CCD versus CMOS image sensors

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Outline

• Charge-Coupled Devices, CCD
• CMOS image sensors
• Similarities and differences / strengths and weaknesses of CCD and CMOS imagers
• Single-chip imagers
• Smart sensors and pixels
• Conclusion / outlook
Charge-Coupled Devices (CCD)

1971  Invention of the CCD image sensor at Bell Lab.
M.F. Tompsett et. Al, Line array with 96x1 pixels

+ high resolution
+ small pixel
+ high dynamic range
+ low noise
+ high speed
+ optimized technology

Example: CCD imager from Philips. 6” wafer-size CCD with 7168x9216 pixels, 12 µm pixels
## CCD examples

<table>
<thead>
<tr>
<th>Model</th>
<th>KAF-6303E</th>
<th>FTF3020-M</th>
<th>SI-424A</th>
<th>THX7899M</th>
</tr>
</thead>
<tbody>
<tr>
<td>manufacturer</td>
<td>KODAK</td>
<td>Philips</td>
<td>SiTe</td>
<td>Atmel / Thomson</td>
</tr>
<tr>
<td>resolution</td>
<td>3088x2056</td>
<td>3072x2048</td>
<td>2048x2048</td>
<td>2048x2048</td>
</tr>
<tr>
<td>pixel size μm²</td>
<td>9x9</td>
<td>12x12</td>
<td>24x24</td>
<td>14x14</td>
</tr>
<tr>
<td>active area mm²</td>
<td>27.65x18.48</td>
<td>36.864x24.576</td>
<td>49x49</td>
<td>28.7x28.7</td>
</tr>
<tr>
<td>chip size mm²</td>
<td>29x19.1</td>
<td>39.148x26.508</td>
<td></td>
<td></td>
</tr>
<tr>
<td>optical fill factor</td>
<td>100%</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>output sensitivity</td>
<td>10 μV/e</td>
<td>7.5 μV/e</td>
<td>1.3 μV/e</td>
<td></td>
</tr>
<tr>
<td>full-well capacity (saturation)</td>
<td>100'000 e</td>
<td>500'000 e</td>
<td>200'000 e</td>
<td>150'000 e</td>
</tr>
<tr>
<td>S/N max</td>
<td>50 dB</td>
<td>57 dB</td>
<td>53 dB</td>
<td>51 dB</td>
</tr>
<tr>
<td>readout noise</td>
<td>15 e_{rms} @ 10 MHz</td>
<td>25 e_{rms} @ 9 MHz</td>
<td>5-7 e_{rms}</td>
<td>13 - 25 e_{rms}</td>
</tr>
<tr>
<td>dark current</td>
<td>&lt; 10 pA/cm² @ 25°C</td>
<td>20 pA/cm² @ 25°C</td>
<td>50 pA/cm² @ 20°C</td>
<td>25 pA/cm² @ 25°C</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>74 dB</td>
<td>&gt; 72 dB</td>
<td>&gt; 88 dB</td>
<td>&gt; 74 dB</td>
</tr>
<tr>
<td>QE</td>
<td>35% @ 550nm</td>
<td>26% @ 530nm</td>
<td>30 - 80% @ 550nm</td>
<td></td>
</tr>
<tr>
<td>Max frequency</td>
<td>10 MHz</td>
<td>36 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read-out</td>
<td>single output</td>
<td>4 outputs or 1 output (5fps)</td>
<td>4 outputs or 1 output</td>
<td></td>
</tr>
<tr>
<td>FPN / PRNU</td>
<td>max 3%</td>
<td>max 5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CCD features and applications

• Excellent performances
  + Resolution / Speed / Noise / Uniformity (FPN/PRNU)

• Maturity / established market

• Technology of choice for
  » high-end camcorders and digital still cameras
  » science, astronomy, medicine, factory automation

• But
  – multiple high supply voltages
  – power consumption
  – not mainstream technology
  – no integrated electronics
First CMOS imagers already in the late 1960s

+ standard CMOS
+ single supply voltage
+ low voltage, low power
+ ROI
Collection of photocharges in CCD and CMOS imagers

