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PRACTICAL ASPECTS OF IMAGE PRIMARY PROCESSING AND DIGITALISATION

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Abstract: *This paper deals with optoelectronic sensors used for optical image sensing. The basic physical principles and properties of sensors, their implementation as well as methods of signal conditioning are treated. A special attention is devoted to the properties important for digitalisation and recording of the output signal of sensors.*
Keywords: CCD Sensor, CCD signal processor, CCD Sensor Noise

1 INTRODUCTION

The devices used for image acquisition are based on photodiodes, photomultipliers, charge injection devices (CID), line (1D array) and matrix (2D array) charge coupled devices (CCD) and 2D CMOS based optoelectronic devices. In the majority of cases image processing is based on complicated digital procedures as special filtration and image enhancement. In the front end of image processing chain the important role plays conversion of preprocessed analogue signals to digital form. Proper design of digitalisation part of processing requires deeper knowledge of physical properties of image sensing devices as methods of scanning as well as those are connected with structure of image sensing elements.

2 THE METHODS OF IMAGE SCANNING

Image sensing can be performed using three basic techniques: point scanning, line scanning, and area scanning. CCD's, by their definition, can take the form of line and area scanning formats - lit. [1].

2.1 Point scanning

Using single -cell detector (photodiode or photomultplier), or pixel (picture element), an image can be scanned by sequentially detecting scene information at discrete X, Y coordinates. This approach delivers high resolution and uniformity of measurement. Continuos movement of image in one direction results in signal continuos output signal. Point scanning is used in drum scanners for acquisition and processing of photographs with high resolution as it is required usually in desk – top publishing.

2.2 Line scanning

An array single -cell detectors can be placed along single axis in such a way that scanning takes place in only one direction. In this case, a line information from the scene is captured and read out of device before stepping to the next line. The scan time of line scanning is much better than that of point scanning. Other benefits include high resolution and less sophisticated scanning mechanism. However, resolution is limited by pixel scanning and size in one direction. Measurement accuracy at each pixel has finite nonuniformities that must be corrected by the system.

This method is used in fax machines, CCD document scanner (flat bed scanner), specialised high resolution digital camera for static pictures.

The extremely high resolution corresponding to10 000 - 12000 pixels in a line can be achieved.

Line scanning is also popular in airborne scanning working in visible or infrared part of spectrum. The advantage of line scanning is possibility to acquire images dimension of which can be much larger in direction of scanning than that in direction of sensing element.

2.3 Area scanning

For the area scanning the 2D array CCD, CID and CMOS sensors are used. The geometrical precision of area scanning depends on optical properties of projection optics and geometry of sensing array. Typical example of area scanning is CCD TV camera with resolution typically 768 pixels x 576 lines, or digital camera with resolution of 1600 x 1200 pixels. In special CCD devices the resolution up to 5000 x 5000 can be reached.

3 THE PRINCIPLE OF CCD SENSOR

Basic building blocks of CCD are following: sensing photoelements, analogue transfer register using CCD cells and charge detector with output amplifier.

The MOS capacitor shown in Fig.1 serves as a photon- sensing, storage and information transferring element. Applying a positive voltage to the electrode generates a depletion layer in the substrate. A photon which is absorbed in the silicon creates an electron-hole pair. If the absorption occurs within the depletion region, the electron and the hole are separated by the electric field; the positively charged hole is drawn to the base electrode whereas the electron is trapped at the SiO_2/ Si interface.

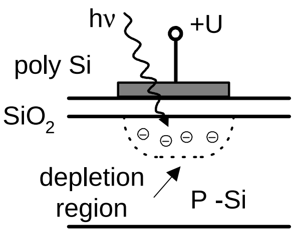

Figure 1. MOS capacitor.

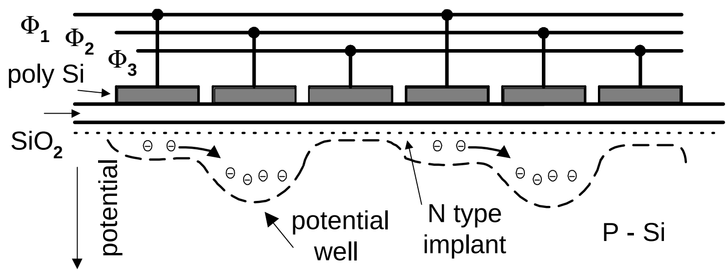

Figure 2. CCD shift register

The array of linearly oriented capacitors forms CCD shift register. By means of control voltage applied to electrodes of capacitors in proper sequence the transfer of charge is performed. Fig.2, shows a part of three phase CCD shift register, which shifts two charge pockets. Thick layer of N type located close to SiO_2 layer shifts the region of charge transfer under surface (buried channel) thus decreasing the influence of parasitic electron traps. lit. [2].

