Photodiode Operation

Module 2

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Contents

1 Objectives

This module introduces photoconductors and photodiodes. The module describes their operation and gives details of their performance. After reading this module, the reader will:

- Understand the device physics and operation of a photoconductor and be aware of the various types of photoconductors available.
- Appreciate the operation of p-n, p-i-n, avalanche and Geiger-mode avalanche photodiodes.
- Understand the doping profiles associated with each diode and the bandwidth and quantum efficiency of the diodes.

2 Photoconductors

The photoconductor is probably the simplest of all photodetection devices. It is simply formed as a thin semiconductor layer with two contacts. The photoconductor experiences a change in its conductance as it is exposed to optical radiation. The change in the conductance is directly proportional to the incident radiant power on the device.

The photoconductor has a wide spectral response, comfortably covering the wavelength range from about 250 nm up to approximately 2500 nm, depending on the choice of material used to make the photoconductor. They have reasonable sensitivity, but do not perform as well as junction photodiodes in terms of bandwidth or noise performance. The overwhelming advantage the photoconductor presents is undoubtedly its simplicity and manufacturability which makes it an ideal candidate detector for non-demanding, high-volume, low-cost applications such as proximity detectors for instance.

2.1 Photoconductance

The photoconductor is shown schematically in Fig. 1. When light is incident on the surface of the photoconductor, provided the layer thickness is large compared to the absorption length, then each absorbed photon will produce an electron-hole pair. A bias voltage, V, is applied between the two contact terminals of the device. The resulting Electric field forces the drift of carriers to the appropriate terminal (i.e. electrons drift to the positive terminal). The e-h pairs produced by absorption will drift to the terminals of the photoconductor resulting in a photocurrent in an external circuit. Of course not every generated e-h pair will make it to the electrodes and so the quantum efficiency is less than unity. The semiconductor itself would have to be free from carrier capturing defects and the drift time to the terminals for the carriers would need to be significantly less than the carrier lifetime for the quantum efficiency to approach unity. Defect states in the device are the main source of carrier capture, thereby reducing the number of photogenerated carriers reaching the contacts and reducing the overall quantum efficiency.

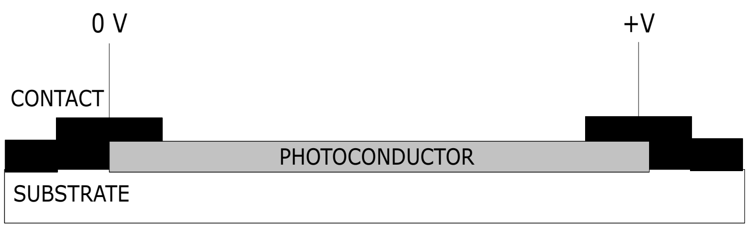

Figure 1: Schematic representation of a photoconductor.

There are other traps in the material that are generally introduced deliberately, by doping. These traps only temporarily capture charge, but release it again after a short characteristic time $\tau_{n,p}$. Suppose a hole is trapped by such a state, its partner electron will continue to drift to the anode where it is collected. This results in a net charge imbalance in the semiconductor, which lowers the potential at the cathode and forces the injection of an electron from the cathode to try to restore the charge balance. The balance is generally not restored until several electrons have been injected and collected at the anode, before the trapped hole is released after a mean trap time of τ_p. This has the effect of producing a gain in the photocurrent:

$$M = 1 + \tau_{n,p}/T \tag{1}$$

where $\tau_{n,p}$ is the trapping time for electrons and holes, T is the drift time for a carrier to travel between the anode and cathode (or vice-versa) and the 1 is to take account of the original generated e-h pair. The drift time can be expressed in terms of the distance between the contacts divided by the drift velocity of carriers:

$$T = L/v_{n,p} = L/\mu_{n,p}E = L^2/\mu_{n,p}V \tag{2}$$

$$M = 1 + \tau_{n,p}\mu_{n,p}V/L^2 \tag{3}$$

It is evident that the trapping gain is related to the applied bias, the geometry of the device and the mobility properties of the material that forms the photoconductor.

The conductance of the device $G = I/V$ has a strong linear dependence on the detected optical power over several decades for photoconductors where the trapping gain $M >> 1$.

2.2 Types of Photoconductor

Cadmium sulfide, CdS, is the most frequently used photoconductor for visible light applications. Its spectral range covers 350 nm to 1100 nm. It can be used both undoped or doped with $CdCl_2$ and $CuCl_2$. Gains of 10^4 are typical with dark current densities of the order of μA/mm^2 at bias voltages in the 80 V range. Trap lifetimes are nominally 50 ms for holes.

