CCDmos

A disruptive technology to photograph fast moving objects with ultra-high quality.

Dr. Ing. Willem-Jan Toren
Semiconsultor bv
Amerikaweg 78
9407 TM Assen
Tel: 0592261666
www.semiconsultor.com

This report gives a description of the CCDmos technology to make 1-dimensional scanning sensors that can take 2-Dimensional pictures with extreme high quality. The report gives a very general overview of imaging fundamentals that help to understand the working principle of this sensor and why this high quality is achieved by concept. This report comes also with some applications where the different advantages of the concept are discussed.

The status of this technology is that only a paper study has been done, and a patent is filed. The next step to take is the realization of a demonstrator to convince potential customers of this high quality.

Different commercial models may be applied for this product. Whether the patent can be sold, or licensed. Also a start-up company can be built to realize and commercialize the sensor.

Contents

1. Introduction

This report explains the working principle of the new innovative sensor, which is called CCDmos that can be used for earth observations from a satellite, as well as many other applications with specifications. First, in chapter 2, some general imaging information is given to explain the working principle of the two major image sensor concepts that exist today in chapter 3. Chapter 4 discusses a special operation of one of the concepts to allow earth observation and other scanning applications with fast moving objects which is the basics of the patent that will be explained in chapter 5. Chapter 6 will discuss some applications where the focus is to highlight specific items that have been improved with this CCDmos concept. This report ends with some conclusions.

2. General information on image recording

Earth observation, why is it so difficult?

Figure 1 shows a schematic satellite that turns around the earth for scanning the earth surface. The reason for this is to provide information about ocean water quality, Ice cap reduction, military displacements, salad crop quality for farmers and much other information.

For Earth observation the satellites are positioned in an orbit of 700km above the earth, and circle with a ground speed larger than 10.000 km/h.

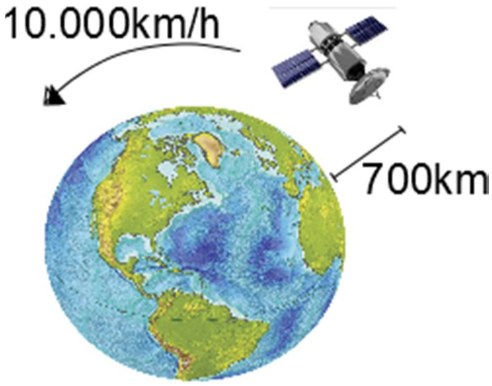

Fig. 1, Satellite rounds the earth 6 times a day.

If a resolution of about 30 cm is required to register the photo, a time to capture all the information on color, light intensity is about 50µs. Normal video cameras have an integration time around 20ms, which is about 400 times longer. Because the lens on the satellite camera system has to scan a wide area, perhaps 10km wide, the opening of the lens is small which result in a low light intensity on the sensor. This short integration time and low light entrance in through the lens makes the signal quality poor as will be seen later in this document.

How photos are recorded?

Everybody knows the digital camera’s or smart phones that take a photo. Not many people have seen the sensor itself, and one needs to be very equipped to see the unity cells of an image sensor: the pixel.

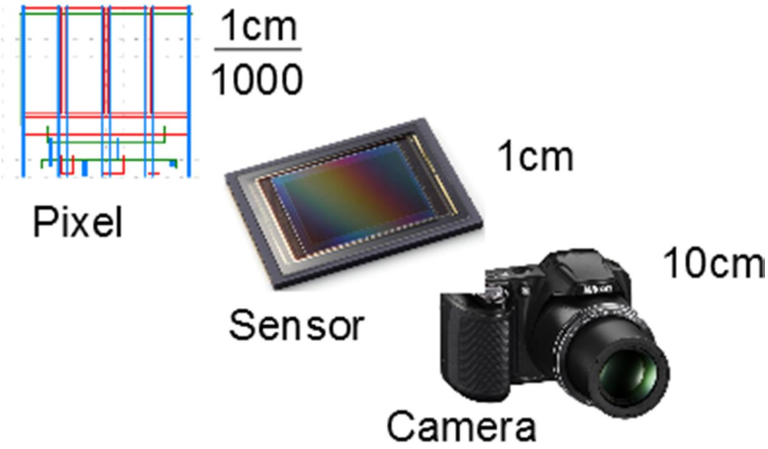

Fig. 2, photo recording system

Current cameras contain millions of pixels. Figure 2 shows the dimension difference between the camera and the pixel. The last one is about 1000 times smaller than a centimeter or for consumer products even 10.000 times smaller. This means that the light intensity or the number of photons per pixel is very limited, the smaller the pixel the less light. For consumer cameras the price is important, for industrial or space cameras the performance is important, which explains the larger pixels sizes around 10µm square.

