ESSCIRC 1999:
“CCD or CMOS image sensors for consumer digital still photography?”

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Outline

• Introduction
• Principle of CCD and CMOS imagers
• Imager requirements
• Overview CCD vs. CMOS: resolution, signal-to-noise ratio, angular response, dark current, dynamic range, linearity, pixel uniformity, architecture
• Summary and Conclusions
Introduction

- CMOS is challenging CCD
- Digital still is emerging imaging market

- Today: almost exclusively CCD in DSC
- Tomorrow: CCD or CMOS?

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CCD principle (1)

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CCD principle (2)

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CMOS principle (1)

photodiode array + MOS switches

vertical scan circuit

horizontal scan circuit

CMOS principle (2)

Photogate APS

Photodiode APS

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Image Sensor Aspects (1)

<table>
<thead>
<tr>
<th>IMAGER PARAMETER</th>
<th>CAMERA SPECIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution</td>
<td>sharpness</td>
</tr>
<tr>
<td>signal-to-noise ratio</td>
<td>ISO speed</td>
</tr>
<tr>
<td>angular response</td>
<td>min. F-stop</td>
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<tr>
<td>dark current</td>
<td>max. exposure time</td>
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Image Sensor Aspects (2)

<table>
<thead>
<tr>
<th>IMAGER PARAMETER</th>
<th>CAMERA SPECIFICATION</th>
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</thead>
<tbody>
<tr>
<td>dynamic range</td>
<td>latitude</td>
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<tr>
<td>linearity</td>
<td>colour fidelity</td>
</tr>
<tr>
<td>pixel uniformity</td>
<td>granularity</td>
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<td>architecture</td>
<td>features</td>
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Resolution Requirements (1)

Resolution Requirements (2)
Resolution Requirements (3)

Resolution Requirements (3)

Trend in Resolution (1)

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Signal-to-Noise ratio (2)

Signal-to-Noise ratio (3a)

\[ ISO_x = \frac{10}{H_x} \]

\[ ISO_{40} \propto A \cdot QE \]

ISO \( x \) = ISO-speed @ S/N=x

\( H_x \) = exposure to get S/N=x

\( A \) = pixel area

\( QE \) = quantum efficiency

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Signal-to-Noise ratio (3b)

\[ ISO_{10} \propto \frac{A \cdot QE}{N_r} \]

\( ISO_x = \text{ISO-speed @ S/N}=x \)
\( A = \text{pixel area} \)
\( QE = \text{quantum efficiency} \)
\( N_r = \text{read noise} \)

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Signal-to-Noise ratio (5)

Improvement QE (1)
Improvement QE (2)

Angular Response (1)
Dark Current (1)

- prof. CCD
- cons. CCD
- standard CMOS

Dark current doubles every 6 ... 8°C.
Example: @ 60°C: 32 times higher!
@ -100°C: 32,000 times lower!

3 pA/cm² @ RT
10 pA/cm² @ RT
500 pA/cm² @ RT

Dark Current (2)

- Compensation for dark current is possible!
- Compensation for dark-current non-uniformities is possible!
- Compensation for dark-current shot-noise is NOT possible!

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Dynamic Range (1)

\[ DR = \frac{Q_{\text{sat}} - Q_{\text{dark}}}{\sqrt{N_r^2 + N_{\text{dark}}^2}} \]

- \( DR \) = dynamic range
- \( Q_{\text{sat}} \) = saturation signal
- \( Q_{\text{dark}} \) = dark signal
- \( N_r \) = read noise
- \( N_{\text{dark}} \) = dark shot noise

Dynamic Range (2)

![Graph showing charge handling versus pixel size](image_url)

- \( Q_{\text{sat}} = 30 \, \text{ke} \)
Dynamic Range (3)

Pixel Size [um]

Charge Handling [ke/um²]

Q_{sat} = 30 ke

CCD
CMOS

Linearity (1)

RAW data
interpolation
white balance
colour matrixing
gamma curve

R = R x 1.40
G = G x 1.00
B = B x 1.46

\begin{array}{ccc}
R & 1.424 & -0.500 & 0.076 \\
G & 0.090 & 1.431 & -0.491 \\
B & -0.390 & 1.302 &
\end{array}

γ = 1.8

RGB data
Linearity (2)

- Due to sampling in colour space: **Interpolations**,  
- Filters do not match perfectly: **Colour corrections**.

- Linearity CCD: 99% (for 70% of $Q_{\text{sat}}$),  
- Linearity CMOS: 97% (for 70% of $Q_{\text{sat}}$).

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Pixel Random Non-Uniformity

- PRNU CCD: < 0.7 ... 1.0 %,  
- PRNU CMOS: < 2.0 ... 5.0 %.

- Can be corrected by LUT,  
- To be non-visible: PRNU < photon shot noise (0.5 % for 40 ke).

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Architecture (1)

- CCD: parallel integration/reset
- CMOS: rolling integration/reset

Architecture (2)

- CCD: parallel integration/reset
- CMOS: rolling integration/reset

  - can be solved by 1 T and 1 C per pixel extra …
  - costs sensitivity, charge capacity, noise, …
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Summary (1)

• Resolution: pixel size of CCD smallest
• Noise: CMOS pixels suffer from reset noise
• Quantum efficiency: CMOS and CCD can be similar
• Angular response: limits set by micro-lenses
• Dark current: CCD outstanding
Summary (2)

- Saturation level can be similar
- Dynamic range of CCD is higher
- Linearity of CCD is better
- Pixel uniformity of CCD is better
- Device architecture of CCD gives more flexibility

Conclusions (1)

CCD or CMOS image sensor for consumer digital still photography?

CCD? YES!

CMOS? YES, provided that noise and dark current problems can be solved!!!
Conclusions (2)

- Main issue: performance
- Then benefit from:
  - low power of CMOS,
  - low driving voltages of CMOS,
  - on-chip functionality,
  - selective read-out mechanism,
  - cost advantage.

Important Remark

This presentation was about digital still photography. For video applications the situation is completely different!!!
References

• R. Baer : IEEE workshop on CCD & AIS, Karuizawa, 1999,
• J. Bosiers et.al. : IEDM, San Francisco, 1998,
• M. Kriss : ICPS, Antwerp, 1998,

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