<table>
<thead>
<tr>
<th></th>
<th>pn junction</th>
<th>MOS Capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>photodiode array</td>
<td>photogate</td>
</tr>
<tr>
<td>CCD</td>
<td>IT-CCD</td>
<td>FT-CCD</td>
</tr>
</tbody>
</table>
Quantum Efficiency: Back-side illuminated CCD versus optimized CMOS

CCD: Hamamatsu S7030
CMOS: Perkin Elmer RL0512T
Read-out: floating diffusion with reset

Output signal: \( V_{\text{out}} = \frac{Q}{C} \)

For \( C = 40 \text{ fF} \), conversion gain: \( \frac{q}{C} = 4 \mu\text{V/e} \)
Noise sources in photodetectors

Photon shot noise:
$$\Delta Q_{\text{photo}} = \sqrt{J_{\text{photo}} \cdot T_{\text{int}} \cdot d^2 \cdot F \cdot \eta \cdot q^2}$$
More light!

Dark current shot noise:
$$\Delta Q_{\text{dark}} = \sqrt{J_{\text{dark}} \cdot T_{\text{int}} \cdot d^2 \cdot q}$$
Process / lower temperature

Reset noise:
$$\Delta Q_{kTC} = \sqrt{kTC}$$
Correlated sampling

Flicker (1/f) noise:
$$\Delta Q_{\text{flicker}} \propto C \sqrt{\frac{I^4 B}{g_m^2 f_{C_{\text{ox}} W L}}}$$
Correlated sampling

FET Johnson noise:
$$\Delta Q_{\text{thermal}} = C \sqrt{\frac{4kTB_{\alpha}}{g_m}}$$
Optimized operation

$$\Rightarrow$$
Reduce charge detection capacitance
The APS (active pixel sensor) concept

MOS photodiode array  Full-frame CCD  APS imager
CMOS Active Pixel Sensor

APS concept + advances in CMOS technology
⇒ New generation of image sensors

- standard CMOS
- single supply voltage
- low voltage, low power
- ROI
  Noise figures improved
- FPN correction required
Photodiode pixel
Fill Factor

- FF CCD / FT CCD \( \approx 100\% \)
- IT CCD \( 25 - 30\% \)
- CMOS APS \( 25 - 65\% \)

\( \Rightarrow \) Microlens array
\( \Rightarrow \) Thin film on ASIC (TFA) \( \approx 100\% \)
Spatial resolution and pixel size: world records

• CCD
  – Highest resolution  9216x9216 pixels
  – Smallest pixel 2.4 μm

• CMOS
  – Highest resolution  4096x4096 (0.18 μm process)
  – Smallest pixel 3.3 μm (0.25 μm process)
Dark current

- Typical dark current @ room temperature

<table>
<thead>
<tr>
<th>Technology</th>
<th>Dark Current (pA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD</td>
<td>2-50</td>
</tr>
<tr>
<td>DRAM 0.5 µm process</td>
<td>25</td>
</tr>
<tr>
<td>TFA</td>
<td>30</td>
</tr>
<tr>
<td>Optimized CMOS</td>
<td>50-200</td>
</tr>
<tr>
<td>Standard CMOS</td>
<td>1000</td>
</tr>
</tbody>
</table>
Noise: numerical example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>15x15 ( \mu \text{m}^2 )</td>
</tr>
<tr>
<td>readout node capacitance</td>
<td>50 fF</td>
</tr>
<tr>
<td>Dark current</td>
<td>0.05 nA/cm(^2) \quad 1.0 \text{nA/cm}^2 )</td>
</tr>
<tr>
<td>integration time</td>
<td>10 msec</td>
</tr>
<tr>
<td>Transconductance</td>
<td>1 mS</td>
</tr>
<tr>
<td>white noise</td>
<td>10 nV/(Hz)(^{1/2})</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
</tr>
</tbody>
</table>

