SPECIAL TOPICS IN COMPUTER ARCHITECTURE AND VLSI DESIGN:
Overview of CMOS Image Sensors

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The Start of Digital Imaging

- Invented in 1969 at AT&T Bell Labs by Willard Boyle and George E. Smith.
- Originally working on memory → "Charge 'Bubble' Devices“, can be used as a shift register and as a linear and area imaging devices.
- CCDs are electronic devices, which work by converting light into electronic charge in a silicon chip (IC). This charge is digitised and stored as an image file on a computer.
- In 2009, they were awarded the Nobel Prize for Physics.
The first Digital Camera from Kodak

using a Fairchild 100 x 100 CCD in 1975
History

- 70s: Fairchild, 80s: Hitachi, Early 80s: Sony
- 1971: FDA & CDS techniques are invented.
- Mid 1980s: Great success in the consumer market

- 1990: NHK/Olympus, amplified MOS Imager (AMI) called CMOS Image Sensor later.
- 1993: JPL, CMOS active pixel sensor
- 1998: A single chip camera
- After 2005: CMOS image sensor becomes dominant
160 million pixel (Seitz)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Seitz Phototechnik AG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenses (interchangeable)</td>
<td>- Schneider or Rodenstock large format lenses</td>
</tr>
<tr>
<td>- on Seitz lens board</td>
<td>- Linhof Technorama, Fuji, other large format lenses</td>
</tr>
<tr>
<td>- on adaptor plate</td>
<td></td>
</tr>
<tr>
<td>Size of 6x17 image</td>
<td>7,500 x 21,250 pixels (60mm x 170mm)</td>
</tr>
<tr>
<td>Total resolution</td>
<td>160 million pixels</td>
</tr>
<tr>
<td>File sizes</td>
<td>raw (16-bit): 307 MB</td>
</tr>
<tr>
<td></td>
<td>uncompressed tiff (48-bit): 922 MB</td>
</tr>
<tr>
<td>Time for 6x17 panorama</td>
<td>~1 sec. at full speed/resolution</td>
</tr>
<tr>
<td>Exposure range</td>
<td>from 1/2’000 sec.</td>
</tr>
<tr>
<td>Exposure control</td>
<td>automatic or manual</td>
</tr>
<tr>
<td>ISO/ASA equivalent</td>
<td>100, 200, 400, 800, 1’600 by stage selection</td>
</tr>
<tr>
<td>Image format</td>
<td>up to 6x17; adjustable vertically and horizontally</td>
</tr>
<tr>
<td>File format</td>
<td>raw (16-bit): .dng, tiff (48-bit), jpg (24-bit), bmp</td>
</tr>
<tr>
<td>Image optimisation</td>
<td>Seitz custom-built image optimiser</td>
</tr>
<tr>
<td>Camera body*</td>
<td></td>
</tr>
<tr>
<td>- dimensions</td>
<td>width: 465mm, height: 175mm, depth: 95mm</td>
</tr>
<tr>
<td>- weight</td>
<td>4.5 kg (camera 3.7 kg, battery 0.8k)</td>
</tr>
<tr>
<td>Image transfer</td>
<td>Gigabit ethernet</td>
</tr>
<tr>
<td>Power supply (camera)</td>
<td>12V 4.5A NiMh battery</td>
</tr>
<tr>
<td>Power charger</td>
<td>Universal speed charger 110-220V</td>
</tr>
</tbody>
</table>
Visible Light

- Photon Energy, $E_{ph}=hc/\lambda$
  - at 400nm (violet) $E_{ph} = 3.1$ eV
  - at 600nm (yellow) $E_{ph} = 2.0$ eV
  - at 700nm (red) $E_{ph} = 1.77$ eV
  - at 1100nm (infra red) $E_{ph} = 1.12$ eV

- photons in the visible range have enough energy to generate e-h pairs for silicon ($E_g=1.124$eV)
Photoresponsibility
Silicon Photo Sensor

- Electron-hole pair is generated when $E_{ph} > E_g$
- The generated e-h pair will be recombined in short time
- In the vicinity of P-N junction, electrons are captured in n+ region
Photo sensing in PN junction

Light

Neural n-region

depletion region

Neural p-region

Photon

e

h

p

n
1. incident light = photon flux

2. absorption of photons in silicon bulk

3. electron-hole pair generation

4. some of the generated carrier are separated before recombination by potential well

5. charge flow to photo current
CCD Charge Transfer
“Bucket brigade” analogy

From Claudio Cumani
Exposure finished, buckets now contain samples of rain.
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the metering station.
After each bucket has been measured, the metering station is emptied, ready for the next bucket load.
CMOS Imaging Device

• Passive Pixel Sensor
  – 1 transistor per pixel
  – small pixel, large fill factor
  – but slow, low SNR

• Active Pixel Sensor
  – 3-4 transistors per pixel
  – fast, higher SNR, but
  – larger pixel, lower fill factor
  – 3 Tr structure, 4 Tr structure, photo gate structure
Passive Pixel Sensor Structure

