Camera CMOS Technology

CMOS Sensor Technology
Characteristics and Relevance for HDTV Cameras

HD Technology Briefing
EBU Headquarters, Geneva, Nov. 2005

ARRI R&D
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Camera CMOS Technology

- ***CMOS sensors have specific advantages if it depends on resolution and speed (and of course image quality)***

- ***CMOS sensors have a share of > 90%
in high end still cameras (> 10 MPix, 3000..8000 USD)
[dpreview.com, 11.2005]***

- ***these still cameras offer up to 5 fps at 12 MPix (60 MPix/s)***

- ***moving images HD cameras require significant bandwidth above that if full resolution (1920*1080) and progressive capture (50p/60p) or even slow motion is required. For a slow motion factor of 3, as known from SD slow motion cameras, the rate is 300/360 MPix/s.***

Camera CMOS Technology

Topics

- ***Sensor Architectures***
- ***Fundamentals for Challenging Sensor Systems***
- ***Advantages and Inconveniences***
- ***Sensor Characterization***
- ***Applications***
- ***Aspects for ARRI D20***

Sensor Architectures

CCD / CMOS / APS / (PPS) / MOS-XY

- ***CCD/CMOS and all the other sensor architectures named do not concern how to convert photons to electrons.***

  Photons above an energy level of 1.1 eV (equivalent to a wavelength < 1000 nm) generate charge carriers when impinging silicon. The separation of the electrons and the holes is effected by the electrical field across a pn junction in each pixel.

- ***The difference between sensor architectures is how they transport the electrons out of each pixel (millions of pixels, each working at a frame rate of ~ 30 frames/s) to the outputs of the sensor (very few, so 10..100 MPix/s per output)***

Sensor Architectures

- ***CMOS sensors name comes from their manufacturing process (Complementary Metal-Oxide Semiconductor). It is the standard process for most integrated circuits today.***

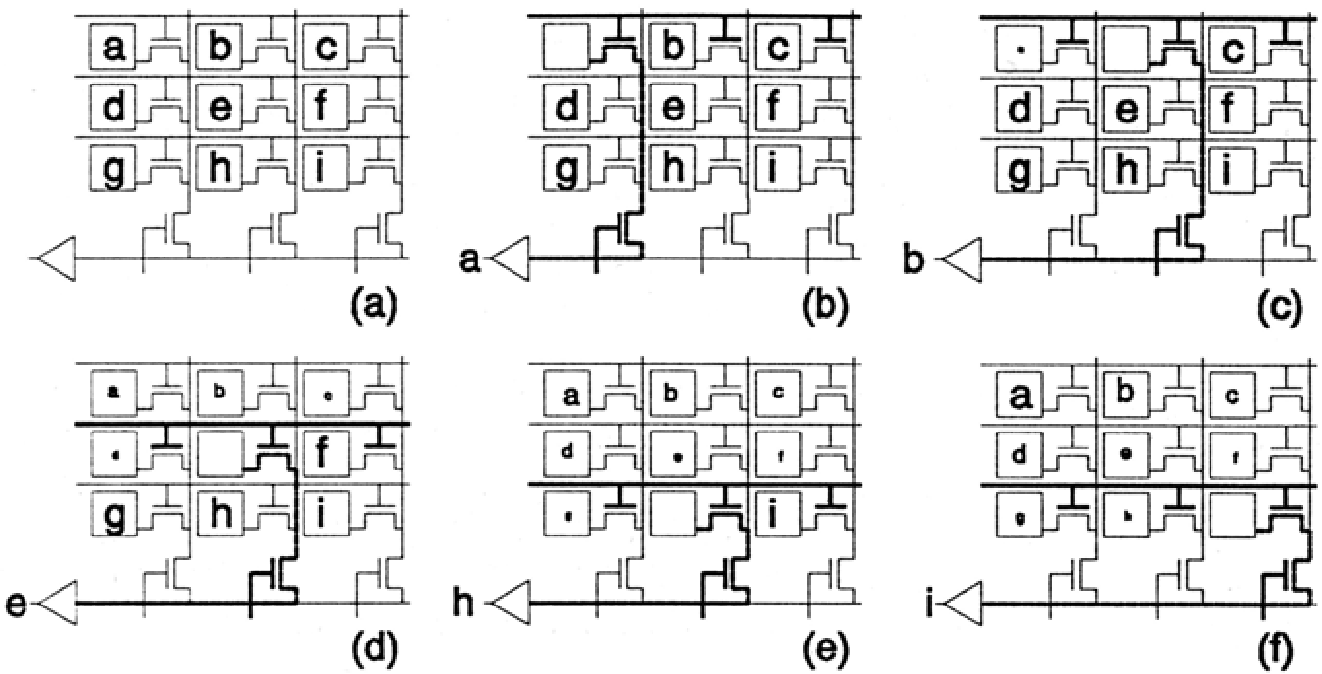
- ***CMOS sensors have amplifying (active) elements (transistors)in each pixel. So they are sometimes also called Active Pixel Sensors (APS)***