MOS photocapacitors serving for charge transfer only are shielded by aluminium layer. The direction of charge transport is determined by time sequence of three control voltages Φ_1,Φ_2, Φ_3.

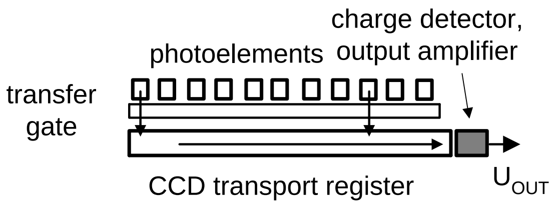

Figure 3. CCD line sensor

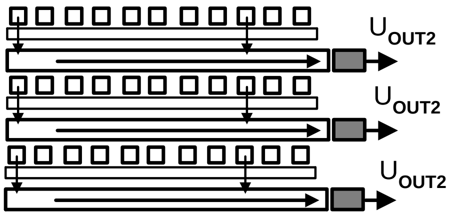

Figure 4. CCD Trilinear sensor

The principle of line sensor operation is on Fig.3. Incident radiation generates charge which accumulates in photoelements (MOS capacitors or photodiodes). By means of transfer gates the accumulated charge is then transferred from photoelements to CCD transport register (read-out register). The charge image in two or three phase transport register is then moved towards charge detector and output amplifier in which charge is converted to a voltage level. Colour CCD sensors contain three lines of elements in parallel each of them covered by a suitable colour filter Fig.4.

4 AREA CCD SENSORS

2D array CCD sensors are produced as full frame sensor, frame transfer a interline transfer. Images are optically projected onto the parallel array, which acts as the image plane.

4.1 Full Frame sensor

Full frame sensor has the simplest architecture. Vertical CCD registers serve both for accumulation of charges and their transport - Fig.5a. The array of sensing elements is exposed to light. At the end of integration period all the rows are vertically clocked by one position, shifting the photocharges down by one position. The bottom row of image is therefore shifted into horizontal CCD (H-CCD) - read out register. Once this is done, the charges in the HCCD, are very rapidly shifted by horizontal clock out to the output charge detector. After all the HCCD pixel charges are shifted out, the next row of image is shifted into HCCD. The duration of image read out must be substantially shorter then accumulation time in order to avoid distortion of picture by parasitic accumulation. If it is not possible, an additional electromechanical shutter, activated during vertical transfer period should be used.

Full frame sensors have high resolution (up to 5000x5000 pixels) and are used in astronomy and special purpose cameras.

4.2 Frame transfer sensor

They have architecture similar to these of full frame CCD. Only upper half of vertical CCD is used for the charge integration -Fig.5b. As the control signals of both halves are accessible at the same time, the charge can be shifted in both parts simultaneously or independently. After integration, the charges collected in the imaging (sensing) area are shifted rapidly into the storage area. While the sensing area is integrating the next field the signal charges in the storage area are read out line by line. After integration, the charges collected in the imaging (sensing) area are shifted rapidly into the storage area. While the sensing area is integrating the next field the signal charges in the storage area are read out line by line.

