Devices for Integrated Multi-Aperture Imaging

Ph.D. Oral Examination
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Camera History
Camera History

• Despite progress, each of these cameras form images in the same way
Image Formation in a Camera

- real object
- pinhole
- image
Image Formation in a Camera

- real object
- lens
- image
Image Formation in a Camera
Advances in the Image Recording Process

• Images recorded by hand (1015-1900)

• Images recorded by film (1829-2000)

• Images recorded by semiconductor (1974-present)
Solid-State Photon Conversion

* A. Theuwissen, Solid-State Imaging with CCDs, p. 111
CCD and CMOS Comparison

Interline Transfer CCD

- Low dark current, low non-uniformity
- Minimal integration of circuits, slow readout, high power

CMOS

- Integration, fast readout, low power
- Higher dark signal, non-uniformity

Photodiodes
CMOS Active Pixels

- Low dark current
- Low temporal noise with CDS
- Allows for readout multiplexing
4T Buried Diode Operation

Exposure

Readout
Recent Pixel Scaling

- Increase spatial resolution
- Decrease format size

Pixel Sizes reported at IEDM, ISSCC, IISW

![Graph showing recent pixel scaling with data points and trend line]
Ray Diagrams for CMOS Pixel

(a) ulens
(b) CFA
(c) metal 3
(d) metal 2
(e) metal 1
diode
Recent Pixel Scaling Technology

4T sharing

Stack height reduction


* H. Sumi, IEDM 2006, p119-122
Spot Size Limitation

• Point in object space is focused to a small spot in focal plane
• Spot size is limited and dependent on:
  – Relative size of the aperture
  – Aberrations of lens
  – Wavelength of the source
Outline

• Multi-Aperture architecture
• Detailed operation
  – FT-CCD array
  – Multi-Aperture array
  – Column ADC
• Results
• Summary
Multi-Aperture Image Sensor

Imager subarray with integrated optics

Imager subarrays integrated to form multi-aperture array
Conventional vs. Multi-Aperture

Conventional imaging

Multi-Aperture imaging

Multi-Aperture Imaging

Image in focal Plane

Image captured at MA-imager

Final reconstructed image

Image processing
Benefits of Multi-Aperture Imaging

- Capture depth information
- Close proximity imaging
- Achieve better color separation
- Reduce requirements of objective lens
- Increase tolerance to defective pixels
Depth from Multi-Aperture
Why Use Small Pixels?

- Depth resolution improves with pixels smaller than the spot size
- Spatial resolution is limited by the spot size
- Depth resolution is limited by accuracy in localization of the spot
Feature Localization vs. Pixel Size

Poor location accuracy

High location accuracy
Color Separation with Multi-Aperture

- Color filter placed over each subarray of pixels rather over each individual pixel
Color Imaging with Multi-Aperture

Objective lens

Multi-aperture imager
(color filter at each aperture)
Fabricated Multi-Aperture Imager

- 0.11µm CMOS (TSMC)
- Chip size: 3.0 x 2.9mm²
- 166 x 76 aperture array
- 16 x 16 pixel FT-CCD per aperture
- Pixel size: 0.7 µm
- Max frame rate: 15fps
- ADC resolution: 10 bit
- Power: 10.45mW

* Local optics are not integrated on this chip.

Block Diagram of Fabricated Chip
Layout Masks for Chip
16 x 16 FT-CCD schematic
Relative Pixel Size for This Work

- Increase spatial resolution
- Decrease format size

Pixel Sizes reported at IEDM, ISSCC, IISW
Multi-Aperture Optical Stack

Using CMOS active pixels

Using FT-CCD pixels
FT-CCD Test Chip

- 1.4, 1.0, 0.7, 0.5 µm pixel sizes
- Surface, Buried, Pinned-phase
- Analog readout

The 0.5µm Pixel

Across Channel

Along Channel

Pixel
CCD Structure

STI forms the channel stop

Single-level poly electrodes
The 0.7µm Buried Channel Pixel

cross section along channel

cross section against channel
Layout Masks for Buried Channel CCD
Operation

- Flush
- Integrate
- Frame Transfer
- Horizontal Readout
Operation (Flush)

\[\text{VTRANS} = 3.0\text{V}\]
\[\text{VSTORE} = 1.0\text{V}\]
\[\text{VISOLATE} = -0.5\text{V}\]
Operation (Flush)
Operation (Integrate)

V0
V1
V2
V3
V4
V5
V6
V7
V8
V9
V10
V11

VTRANS = 3.0V
VSTORE = 1.0V
VISOLATE = -0.5V

TS   H4   H3   H2   H1   H0   TX   RT
RS    VP   COLB  VP
Operation (Integrate)

VTRANS = 3.0V
VSTORE = 1.0V
VISOLATE = -0.5V
Operation (Frame Transfer)

- VTRANS = 3.0V
- VSTORE = 1.0V
- VISOLATE = -0.5V
Operation (Frame Transfer)
Operation (Horizontal Transfer)
Potential Profile Along Channel

-0.5V
V1
-0.5V
V2
-0.5V
V3
-0.5V
V4
-0.5V
V5
-0.5V
V6
Potential Profile Along Channel
Potential Profile Along Channel

-0.5V  -0.5V  -0.5V  -0.5V  3.0V  2.0V
V1     V2     V3     V4     V5     V6

Potential (V)

x (Microns)
Potential Profile Along Channel
Potential Profile Along Channel
Potential Profile Along Channel
Potential Profile Along Channel

