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Electronic Infrared Sensors

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Abstract—Infrared sensors are found in everyday household items throughout the developed world. Despite this, there is little literature describing or detailing the underlying physics of these devices. This paper reviews the physics behind various infrared detectors, the production of these devices, and discusses current and future applications of this technology.

Index Terms—infrared, infrared electronics, infrared sensors, thermal detector, optomechanical, microbolometer

I. INTRODUCTION

Light sensors are devices which detect incident light via chemical or electronic means. Optoelectronics are electronic devices which interact with light. Photodetectors are able to detect light through the photoelectric effect. Optomechanical detectors detect the momentum of individual photons. Thermal detectors measure fluctuations in temperature caused by radiation - in this case light. These few simple concepts are the basis of all modern Infrared (IR) sensors. Infrared light is the same as visible light except that it has a longer wavelength, so humans cannot see it. Infrared light has useful properties which have led to its usage in several fields.

Infrared radiation is commonly divided into three categories: Near Infrared (NIR), Mid-Wave Infrared (MWIR), and Long-Wave Infrared (LWIR) [1]. NIR has the shortest wavelengths and LWIR has the longest wavelengths of the three. Infrared light detectors detect light within any of the three IR bands. The infrared spectrum is particularly useful because all objects at temperatures higher than 0 Kelvin emit infrared radiation. NIR ranges from 850 nm to 3 μm - just above that of visible red light. MWIR ranges from 3 μm to 5 μm . LWIR is considered any wavelength between 5 μm and 14 μm .

There are three classes of infrared detection devices. The first is thermal detectors, which function via the heating of an active element and measure some physical property that changes with temperature. By measuring this repeatedly and precisely thermal detectors determine the level of incident radiation on their active sensors. The second class of infrared detectors are photodetectors, which function via the photoelectric effect. In this text photonic infrared detectors will be referred to as Infrared Photodetectors (IRPDs). More generally, these devices can be called optoelectronic photodetectors. The third kind of infrared detectors are optomechanical infrared detectors. These function by transforming the momentum of incident infrared photons into motion of a microcantilever. This motion is then measured and used to determine the intensity of incident IR light.

II. APPLICATIONS

The usage of IR sensors ranges the gamut of applications from household television remote controls to safety equipment to missile guidance systems. The physical characteristics of a photodetector's physical composition and arrangement ultimately determine its sensitivity to different wavelengths of the light spectrum.

LWIR is most commonly used in industrial, safety, and hobby applications. One common use of LWIR is to measure the temperature of an object from a farther (and safer) distance. A common use of MWIR and LWIR is in consumer electronics such as television sets. In these devices, an infrared light emitting diode (LED) inside a remote control flashes off and on to send a coded message to an infrared sensor embedded in the television set.

For NIR the most common uses are military purposes. One example is surface to air missiles (SAMs) which utilize IRPDs to track their targets.

To do this, an IRPD senses the faint infrared radiation emitted by an aircraft's exhaust. The FIM-43 Redeye is a SAM which used a lead sulfide (PbS) IRPD to track aircraft [2]. This technique is still used in modern evolutions of the SAM such as the Stinger, which used both infrared and ultraviolet photodetectors. NIR is so effective in anti-aircraft uses that infrared cameras and IRPDs are regulated as munitions under International Traffic in Arms Regulation in the United States.

III. BLACK BODY RADIATION

Any body above absolute zero emits radiation into its environment. The lower the temperature of a body, the lower the average energy of light that is emitted (and the longer its wavelength). The infrared range of light has the convenient property that it is emitted from practically all objects. This is the virtue of infrared detection: a passive viewer at a distance may observe the difference between the ambient background radiation and a subject of interest such as a hiker lost in the woods, a vehicle, or a leak in a furnace.

Planck's Law describes the relationship between a black body's temperature and its relative emission of radiation for a given wavelength of electromagnetic radiation. It is a two variable function defined as

$$B_{\lambda}(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (1)$$

where e is Euler's number, k is the Boltzmann constant, h is Planck's constant, c is the speed of light, λ is the wavelength of light, and T is the temperature of the black body. A graph of this relationship for several selected temperatures is shown in Figure 1.

