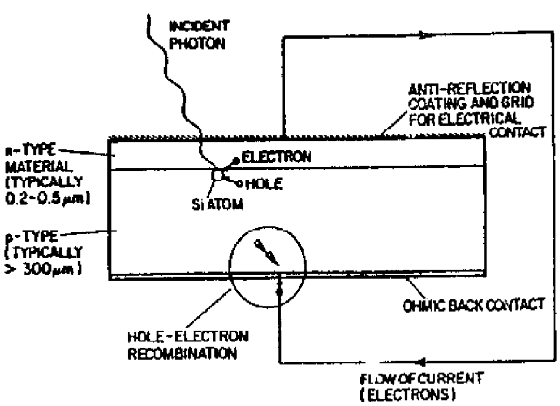

Fig. 1. Photovoltaic cell

A typical sensor will consist of an array of thousands to millions of these cells, depending on the resolution required for the application. The ROIC is typically located under the sensor array.

The semiconductor used in this sensor will be different depending on the band of infrared that it is designed to detect. The most common semiconductor currently used in infrared sensors is Mercury Cadmium Telluride (HgCdTe) due to its ability to be doped for use in a very wide band of infrared light [8].

Since the light being detected is millions of miles away, very little light makes it to the sensor. There are a few requirements for infrared sensors for Astronomical applications. They must have low noise ROICs, very low dark current, high pixel counts, and must be cooled to sub-200K, sometimes cooler.

B. Bolometers

A less common astronomical infrared sensor is the Bolometer. A bolometer's resistance changes as its temperature changes due to absorbed radiant energy. Change in resistance occurs as the temperature of the sensor changes. The material used will have a high temperature coefficient of resistance (TCR) so that the miniscule amounts of infrared light that reach the sensor create a large enough signal to be read.

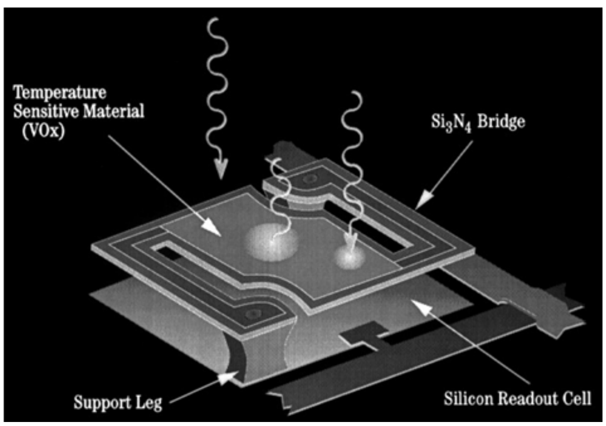

Fig. 2. Microbolometer cell

III. CHARACTERISTICS

Infrared detectors are designed around several key characteristics. This section will discuss some of these characteristics in order to shed some light on the physical and electrical aspects of designing an HgCdTe infrared detector, commonly used in astronomy to study near and mid-infrared light.

A. Dependence of Resistance/Area on Current

The following figure is a graph of HgCdTe photo detectors with different band gaps tested at 78K [1]. The solid line is a theoretical calculation of R_0A_{opt} in comparison to three materials. The experimental values were measured from I-V characteristics and flood/focused measurements of quantum efficiency [1].

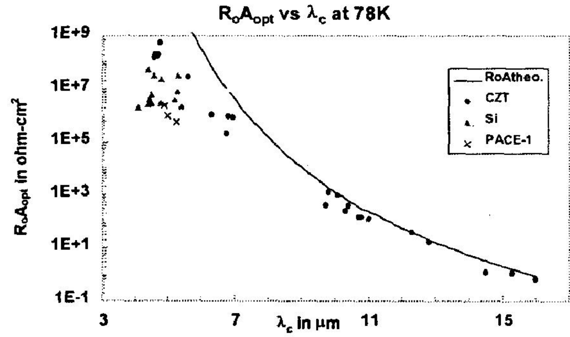

Fig. 3. R_0A_{opt} versus λ_c

The temperature dependence on R_0A may be used to isolate the limitation of dark currents [1]. Detectors with a larger R_0A have less dark current for a larger area due to the increased resistance of the detector material. The dependence of area on R_0A also helps elucidate the surface vs. bulk performance limitation [1]. Generally, detectors with larger areas have worse performance due to additional resistance attributed to the mismatch between the Si readout circuit and the heterogeneous detector materials. Also, detectors with higher cutoff frequencies are more difficult to build due to increased dark current to lower resistance, which allows only for small detectors to be built. There is much research going on in building detectors of larger than 1Kx1K for mid and far infrared regions with dark currents comparable to near infrared detectors of similar size.

