# CCD or CMOS image sensors for consumer digital still photography ?

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

# 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

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# Introduction

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



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# 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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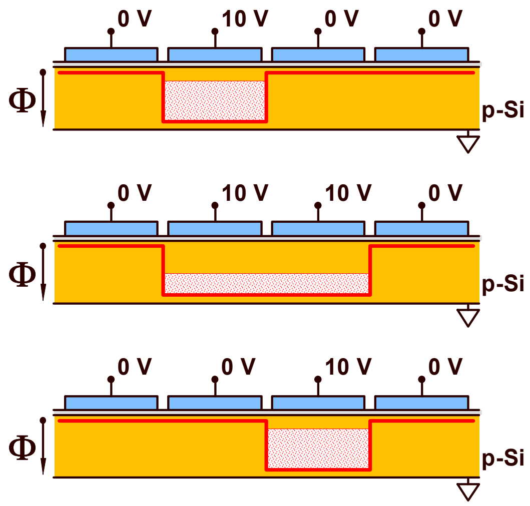
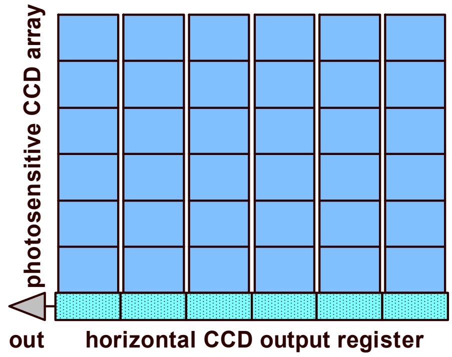
# CCD principle (1)



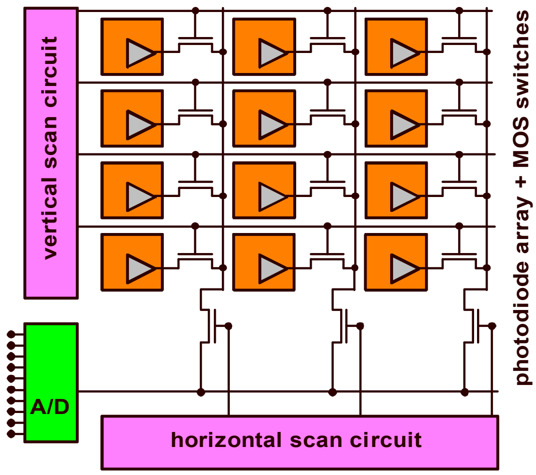
# CCD principle (2)








# CMOS principle (1)



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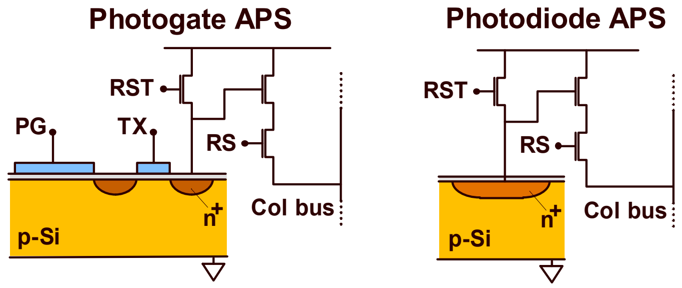
# CMOS principle (2)



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# Image Sensor Aspects (1)

| IMAGER PARAMETER | | CAMERA SPECIFICATION |
|---|---|---|
| resolution | → | sharpness |
| signal-to-noise ratio | → | ISO speed |
| angular response | → | min. F-stop |
| dark current | → | max. exp. time |



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# Image Sensor Aspects (2)

| IMAGER PARAMETER | | CAMERA SPECIFICATION |
|---|---|---|
| dynamic range | → | latitude |
| linearity | → | colour fidelity |
| pixel uniformity | → | granularity |
| architecture | → | features |