Dark current in standard CMOS image sensors limits exposure time at RT

<table>
<thead>
<tr>
<th>Noise Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark current noise</td>
<td>3 e(<em>{\text{rms}}) \quad 12 e(</em>{\text{rms}}) (120 e(_{\text{rms}}) for 1 s integration)</td>
</tr>
<tr>
<td>flicker noise</td>
<td>15 e(_{\text{rms}})</td>
</tr>
<tr>
<td>thermal noise</td>
<td>6 e(_{\text{rms}})</td>
</tr>
<tr>
<td>reset noise</td>
<td>90 e(_{\text{rms}})</td>
</tr>
</tbody>
</table>
High-speed CMOS sensors and cameras

- More than 1 million pixels @ 1000 fps
- Partners: Weinberger AG / Augusta
  Fraunhofer Institute IIS
Low power digital “camera on chip”

- Low voltage, low power capabilities
- Monolithic integration
- Miniaturization / overall costs

Example:
- Die size: 6.4x4.8 mm²
- Output rate of 60 frames/s
- Total power consumption: 12 mW
- 256x256 pixels
- On-chip 10 bit AD conversion
- Voltage supply 2.4 to 3.2 V
- Digital and analog outputs
- auto-exposure, preview mode
- serial programming
Single-chip digital camera with global shutter

- resolution 640x480 pixels
- on chip ADC 10 bits
- power consumption 20-65 mW
- auto-exposure on chip
- monochrome and color version
- up to 45 frames/s
- serial interface
- line and global exposure

Courtesy of EM Microelectronic, IMT, CSEM
### CMOS digital imagers with VGA resolution

<table>
<thead>
<tr>
<th>manufacturer</th>
<th>National semiconductor</th>
<th>ST (VVL)</th>
<th>Agilent (HP)</th>
<th>Photobit</th>
<th>Motorola</th>
<th>Toshiba</th>
<th>Omnivision</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution</td>
<td>648x488</td>
<td>640x480</td>
<td>640x480</td>
<td>640x480</td>
<td>640x480</td>
<td>640x480</td>
<td>640x480</td>
</tr>
<tr>
<td>pixel size μm²</td>
<td>7.5x7.5</td>
<td>7.5x7.5</td>
<td>9x9</td>
<td>7.9x7.9</td>
<td>7.8x7.8</td>
<td>5.6x5.6</td>
<td>8.4x8.4</td>
</tr>
<tr>
<td>optical format</td>
<td>1/3&quot;</td>
<td>1/3&quot;</td>
<td>1/2&quot;</td>
<td>1/3&quot;</td>
<td>1/3&quot;</td>
<td>1/4&quot;</td>
<td>1/3&quot;</td>
</tr>
<tr>
<td>optical fill factor</td>
<td>47%</td>
<td>N/A</td>
<td>42%</td>
<td>20%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>output sensitivity</td>
<td>1.1 V / lux sec</td>
<td>3 V / lux-sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/N max</td>
<td>49 dB</td>
<td>N/A</td>
<td>57</td>
<td>&gt; 48 dB</td>
<td>57</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>57</td>
<td>57</td>
<td>63</td>
<td>60</td>
<td>50</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>ADC</td>
<td>8, 10, 12 bits</td>
<td>10 bit</td>
<td>8-10 bit</td>
<td>8 bit</td>
<td>10 bit</td>
<td>10 bit</td>
<td>8 bit</td>
</tr>
<tr>
<td>Power [mW]</td>
<td>80</td>
<td>200</td>
<td>300</td>
<td>215</td>
<td>60</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Supply voltage [V]</td>
<td>3.3</td>
<td>3.3</td>
<td>5</td>
<td>3.3</td>
<td>2.5 - 3.3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 fps</td>
<td>N/A</td>
<td>15</td>
<td>39</td>
<td>40 at 13.5 MHz</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>FPN / PRNU</td>
<td>0.35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Megapixel CMOS digital imagers