- Horizontal Scanner
- Vertical Scanner
- Vertical MOS Switch
- Photo Diode
- Output
Active Pixel Sensor Structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>Description</th>
</tr>
</thead>
</table>
| 3-Tr Structure | - simple process  
- high fill factor  
- pixel reset noise  
- low S/N |
| 4-Tr Structure | - process for low shallow potential photodiode  
- low fill factor  
- low dark level  
- higher sensitivity |
| 5-Tr Structure | - 4-Tr + addressed readout  
- full random access  
- single CDS possible  
- lowest fill factor |
| Photogate Structure | - simple process  
- 4-Tr like operation  
- signal charge shifting by PG & TG pulse  
- additional signal line  
- low blue response |
Analog-Digital Converter

**Single Channel ADC**
- simple
- small area
- data rate limitation
- higher power consumption

**Dual Channel ADC**
- separated gain for each color component
- multi-port output or merged into single port

**Column Parallel ADC**
- simple & low speed ADC
- large area
- ADC mismatching
- lower power consumption
CCD Image Sensor vs. CMOS Image Sensor

- Optimized photodetectors
  - high QE, low dark current
- Very low noise
  - no noise introduced during shifting
- Very low fixed pattern noise (nonuniformity)
  - no FPN introduced by shifting

- Integration
  - analog and digital circuits, *e.g.*, for clock generation, control, or A/D conversion
- Highly Programmable
  - windowing and panning
  - fully random access of a pixel in array
- Low power consumption
  - low voltage operation
  - for CCD, entire array switching all the time (high $C$, high $V$, and high $f$ results in high $CV^2f$)
- High frame rate possible
  - no limitation in signal transfer speed
Post processing (Color Filter & Microlens)

CCD, CIS’s sensitivity is improved by **Microlens**

*For color image, Color Filter Layer is implemented*

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**Microlens**

- w/o Microlens
- w Microlens

**Color Filter**

- RED
- BLUE
- GREEN
Micro Lens

- Micro Lens
- Color Filter
- Shield Metal Layer
- MOS Transistors
- Silicon Substrate

PD Area
μ-lens Comparison

Sony 680k
Sony 380k
SEC 380k
Color Filter

RGB (Red-Green-Blue)

CMY (Cyan-Magenta-Yellow)
Back-illuminated CMOS image sensor

Back-illuminated Cross sectional SEM photographs

Conventional
CIS Camera System Block Diagram
Temporal Noise (1)

- the (temporal) variation in pixel output values under uniform illumination due to device noise, e.g., thermal and shot noise, substrate noise, and supply voltage fluctuations
- it increases with signal (photo current), but its effect is most pronounced at low signal values (low illumination) - SNR increases with signal
- temporal noise under dark conditions sets a fundamental limit on the sensor dynamic range
### Temporal Noise (2)

#### Dark level & Dark shot noise

<table>
<thead>
<tr>
<th>Integration time</th>
<th>X1</th>
<th>X4</th>
<th>X8</th>
<th>X16</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dark level:</strong></td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
</tr>
<tr>
<td><strong>300mV/sec @60C</strong></td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
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<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
</tr>
<tr>
<td><strong>15mV/sec @60C</strong></td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
<td>&lt;image&gt;</td>
</tr>
</tbody>
</table>
Temporal Noise (3)
10 % pixel random noise
Temporal Noise (4)
25 % pixel random noise
Fixed Pattern Noise (1)

- FPN (also called nonuniformity) is the spatial variation in pixel output values under uniform illumination due to device and interconnect parameter variations (mismatches) across the sensor
- it is fixed for a given sensor, but varies from sensor to sensor
- FPN consists of offset and gain components - increases with illumination, but causes more degradation in image quality at low illumination
- FPN for CCD image sensors appears random
- from column FPN, which appears as “stripes” in the image and can result in significant image quality degradation
Fixed Pattern Noise (2)
Fixed Pattern Noise (3)
0.5 % column FPN
Fixed Pattern Noise (4)
2 % column FPN
Crosstalk

- Blooming
- Smearing
Defect

- Dark defect, White defect, Black defect, Saturation defect
Motion Distortion

1st row readout
2nd row readout
3rd row readout

1st row readout
2nd row readout
3rd row readout
Final row, Integration Time
Final row, Integration Time
Flash Strobe

Time

EEE Spring 2013
Slide 40
CMOS Image Sensors @ Yonsei

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Electrical and Electronic Eng.
Yonsei University, Seoul, Korea
CMOS Image Sensors

Readout Circuits, APS Pixels and Smart Sensors
High Speed Image Sensor

Sample Image: 1200 fps
Low Noise, high speed CMOS Image Sensor

- 2Mpixel, 120fps, 1.9e-TRN, and 180mW CIS
- State-of-the-art noise and energy efficiency (3.5x)

ISSCC’10, JSSC’11
0.7e TRN CMOS Image Sensor

- Sample image taken at 0.06-lux
- State-of-the-art Noise Performance (0.7e- TRN)
- The lowest noise CMOS image sensor!
High-Speed Eye Tracker

- Pixel level signal processing.  → 5000 fps eye tracker.
Smart 3D Range Finer

- Light section based 3D imager.
- Smart pixel, Multiple sampling, -56dB worst case SBR.

TED’ 09
Current Research

- CMOS Image Sensors
  - 3D Imaging
  - Medical Imaging
“There’s More To The Picture Than Meets The Eye”

Neil Young in HeyHey,MyMy, 1978