B. Dependence of Detectivity on Temperature

Although the figure-of-merit, Detectivity (D*) is no longer used as a measure of detector performance in astronomy – exceptional high grade astronomical detectors have D* values that are so large they are illogical – the following plot reveals a distinct relationship between detector sensitivity and temperature [1].

Infrared detectors are cooled primarily because as temperatures increase, the detectivity rolls off, similar to a low pass filter. Increasing temperature causes electrons to jump the band gap and add to the dark current, thus decreasing the minimal amount of electrons the detector can effectively measure.

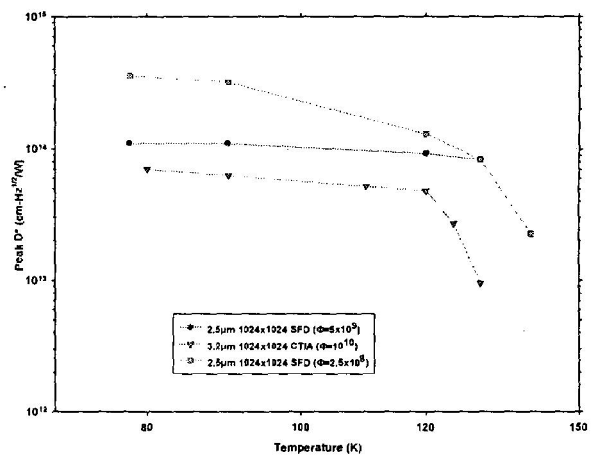

Fig. 4. Peak Detectivity versus Temperature (1Kx1K, HgCdTe)

C. Dependency of Noise on Frequency

A discussion of frequency response of mid-infrared HgCdTe detector is summarized in the following figure. It has been found that HgCdTe detectors function better at higher frequencies due to the attenuation of 1/f noise above the 1/f knee frequency.

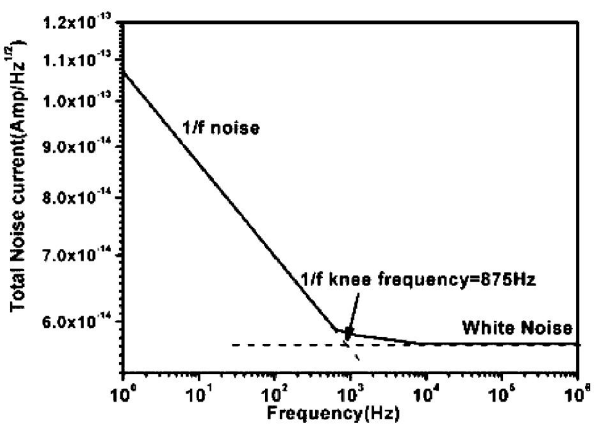

Fig. 5. Total Noise Current versus Frequency (Mid-Range HgCdTe)

The 1/f noise increases linearly below the knee frequency, which is 875 Hz in the figure. White noise is cutout below this frequency and doesn't have much of a role. The authors report that the detectivity of the detector below the 1/f knee frequency measured at ~ $9.8*10^9$ cm $Hz^{1/2}$ W^{-1} [11]. D* at the 1/f knee frequency was calculated to equal $3.0*10^{10}$ cm $Hz^{1/2}$ W^{-1}. The attenuation of D* below the 1/f knee frequency is minimal and doesn't play much of a role on the detectivity of the detector. But it is true that for long-range detectors, 1/f noise has a more prominent effect on D*. Operating an infrared detector at low frequencies minimizes the power dissipation of the read-out circuit, but at the cost of reduced detectivity. Therefore a decision must be made on how to maximize D* and minimize total power dissipation effectively.

D. Doping Profiles

The doping concentrations of the layers that make up the HgCdTe detector have various effects on the detectivity of the device. In the following figure, the doping concentration of the absorber layer increases linearly until it peaks at about $3.0*10^{15}$ cm^{-3} [11]. Increasing the doping further leads to a much faster decay of D*, compared to the slope before peak doping.