- ***the passive analogy (PPS) also existed some ten years ago.***

- ***both imagers, APS and PPS, have the same internal structure and are sometimes called MOS-XY addressable imagers since each pixel in the xy-array can be addressed independently.***

Sensor Architectures

- ***this is implemented as an (analog) bus system in vertical and horizontal direction***

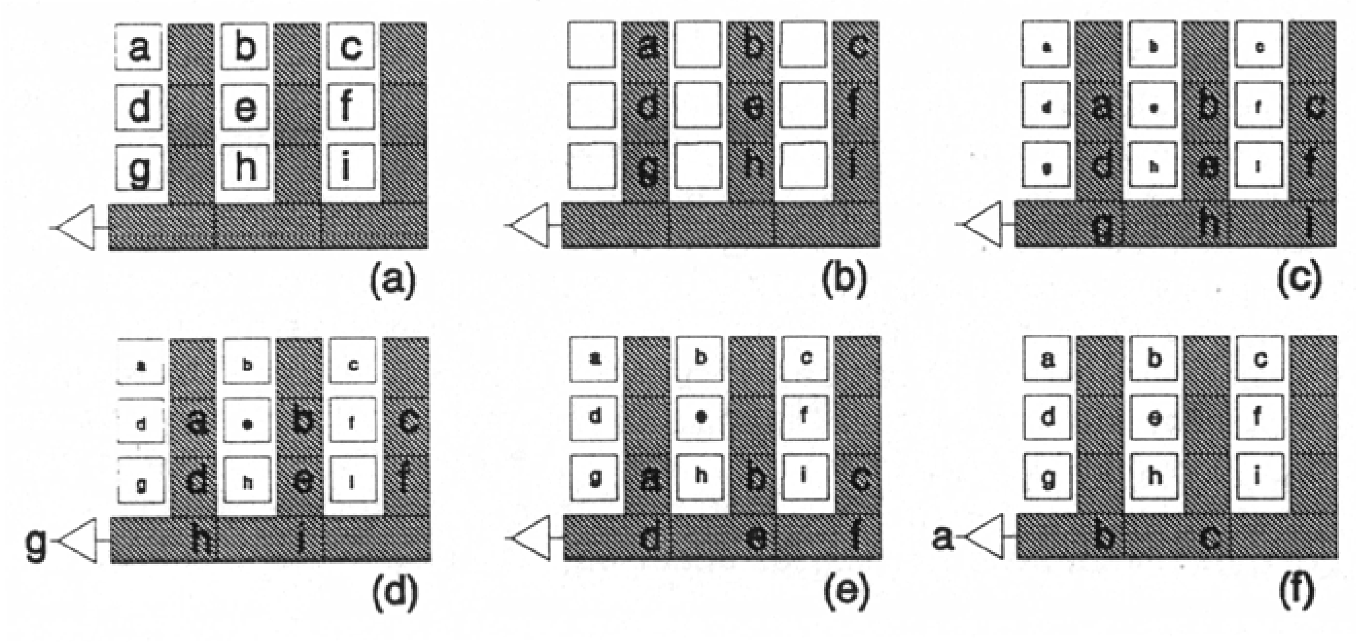


[Theuwissen]

- ***this means in principle that a pixels signal is connected directly to the output when its xy address is applied***

Sensor Architectures

- ***this is in contrast to CCDs where the signal of every pixel***
  is sequentially shifted through its vertical and horizontal neighbours until it appears at the output.
  This means several thousand shifts for an HD sensor.



