What are all the discussions about global vs. rolling shutter?

Control of exposure times and acquiring sharp images

The shutter offers control of the exposure time and thus, the level of signal in an image. The shutter also defines the quality of an image if the objects are moving and settles the environment for experiments, especially involving synchronization with illumination light.

In the beginning: mechanical and electro-mechanical shutters

Prior to the arrival of digital image sensors, shutters had to control and limit the time that light sensitive films were exposed to by a particular scene or a sample. For single lens reflex (SLR) cameras used in photography, two electro-mechanical types of focal-plane shutters existed. Figures 1a and 1b depict a focal-plane shutter with vertical metal shutter blades, while Figure 1c shows a horizontally moving slit shutter, generally used in less expensive applications.

Controlling the shutter width and timing allows for adjusting the optimum exposure time for an application. The horizontal slit shutter in Figure 1c shows a short exposure time, where the slit allowing light to enter is smaller than the total opening. Various shutter configurations were developed, like central shutters within the camera lens or a moving slit shutter for film cameras. Even external shutters in optical bench set-ups are utilized to interrupt the light path. In the case where the movement of an object to be imaged was faster than a shutter could physically move, short pulses of light can be used, allowing to effectively "freeze" the motion, even with longer exposure times.

Shutters in CCD image sensors – electrical shutters appear

Charge Coupled Devices (CCD) image sensors were the first prominent digital image sensors used extensively in both consumer and scientific imaging. For the first time, the architecture allowed a purely electrical method of controlling the exposure time. Figure 2 is a schematic of the various primary architectures of CCD image sensors.

The first CCD architecture developed was the full frame CCD (figure 2a). Here, all pixels are illuminated at the same time, with a maximum fill factor (which means nearly all of the pixel area is light sensitive). The exposure control always requires a mechanical or electromechanical shutter to open and close the light falling onto the image sensor. When the exposure is finished and the shutter is closed, the whole image is shifted vertically downward row-by-row into the horizontal shift register, which is the serial readout register. Once a row is shifted into that horizontal register, it is shifted pixel by pixel to the output amplifier and A/D converter (figure 2 – triangle). When the row is read out, the next row is shifted into the horizontal shift register. These image sensors were often found
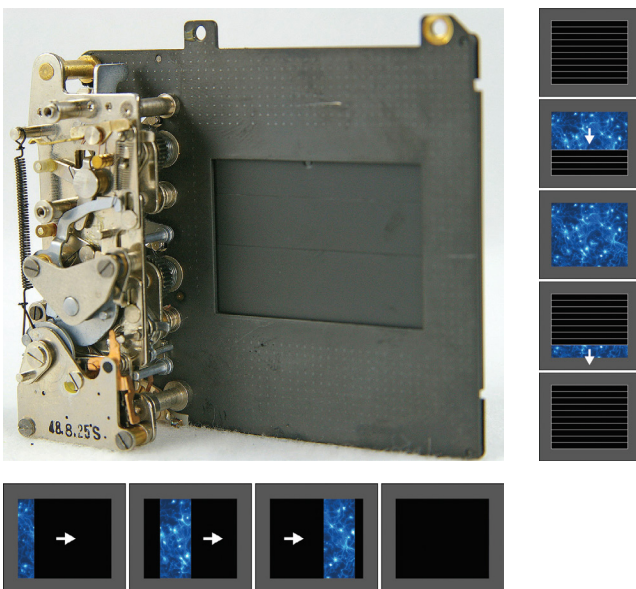

Figure 1: (a) Electro-mechanical focal-plane shutter with vertically moving shutter blades, (b) a schematic of shutter movement for a vertical shutter and (c) a schematic of shutter movement for a horizontal shutter (photo taken from Wikipedia1)

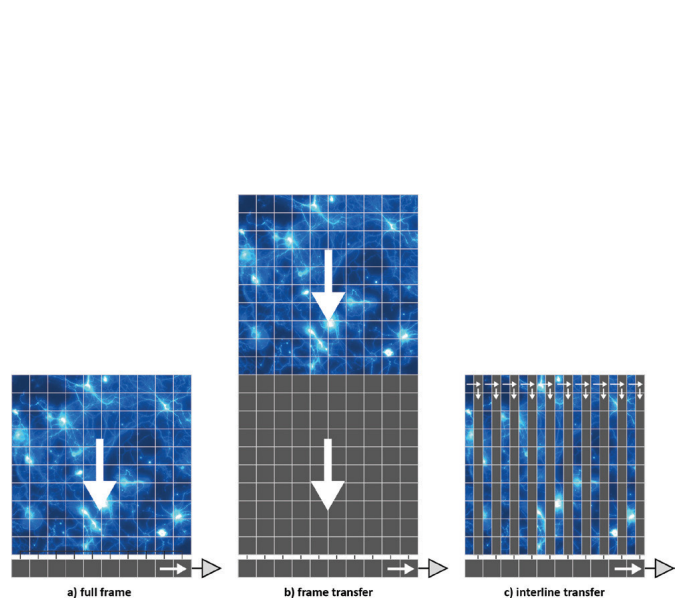a) full frame   b) frame transfer   c) interline transfer

Figure 2: Schematic of the three relevant architectures of CCD image sensors: a) full frame b) frame transfer and c) interline transfer. Arrows indicate the shift and readout direction.

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in the first digital still cameras, because the image sensors were relatively inexpensive, displayed aedequate sensitivity, and the manufacturers already had electro-mechanical shutters in their cameras from the time they used film as light detector.