Light to electron conversion

Light is converted to electrons in silicon (blue part in figure 3) by the so called photo-voltaic effect. Light that is coupled in the silicon has so much energy that it can generate an electron-hole pair. The hole is drained away, but the electron is captured to be detected later. During a certain time, which is called the **integration time**, a certain number of electrons are generated and collected. After this time the charge is transported to a detection node that converts charge in potential which is a measure of the light intensity of the individual spot of the scene. By doing so for all pixels in the total matrix a 2D image can be generated, or in case of sensor that is discusses in this document, which is a line sensor, only a 1D line can be recorded in one single integration time.

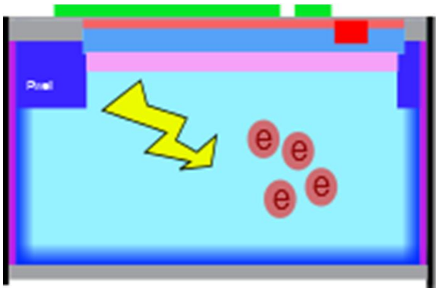

Fig. 3 how light is converted to signal electrons in Silicon

Noise

This light conversion process in electrons has a fundamental noise component, which is the photon shot noise given by the square root of the total amount of generated electrons. If 100 photons enter the pixel, 100 electrons are generated with a noise of $\sqrt{100}=10$ electrons. The signal to noise ratio (SNR) is 10. If 1 million photons enter the pixel, it will contain 1000 noise electrons that will result in a SNR of 1000.

Additional to this, other noise sources are added. One is dark current, which is a generation of these signal electrons by thermal excitation. So even in the dark, signal is generated.

Also the conversion process introduces noise which is more or less independent of the number of electrons integrated in the pixel. This conversion noise should be added to the shot noise and dark noise to calculate the SNR.

The conclusion for recording a high quality photo is that the maximum number of electrons should be generated per pixel. This results that scientific cameras are in general large. Pixel sizes of 10*10µm are normal, while for consumer products this size is reduced to 1*1µm assisted by a large algorithm to improve the SNR.

Dynamic range

The dynamic range DR is defined as the ratio between the maximum and minimum signal that can recorded in a pixel. The maximum is given by the maximum number of electrons that can be stored in a pixel Qmax, and the minimum is defined by the noise floor Nf. If Qmax is 100.000 electrons, and the Nf is 100 electrons, the DR is 1000.

If the dynamic range of a scene is higher than 1000, bright and dark parts will be recorded such that details of the scene will get lost.

3. Two image sensor concepts

CCDmos sensor technology is a combination of two main technologies for recording images: CCD (Charge Coupled Devices) and PPD (Pinned Photo Diode). To understand the new CCDmos technology, CCD and PPD will first be explained.

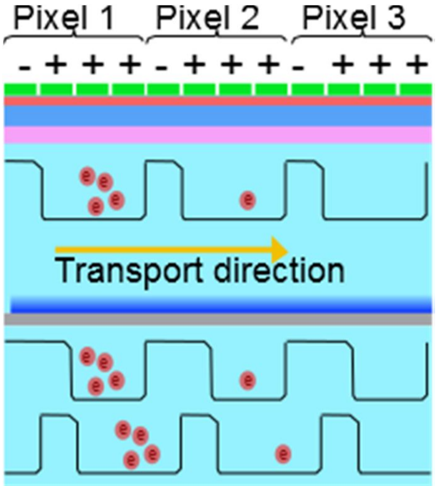

Fig. 4 Confined charge packages in a CCD shift register.

CCD, Charge Couple Device

The oldest technology is the CCD, which has been invented in the 1960's to replace the cameras using film. A CCD works rather simple, the charge will be integrated during the integration time in every pixel, followed by a transport of the confined charge packets to a single output amplifier that converts the integrated charge in a potential. The integration is done in the potential wells under a gate that is positively biased and the transfer is done by alternating the gate bias between positive and negative as to get toothpaste out of tube.

