SPAD-Based LiDAR Sensor in 0.35 μm Automotive CMOS with Variable Background Light Rejection [†]

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Abstract: We present a SPAD-based LiDAR sensor fabricated in an automotive certified 0.35 μm CMOS process. Since reliable sensor operation in high ambient light environment is a crucial factor in automotive applications, four SPADs are implemented in each pixel to suppress ambient light by the detection of photon coincidences. By pixel individual adjustment of the coincidence parameters to the present ambient light condition, an almost constant measurement performance is achieved for a wide range of different target reflectance and ambient illumination levels. This technique allows the acquisition of high dynamic range scenes in a single laser shot. For measurement and demonstration purpose a LiDAR camera with the developed sensor has been built.

Keywords: light detection and ranging (LiDAR); single-photon avalanche diode (SPAD); range imaging; time-of-flight (TOF); background rejection; photon coincidence

1. Introduction

For applications like advanced driver assistance systems and autonomous driving a fast and reliable perception of the vehicle's environment is essential. Light detection and ranging (LiDAR) uses light waves in the infrared range to determine the distance by measuring the time-of-flight (TOF) of an emitted laser pulse [1]. Since the sun emits light in the infrared range as well, this so-called background light can reduce the measurement performance [2]. Therefore, the rejection of ambient light is an important facet in the sensor design for automotive applications. With single-photon sensitivity and timing resolution in the picosecond range [3], single-photon avalanche diodes (SPAD) are able to detect temporal correlated photons [4,5]. In this technique at least a certain number of single photons have to be detected within a defined timespan to be classified as an event which stops the time measurement. Since the ambient photons are distributed equally over the whole measurement window while the laser photons are confined to the laser pulse width, the probability to generate an event during the laser pulse reception is increased and the influence of the background light is reduced.

2. Photon Coincidence

In the direct TOF technique the time between the emission and reception of a short laser pulse is captured to determine the distance. Usually the time measurement is started with the emission of the laser pulse and stopped with the first detected photon. If ambient light is present, there is a certain

probability for the first photon to result from the ambient light instead of the laser signal. As a result, the measured time value is incorrect [6]. To reduce the probability of false measurements, the photon rate of the ambient light should not exceed a certain level. However, reducing the ambient light by reducing the reception aperture or using gray filters decreases the laser pulse intensity as well. By applying photon coincidence the rate of ambient light generated events can be reduced more than the laser generated event rate, because the rate reduction increases for lower light intensity due to the exponential distribution of the photon inter-arrival time[7].

3. Sensor Design

In Figure 1 the micrograph and an assembled version of the SPAD-based CMOS LiDAR sensor fabricated in an automotive certified 0.35 μm standard CMOS process is shown. The chip has a total size of $5.9 \times 8.96 \text{ mm}^2$ and two lines with 192 pixels each. The lower line is located in the vertical center of the chip, while the upper line is around 1 mm above.

Each pixel comprises four circular 12 μm SPADs with an active quenching and reset circuit similar to [8]. At the output of these circuits pulses with a width corresponding to the hold-off time of the quenching circuits are generated. A following shaper reduces the pulse width to the desired coincidence time, which can be set to values between 1.5 ns and 16 ns. Afterwards the output signals of the four shapers are connected by logical circuits to find photon coincidences in the single photon detection signals. To adjust the number of required single photon detections—called coincidence depth—four separate logical circuits are used whereas each is responsible for a specific depth. By choosing one of the circuits by means of a multiplexer, the coincidence depth can be set between one and four. To have a further degree of freedom to adjust the resulting event rate, the number of active SPADs is variable as well. Control logic ensures the number of active SPADs to be at least the chosen coincidence depth.

Figure 1. (a) Micrograph of the SPAD-based 2×192 pixel LiDAR sensor fabricated in 0.35 μm CMOS; (b) LiDAR sensor mounted in 84-pin ceramic housing.

The coincidence parameters as well as the number of active SPADs are adjusted by six 384-bit shift registers. Each line of the sensors uses separate registers for the three parameters and each pixel has two bits for each parameter. To allow simultaneous parameter application, latches are connected to the shift register which are clocked by a global signal. This allows the writing of new parameters during a running measurement.

For the time measurement a pixel-parallel time-to-digital converter (TDC) is implemented. In the coarse stage an 8-bit asynchronous counter running at 200 MHz gives a resolution of 5 ns. To improve the resolution a delay-locked-loop based time interpolator with a fine resolution of 312.5 ps corresponding to a distance of 4.68 cm is used. The TDC starts with the reception of the first photon or coincidence event and stops at the end of the measurement window. After the measurement cycle the 384 pixel are read out serially by using a 20 MHz clock allowing a frame rate of 52 kHz.

4. Measurements

In a first step we measure the influence of the coincidence parameters on the effective event rate. In Figure 2a the event rate for increasing illumination corresponding to increasing single photon detection rate is shown. In the log-log plot the curves show a slope higher than one. This results in an increased signal-to-background ratio (SBR) if photon coincidence is applied. The Figure also shows that the slope of the curve increases with the coincidence depth n . Therefore, a higher coincidence depth results in a higher gain in SBR but requires higher single photon rates. Due to the dead time of the SPADs the curves saturate for high single photon rates resulting in less SBR gain. Besides the slope also the absolute event rate is affected by the coincidence parameters. Since the highest range is achieved for a distance specific ambient event rate, the range decreases if the event rate changes due to ambient light conditions or target reflectance. To keep the ambient event rate, and hence the range, constant, the coincidence parameters can be adjusted depending on the ambient light level. For ambient light measurement the sensor can be operated in event counting mode. In Figure 2b the normalized event rate is shown as a function of the coincidence time. Here a dependence of the slope on the coincidence depth can be observed as well.

