Image sensors for digital photography: a short course for undergraduates. II: Optoelectronics

Sensores de imagen para fotografía digital: un minicurso para estudiantes universitarios. II: Optoelectrónica

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ABSTRACT:

In the previous chapter, we have browsed upon the optics of photographic cameras, focusing on the specific features of digital cameras and their sensors. We have also compared the camera performance with eye, including grayscale, sensitivity, dynamic range, field of view and many others. Eyes are far superior to cameras in several aspects, those favored by evolution, while cameras prevail in other aspects not so relevant for vision.

Yet digital cameras are still quite similar to analog film-based cameras in all issues related to optics. In this part we will concentrate on the most distinctive element of modern digital cameras, the optoelectronic sensor. We will study the fundamentals of optoelectronic light to electric signal conversion, the different families of sensors and detection modes, their advantages and flaws. Finally we will show the current trends in sensors and explain the reasons why manufacturers have chosen them.

Key words:

Digital imaging, CMOS, CCD, optoelectronic sensor

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1. Introduction

The second part of this short course on Digital Photography is entirely devoted to optoelectronic sensors. Sensors are in the core of each and every photographic or video digital camera. They substitute the traditional photographic film, handling the optical information and storing it in electronic format. The advent of sensors has marked a milestone in the history of photography. Digital photography is not a mere alternative to analog devices, but a revolutionary new way to handle optical information, with limitless possibilities and, most important, at substantially no cost per picture. At present, everybody carries a smartphone storing hundreds or thousands of pictures of everything including themselves –*selfies*– simply because pictures cost nothing. Turning a relative infrequent hobby into a massive activity has been the utmost consequence of the currently ubiquitous digital photography.

This part will analyze in depth the two existing types of sensors, CCDs and C-MOS, their pros and cons, as well as their dynamic, resolution and color features. Since the first generations of sensors in the last decades of past century, the evolution has been constant, not only in performance but in working modes. At present, most camera makers employ *backside illumination* (BSI) sensors; to understand the grounds of this selection, and the rationale of their working principles, it becomes necessary to explore the fundamentals of sensors as parallel detection devices, the light to electric signal conversion, and the transfer of information by electronic means. These will be covered in the first part of the chapter, while the second part will deal with particular models of sensors created to overcome specific issues in light detection and handling.

2. Digital sensors for video and photographic cameras

An optoelectronic sensor is a matrix of optoelectronic elements (nicknamed pixels) usually distributed in rows and columns, like pixels of displays. In fact, the camera sensor performs the same transformation as the display pixels in the opposite direction: optical signal into electrical signal and vice versa. Sensor pixels

are quite small (μm size); indeed, the rectangular area of the sensor, the size of a post-office stamp, contains several millions of pixels.

The **sensor size** and **pixel density** determine several relevant parameters ultimately related to the quality of the recorded picture. Some of these have been studied in the previous chapter. Other relevant parameters, such as the **response time**, are related to the electronic structure on the sensor. For example, a photographic camera may require the acquisition time to be minimized, in order to “freeze” pictures of moving objects. However, data transfer from the sensor to the storage medium need not be extremely high. A video camera, on the contrary, needs to speed up data transfer so that the sensor is freed, and a new photogram can be taken at video rate. These and other features are studied in this section. A basic knowledge on semiconductors and photodetectors is required to follow the explanation.

At present, cameras employ two different sensor types (or families): the **charge coupled device** or CCD and the **complementary metal-oxide-semiconductor** structure or CMOS. To understand how these sensors are fabricated, and how they work, we will start studying the coupled-charge principle in a basic MOS cell of the CCD and CMOS sensors. Eventually we will study the different CCD types, their evolution and improvements. Finally, we will review the CMOS sensors; initially these were the core of high-end cameras, but currently they are in mobile phones, low and medium range cameras as well.

3. The MOS cell

3.a. Three-gate MOS cell

A classic three-gate MOS cell (Fig. 1, left) is made of p^+ -type semiconductor (heavily doped p type) on which an isolating barrier of silicon dioxide (SiO_2) is deposited. The polarization electrodes (gates) are deposited on the silicon dioxide. These are made of metal, polysilicon or, more recently, indium-tin oxide (ITO). Applying a field as in Figure 1, holes migrate from the region under the electrodes positively polarized, concentrating under the negative electrodes. Being a p^+ semiconductor, the material has a hole excess in the valence band, and virtually no electron conductivity. The hole migration creates a **depletion area** under the electrode. The result is an **induced p - n junction** with reversed polarization (Fig. 1, right).