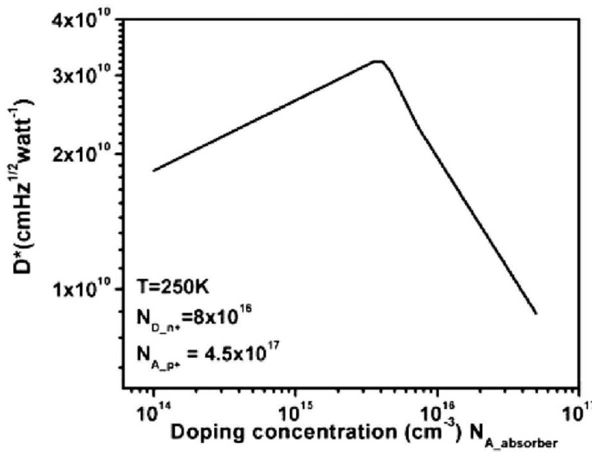

Fig. 6. D* versus Doping Concentration for Absorber Layer (250K)

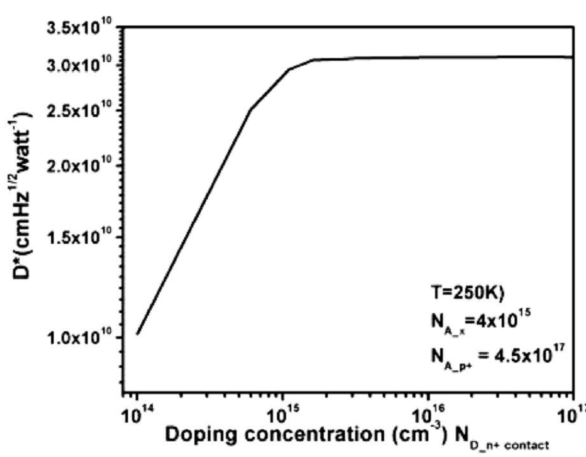

Fig. 7. D* versus Doping Concentration for Contact Layer (250K)

The doping of the contact layer displays different characteristics. Increasing the doping concentration leads to a linear increase in D* until about the 3dB point, where D* begins to taper off and remains constant at high doping concentrations. Ensuring that each layer is doped accordingly will ensure that the detector is limited due to inefficient doping schemes.

E. Dependency of Detectivity on Absorber Width

Another important parameter to consider is the width of the absorber layer. The incident photons react with this layer and generate carriers, thus inducing a current. Increasing the width of the absorber layer increases the detectivity of the detector, but decreases the collection efficiency of optically generated carriers is maximized [11].

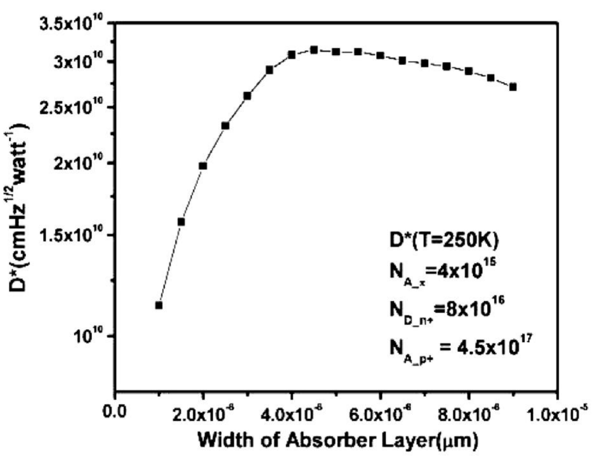

Fig. 8. D* versus Width of Absorber Layer

Increasing the absorber layer width causes a sharp rise in D* then begins to taper off. After a certain width, increasing the absorber layer width becomes detrimental to the detectivity. Depending on the width of the absorbing layer and the temperature of the detector at operating conditions, D* can be maximized within a certain range of absorber layer widths.

F. Dependency of Quantum Efficiency on Width

The input/output characteristics of an HgCdTe infrared detector is a function of absorber layer thickness. By varying the thickness of the absorbing layer, the efficiency of a 1:1 conversion of photons to electrons can be manipulated to achieve an optimal condition.