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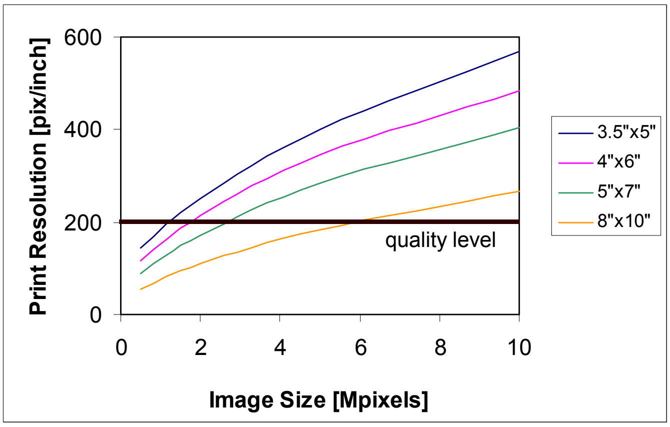
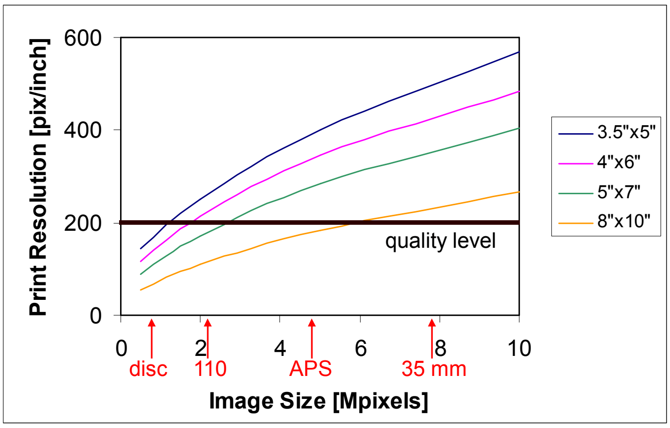
# Resolution Requirements



# Resolution Requirements







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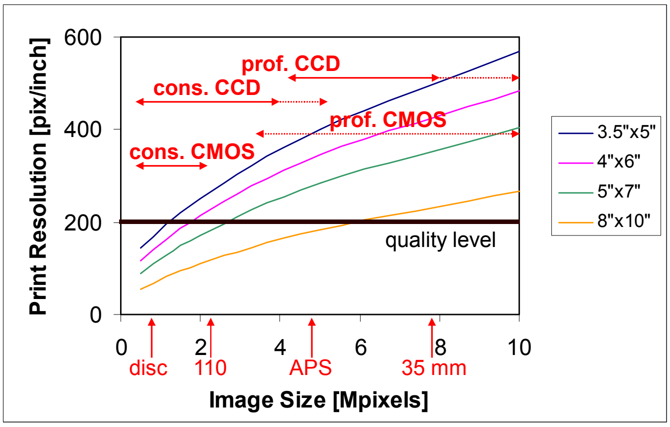
# Resolution Requirements



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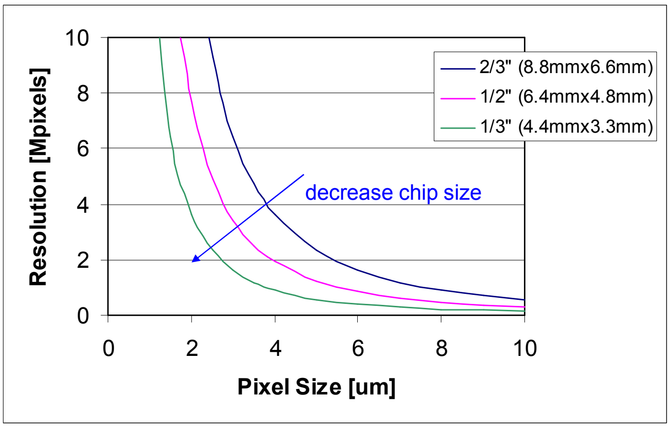
# Trend in Resolution