Cadmium selenide also uses Cl and Cu as dopants with a hole trap lifetime of about 10 ms, a typical dark current density of 10μA/mm^2 at a bias voltage of about 20 V. The spectral response is red-shifted by about 100 nm compared to CdS.

Other common materials used in the fabrication of photoconductors include: ZnS, Si, Ge, GaAs, PbO, InSb, HgCdTe and PbSnTe.

3 p-n and p-i-n Junction Photodiodes

3.1 Basics of Operation

A p-n junction photodiode is shown in Fig. 2. It is typically doped p^+-n, with the p^+ region relatively thin so that photons will be absorbed mostly in the depletion region formed at the junction of the p and n-type regions. Carriers generated within the depletion region are separated by the electric field present and they are collected at the ohmic contacts after drifting through the depletion region. The response time of the detector is on the nanosecond timescale because of the inherently high mobility of the carriers. Carriers that are generated outside the depletion region do not generally contribute to the photocurrent, only e-h pairs generated within a minority carrier diffusion length of the depletion region will be captured and swept by the electric field. These carriers will contribute to the photocurrent, but because there is a large element of diffusion involved in this mechanism it has a larger characteristic time on the order of microseconds, compared to the nanosecond timescale for carriers generated within the depletion region.

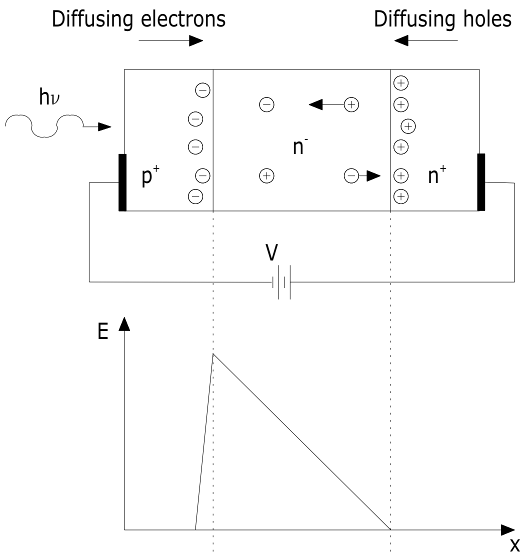

Figure 2: Schematic representation of a p-n diode.

Since it is most desirable to generate most of the carriers within the depletion region, it is important that the depletion region is large. This is generally achieved by reverse biasing the p-n junction. Most of the generated carriers will cross the depletion region and reach the contacts without recombination, particularly if the semiconductor material is of sufficiently high quality. This means that the internal quantum efficiency (the ratio of collected carriers to absorbed photons) is close to unity.

3.2 p-i-n Photodiodes

The p-i-n photodiode has an undoped or intrinsic region inserted between p^+ and n^+ regions. The intrinsic layer has a low density of free carriers and is fully depleted at moderately low values of reverse bias. Almost the entire applied bias is dropped across this intrinsic region. The width of the intrinsic region is chosen to obtain a relatively high quantum efficiency (wide depletion layer required) while at the same time achieving a fast response (narrow depletion layer required). Since the requirements for both are opposites, this leads to an inherent trade-off. Fig. 3 shows the structure, band diagram and electric field profile of a reverse biased p-i-n diode.

4 Avalanche Photodiode

The avalanche photodiode (APD) differs from both the p-n and p-i-n diodes in that several e-h pairs are produced from a single absorbed photon. Thus the APD possesses an internal gain, established by the process of impact ionisation. The internal gain of the APD is one of the reasons these detectors are chosen for sensitive optical receivers.

A typical APD structure is shown in Fig. 4. This is the general structure for a separate absorption and multiplication APD (SAM-APD). Under high reverse bias the APD breaks down because charged carriers in the device are accelerated by the strong electric field present. These carriers have sufficient kinetic