Figure 1. Left, polarized MOS cell; right, p - n junction induced in a polarized MOS cell. SCR is the **spatial charge region**

When studying photodetectors, three conditions are formulated for a diode to work efficiently as a photodetector (Fig. 2):

- The input zone where the light impinges must be thin and transparent.
- The diode must be reversely polarized.
- The **spatial charge region** (or depletion zone) must be as large as possible for the photons to be absorbed in this region and the photogenerated carriers do not recombine.

The MOS structure matches the three conditions, accumulating charges as long as the applied voltage is kept. The SiO_2 layer and the electrodes are made very thin, and the depletion region is made very deep to allow the structure to absorb the longest wavelengths (red). Fig. 3 shows the sketch of voltage distributions in a MOS cell.

The MOS structure may work as a photosensor (photocapacitor), absorbing photons and piling up charges. However, comparing to the p - i - n photodetector, one realizes that there are no available electrodes to extract the photogenerated charge, since electrodes are isolated. In order to recover the information (charge) stored during the exposure time, it is necessary for the MOS cell to work as storage cell and charge-transfer

Figure 2. A diode working as a photodetector

Figure 3. Distribution of voltages in a polarized MOS cell

device (in the absence of light). In other words, it is necessary to extract the charge towards a *charge-voltage converter*, by moving the charge of each MOS cell to its neighbors.

3.b. Basic CCD types

The simplest CCD sensors, at least conceptually, are **full-frame** or CCD-FF. These sensors (Fig. 4) are made of three-gate MOS cells as shown previously. Sensor shining (illumination) is controlled by an external

Figure 4. Full Frame CCD sensor. All the charge is brought to a single charge-voltage converter.

Figure 5. Charge-voltage converter

shutter. Once the shutter is closed, the sensor reading process starts. The information of all sensor rows is moved downwards. The charges of the last row are shifted to the horizontal register (also made of MOS cells) and are sequentially read in a charge-voltage converter.

The **charge-voltage converter** (Fig. 5) works like a capacitor. Depending on the transferred charge, the voltage between terminals varies. This voltage is eventually amplified in a further step.

The sensor cannot be illuminated again until all the sensor rows have been read. This sensor is called full-frame because every MOS cell is used as detector as well as storage and charge-transfer cell.

A second basic CCD type is the **interline transfer** sensor (CCD-IT). In these sensors (Fig. 6, left), each MOS cell used to catch light has a “dark sibling” dedicated to storage and charge transfer. This homologous cell is never exposed to light. Once the exposure time ends, every sensor cell transfers simultaneously its charge to its hidden colleague. In this way, the sensor can continue detecting light and storing charge while the reading process is carried out.

Figure 6. Left, interline transfer sensor (CCD-IT); right, frame transfer sensor (CCD-FT)

Figure 7. Different kinds of CCD linear arrays

Figure 8. Left, charge transfer in two steps using three voltage levels; right, charge transfer in three steps

In CCD-IT sensors, the MOS cells have only two gates; each sensor cell is separated from its hidden neighbor by a single gate. This arrangement speeds up the charge transfer process.

The **frame-transfer** sensors (CCD-FT) are an intermediate alternative (Fig. 6, right) between full-frame and interline transfer sensors. Their chief drawback is price, since its manufacturing process is comparatively expensive.

Finally, there exist CCD **linear arrays** (Fig. 7), mainly employed in scanners.

3.c. The coupled-charge principle. Charge transfer

Let us consider n adjacent MOS cells. Modifying correctly the voltage levels of the gates, charge can be transferred from one cell to another.

Charge transfer in CCD-IT is performed in two steps using three voltage levels (Fig. 8, left). CCD-FFs perform a three-step charge transfer by alternating positive and negative voltages (Fig. 8, right).

4. Structure of a CCD-IT image sensor

Figure 9 shows the structure of an interline transfer CCD (CCD-IT) sensor.

The storage and charge transfer schemes are substantially identical to CCD-FF sensors. However, the light detecting MOS cell is substituted by a photodiode with two lateral gates: charge-transfer gate and electronic shutter gate. The first is used to transfer charges to the adjacent MOS cell once the exposure time is over. The shutter gate is used to bring all the charges accumulated in the photosensor to the lateral drain. This drain receives the charges when its electrode is set at low voltage. Moreover, the beginning of the exposure time is triggered by setting the drain at high voltage; therefore, no external shutter is required.

Saturation of the detector is controlled in two ways. The lateral gates are set at different voltages. During the illumination and charge accumulation, the charge-transfer gate is set at a higher voltage than the electronic shutter gate. Therefore, the excess of charge runs over the evacuation drain through the shutter gate (Fig. 10, left). There are two voltage barriers, called channel inhibitors, in the perpendicular direction.

