Magenta: Etched Focusing Lens for Photodiode Array

Avalanche Photodiodes

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Introduction

When discussing electro-magnetic radiation, we often use the measurement of photons to describe the intensity of illumination. While using photons to describe illumination works well for theoretical calculations, measuring photons on an individual level is beyond the capability of most light detection systems. However, an avalanche photodiode (APD) utilizes a positive feedback mechanism to generate a measurable signal from a single photon. This is possible by imposing extreme conditions on the diode that causes a large current to arise from the absorption of a single photon.

Background

Semiconductors

Diode are made of semiconductors, materials that can have their electrical properties altered through adding dopants to them. The added dopants alter the electrical properties of silicon by affecting the number of charge carriers within the material. Charge carriers come in two varieties: electrons and holes. Electrons are a negative charge carrier and can be studied as a particle. Holes on the other hand, are not actually particles, but the absence of an electron. When a hole exists, the positive charge generated by the nucleus of an atom is not countered by an electron, thus generating a net positive charge in a region. Holes are not actually particles, but still exhibit many particle-like properties and for an application such as APDs can be discussed as particles. Dopants are used to alter the number of electrons and holes within a material. Dopants come in two varieties: donors and acceptors. Donor dopants are materials such as phosphorus, arsenic, antimony, and bismuth. These materials all have five valence electrons, one more than silicon. When added to silicon in relatively small amounts the donors take the place of a silicon atom and the fifth unmatched electron can leave the donor dopant and become a free charge carrier. Acceptor dopants act very similarly. Acceptors are materials such as boron, aluminum, indium, and gallium. Unlike donors, acceptors have three valence electrons and when the donor sits on a silicon lattice site, three of the nearby silicon atoms have matched electrons and the fourth is unmatched. The lack of an electron creates a gap. A nearby electron then hops to fill the gap. The hole left behind from the moving electron is then the charge-carrying hole.

Diodes

When a semiconductor such as silicon is doped with donors or acceptors, the natural charge carrying method is disrupted. The increase of holes or electrons creates a similar decrease in the other charge carrier within the doped region. For example, a piece of silicon doped by boron becomes a p-type region where the number of holes increases drastically, and the number of electrons decreases drastically. The carrier type with the lower number of carriers is the minority carrier. On their own each region acts similarly to each other, increasing conductivity as doping increases. However, something interesting happens when the two regions are brought together. When the two regions are placed next to each other, the excess electrons and holes are pulled toward each other due to their opposite charge. They encounter each other and combine to create a region devoid of open holes and free electrons. This region where the electrons and holes are combined is known as the depletion region. The region's width is inversely proportional to the number of dopants injected into the semiconductor.

So as more dopants are injected the width of the depletion region decreases. While the depletion region is lacking in free carriers (holes and electrons), the region is charged due to the holes being filled with electrons thus making P-type regions negatively charged, and electrons leaving N-type regions to fill those holes thus making N-type regions positively charged. The result of the charge imbalance is an electric field within the depletion region. This is like how a capacitor has an electric field due to the buildup of charges on the two plates.

The diode can be manipulated further by changing the external voltage applied to it. If a higher voltage is applied to the P-type than the N-type region the diode will be forward biased. The more forward biased the diode is the more the depletion region will shrink, until the region collapses and allows current to flow mostly unimpeded. If the diode is reverse biased, the N-type is put at a higher voltage than the P-type, the depletion region will grow to accumulate enough charge to match the voltage applied [1].

Avalanche Diodes

While avalanche diodes are derived from classic diodes, the surrounding electronics and conditions imposed on the diode drastically change the governing physics of operation. The most important distinction between classic diodes and APD is that the APD is placed under a high reverse biasing voltage. In classic photodiodes photons that collide with the depletion region generate hole electron pairs. Then the freed minority carriers migrate from the depletion region to their respective end of the diode based on the equilibrium electric field. This ultimately generates current that is linearly proportional to the intensity of the incoming irradiance.

When the depletion region is subjected to a very high reverse bias voltage, like in an APD, the freed minority carriers accelerate in the appropriate direction according to the charge sign. The accelerated carrier in the high electric field influences other bound electrons in the lattice. The accelerated carrier impacts a bound electron acting almost as a billiard ball hitting another. The impact imparts enough energy on the bound electron to promote it from the valence band to the conduction band “freeing” it from the atom. This leaves behind a hole which accelerates in the opposite direction. Now the freed carriers are subject to the high electric field and accelerate, repeating the process until a very large current has arisen from the initial photon impact. The self-sustaining avalanche of carriers is where the device gets its name. Eventually the device reaches a point where the current saturates, and no additional current can be generated. The saturation level is largely determined by outside mechanisms such as the circuit the APD is attached to and the physical parameters of the APD [2].