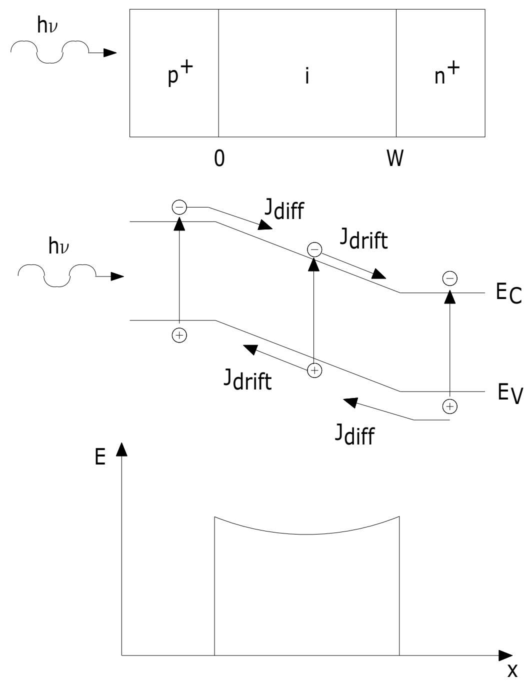

Figure 3: Structure, band diagram, electric field profile and absorption/carrier generation in a reverse biased p-i-n diode.

energy to ionise atoms in the semiconductor crystal upon impact. These impact ionisations generate additional carriers which are also accelerated by the electric field leading to a rapid increase in current flow causing avalanche breakdown in the device.

In Fig. 4 the structure is optimised to ensure that photons are mainly absorbed in the lightly doped semiconductor region, forming e-h pairs. Carriers drift under the electric field gradient present in the absorption region until they reach the edge of the gain region. All carriers that reach the gain region are accelerated by the large electric field present and are given sufficient energy to undergo ionising collisions with the crystal lattice, releasing additional carriers which may also participate in additional impact ionisations leading to the rapid build-up of an avalanching current.

The SAM-APD is used to balance the need for a relatively high quantum efficiency by having a large absorption region, while at the same time having a

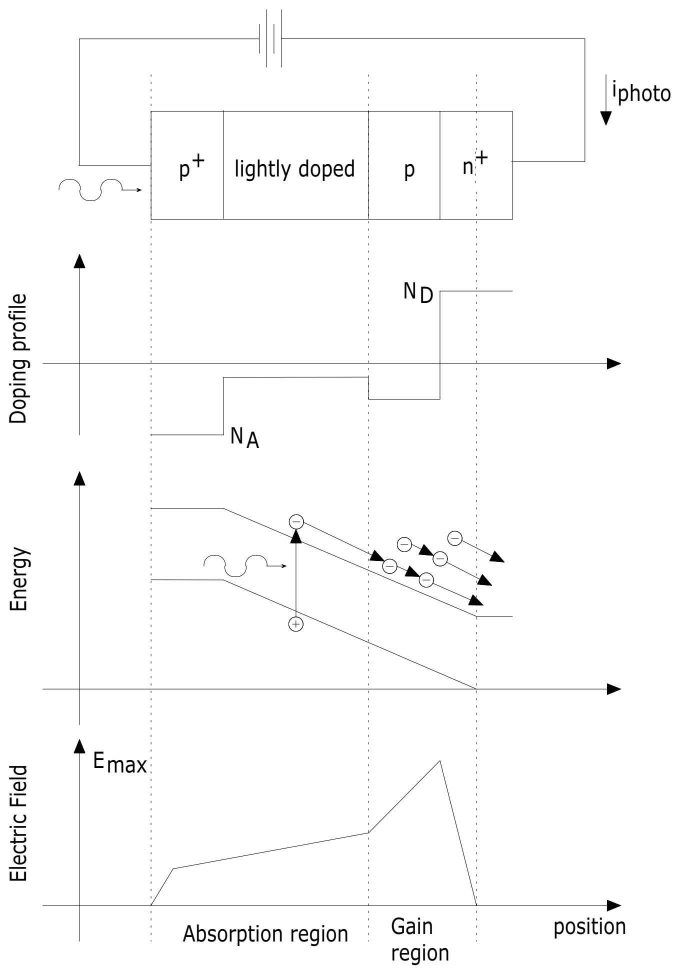

Figure 4: Separate absorption and multiplication APD, showing the diode structure, doping profile, band diagram and electric field profile.

relatively short multiplication region to ensure uniformity in the breakdown of the junction. The uniformity of the junction breakdown is critical when the APD is to be operated in the Geiger-mode (above breakdown) as any inconsistencies in the junction lead to local *hot spots* of localised breakdown that are usually termed *microplasmas*. Several structures have been employed to ensure that the junction breakdown is itself limited to the central active region of the APD and not at the edges. Examples of such structures include the guard-ring, mesa and bevelled edge devices.

