IEDM 70th International Electron Devices Meeting

Image Sensors at IEDM : Yesterday, Today, and Tomorrow

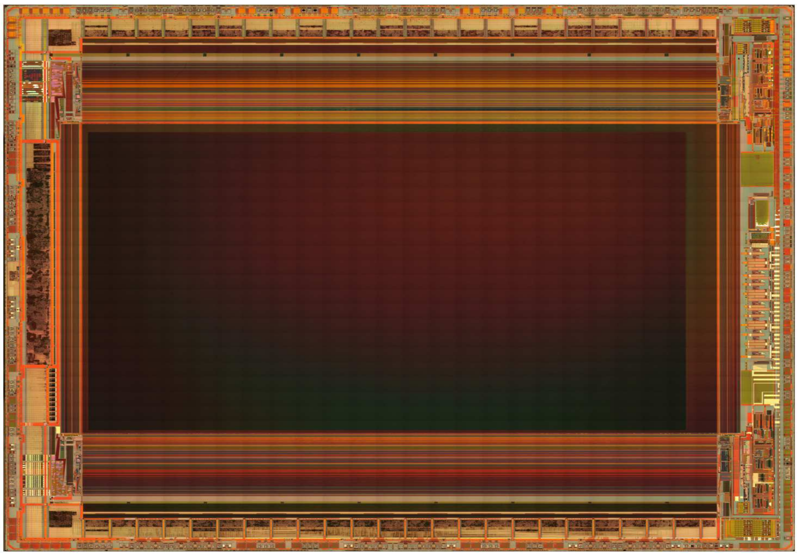
Prof. Em. Dr. Albert Theuwissen

harvest imaging

Agenda

- Introduction
- Major CMOS Image Sensor (CIS) inventions presented at past IEDM conferences
- Personal IEDM jewel
- What about new CIS developments at future IEDM conferences ?
  - Quantum efficiency
  - Dynamic range
- Conclusion

CMOS Image Sensor Floor Plan

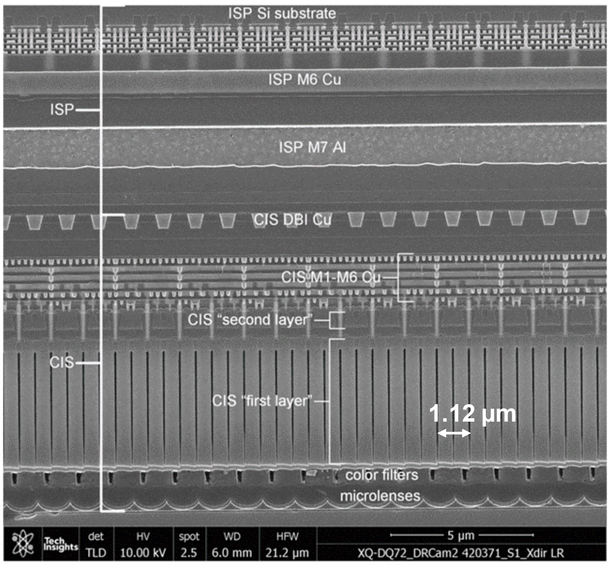


Source : Chipworks/TechInsights

- **Pixel size :**
  0.5 µm … 20 µm …
- **Number of pixels :**
  100k … 500M …
- **Chip Size :**
  0.5 mm^2 … 400 cm^2

CMOS Image Sensor Dissection (1)

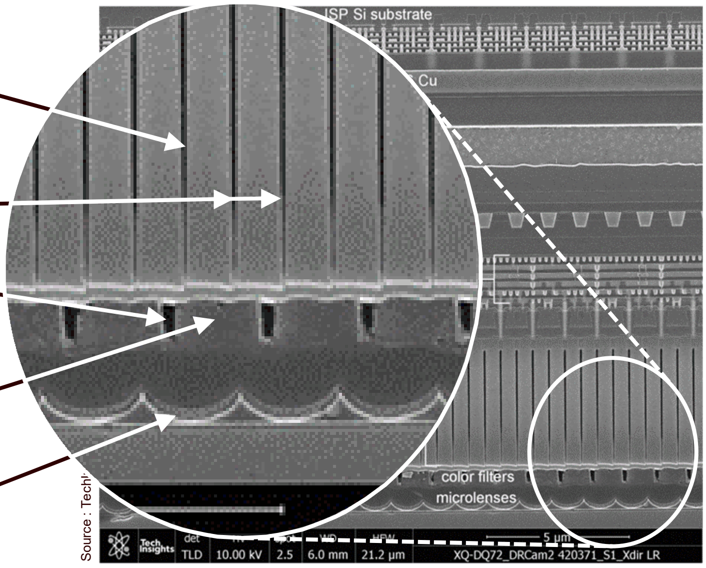
- **Major CMOS Image Sensor innovations, first introduced at IEDM, will be highlighted**
- **"Device under Test" : Sony CMOS image sensor present in iPhone, 48 Mpixel, 1.12 µm pixel pitch, back-side illumination, triple stacked, full PDAF**