Planck's Law is somewhat cumbersome to use, and in many cases one only cares about the peak wavelength emitted from a black body. We may find this with Wien's Displacement Law [3]. Wien's Law relates the most emitted wavelength of blackbody to its temperature as

$$\lambda_m T = 2.898 \times 10^{-3} \text{ m} \cdot \text{K} \quad (2)$$

where λ_m is the wavelength of the maximum intensity of light emitted from a black body. A graph

of some selected temperatures and their associated peak emission wavelengths is shown in Figure 2.

IV. THERMAL DETECTORS

Thermal detectors are the most widely used and common type of IR detector. IR Thermal Detectors (IRTDs) function via incident photons heating an active element with electrical properties that are dependent on temperature. By measuring the changes in these properties IRTDs are able to detect incoming infrared radiation. IRTDs are relatively insensitive compared to IRPDs, but are simpler to manufacture and use.

There are three main kinds of IRTDs: microbolometers, thermopiles, and pyroelectrics. Each uses slightly different techniques to measure changes in temperature.

A. Microbolometers

Microbolometers detect infrared radiation by measuring the change in resistance of an active element.

Microbolometers consist of an active element which absorbs photons as heat and its support structure. The resistance of the bolometer's active element changes with its temperature as

$$\Delta R = R_0 \alpha \Delta T \quad (3)$$

where ΔR is the change in resistance, R_0 is the initial resistance, α is the temperature coefficient of resistance, and ΔT is the change in temperature in Celsius (or Kelvin) of the bolometer [1]. An example of a microbolometer test circuit is shown in Figure 3. Optionally there may be a reflector behind the active element to reflect incident light not absorbed on the first pass [4]. This significantly improves the sensitivity of the bolometer.

B. Thermopiles

Thermopiles detect infrared light via the Seebeck Effect where a small voltage is generated across a series of thermocouples corresponding to their temperatures [4].

Thermopiles utilize thermocouples, which are made from at least two different materials. As the

Fig. 1. A model of the relative electromagnetic emission intensity versus wavelength for black bodies of temperatures from 300 to 800 Kelvin.

Fig. 2. A model of the predicted peak wavelengths emitted for temperatures between -50 and 600 degrees Celsius per Wien's Law.

Fig. 3. An example test circuit of a microbolometer [1]. V is the bias voltage, i is the current through the bolometer, and V_s is the voltage drop across test load.

thermocouple heats up, the Fermi level of materials in the thermocouple changes and causes the shift of electrons through the thermocouple. This gives rise to a voltage difference in the range of a few millivolts. This signal is then filtered, amplified, and measured to determine the temperature of the junction of the thermocouple. An image of a thermopile is shown in Figure 4.

C. Pyroelectrics

Pyroelectrics function by means to the pyroelectric effect. This phenomenon is similar to the thermoelectric effect, yet is distinctly different.

In the pyroelectric effect a crystal with a pre-existing polarization changes temperature which consequentially creates a voltage difference across the crystal [1].

Fig. 4. A 3-dimensional drawing of a thermopile [4]. Here the thermopile is simply a network of micromachined thermocouples in series.

V. OPTOMECHANICAL DETECTORS

Optomechanical light detectors are a recent invention. These function by transferring the momentum of a photon to a microcantilever and then measuring the displacement of said cantilever to determine the incident photon's properties.

Using de Broglie's relation, the momentum of a photon is proportionally related to its wavelength as

$$p = \frac{h}{\lambda} \quad (4)$$

where p is the momentum of the incident photon. By absorbing an incident photon optomechanical detectors such as microcantilevers detect photons striking their absorbers [5]. This is done because of the conservation of momentum: when a photon is absorbed into a material its momentum is also transferred to that material. The absorbed momentum causes the active area of the sensor to move, which can be then measured.

VI. PHOTODETECTORS

Photodetectors utilize the photoelectric effect. This makes them quite efficient relative to other kinds of light detectors. Unlike other kinds of detectors, photodetectors can be "tuned" to respond to certain frequencies of infrared light. However, photodetectors have traditionally been more difficult to use compared to other kinds of IR detectors.

