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Effects of varying light bias on an optically-addressed two-terminal multicolor photodetector

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ABSTRACT

Multicolor photodetectors often require more than two terminals, making it very difficult to construct multicolor FPAs, due to the increased processing complexity. A novel approach is proposed to overcome this problem: an optically-addressed two-terminal multicolor photodetector. This two-terminal detector design is important for FPAs because it maximizes the fill factor and simplifies the necessary ROICs. This novel device concept is demonstrated using LEDs as the optical bias sources and a three-color detector. Varying light bias levels expose the effects of, luminescence coupling, optical leakage, and shunt leakage currents on the detector performance. The measured dark current, responsivity, and linear dynamic range of the detector reveal a tradeoff between low optical bias for minimal dark current and maximum responsivity and high optical bias for maximum dynamic range for optimal detector performance.

1. Introduction

Multicolor detectors and FPAs have been developed for several defense and commercial applications, such as sensing and imaging [1–3]. Two typical dual-band detectors are the three-terminal with two photodiodes [2] and the two-terminal, voltage-bias-switchable, back-to-back photodiodes [4,5]. Reducing the number of terminals from three to two allows the dual-color detector to be integrated with existing single-color ROICs [6]; however, the number of colors is limited to two. To increase the number of detecting bands, existing multicolor detectors require additional terminals for each pixel [6–8], which greatly complicates the FPA layout and device processing, decreases the fill factor, and increases the ROIC complexity [6]. A novel approach is proposed in this paper to increase the number of colors with only two terminals per pixel. This is accomplished by using a multi-junction detector and appropriate optical biasing to achieve single-color detection. The detector structure and operating conditions are described in detail. Non-ideal effects, such as luminescence coupling, optical leakage, and shunts, are explored using the experimental results for the dark current density, responsivity, and linear dynamic range of a two-terminal three-color detector under varying optical bias.

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2. Detector structure and operation

Fig. 1 is a schematic illustration of the proposed two-terminal photodetector, which consists of multiple photodiodes with different cutoff wavelengths connected in series with tunnel diodes adjoining the photodiodes. The tunnel diodes provide low resistance connections between two photodiodes by converting the electrons to holes, or vice versa, at the junction interface. They absorb little signal light due to very thin layer thicknesses. This structure allows the number of detecting bands to increase without raising the number of contacts above two per pixel. Due to the series connection, the photodiode with the smallest current determines the total output of the device. Optical-addressing of a single photodiode, the active detector, is accomplished by optically biasing all of the other photodiodes with a set of LEDs or laser diodes having output wavelengths within the spectral response range of the individual photodiodes. The spectral response of the active photodiode ranges from the cutoff wavelength of the photodiode above it to its cutoff wavelength.

Fig. 2 shows the ideal *I–V* curves of the individual photodiodes and the load line for the active detector for two input signal intensities resulting in: (a) the photogenerated current from the signal being *less* than the photogenerated current due to the optical bias and (b) the photogenerated current from the signal being *greater* than the photogenerated current due to the optical bias. The optical bias condition in Fig. 2 is such that the photon flux is equal for all of the inactive photodiodes. In Fig. 2a, the optically-biased diodes operate in the photovoltaic mode with their forward voltages determined by the operating current of the entire device [9], which in this case is due to the signal, I_{sig}. The optical bias results

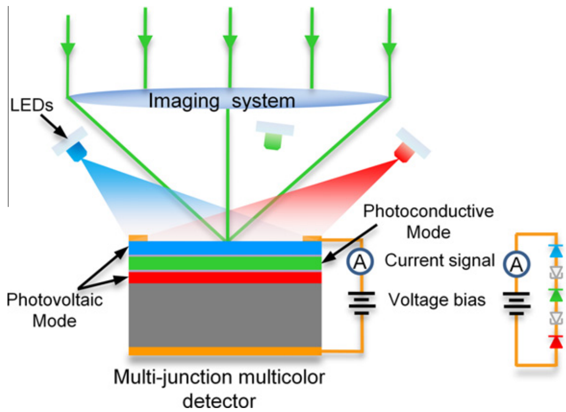

Fig. 1. Schematic diagram of the optically-addressed, two-terminal, multicolor photodetector. The detector structure consists of multiple photodiodes with different cutoff wavelengths connected in series with tunnel diodes between adjacent photodiodes. The LEDs optically bias the inactive photodiodes in the detector to enable single-color detection.

in a reverse voltage bias on the active photodiode, causing it to operate in the photoconductive mode, as shown by the intersection of the active photodiode's *I–V* curve and the load line in Fig. 2a. When the input signal is not within the active photodiode's spectral response range, the total device current is very small (the dark current of the active photodiode). Thus, the device is a single-color detector with the spectral response of the active photodiode only. As long as the photogenerated current due to the signal is smaller than the photogenerated currents from the optically-biased photodiodes, this single-color detection condition is maintained. But when the current generated from the input signal becomes greater than the current due to the light bias, as shown in Fig. 2b, the operating points of the individual photodiodes change. The device current is no longer due to the signal but to the optical bias, and the single-color operating principles just described are not applicable.