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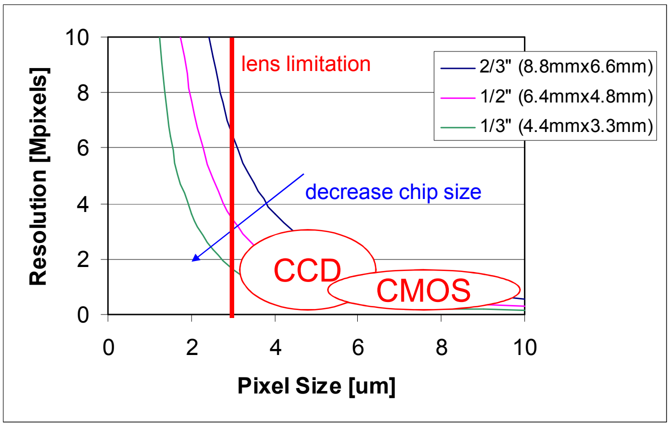
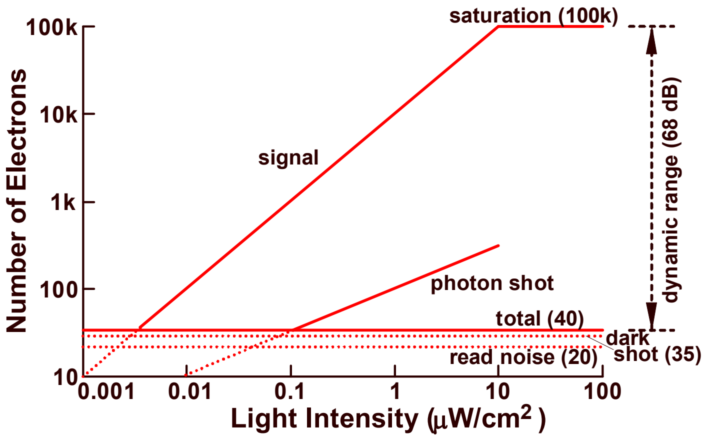
# Trend in Resolution



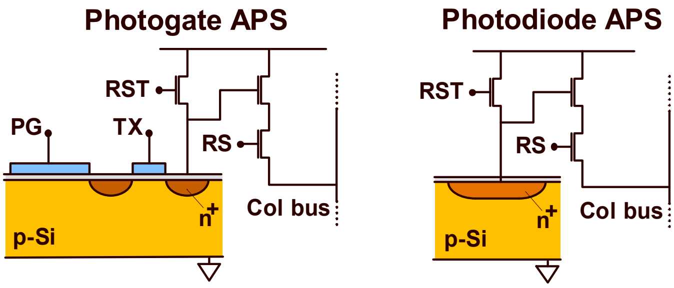
# Signal-to-Noise ratio (1)








# Signal-to-Noise ratio (2)




| | |
|---|---|
| FREE of reset noise | NOT FREE of reset noise |
| LOW light sensitivity | HIGH light sensitivity |

# Signal-to-Noise ratio (3)

$$ISO_x = \frac{10}{H_x}$$

$ISO_x$ = ISO-speed @ S/N=x

$H_x$ = exposure to get S/N=x

$$ISO_{40} \propto A \cdot QE$$

$$ISO_{10} \propto \frac{A \cdot QE}{n_r}$$

$A$ = pixel area

$QE$ = quantum efficiency

$n_r$ = read noise



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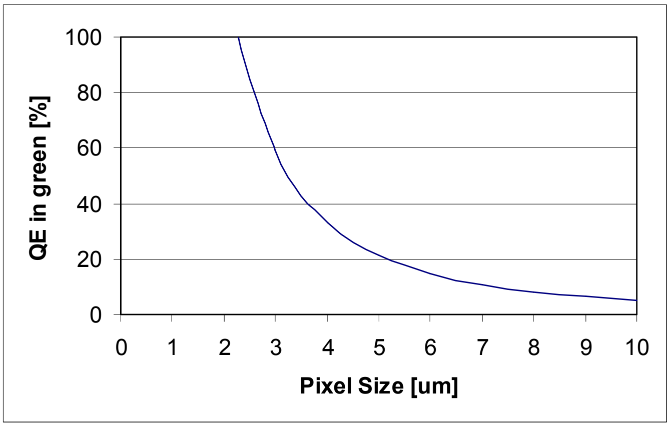
# Signal-to-Noise ratio (4)

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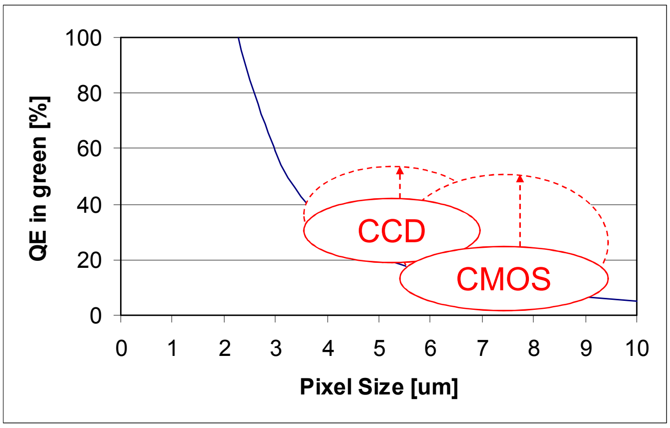
# Signal-to-Noise ratio (4)



