A New Type of Photodetector - the Dynamic Photodiode

Traditionally, photodiodes operate at static reverse bias and incident light intensity is obtained from a relatively weak photocurrent. We introduce a new concept of photodiode operation: the photodiode is used in a dynamic regime where it is switched from the reverse to forward state. Thus, the light intensity is defined not by the measured photocurrent but by the delay time of appearance of the strong forward current with the amplitude independent of the light intensity. This new mode of photodiode operation provides a great improvement of the device performance.

Semiconductor photodiodes are the most common type of photodetector and are widely used in the electronics industry from ambient light sensors to wide bandwidth optical telecommunications systems. The technology of photodiodes was developed long ago, in the 1950s. Apart from the introduction of the PIN photodiode at the end of the same decade[1], conceptually, nothing changed since that time. A PIN photodiode contains two strongly p- and n-doped regions separated by a weakly doped (or undoped) region (schematically shown in Fig. 1a).

All photodiodes operate the same way: the diode is kept at a fixed reverse bias (point A on the dark current-voltage (I-V) curve of a PIN diode which is shown in Fig.1b), where the dark current is very small. Under illumination the device current increases proportionally to the rate of absorbed photons. However, typically this photocurrent is rather small and an external amplifier is generally required. The amplifiers consume power and silicon area, have limited bandwidth, and introduce additional noise. That’s why in applications requiring fast measurement of weak light signal, like Time-of-Flight (ToF) 3D sensing, detectors with an internal gain are used. These detectors, such as Avalanche Photodiodes (APD) and Single Photon Avalanche Diodes (SPAD) use impact ionization mechanism to amplify the signal. This mechanism requires high voltage, which makes their integration into mobile devices complex and expensive.

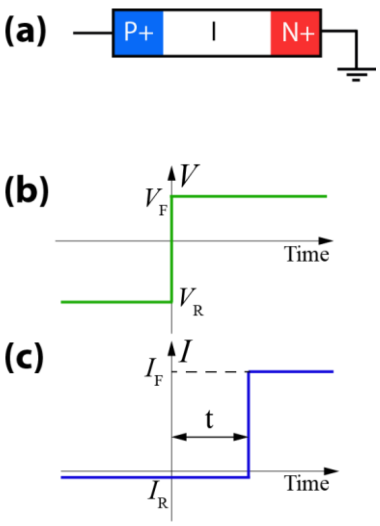

Figure 1. PIN diode in dynamic mode. (a) A schematic PIN diode structure. (b) Applied voltage and (c) current time dependence for Dynamic Photodiode (DPD). Triggering (delay) time *t* depends on light intensity.

The Dynamic PhotoDiode (DPD) uses an operating mode of the PIN diode where the applied voltage is switched as is shown in Fig.1b from negative (reverse) to positive (forward). Applied forward bias induces a large forward current after a *time delay* (Fig. 1c). The forward current magnitude is controlled only by the applied voltage, and its value does not depend on the light intensity. In contrast, the *delay time* is a function of the absorbed *light power*.
The high amplitude of output signal allows direct integration of DPD with digital circuits, without any analog amplification. As a result, there is no additional noise in the system and the detector is shot-noise limited over the whole range of light intensities. At the same time, DPD operates at voltages around 1 V and can be manufactured with standard CMOS technologies.

The device behavior can be explained with an equivalent circuit that consists of a photodiode, capacitor, and a comparator (Fig. 2). Under illumination, DPD integrates the photo-generated charges up to a certain critical charge Q_{crit} before device triggers and a strong forward current flows. The positive feedback mechanism guarantees a fast switching.

For higher light intensities, the capacitor charges faster and the triggering time is shorter. The triggering time T_{trig} is inversely proportional to light intensity I_{light}: $T_{trig}= Q_{crit}/(QE*I_{light}+i_{dark})$, where i_{dark} is the dark current, QE is the quantum efficiency. The critical charge depends on the device geometry and bias voltage and can be adjusted to optimize DPD performance for the particular application.

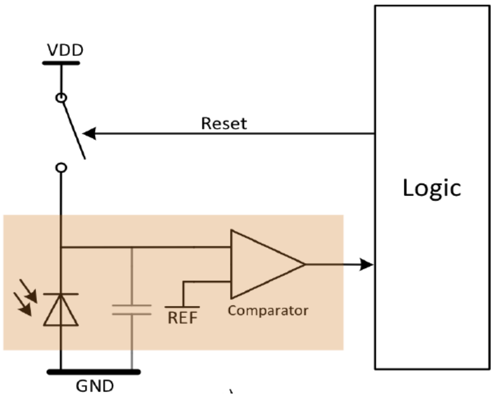

Figure 2. DPD equivalent circuit. Dynamic Photodiode replaces a standard photodiode, capacitor, and comparator.

Depending on the application, device geometry and voltage biasing can be tuned in order to set Q_{crit}, which can vary from 10^8 electrons down to 1.