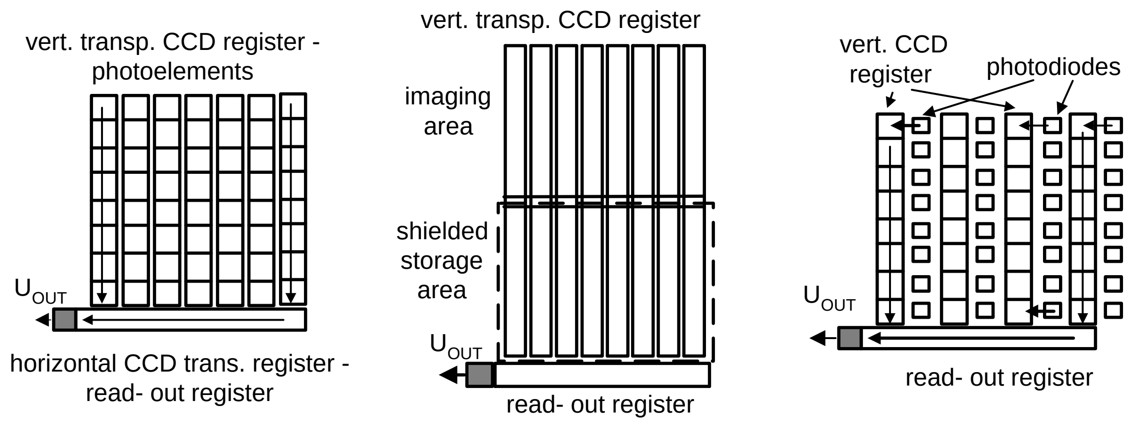

Figure 5. a) Full Frame sensor b) Frame transfer sensor c) Interline sensor

4. 3 Interline sensor

In the interline structure a separated, shielded vertical CCD register is needed along each column of sensing photodiode cells- Fig.5c. After the end of integration, the charges in the sensing cells are transferred into the vertical CCD shift registers in parallel. While photosensors are integrating the next field, the vertical shift registers transfer charges into the horizontal read -out register one line at a time.

5 PREPROCESSING OF SIGNAL IN CCD SENSOR

Two or three phase CCD shift registers are used in line and array sensors. The principle of two phase CCD shift register is on Fig.6. The P-type implant causes the asymmetry of potential well which forces the charge to flow towards the charge detector.

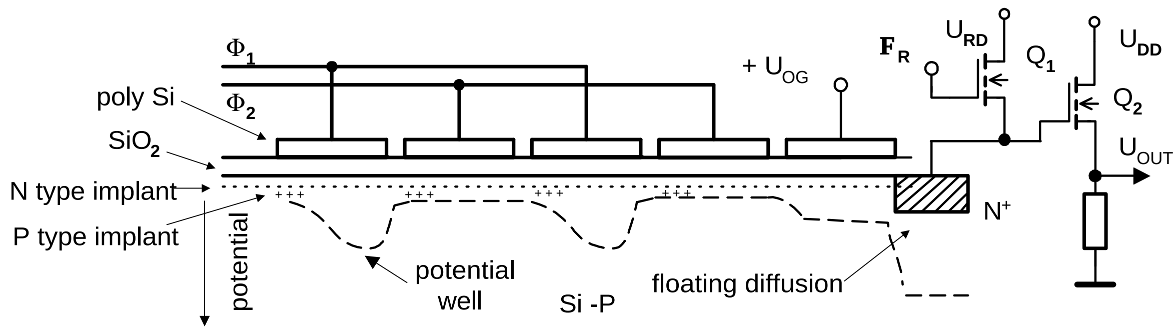

Figure 6. Read out register and charge detector

The charge detector is represented by negatively biased PN junction (floating diffusion). The charge detector is reset to initial state by a positive pulse F_R applied to a gate of Q_1 in time interval t_1 to t_2 -Fig.7. The feedthrough of this pulse is visible on waveform of signal. The voltage U_R corresponding to a dark level of signal appears on the output of detector since time instant t_2.

Charge pocket proportional to exposition of photoelement is transferred to a charge detector on falling edge of signal F_2 in time instant t_3. The voltage on the floating diffusion drops by value U_v to the level of U_{SIG}. The voltage from charge detector is then transferred to the output of via voltage follower. The output voltage has waveform of negative pulses with amplitudes proportional to exposition of individual photoelements superimposed on a constant positive level. For further application is necessary to use sampling. Some CCD sensors already contain internal sampling and hold unit.

5.1. KTC noise and correlated double sampling

The output signal of CCD sensors is composed from signal proportional to exposition and noise. The noise has following components: noise of output amplifier, noise of dark current and noise caused by reset signal (reset noise). The reset noise arises in charge detector as the result of periodical charging of capacitor through a resistor R_{ON} which represents the equivalent resistance of transistor *Q1* in ON state.