Figure 2. (a) Photon coincidence rate versus single photon rate for coincidence depth 2 to 4; (b) Normalized photon coincidence rate versus coincidence time for coincidence depth 2 to 4.

For demonstration and measurement purpose a flash LiDAR camera for the fabricated chip has been built. Besides the sensor and optics the camera has two laser sources which emit 15 ns laser pulses at 905 nm wavelength and a peak power of 75 W. The field-of-view (FOV) of the two light sources is designed to match the sensor FOV, whereas each laser source is aligned to illuminate one pixel line of the sensor. With the used optics the FOV of a single line is 0.8° by 35.8° .

In Figure 3 the results of the outdoor measurement at around 65 klx sunlight are shown. To determine the performance of the system, we calculate the success probability, which is defined as the probability to measure the true distance with a maximum deviation of 10%. For the two plots the success probability has been determined from 100 single distance measurements, whereas each measurement uses 4000 single laser pulses and time measurements, respectively. In Figure 3a low coincidence depth is applied (i.e., coincidence depth 2, coincidence time 8 ns, and four active SPADs) and, therefore, a higher range is achieved for the black paper target with a Lambertian reflectance of around 8%. This is because for the white paper target with a reflectance of around 70% the reflected ambient light is too high causing most of the time measurement to fail. Otherwise for the high coincidence depth applied in Figure 3b (i.e., coincidence depth 4, coincidence time 16 ns, and four active SPADs); here the white target achieves the higher range. In this case the number of laser generated events of the black target is too low to allow a reliably location of the laser pulse position in the histogram. As can be seen from the results, by adjusting the coincidence parameters to the actual ambient light conditions and target reflectance, respectively, an almost constant range can be achieved over a high dynamic range of target reflectance. For the applied targets the difference in reflectance is around 19 dB.

Figure 3. Outdoor measurements at 65 klx ambient light; (a) At low coincidence depth a higher range is achieved for the black target; (b) For high coincidence depth the white target allows a higher range.

5. Conclusions

We have presented a 2×192 pixel CMOS SPAD-based sensor for LiDAR applications. To allow a reliable measurement at high ambient illumination four SPADs have been implemented in each pixel to enable the detection of photon coincidences. By applying this technique an ambient light suppression and an improvement of the SBR is achieved. In addition, adjusting the parameters of the photon coincidence detection circuit to the actual ambient light event rate allows an almost constant range for different target reflectance coefficients.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Remondino, F.; Stoppa, D. *Tof Range-Imaging Cameras*; Springer: New York, NY, USA, 2013; ISBN 978-3-642-27522-7.
2. Perenzoni, M.; Perenzoni, D.; Stoppa, D. A 64×64 -Pixels Digital Silicon Photomultiplier Direct TOF Sensor With 100-MPhotons/s/pixel Background Rejection and Imaging/Altimeter Mode With 0.14% Precision Up To 6 km for Spacecraft Navigation and Landing. *IEEE J. Solid-State Circ.* **2017**, *52*, 151–160, doi:10.1109/JSSC.2016.2623635.
3. Bronzi, D.; Villa, F.; Bellisai, S.; Markovic, B.; Tisa, S.; Tosi, A.; Zappa, F.; Weyers, S.; Durini, D.; Brockherde, W.; Paschen, U. Low-noise and large-area CMOS SPADs with timing response free from slow tails. In Proceedings of the 2012 Proceedings of the European Solid-State Device Research Conference (ESSDERC), Bordeaux, France, 17–21 September 2012; pp. 230–233.
4. Portaluppi, D.; Conca, E.; Villa, F. 32×32 CMOS SPAD Imager for Gated Imaging, Photon Timing, and Photon Coincidence. *IEEE J. Sel. Top. Quantum Electron.* **2018**, *24*, 1–6, doi:10.1109/JSTQE.2017.2754587.
5. Niclass, C.; Soga, M.; Matsubara, H.; Ogawa, M.; Kagami, M. A 0.18- μ m CMOS SoC for a 100-m-Range 10-Frame/s 200 $\times$ 96-Pixel Time-of-Flight Depth Sensor. *IEEE J. Solid-State Circ.* **2014**, *49*, 315–330, doi:10.1109/JSSC.2013.2284352.
6. Beer, M.; Hosticka, B.J.; Kokozinski, R. SPAD-based 3D sensors for high ambient illumination. In Proceedings of the 2016 12th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME), Lisbon, Portugal, 7–30 June 2016; pp. 1–4.
7. Beer, M.; Schrey, O.M.; Hosticka, B.J.; Kokozinski, R. Coincidence in SPAD-based time-of-flight sensors. In Proceedings of the 2017 13th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME), Giardini Naxos, Italy, 12–15 June 2017; pp. 381–384.
8. Bronzi, D.; Tisa, S.; Villa, F.; Bellisai, S.; Tosi, A.; Zappa, F. Fast Sensing and Quenching of CMOS SPADs for Minimal Afterpulsing Effects. *IEEE Photon. Technol. Lett.* **2013**, *25*, 776–779, doi:10.1109/LPT.2013.2251621.