All photons carry energy. According to Planck's law, the energy of a photon is

$$E_{\text{photon}} = hf \quad (5)$$

where E_{photon} is the energy and f is the frequency¹ of the incident photon. IRPDs function by converting the energy of incident photons into electrical energy either in the form of a current or voltage potential. The proportion of an IRPD's electrical output to its luminescent input is called its quantum efficiency.

$$\text{Quantum Efficiency} = \frac{\text{Energy Output}}{\text{Energy Absorbed}} \quad (6)$$

Sometimes IRPDs are called Quantum Well Infrared Photodetectors (QWIPs). The “quantum well” portion of the name hints how IRPDs function via the photoelectric effect. The effect requires an incident photon to carry a minimum threshold energy; otherwise, the effect will not occur. This minimum energy depends on various factors, including the material and its environment, which complicates the manufacturing process of IRPDs. The factors affecting IRPD sensitivity are discussed later in Section VIII.

VII. THE PHOTOELECTRIC EFFECT

The photoelectric effect occurs when light hits a material and creates an electrical current, called the photocurrent. In 1905 Einstein explained the phenomenon by stating that photons behaved like discrete energy packets. The photoelectric effect depends on the binding energy of electrons to an atom, the atom's electron band structure, and an incident photon's energy.

According to Einstein, the relationship between the maximum energy of an ejected electron E_{max} , the photon's energy, and a “work function” ϕ is

$$E_{\text{max}} = E_{\text{photon}} - \phi \quad (7)$$

where E_{photon} is the energy of the incident photon. Note that the energy of the ejected electron cannot be negative since if $E_{\text{photon}} < \phi$ the photoelectric effect does not occur. This formula is rarely directly used for practical purposes: most literature on optics refers to the wavelength of light. The speed of

light is simply the product of its frequency and wavelength

$$c = \lambda f \quad (8)$$

For Einstein's relation, a more useful formula may be found for Einstein's E_{max} . After solving for frequency in (8) and substituting (5) and (8) into (7) one may find

$$E_{\text{max}} = h \frac{c}{\lambda} - \phi \quad (9)$$

which is more commonly used.

If these were the only factors affecting the performance of optoelectronic devices then they would be widely used, but such is not the case. The craftsmanship, chemical composition, temperature, bias voltage, and even mechanical deformation also change how optoelectronics behave.

VIII. THE WORK FUNCTION

The work function ϕ of a material is the minimum energy a photon must have to induce photocurrent. This is particularly important with infrared optoelectronics - which, relative to visible light, carries less energy. This brings rise to many of the issues associated with use and fabrication of infrared photodetectors.

The work function is an intrinsic property of a material, but its value may change with a material's extrinsic properties such as deformation, temperature, or the presence of a magnetic field.

The work function of a material is related to the material's composition. Specifically, it is the energy required to promote an electron from an atom's valence band to the conduction band. This energy difference is known as the band gap. This is the primary factor which determines the work function of a material.

Most existing literature referring to band gaps assumes that each material has a uniform and constant band gap. This is not the case - to be correct said atoms should be isolated or in a perfect cubic crystal or an infinite Bravais lattice.

A lattice (or repeating arrangement) of atoms will have variation in the binding energy of electrons in each atom's electron orbitals [6]. This is due to the nature of quantum mechanics, Schrödinger's

¹in this text frequency is denoted with the symbol f rather than ν (pronounced “nu”).

Equation as well as the irregular arrangement of atoms [7]. This variable band gap is responsible for the variation of the work function.

IX. MANUFACTURING

Infrared sensors are constructed in a similar fashion to traditional integrated circuits semiconductor. How much the manufacturing process differs from the well-known industry standard varies depends on the type of IR sensor being constructed. For the sake of brevity the phrase “semiconductor fabrication” will be used to refer to the general manufacture of components used in electronics.

The manufacture of photodetectors is the most similar to the well-known silicon process. The sole exception is that the substrate material is typically a Gallium Arsenide (GaAs) wafer instead of the traditional silicon wafer used in production of microchips [1].