A second control mechanism for overexposure is the vertical overflow drain –actually it should be called *overflow drain in depth*, since it is referred to the direction perpendicular to the photosensor surface. Besides the voltage well for charge trapping, created by the gate voltage and the barriers of the channel inhibitors, a second well is created towards the internal part of the sensor (Fig. 10, right). This is done by integration of electrostatic potential barriers in the polarized substrate. The vertical overflow drain is

Figure 9. Structure of a CCD-IT sensor

Figure 10. Working principle of the lateral drain (left) and the vertical overflow drain (right)

polarized at a lower voltage than lateral overflow drain, thus being the main mechanism to avoid overexposure. When the stored charge exceeds the selected level, it diffuses vertically and vanishes out through the reversed polarization of the silicon.

These two evacuation mechanisms avoid, or at least reduce, the two classical effects of overexposure in a CCD: overflow through the channel inhibitors –producing *smear*, bright vertical lines in the image– and

Figure 11. HAD structure CCD

Figure 12. Comparison between the structure of a CCD-IT based on MOS structure and another based on HAD structure

overflow affecting all the pixels around –producing **blooming**, where the size of the bright image is much larger than the actual size of the light source in the image.

5. CCD-IT Sensor with HAD structure

The most important advance in CCD-IT sensors was the **Hole Accumulated Diode** (HAD) structure developed by Sony. Most current CCD-ITs employ this structure or some variations of the same.

The MOS cell for detection is substituted by a photodiode (Fig. 11). The CCD is fabricated on a n-type silicon on which a thin layer of p-type silicon is grown.

Comparing the MOS-type and HAD-type CCD-ITs (Fig. 12), several differences are found:

- Detection in the HAD structure is performed by a photodiode created by the n^+p structure. Between the photodiode and the SiO_2 layer, a **Hole Accumulated Layer** (HAL) is set. Its aim is to catch and destroy by recombination any parasitic electron generated by thermal effect in the Si-SiO₂ interface. This strategy reduces the dark current by a factor of 10.
- The transparent polarization electrode (typically made on polysilicon) –located on the photosensor in the MOS cell– is eliminated in the HAD structure. This improves the detection sensitivity, especially for shortest wavelengths (blue region)
- The lateral overflow drain is eliminated as well. The smear and blooming controls are performed by means of the (buried) vertical overflow drain. Actually, the n-type substrate itself is used as overflow drain. This increases the active region of the sensor from 23% in a classic CCD-IT to about 34%.
- Finally, the bottom of the detection well is not fixed in a classic CCD-IT. When charges are transferred to the adjacent MOS cell, a residual number of electrons remains, reducing the quantum yield of the sensor (Fig. 13). In the HAD structure CCD-IT, the HAL layer adjusts the bottom potential to a fixed value (known as *clamp* potential). In this way, all charges useful for reading can be transferred.

At present, CCD sensors are extensively being substituted by C-MOS sensors, commented below. C-MOS is the favorite choice in video, smartphone and digital single-lens reflex (DSLR) applications [1]. Yet some

Figure 13. During the charge-transfer process, residual charges remain in the classic CCD-IT structure (a), while the HAD structure eliminates these charges improving the sensor efficiency.

specific niches still opt for CCDs when some of their distinctive features are required. Spectral response of CCDs is much more linear than C-MOS response. Moreover, long exposure applications are subjected to **amp glow** phenomenon, by which the small amount of light any biased semiconductor junction emits becomes a parasitic noise. CCDs easily avoid this phenomenon by reducing the voltage applied to the on-chip amplifiers. This is not so easy in C-MOS and, as a result, many of these sensors saturate after some time (minutes). Therefore, CCD sensors are preferred in astronomical instruments. As a striking example, the world largest optoelectronic sensor up to date is a behemoth 3.2 billion (10^9) pixels CCD –189 tiled 4k×4k CCDs– of the Large Synoptic Survey Telescope (LSST, a.k.a. *Legacy Survey of Space and Time*), a new telescope being built for wide-angle survey of sky (Fig. 14). LSST bears a car-size (1,7×3 m, 1800 kg) camera attached to one of the biggest lenses ever built [2].

Figure 14. Section of LSST telescope CCD camera [3]

6. The C-MOS Sensor

C-MOS sensors were developed from the initial NASA realizations [4] on active-pixel sensors (APS). The chief difference between a C-MOS sensor and a CCD sensor is that the former features a charge-voltage converter and an amplifier for each pixel (active-pixel sensor, APS), or for each pixel column (passive-pixel sensor, PPS) [5].