Source : TechInsights

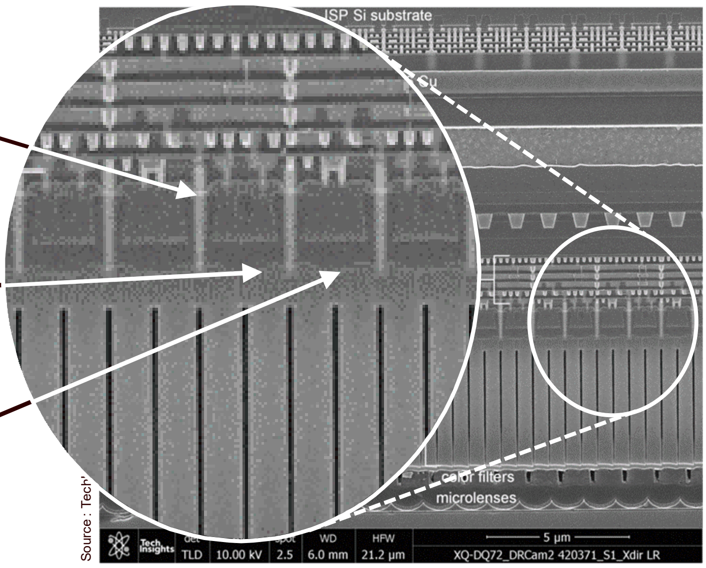
CMOS Image Sensor Dissection (2)

- Deep trench isolation (DTI) to limit optical and electrical cross-talk (de Munch, IEDM 2006)
- All PDAF pixels for auto-focusing applications (Okawa, IEDM 2019)
- Wave guides to limit colour cross-talk (Watanabe, IEDM 2011)
- On-chip colour filters (Dillon, IEDM 1976)
- Micro-lenses to increase the fill-factor and focus the incoming light into the middle of the pixels (Ishihara, IEDM 1983)



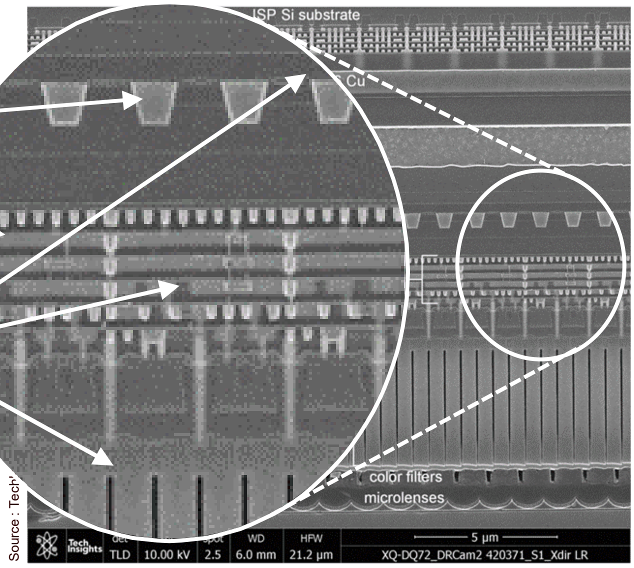
CMOS Image Sensor Dissection (3)

- Sequential processing to allow optimization of in-pixel transistors (Coudrain, IEDM 2008)
- Intra-pixel charge transfer to allow CDS and cancel kTC noise (Mendis, IEDM 1993)
- Pinned-photodiode for noise-less transfer, low dark-current, pixel sharing (Teranishi, IEDM 1982)



CMOS Image Sensor Dissection (4)

- Cu pads for hybrid bonding (Kagawa, IEDM 2016)
- Full Cu metallization in image sensors (Cohen, IEDM 2006)
- Triple stacking of silicon layers (Kioi, IEDM 1983)