Each pixel consists of 4 gates (drawn in green in figure 4) on top of the pixel which can be biased negative and are blocking or positive to be able to accumulate the charge package. Pixel 1 of figure 4 contains 4 schematic electrons pixel 2 contains only 1, which are separated by a negative gate such that the packages will not be conjoined (left gate of every pixel).

During the integration period the gates remain unchanged as is drawn on top of figure 4, where the black lines represent the potential wells to trap the electrons.

To transport the charge packages to the right, the second gate from the left of every pixel will be made negative as well, such that there are two gates blocking and the charge packages are confined only under two gates (two right ones of every pixel). The transport sequence continues by biasing the first gate of every pixel positive, such that the charge packages are shifted 1/4th pixel to the right. This is repeated multiple times such that all pixels have arrived one by one at the output amplifier and are recorded.

To realize a CCD sensor a dedicated process is required in which only these sensors can be made. No logic can be integrated for on-chip signal processing. The potentials used in CCD's are around 20V, which makes the driver logic power consuming and needs a very large foot-print, which makes it rather inconvenient for satellites. Because of this dedicated process to make a CCD sensor, this process can be tailor made and fine-tuned to achieve the lowest dark current noise and signal conversion noise to realize the optimum photo or video performance.

PPD, Pinned Photo Diode

The pinned photo diode is rather new, discovered in the end 1990's but took a long time to start off in production, partly because CCDs were still largely available and the CMOS processes in which the PPD sensor is made were not performant enough on noise.

The biggest difference with a CCD is that there is no transport to one single output amplifier, but every pixel has its own amplifier. The PPD can be realized in a CMOS process, such that full sensor integration can be done on chip, with low power CMOS drivers.

Figure 5 shows a schematic cross section of the PPD pixel. The electrons are again confined in the silicon by a potential well which can be opened and closed by one single gate (transfer gate TG) on top of the pixel (green rectangle). The red part on top is the detection node and is connected to the output amplifier in the pixel (black triangle). During integration the TG is biased negatively, and the electrons are confined in the pixel. For readout the TG is biased positively (potential profile is given by the dotted black line) and the electrons will be transferred to the detection node. Then the TG will be biased negatively again and integration of the second frame starts. There is no transfer of charges to adjacent pixels to achieve the output amplifier; all is done in the pixel.

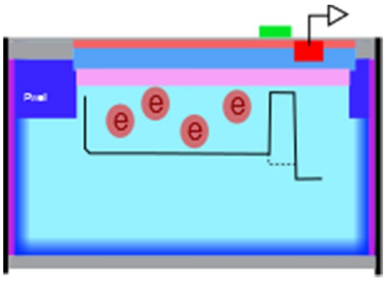

Fig. 5 PPD pixel cross section

There is a line scan image sensor technology that uses this PPD, which is called a line scan sensor. There is only one single row of pixel that will scan the subject. The performance is not very high, but the price is rather low.

4. TDI Time delayed integration

The CCDmos image sensor concept is based on TDI.

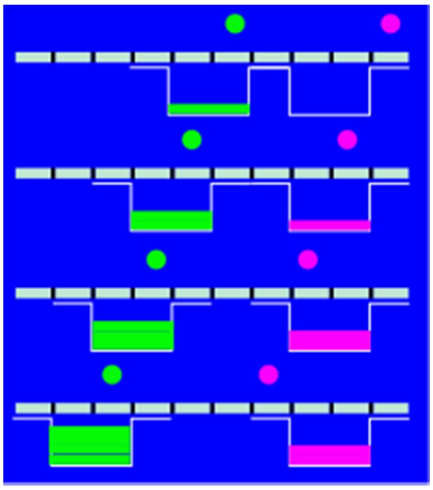

Fig. 6 TDI principle

Chapter 2 explains earth observation, where the earth surface moves very fast relative to the satellite. Figure 6 describes the TDI principle, where an object on the earth surface is represented by the red circle. This red circle moves from right to left of the picture, or the satellite moves from left to right as is drawn in 4 representations in time from top to bottom in figure 6. In the figure the gates of the CCD are drawn as in chapter 3, and the potential wells are drawn with the white lines. The charge that is accumulated is drawn in these wells.

In the top scheme the red dot is not above the integrating gates, and therefore the generated electrons will not be accumulated in the pixel. This happens only in the second and third situation. In the last situation the red circle has already past the pixel and will not contribute to the total pixel signal either (as the top situation).