C-MOS sensors (Fig. 15) have some advantages over CCDs. Nevertheless, introducing specific conversion and amplification electronics for every pixel brings several drawbacks as well:

- **The pixel effective area is reduced.** This decreases the sensitivity and avoids reducing the pixel size as much as CCDs. Large and medium formats have been commercialized since the beginning of the century (the Canon's EOS-I Ds full format 24×36 was introduced in 2003). Nowadays, all the cameras featuring high resolution, small or big format and mobile phones have C-MOS sensors.

Figure 15. Sketch of a C-MOS sensor

Figure 16. Random Access in a CMOS sensor

- The presence of additional electronics in the pixels introduces inhomogeneities between pixels and between transistor switchings, as well as increased leak currents. These inhomogeneities are corrected through a **correlated double sampling** (CDS), that consists of extracting a pixel sample after resetting, and storing the value (*offset*) to be eventually used for image processing after the exposure period. In order to simplify and speed up the processing, just one CDS circuit is usually installed for every sensor column.

Notwithstanding these drawbacks, C-MOS sensors are intrinsically better than CCDs, and have substituted them in almost all product lines, as commented. The most relevant advantages of C-MOS sensors are:

- **Random access is allowed**, sampling selected windows if desired (Fig. 16).
- **C-MOS are faster than CCDs**. The reading speed is much higher, what is quite appreciated among the professionals.
- **Pixels can be associated** with their neighbors, what is useful under low illumination.
- The external equipment is more compact, for **many functions can be integrated** in the chip itself.
- **Less power consumption**, about 30% less than a CCD of the same characteristics.
- As in CCDs, **photodiodes can be integrated**, improving the sensitivity.

7. Trends in C-MOS sensor improvements

In the last decade, many improvements have been proposed for digital light sensors:

- **Sensitivity**: increasing the active area, use of photodiodes, microlenses, hydrogenated amorphous silicon sensors.
- **Spectral sensitivity**: improved filters, elimination of the input transparent electrode.
- **Response time**: C-MOS sensors

Figure 17. Increasing the aperture ratio with microlenses.

A number of new sensor technologies have been introduced as well. In some cases, specific features were notably improved; nevertheless, their high complexity and price have complicated their massive introduction in the markets. This section reviews the most relevant improvements and novel technologies.

7.a. Improving the pixel aperture ratio with microlenses

The pixel effective area or aperture ratio is quite modest in most cases. Table 1 shows the aperture ratio for several sensor structures.

TABLE 1. Aperture ratios for some popular sensor types

Sensor structure	Aperture Ratio (%)
CCD-IT	23
CCD-IT w/ HAD structure	34
CCD-FF	80
C-MOS	25-60

In 1991, Sony introduced microlenses in its CCD-IT sensors (Fig. 17), increasing their aperture ratio up to 40%. At present, nearly all manufactured sensors employ microlenses. Nevertheless, the use of microlenses brings also some drawbacks:

- Differences between neighboring microlenses or on separate areas of the sensor may introduce variations of luminosity between pixels. In the case of C-MOS sensors, these differences can be partially alleviated with the already mentioned correlated double sampling.
- The use of super wide-angle objectives (focal length below 21mm in a 24×36 mm or similar sensor) is severely limited, for light rays impinging from quite oblique directions at the image corners are skewed by the microlenses outside the pixel detection area. This produces a vignetting effect.

On the other hand, fabrication of microlenses is relatively easy (Fig. 18). First, a planarization layer is deposited on the sensor surface by spin-coating. This transparent layer is usually made of polyorganosiloxane or polyorganosilicate. Once cured, a transparent photoresin is spin-coated onto it. After an insolation/developing process, rectangles or circles of photoresin become defined on every pixel. These photoresin pieces get a rounded shape by thermal treatment, forming spherical or cylindrical lenses.

Figure 18. Fabrication of microlenses.

7.b. The Foveon X3 C-MOS Sensor

An original sensor architecture was developed some time ago by the Foveon company. The first Foveon sensor was introduced in cameras Sigma SD-9 in 2002. In 2010, Foveon presented the Foveon X3 C-MOS sensors up to 14.4 Mpixel [6], used in cameras Sigma, Toshiba and Fomos (for research applications).

Figure 19. Structure of a Foveon sensor

The Foveon sensor was based on the overlapping of three doped silicon layers (Fig. 19), connected to three different voltages, thus creating three potential wells. The first layer absorbed the blue spectral region, the second the green region, and the third the red region.

