Novel Standard CMOS Detector using Majority Current for guiding Photo-Generated Electrons towards Detecting Junctions

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A novel photo-detector is demonstrated using a majority current to drive photo-generated minority carriers from deep within the substrate towards a detecting junction. This improves detector sensitivity and speed and allows obtaining simultaneously a large sensitive area and a small detector capacitance, enhancing output signal to noise ratio and/or speed of attached readout circuits. When the applied current is modulated, a very efficient photonic mixer can be conceived, useful as pixel for Time-Of-Flight 3D image sensing. Measurement results in standard CMOS are presented showing an infrared responsivity of 0.32 A/W and a demodulation efficiency of over 99%.

Introduction

In recent years, CMOS image sensors have come into practical use, many mobile applications and digital still cameras employ CMOS image sensors. Solutions to enhance the detector bandwidth or sensitivity have been researched over the last decades, e.g. in [1] higher bandwidth is achieved using blocking metal strips but traded in for overall sensitivity. Next to enhancing detector properties new emerging techniques have created new specific functionality requirements. This is the case in continuous time-of-flight based 3D cameras [3] where in pixel demodulation is needed to measure phase differences of reflected modulated light towards the modulation signal. In such systems demodulation efficiency and overall sensitivity need to be maximized so that high distance accuracy and/or speed can be acquired. Attempting to do this, structures, called photonic mixers [2], were built, having the ability to demodulate incoming light during detection. In this paper a novel standard CMOS photo-detector structure is discussed, that provides potential to improve both sensitivity and speed. Further the structure can also be used to build a very efficient and sensitive photonic mixer.

Majority Current Photo-detector

A standard photo detector has typically drift zones and diffusion zones. Drift is present in the depletion zones of junctions and diffusion is primarily present in the neutral zones. By introducing a current through the bulk at the neutral zone, a moderate drift field can be invoked. This will accelerate detection because minority carriers are now, in contrast to the slower random diffusion, directed and accelerated by the invoked drift-field. Figure 1 shows how such drift-

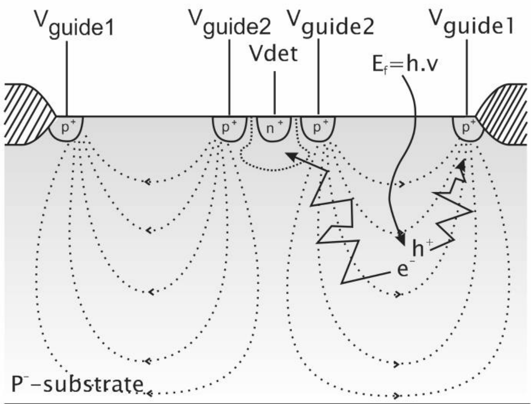


Figure 1: Basic principle of photo-detector based on majority current (Vguide2 > Vguide1)

field can be applied through the use of extra terminals to the p-substrate. Applying a voltage over these terminals (guide1 and guide2) induces a majority current and associated field, separating photo-generated electron hole pairs. The hole will become part of the flowing majority hole current and start moving towards the p^+ region with the lowest voltage. The electron will be accelerated in the opposite direction, driven by the same electrical field. When it comes near the built-in p^-/p^+ barrier of the p-substrate terminal it has, due to its erratic behavior (or diffusivity), a large chance to enter the depletion drift field of the nearby p^-/n^+ junction and thus be detected. In Figure 2 the electron current density vectors around this junction are shown, as simulated by a device simulator, demonstrating that minority carriers pass the attracting p^+ region and get collected in the depletion region at the p^--substrate/n^+-junction. Advantages of this drift based technique are that, because it sweeps minority carriers quickly from deep within the substrate, detector sensitivity and speed are improved. Further, since all generated electrons are guided to one place, a large sensitive area can be achieved in combination with a small detecting junction and capacitance, thereby uplifting output signal to noise ratio and/or speed of attached readout circuits.

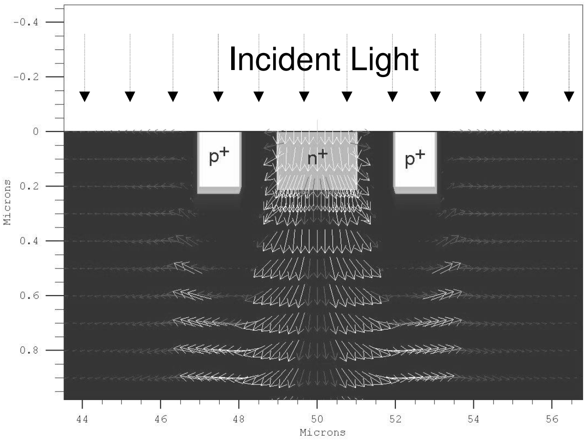


Figure 2: Simulated current density of the minority carriers (electrons) being attracted to the p zone, but getting collected in the depletion region at the pnp-junction

Demodulating configuration

Figure 3 shows an alternative structure having two detector nodes, one at each side. The current sense will now determine to which detector node the photo-generated minority carriers will be guided. By alternating this current, incident modulated light can be demodulated so that a photonic mixer is created. The applied drift field now realizes, next to good sensitivity, fast demodulation with high demodulation efficiency.