[Theuwissen]

Sensor Architectures

- ***PPS have been more easy to manufacture and operate compared to CCDs:***

  - just a MOS switch per pixel to connect the pixel signal to the bus line instead of multiple and overlapping gates for a CCD shift register

  - just activation of a horizontal and vertical address instead of multiphase clock patterns with precise timing to obtain an efficient charge transfer

- ***S/N of PPS was below of the S/N in the pixel since they switched the small pixel capacity to the relatively large capacitance of the bus without any gain and thereby reduced the signal amplitude.***

Sensor Architectures

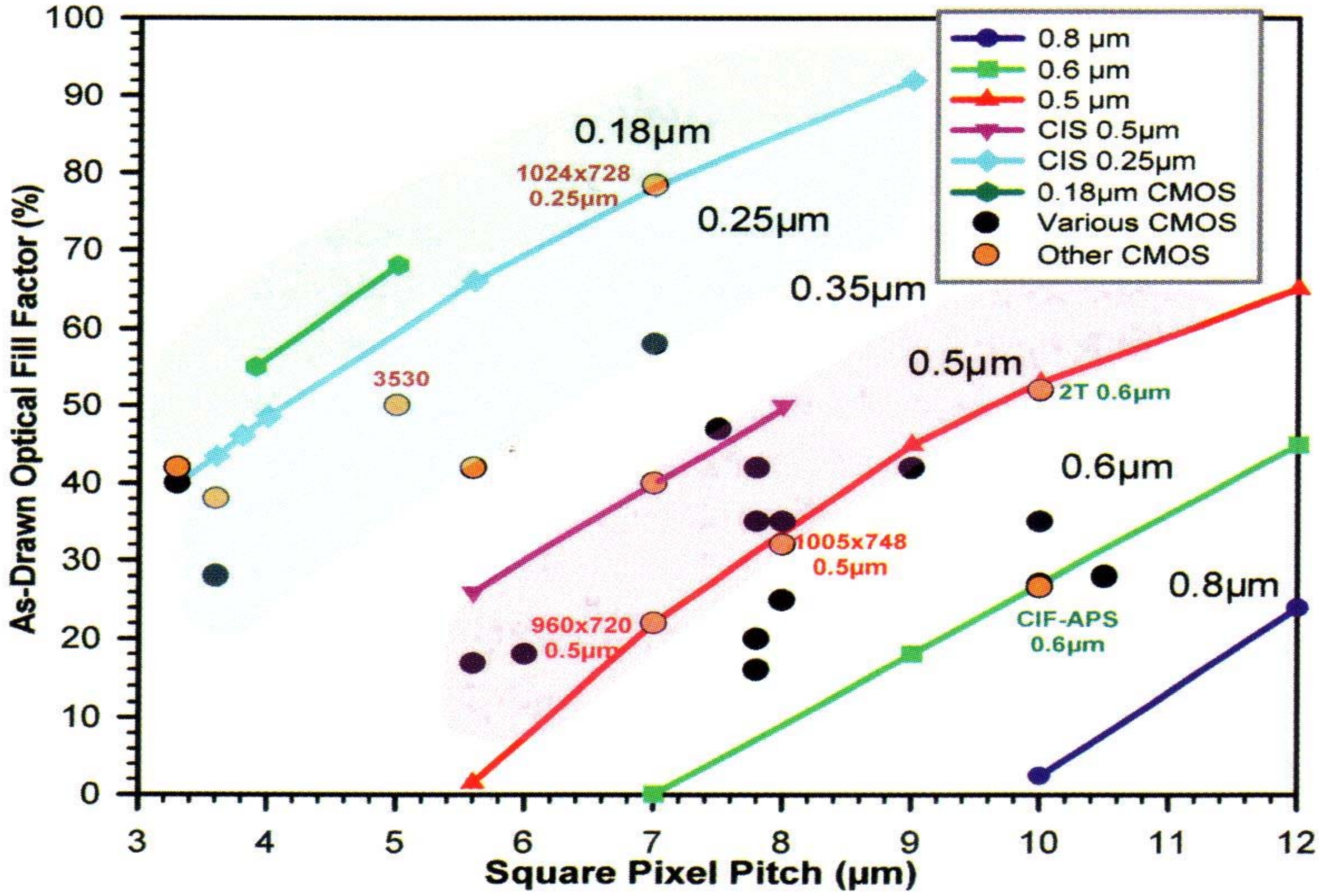
- ***the situation changed (~1990) with sub-micron semiconductor processes that allowed the integration of multiple transistors in each pixel. The bus with its capacity can now be decoupled from the pixel.***