This sensor type had a number of advantages:

- The color mask or Bayer mosaic filter (Fig. 20) was not required, thus increasing the pixel sensitivity, since every pixel received the whole spectrum.
- The color information could be extracted separately for each color. This eased the pixel binning in any configuration

The main drawback was the intrinsic complexity of the sensor. This ultimately jeopardized the price-resolution ratio. Moreover, the response time of Foveon sensor was remarkably worse than the time of other commercial sensors. These two issues were probably the reason for the Foveon sensor not to succeed, silently vanishing about 2015 –although Foveon Sigma cameras of 29, 39, and 51 equivalent Mpixel are still being sold [7].

It is also important to realize that the Mpixels claimed by Foveon sensor are not calculated like other sensors. For example, the 39 Mpixel sensor named above is actually a 13 Mpixel sensor whose intended resolution derived from the ability of detecting the three primary colors separately. Therefore, the value given by the company is correct taken as color resolution, not for spatial resolution. A 13 Mpixel resolution nowadays is barely acceptable for a reflex camera.

Figure 20. The Foveon X3 sensor improves the efficiency avoiding the use of Bayer filters.

7.c. Fuji octagonal Pixels

The first model of octagonal pixels (Super CCD I) was launched in 1999. “Super CCD” –the term has been kept until the 2010 model, the Super CCD EXR– was actually the name Fuji gives to its CCD-IT HAD technology. The innovation was related to an optimized use of the sensor surface, employing octagonal rather than square pixels, organized in zigzag lines (Fig. 21). The technology was steadily improved over

Figure 21. Conventional CCD and Fuji EXR CCD

time. An interesting improvement was the inclusion of small pixels located in dead areas, to be used under high illumination conditions.

According to Fuji, as the eye detects easily vertical or horizontal lines, images having higher resolution than the original sensor could be obtained by software using interpolation procedures. The most prominent advantages of this architecture are the improved anti-aliasing and color rendering. However, the pixel binning in groups of 4 is avoided by symmetry. At present, the interest for these geometries is negligible.

7.d. Back-side illuminated sensors

Contrary to the previous examples, back-side illuminated sensors have become the standard alternative for any kind of photosensor either for cameras or for smartphones.

BSI technology basically consists in exchanging the last two layers of the CMOS sensor (metallizations and detectors) so that there are less obstacles in the light path through the sensor (Figure 22). Certainly the idea was not new, but the technology implementation resulted particularly complex. The first BSI sensor was presented by Omnivision in May 2008. Sony introduced another sensor the same year,

Figure 22. Structure of a BSI sensor [8]

Front-side illuminated (FSI) sensors are based on chips that start with the photodiode array on the bottom, then build up the rest of the chip, including control electronics and metal layers, above and around the photodiodes that are expected to detect light... kind of the structure of human eyes (when evolution finds a way to achieve a goal like vision, Mother Nature never steps back for better alternatives). The obvious issue is that considering the metal interconnections and the space left for control electronics, the *pixel fill factor* –the effective part of each pixel occupied by active photodiode area– is smaller than it ought to be. There's also a long distance between microlenses and photodiodes, so the angle of light is narrow.

Back-side-illuminated sensors (BSI) take this basic structure and essentially flip it upside-down. BSI is a generic term for this technology, not a marketing term or brand name by itself. Build up a chip, slice your wafer just below the photodiodes, flip it over and bond it to some bulk to make it strong enough for use. Now all those formerly buried photodiodes are on the top of the chip, no electronics in the way... like octopus' eyes.

The sensor introduced by Sony in 2008 was a 5 Mpixel prototype having $1.75 \mu\text{m}^2$ active pixel area and 60 fps. The technology spread over all kinds of applications at stunning speed. From 2010, BSI became the preferred choice in many areas of the consumer electronics market. For example, the iPhone 4 (launched in 2011) included this type of sensor. Nowadays, nearly all the cameras and mobile phones use this technology.

In 2012, a new concept was introduced (by Sony again): the **3D stacked sensor** (Fig. 22, right). The idea is simple: a wafer of bulk silicon is needed to support a BSI chip anyhow. If this support silicon is made functional, most of the electronics can be transferred to the wafer, leaving the sensor chip reduced to just the sensor array. This reduces dramatically the rate of manufacturing failures; moreover, the upper sensor wafer can be tested separately before bonding both wafers together.

According to Sony, these sensors –or at least those produced by them (Fig. 23)– increase the sensitivity by 6dB (two stops) and reduce the noise in the image by 2dB compared to traditional CMOS-FSI sensors. Other benefit of the sensors is the possibility of making the pixels smaller without losing sensitivity and without increasing the noise too much.