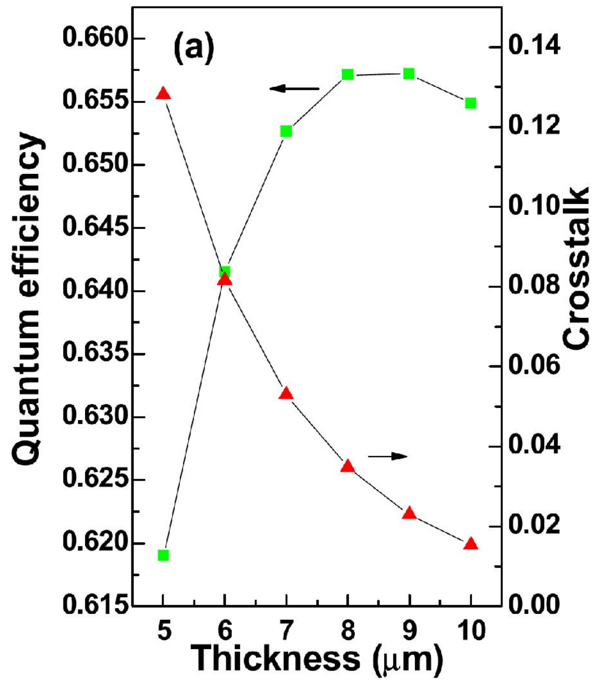

Fig. 9. Quantum Efficiency versus Width of Absorber Layer

Increasing the width of the absorber layer increases the quantum efficiency of the detector, as well as the detectivity [4]. After a sharp increase, the quantum efficiency begins to taper off and begins to degrade above a certain optimum absorber layer thickness.

G. Dependency of Signal-to-Noise to Temperature

The signal-to-noise ratio, equivalent to photon current (I_{ph}) over dark current (I_d), can be measured and plotted [12]. The dark current has a strong presence at temperatures below 180K and above 240K. In the region of 180K to 240K, the photon current begins to equalize to the dark current; at one point the ratio is equal to one. This graph shows the difficulty of first, to find an optimal signal-to-noise ratio, and second to create a signal-to-noise ratio above one for Amorphous HgCdTe infrared detectors at such uncommonly warm temperatures.

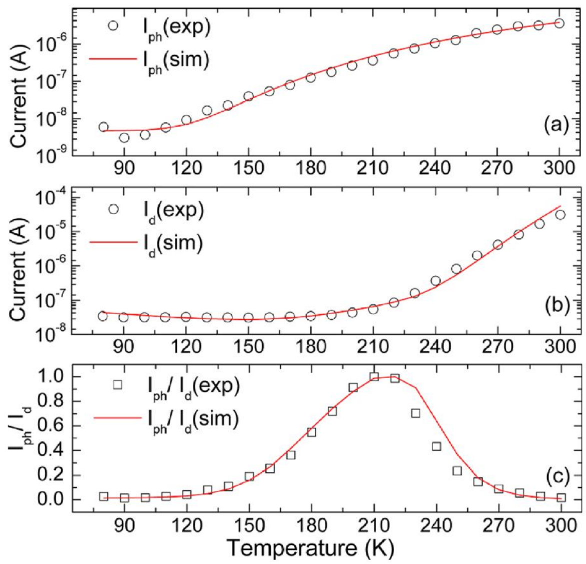

Fig. 10. I_{ph}/I_d versus Temperature (Amorphous HgCdTe)

H. Accuracy

The accuracy of an infrared detector depends on three primary characteristics: quantum efficiency, readout noise, and dark current. There is no easy calculation of infrared detector accuracy, or comparison of accuracies, therefore all three parameters must be analyzed and matched for their intended purpose. A ground based telescope will require much better quantum efficiency than a space telescope, primarily due to maximizing the conversion of the limited infrared radiation coming through Earth's atmosphere to a current. Space telescopes require better readout circuits, which are not affected by the ionized solar wind. Keeping the temperature stable is another challenge in space that must be overcome in order to achieve maximum detectivity.

By achieving 100% quantum efficiency and minimizing the readout noise and dark current to the levels of 12-e and 0.01-e/s respectively, the accuracy of the infrared detector could detect levels of infrared radiation comparable to a match flame on the moon or better. With dark current sufficiently extinguished to nonthreatening levels, and the rise of better readout circuits and infrared detecting materials and structures, the newest astronomical detectors will have the ability to peer farther into the past of the universe than ever before.

IV. Advantages and Disadvantages

There are three bands of infrared light in astronomy:

Near Infrared (1µm-5µm)
Mid Infrared (5µm-28µm)
Far Infrared (28µm-200µm)

Each band requires different semiconductors with narrow bandgaps to react to specific bands of infrared light.

A. Indium Antimonide (InSb)

InSb has a band gap of 0.17eV at 300K and 0.23eV at 80K, and is ideal for capturing near-infrared light from 1µm to 5µm. InSb is a competitor with HgCdTe since HgCdTe can also be used to capture light in this band.

InSb can be grown using Molecular Beam Epitaxy (MBE) where the semiconductor is formed one layer at a time with layers one molecule thick. At 77K maximum voltage responsivity of $1.0*10^3$ V/W and Johnson noise limited detectivity estimated at $2.8*10^{10}$ cm $Hz^{1/2}$ W^{-1} is measured at 4µm [7]. It can be grown with good crystallography, high purity, and excellent uniformity.

InSb's internal quantum efficiency is effectively 100%, but is a function of the thickness. Real-world applications of a sensor based on InSb quote >80% quantum efficiency [9].