In darkness, triggering times in the 100ms range can be reached. For high intensities, sub nanosecond triggering times are possible. Hence, the DPD has an extremely high dynamic range, limited by dark current on the low-light side and by the resolution of the time to digital converter (TDC) on the strong-light side.

Measuring the delay time of photocurrent instead of its magnitude provides a new way of light sensing. An important feature of the DPD is high output signal, which is normally several orders of magnitude higher than that of a standard PIN photodiode. Here, we should say that any PIN photodiode could in principle operate in the proposed dynamic mode, although device optimization is required to obtain desired characteristics.

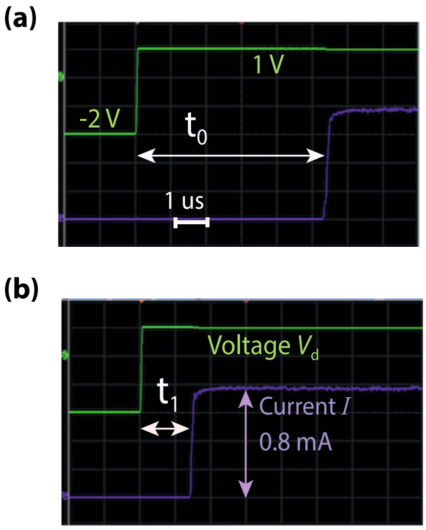

Figure 3. Measured output current. Scope screen shot of applied voltage V_d and output current I with and without light. Triggering time t decreases with light intensity increasing. Triggering time t_0=5.5 µs - no light (a), t_1=1.5 µs - absorbed power 35 nW (b)

Figure 3 illustrates the performance of a real device in the dynamic regime described above: an optimized PIN structure is switched from the reverse to the forward state with the delay time dependent on the continuous light intensity. The switching from the low current to the high-current state occurs very abruptly, which is favorable for precise measurements of the delay time. The DPD output current of 0.8 mA is more than four orders higher compared to the output current which could be achieved with a normal photodiode at absorbed power of 35 nW (the maximum absorbed power in this experiment). Typically, dependence of the reciprocal triggering time on the absorbed light power is linear, as it is shown in Fig. 4.

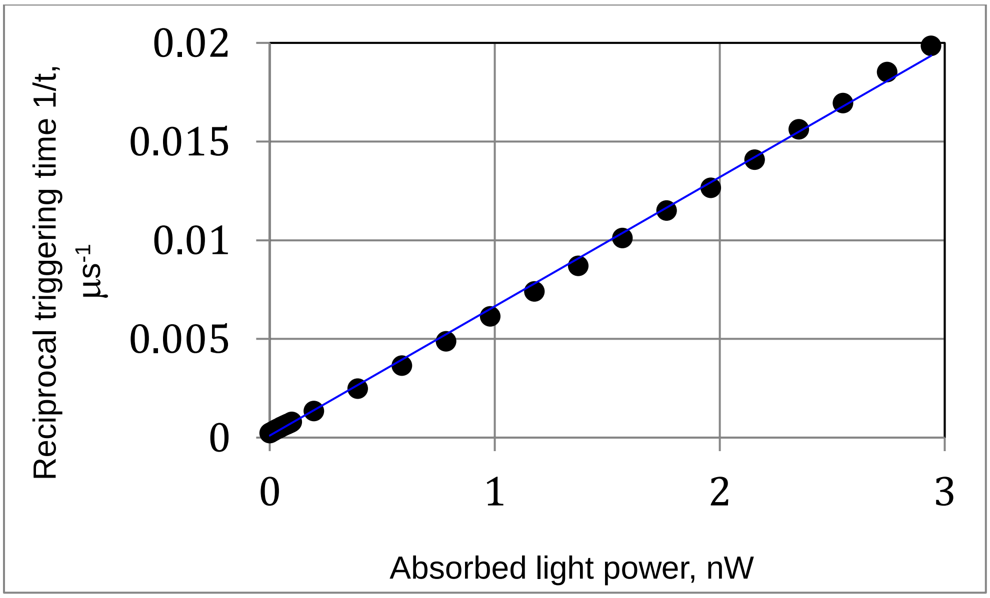

Figure 4. Reciprocal triggering time as a function of the absorbed light power. The measurements were done with 635 nm continuous wave light source.

DPD IP includes two families: Stand-Alone and Embedded detectors. Stand-Alone DPD can be produced with a very simple and low-cost process. The device is flexible in size and can be used to replace discreet photodiodes. The structure is compatible with non-silicon materials and thus can be used for a longer wavelength (SWIR) detection.

Embedded DPD can be produced with CMOS technology. The detector and circuits can be integrated on the same chip. It can be used to produce arrays with the small pixel size.