- ***the charge to voltage conversion now takes place in each pixel***

- ***S/N significantly increases and may even go beyond CCDs in moving image applications***

- ***for the 3 transistor pixel (1 Reset, 1 Gain, 1 Select), currently dominating, the process size has to be about a factor of 15 or more below the pixel pitch.***

Sensor Architectures



[AltaSens]

Sensor Architectures

- ***industrial (and commercially successful) pioneers in the professional market segment:***

  - Photobit (Eric Fossum)
  1995 spin-off by JPL/ NASA
  (acquired by Micron)

  - FillFactory (Bart Dierickx, et al.)
  1999 spin-off by IMEC Leuven/Belgium
  (acquired by Cypress)

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Fundamentals

- ***first stage (transistor) determines S/N of the whole system.***
  The proportion of noise of subsequent stages is significant smaller on the signal after some gain than it is on the signal before any gain.

- ***first stage shall be at the position of the best possible S/N.***
  That is at the origin of the signal path and before attenuation and interference on its further way (cable, transport, ..). Signal goes down, noise adds, S/N goes down above average.

- ***keep the bandwidth of the signal path as small as possible since noise increases with bandwidth***

Fundamentals

- ***this means for an image sensor***

- boost the signal at the position of the best possible S/N ratio. This is immediately in the pixel and before degradation of the signal on its way to the output can happen

- boost the signal at the position of the lowest possible bandwidth. This is again in the pixel where the bandwidth of the first transistor is matched to a rate of some 10..100 frames/s (Hz) and not at the output where a bandwidth for 10..100 MPix/s (MHz) per output is needed.

Fundamentals

- ***These fundamentals are important for an image sensor since:***

  - the noise floor of good motion imagers represents few 10 e

  - it becomes increasingly difficult to keep this number as resolution and frame rate of an image sensor go up

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Advantages and Inconveniences

- *the above criteria are met by CMOS sensors.*
  This establishes the good characteristics of these sensors
  for high frame rate in parallel with high resolution.

- *reduced power consumption inside and outside of the sensor despite high frame rate and resolution.*
  There is no need for driving the transfer gates of all pixels (millions) in parallel, which means driving a high capacitance via high resistance at high frequency.

- *the active elements establish a low resistive drain for overflowing charges and assure a high isolation between each pixel and the low impedance (metal) bus.*
  This makes these sensors inherent free from the classical blooming and smear effects.

Advantages and Inconveniences

- *however all the active elements have tolerances.*
  I.e. the varying threshold voltages of the transistors cause
  a dark level and a gain slope specific for each pixel

- *the result is an inhomogeneous, noisy looking image*

- *but this so called Fixed Patter Noise (FPN)*
  must not be mixed up with temporal noise:
  - the latter affects the image irreversible
  - the first can be removed completely

Advantages and Inconveniences

- ***high quality images require a correction of the above factors specific for each pixel***

- ***this can be done to some extent directly on the image sensors. However for all the corrections mentioned above and i.e. for large sensors off chip corrections are common.***

- ***this is possible today even for high speed cameras. Available monolithic integrated circuits offer hundreds of parallel multipliers / adders running single cycle at rates of several hundred MHz This gives a processing power of many GOps/s (Giga Operations per sec) per chip. That is enough for several hundred fps.***

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Sensor Characterization

- *the photodiode shares the pixel area with the transistors in the pixel and the bus that goes along each pixel. (Bus and transistors can be placed above each other)*

- *The relation „photodiode sensitive area / total pixel area“ is called fill factor. It increases with the relation „pixel pitch / semiconductor process size“. A value of about 50% for the fill factor is common and corresponds roughly to the value of interline CCDs.*

- *however the photo diode of CMOS sensors is not covered by the (not fully transparent) transfer gates that are needed for CCDs. So a better number to describe a sensors performance is QE * FF or SR * FF that represent the effective response of a pixel.*

Sensor Characterization

- *QE * FF is a clear number and gives the relation of electrons compared to the impinging number of photons per pixel.*
  The value is dependent on wavelength. The peak values in the visible spectrum for moving image sensors today are in the range of 30% to a 60%.