In the next architecture, the so-called frame transfer CCD (figure 2b), essentially two full frame CCD image sensors, are used side by side. One of them is covered with a light shield so that the exposure can be controlled via a fast vertical shifting of all the light sensitive rows. When they reach the shielded area, they are shifted slower vertically again row-by-row into the horizontal readout register, and the serial readout process is the same as in the full frame CCD. These image sensors had a kind of electronical shutter with the fast downward shift, but nevertheless, the uppermost row catches the most unwanted light, because it is the last row that reaches the shielded area. This architecture was often used for emCCDs and it requires the largest area on the wafer, because the image sensor has to be twice as large, yet still has a good fill factor.

The final architecture is the interline transfer CCD (figure 2c), where for the first time an electronical shutter was introduced, allowing for even shorter exposure times. Each pixel had approximately 30 % area light sensitivity, while the remaining area was shielded. Now the exposure was started with stopping the connection to the substrate and it was stopped by a fast horizontal shift into the registers in the pixels. From here the readout process is identical to the other architectures. Row-by-row, the charges are shifted downward vertically and subsequently read out horizontally. The poor fill factor (< 50 %) of this architecture was compensated by the use of micro lenses on each pixel, which focused the incoming light onto the light sensitive part of the pixel. Exposure times down to hundreds of nanoseconds were now a possibility. While the above described architectures are the most relevant in CCD image sensors, there have always been special solutions or special versions as well. There was for example also a frame interline transfer CCD for TV applications from Texas Instruments, called Impactron TC246.

Note: Shutter Eficiency!

The electronical shutter in CCD, CMOS or sCMOS image sensors has a limited blocking efficiency, when compared to the early mechanical shutters. Although the charge storage nodes or registers are usually shielded by a metal layer in the semiconductor material, which are more or less "impermeable" for photons, light always can be scattered below the shields coming in through the open spaces, which are necessary for the light sensitive parts of the pixels. Further, since the semiconductor material around the photodiodes is differently doped but it is nevertheless silicon. Thus it can as well absorb light and generate charge carriers which might contribute to the signal charge package. Therefore, the shutter efficiency usually given as a ratio of 1 to something describes how good the electronic shutter in the given image sensor works. Small ratios are those below 1 : 200 and good ones are above. In case one has an application with a lot of continuous light, this should be taken into account.

Shutters in CMOS image sensors – new electrical shutter options: rolling & global

With the development of new CMOS image sensors (Complementary Metal-Oxide Semiconductors), new possibilities for a large variety of architectures appeared with the most prominent shutter differences in "Rolling" and "Global" Shutters. In theory, CMOS image sensors are operated and read out per pixel, which was claimed as an advantage of CMOS over CCD image sensors. The true technical realizations of CMOS image sensors resulted in row-oriented readout structures (in CCD image sensors as well), but with amplification and A/D conversion per element of the row. Thus, all pixel columns are interconnected, so that the signals are then switched row-wise onto the column and the whole row is then converted at the same time at the top, the bottom, or both. Using this design of architectures, very efficient CMOS and sCMOS image sensors have been created.

What are all the discussions about global vs. rolling shutter?

At the beginning, the disadvantage of CMOS image sensors was that each pixel requires a charge to voltage conversion with a certain amount of transistors on each pixel, because only voltages can be transferred extremely fast to the amplification and A/D conversion at the end of the column. The consequence is that these devices need physical space in each pixel, and the more transistors one needs, the worse the so-called fill factor[2] and resulting sensitivity becomes. Despite the fact that to a certain extent the poor fill factor might be improved by the use of micro lenses, the fill factor also plays an important role in the decision between rolling shutter and global shutter CMOS image sensors, because the latter require more transistors per pixel.

Rolling shutter operation

The rolling shutter represents an electrical version of the aforementioned focal-plane shutters with a slit curtain. Figure 3 shows the typical timing of the sCMOS image sensors CIS2521 or CIS2020A if operated as rolling shutter image sensors and an exposure time which is shorter than the readout time. The picture on the left shows (per row) the snapshot of an image sensor model with just 10 x 10 pixels to explain the functionality and on the right the corresponding timing of the different operations at this specific moment.

The readout direction of this sCMOS image sensor is from top to bottom, in the first "snapshot" the first row had already been started with the exposure and the second row is just started in that very moment (see figure 3), the start is indicated by a thin gray rectangle and the exposure time is depicted by a light gray arrow. This process goes continuously further down the image sensor. While in snapshot 2, row 4 in image 1 starts with the exposure, row 1 of image 1 has already been stopped and the image information of this row has been started to be read out. This pro-

cess moves further down the image sensor as can be seen in snapshot 3 in figure 3. While the exposure of row 7 is started, the first three rows of image 1 have already been readout, the exposure of row 4 has been stopped, and the image information has been started to be read out.

As can be seen from snapshot 1 to 3, the slit which exposes two rows at the same time, is moving downward like the exposure slit in a focal plane shutter. The snapshots 4 to 7 show the ongoing process. While the exposure of the second image can be started before the last row has been read out, it cannot be stopped before that moment.

A special situation is given by an exposure time which is equal to the readout time of an image. This is shown in the same manner in figure 4. Here, the area of the image sensor, which has an exposure at the same time, is larger as can be seen by the different snapshots. In case the exposure time is further increased, there is some time during which the whole image sensor is exposed with all rows simultaneously. In case the image sensor has only rolling shutter but all pixels should be illuminated at the same moment, this timing situation can be used together with a flash illumination to achieve an "effective" global exposure. Figure 5 depicts the "effective" global shutter (compare figure 10).

Two snapshots in figure 5 show the situation that the whole image sensor is exposed simultaneously (figure 5 snapshots 3 and 5).