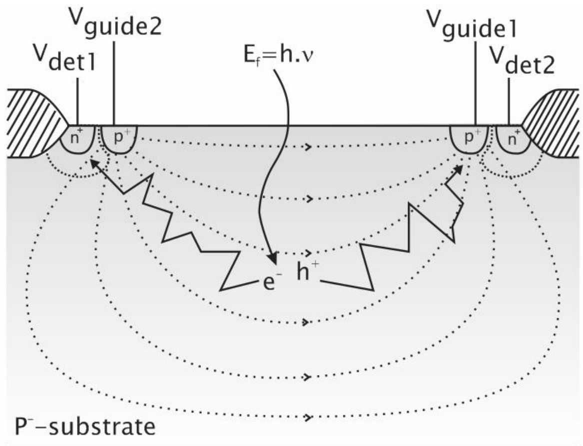
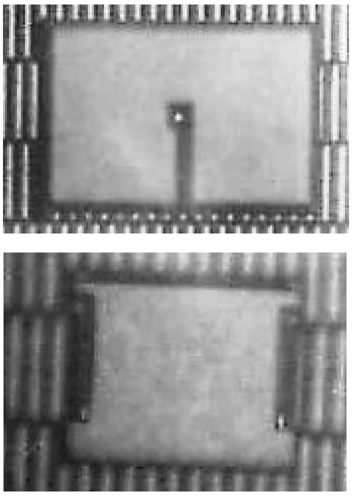


Figure 3: Photonic mixer, whereby the configurable current determines towards which detecting junction the minority carriers are driven

Measurements

Measurements were performed on a test-chip fabricated in standard CMOS XFab 0.35um technology. In this technology a 15um 10Ω.cm epi-layer is used on top of a 7mΩ.cm p-substrate. Measurements were limited to infrared laser light (λ=860nm) because discussed sensor properties will even improve when using shorter wavelengths. In Figure 4 a rectangular 49µm x 33µm prototype is shown (top-left) with measurements of photo-responsivity vs. substrate voltage (right). At a voltage of around 250 mV a value of 0.30 A/W was measured and at a voltage of 720 mV responsivity reaches it's maximum of 0.32 A/W. It is to be noted that responsivity can be significantly boosted if



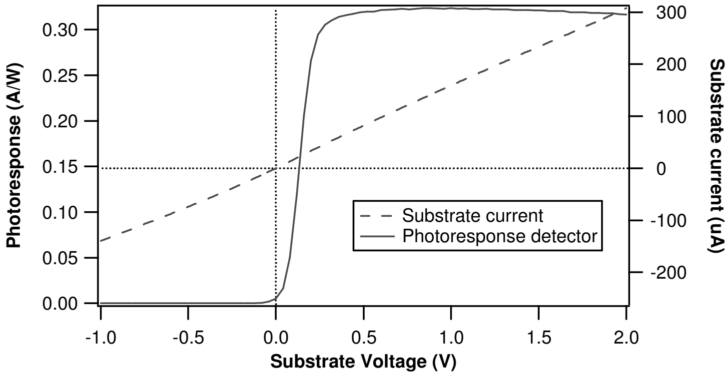


Figure 4: (left) Prototype pictures (top=sensor, bottom=photonic mixer) with measured sensor photo-responsivity vs. substrate voltage (right)

thicker epilayers are used. The associated majority current totals several hundreds of µA and can be considerably reduced by using a higher resistive substrate. Figure 5 (left) shows measured detector currents of the 30µm x 25µm photonic mixer device shown in Figure 4 (bottom-left). The deduced demodulation efficiency (calculated by dividing the difference of the detected currents by their sum), as shown in Figure 5 (right), reaches 87% at a substrate voltage of 1V. A maximum demodulation efficiency of over 99% was measured above 2V. When scaling the detector several properties change : the bandwidth is inversely proportionate to the square of the distance between detector