- *limiting factors for QE (even at a 100% FF) are:*
  - reflection
  - limited transparency of several layers on top of the photo diode
  - recombination of charge carriers generated to far away from the so called depletion region of the pn junction (affects mostly red and blue)

Sensor Characterization

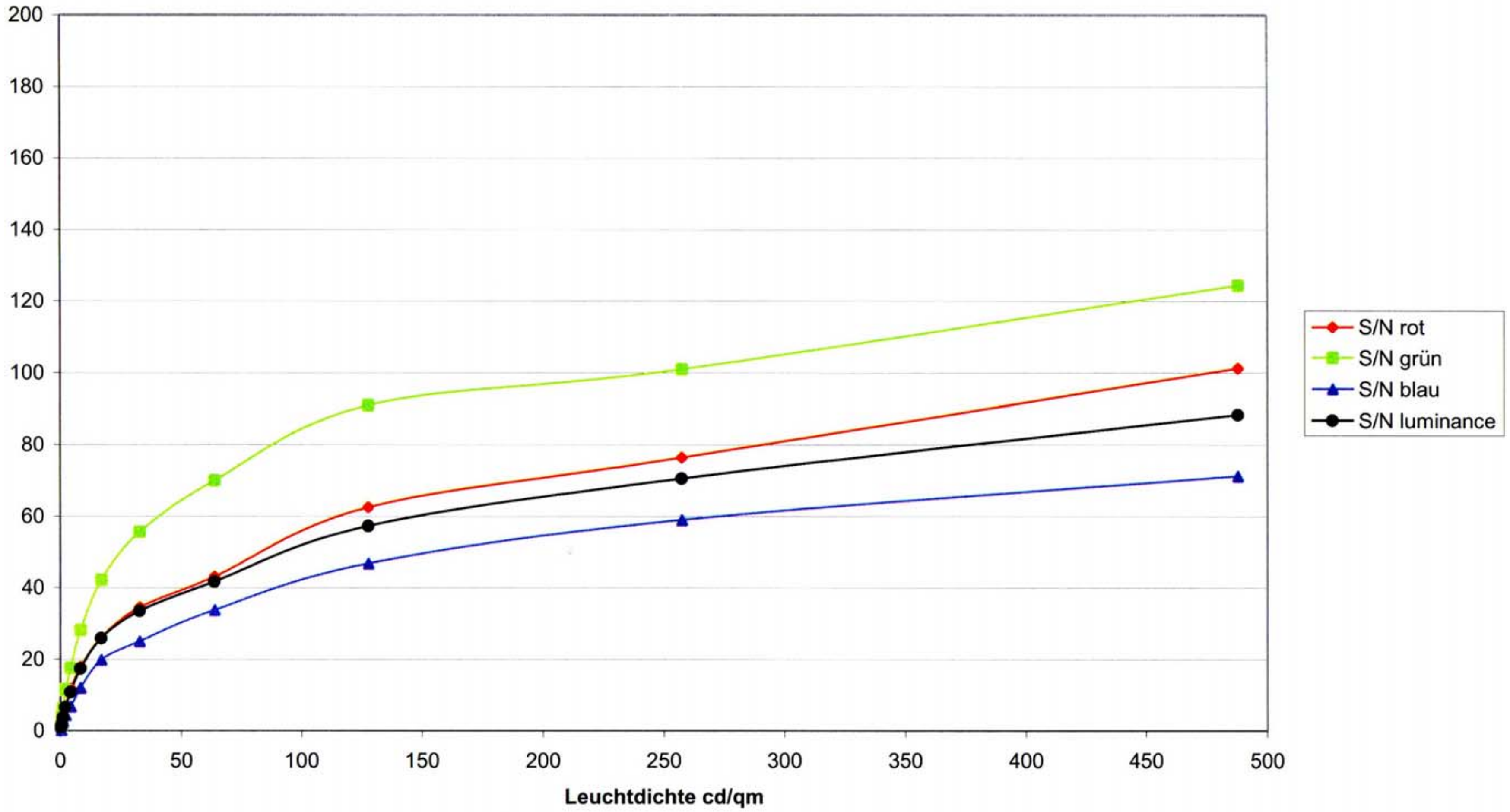
- ***noise performance and sensitivity of a complete camera can be determined according to ISO 12232***