Since in most CMOS and sCMOS image sensors the readout is row-oriented, the readout time for a whole image or frame is one of the major time dominating factors. While the rolling shutter very much looks like the old slit curtain shutters, the other type of shutter, the global shutter, is more like a central shutter or near to the former interline transfer CCD shutter, which allowed for very short exposure times.

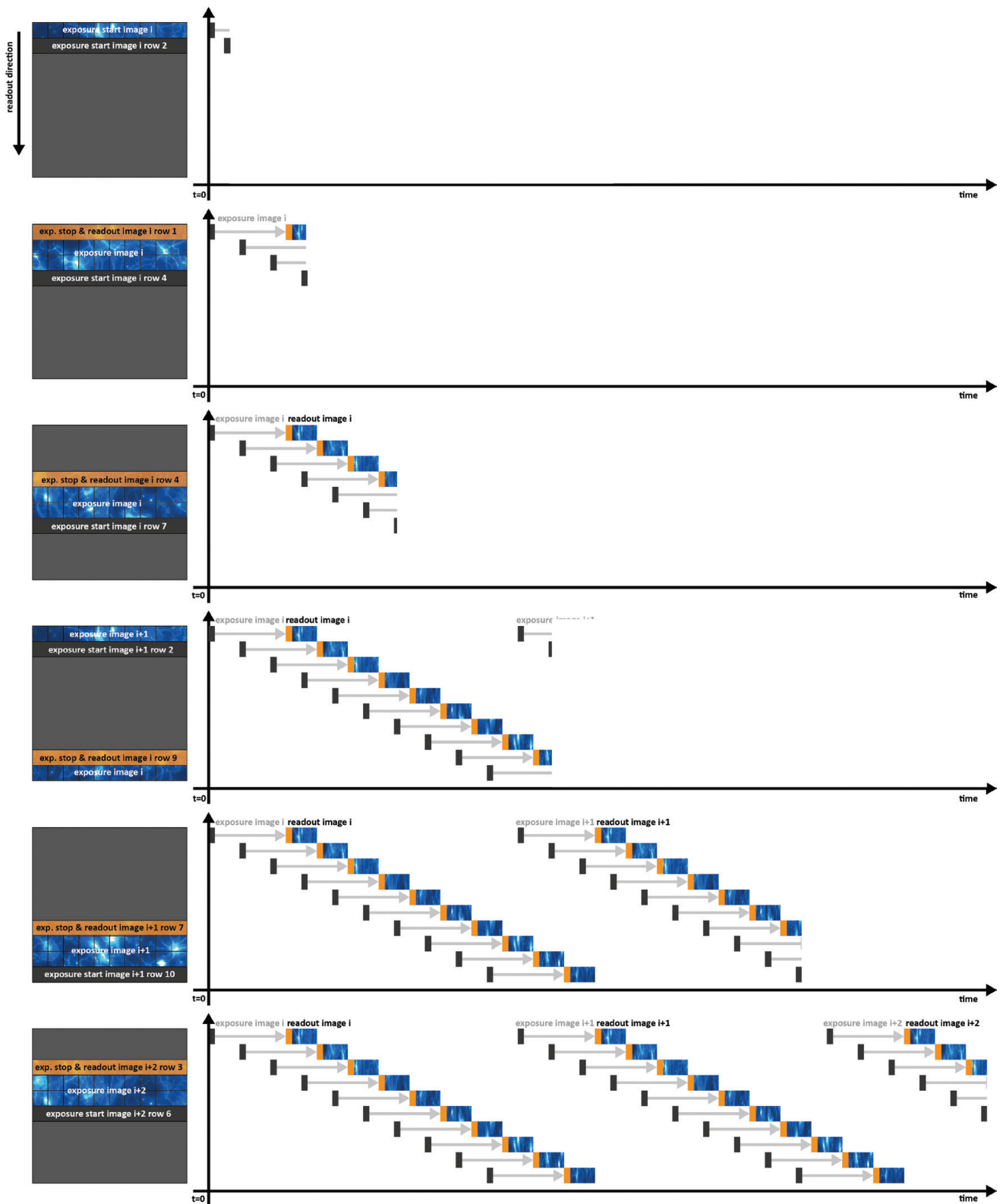# What are all the discussions about global vs. rolling shutter?

Figure 3: Schematic of the rolling shutter operation with the example of the sCMOS image sensors CSI2521 or CIS2020 with an exposure time < readout time. The different rows show different moments in time of an sCMOS model with 10 x 10 pixels. Left, a snapshot of the image sensor is shown while on the right side the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