4.1 Impact Ionisation

The process of avalanche breakdown is initiated by carriers with sufficient kinetic energy to ionise atoms in the semiconductor crystal upon impact, thereby generating further carriers that may themselves undergo ionising collisions. If an ionisation coefficient is defined for both electrons and holes then an important parameter for describing the performance of avalanche photodiodes is the ratio of the ionisation coefficients for electrons and holes given by:

$$k = \frac{\alpha_h}{\alpha_e} \tag{4}$$

The ratio can also be written α_e/α_h, since the important point is that one of the carriers should dominate the ionisation process i.e. it is desirable that $k \to \infty$ or $k \to 0$ for this to occur. It is undesirable that $k \to 1$ as this means that both carrier types participate equally in the avalanche process. By having an asymmetric avalanche process, the avalanche proceeds in a well-defined manner requiring the minimum transit time across the gain region. If however, $k \approx 1$ then the avalanche has no set direction across the gain region and in fact oscillates back and forth leading to additional uncertainty in the multiplication process and an increased time to clear all of the ionising carriers. It is fortunate therefore that in silicon electrons are much more ionising than holes and values of k between 0.003 and 0.01 are readily obtained.

Even in the ideal cases where $k = 0$ or $k = \infty$ there is uncertainty and randomness associated with the number of generated carriers per primary carrier. This is a source of noise unique to devices with gain and it is typically referred to as multiplication noise or excess noise.

4.2 Multiplication Gain

The gain or multiplication factor of an APD is given by:

$$M = \left(\frac{I_{mult}}{I_{primary}}\right) \tag{5}$$

where I_{mult} is the current measured in the APD under illumination at some bias value close to breakdown, where the gain is greater than unity and $I_{primary}$ is the internal photocurrent before multiplication takes place.

The expressions for electron and hole multiplication in a gain region of length, l_g are [1]:

$$M_e = \frac{1}{1 - \int_0^{l_g} \alpha_e exp(-\int_0^x (\alpha_e - \alpha_h) dx') dx} \tag{6}$$

and

$$M_h = \frac{exp(-\int_0^{l_g} (\alpha_e - \alpha_h) dx)}{1 - \int_0^{l_g} \alpha_e exp(-\int_0^x (\alpha_e - \alpha_h) dx') dx} \tag{7}$$

It is difficult to obtain exact solutions to Eq. 6 and Eq. 7 since the ionisation coefficients in most devices are functions of position in the gain region. It is common to use least square fits to experimental data. There are also special cases that lead to closed form solutions, one example of this is the case where $\alpha_h \neq \alpha_e$, where only electrons are injected into the gain region having a uniform electric field and a large number of ionising collisions occurs per primary electron. In this case the electron multiplication is given by:

$$M_e = \frac{1 - k}{exp(-(1 - k)\alpha_e l_g) - k} \tag{8}$$

For the case where $k = 1$ this reduces further to:

$$M_e = \frac{1}{1 - \alpha_e l_g} \tag{9}$$

4.3 Bandwidth of the APD

The main limitations to the bandwidth of an avalanche photodiode are the RC time constant, the transit time and the avalanche build-up time.

The separation of charge in the depletion region of the APD can be modelled as a parallel-plate capacitor whose area, A, is the cross-sectional area of the depletion region. The separation between the capacitor plates is the width of the depletion region, W. Thus the junction capacitance is given by:

$$C_j = \frac{\epsilon_r \epsilon_0 A}{W} \tag{10}$$

where ϵ_r is the relative permittivity of the semiconductor and ϵ_0 is the permittivity of a vacuum.

The photodiode has an internal resistance associated with the bulk series resistance and the contact resistance. The series resistance (R_s) and the junction capacitance (C_j) are responsible for the RC time constant and the cut-off frequency due to this is:

$$\omega_{RC} = \frac{1}{R_s C_j} \tag{11}$$

The cut-off frequency due to the time it takes carriers to cross the depletion region is given as:

$$\omega_t = \frac{2.78}{t_t} \tag{12}$$

where $t_t = W/v$ is the carrier transit time and v is the carrier drift velocity. The bandwidth of the APD is independent of avalanche multiplication for the case where $M < \alpha_e/\alpha_h$. Under these circumstances the ultimate bandwidth achievable is determined solely by the RC time constant and the carrier transit time. The bandwidth is thus estimated as:

$$B = \frac{1}{\sqrt{\left(\frac{1}{f_{RC}}\right)^2 + \left(\frac{1}{f_t}\right)^2}} \tag{13}$$

where $f_{RC} = \omega_{RC}/2\pi$, and $f_t = \omega_t/2\pi$.