Personal IEDM Jewel

Influence of Terrestrial Cosmic Rays on the Reliability of CCDs

Albert THEUWISSEN
Elke THEUWISSEN
Lien THEUWISSEN
Kim THEUWISSEN

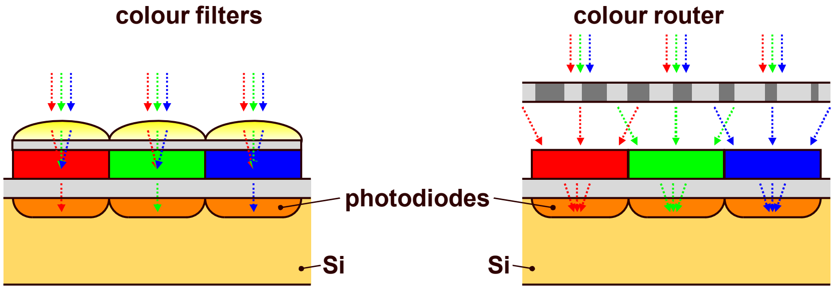
Dec. 7th, 2005 IEDM 2005, Washington DC 1

End of Image Sensor Developments ?

For several performance parameters, the CIS approach is the "ideal" situation, such as :

- Temporal noise < 1 electron (sub-electron levels reached)
- Fixed-pattern noise (light and dark) << 1 % (FPN is below visibility level)
- Dark current : 1 pA/cm^2 at RT (theoretical limit is reached)
- Quantum efficiency > 90 % (but only for B&W sensors)
- Dynamic range > 80 dB (but way too low for automotive)

Colour Router (1)

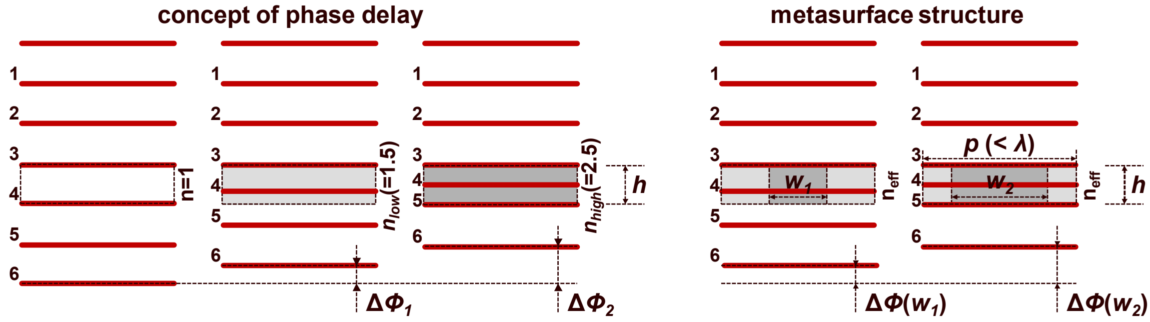


- a (micro-)lens focuses the light into a single point
- R + G + B fall on the colour filter and but only 1 component can pass
- the 2 others are absorbed into the colour filters

- a colour router structure allows 1 component to pass
- and bends the 2 other components to neighbouring pixels
- fewer photons are absorbed

Source : Choi, IEDM2023

Colour Router (2)



- The phase-delay of an optical wave can be influenced by the refractive index of the material :

$$\Delta\Phi = \Delta n \cdot h \cdot (\lambda/2\pi)$$

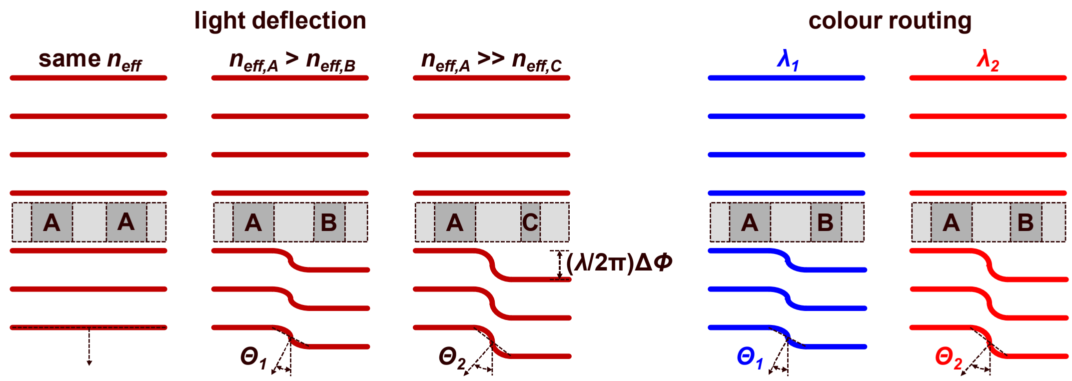
- The (effective) refractive index can be influenced by small pillars with widths smaller than the wavelength of the incoming light

$$\Delta\Phi = \Delta n_{eff} \cdot h \cdot (\lambda/2\pi)$$

$$n_{eff}(w) = (1-w/p) \cdot n_{low} + (w/p) \cdot n_{high} \quad (0<w<p)$$

$\Delta\Phi$: phase delay
n : refractive index
h : layer thickness
w : pillar width
λ : wavelength
p : repetition pitch

Colour Router (3)



- The pillar width and the wavelength have an effect on the phase shift.