The total integration time is now half of the pixel time that the subject passes by, which is about 50µs as is explained in chapter 2. When this time is not long enough the trick of TDI can be applied as is schematically shown by the green dot.

If the speed of the green dot is known (speed of the satellite is known), the CCD register can be clocked in a semi-integration / semi-transport mode such that the integration part of the pixel will “follow” the subject. The green dot is situated in all 4 cases above one of the integrating gates. This can be continued for a 100 pixels (these are called stages) to have 100 times more signal! For the situation of the red dot, this is not possible because the spot has already passed the pixel.

One can say that the integration is delayed in time, which explains the name.

The conclusion on TDI is that the integration time can be increased to improve the image quality.

5. CCDmos: the patent.

TDI sensors are, until now, always made in a CCD process because of this transfer of charges required to follow the object during integration. In a standard PPD pixel this transfer is not possible. However, if pixel design and process are changed such that it is possible, the advantage to make these sensors is enormous. The footprint and power consumption will decrease with many orders of magnitude, the integration of the full system on chip is now possible, multiple production facilities can make this sensor without large investment in process development, the price will go down etc. etc. However, there is one advantage that addresses directly the image quality and that will be discussed in this chapter.

A CCD process is tailor made and fine-tuned to get the best image quality as was discussed in chapter 3. Indeed, the quality of a TDI sensor made in CMOS process will be much poorer because there is nothing in this process optimized for the CCD action. To overcome this lag of performance a trick is used, which results together with the pixel design and process to the CCDmos patent.

The dark current noise and signal conversion noise can be neglected at full charge packages because the photon shot noise is larger. In dark scenes where the number of generated electrons is limited, these noises are deteriorating the image quality. So, every pixel needs to get a large number of electrons before read-out. This is rather simple to realize by increasing the number of transfers of the TDI action. However, scenes with a high illumination will achieve Qmax, and no signal information is available only that it is bright. Therefore multiple readouts will be done let's say at 1, 10 and 100 times. For high illumination scenes the one stage readout will be taken and for dark scenes the 100 stage TDI signal is taken. In this way, the signal to read is always much higher than the noise sources, even in a CMOS process. Some post processing is required to correct the signal level for the different integration times.

A second advantage is that the dynamic range will increase with at least two orders of magnitude due to this multiple signal generation. Dark scenes become visible now.

A third advantage, which is for free, is that the resolution due to this multiple readout is doubled. Today the satellites see spots of a meter; new sensors need to be able to identify difference of 30 cm; while this sensor can easily detect objects of 15 cm. This from an altitude of 700 km and a speed of 10.000 km/h!

The CCDmos sensors are easy to realize by changing slightly the baseline CMOS process by adding 3 implants. The additional production cost is estimated at standard CMOS product + 10%. The development if this sensor needs some dedicated device simulation, TCAD and experiments to verify the simulations.

6. Applications

The market of these TDI sensor applications is small compared to the photo and film cameras, telephone cameras, surveillance cameras etc. However, the margins are in consequence. The price of a telephone image sensor is about 1 euro, while a TDI sensor for industrial purpose cost about 1000 euros. Some applications for this new TDI sensor (that benefit of the CCDmos sensor technology) are discussed in this chapter.

Earth observation from space (dynamic range)

Earth observation is already explained in chapter 2 and is the cradle of this development. The advantages to use CMOS in space are the smaller foot print and power consumption.

A second advantage is that the production lines will remain available for a longer time. The way of working for space applications is that they develop a product in a certain production line which will be tested and qualified during 2 or 3 years. If this is a pass, a new series of sensor is produced to be sent to space. With the disappearance of the CCD production lines, CMOS is the only remaining process.

The higher dynamic range is clearly a very big advantage for space observations. If a spot is in the shadow, the same information can be obtained as from scenes in sun-light, while the current sensors give only black as a signal.

The market for these sensors is very small. It is estimated that there will be 1 or 2 satellite launches every year. However, the price of the sensors will be multiple millions of euros per sensor. Total market for the next 5 years is estimated on 200 million euros.

Mail address on an envelope scanning (price)

For almost all industrial scanning applications it is valid that the faster the sensor can scan, the cheaper the scanning equipment. Some scanning applications use a 2D sensor (accompanied by a lot of light) because it is commercial available. The postal machines use in general the TDI sensors because they have increased speed such that this is no longer possible with a 2D sensor.

