R34: LARS II – A High Dynamic Range Image Sensor with a-Si:H Photo Conversion Layer

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Abstract

The rapidly growing market of industrial and automotive vision systems demands for image sensors with very high dynamic ranges of more than 100dB. State of the art linear imagers are not capable of delivering this signal range at standard video speeds while sensors with logarithmic signal compression suffer from high fixed pattern noise, low contrast and excessive temperature drift. The newly developed locally autoadaptive image sensor LARS II (**L**okal-**A**utoadaptive**R** **S**ensor) with its 100.000 pixels is able to deliver 120dB with linear signals by splitting the total dynamic range into a time information and an integration signal. The LARS employs the TFA technology where the optical detector made of amorphous silicon is deposited on top of the CMOS ASIC, providing a fill factor of nearly 100%. Sample images taken with the LARS from scenes with high contrast show the power of the local autoadaptivity to cope with high dynamic ranges.

Introduction

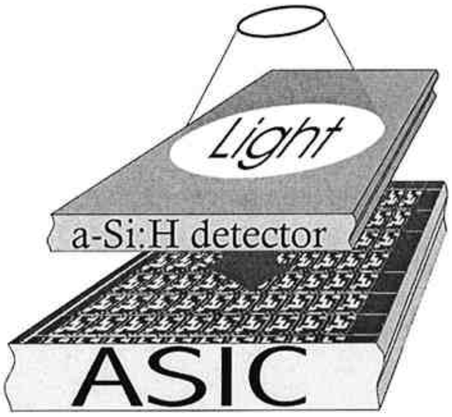

Fig. 1 Principle of TFA technology

Optical sensor arrays are key components in the rapidly growing market of vision systems. In order to fullfill the industrial needs for additional functions and performance, especially for high dynamic ranges, new generations of image sensor systems-on-a-chip are demanded. With state of the art CCD sensors it is hard to handle higher dynamic ranges in a linear signal under the harsh environment of most industrial applications. Lately, CMOS image sensors have entered competition, offering significant advantages over conventional CCDs, such as random access mode, individual pixel processing and an improved dynamic range for sensors that make use of a logarithmic signal compression. However, these sensors suffer from excessive fixed pattern noise (FPN) and temperature drift. Furthermore CMOS and CCD technologies are limited in fill factor since optical detector and circuitry share the same chip area.

TFA (Thin Film on ASIC) technology overcomes this drawback with the three dimensional integration of an amorphous silicon detector on top of a crystalline ASIC. The vertical integration of the device provides a fill factor of nearly 100% for both the detector and the underlying pixel circuitry [1]. Furthermore the pixel circuitry and the optical detector are separately designed and optimized for handling strong illumination conditions in natural scenes [2]. Fig. 1 illustrates the basic structure of a TFA imager. The detector is formed by an a-Si:H thin film system which is sandwiched between a metal rear electrode and a transparent front electrode. The crystalline ASIC includes the corresponding pixel circuitry underneath each detector and further the necessary peripheral circuitry for addressing and reading out the imager. The following chapters investigate the demands for high dynamic range images and describe the autoadaptive concept as the solution, its technical realization and the performance measured on the LARS II imager.

High Dynamic Ranges and Local Autoadaptivity

Under real world conditions, video cameras currently are not capable of providing satisfactory images under all conditions. Changes in illumination level account for the extremely large dynamic range encountered in many natural situations; the illumination level on a clear sunny day can vary by a factor of more than 100 from outside to inside a tunnel for example. This 40 dB illumination level difference combined with the 48 dB of desirable contrast resolution defines a requirement of roughly 90 dB of minimum dynamic range. Standard image sensors have technology inherent dynamic ranges of slightly more than 70 dB. And since this entire range is covered throughout a single frame, global sensitivity control is ineffective, since saturation as well as signals below the noise level may occur simultaneously.