<table>
<thead>
<tr>
<th>Model</th>
<th>manufacturer</th>
<th>resolution</th>
<th>pixel size $\mu m^2$</th>
<th>optical format</th>
<th>chip size</th>
<th>optical fill factor</th>
<th>output sensitivity</th>
<th>Dynamic range</th>
<th>ADC</th>
<th>Max frequency</th>
<th>Read-out</th>
<th>Frame rate</th>
<th>FPN / PRNU</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX20450</td>
<td>Conexant</td>
<td>1280x1024</td>
<td>5.6x5.6</td>
<td>2/3&quot;</td>
<td>9.1x9.9</td>
<td>70%</td>
<td>50 to 400 mV/decade</td>
<td>120 dB</td>
<td>10 bits</td>
<td>40 MHz</td>
<td>single output</td>
<td>27 fps</td>
<td>&lt;100mVpp</td>
</tr>
<tr>
<td>FUGA1000</td>
<td>Fillfactory</td>
<td>1024x1024</td>
<td>8x8</td>
<td>2/3&quot;</td>
<td>15.4x12.3</td>
<td></td>
<td></td>
<td>68 dB</td>
<td>10 bits</td>
<td>30 MHz</td>
<td>single output</td>
<td>9 fps</td>
<td>&lt; 0.5 %</td>
</tr>
<tr>
<td>PCS2112</td>
<td>Zoran</td>
<td>1280x1024</td>
<td>7.5x7.5</td>
<td>2/3&quot;</td>
<td></td>
<td></td>
<td></td>
<td>72 dB</td>
<td>10 bits</td>
<td>16 MHz</td>
<td>8 outputs</td>
<td>500 fps</td>
<td></td>
</tr>
<tr>
<td>PB1024</td>
<td>Photobit</td>
<td>1024x1024</td>
<td>10x10</td>
<td>1&quot;</td>
<td></td>
<td></td>
<td></td>
<td>59 dB</td>
<td>8 bits</td>
<td>66 MHz</td>
<td>10 outputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PB-MV13</td>
<td>Photobit</td>
<td>1280x1024</td>
<td>12x12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 dB</td>
<td></td>
<td>66 MHz</td>
<td>single output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACS-I 2048</td>
<td>PVS</td>
<td>2048x2048</td>
<td>12x12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24 MHz</td>
<td></td>
<td>24 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Model**: Various models of megapixel CMOS digital imagers.
- **Manufacturer**: Conexant, Fillfactory, Zoran, Photobit, Photobit, PVS.
- **Resolution**: Resolution of the cameras in pixels.
- **Pixel Size**: The size of each pixel in micrometers ($\mu m$).
- **Optical Format**: The size of the optical format in inches (").
- **Chip Size**: The size of the chip in millimeters (mm).
- **Optical Fill Factor**: The ratio of the optical area to the chip area.
- **Output Sensitivity**: The sensitivity of the output in millivolts per decade (mV/decade).
- **Dynamic Range**: The dynamic range in decibels (dB).
- **ADC**: The number of bits used in the Analog-to-Digital Converter (ADC).
- **Max Frequency**: The maximum operating frequency in megahertz (MHz).
- **Read-out**: The number of outputs for the read-out signals.
- **Frame Rate**: The frame rate in frames per second (fps).
- **FPN / PRNU**: The frame precision noise and pattern reference noise (mVpp).

- **Manufacturer**:
  - Conexant
  - Fillfactory
  - Zoran
  - Photobit
  - Photobit
  - PVS

- **Resolution**:
  - 1280x1024
  - 1024x1024
  - 1280x1024
  - 1024x1024
  - 1280x1024
  - 2048x2048

- **Pixel Size**:
  - 5.6x5.6
  - 8x8
  - 7.5x7.5
  - 10x10
  - 12x12
  - 12x12

- **Optical Format**:
  - 2/3"
  - 2/3"
  - 2/3"
  - 1"

- **Chip Size**:
  - 9.1x9.9
  - 15.4x12.3
  - 24.6x24.6

- **Optical Fill Factor**:
  - 70%
  - 60%

- **Output Sensitivity**:
  - 50 to 400 mV/decade
  - 1.3 $\mu$V/e

- **Dynamic Range**:
  - 120 dB
  - 68 dB
  - 72 dB
  - 59 dB
  - 60 dB

- **ADC**:
  - 10 bits
  - 10 bits
  - 10 bits
  - 8 bits
  - 6.5 EBN
  - 10 bits
  - 10 bits

