Fresnel Zone Plates : plasmonics filtering for SPADS sensors

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Abstract: It is proposed to present in this paper the integration of Fresnel Zone Plate (FZP) directly inside SPAD-based test chips in the context of advanced development of Time-Of-Flight sensors. The FZP dimensions and pitches have been estimated using FDTD modeling. We present here spectrum and angular selectivity achieved with such structures.
Keywords: Single Photon Avalanche Diode, Finite Difference Time Domain, Plasmonics, Fresnel Zone Plate, Time-Of-Flight.

In parallel to CMOS image sensors a new market is emerging based on Time-Of-Flight sensors. These sensors are derived from CMOS image sensors technology and are dedicated to sense proximity and/or gesture monitoring and control for mobile phone applications, medical applications, automotive or industrial applications.
Several technologies and architecture solutions address Time of Flight, among them ST proposes products based on Single Photon Avalanche Diode (SPAD). These products are active illumination systems constituted in particular of SPAD return arrays and of near infrared VCSEL emitter.

The small foot-print package of such proximity sensor can be sensitive to ambient light illumination and to internal reflections coming from the emitter. It is proposed to present in this article the integration of Fresnel Zone Plates (FZP) directly inside the back-end of the sensor device in order to improve spectrum selectivity and to narrow angular response of the SPADs.

1. SPADS basics

A SPAD is based on a p-n junction device biased above its breakdown region (“Geiger mode”). The high reverse bias voltage generates a sufficient magnitude of electric field such that a single carrier photogenerated near the depletion layer of the device can cause a self-sustaining avalanche via impact ionisation. This produces a measurable current pulse signaling the arrival of the photon. The avalanche is stopped by a passive or active quenching circuit that allow the device to be “reset” to detect further photons (see Figure 1).
Typically SPAD devices are composed of circular diode with shallow implants that allow high voltage bias (around 14V), driven through an anode finger and a circular cathode (see Figure 2) **[1-5]**.

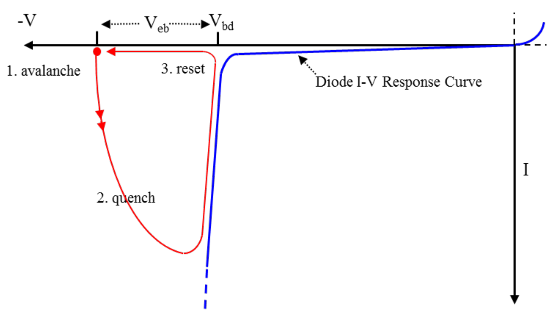

Figure 1 :SPAD basic operations

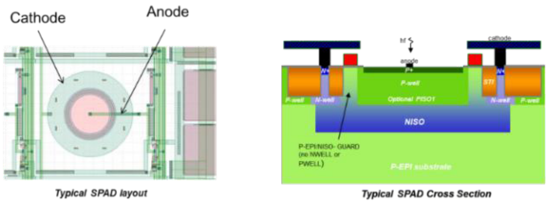

Figure 2 : Typical SPAD design

The photonic sensor is composed of a small footprint module. The return array constituted of SPADS is rather close to the VCSEL emitter. Several filters are dedicated to filter the ambient illumination but internal reflections due to coverglass can induce crosstalk between emitter and return array that can disturb the detection accuracy (see Figure 3). We propose here to describe the introduction of plasmonics-based Fresnel Zone Plate inside the SPAD device to add spectral selectivity and angular selectivity.

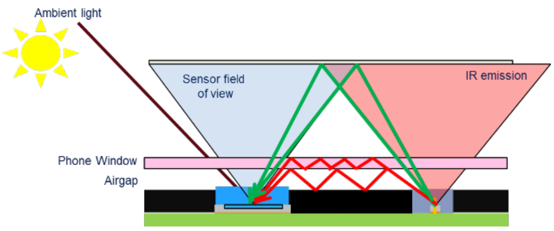

Figure 3 : TOF sensor optical challenges

2. FZP design and simulations

Fresnel Zone Plates are a set of alternate opaque and transparent radially concentric rings that have the property to diffract the incident light, creating constructive or destructive interferences at the desired focus. It is possible to design and fabricate rings in compatibility with CMOS fabrication process directly inside the oxide layers of the SPAD, by using a given metal level. At this scale, the dominant effect that drives the interferences is plasmonics: an incident electromagnetic wave reaching a metal layer can induce a surface current. The resulting electron density wave that propagates along the surface of the metal is referred to as surface plasmon polaritons which in return interact with the incident photons. Depending on the dimension characteristics of the rings, the surface plasmons resonance can be tuned to optimize the wavelength selectivity of the structure. As the FZP have the ability to refocus the electromagnetic waves as a large aperture lens, it is possible to narrow the angular response **[6-11]**.

We have designed and simulated such structures on a real layout of SPAD using Finite Difference Time Domain solver (Lumerical) (Figure 4).

Several trials have been defined in compatibility with CMOS fabrication process, the rings widths and spacings have been estimated in order to bracket worst cases and best cases from spectral selectivity point of view.