For the case where $M > \alpha_e/\alpha_h$ the multiplication build-up time severely limits the bandwidth. The bandwidth equation is as before, except that ω_t is now $1/t_{eff}$ where $t_{eff} = t_a + t_h + t_m$. The transit time is now included in t_{eff} as t_a - the time taken for an electron to transit the absorption region, t_h - the time taken for holes generated in the multiplication process to transit both the gain and absorption regions and t_m - the time taken for electrons to transit the gain region.

5 Geiger-Mode Avalanche Photodiodes

5.1 Principle of Operation

As the bias voltage applied to an APD is increased approaching the breakdown voltage of the device the gain begins to increase rapidly. As breakdown approaches the gain becomes so great that only a few primary carriers are required to generate a self-sustaining avalanche current. Once the device is biased above breakdown the electric field is close to the critical breakdown field for the semiconductor and a single charge carrier entering the depletion region of the device is sufficient to cause a self-sustaining avalanche current to be generated. The magnitude of the avalanche current is limited only by the reverse on resistance of the device and any external resistance connected to the device. The device is thus biased in the so-called *Geiger-mode* and the detector becomes statistically sensitive to single photons of light. Geiger-mode avalanche photodiodes (GM-APDs) are sometimes also known as single-photon avalanche diodes (SPADs).

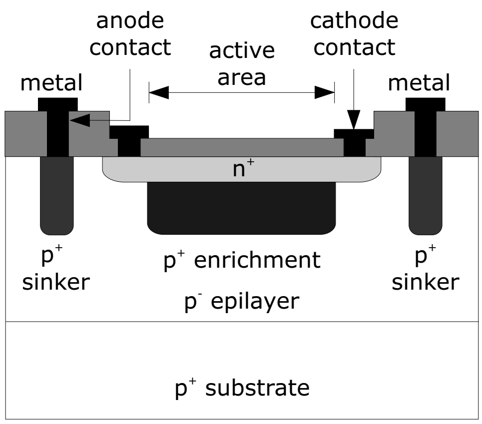

Figure 5: Schematic representation of a silicon Geiger-mode avalanche photodiode.

In reality, an APD biased above breakdown will be sensitive to any charge carrier entering the depletion region. It does not discriminate between photogenerated carriers and thermally generated carriers. Avalanche events triggered by thermally generated carriers are a source of noise in the detector and they lead to *dark counts*, which must be subtracted from the mean measured countrate to determine the signal count.

Since the device is biased above breakdown, one would expect that an avalanche current should automatically flow in the device. This is not the case - in fact the diode can be held in a quiescent state above breakdown until a charge carrier enters the depletion region causing the avalanche current to flow. Since the avalanche current is self-sustaining the device is no longer sensitive to additional photogenerated or thermally generated carriers unless the diode is turned off and subsequently reset to its quiescent state above breakdown awaiting for the next charge carrier to create another avalanche event. To turn the avalanche current off it needs to be *quenched* by reducing the bias voltage below breakdown. The device can then be reset above the breakdown voltage to await the carrier that will create the next self-sustaining avalanche current. The process by which this occurs is described in Modules 5 and 6.

5.2 Device Structure

A typical silicon Geiger-mode APD structure is shown schematically in Fig 5. The main points to note in this structure are:

- the active junction is formed by a shallow n^+ implant over a p^+ well
- the n^+ region extends laterally beyond the p^+ well to provide a virtual guard ring, which ensures that the edges of the device breakdown at a larger voltage than the active junction
- the doping profile is engineered to set the depletion region width close to 1μm wide to ensure a large enough region for multiplication
- the doping profile also sets the peak electric field close to the critical breakdown field in silicon while maintaining a low breakdown voltage (~ 30 V)
- the structure provides lateral conduction with both anode and cathode contacts on the top surface of the device

- the active region is circular and its active diameter can be fixed between 10 μm and 500 μm

The process used to fabricate these planar devices is CMOS compatible which allows for integration with CMOS electronic circuits. The devices are robust, small in size, mature in technology, easily packaged in different configurations, immune to strong magnetic fields, and are not damaged by exposure to high light intensities.

6 Summary

This module has examined photoconductors and photodiodes. It has described photoconductor operation and the different photoconductor types available. Most importantly, however, the module has introduced the photodiode. The operation of p-n, p-i-n, avalanche and Geiger-mode avalanche photodiodes has been described. Emphasis has been placed on doping profile, bandwidth and quantum efficiency in the descriptions.

7 Acknowledgements

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References

[1] S.B. Alexander. Optical communication Receiver Design. *SPIE Press*, 1997.