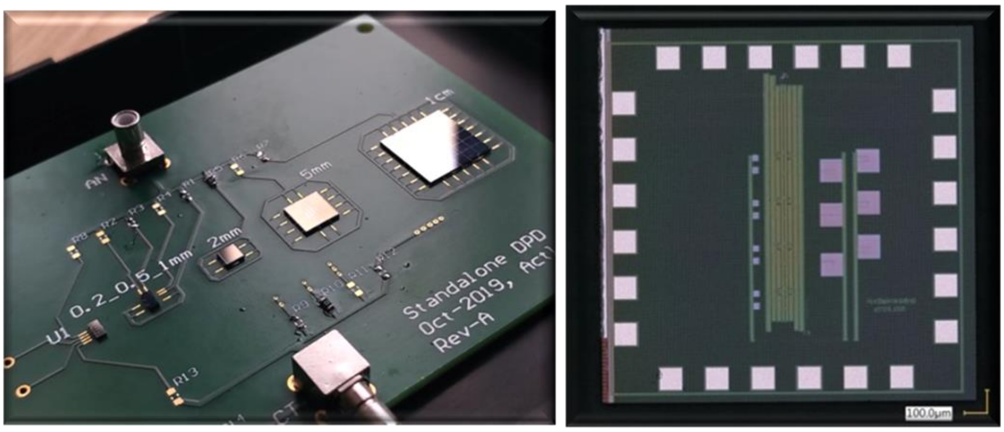

Figure 5. Stand-alone (left) and Embedded (right) DPD.

Application Example:

Vital signs monitoring for wearable devices

In the last years, the number of wearable devices used for health monitoring, sport and fitness tracking has experienced a strong growth. These devices require accurate, low power, and affordable vital signs sensors. Photoplethysmography (PPG) is a technology of choice for wearable devices, enabling the monitoring of vital signs such as heart rate, blood oxygen saturation (SpO2), and blood pressure.

In PPG sensors, the light emitted by LEDs and reflected from the human tissue is measured with a photodiode. The reflected signal depends on the blood concentration in the tissue. With each cardiac cycle heart pumps blood, which change absorption and, consequently, the light intensity at the photodiode. The modulation of the photodiode signal gives information about vital signs. This modulation is typically small (0.1%-1%), and a good signal-to-noise ratio (SNR) is essential to provide a reliable data.

Figure 6(a) shows general structure of a PPG system with a standard photodiode and analog front-end (AFE); many commercially available integrated designs use this principle. The AFE is the main source of noise, and the LED power should be relatively high to provide a required SNR. This is the main part of the overall power consumption of the system.

In the case of the PPG system based on DPD with a time-to-digital converter (TDC) depicted in Fig. 6(b) light is converted directly into a digital signal, avoiding the need for an area- and power-consuming analog front-end. The fully digital circuits allow complete removal of the noise associated with the analog signal chain. We demonstrated more than 20 dB SNR improvement at low light conditions compared to state of the art systems. This also means that less light is needed to achieve the same SNR. The LED power consumption can be significantly reduced, improving battery powered devices autonomy. The size of the photodetector also can be reduced which is critical for PPG application in hearable devices.

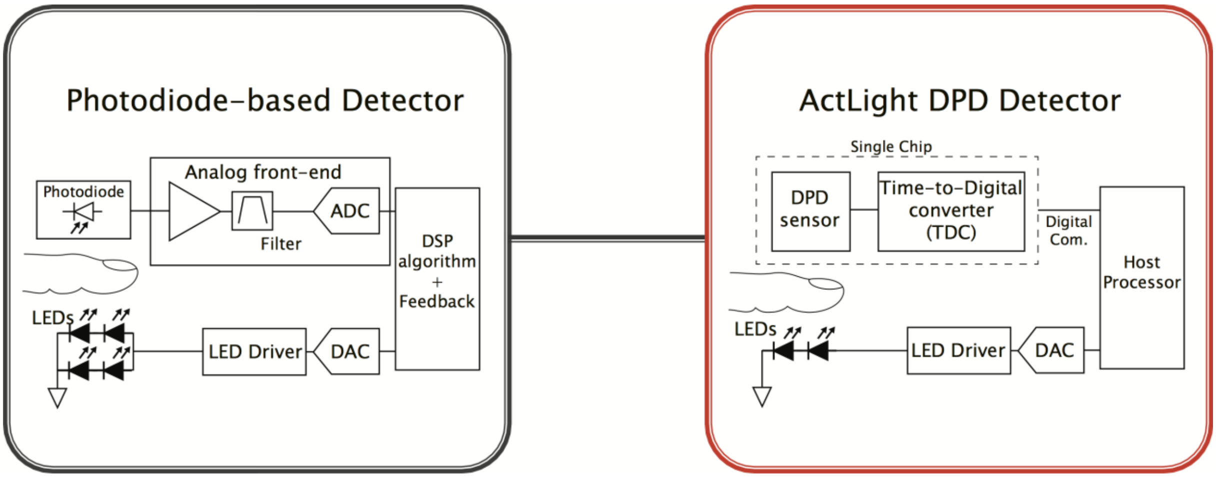

Figure 6. The general structure of PPG system based on standard photodiode (a) and Dynamic Photodiode (DPD) (b).

Investor?

We're happy to discuss. If you're interested in exploring applications, reach out at:

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