The traditional process of semiconductor fabrication uses optolithography (i.e. light imaging) to construct patterns on a substrate (e.g. a silicon wafer). Lithography consists of four general steps: layering, patterning, doping, and heat treatment [8].

Layering consists of chemically or physically depositing a layer of conductive, insulating, or dopant materials onto or into a substrate. This is achieved via either physically depositing material or oxidation of the semiconductor wafer.

In patterning, the top of a semiconductor wafer is covered with a photoresistive chemical. The wafer coated with resist is then exposed to some sort of radiation which causes a reaction in the photoresist. Unwanted resist and material are removed by etching.

The third step in the process is doping, which gives semiconductors their desired effect. In doping elements, electron donors (i.e. negatively charged) and electron acceptors (positively charged) are deposited into the material to create P-N junctions - the building block of transistors.

The final step in the traditional semiconductor fabrication process is heat treatment. In this step, the wafer and deposited layers are heated to high temperatures and annealed (i.e. bound together).

To manufacture optomechanical and thermal detectors, a process known as Microelectronic Machining System (MEMS) is used. MEMS fabrication differs from traditional semiconductor fabrication in that it may be used to create *free standing* structures. To do this, an additional layer is added when creating the device known as the sacrificial layer [9]. As the name implies, it is meant to serve as structural support in the creation of the MEMS device and is later removed (i.e. sacrificed). When the sacrificial layer is removed, any layers deposited on top will now have a void (i.e. empty space) beneath them and will now be free standing.

X. USAGE

Infrared sensitive sensors behave much like potentiometers or variable voltage sources in a circuit. Depending on the necessary sensitivity, power, and noise elimination special consideration must be taken in the use of these sensors.

A. Thermal Detectors

Thermal detectors use a change in either voltage or resistance to detect incident IR light.

Thermal detectors which rely on resistance may use a resistance-measuring circuit such as a Wheatstone Bridge [1]. Detectors which function via changes in voltage potential require a voltage measuring device such as a voltmeter.

B. Optomechanical Sensors

Optomechanical sensors require some method to measure the movement of the cantilever.

One method by which this may be done is by the cantilever as part of a capacitor [10]. By measuring changes in capacitance, the movement of the cantilever can be found. For this the capacitance is modeled as a parallel plate capacitor with variable distance d between the plates. This can be expressed as

$$C = \epsilon_0 \frac{A}{d} \quad (10)$$

where ϵ_0 is the permittivity of the space between plates, A is the overlapping area between the plates, and d is the distance between the plates.

Another fashion this may be done is by attaching a strain cell to the cantilever. By measuring the change in resistance of the cell, the displacement of the active area may be found. A third recently-developed method uses interferometry, where an interferometer is used to determine the displacement of the active area [5].

C. Optoelectronic Sensors

Until this point, this text has neglected to mention the primary difficulty in using optoelectronic sensors: most IRPDs must be cryogenically cooled to achieve acceptable levels of signal-to-noise.

The cooling of conventional IRPDs is necessary because at higher temperatures so much noise is detected by the sensor that it drowns out the actual signal. This noise is caused by leakage (or dark) current, and occurs in all semiconductors.

Supercooling of IRPDs prevents this by lowering the material's Fermi Level, which is related to temperature. When the Fermi Level is sufficiently lowered electrons are no longer present in the conduction band of atoms in the sensor. This means that zero electrons are available, and no current occurs. Electric current will only flow when an electron is excited by the photoelectric effect.

Recent efforts have attempted to create IRPDS which function acceptably at room temperature [11]. In their tests Camargo et. al created such a sensor capable of detecting MWIR with high signal-to-noise ratios. These sensors are not as sensitive as their cryogenically cooled counterparts, but represent a substantial improvement in ease of use.

XI. CONCLUSION

Infrared sensors are incredibly useful devices that come in a variety of fashions. These devices function in a variety of ways and depend on various physical phenomena. Electronic IR sensors may be used in safety, military, and even consumer applications.

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