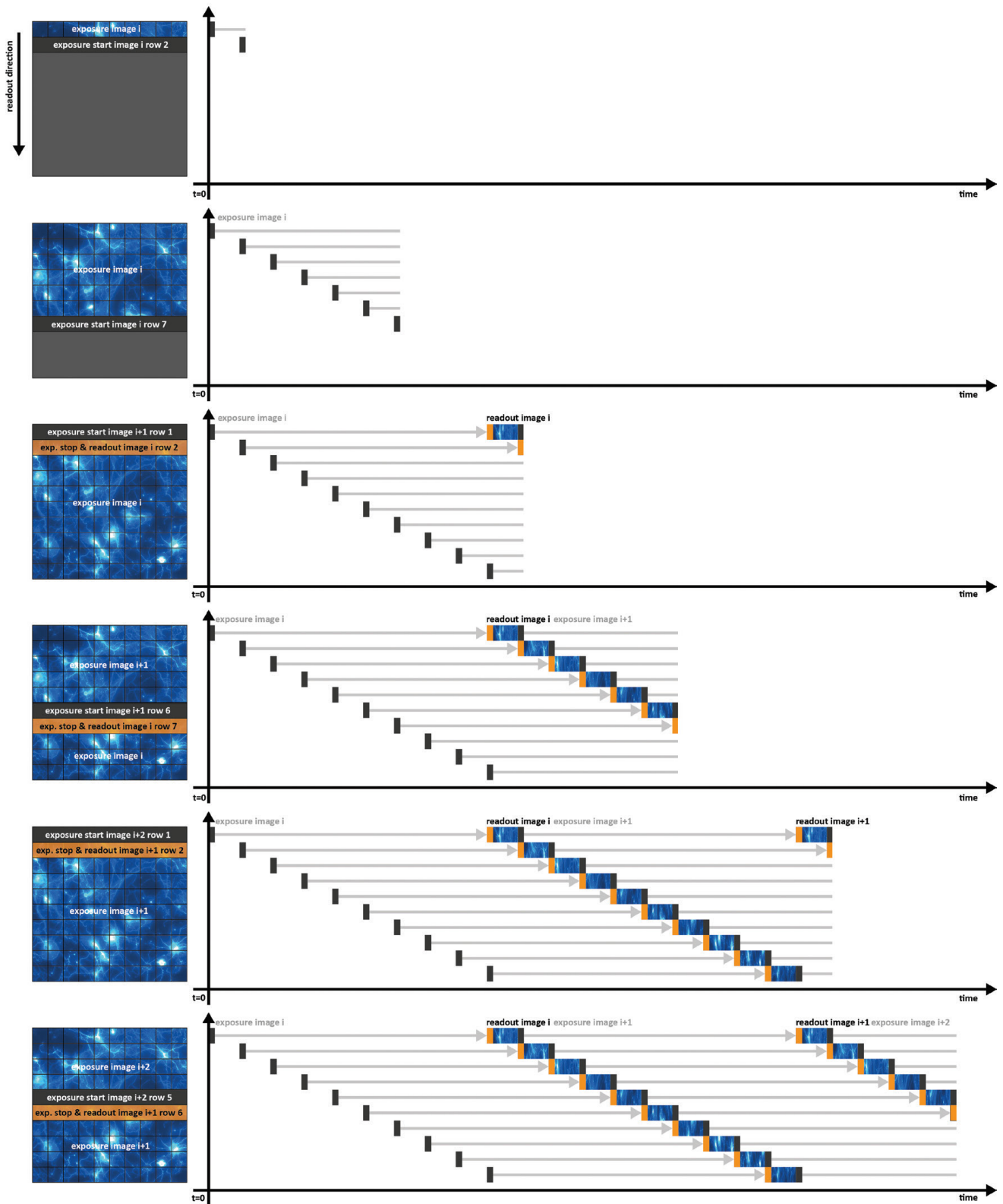# What are all the discussions about global vs. rolling shutter?

Figure 4: Schematic of the rolling shutter operation with the example of the sCMOS image sensors CSI2521 or CIS2020 where Exposure time = Readout time. The different rows show different moments in time of an sCMOS model with 10 x 10 pixels. On the left, a snapshot of the image sensor is shown, while on the right, the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

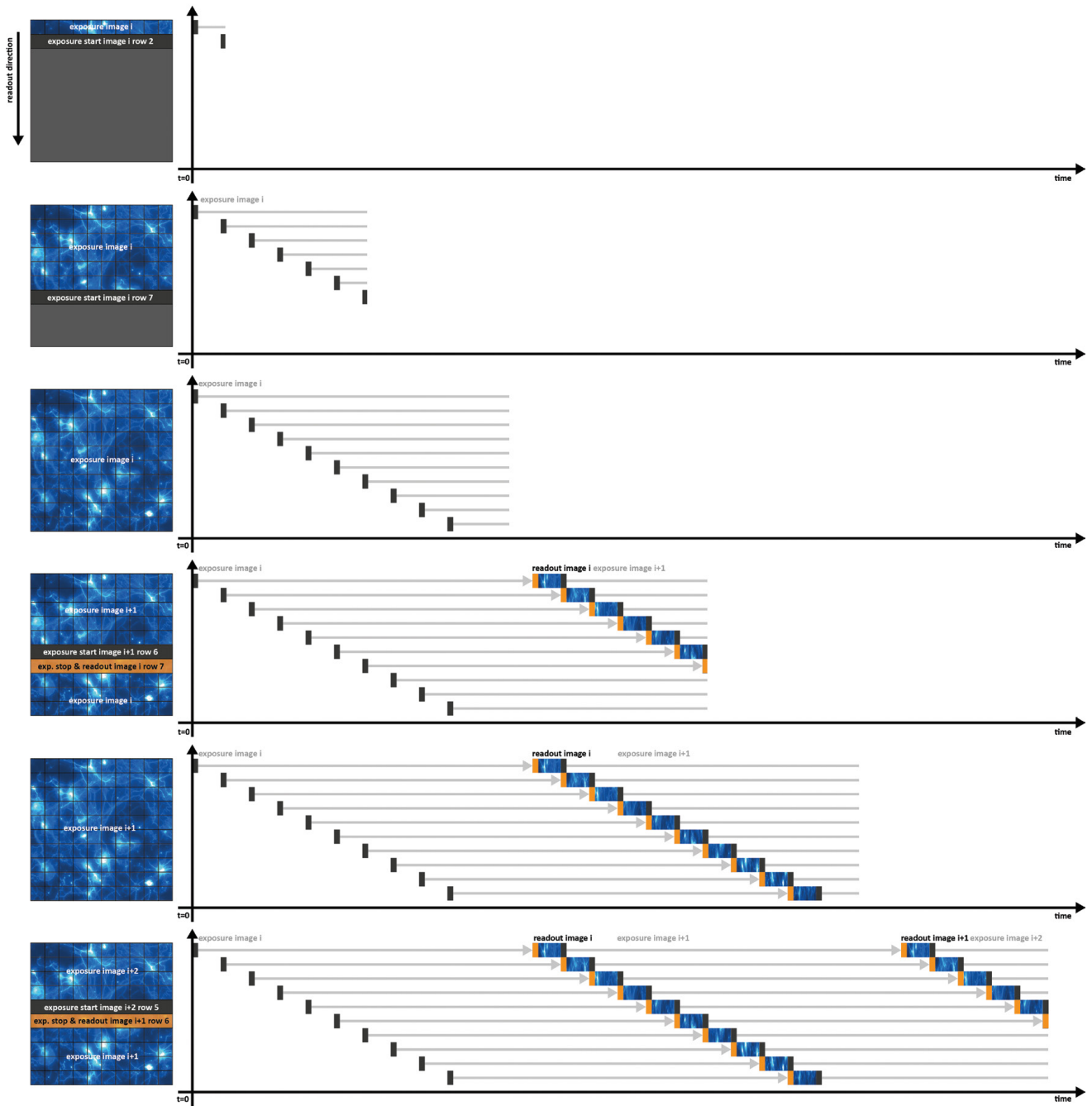# What are all the discussions about global vs. rolling shutter?