Figure 23. The Sony EXMOR-RS BSI sensor

BSI sensors are nowadays supported by many stakeholders, electronic companies that want a share of this market [9]. One of the most prominent companies is Samsung, manufacturer of ISOCELL sensors. Samsung claims that its sensors (Fig. 24) balance the light between different colors more efficiently. Moreover, the cells include reflective interpixel barriers, so that no spurious light from grazing incidence may be shared between contiguous pixels, effectively reducing crosstalk. With these grounds, Samsung has achieved some remarkable results [10]. The ISOCELL Bright HMX Tetracell features 108+Mpixel, able to generate video 6K (6016×3384) @ 30fps. Some smartphones like Xiaomi Mi Mix Alpha [11] are using this sensor, although they usually employ 27 Mpixel resolution gathering groups of 4 pixels, thus increasing sensitivity.

Figure 24. The Samsung ISOCELL BSI sensor has physical walls between pixels to avoid crosstalk [13]

In 2018, Phase One announced its IQ4 iXM-RS150F camera that includes a 150 Mpixel (14204×10652) BSI sensor (from Sony) [12], whose pixel size is $3.76 \times 3.76 \mu\text{m}$; the sensor size is $53.4\text{mm} \times 40\text{mm}$. Another remarkable feature is its sensitivity, from ISO 200 to $>100,000$. This performance is obviously translated to the camera price, over 50,000\$, acceptable for the professional and industrial sectors, but far from consumer electronics.

7.e. Under-display camera

One of the most demanding current trends on modern smartphones is full-screen design, *i.e.*, a display occupying the full phone surface, where bezels are absent or minimized. Fingerprint sensors, speakers and microphones have been hidden or moved away from the front side; the only remaining gadget, difficult to avoid, is the front camera for *selfies*, a feature any smartphone must bear nowadays. Many solutions have been proposed to conceal, to hide or simply to get rid of front cameras. A number of notches have been shown, from the large ugly 'eyebrow' of iPhones X and 11 to the minimum size circles, notches or holes of Samsung, Oppo, or Xiaomi to name a few. Other more radical proposals include mechanical pop-up cameras –Oppo, Vivo Nex S– or even dual displays –Vivo NEX Dual Display Edition– where selfies are shot with the rear camera making use of a rear display. Anyhow most professionals and users agree that the definite and most elegant solution would be to make the display (or a section of it) transparent and to place the front camera under the display (Fig. 25). Unfortunately, this is easy to say but not so easy to make.

By summer 2019, Xiaomi [14] and Oppo [15] presented prototypes of under-screen sensors (Fig. 26). Other companies like Samsung and Nokia announced their commitment towards this technology. The first prototypes were teased, *i.e.*, not real devices in actual working conditions.

Anyhow, by the end of the year, both companies had shown working prototypes. In both cases, a small area of the display was made transparent so that the camera behind it could receive the external image [16]. The area of the screen over the camera still bears touch control. The display uses a transparent material for the OLED anodes, and the pixel structure has been redesigned to allow light to get through the screen.

Figure 25. Different solutions for hiding the front camera in smartphones. Left, dot-drop notch, minimizing the size. Right, prototype of under-display camera. Sensors are made larger to compensate for the lower light input. The bottom part of the figure shows the light transmitted in both setups.

Figure 26. Under-display camera prototypes from Xiaomi (top) and Oppo (bottom). The display area made transparent in the Xiaomi model is circular while the Oppo model features a square area.

Since then, less optimistic predictions assume that under-display cameras will not be integrated into new phone models in the near future, since there are a number of technological issues that must be solved in advance [17]. The area made transparent for the picture became visible under certain conditions of light incidence and dark display areas. Even worse, the picture quality is not as good as desirable. Indeed, placing a screen between a camera and a scene seems not a good idea for shooting remarkable pictures. The screen produces significant color deviations, haze and glare. Companies allege that the picture can be corrected with some software witchcraft, but apparently this is not enough for the moment.

The key issue for this deadlock is *display resolution*. The highest the resolution, the lowest the light transmittance to the camera; this in turn has a dramatic effect on the image quality. Current high-end smartphones have extremely high resolutions, in the range of 300-400 pixels per inch (PPI). The obvious solution of reducing resolution to enhance transmission is out of question: consumers would not accept such arrangement. Reducing the resolution just in the camera area would cause phenomena such as color patches.

There is a positive factor, nevertheless. Front cameras placed on notches intend to be as small as possible, for the same trend of hiding the non-display features in the front surface. The sensor, consequently, has to be made small as well. But this is not the case in under-display cameras. **Sensors can be made significantly larger** than other selfie cameras, and associated lenses can accept wider aperture. A sufficiently large sensor could overcome the low transmittance issue. If consumer demand increases, development of custom sensors for under-display front cameras could become a reality in a few years.