- ***the noise and the "local S/N" has to be determined at different levels of exposure from black to saturation (OECF).***
  The dependency on the camera characteristics is eliminated by calculating all numbers back to the linear object space based on the local inclination of the OECF (and independent of any information of the camera menu)

- ***3 numbers are delivered:***
  - ISO (ASA) for saturation
  - ISO (ASA) for a "local" S/N of 40, "excellent image"
  - ISO (ASA) for a "local" S/N of 10, "first acceptable image"

Sensor Characterization

Example of differential (local) S/N vs. exposure



[ARRI]

Sensor Characterization

- *the numbers show:*
  - the amount of light needed for a certain level of image quality
  - the latitude the camera can offer from a certain level of image quality up to saturation

- *the method is robust against camera characteristics and camera gain but not against "special" noise reduction technics that can be seen in the OECF of some still cameras*

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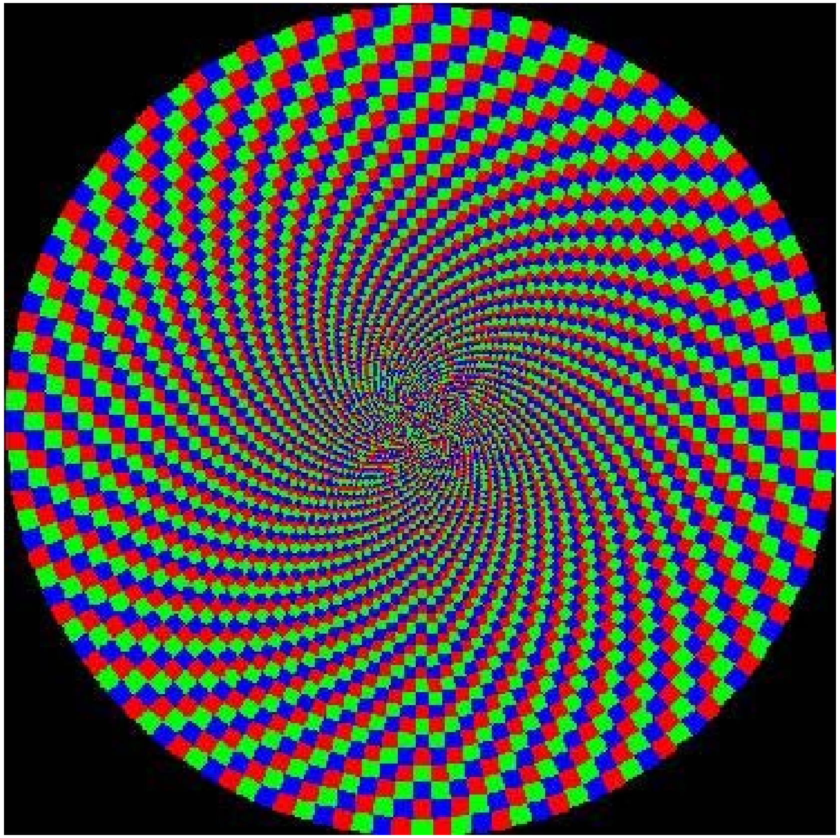
Applications

- ***the potential of this technology for imagers is large and has created solutions that are not possible otherwise. E.g.:***

  - single chip 3D sensor including data processing that delivers in parallel intensity and depth of a scene
  - 360° „human retina-like“ sensor where the resolution decreases from the central point outwards (next page)
  - readout of small windows of the sensor at a increased frame rate
  - „single chip cameras“ that include image preprocessing (e.g. variable gain), sensor timing control, analog to digital converters, auto white balance / color correction, formatted data output according to established (bus) interfaces

Applications

CMOS Retina Sensor with „rotating color pattern“



[FillFactory / Liralab]

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Applications

- ***not all is relevant for HD cameras - but some is (or may become) as:***

- ***high resolution and high frame rate in parallel with low power consumption and good image quality***

- ***single Chip RGB Sensor.***
  - every pixel delivers RGB information in parallel
  - makes use of the wavelength dependent depth of penetration of photons
  - collects electrons by 3 pn junctions at 3 different levels of depth

Applications

- ***option for color correct binning of Bayer Mask sensors***

- ***high dynamic range sensors by means of:***

  - pixel with logarithmic electrical response (susceptible to fixed pattern noise)