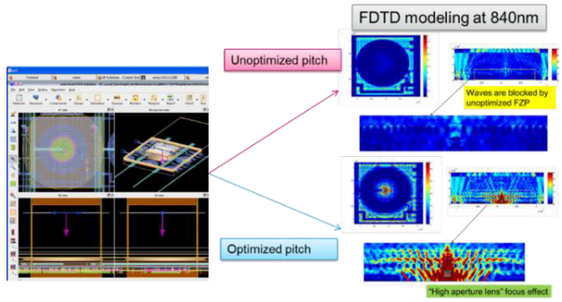

Figure 4 : FZP FDTD modeling

3. FZP implementation and characterization

Among other variants 25 predefined trials have been embedded on a 32x32 SPADS testchip (see Figure 5).

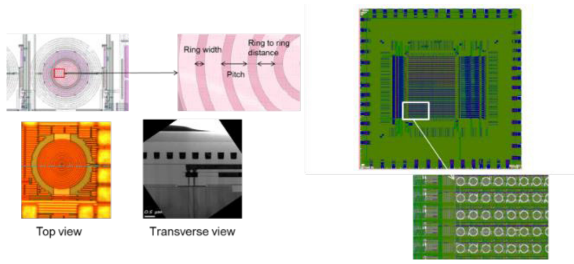

Figure 5 : FZP implementation on a 32x32 SPADs testchip

Photon Detection Probability has been measured using a monochromator at fnumber = 2.8.

Spectral selectivity of the FZP trials has been confirmed as well as the ranking between the trials, in agreement with the simulations. However the amplitude of transmission is lower than expected. This is due to the aperture of the measurement setup, and to process variations that tend to smooth oscillations compared to simulations.

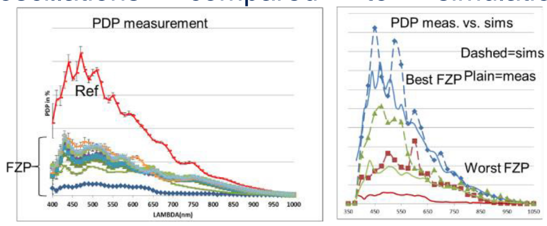

Figure 6 : Photon Detection Probability measurements vs. simulations

In order to characterize the immunity of the trials to the ambient illumination a specific methodology has been developed. We use a metric that we call Ambient Rejection Ratio (ARR), corresponding to the ratio of count rates of a given SPAD under visible illumination and laser, over the count rates under visible only, for a given controlled level (using neutral density ND) of power of the laser and the ambient illuminations.

$$ARR(840nm, Visible, ND) = \frac{CR(840nm, Visible, ND)}{CR(Visible, ND)}$$

A specific setup has been developed allowing characterizing the trials count rates under both configurations. A solar simulator with an atmospheric filter AM1.5 is placed on the primary optical path to the sensor, a fibered pulsed infrared laser is placed in a parallel secondary optical path. The laser beam is 20x expanded, and is derived to the primary axe using a beam splitter. Finally a dichroic filter allows to mix the visible part of the solar simulator and the laser until the sensor.

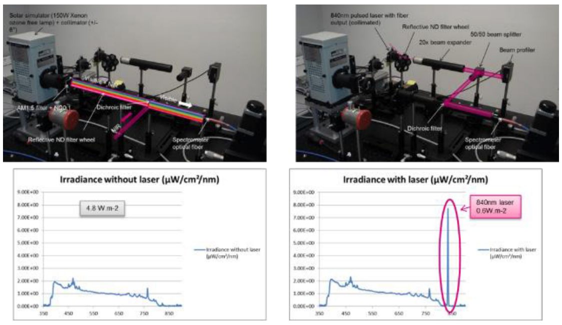

Figure 7: Ambient rejection measurement setup

The measured ARR have shown an improvement of the best FZP from 10% to 30%, depending on the relative power of the laser to the visible ambient power.

Finally the angular response under IR only has been measured using an IR-pass filter in front of the solar simulator. By plotting the relative count rates of the trials over the reference as a function of the angle we see that the angular response is reduced for angles higher than 10°, from 90% down to 50% of the reference. Results are plotted on figure 8.

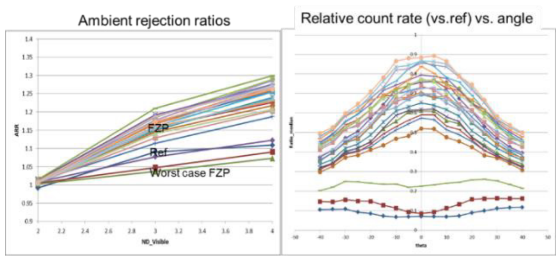

Figure 8 : Measured ambient rejection ratios and angular response

4. Conclusion

Plasmonic-based Fresnel Zone Plates have been designed and implemented on a SPAD testchip. They are composed of copper rings which dimensions are compatible with the CMOS manufacturing process.

It has been demonstrated some spectral selectivity as a proof-of-concept.

The ambient rejection under visible has been increased and the angular response has been decreased form 90% to 50% for angles higher than 10°, allowing to help improve the sensor's immunity to visible, as well as the sensitivity to crosstalk induced by multiple reflections from the emitter inside the module. In the future, such structures might be good candidates in helping relaxing packaging constraints in terms of filtering and parasitic reflections.

5. References

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