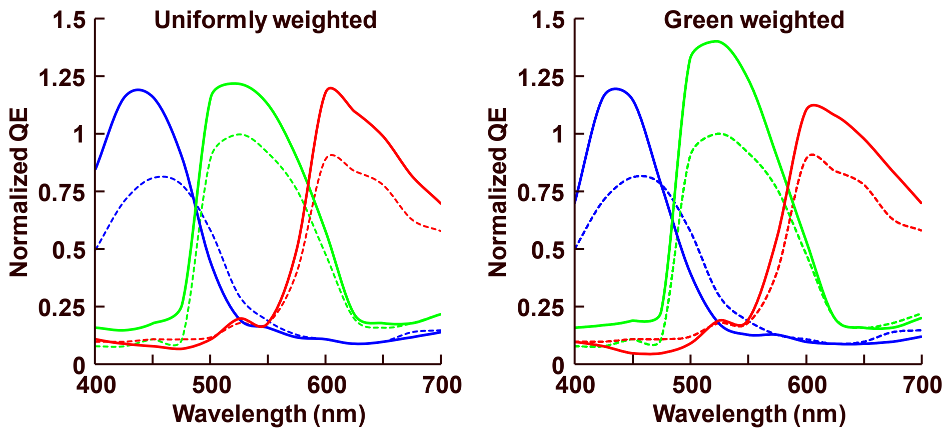
$$\Theta = \sin^{-1}((\lambda/2\pi) \cdot (\Delta\Phi/p))$$

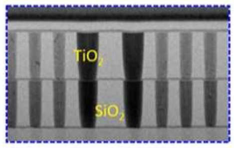
$$\Delta\Phi = \Delta n \cdot h \cdot (\lambda/2\pi)$$

$$\lambda_1 < \lambda_2 \rightarrow \Theta_1 < \Theta_2$$

Θ : deflection angle
λ : wavelength
p : repetition pitch

Colour Router (4)



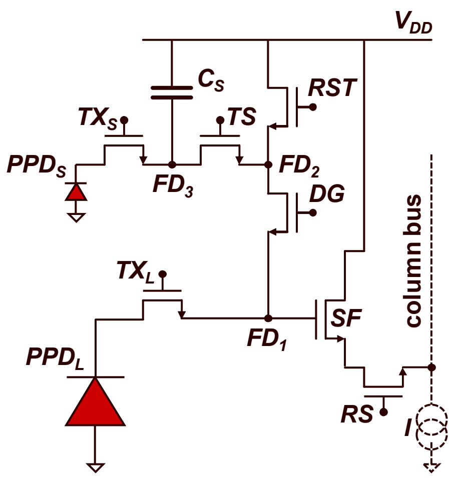


- 0.64 µm pixel
- SiO_2-TiO_2
- double layer

- Dashed lines : standard color filters, solid lines : color router technology
- Specific colour components can get more "attention" without changing colour filters

Source : Choi, IEDM2023

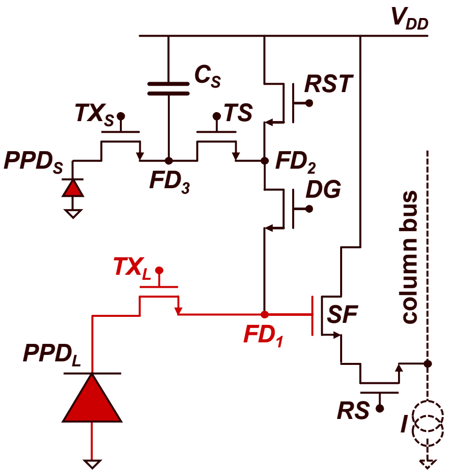
Wide Dynamic Range (1)



- This pixel combines :
  - Photodiodes of different sizes
  - Dual gain amplification
  - Local in-pixel overflow