A common concept for very high dynamic range image sensors exploits the compressing nature of the logarithmic voltage-current response of diodes where the photocurrent of a photodiode is fed into a second diode which may be a bipolar diode or a MOS transistor in diode configuration 3. The voltage response V across the diode is logarithmically compressed with regard to the photocurrent I:

$$V = n\frac{kT}{q}\ln\left(\frac{I}{I_0}+1\right)$$ (k: Boltzmann´s constant, T: Temperature, n: Diode factor, q: Electron charge, I_0: Reverse saturation current)

This voltage is usually read out through sourcefollower type signal chains. Logarithmic sensors may seem favorable since they require only three transistors plus one photodiode per pixel and the compression easily fits 120 dB of intensities into a voltage range of a few hundred millivolts. However, there are some major drawbacks which must be considered. First, these devices are especially susceptible to CMOS inherent fixed pattern noise, since a minor pixel-to-pixel variation in output voltage leads to an exponentially amplified difference in the reconstruction of the photocurrent. Self-offset reduction schemes such as correlated double sampling, however, cannot be applied since there is no reset level per pixel which may be subtracted for reference. The only successful fixed pattern noise reduction scheme to date is the off-chip compensation by means of storing the per-pixel conversion characteristics into a memory and stripping the pixel-to-pixel variations in a signal processor. However, the output signal is strongly dependent on temperature, which also has an exponential influence on the intensity information. Therefore off-chip fixed pattern compensation schemes must include this temperature effect. Finally, the transient response of logarithmic sensors proves to be very poor at low light intensities due to an unfavorable relation of photocurrents to load capacitance.

The LARS II (**L**okal-**A**utoadaptive**R** **S**ensor) image sensor overcomes these disadvantages by splitting the total dynamic range into two uncompressed signals each with moderate dynamic range. Since both signals are stored on in-pixel capacitances self-offset-correction schemes such as correlated double sampling (CDS) can be applied which effectively reduce FPN and temperature drift. The important feature of the LARS imager is the ability of the pixels to adapt themselves to the local illumination conditions: Every pixel optimizes its integration time to make best use of the available voltage swing without saturating [4].

The function principle of the LARS II can best be understood when looking at the block diagram and timing chart of Fig. 2 and Fig. 3, respectively. The photo current I_{ph} is integrated to a voltage V_{signal} on the integration capacitance. This voltage is compared to a fixed reference voltage V_{comp} at discrete points in time (rising edge of Clock). If the pixel voltage has exceeded this reference level, integration is terminated to avoid saturation. Otherwise the integration time is doubled to make better use of the voltage swing. In this way the integrated voltage is always within the range of V_{comp} to $2\bullet V_{comp}$ for higher illumination levels.