Quenching Circuits

With the saturated current, the device can no longer give any information on incoming photons as they are encompassed by the large saturated current. The device needs to be reset before further photon counting can occur. There are two primary methods of resetting the device: active and passive external quenching circuits. Passive quenching methods use capacitors and resistors. However, they suffer from long reset times and large areas are required on fabricated devices for resistors.

Active quenching circuits use external sensing circuits to indicate when an APD is triggered. The circuit then reduces the voltage on the diode and resets the diode to its ready state. Active quenching circuits are much more effective than passive circuits at quickly resetting the diode to its ready state. This allows for APD’s with active quenching circuits to count photons at a much faster rate than passive circuits would allow. However, the addition of more electronics onto a chip limits the size of the diode area. Unlike solar cells where the active area (the area sensitive to light) covers most of the space, APD’s active area is often much lower, often on the order of a few up to ten percent of the area on the chip [3]. This results in less photons reaching the active area of the photodiode. To compensate for the reduced photon signal APDs are often equipped with focusing lenses to redirect incoming photons onto the active area of the chip.

APD Parameters

There are a few key metrics that are used to evaluate the performance of an APD: photon detection efficiency, dark count, full-width half-maximum of photon timing, and quenching time. Photon detection efficiency is the likelihood that an incoming photon will cause an avalanche effect and register in the circuitry. The photon detection efficiency can range from as low as a few percent to ~72% with optimal setups and well-designed detectors [3]. Generally, the efficiency increases as a function of applied voltage. Dark count describes the number times per second the detector registers a hit caused by thermal generation of electron- hole pair in the depletion region. The dark count acts as noise in the system and increases as a function of applied voltage and temperature. Full width half maximum describes the variance of the timing measurements. A lower full width half maximum can be achieved by increasing the applied voltage and using active quenching circuits.

Materials used in an APD play an important role in what wavelengths of light the device can absorb. Silicon based structures are used for 450 nm to 1100 nm range whereas indium gallium arsenide photodiodes are used for longer wavelengths [4]. The photodiode in use in our senior design project is an indium phosphide diode used at the important telecommunication wavelengths of 1064 nm and 1550 nm.

Applications

Avalanche diodes are used in a wide variety of applications, including lidar, time of flight 3D imaging, PET scanning, optical communication, and scientific experiments utilizing single photon generation [3]. The advantages of APDs over classic diodes fall into two main categories: detecting low amounts of light (individual photons) and giving accurate measurements of the time between an optical pulse leaving a transmitter and detecting the reflection back at the receiver.

Time of flight imaging is a relatively new technology that utilizes APDs. They operate by sending an infrared/optical pulse and measuring the time it takes to reflect off a surface and return to the sender. Extremely fine temporal resolution is required to get an accurate measurement of the distance the traveled. Signal speed in photodiodes is dependent on the mobility of the carriers which depends on a few physical parameters. However, avalanche photodiodes overcome even slow carrier mobility by introducing an electric field which naturally accelerates the carriers. This reduces the signal response time from around 5-10 nanoseconds in classic silicon photodiodes to only 0.1 nanoseconds in an indium-gallium-arsenide avalanche photodiode. The reduction in response time increases the resolution of an image from 1.5-meter to a 3-centimeter resolution based on the speed of light [3].

Conclusion

Avalanche diodes are an interesting application of the classic photodiode setup and have a myriad of applications from time-of-flight imaging to detection of single photons emitted from scientific experiments. While they are established devices, new technologies create novel applications for avalanche diodes. For our Senior Design project, we are designing focusing lenses to increase the incident illumination on the active area of the avalanche photodiode.

References

[1] S. M. Sze, Physics of semiconductor devices, 2nd ed. New York: Wiley, 1981.

[2] F. Piron, D. Morrison, M. R. Yuce, and J.-M. Redouté, “A Review of Single-Photon Avalanche Diode Time-of-Flight Imaging Sensor Arrays,” IEEE Sensors Journal, pp. 1–1, 2020, doi: 10.1109/JSEN.2020.3039362.

[3] S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa, “Avalanche photodiodes and quenching circuits for single-photon detection,” Appl. Opt., vol. 35, no. 12, p. 1956, Apr. 1996, doi: 10.1364/AO.35.001956.

[4] X. Zeng et al., “Silicon–germanium avalanche photodiodes with direct control of electric field in

charge multiplication region", Optica 6 (6), 772 (2019), doi:10.1364/OPTICA.6.000772