Figure 5: Schematic of the rolling shutter operation with the example of the sCMOS image sensors CSI2521 or CIS2020 with an exposure time > readout time. The different rows show different moments in time of an sCMOS model with 10 x 10 pixels. On the left, a snapshot of the image sensor is shown, while on the right, the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

What are all the discussions about global vs. rolling shutter?

Global shutter operation

The global shutter has the advantage that all pixels have an exposure start and stop simultaneously, which corresponds to a real snapshot. All motion (as long as it is slower than the shutter) "freezes" in the image. The most crucial drawback is the higher amount of devices per pixel (more transistors). A higher amount of transistors results in poorer fill factors and more noise, due to more parts contributing to the noise, and in some cases even more layers in the semi-conductor.
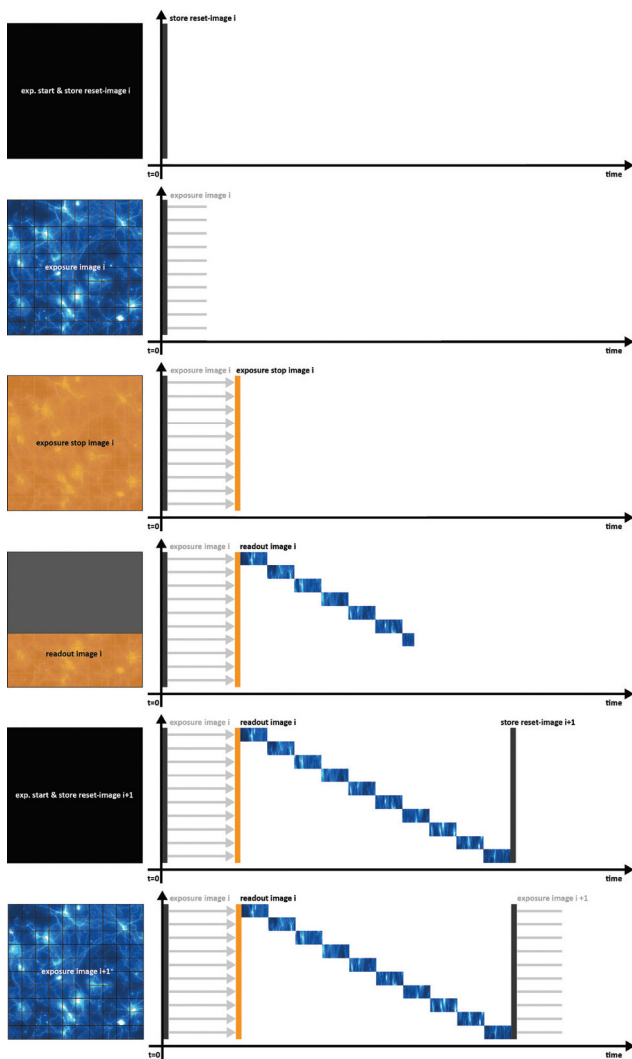

Figure 6: Schematic of the global shutter operation with the idea of a normal global shutter CMOS image sensor with an exposure time < readout time. The different rows show different moments in time of an CMOS model with 10 x 10 pixels. On the left, a snapshot of the image sensor is shown, while on the right, the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

As can be seen in figure 6, all pixels are reset at the same time, so that the exposure starts for all. Then the exposure is stopped for all and the readout starts row-wise or line-wise. When this readout is finished, usually the next exposure can be started. In some image sensors, the exposure could have been started earlier, but it could not be stopped before the last row of the previous image has been read out.

The first sCMOS image sensor made by BAE Fairchild, the CIS2521, has a peculiarity. It can be operated either in rolling or in global shutter mode. Yet in order to not spoil the area of the pixel with too many transistors, it was decided to read out two images in global shutter operation. The required reset value subtraction for correlated double sampling externally is carried out either in the camera RAM or in the computer. Hence, the timing in the global shutter sCMOS image sensor is shown in figure 7. First all rows or lines are reset and the dark values of each pixel are read out. The reference point in time is the moment when the last row is read out. From there, the exposure could be started backwards, because it may not be stopped until the last row / line of the dark reset "image" (it is treated as an image but reflects the start value of the collection sites in each pixel) has been read out. Figure 7 assumes an exposure time shorter than the readout time. First, the reset image is read out, and while the last rows are read out the exposure for all pixels is started and stopped when the last row of the dark image has been read out. Then the row-wise readout of the image is started. After the readout is finished, the next image process can start. The subtraction of the dark image from the data image is done either in the camera or externally, depending on the camera system design.