In principle, this multicolor detector structure is suitable for any range of the spectrum from UV to infrared and for any number of colors. Practically, the bias LEDs can be mounted on the cold shield side walls between the cold stop aperture and the FPA without affecting the field of view and the cold stop efficiency. This configuration also allows the LEDs to operate at cryogenic temperatures, which increases their efficiencies. Fiber optics or liquid light guides can also be used to bring the LED light to the FPA. A control algorithm can cycle through the various combinations of biasing LEDs to address the different bands and enable multicolor detection. This sequential sampling method, also used for the current two-color back-to-back diode FPA, leads to a tradeoff between frame rate, integration time, and the number of colors for the optically-addressed two-terminal multicolor detector. The two-color three-terminal detectors can sample each color simultaneously, but they suffer from a lower fill factor due to the extra contact, which then requires a longer integration time to reach a certain signal-to-noise ratio, limiting the maximum frame rate. The integration of a multi-junction detector and the optical biasing scheme allows the number of detecting bands to increase without raising the number of contacts above two per pixel.

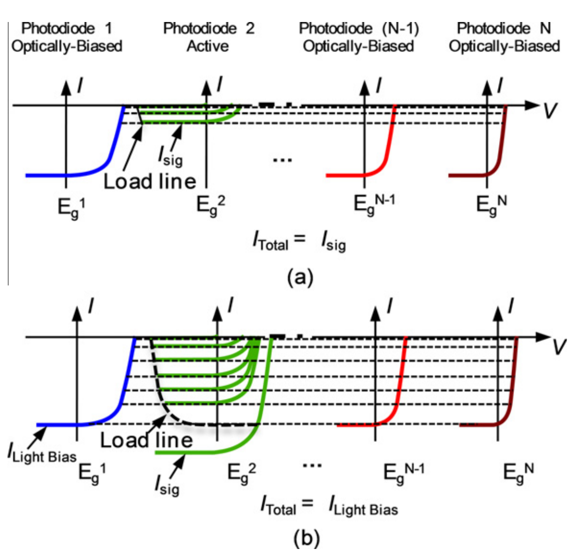

Fig. 2. Schematic illustration of the ideal *I–V* curves of the individual photodiodes and the load line for the active detector for two input signal intensities: (a) the signal intensity is less than the optical bias flux and (b) the signal intensity is greater than the optical bias flux. The optical bias photon flux is equal for all inactive photodiodes.

3. Experimental procedure

To demonstrate this novel device concept, a commercial InGaP/InGaAs/Ge triple-junction solar cell (2 cm × 2 cm) is used as the multicolor photodetector. This is suitable because the solar cell also has a multi-junction structure with diodes of differing band gaps connected via tunnel junctions. The band gaps of the InGaP, InGaAs, and Ge photodiodes are 1.9, 1.4, and 0.7 eV, respectively. LEDs with center wavelengths (470 nm, 780 nm, 940 nm) within the response ranges of the photodiodes are used as optical biasing sources. The photon flux is measured with a calibrated silicon photodetector. The conditions for measuring the "dark" current density vs. voltage (*J–V*) curves (Fig. 3) of the three photodiodes are matching light bias photon flux on the inactive photodiodes and no light bias or signal on the active photodiode. The voltage applied is across the entire device, not just the active photodiode. The spectral responsivity (Fig. 4) is measured using a Newport QE/IPCE system, with the spectral range limited by the monochromator gratings. The bias condition is also equal photon flux illuminating the inactive photodiodes. In addition, a 2.1 V bias across the entire device is used for the Ge photodiode's responsivity to reduce measurement artifacts [9,10]. The linear dynamic range measurement setup is described elsewhere [11].

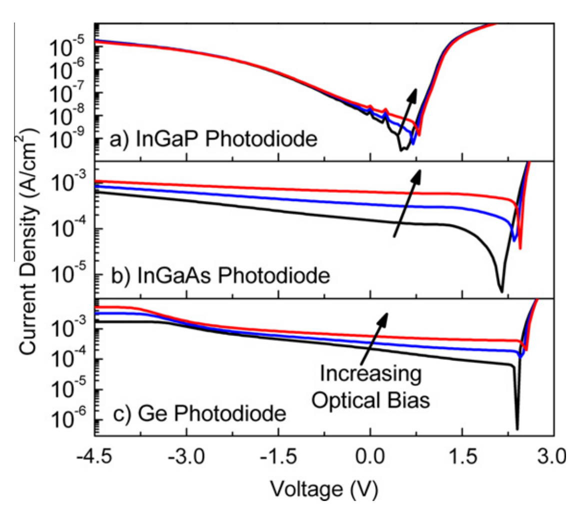

Fig. 3. Dark current density vs. voltage curves under varying optical bias. The *J–V* curves were measured with matching optical bias photon flux on the inactive photodiodes and no input signal to the active photodiode. The voltage is across the entire device, not just the active photodiode.