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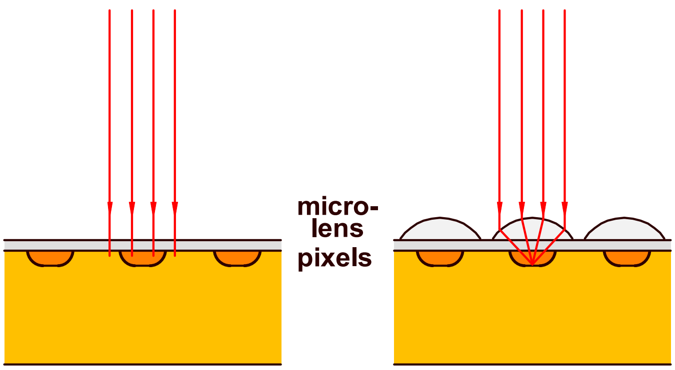
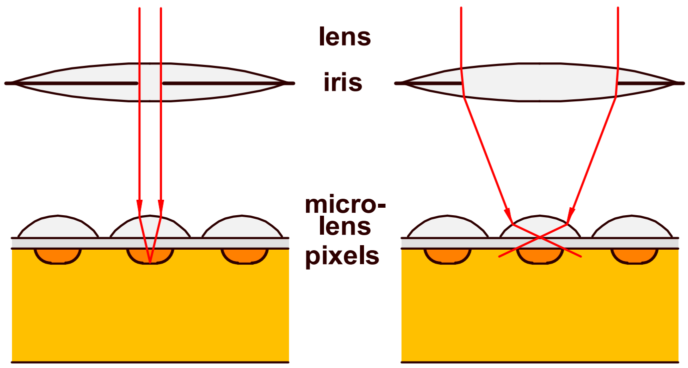
# Improvement QE (1)



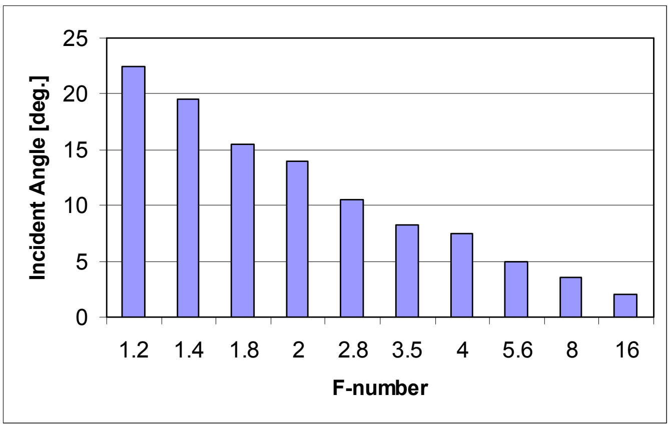
# Improvement QE (2)








# Angular Response (1)



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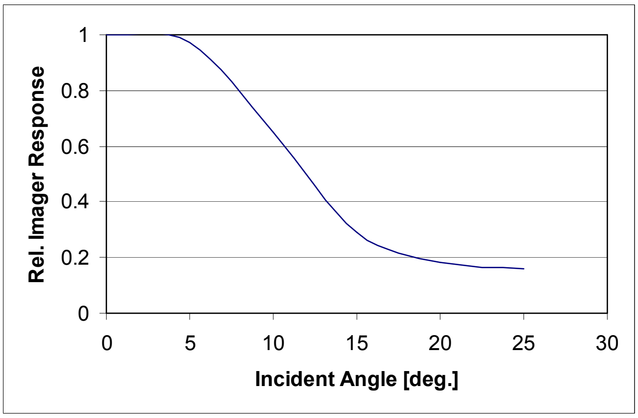
# Angular Response (2)