Global reset or global start operation

For some applications when the camera has to follow an external trigger event instantaneously, using a flash illumination, it may be important to have a global start of the exposure. The main exposure control is achieved by the duration of the flash illumination. In order to accomplish this, the global reset or global start was introduced, made possible in the sCMOS image sensors CIS2521 and CIS2020. It has the disadvantage of a non-constant dark current, since the dark current of the last row would be the largest, but it enables a global reset operation for the pure rolling shutter image sensor CIS2020, and enables better readout noise values and frame rate in conjunction with a global start but rolling stop with the CIS2521 sCMOS image sensor.

What are all the discussions about global vs. rolling shutter?

Figure 7: Schematic of the global shutter operation with the example of the sCMOS image sensor CSI2521 with an exposure time < readout time. The different rows show different moments in time of an sCMOS model with 10 x 10 pixels. On the left, a snapshot of the image sensor is shown, while on the right, the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

What are all the discussions about global vs. rolling shutter?

As shown in figure 8, all pixels start at the same time, but then the first row exposure is stopped and read out and then the second row, etc. The last row will have the largest exposure time, which is exposure time + image readout time. In case of exposure times below 100 ms, the additional amount of dark current could be neglected, and in these applications the exposure is anyhow controlled by the flash illumination duration.
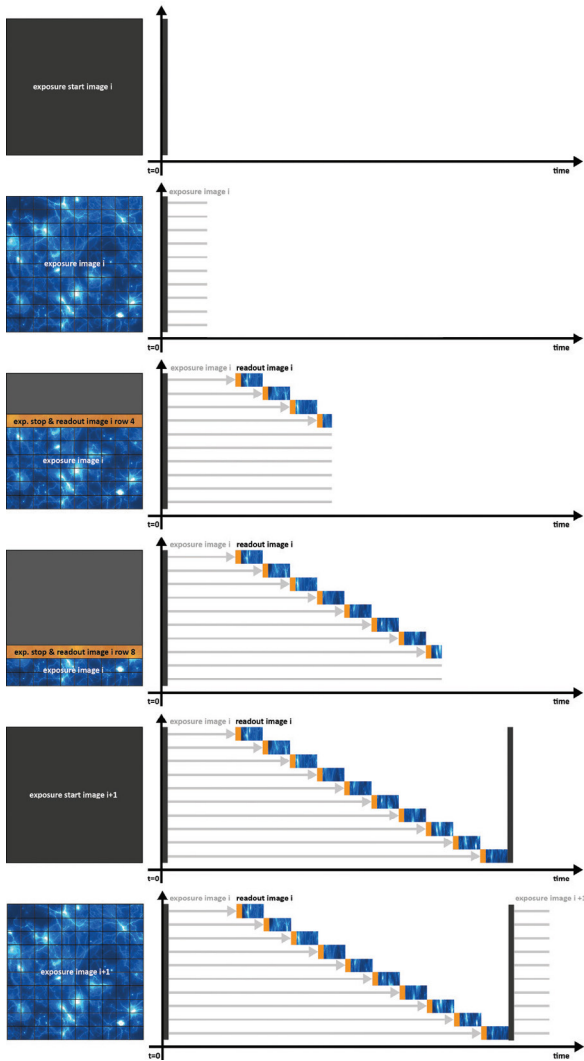

Figure 8: Schematic of the global start or reset operation with the example of the sCMOS image sensors CSI2521 and CIS2020 with an exposure time < readout time. The different rows show different moments in time of an sCMOS model with 10 x 10 pixels. On the left, a snapshot of the image sensor is shown, while on the right, the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

Features for applications
Global and rolling shutter for motion

The general discussion of whether a global or a rolling shutter is better is similar to many camera conversations, and extremely application-dependent. The most common warning for using a rolling shutter is related to objects, which move perpendicular to the view axis faster than the readout time of a rolling shutter image sensor. This means each of the exposed rows gets the image information of the object at slightly different positions, and when image sequences are played back, well-known distortions appear as in the case of a fan propeller (figure 9 [d]).
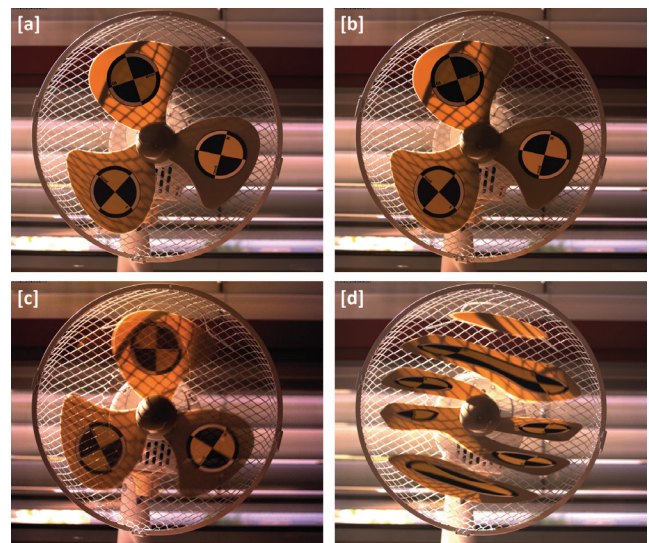

Figure 9: Four pictures of a fan: [a] global shutter image of a stopped fan, [b] rolling shutter image of a stopped fan, [c] global shutter image of an actively turning fan, and [d] rolling shutter image of an actively turning fan (same sCMOS camera).

