How an electronic shutter works in a CMOS camera

I have been asked many times how an electronic shutter works in a CMOS camera and how it affects the camera's performance. Here's a description of the way it works and its affect.

It is essential that you first understand clearly how mechanical shutters work in film cameras as there is an important correlation to the operation of CMOS sensor shutters. CMOS sensors have a shutter mechanism that is quite similar to a mechanical focal plane shutter as found in a 35mm camera with removable lenses. It has the same limitations with additional limits on performance which result from the speed of the circuitry.

First, let's review how shutters work in film cameras.

There are two types of mechanical shutters that are commonly used in film cameras: a focal plane shutter and an iris, leaf or copal shutter. The focal plane shutter is located at the film plane while the iris shutter is located within the lens.

The Iris Shutter (copal or leaf shutter)

The Iris shutter consists of leaves that open yielding an ever larger hole (or iris) or, conversely, when closing, constrict the hole in the center of the lens to be smaller and smaller. This shutter has several advantages in design.

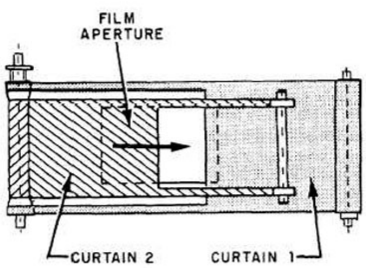
First, it is located within the lens at the focal point, typically where one would locate an iris. If one were to trace rays through the lens, one would find that for any given size iris, there are an equal number of rays hitting all parts of the film. Thus, changing the size of the iris has the effect of changing the F#, or the speed of the lens, without causing differential exposure at, for example, the edges of the film (commonly known as vignetting). Thus, a shutter located at the focal point, can open and close at any speed without causing vignetting or differentially exposing any portion of the scene.

Oddly enough, note that the depth of field of the image is changing as the shutter is in motion.

A second advantage for an iris type shutter is that it can be limited to a pre-selected maximum aperture when opening, thus serving as both the shutter and iris in a lens system. Importantly, the iris shutter can be operated at any speed with a flash, so long as it is open when the flash fires, the amount that it is open will affect the f# and thus the exposure, but will not differentially affect the exposure over the film plane. Thus, in flash photography, when using an electronic flash, so long as the flash and iris shutter are properly synchronized, one can use shutter speeds of mere thousandths of a second.

The principal disadvantage of the iris shutter is that it must be integrated into the lens and therefore, makes a set of removable lenses more expensive by forcing the shutter cost to be borne by each lens. Cameras like the Hasselblad medium format 2.25 inch use Zeiss lenses with integral focal shutters. In addition, many inexpensive film cameras have focal shutters since their lenses are not removable.

The focal plane shutter



The advent of the 35mm film camera with inexpensive interchangeable lenses brought with it the focal plane shutter. This shutter is located just above the film plane and can easily be seen when removing the lens and looking into the camera body. In this design there are two opaque curtains made of extremely thin steel. One extends from the left of the film, the other from the right. They move independently. Prior to taking a photo, the right curtain covers the film. When the shutter is depressed, the right curtain moves at a uniform rate (independent of the shutter speed) from left to right, thus exposing the film, first at the left edge, and then more and more to the right. Depending upon the shutter speed, the left curtain will begin to follow and obscure the film, thus ending the exposure. It also moves from left to right.

For very slow shutter speeds, there will be times for which the entire frame of film will be exposed simultaneously. The fact that the left and right curtains move at the same speed, results in all parts of the film receiving the same amount of light.

As one makes the shutter speed faster and faster, the time delay between when the two curtains begin their motion gets smaller and smaller. Typically, for shutter speeds of 1/125 or faster, the left curtain actually begins before the right curtain has reached the end of the frame. Thus, importantly, for these faster shutter speeds, at any single moment of time, only a vertical slit of film is actually being exposed. This is why there is a maximum shutter speed when taking flash pictures with a focal plane shutter. One must ensure that the flash is fired when the entire piece of film is uncovered. Otherwise, a portion will be obscured by one or both of the two curtains and only a slit will be exposed.

This creates a serious problem for fill flash photography. If for example, your scene is well lit and a short exposure is required for the aperture (and depth of field) that you would like to use, it may not be possible to use the flash and have it expose the entire frame. Fortunately, for these cameras, you typically do have independent control of the aperture, so you can use fill flash if you are willing to stop down the lens adequately to prevent overexposure.

Electronic Sensors

There are two types of electronic sensors commonly found in digital cameras: CMOS and CCD. Their difference in design makes the shutter choices also different.

CCD Sensors

CCD sensors were originally designed for video cameras. As such, they had an interlaced design. In an interlaced design, there are R rows of pixels with ½ R rows per single frame. The odd and even rows can be considered to be really two different sensors, which alternate taking images. This design was based upon the design of television signal formats. In an interlaced CCD, there is an extra row of pixels that are masked and unaffected by light, located between the odd and even rows. This is called the shift row. When the sensor is operating, the sequence of events is as follows:

- Expose the odd row of pixels
- Shift the odd row into the masked shift row
- While shifting the masked row out of the sensor, expose the even row
- Shift the even row into the masked shift row
- While shifting the masked row, expose the odd row
- And so on…

Interlaced sensors required no shutter. The shutter speed was fixed at 1/30 of a second (for American TV) and the exposure was otherwise controlled by controlling the f# of the lens.