- **Max Frequency**:
  - 40 MHz
  - 30 MHz
  - 16 MHz
  - 66 MHz
  - 66 MHz
  - 24 MHz

- **Read-out**:
  - Single output
  - Single output
  - 8 outputs
  - 10 outputs
  - Single output

- **Frame Rate**:
  - 27 fps
  - 9 fps
  - 500 fps
  - 500 fps
  - < 0.5 %

- **FPN / PRNU**:
  - <100mVpp
  - < 0.5 %
Suppliers of CMOS imagers

- Agilent
- Atmel Corporation, Thomson-CSF
- C-Cam
- Chronet
- Conexant, Rockwell, Sierry Imaging
- CSEM
- Dalsa
- Eastmann-Kodak
- FillFactory
- Foveon
- IC Media Corp.
- IMS Stuttgart
- Infineon
- (Intel)
- FHG Duisburg
- Hamamatsu
- Hyundai Electronics
- Integrated Vision Products AB
- Kodak
- Lucent Technologies
- Matsushita*
- Motorola
- Mitsubishi
- National Semiconductor
- Neuricam
- OmniVision Technologies, Inc.
- Philips
- Photobit
- Photon Vision Systems
- Zoran, PixelCam Inc
- Polaroid
- Sarnoff Corporation
- Sharp*
- Siemens
- Sony*
- SMaL Camera
- STMicroelectronics - VVL
- Suni Imaging Microsystems
- Texas Instruments
- Toshiba
- Y Media
CMOS features, summary

• Strengths and weaknesses

  + Single voltage supply (5 and 3.3 V, down to 1.2 V)
  + Low power consumption (50 µW for QCIF @ 20fps)
  + no blooming, no smearing
  + ROI, random access
  + Standard/generic processes
  + Monolithic integration with analog and digital circuitry ⇒ Single-chip digital imagers

  – dark current
  – noise / uniformity

  + **Smart sensors and pixels (added functionality)**
Pixels with added functionality

• In-pixel analog or digital data processing

• Examples
  – Pixel level ADC (e.g. Digital Pixel Sensor, Stanford University)
  – 256x256 imager with in pixel ADC, tiny digital processor and local memory (T. M. Bernard, ENSTA, FRANCE, IS&T/SPIE’s Electronics Imaging 2001: Science and Technology)
  – Color pixel without color filters
  – High dynamic image sensor
  – Solid-state time-of-flight range (3D) camera
Color pixels without color filters

[Graph showing absorption coefficients and light penetration depths for different materials (CdS, GaAs, Si) at various wavelengths (nm).]

[Diagram showing a cross-section of a semiconductor device with labels for n- well, p base, n+ implant, and contacts.]
High dynamic range imaging

- Multiple exposure times
- Logarithmic compression
- Analog combination of
  - linear response for dark scenes
  - logarithmic for bright scenes
    (LinLog™, patent pending)
High dynamic with linlog™ mode

Samples images with:
- short exposure
- long exposure
- in linlog mode
Solid-state 3D camera

- Based on a standard CMOS technology with CCD option
Phase can be measured by synchronous sampling. (Discrete Fourier transform)

\[ \varphi = - \arctan \frac{A_1 - A_3}{A_0 - A_2} \]
3D camera with 25x64 pixels

Optical range camera without any moving parts

Resolution as function of illumination intensity

Resolution in cm

Optical power in fW per pixel

Measurement Theory
Sample images 3D camera
Conclusion and Outlook

- CMOS imagers today present excellent performances, i.e. equivalent (spatial resolution, QE, linear D/R, …) or superior (speed, intra-scene D/R) to CCDs, except for very low illumination levels (sensitivity, FF, uniformity).

- CMOS imagers open up completely new opportunities
  - miniaturized, low power “system-on-chip”
  - smart sensors and pixels, i.e. vision components which not only acquire image data but also locally process this data to extract the relevant information

- “The photon will be to the 21st century what the electron was to the 20th“, Sen. Daniel Moynihan, New Yorker, 20.3.2000