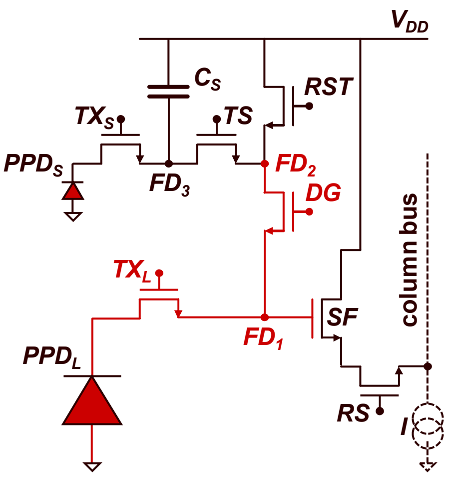
Source : Sakano, ISSCC 2020; Oh, IEDM 2022; Geurts, AutoSens 2023

Wide Dynamic Range (2)



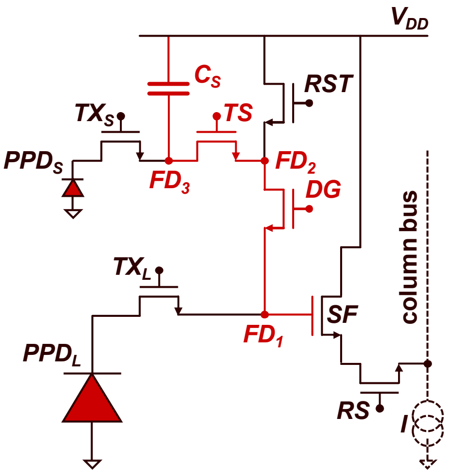
- This pixel combines :
  - Photodiodes of different sizes
  - Dual gain amplification
  - Local in-pixel overflow
- Highest sensitivity : large photodiode (*PPD_L*) with the smallest floating diffusion capacitance (*FD_1*)

Wide Dynamic Range (3)



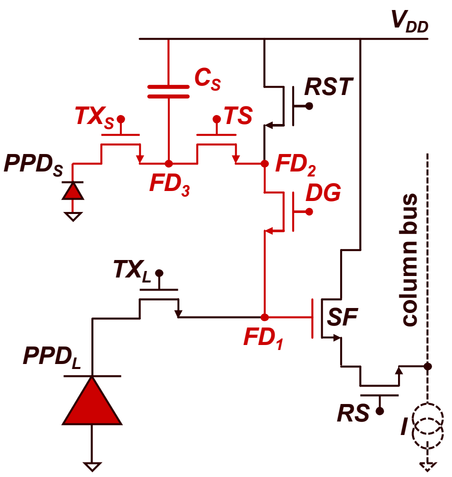
- This pixel combines :
  - Photodiodes of different sizes
  - Dual gain amplification
  - Local in-pixel overflow
- Highest sensitivity : large photodiode (*PPD_L*) with the smallest floating diffusion capacitance (*FD_1*)
- High sensitivity : large photodiode (*PPD_L*) with the extended floating diffusion capacitance (*FD_2*)

Wide Dynamic Range (4)



- This pixel combines :
  - Photodiodes of different sizes
  - Dual gain amplification
  - Local in-pixel overflow
- Highest sensitivity : large photodiode (*PPD_L*) with the smallest floating diffusion capacitance (*FD_1*)
- High sensitivity : large photodiode (*PPD_L*) with the extended floating diffusion capacitance (*FD_1 + FD_2*)
- Smallest sensitivity : readout of overflow signal on *C_S* with a low gain (*FD_1 + FD_2 + FD_3*)

Wide Dynamic Range (5)



- This pixel combines :
  - Photodiodes of different sizes
  - Dual gain amplification
  - Local in-pixel overflow
- Highest sensitivity : large photodiode (*PPD_L*) with the smallest floating diffusion capacitance (*FD_1*)
- High sensitivity : large photodiode (*PPD_L*) with the extended floating diffusion capacitance (*FD_1 + FD_2*)
- Smallest sensitivity : readout of overflow signal on *C_S* with a low gain (*FD_1 + FD_2 + FD_3*)
- Small sensitivity : readout of signal in *PPD_S* with a low gain (*FD_1 + FD_2 + FD_3*)
- 130 dB dynamic range is reported, complex large pixel, 8 readouts (4 reference signals, 4 active signals), large power consumption

Source : Sakano, ISSCC 2020; Oh, IEDM 2022; Geurts, AutoSens 2023
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Conclusions

- Image Sensors are complex, multi-disciplinary circuits which have found a home at various conferences (IEDM, ISSCC, IISW, IS Europe, VLSI Symposium, …)
- IEDM was a conference at which major CIS innovations were announced : pinned photodiode, colour filters, micro-lenses, stacking technology, deep trench isolation, dark current reduction, stitching, …
- IEDM will be a conference at which major CIS innovations will be announced : colour router, dynamic range expansion, power reduction, data reduction methods, new materials, …
- Congratulations for reaching 70 IEDM conferences !!!

Thank You !