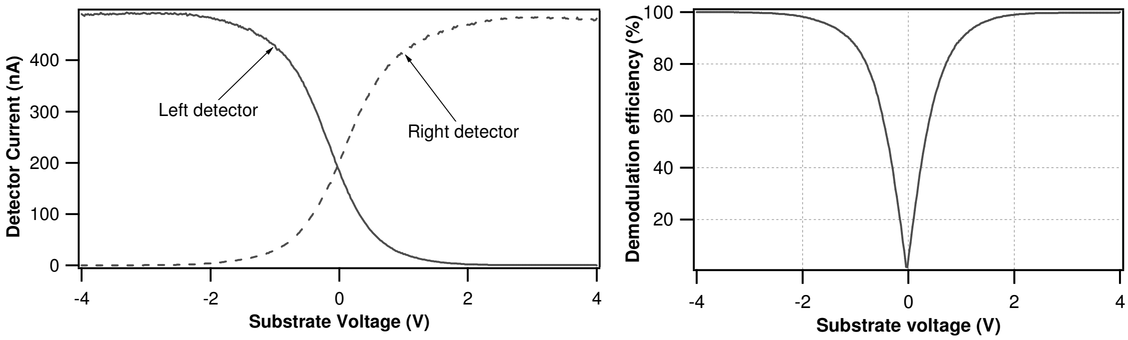


Figure 5: Photonic mixer detector current vs. channel voltage (left) with derived demodulation efficiency vs. channel voltage (right)

nodes. When injector nodes are placed further apart, significant drift field lines will reach deeper in the substrate, enhancing sensitivity at the expense of speed. Figure 6 presents dynamic properties of the detector showing on the left the amplitude of the norm versus mixing frequency when a substrate voltage of 2.2 V is used. The DC mixing efficiency is more or less maintained up to the MHz range, a -3dB frequency was measured at 19,9 MHz. In Figure 6 on the right the measured -3dB frequencies are plotted versus the applied substrate voltage showing the linear relation with a slope of 5 MHz/V. This relation is valid as long as the mean electron drift time is larger than the time the electron needs to travel by diffusion from the attracting p^+ region to the detecting n^+ region. In practice the latter time is less than a ns and thus the relation is preserved up to the hundreds of MHz range. Also to be noted is that, because the photo-generated minority carriers get demodulated in the substrate, the device is able to

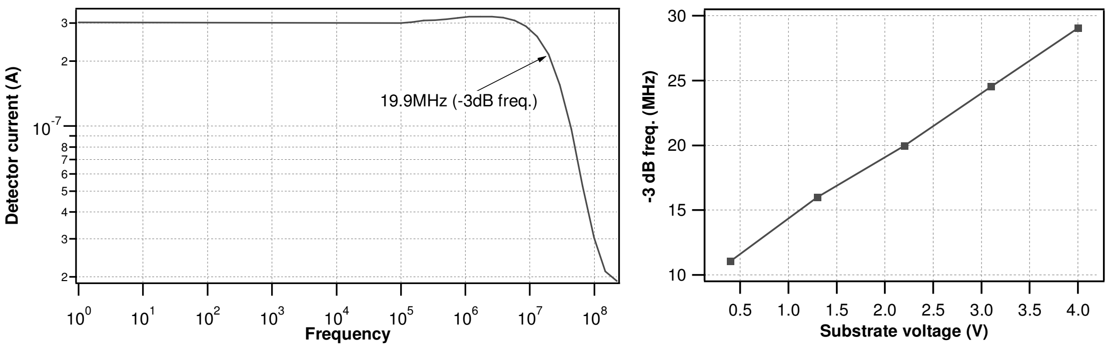


Figure 6: Amplitude of detector current after demodulation vs. frequency for a substrate voltage of 2.2V (left) / -3dB frequency vs. substrate voltage having a linear relation (right)

measure phases even beyond the -3 dB frequency. In [3] another recent photonic mixer is described having a maximum infrared demodulation efficiency of around 48% at modulation frequencies below 300kHz. Figure 7 shows the linearity properties of the photonic mixer of Figure 4 (bottom-left) obtained at a modulation frequency of 10 MHz.

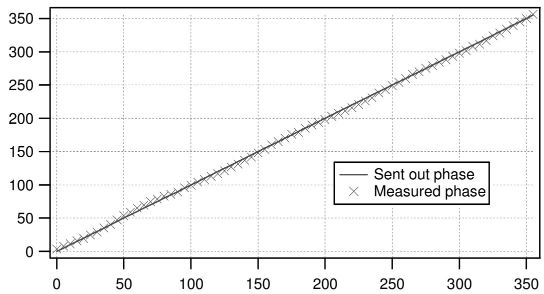


Figure 7: Measured phase linearity when using the photonic mixer structure for phase measurement at a mixing frequency of 10 MHz

Conclusion

In this paper we presented a novel photo-detector with high sensitivity, high speed and low detector capacitance, even when a large sensitive area is required. The detector makes use of a drift field, invoked in the substrate by applying a small majority current, that reaches deep in the silicium to accelerate minority carriers towards the detecting junction. A highly efficient photonic mixer configuration was also discussed. Conducted measurements, using λ=860nm infrared light, confirm above properties. A detector photo-responsivity of 0.323 A/W was measured. The photonic mixer demodulation efficiency measured over 99% with a demodulation bandwidth of 30 MHz for a 4V substrate voltage.

References

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