A 2/3 inch CMOS Image Sensor for HDTV Applications with Multiple High-DR Modes and Flexible Scanning

\textit{P. Centen}\textsuperscript{1}, S. Lehr\textsuperscript{2}, S. Roth\textsuperscript{2}, J. Rotte\textsuperscript{1}, P. Vogel\textsuperscript{2}, V. Neiss\textsuperscript{2}, H. Schemmann\textsuperscript{2}, M. Schreiber\textsuperscript{2}, B-K. Teng\textsuperscript{2}, K. Damstra\textsuperscript{1}

\textsuperscript{1} Grass Valley, Breda, The Netherlands
\textsuperscript{2} Thomson Silicon Components, Villingen, Germany

peter.centen@thomson.net
Agenda

- Design approach
- Chip Block diagram and Architecture
- Flexible scanning
- High-DR modes
- Results
- Conclusion
Design Approach

- **Broadcast is a low volume high performance market**
  - In Q1 2005 nobody in the CMOS field was interested in a dedicated development or had a design available!

- **Special challenges for a CMOS-imager in broadcast applications**
  - 1920(H) x 1080(V) : 5µm x 5µm pixels and 11mm image diagonal
  - Multimode : Interlaced (eg. 1080i60), progressive (eg. 1080p30)
  - QE and Noise : 2000 lux, 3200 K, 90%, f/8-f/11, SNR=54 dB in Y
  - Dark current : FPN, shot noise
  - Qmax : over exposure margin > 400%
  - Lag : None
  - ‘Blooming’ : must handle 16-fstop overexposure
  - Pixel-to-pixel : PRNU<1%
  - column-to-column: <0.06%
  - 3-imagers synchronized for use in R, G and B simultaneously
  - And many other imaging related topics both optical and electrical
Design Approach

- An imager is an ANALOG device
  - Keep the imager as simple as possible and make use of of-the-shelf components like FPGA, memory, processing blocks
  - Allow for a simple state machine and ADC’s on-chip
  - Flexibility in readout and in frame rate
  - Chose a camera architecture: video processing and imager, that eases CMOS image sensor design
  - Use a 3T-pixel in 0.18μm process
    - do real CDS off-chip
    - use hard reset, no soft reset because of inherent lag problems
      - the same performance as a 4T-pixel
      - many other advantages
Chip Block Diagram

Black Reference Pixels
- 80 black reference columns
- 40 black reference rows

Active Pixels
- 1978 active columns (1920)
- 1108 active rows (1080)
Shift Registers

Multiple select and reset shift registers for flexible scanning
Flexible Scanning

- Load the shift register with a proper “000XX00” pattern and define the ROI
- At 2/3 inch image diagonal
  - 1920(H) x 1080p(V)
  - 1920(H) x 1080i(V) with Frame or Field mode
  - 1920(H) x 540p(V) with 1080p or 540p aperture
- At different image diagonals (ROI)
  - 1280(H) x 1440i(V)
  - 1280(H) x 720p(V)
  - 1724(H) x 485p(V)
  - 1724(H) x 485i(V)
- Raw frame rates for the 3 main modes
  - 1080p90 or 1080i180 or 720p180 (=>1080p120)
  - Maximum clock frequency ADCs: 2x112 MHz (=> 2x148 MHz)
Evaluation: Shot Noise Transfer Curve

Signal: \( V = K N \)  
Noise: \( \text{VARIANCE} = E_n^2 = K^2 \left( N + N_{\text{amp}}^2 \right) \)

Asymptotically: \( E_n^2 = KV \Rightarrow K \) can be determined

K: conversion gain  
N: number of electrons in one pixel  
V: Output signal  
\( E_n \): Output noise

Progressive: Charge packet: N  
Interlaced: Charge packet: 2 N

\( K = 3.3 \, \text{e}/\text{DN} \)  
\( N_{\text{amp}} = 11.5 \, \text{e} \)
Evaluation: Zonechart

• The ALIASING in 1080i60, after adding two consecutive lines, is gone
High-DR modes

• *Implemented and under investigation*
• Time sub sampling, 3 samples of the pixel voltage
  – First sample at black
  – Second sample at eg ¼ of the nominal integration time
  – Third sample at the end nominal integration time
• Vertical sub sampling
  – Even rows have pixels with a nominal integration time
  – Odd rows have pixels with eg ¼ of the nominal integration time
• Horizontal sub sampling
  – Even columns have pixels with a nominal integration time
  – Odd columns have pixels with eg ¼ of the nominal integration interval
• Adjustable Linear-Logarithmic pixel
Evaluation: High-DR Image
New Technique for Dark Current Investigation

2-Dimensional Binarized Histogram

- 2-images at different temperature
  Eg 50C and 70C;
- A pixel-by-pixel comparison in both images
  for m,n do HISTO[ IMAGE1[m,n] , IMAGE2[m,n] ]:=1

Y-axis: 70C =>
X-axis: 50C =>

Info on activation energy
for ALL pixels!

<= Y-axis: 70C
<= X-axis: 31C
Chip Micrograph
## Table of characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size, transistor count</td>
<td>5µm x 5µm; 3T</td>
</tr>
<tr>
<td>Number of pixels including opt. black</td>
<td>2048(H) x 1148(V)</td>
</tr>
<tr>
<td>Pixel fill factor (without micro-lens)</td>
<td>56%</td>
</tr>
<tr>
<td>Analog to digital conversion</td>
<td>2 ADCs of 12bit</td>
</tr>
<tr>
<td>Scanning rate demonstrated (2x148MHz)</td>
<td>1080i240 or 1080p120</td>
</tr>
<tr>
<td>Conversion gain FD</td>
<td>80µV/e⁻</td>
</tr>
<tr>
<td>Idark @ 60°C</td>
<td>0.4nA/cm²</td>
</tr>
<tr>
<td>Temporal noise, pixel only, 27°C</td>
<td>4e⁻</td>
</tr>
<tr>
<td>Temporal noise, all contributors, 27°C</td>
<td>11.5e⁻</td>
</tr>
<tr>
<td>Sensitivity in green (color splitter)</td>
<td>32ke⁻/lux-sec</td>
</tr>
<tr>
<td>Maximum reachable dynamic range</td>
<td>116dB in interlaced mode</td>
</tr>
<tr>
<td></td>
<td>122dB in progressive mode</td>
</tr>
<tr>
<td>Linear saturation level</td>
<td>&gt;15ke⁻</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>550mW@1080i120</td>
</tr>
</tbody>
</table>
Conclusion

- A 2/3 inch CMOS image sensor with 3T-pixel, in 0.18µm 1P4M process, is presented that fulfills full HDTV broadcast quality
- Among the many scanning formats are 1080p, 1080i and 720p with matched anti-aliasing properties
- The imager has multiple ways for generating High-DR images
- Compared with a CCD application with the additional pulse pattern generator + CDS + gain stages + ADC the power consumption went down with a factor of 3
- A noise level of 4e⁻ for the pixel and 11.5e⁻ overall was obtained with off-chip CDS
- At 2000 lux, 90%, 3200K and 54dB in Y
  - In 1080i60 the f-number is f/8 and f/11 in 1080p30
- The maximum raw capture rate is 1080i180, 1080p90 and 720p180
  - 1080i240 or 1080p120 has been demonstrated