A SPAD-Based, Direct Time-of-Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology

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Summary

• Introduction to ranging device

• Summary of C40SPAD technology platform

• SPAD pixel and array

• SPAD array re-configurability

• SPAD output – TDC to histogram

• Histogram processing
  • Range extraction
  • Cross-talk mitigation
  • Dynamic scene adaption
FlightSense™ Market Highlights

100% AAGR  >100 Phones  >20,000 EVKs  >500Mu  #1 Worldwide ToF Supplier
FlightSense™
… making light work

- Face Identification Assist
- Presence, User Detect
- Ranging & Proximity
- Camera Assist
- Gesture
- Depth Map & AR/VR
- User Detect, Gesture
- Ranging
- Face ID
- Camera Assist
- User Detect
- Gesture
- AR/VR
- Proximity
- Depth Map
- User Detect
Abstract

- SPAD based direct time of flight multi-zone parallel device
- Implemented in STMicroelectronics C40SPAD technology
- Capable of 64 zones at 15fps for both signal and distance
- All in one device including on-chip VCSEL driver and in module VCSEL
- 16 parallel full histogram readout channels capable of multiple target detection
Device Overview

8x8 signal map
+ 16 histograms for each subranging period

VCSEL V ➔ Photons

128Bits @ 1GHz

16 TDC frontend

16 histograms
Standard logic

32bits 250MHz
MCU + Custom
HW acceleration

Flexible user interface

8kbit OTP

I2C

VCSEL Driver

125ps pulse width granularity

Results
data / use cases

Commands

Flexible user

I2C

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C040 Technology Platform

40nm CMOS Core Process
- Dual Gate Oxide
- Single/Dual Vt MOS
- 7 Copper Dual Damascene Metal Levels
- 0.14µm metallization pitch
- Ultra low k dielectrics

Technology available since 2010 - Source : Crolles 12”

CMOS040_LP technology is designed for Low Power (1.1V) to serve battery operated and wireless applications. It is a single IO oxide + single core oxide dual-Vt process. It gives access to standard Vt transistors (SVT), low Vt transistors (LVT) & SRAM using LP core oxide and IO transistors. IO transistors (1.8 V or 2.5 V) are using IO oxide (32 or 50A respectively). It uses Copper metallization with 7 metal levels (5 thin + 2 thick) and ultra low-K dielectrics (k=2.55).
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VCSEL
V→Photons

VCSEL
Driver

125ps pulse width granularity
4x4 Macro-Pixel

- 40% fill factor (with micro-lens)
- Per diode quench circuit and pulse shaper
- OR-tree used to aggregate pixel outputs
- Local intensity counter to monitor per macro-pixel signal rate
Multi-Zone SPAD Array
Multi-Zone SPAD Array

- 14 x 10 array of macro-pixels
- Each macro-cell features 16 didoes
- System features 16 parallel readouts from array
- Location and size of each zone is configurable
Multi-Zone SPAD Array

- 16 primary array zones
- In default configuration each zone features 64 SPADs
  - Aggregation of outputs from 4 “macro-pixels”
Individual macro-pixel outputs can be summed together to create “ranging zones”
Reconfigurable SPAD Array

- The SPAD Array is over-sized to allow active area to be dynamically adjusted.
- Default mode: 4x4 parallel ranging zones with 8x8 signal map (no. of ranging and signal zones can be adjusted to system needs)
- Each ranging zone made up of 2x2 macro pixels (although this is configurable)
- Ranging zone position can be adjusted in X and Y with macro-pixel resolution
- Allows the active array ROI to be adapted to compensate for build tolerances or application needs

Intensity Map Resolution
Reconfigurable Active Region

“Ranging Zone”
Multi-Zone SPAD Array – Alternative Configurations

- 5 x 3 zones in 16/9 format
Multi-Zone SPAD Array – Alternative Configurations

- 4 x 3 zones in 4/3 format
- SPAD diode resolution zone size
Multi-Zone SPAD Array – Alternative Configurations

- Over-sizing of peripheral zones to compensate for lens roll-off
- Possible to have gaps between sub-zones if application requires it
Multi-Zone SPAD Array

- 64 zones can be readout over 4 sequential range measurements at a rate of 15fps

Frame 1
Frame 2
Frame 3
Frame 4
Three stage re-configurable OR tree:

- Macro Pixel: 16 SPADs
- In-Pixel Counter
- & Gate
- Vertical OR: From Up, From Dn
- Horizontal OR: From R, From L
- Vertical & Horizontal Muxes: 5-way VMUX, 14-way HMUX
- To RDOUT X, Y
Re-Configurable OR Cell Combinations

