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
- Summary and Conclusions
Introduction

• CMOS is challenging CCD
• Digital still is a continuously growing imaging market

Introduction

• CMOS is challenging CCD
• Digital still is a continuously growing imaging market

• Today : almost exclusively CCD in DSC
• Tomorrow : CCD or CMOS ?
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- Introduction
- Principle of CCD and CMOS imagers
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- Overview CCD vs. CMOS: resolution, signal-to-noise ratio, angular response, dark current, dynamic range, linearity, pixel uniformity, architecture
- Summary and Conclusions

CCD principle (1)
CCD principle (2)

- introduction
- principle of imagers
- CCD
- imager requirements
- overview CCD vs. CMOS
- summary and conclusions

CMOS principle (1)

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CMOS principle (2)

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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>
</tr>
<tr>
<td>dark current</td>
<td>max. exp. time</td>
</tr>
</tbody>
</table>

## Image Sensor Aspects (2)

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

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Resolution Requirements

![Resolution Requirements Graph](image_url)
Resolution Requirements

- introduction
- principle of imagers
- imager requirements
- summary and conclusions

Resolution Requirements

- introduction
- principle of imagers
- CMOS
- imager requirements
- overview CCD vs. CMOS
- resolution
- summary and conclusions
Trend in Resolution

- introduction
- principle of imagers
- CCD
- CMOS
- imager requirements
- overview CCD vs. CMOS
- resolution
- summary and conclusions

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- principle of imagers
- CCD
- CMOS
- imager requirements
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- resolution
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Signal-to-Noise ratio (1)

- Introduction
- Principle of imagers
- Imager requirements
- Overview CCD vs. CMOS
- Resolution
- Summary and conclusions
- S/N ratio

**Signal-to-Noise ratio (2)**

<table>
<thead>
<tr>
<th>Photogate APS</th>
<th>Photodiode APS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FREE of reset noise</td>
<td>NOT FREE of reset noise</td>
</tr>
<tr>
<td>LOW light sensitivity</td>
<td>HIGH light sensitivity</td>
</tr>
</tbody>
</table>

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**Signal-to-Noise ratio (3)**

\[
ISO_x = \frac{10}{H_x} \quad \text{ISO}_x = \text{ISO-speed @ S/N=x}
\]

\[
H_x = \text{exposure to get S/N=x}
\]

\[
ISO_{40} \propto A \cdot QE \quad A = \text{pixel area}
\]

\[
ISO_{10} \propto \frac{A \cdot QE}{n_r} \quad QE = \text{quantum efficiency}
\]

\[
n_r = \text{read noise}
\]
**Signal-to-Noise ratio (4)**

![Graph showing QE in green (%) vs. Pixel Size [µm] for CCD and CMOS technologies.](image)

**Improvement QE (1)**

![Illustration of microlens pixels improving QE.](image)
Improvement QE (2)

Angular Response (1)
Angular Response (2)

Angular Response (3)
Dark Current (1)

- prof. CCD 1...3 pA/cm² @ RT
- cons. CCD 5...10 pA/cm² @ RT
- standard CMOS 200...500 pA/cm² @ RT

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

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 !
Dynamic Range (1)

$$DR = \frac{N_{sat} - N_{dark}}{\sqrt{n_r^2 + n_{dark}^2}}$$

**DR** = dynamic range

- **$N_{sat}$** = saturation signal [e⁻]
- **$N_{dark}$** = dark signal [e⁻]
- **$n_r$** = read noise [e⁻]
- **$n_{dark}$** = dark shot noise [e⁻]

Dynamic Range (2)

![Graph showing charge handling vs. pixel size with $N_{sat} = 30$ ke⁻](image)

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Dynamic Range (2)

![Dynamic Range Graph]

Charge Handling [ke/um²] vs. Pixel Size [µm]

$N_{sat} = 30 \text{ ke}^-$

CCD

CMOS

Linearity (1)

RAW data

interpolation

white balance

colour matrixing

gamma curve

$\gamma = 1.8$

$R = R \times 1.40$

$G = G \times 1.00$

$B = B \times 1.46$

RGB data
Linearity (2)

- Due to sampling in colour space: **Interpolations**,
- Filters do not match perfectly: **Colour corrections**.
- Linearity CCD: 99 % (for 70 % of $N_{sat}$),
- Linearity CMOS: 97 % (for 85 % of $N_{sat}$).
Pixel Random Non-Uniformity

- **PRNU CCD**: < 0.7 ... 1.0 %,
- **PRNU CMOS**: < 2.0 ... 5.0 %,
  (column + pixel FPN)

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

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

- Can be solved by 1 T and 1 C extra in every 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: S/N 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 changes completely !!!
References

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