B. HgCdTe Advantages

When a sensor formed with HgCdTe is configured for the near-infrared band the sensor doesn't need to be kept as cool due to the shorter cutoff wavelength. These detectors are cooled using liquid Helium when placed in satellites and telescopes on Earth. Because only a limited amount of liquid helium can be stored in a satellite, they can usually only be used for about 10 months before their supply runs out. The ability to operate the detector at a warmer temperature is beneficial in that it can cause a satellite's supply of coolant for the sensor last longer before it becomes unusable.

The cutoff wavelength (λc) can be changed by modifying the amount of Mercury and Cadmium in the semiconductor. For example, $Hg_{0.70}Cd_{0.30}Te$ will have a cutoff wavelength of 5µm and $Hg_{0.55}Cd_{0.45}Te$ will have a cutoff of 2.5µm [9].

Originally it was difficult to produce HgCdTe detectors with the same uniformity as InSb due to its increased complexity, but Teledyne developed a manufacturing process to produce HgCdTe with MBE. This results in HgCdTe that is much more uniform.

C. *Mid and Far Infrared Detectors*

Long-wavelength detectors tend to have higher dark currents. This is because materials with small band gaps only allow a small contact voltage to maintain the depletion region. HgCdTe detectors can be manufactured with cutoff wavelengths above 15µm but they tend to have dark currents that are too large for most astronomical applications [9].

One solution is to use impurity band conduction (IBC) sensors. These can be built using Si:Ga, Si:As, or Si:Sb for cutoff wavelengths of 18µm, 28µm, and 40µm, respectively [9]. This IBC detector only allows leakage current through thermal excitation into the conduction band due to the highly doped thin active layer.

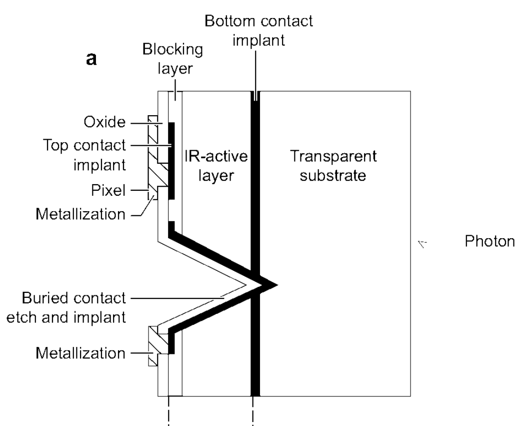

Fig. 11. IBC Sensor (Mid, Far-infrared)

Bolometers can be used for far-infrared wavelengths. They are among the most sensitive sensors for this band of infrared, but they must be cooled to less than a degree above absolute zero in order to get accurate readings. Despite the extreme cooling required for this detector to function correctly, bolometers are the most understood sensor in astronomical infrared detectors due to their simple nature.

V. Applications

Infrared detectors for astronomical purposes are primarily utilized for ground and space-based observation. The two most prominent utilizations for infrared detectors may be found on the upcoming James Webb Space Telescope (JWST) and on the Keck II telescope, stationed in Mauna Kea in Hawaii. Both telescopes have designs, which allows light to be funneled into the detectors and an image is created.

A. *Space-Based Telescopes*

The JWST telescope is optimized to detect light in the infrared region. It has an instrument called Near InfraRed Camera (NIRCam), which will process light from 0.6µm to 5µm. It has a collection of infrared detectors, 4Kx4K detector arrays to measure 0.6µm to 2.3µm infrared light and 2Kx2K detector arrays to measure 2.4µm to 5µm infrared light. Quantum efficiency is greater than 80%. Read noise has been measured to be 9-e in 1000 seconds. Dark current has been measured to be as low as 0.01-e/s. The NIRCam detectors will be able to detect as much as 80,000 electrons per pixel before the pixel saturates [10].

Not all space telescopes utilize infrared detectors. There are many telescopes in the radio, microwave, visible, ultraviolet, x-ray, and gamma ray range that don't have an infrared detector on board. Each telescope has a specific function that it is optimized for, just as the JWST is optimized for infrared light. Depending on the mission at hand, a select number of instruments are placed inside, some of which may be infrared detectors.

B. *Ground-Based Telescopes*

The most powerful infrared ground-based telescope today is the 10m Keck II telescope. It is equipped with an instrument referred to as the Near Infrared Camera 2 (NIRC-2). It is able to detect infrared light in the near infrared region, 0.9µm to 5.3µm. It has a 1Kx1K InSb infrared detector. Quantum efficiency is maximal at 80% for 1.7µm. Read noise has been measured to be 60-e for one read. Dark current has been measured to be as low as 0.1-e/s, which is 10 times worse than the JWST. The previous version of NIRC was decommissioned in 2010; it had a sensitivity of about 5 to 10 times less than the current NIRC-2.