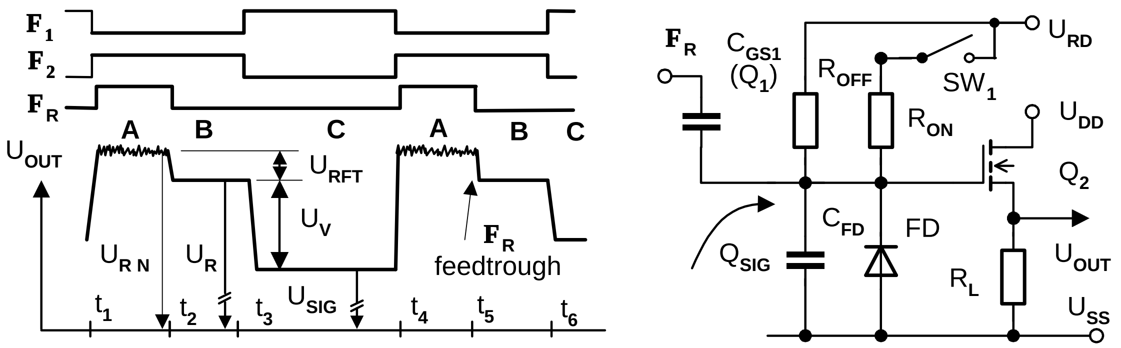

Figure 7. The function of charge detector

The value of thermal noise of R_{ON} at the time when switch SW goes OFF is frozen on C_{FD}. The parasitic capacitance C_{GS1} when SW is OFF causes feedthrough of reset clock and drop of level to the value of U_R at t_2. The RMS value of noise voltage U_{nkTC} on C_{FD} is given by Equ. (1). For further calculation is more suitable to express noise in number of noise electrons n_{KTC} as given by Equ. (2).

$$U_{nkTC} = \sqrt{\frac{kT}{C_{FD}}} \qquad (1)$$

$$n_{kTC} = \frac{\sqrt{kTC_{FD}}}{q} \qquad (2)$$

Where k is Boltzman´s constant, T - absolute temperature, C_{FD} - capacity of floating diffusion, q - charge of electron. Number n_{KTC} is typicaly 100 - 300 (RMS).

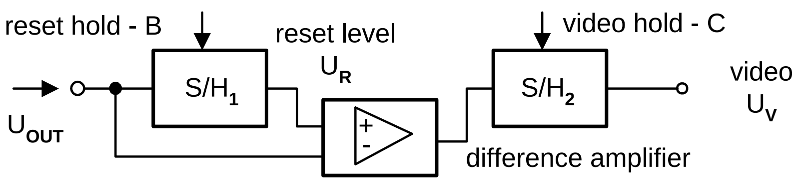

Figure 8. Correlated double sampler

Simple sampling of voltage during interval *C* between t_3 and t_4 would not avoid the influence of reset noise. The remedy is application of Correlated Double Sampling (CDS) performed by the circuit on Fig. 8. The sampling circuit SH_1 samples reference level U_R in the time period B. Difference amplifier inverts the signal and amplifies the difference U_R - $U_{OUT.}$ Second sample and hold circuit SH_2 samples this difference (U_V). On the output of CDS circuit is sampled videosignal with positive polarity which can be amplified and converted to digital form.

5.2. Noise of CCD sensor

Noise of the output signal is combination of noise of output amplifier, rest noise, noise corresponding to limited charge transfer efficiency, noise of dark current and photon noise.

Photon noise - The emission of photons from any source is a random process. The number of photoelectrons collected in a potential well in time *Dt* is therefore a random variable. The standard deviation of this random variable is the photon noise. Since the statistics for the emission are Poisson, the standard deviation equals the square root of the mean value- lit. [3].

The number of noise electrons n_{nPH} is given by relation (3). The photon noise is the most important source of noise which affects signal to noise ratio in CCD cameras. The maximum value of N_{PH} is usually from 50 000 to 200 000.

$$n_{nPH} = \sqrt{N_{PH}} \quad (3)$$

Dark current noise -The thermal generation of electrons in the semiconductor is a random process with Poisson distribution - lit. [4]. The number of noise electrons n_{nD} corresponding to dark current can calculated from total number N_D again by formula (3).

MOS amplifier noise - There exist various noise sources in the MOS amplifier. Their influence is again expressed in number of noise electrons n_{AMP}. The total noise signal of CCD sensor expressed in number of noise electrons n_n can be found from relation (4).

$$n_n = \sqrt{n_{nD}^2 + n_{nPH}^2 + n_{AMP}^2 + n_{kTC}^2} \quad (4)$$

The additional noise components in CCD camera can be caused by control logic circuits and eventually by other electronic circuits included in camera.

$$DR = \frac{U_{sat}}{U_{nRMS}} \quad (5)$$

Dynamic range - *DR* of an CCD sensor is given by (5), where U_{sat} is output voltage of sensor in saturation and U_{nRMS} is noise voltage of sensor measured at dark. Dynamic range of CCD sensors is in order of 1 000 up to 3 000. For low level of radiation intensity prevails the components of intrinsic noise of CCD sensor (dark current noise, amplifier noise...). When exposition increases the influence of n_{PH} becomes more and more important. The signal to noise ratio of CCD camera can not exceed the theoretical limit given by expression 20 log n_{PH}, i.e. approximately 50 dB.