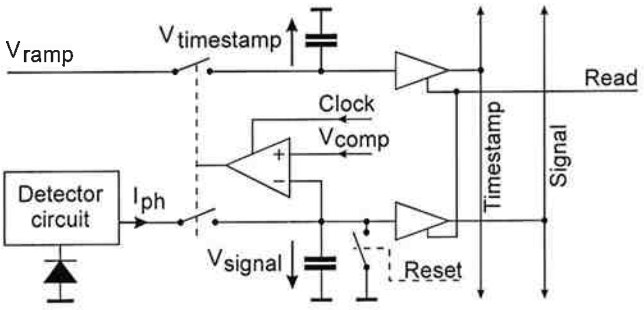

Fig. 2 Block diagram of LARS pixels

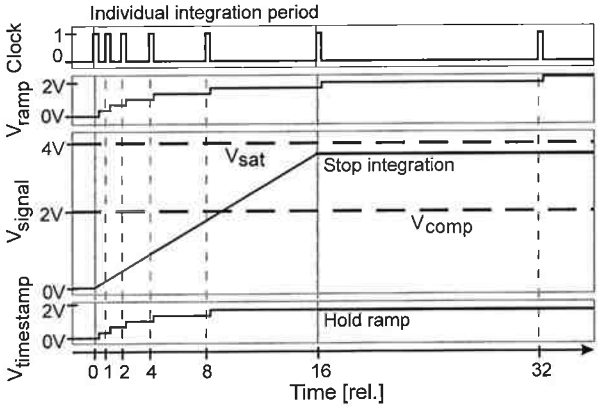

Fig. 3 Timing of LARS image sensors

In order to determine the chosen integration time, a voltage ramp V_{ramp} that ramps up one step after every comparison is applied to all pixels. If a pixel stops the integration it stores the actual value of V_{ramp} as a timestamp information. The value of this voltage allows the signal processor to determine which integration period the pixel had chosen. Most economically the integration times are in a powers of two series, reducing the effort for clock generation and signal processing.

Both values, the timestamp and the integrated signal are read out during the following readout phase. The absolute intensity value is split into these two signals, an absolute time information (T) and intensity information (I) relative to the time information. Low cost components (e.g. 10bit ADCs) may be used for the processing of these signals and still dynamic ranges beyond 100dB are possible. For example 60dB linear intensity range (10bit) and a 10ms/10µs time range (60dB, encoded as 10 different time steps into a 4 bit signal) yield 120dB total dynamic range.

For clarity the two output signals of the LARS are plotted against input intensity semilogarithmically in Fig. 4. For low intensity the integrated value ramps up; but before saturation is reached the integration time is halved, represented by the first step in the time stamp, and integration value ramps up again from half to full signal. The multiple folding characteristic allows the top half of the signal range to be used multiple times. In contrary, the logarithmic response curve (also Fig. 4) uses the signal range only once. For comparison of the input referred signal to noise ratios in Fig. 5, identical illumination and integration time independent chip noise components were asssumed while photon noise is disregarded. Due to the nature of the exponential back-transformation of output noise to input noise equivalent signal the signal to noise ratio remains constant over the whole illumination range. In contrary, the SNR of the LARS rises from 0 to the full signal range as for any linear sensor. Yet, at the foldover points the signal to noise ratio jumps down by 6dB, the sensor is half as sensitive now, and then ramps up these 6dB again.

Altogether the gray scale resolution of the LARS, represented by the input SNR, is superior to that of the logarithmic sensor for most of the illumination range except for the lowest intensities, where log sensors are prohibitively slow.