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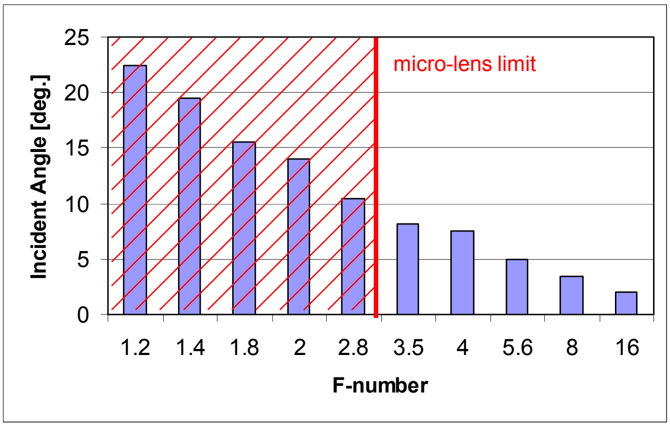


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# Dark Current (1)

- prof. CCD 1...3 pA/cm$^2$ @ RT
- cons. CCD 5...10 pA/cm$^2$ @ RT
- standard CMOS 200...500 pA/cm$^2$ @ RT

Dark current doubles every 6…8$^o$C.

Example : @ 60$^o$C : 32 times higher !

@ -100$^o$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 !

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# 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 [$e^-$]



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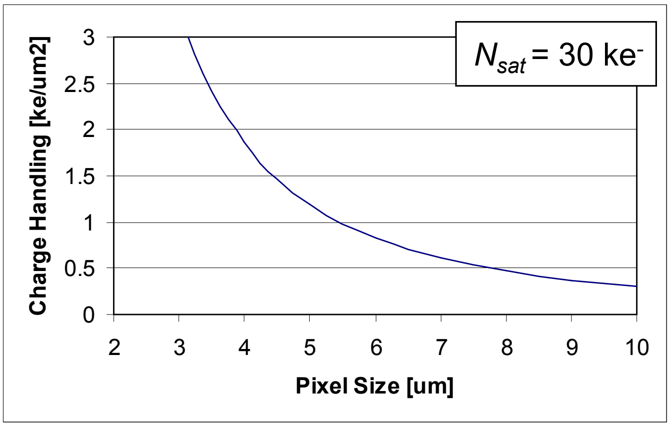
# Dynamic Range (2)



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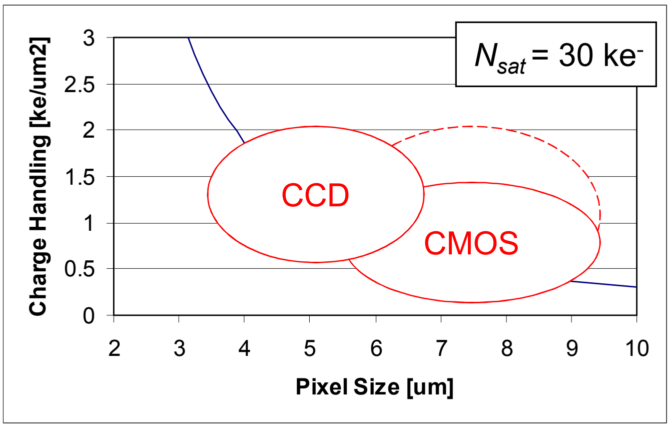
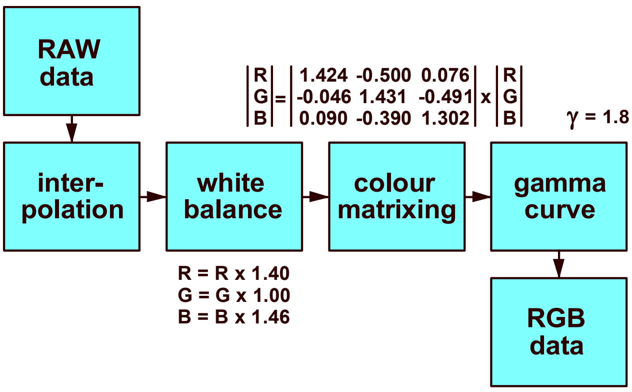







# Linearity (1)



# Linearity (2)

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



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# 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)



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# 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



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# 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 !!!

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# 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.



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# Important Remark

**This presentation was about digital still photography.**

**For video applications the situation changes completely !!!**

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