Ground-based telescopes with infrared detectors must be cooled to very low temperatures in order to minimize the dark current and boost sensitivity. This is however easier to accomplish on earth; space telescopes have a limited supply of refrigerant. Once it runs out, the detector is useless.

Another issue with ground-based telescopes is that there are certain regions where Earth's atmosphere is no transparent to infrared light. Light coming from the universe is absorbed by the atmosphere and never reaches the detector. Ground-based telescopes also need to worry about atmospheric disturbance caused by the movement of heat through the atmosphere, which contributes to the twinkling of starts. Adaptive optics are now used to correct the distorted image caused by the atmosphere before it reaches the infrared detector.

C. Market

The market for astronomical grade detectors is limited to several agencies such as NASA, European Southern Observatory, and several others. The very first astronomical infrared detectors originated from military research. Eventually agencies began to build their own, especially in the mid and far-infrared spectrums. Teledyne is the main manufacturer of HgCdTe near infrared detectors. Their detectors are used in many space and ground-based applications.

Several universities and research groups have begun to investigate the design and implementation of infrared detectors. Their combined work has been instigated with the hopes of building detectors out of other materials such as InSb for near-infrared primarily because it is cheaper and has a higher yield. There is not much improvement left in HgCdTe detectors; research has also stagnated and produced little noteworthy achievements.

The design of infrared detectors for astronomy purposes is a niche market with limited expandability. Although this market is rather small, the commercial and military market for infrared detectors has increased significantly. Military uses have included target acquisition, search and rescue, and night time combat. Commercial uses have expanded heavily in the creation of infrared cameras, most notably the thermal imaging company, FLIR. Other uses include non-contact temperature measurement, weather forecasting, and het-loss detection in homes. It may soon become standard for cell phones to also include an infrared camera to complement the visible spectrum camera already in place in most cell phones.

VI. Design and Simulation

Due to the nature of high-tech infrared detector design, the implementation of an actual detector will not be attempted due to the need for expensive equipment, as well as many years of knowledge of detector design and growth. The design and simulation of an infrared detector on the other hand is practical and will be explored in this paper. The following subsections will touch upon the design of an HgCdTe infrared detector, its associated readout circuit, and modelling of the input MOSFET.

A. Tuning an HgCdTe Infrared Detector

Designing an HgCdTe detector first starts with selecting what wavelengths of light you would like to detect. Research has been done to model the interaction of temperature and the concentration of Cadmium (Cd) with respect to Mercury (Hg) in terms of:

- Intrinsic Carrier Concentration (n_i) [2]
- Bandgap Energy (eV) [3]
- Cutoff Wavelength (λ_c)
- Minority Carrier Lifetime (τ) [5]
- Dark Current Density (J) [5]
- Quantum Efficiency [11]

as well as many other important parameters for implementing a high quality HgCdTe infrared detector.

The following design will cover the first three parameters mentioned before, which are the most important for the design of an HgCdTe infrared detector.

1) Intrinsic Carrier Concentration:

The intrinsic carrier concentration was modelled extensively in [2]. The author developed a formula that depended on the bandgap voltage, concentration of Cd, and temperature, found below:

$$n_i = (5.585 - 3.82x + 1.753E^{-3} \cdot T - 1.364E^{-3} \cdot x \cdot T) \cdot 10^{14} \cdot E_g^{0.75} \cdot T^{1.5} \cdot e(-E_g/2k_bT) \quad (1)$$

Note that k_b is in the units (eV K^{-1}). Plotting n_i against different concentrations of x and temperature T in Kelvin will yield the following plot. As the concentration of Cd increases with respect to Hg, the intrinsic carrier concentration decreases. This phenomenon is directly correlated to how much Hg is in the detector composition. HgTe is a metal with a bandgap voltage of approximately 0 eV; therefore by reducing the amount of Cd in the device, you are increasing Hg, which boosts the intrinsic carrier concentration. This can push the material to attain an electron mobility of several thousand $cm^2/(V \cdot s)$. Temperature also has a major role on controlling the intrinsic carrier concentration. Higher temperatures lead to higher intrinsic concentrations. Higher temperatures allow electrons to flow more easily, which has the adverse effect on increasing the dark current.