Because the number of letters that is send today reduces due to internet, one might think that this market is of less importance. The opposite is true: before the price of the sorting machines was of 2nd order importance, because the load was sufficient. However, now the price of the sorting machine can win or lose markets such that competition will be stronger.

The dynamic range of the sensor is in this application of less importance. However, the system price is very important.

The market for industrial applications is large. It is estimated that at least 10.000 sensor per year can be sold for an asp of 500 euros. For the next 5 years the total market is about 25 million euros.

Car speed measuring systems (CMOS integration)

For earth observation and mail address scanners the speed of the satellite and letters are known by system specifications. Therefore the TDI operation can be used, because the clock signal that moves the pixels forward need to match exactly the speed of the object to follow. If not, the image will be vague. For car speed measuring systems, the speed of the object is just the parameter to measure such that the TDI action seems to be not possible. However, it will make the system only stronger as will be explained.

The current way to measure the speed of a car is to take two pictures at two different times and determine (by heavy image processing) the displacement of the car in this time interval.

A simple circuit in CMOS in combination with the CCDmos pixel is able to measure the speed of a car, in which the displacement of the car is detected in one pixel. This makes the measurement very accurate with an error < 0.2km/h. This additional circuit can be integrated in the sensor as the first pixel rows. This circuit’s output will generate the clock signal with the right frequency for the TDI sensor to record the image with a very good quality. If for one reason the speed detection is incorrect, the photo taken will be vague and disqualify the police ticket to send to the driver of the car.

The market for this car speed enforcement systems is very large. The current systems cost about 30.000 euros. In France about 2000 new systems will be installed in 2015. The total EU market is estimated as 10.000 systems. The asp of these sensors could be about 2000 euros because the expensive radar and flash light can be removed out of the system. The total estimated market for the next 5 years is therefore 100 million euros.

Dental X-ray inspection (Noise)

If a special layer is deposited on top of the sensor, X-rays can be converted in light that can be detected with an image sensor. This is a well know technology for specialists in this markets. However, the X-ray dose for human scanning needs to be reduced because of its danger. The CCDmos sensor can use a 100 times lower dose because of this TDI action and produce noise free images of high quality.

It is not clear what this market size is. However, if this sensor will be used by every dentists, also multiple millions of euros are involved.

Wide angle observation (replacement for line scan sensors)

Football supporter observation in stadiums, as an example, is another application where this sensor can be used. This camera contains a mirror that scans the supporters at a large angle. Examples can be found at http://www.sentryscope.com/imagelibrary.html. This company uses a line scan sensor (only one dimension PPD with 1 pixel wide), such that the dynamic range and noise performance is not optimal as can be observed in the demo pictures. The quality will be much higher using CCDmos. Some example photos show a kind of movement error, supporters are moving too fast and their face becomes vague. By a faster scan, this can be avoided. Also the resolution can be improved to better recognize supporters that don't behave nicely.

Line scan applications

Many line scan applications exists today, low cost sensors that are able to scan an object with poor quality. A TDI sensor is not considered for these kind of applications because of the price (this will be reduced in CCDmos) but also because of syncing of the speed of the object and the CCD shift register complexity. Due to the speed measurement circuit as used for the car speed enforcement this is now easy to realize.

The number of these sensors that can be sold is enormous. Better market study is required to have an accurate number. However, millions of euros is easy achieved.

Other applications

Besides the above mentioned applications, many new applications might be considered using some additional engineering. For ill potato sorting, an infrared detection needs to be integrated which is possible. Drones can be equipped with this sensor to make observations of wine yards. The sensor is less sensible to movements due to wind or air pressure. Surveillance cameras might be replaces by this system, by using a rotating mirror. The future will learn what application can be equipped with this sensor.

The estimated market that needs to be developed is estimated at 100s of millions per year.

7. Conclusion

In this report the CCDmos concept is explained. The process is cheap and easy to install which makes the sensors accessible for many applications. The gain in image quality is huge on signal to noise ratio (> 9 bits), dynamic range (1: 1 million), and resolution (two times higher than current technologies). By concept it is less sensitive to vibrations or small movements. This all makes the difference in an application compared with current solutions.

Several markets are addressed, all with a value of 100's of millions euros where the sensor is key for success.