8. Autofocus

Autofocus (AF) is another must in any modern camera or smartphone. AF allows the selected foreground of the scene to be precisely focused onto the sensor, while the remaining items become more or less blurred depending on the field of depth.

AF optical systems employ a sensor –usually the main sensor or a fraction of pixels in it–, a control system and a motor to focus on an automatically or manually selected point or area. There are two families of AF systems [18]:

- **Passive:** AF relies on certain characteristics of the image as received by the camera. There are two main passive systems for focusing: **contrast detection** and **phase detection** (Fig. 27). Passive autofocus, whether contrast or phase, is used in most cameras and mobile phones.
- **Active:** the camera emits a signal that strikes on the objects and returns to a detector; the camera then computes the time of flight and estimates the distance. Signals may be ultrasounds or infrared beams (lidar, using laser diodes)

Figure 27. Comparison of passive systems for autofocus: contrast (left) and phase (right) detection [18].

- Some new cameras and smartphones employ **hybrid systems** combining active focusing and passive focusing (e.g., laser focusing in Lenovo Z6 Pro).

8.a. Contrast detection autofocus (CDAF)

Contrast-detection autofocus is achieved by measuring contrast within a sensor field through the lens. The intensity difference between adjacent pixels of the sensor naturally increases with correct image focus. The optical system can thereby be adjusted until the maximal contrast is detected. In this method, AF does not involve actual distance measurement at all. This creates significant challenges when tracking moving subjects, since a loss of contrast gives no indication of the direction of motion towards or away from the camera.

Contrast detection places different constraints on lens design when compared with phase detection. While phase detection requires the lens to move its focus point quickly and directly to a new position, contrast-detection autofocus instead employs lenses that can quickly sweep through the focal range, stopping precisely at the point where maximal contrast is detected. This means that lenses designed for phase detection often perform poorly on camera bodies that use contrast detection.

Contrast-detect autofocus was a common method in digital cameras that lacks shutters and reflex mirrors. Most digital single-lens reflex (SLR) cameras used this method (or a hybrid of both contrast and phase-detection autofocus) when focusing in live-view modes. Then Canon introduced digital cameras with *Dual Pixel CMOS autofocus*. Nowadays SRL cameras in live view, EVIL mirrorless cameras, and new smartphones employ the Canon approach in different ways to use phase detection focusing.

8.b. Phase detection in SLR cameras (PDAF)

Phase detection is the most common applied passive AF method currently used in SLR cameras. As shown in Figure 28, it consists of a beam splitter (semitransparent mirror) that splits the beam into two. A ray of light from the object falls on the camera lens. This light transmits through the lens assembly and falls onto the primary mirror, in which a light fraction goes through while the remaining light is reflected towards the

Figure 28. Phase detection in an SRL camera.

pentaprism. The light gone through the main mirror is reflected by a secondary mirror onto the Phase Detection Sensor. The Phased Detection Sensor determines whether the image is in- or out- of phase and the information is passed on to the driver which may move the lens or not.

Figure 29 describes the mechanism of phase detection based autofocusing. The left sketch shows an out-focused position while the right sketch shows the focused position of the phase-based system. Rays going through the center of the lens are masked, only peripheral rays impinge onto the CCD arrays. When the peripheral rays are in focus, they produce the same signal on both arrays [19].

To improve the phase detection mechanism, instead of line detectors, normal CCD detectors in combination with special lenses called “spectacle lenses” are used, providing phase detection in all directions, and more focusing accuracy. The focusing speed is faster than in contrast detection focusing but still not very fast.

8.c. Phase detection in smartphones (Dual-Core focus)

Figure 29. Mechanism of phase detection in SRL cameras

Figure 30. Comparison of phase detection sensors. In the traditional PDAF (left), less than 5% of pixels are employed for focus. In the full-pixel Dual Core AF (right) all pixels are used

The first systems of phase detection in mobile phones (and in live-view mode in SRLs) were based on masking some green pixels (the most common) in the sensor, leaving only the left part or the right part exposed. Making a correlation of the signal of adjacent masked pixels the scene could be easily focused in the desired zone of the image.