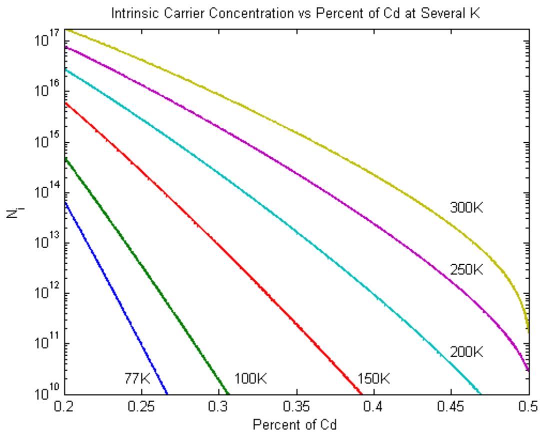

Fig. 12. N_i versus Cd Concentration at Several Temperatures

2) Bandgap Energy:

The bandgap energy was modelled extensively in [3]. The author developed a formula that depended on the concentration of Cd and temperature, found below:

$$E_g = -0.302 + 1.93x + 5.35E^{-4} \cdot T \cdot (1 - 2x) -0.81x^2 + 0.832x^3 \quad (2)$$

A contour plot was generated with Cd concentration on the x-axis and temperature on the y-axis. The color bar on the right of the plot displays the bandgap energy for a certain $E_g(x,T)$.

Increasing the concentration of CdTe, a semiconductor, will increase the bandgap energy. A common detector, $Hg_{0.80}Cd_{0.20}Te$ would have a bandgap voltage of 0.0830 eV at 77K. Adding more Cadmium, $Hg_{0.70}Cd_{0.30}Te$ would increase the bandgap energy to 0.2430 eV.

Temperature doesn't have as strong of an effect on the bandgap energy as the concentration of Cd. Changing the temperature of the $Hg_{0.80}Cd_{0.20}Te$ material to 300K would increase the bandgap energy to 0.1546 eV, which is approximately an 86% increase. Exposing $Hg_{0.70}Cd_{0.30}Te$ to the same temperature would change the bandgap energy to 0.2908 eV, which is approximately a 19% increase.

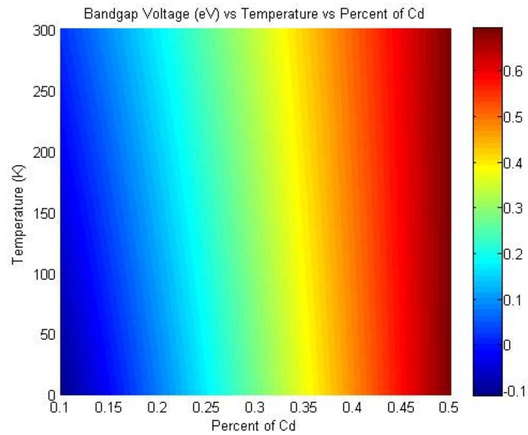

Fig. 13. Bandgap energy versus Cd Concentration versus Temperature

3) Cutoff Wavelength:

The following subsection will show the dependence of bandgap energy and on the detector cutoff wavelength. The cutoff wavelength can be easily calculated with the following relationship:

$$\lambda_c = 1.24 / E_g \quad (3)$$

This equation can be plotted over multiple Cd concentrations and temperatures to better represent the impact of bandgap energy on the cutoff wavelength.

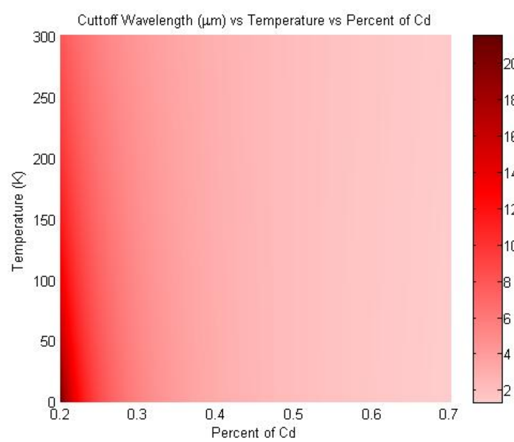

Fig. 14. Cutoff Wavelength versus Cd Concentration versus Temperature

The plot portrays infrared light using an intuitive scheme; the progression from pink to dark red is synonymous with the transition from near-infrared to far-infrared. Pink portions are considered near-infrared, the red regions denote mid-infrared, and the dark red region denotes far-infrared.

Increasing the concentration of CdTe limits the wavelength of light the detector can support. The shift from a Cd concentration of 0.2 to 0.3 has a drastic effect on the cutoff wavelength. For example, cooling the detector at 77K with a concentration, $Cd_{0.20}Te$ will place the cutoff wavelength at ~15µm. Shifting to a $Cd_{0.30}Te$ concentration will limit the detector to ~5µm.