As CCD sensors found their way into still cameras, their design changed from interlaced to progressive. In a progressive sensor, there is no concept of independent odd and even rows, or masked rows. After exposure, all of the pixels are shifted to out of the sensor by being passed in a bucked brigade fashion from pixel to pixel. Thus, it is essential that while shifting the image out of the sensor, one must put the sensor in the dark so as to not confuse the image. In fact, progressive CCD sensors require a mechanical shutter that is closed while the image is being shifted out.

One should note that there are some CCD designs that did have complete secondary image arrays that are masked, into which the entire image is dumped prior to being shifted out. These sensors were designed for high speed photography and are quite expensive and not typical.

Thus, CCD still cameras require mechanical shutters and depending upon whether the shutter is located in the lens or at the focal plane, the limitations of its operation are identical to those found in film cameras.

CMOS Sensors

The advent of the CMOS sensor enabled the development of cameras without mechanical shutters. This was possible because the CMOS design allowed more complicated circuitry to be built into the sensor to control each pixel or column independently in its ability to integrate light.

In a CMOS sensor each column of pixels can be independently reset to zero and allowed, after the reset, to integrate the light hitting it. As well, each column can be instantaneously read out, effectively ending the exposure time for that column. The method used for controlling the exposure is to reset a column, and then to wait the "exposure time" and finally to read out the accumulated values of that column. When one is performing this process for an entire sensor, one begins on the left side with the first column and resets it, then moves to the next column and resets it, and so on. Eventually, the entire sensor is reset and has been accumulating light. Note that the leftmost column has been in integration longer than the rightmost column.

After the exposure time of delay is waited, the leftmost column is read out and then the next column, and so on until the last column is read out.

It is important to notice the similarity between this type of process and the focal plane shutter described above for film cameras. When the shutter time is long, all of the columns will be reset before the first one is read out. For faster shutter speeds, the readout of the first column will begin before the last column is reset, thus resulting in a slit shutter where only a slit of vertical columns are being exposed to light any given moment in time, identical to the film case.

An important difference between the focal plane shutter and the CMOS sensor shutter is the speed of the curtain. The speed of the curtain for a CMOS sensor is limited by the read speed of the A/D converters and the number of pixels that must be read. Unfortunately, as the resolution goes up, the A/D has more to do for each column (more pixels) and the curtain moves slower. Thus, for 3.3 mega pixel sensors, with 1200 columns and with A/D speeds of 50ns, the transit time for each curtain would be 165ms, quite slow for a hand held camera.

For normally lit images, this might be noticed as an aberration where movement of the camera causes distortion of the image in the form of either a wave or elongation of the object.

When taking flash images with a CMOS sensor, thus, one must use a shutter speed that is slow enough, just like the focal plane shutter, so that the entire sensor is in integration at the time that the flash is fired. In the case above, this would be no faster than a 165ms exposure time, causing a blurred secondary image if there is a modicum of light already in the scene.

Unfortunately, many CMOS cameras are quite inexpensive and do not have aperture control. Thus, fill flash becomes impossible to use, especially when one considers that the synchronization speed for the sensor, or equivalently, the speed for which the entire sensor is in integration at once is typically quite slow.

This then describes why a mechanical shutter is required for flash and fill-flash photography when using a CMOS sensor that appears to already have a shutter. For a CMOS sensor with a mechanical shutter, the sequence of events for taking a picture is:

- With the shutter closed, start the reset of the sensor at the left edge
- Allow the reset curtain to completely transverse the sensor, clearing all of the columns.
- Open the mechanical shutter for the desired amount of time
- Fire the flash. Note that if the mechanical shutter is not located at the focal point of the lens, then one must be careful about vignetting and one must fire when the entire frame is exposed equally.
- Close the mechanical shutter
- Begin the readout curtain from the left edge and read out the pixel values
- Allow the readout curtain to completely transverse the sensor, reading all of the columns.

Keep in mind that the advent of CMOS sensors was in the interest of reducing the cost of the camera. This was done by, among other ways, eliminating the mechanical shutter, and by using the CMOS sensor as the light meter for calculating the proper exposure time prior to taking the still image. Placing a mechanical shutter over a CMOS sensor additionally limits its ability to serve as the light meter unless the shutter is normally open, then closes while the sensor is being reset and opens again for exposure and finally closes again for readout. This is an unconventional design and can cost more in both dollars and power.

Historically, CCD sensors, by the nature of their more mature technology have had better signal to noise ratios for equivalent resolutions to their CMOS counterparts. Thus, for higher performance cameras if a mechanical shutter is required for reasons other than the selection of the sensor type, it may be wiser to choose a CCD in place of CMOS sensor for superior image quality.

Within the last few years, some CMOS sensor manufacturers have been attempting to develop sensors that had both a common reset that would reset the entire sensor at once, and a control that would turn off the light sensitivity of all of the pixels, thus ending the exposure time. In the event that these devices become commonly available, they will eliminate the need for mechanical shutters unless they introduce new, as of yet, discovered problems with their operation.