In the case where the application requires an accurate freeze of the motion of an object, then obviously a rolling shutter image sensor is not the best choice. On the other hand, this topic was pretty much the same in the old days of analog photography, since most of the cameras had vertical or horizontal focal plane slit shutters. If a motion should be captured at the time, the requirement was either to use an extremely short exposure time (the slit runs faster than the motion) or to use a flashlight with a short flash duration, which then freezes the motion.

What are all the discussions about global vs. rolling shutter?

Stop the motion via flashlight

If the application allows, a flashlight can be used to get sharp snapshots. For example, in particle tracking velocimetry (PTV), which is the established technique to measure and visualize all kinds of flow, two light flashes are always used to snapshot the position of seed particles. But the technology of the electronical shutter has a consequence for the timing of the trigger signals and it defines which can be the master of the trigger signals: the camera or the flashlight.

Figure 10 shows the timing options for the flashlight. Let us start with the normal global shutter, which is simple because either the camera or the flashlight could be the master trigger source. During the global exposure, the flashlight can be started at any time. It could as well be shorter than the shortest exposure time. In case of the CIS2521 sCMOS image sensor with its special global shutter mode, it is more convenient to let the camera be the master trigger for the flashlight (using the exposure signal). In case of the global start or reset, again it doesn't matter which is the master, since either the camera can start the flash or the light can trigger the camera exposure. Finally, in the case of the rolling shutter, if the exposure time is longer than the image readout time, there is a time when the whole image sensor is exposed to the signal, then a flashlight could be triggered by a last row exposure start signal. With this it is also possible to take snapshots without distortion with a rolling shutter image sensor.

Scanning with an area image sensor

Due to the issues with timing and distorted results (figure 9), the rolling shutter sometimes gets a bad reputation. On the other hand, in all existing CMOS and sCMOS image sensors the rolling shutter image sensors always have better quantum efficiency and better readout noise performance due to the smaller amount of required electronic devices in the pixel architecture and the smaller amount of required layers in the semi-conductor. Further, the moving slit similarity of the rolling shutter enables applications which can benefit from this "scanning" like behavior of the moving rolling shutter exposure.

Figure 11 illustrates how the synchronization can be done. On the left, the snapshot of the moment in time is shown, and on the right, the corresponding timing of the signals is given. The exposure is just one row (but can be longer if required) and the camera gives out a trigger signal, which can be used to synchronize for example an illumination line in the sample image, and while the exposure slit moves on, a scanner moves the illumination line through the focal plane of the sample. By this, the light energy load (photo stress) on the sample can be reduced. This may be called "lightsheet mode" by certain camera manufacturers, because it fits nicely to lightsheet microscopy applications and readout techniques.
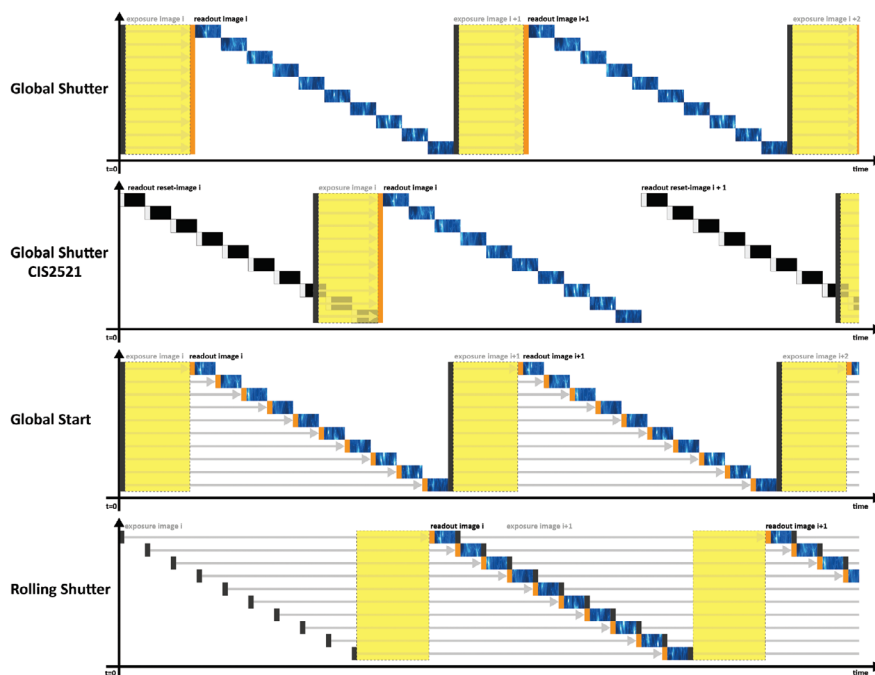

Figure 10: Schematic of the different timing requirements, if a ash illumination should be used. The yellow area indicates when the ashlight should be started in case (from up to down) a global shutter CMOS image sensor, a global shutter sCMOS image sensor (CIS2521), an image sensor with global or rolling shutter which allows a global start, and a rolling shutter sCMOS image sensor should be used with the flash illumination.