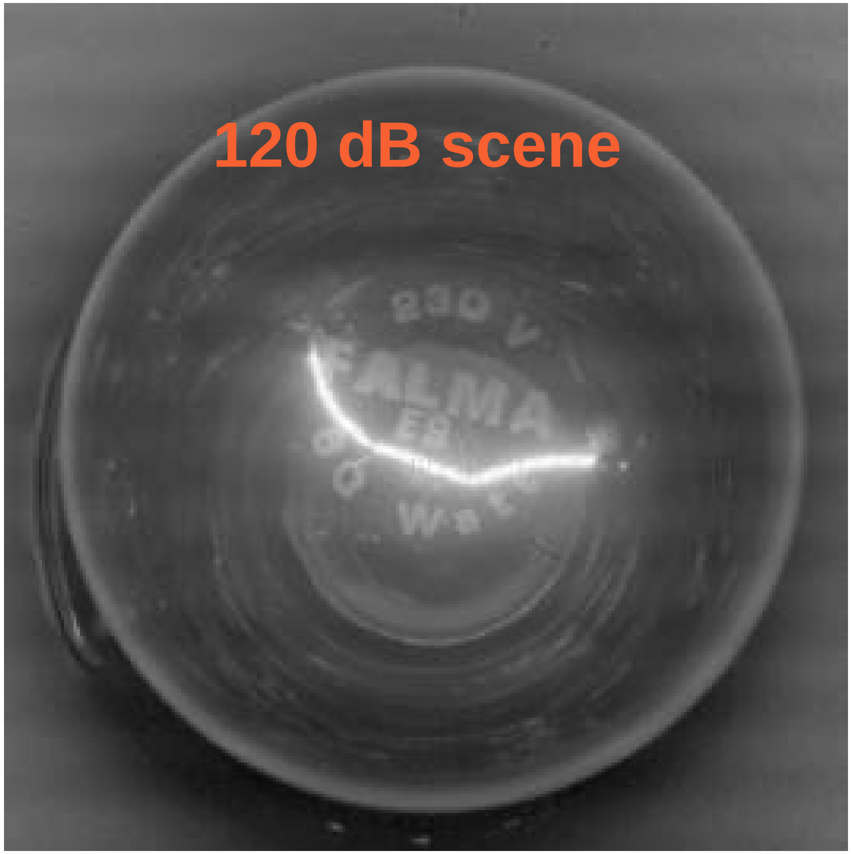
  - auto adaptive electronic shutter inside each pixel. (increased number of transistors; lower fill factor)

  - multiple readout during the integration phase by the feasibility of non destructive readout (dual slope integration by double sampling)

  - and several other techniques

Applications

CMOS Sensor with dual slope integration



[FillFactory]