The choice of resolution of A/D converter according to dynamic range DR of CCD sensor allows to process even signals comparable with intrinsic noise of CCD sensor. The influence of noise can be then reduced by averaging. The photon noise could act as additive dithering signal and could be eventually used for improving of resolution and differential nonlinearity of A/D converter assuming that its value is grater then quantum level of converter.

6 THE CIRCUITS FOR PROCESSING AND DIGITALISATION

On Fig.9 is a block diagram of circuit for the processing of output signal from CCD line sensor. The monolithic analog signal processor/digitiser is designed to interface the linear charge-coupled device (CCD) image sensors in scanner applications. The input allows direct ac coupling of the linear CCD.

The CCD signal processor performs the analog processing functions necessary to maximise the dynamic range, correct various errors associated with the linear CCD sensors, and then digitise the results with an on-chip A/D.

It contains 3 input channels for individual colour components of trilinear CCD sensor. On the input is clamping circuit followed by CDS block, programmable gain amplifier, multiplexer which switches signal from individual channels to a common A/D converter. The resolution of A/D converter is usually 8-12 bits, the rate of output data flow is from 6 to 12 Ms/s.

The 2D array CCD sensors are used predominantly in TV cameras working according to CCIR (black and white), or PAL (colour) standard. The duration of active reading of a TV line is 52 µs. The output signal in individual lines of B/W camera is due to sampling and filtration continuos. For subsequent digitalisation is required only clamping circuit, amplifier and A/D converter. In case a digitiser is not working synchronously with circuits for controlling of read out register in CCD sensor, the frequency of sampling signal could be chosen with respect to requirements of other digital circuits.

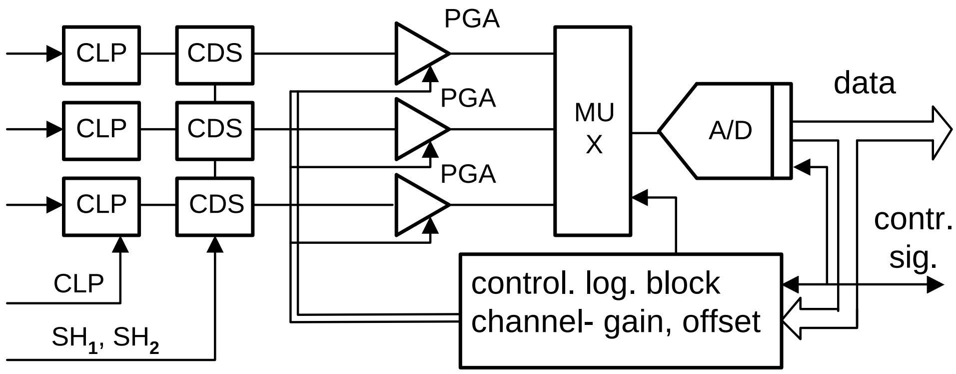

Figure 9 CCD signal processor

In order to fully employ resolution N_{PIX} pixels of CCD sensor in horizontal direction and to avoid aliasing the minimum sampling frequency should be chosen according the relation (6). The sampling frequency for CCD sensor with 768 x 576 should be 14,8 MHz.
The digitised picture from CCD TV camera can have number of samples which differs from the number of pixels of CCD sensor itself.

$$f_{samp} = \frac{N_{PIX}}{52\,\mu s} = 0{,}0192\,.\,N_{PIX}\;[\;MHz\,] \qquad (6)$$

In a specialised CCD array cameras and digital photocameras (and always at line scanning cameras) the sampling signal of A/D converter is synchronous with a signal which controls the read out register. The number of samples corresponding to a digitalisation of one picture from CCD sensor is identical to a number of photoelements (pixels) of sensor.
The sampling frequency depends on application. For special digital cameras used in astronomy the sampling frequency could be in order of tens to hundreds kHz. The sampling frequencies for digital cameras are in range of 1 to 20 MHz. Typical integrated analog front end circuits for CCD area sensors can process and digitise CCD output videosignal up to sampling rate 20 or even 30 Ms/s.

7 CONCLUSION

The digitalisation of video signals from CCD cameras and their record or storage is becoming more and more important due to the rapid development of digital photography and Internet. This segment of a market is a driving force of development of high speed A/D converters as well as complete CCD processors. The sampling frequencies used for A/D converters are usually in range of 15 to 30 Ms/s with resolution between 8 to 12 bits. In case of line scan CCD sensors the required resolution can reach up to 12- 14 bits.

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