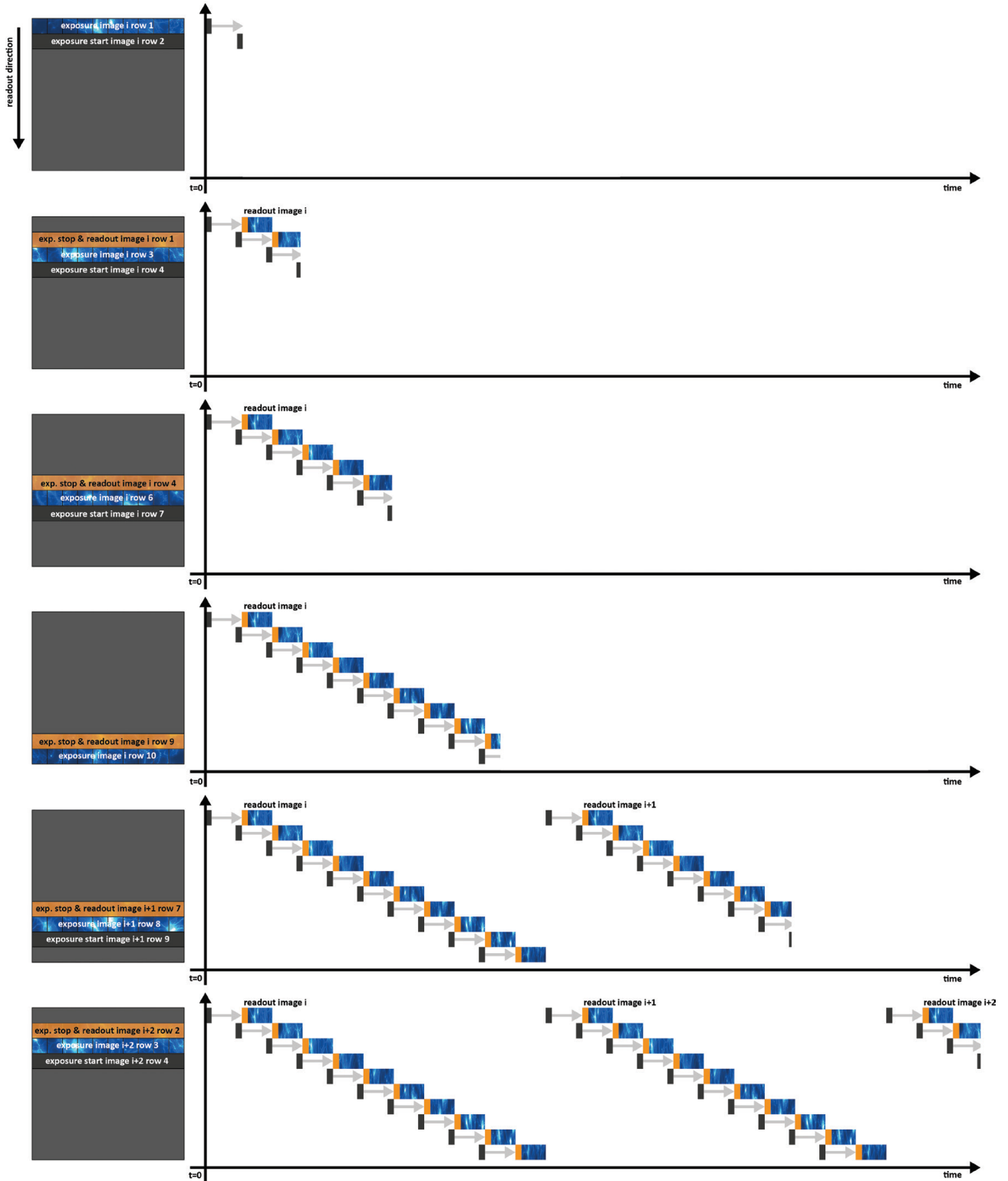# What are all the discussions about global vs. rolling shutter?

Figure 11: Schematic of the rolling shutter operation which can be synchronized with a line scan movement of the illumination (example of the sCMOS image sensors CSI2521 or CIS2020 with a row exposure time). The different rows show different moments in time of an sCMOS model with 10 x 10 pixels. On the left, a snapshot of the image sensor is shown, while on the right, the corresponding timing diagram is given. Dark gray means exposure start (reset), light gray arrows are the real exposure time, orange represents exposure stop, and the blue neuron image is the image data or information, medium gray means non-relevant.

What are all the discussions about global vs. rolling shutter?

A final comparison of rolling shutter vs. global shutter CMOS / sCMOS image sensors

Parameter	Global Shutter (GS)	Rolling Shutter (RS)
Readout Noise	Larger than RS	Smaller than GS
Frame Rate	Up to RS	Can be faster than GS
Fill Factor	Smaller than RS	Larger than GS
Complexity of pixel achitecture	Higher than RS	Lower than GS
Snapshot Ability	Better than RS	Worse than GS
Risk of Distortion of Moving Objects[3]	Low Risk	High Risk

Since the question was: "*What are all the discussions about global and rolling shutter?*" there should be a conclusive comparison of the impact of each shutter on important imaging parameters. Like usual, each decision for an image sensor in this case with a specific shutter mechanism depends on the requirements of the application.

The most important difference might be the risk of distorted images of moving objects, which definitely is higher in rolling shutter image sensors. Nevertheless, it should always be evaluated, if the movement is fast enough to cause these distortions, and in case the exposure time is longer than the image readout time, the movement can be frozen if a proper flash light illumination can be used. Since rolling shutter image sensors are less complex in architecture, they also have less components in each pixel, and therefore they tend to be cheaper, they have better fill factors and lower readout noise. On the other hand, there are imaging methods like particle tracking velocimetry (PTV) which require global shutter operation. Therefore, all the discussions about global and rolling shutters are necessary to figure out which is the best image sensor for the respective application.

END NOTES

1 https://en.wikipedia.org/wiki/Focal-plane_shutter
2 The fill factor describes the ratio of (the light sensitive area of a pixel)/(total area of a pixel)
3 The distortion depends of the speed of the movement compared to the exposure time

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