2 Macro Pixel OR

Column Configuration Bit

L  C  L  C  L  C

Macro Pixel  Macro Pixel  Macro Pixel  Macro Pixel  Macro Pixel  Macro Pixel

OR  OR  OR

3 Macro Pixel OR

Column Configuration Bit

L  C  R  L  C  R

Macro Pixel  Macro Pixel  Macro Pixel  Macro Pixel  Macro Pixel  Macro Pixel

OR  OR
Re-Configurable OR Cell Combinations

2x2 Macro Pixel OR

Column Configuration Bus

L   C

Macro Pixel   Macro Pixel
Macro Pixel   Macro Pixel

Out
Up

Vertical Configuration Bus

2x3 Macro Pixel OR

Column Configuration Bus

L   C

Macro Pixel   Macro Pixel
Macro Pixel   Macro Pixel
Macro Pixel   Macro Pixel

Down
Out
Up

3x3 Macro Pixel OR

Column Configuration Bus

L   C   R

Macro Pixel   Macro Pixel   Macro Pixel
Macro Pixel   Macro Pixel   Macro Pixel
Macro Pixel   Macro Pixel   Macro Pixel

Down
Out
Up
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VCSEL Driver

125ps pulse width granularity
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VCSEL Driver
128Bits @ 1GHz

125ps pulse width granularity
TDC to histograms

- Zone signal from SPAD array
- Custom analog front-end
  - Synchronous events binning
  - 8 phases
  - 8 bits @ 1GHz
  - PLL
  - Multiphase PLL

- 144 bins
- 21 bits

- Standard logic
- Histogram

- Clk 1GHz

- MCU & Memory
The device is designed to subtract Xtalk peak, and then detect up to 4 targets per histogram.

On-board detection algorithm designed to report leading & falling edge position as well as interpolated median pulse position with mm resolution. For each detected target, the MCU is reporting these, as well as confidence level and expected accuracy.
Adapting laser pulse to each situation

- LONG PULSE allows for low SNR detection (long distance over ambient)
- SHORT PULSE allows for selective close multiple target discrimination
Scene dynamic range management

- One of the challenges in ToF system is the management of the scene dynamic range
  - Low ambient/ High ambient
  - Close / Far target
  - Dark / Bright targets
Scene dynamic range management

• Thanks to embedded live signal/background map, the device can dynamically assess the SNR for each zone and disable individual SPADs that contribute poorly or negatively to the ranging of the zone.
Dynamic crosstalk management

- Crosstalk from cover glass can be significant
- Thanks to histograms, natural immunity exists beyond the point of the emitted pulse width
- But below, at shorter distance, the Xtalk still needs subtracting to not add a ranging offset error to the extracted pulse position
- Moreover, on a larger multizone array, the crosstalk may not be uniform across.

⇒ **Our device includes a dynamic crosstalk extraction and application taking into account the spatial non uniformity of the crosstalk**
Noise prediction: sigma estimation

Purpose

• Estimates the expected uncertainty given a single range measurement.
• The estimated standard deviation should be equivalent to the measured standard deviation from a large number of measurements (e.g. 100).
• This gives an indication of the repeatability of the measurement reported by the device.
• The sigma estimator is intended for reporting range quality.

For each target reported, the device takes into account the ambient, signal and crosstalk rate, as well as pulse width, in order to accurately estimate the noise associated with this target.

This is easing considerably the job of the user to estimate the confidence of the reported data.
Device overview
Wide Angle Parallel Multi-zone detection

Highlights

- **All-in-one compact lensed module**
  - Class 1 certified 940nm invisible VCSEL
  - 61° FoV
  - ToF processing on embedded 32bit MCU
- **Target specification**
  - Functional under 100klux daylight & direct light
  - 8x8 15fps operation mode
  - Cover glass xtalk calibration free
  - Zero lag Region of Interest reporting
- **Power modes**
  - Fully autonomous 1.4mW Presence detection
  - Smart power management based on ambient light level
- **Spatial scene understanding**
  - Multiple object detection
  - Cover glass xtalk immune & dynamic subtraction
Conclusions

• A SPAD-Based, Direct Time-of-Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology

• A SPAD-based, direct TOF device is presented

• Up to 64 independent range measurements across FoV can be made

• Zone position and size configurable

• 16-channel histogram processing

• Histogram processing includes
  • Range and signal rate extraction
  • Cross-talk removal
  • Dynamic signal rate management
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