-0.5V V1
-0.5V V2
-0.5V V3
-0.5V V4
3.0V V5
2.0V V6

Potential (V)

x (Microns)
Potential Profile Along Channel
Interlaced Mode (Even Field)
Interlaced Mode (Odd Field)
Vertical to Horizontal Transfer

Even column

-0.5V  -0.5V  1.0V  -0.5V
H0     V11    V10   V9

Odd column

-0.5V  -0.5V  1.0V  -0.5V
H1     V11    V10   V9

to H-CCD

to H-CCD
Vertical to Horizontal Transfer

Even column

3.0V H0 3.0V V11 3.0V V10 -0.5V V9

Odd column

-0.5V H1 3.0V V11 3.0V V10 -0.5V V9

Potential (V)

x (Microns)
Vertical to Horizontal Transfer

Even column

\[ \begin{align*}
3.5V & \quad H0 \\
2.0V & \quad V11 \\
-0.5V & \quad V10 \\
-0.5V & \quad V9 \\
\end{align*} \]

Odd column

\[ \begin{align*}
-0.5V & \quad H1 \\
2.0V & \quad V11 \\
-0.5V & \quad V10 \\
-0.5V & \quad V9 \\
\end{align*} \]
Vertical to Horizontal Transfer

Even column

3.5V
H0

2.0V
V11

3.0V
V10

-0.5V
V9

Odd column

-0.5V
H1

2.0V
V11

3.0V
V10

-0.5V
V9

Potential (V)

x (Microns)

Potential (V)

x (Microns)
Vertical to Horizontal Transfer

Even column

Odd column

1.0V H0 -0.5V V11 1.0V V10 -0.5V V9

-0.5V H1 -0.5V V11 1.0V V10 -0.5V V9

Potential (V)

x (Microns)
Chip Operation

ACTIVE CCD AREA

RT
TX
RS<1>

ACTIVE CCD AREA

RT
TX
RS<0>

ACTIVE CCD AREA

ADC<0>

ACTIVE CCD AREA

ADC<1>
Chip Operation (Integrate)

integrated charge
Chip Operation (Frame Transfer)
Chip Operation (Reset FD)
Chip Operation (Read Row<0>)
Chip Operation (Read Row<1>)
Chip Operation (Transfer Charge)
Chip Operation (Charge Row<0>)
Chip Operation (Charge Row<1>)
Chip Operation (Shift Charge)
Layout Masks for ADC
Photon Transfer Curve (0.7µm Pixel)

- **Noise Floor**: (5 e-)
- **Conversion Gain**: (165µV/e-)
- **Full Well**: (3500 e-)
- **PRNU**: (2%)

**Axes:**
- **Y-axis**: Noise (e-)
- **X-axis**: Mean Signal (e-)

**Legend:**
- Total Noise
- Temporal
- FPN
# Measured Pixel Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well capacity</td>
<td>3500 e-</td>
</tr>
<tr>
<td>Conversion gain</td>
<td>165 μV/e-</td>
</tr>
<tr>
<td>Sensitivity at 550 nm</td>
<td>0.15V/lux-sec</td>
</tr>
<tr>
<td>QE at 450, 550, 650 nm</td>
<td>20, 48, 65 %</td>
</tr>
<tr>
<td>Pixel read noise</td>
<td>5 e- rms (1mV)</td>
</tr>
<tr>
<td>Dark current at RT</td>
<td>33 e-/sec (5.5 mV/sec)</td>
</tr>
<tr>
<td>DSNU</td>
<td>35 % rms</td>
</tr>
<tr>
<td>PRNU</td>
<td>2 % rms</td>
</tr>
<tr>
<td>Peak SNR</td>
<td>35 dB</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>57 dB</td>
</tr>
</tbody>
</table>
Measured ADC Linearity

Input Range = 1V
Measured ADC Noise

Image at constant ADC test input level

FPN (10-b LSBs)

Temporal (10-b LSBs)
Images from Single Subarray

3000 electron charge packets from fill/spill input

Captured with F/2.8, f=6mm lens at 1/10 sec

Raw data

Added contrast
Raw Image Captured with Multi-Aperture Views
Processed Multi-Aperture Image
Summary

• Designed and characterized the first integrated multi-aperture image sensor
• Achieved good imaging performance with submicron pixels
  – FT-CCD structure in deep submicron CMOS
  – Ripple charge transfer
• Extensible architecture well suited for ultra-high pixel count imagers
• Many potential applications or benefits
  – Depth
  – Close proximity imaging
  – Color imaging with good spectral separation
  – High defect tolerance
  – Relaxed external optical requirements
• Results suggest that further scaling while maintaining performance is possible
Acknowledgement

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• Hertz Foundation
  – Fellowship support

• TSMC

• Lane Brooks, MIT EECS
  – Collaboration on the design of the testing platform and software system

• GNU/Linux, FSF, open source community
  – Providing the best software development tools
Photon Transfer Curve (0.5μm Pixel)

- Noise Floor: 3.7 e- (3.7 e-)
- Full Well: 3550 e- (3550 e-)
- Conversion Gain: 193μV/e- (193μV/e-)
- PRNU: 5.8% (5.8%)
• CTE is 99.9% with 3000 electron charge packets

• CTE limited by surface interface traps

• CTE is reduced to 98% if holes are accumulated between storage electrodes.
Is There a Biological Equivalent?
Compound Eye

* Wikipedia, Compound Eye

* Buschbeck, 1999
Eye of the Strepsiptera

* Buschbeck, 1999