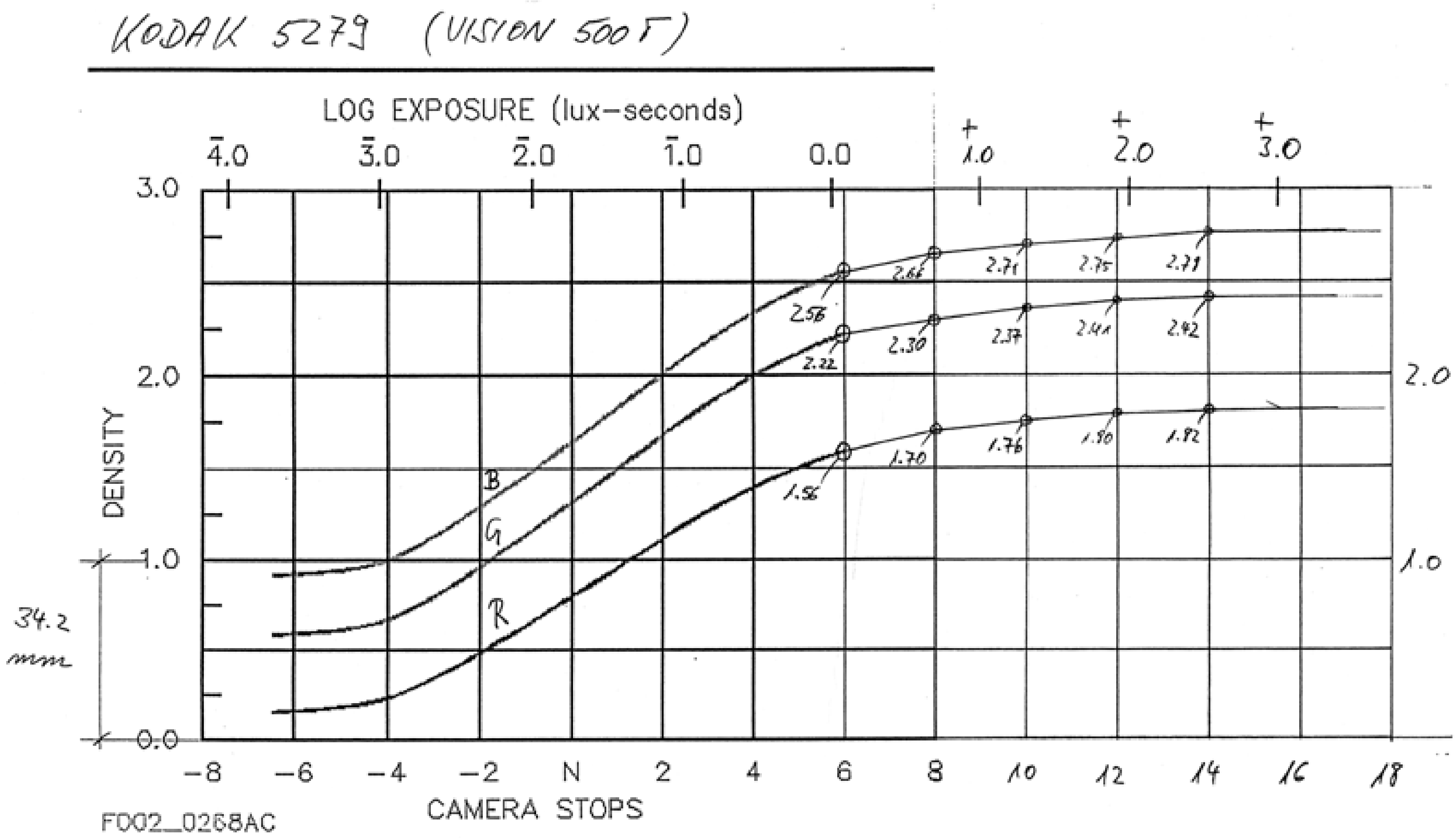
Applications

CMOS Sensor with dual slope integration (right image)

[FillFactory]

Applications

Cine Film



[ARRI]

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Aspects for ARRI D20

- ***full custom design based on a flexible standard technology offering:***

  - straight forward implementation of requirements

  - internal bus structure of the sensor gives design flexibility with respect to size of the sensor, number of pixels, number of outputs and frame rate

  - large image area compatible with existing cine lenses

  - multi format support (4:3, 16:9 or other) while keeping the center of the image in the optical axis. Thereby no penalty with respect to frame rate.

Aspects for ARRI D20

- ***non destructive readout***

  - means that an image can be read out of the sensor without loosing the charge in the pixels

  - allows extending the dynamic range by double reading an image after e.g. 10% and 100% of its integration cycle.
  The 10% image saturates about 3 stops after the 100% image and delivers highlight information for additional 3 stops

  - allows true CDS (correlated double sampling) by double reading an image after 0% and 100% of its integration cycle and getting rid of the so called kTC noise (reset noise).

Aspects for ARRI D20

- ***high potential with respect to speed AND resolution***
  - 800 MPix/s currently used, 1200 MPix/s possible
  - no degradation of image quality with speed and within the given bandwidth
  - product of „frame rate * size of image“ is nearly constant and independent of the position of the window in the image

- ***option for color correct binning in conjunction with the efficient Bayer Mask for color separation***
  - mosaic pattern of red, green (2x) and blue
  - ! no direct neighbourship of pixels of the same color

Aspects for ARRI D20

- *robust interface to the camera electronics*
  - few supply voltages
  - no multiphase clock patterns for read out (voltage, power, narrow analog tolerances)
  - (nearly) no dependency of image quality (charge transfer efficiency, ..) on external control
  - no analog adjustment elements

- *low power consumption*
  - about 1.1 W power consumption of the sensor at full speed
  - „powerless“ control of the sensor by pure logic
  - otherwise several watts of clock power to generate and to „pump“ into a sensor of this size and speed
  - that would mean increased sensor temperature and decreased image quality.