Therefore there are many aspects to consider when designing the detector material. But the designer must primarily factor in Cd concentration, temperature of the detector, and the required cutoff wavelength before any more adjustments are made, such as the well structure or the thickness of the absorbing layer, which has an impact on the quantum efficiency of the device.

4) Other Design Parameters:

The optimization of other parameters such as the quantum efficiency is another parameter that is critical, particularly to the minimum amount of light the detector can support. The authors of [11] go into much more detail with a performance study of the design of an HgCdTe detector using numerical simulation. They offer methods for determining total noise current and generation/recombination rates, among other design criteria.

B. Readout Circuit for a HgCdTe Infrared Detector

The readout circuit for an astronomical infrared detector must be small and be extremely frugal with power. An example of a readout circuit for a 2048x2048 HAWAII-2 can be found in [6], as well as in the following figure.

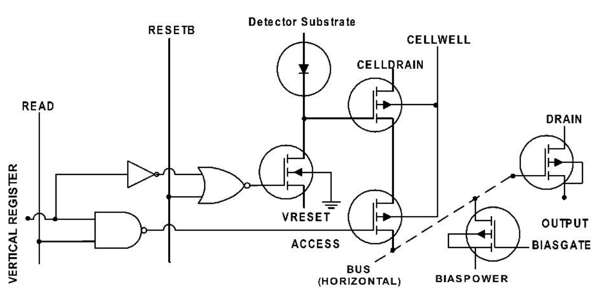

Fig. 15. HAWAII-2 Single Pixel Readout Circuit

The pixel is connected to the detector substrate on the anode. The cathode of the pixel is connected to the gate of the Celldrain transistor, as well as the drain of the Vreset transistor. The Celldrain must be very large, on the order of 10's of µm to effective amplify the electrons on its gate. The Vreset transistor is used to clear the gate of electrons so that another measurement can be taken. The Vreset transistor must have a high threshold voltage to virtually eliminate any electrons from leaking from the gate of Celldrain through Vreset. During the modeling of the input MOSFET, the designer must first choose whether to use a PMOS or NMOS. This choice is made by finding the MOSFET that can measure the minimum amount of electrons (ENC) for a certain peaking time (τp). Depending on the peaking time, it may be more beneficial to select one type over the other, which is often the case.

C. Input MOSFET Modelling

The following figure displays the minimum amount of electrons an NMOS or PMOS can detect at some peaking time. By factoring foundry MOSFET parameters, 1/f and white noise, as well as modelling the MOSFET characteristics in moderate inversion, the designer can find an optimum solution.

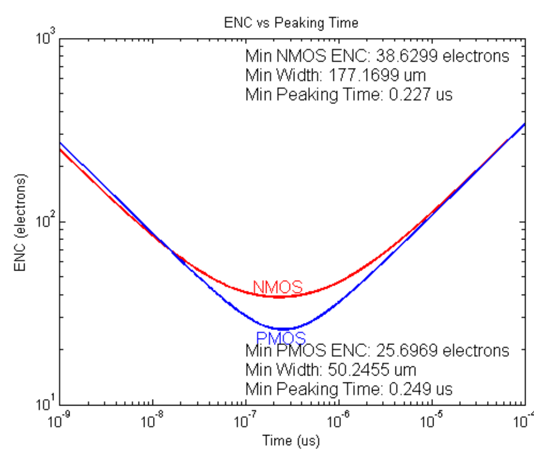

Fig. 16. Input MOSFET Modeling

Factoring in the sensor parameters, including sensor capacitance and leakage is also critical in order to achieve an accurate model. The MOSFETs modelled in the above figure were based on TSMC 0.25µm technology. Clearly, the PMOS can detect a fewer amount of electrons, ~25-e to the NMOS ~39-e. Also the PMOS is several times smaller than the NMOS, ~50µm to ~177µm, which is important during layout. Implementing a NMOS approximately 180μm is highly impractical, wasteful, and most likely will not be very effective.

VII. CONCLUSION

The years of dedicated design to high quality astronomy grade infrared detectors has led to numerous discoveries in astronomy and our understanding of the universe. The redshift of far off galaxies has relegated the furthest known galaxies to only emit light in the infrared spectrum. Infrared detectors have been the key to detecting these galaxies, some as young as 400 million years old. Infrared detectors have also played a key role in the detection of extrasolar planets, some the size of Earth. With new advances in the design of infrared detectors, there will eventually be a day when the first light of the universe and the first habitable planet will be found, and humans will know where they came from, and who else is out there.

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