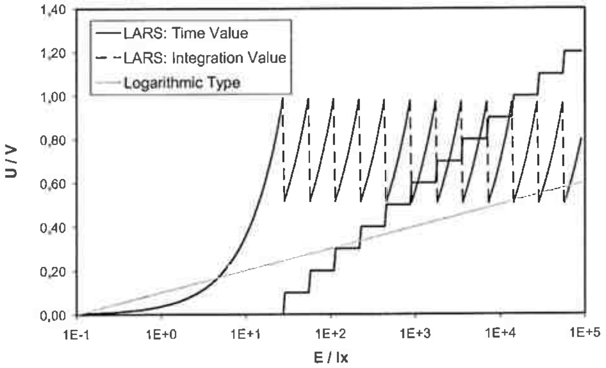

Fig. 4 Typical output signals of LARS sensors and log sensors

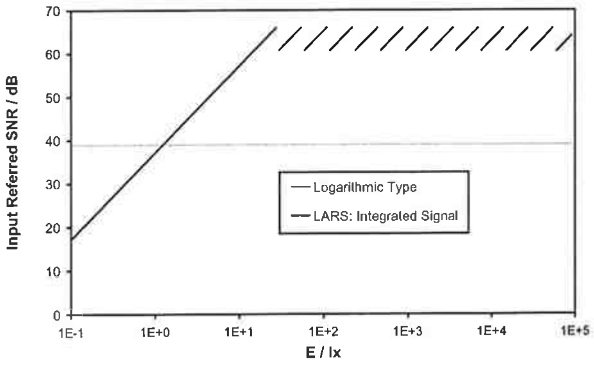

Fig. 5 Comparison of input referred signal to noise ratios

Design of Autoadaptive Sensor

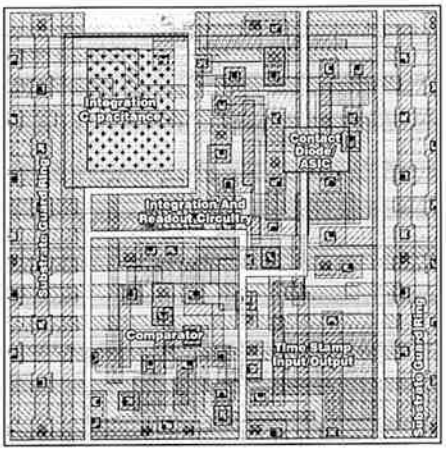

Fig. 6 Layout of the locally autoadaptive pixel

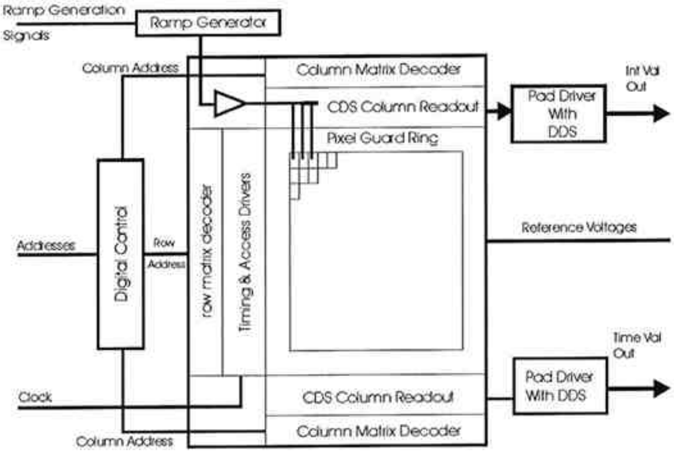

Fig. 7 Block diagram of the LARS II chip

The LARS II was implemented by Silicon Vision in a double metal double poly 0.8μm CMOS process for 5V. The pixels implement the autoadaptive functionality in 17 transistors and 2 capacitors. Fig. 6 shows the layout of one pixel with an area of 40μm x 38.3μm. The large integration capacitance yields a sensitivity of 0.47μV/e$^-$, while kTC noise is below 150μVrms and the light referred sensitivity is 3V lux^{-1} sec^{-1} or 24mV/lux after 8ms as calculated. Every pixel consumes 200nA, summing to 19mA per chip, sufficient to allow for 10μs as the shortest integration time. Power consumption may be reduced below 1mA for applications where 100μs are short enough.

Fig. 7 shows the block diagram of the imager. The column readout circuits employ capacitively coupled CDS. In this way, ASIC fixed pattern noise and 1/f noise components are suppressed effectively. Equivalently the column fixed pattern noise is reduced by a delta double sampling (DDS) circuit in the pad driver. The readout circuits consume 30μA per column, i.e. a total of 11mA for the column readout and 5mA per pad driver. This allows 10μs for row access and readout speeds of 14Mpix/sec with an accurate settling to 1% into 20pF load capacitance. The power consumption for the entire chip sums up to 50mA at 5V. Beside the pixel matrix and column readout the chip contains a ramp generator and some digital control functions. Both the column matrix decoder and the CDS column readout stages are repeated on top and bottom of the array due to the two output signals (integration and time signal) per pixel. The active area is 14.1mm x 10.24mm large while the chip has a total size of 16.5mm x 14.9mm.

Performance of LARS II Image Sensor

Measurements were carried out on the LARS II with white light at 50Hz frame rate and 3ms integration period. The noise floor is below 2mV$_{rms}$ whereas the full scale signal is 2V which is equivalent to 60dB of linear dynamic range. The pixel shutters work from as short as 10μs to 10ms or more of self chosen integration time which adds to a minimum of 120dB.