Canon introduced the **full-pixel dual-core sensor** in their EVIL cameras in 2013, to improve the focusing speed in live view mode. With standard PDAF, only 5 % of the available pixels participate in focusing. In Full-Pixel Dual Core (FPDC, *a.k.a.* Dual Pixel) focusing [20], however, a phase detection photodiode is embedded into most pixels of the camera sensor (Fig. 30). Canon strategy certainly implied an appreciable increase in sensor complexity; however, this was compensated by the impressive boost in performance shown by FDPC sensors. Since then, Canon has routinely included FPDC in all its product lines, *e.g.*, the EOS C300 cinema camera, the pro EOS 1DX MarkII, the mirrorless EOS M6, and the consumer EOS Rebel T7i. Anyhow, landscape photography would barely appreciate the difference. Video recording, on the contrary,

Figure 31. Phase detection focusing by full-pixel dual-core sensor [22].

would do, since the AF speed achieved by FDPC is extremely useful in moving scenes [21].

The full-pixel dual-core sensor has two photodiodes at each pixel point –photodiode A and photodiode B (Fig. 31). When focusing, the two sets of photodiodes detect an image A and B respectively. The two images will coincide when focused. In the case of incomplete focusing, the images appear blurred and staggered.

The principle of focusing is still through relative detection. By detecting the deviation (signal difference) and deviation direction (which side of the center of A image and B image is located respectively), we can calculate the direction and distance that the focusing lens group should move, so the focusing speed will be further improved.

It is worth mentioning that Canon imaging sensors do not have each and every pixel working as dual-pixel sensor. Only about an 80% of pixels (horizontally and vertically) play that dual role. Anyhow, the difference with classical phase detection sensors is remarkable: the sensor on the Canon EOS 5D Mark IV, for instance,

Figure 32. Phase detection in iPhone sensors. The iPhone 11 includes the new full-pixel dual-core sensor introduced in EVIL cameras by Canon.

has 6720×4480 pixels. An estimation of 80% shows that 19+ million pixels have DPAF. By comparison, the Sony a7R iii sensor has 7952×5304 pixels, but only 399 phase detection AF points.

It is interesting to look at the evolution of AF sensors with successive models of the same product. Figure 32 shows the masked pixels of different iPhone models over 5 years. In the most recent models, masking combines horizontal and vertical semi-pixels. The latest model, iPhone 11, employs the full-pixel dual-core sensor developed by Canon [23].

Besides iPhone 11, a number of top rank smartphones are using or have announced to begin using FPDC autofocus [21]. Samsung began using full-pixel dual-core sensors with Galaxy S7 and S7 Edge and has continued since then with S8, S8+, S9 and S9+. Oppo Find X2, Google Pixel 2 and HTC U11 are using dual-pixel as well.

As seen in the previous sections, there are several kinds of focusing methods; however, most of them are realized on the basis of the above described contrast and phase methods. A hybrid use of active and passive autofocusing is expected to become the norm in the future.

8.d. Laser Detection Auto Focus (LDAF)

The first two types of focusing are also known as passive focusing because they rely on the reflection of light from the object. Laser focus is called active focus, or range-finding focus.

The principle of laser focus relies on a separate infrared laser sensor (Fig. 33). A built-in infrared laser shoots low-power, harmless laser pulses that hit the object to be photographed and reflect light towards the sensors. The distance is calculated by computing the time elapsed for the light to perform the round trip (*time of flight*). Once the distance is known, the focusing motor will drive the lens group to the

Figure 33. Laser autofocus on and off. Laser light is actually infrared, it is harmless and not perceived by human eye

corresponding position to complete the focus.

This mode of focusing is very fast and does not rely on reflected light, what results in an obvious advantage: LDAF can still ensure excellent focusing performance in low light or dark scenes. However, due to the focus distance and cost, laser focus is still limited in use. LDAF is useless if the object is too far from the camera, since non appreciable return light is received.

Summarizing, LIDAR focusing (laser-based active focusing) has clear pros and cons that frame its use:

- It is the fastest autofocusing
- Works in very **low lighting**
- However, it **fails to focus objects on long distances** as the laser transmitter has a quite limited power for security reasons.

In these cases, LDAF needs support from an alternative passive AF system, such as contrast or phase AF.

8.e. Hybrid autofocus

Some cameras employ multiple focusing systems to minimize the disadvantages of specific systems. For example, many Sony sensors employ phase and contrast detection together. Laser and PDAF are jointly employed by some smartphones such as Google Pixel [24].

9. Conclusions

This short course on sensors of digital cameras has been designed to provide a detailed overview of the world of digital photography from the point of view of an undergraduate in Optics, Electronics or Photonics. The main issues of the topic have been exposed and alternative solutions have been presented and discussed.

Mastering the subject will certainly require a far more profound study. Nevertheless, the authors believe that these chapters will be useful to grab a general idea of the matter and to learn 'what to look for' when a deeper knowledge is needed.