Fig. 8 through Fig. 12 demonstrate the performance of the LARS II autoadaptive imager. In Fig. 8 the integration time was fixed to 200μs whereas Fig. 9 shows the imager with fixed integration time of 3ms. The contrast in the scene is so high that no integration time is adequate to prevent overexposure or loss of detail in the dark regions. Fig. 10 and Fig. 11 show the integra tion image and timestamp image taken with the LARS II switched to autoadaptive operation. For lower intensities the integrated image looks like a normal grayscale image. However, for increasing intensities the integrated value switches back to

Fig. 8 High contrast scene captured with short integration time

Fig. 9 High contrast scene captured with long integration time

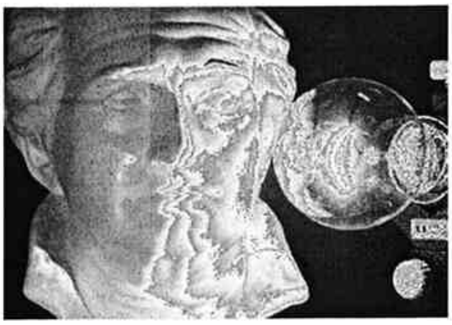

Fig. 10 The same image scene captured with the LARS II: integrated intensity information

darker values multiple times before saturating. The time image clearly shows regions of constant but reduced integration times (brighter is shorter) where the edges match the bright-dark transitions of the time image. Both images Fig. 10 and Fig. 11 where composed together to yield the reconstructed scene of Fig. 12. The detailed information in the dim and bright areas are clearly visible. The contrast had to be compressed by gamma correction to be able to see the full information in a paper print. The sharp image of the bulb filament shows the blooming resistance of the pixels.

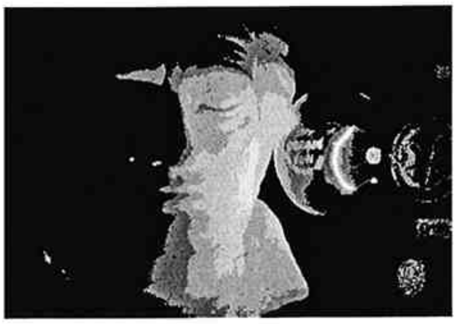

Fig. 11 The same image scene captured with the LARS II: discretized time information

Fig. 12 High dynamic range image reconstructed from time and integration information

Summary and Conclusions

Many vision applications require image sensors with very high dynamic range (>100dB) and blooming resistance at low cost. State of the art CCD and CMOS cameras with high dynamic range (up to 70dB) are very expensive and stress sensitive, whereas logarithmic sensors suffer from excessive, temperature dependent fixed pattern noise. The newly developed and fabricated locally autoadaptive image sensor LARS II with 368 x 256 pixels overcomes these drawbacks. The three dimensional TFA architecture provides a fill factor of nearly 100%. The independent optimization of the detector and the ASIC process makes the detector quality insensitive to impacts of CMOS device scaling effects like reduced quantum efficiency and sensitivity.

The important feature of the LARS imager family is the ability of the pixels to adapt themselves to the local illumination conditions: Every pixel optimizes its integration time to make best use of the available voltage swing without saturating. At the same time the total dynamic range is split into two signals, a time information and an intensity information, each with moderate dynamic range. The locally autoadaptive function was realized with 17 transistors and two capacitors per pixel in a 0.8µm 5V CMOS technology. Self-offset-correction schemes such as CDS and DDS are implemented. With a noise floor of lower than $2mV_{rms}$ and a full scale output signal of 2V the dynamic range of the intensity signal is 60dB. In combination with a range of integration times between e.g. 10ms and 10µs a total dynamic range of 120dB is achieved. This makes the LARS II an ideal solution for all vision systems that have to deal with high contrast scenes.

References

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