2.5 μm Pixel Linear CCD

Nixon O, Lei Wu, Melanie Ledgerwood, John Nam, Jonathan Huras

DALSA Inc.
605 McMurray Road, Waterloo, ON, N2V 2E9, Canada
Tel.: (519) 886-6001 x2248, Fax: (519) 886-5767, E-mail: nixon.o@dalsa.com

1. Introduction

Machine vision systems are constantly being pushed to inspect objects at higher spatial resolution. These systems are cost constrained to keep the total length of the imaging region below 65 mm. Sensors with imaging regions that are longer than about 60 mm require lenses that are costlier and are not readily available. This imaging region length constraint, along with the need for higher spatial resolution, has pushed the development of smaller pixel sensors.

The pixel sizes of successive generations of linear CCDs have historically decreased by a factor of the square root of two. Earlier generations of linear sensors have 14, 10 and 7 μm pixels. We reported 5 μm pixel linear CCDs in 2005 [1]. Currently, 3.5 μm pixel linear CCDs for color image scanners are available in the market [2]. We report the next step in this evolutionary trend, the 2.5 μm pixel linear sensor.

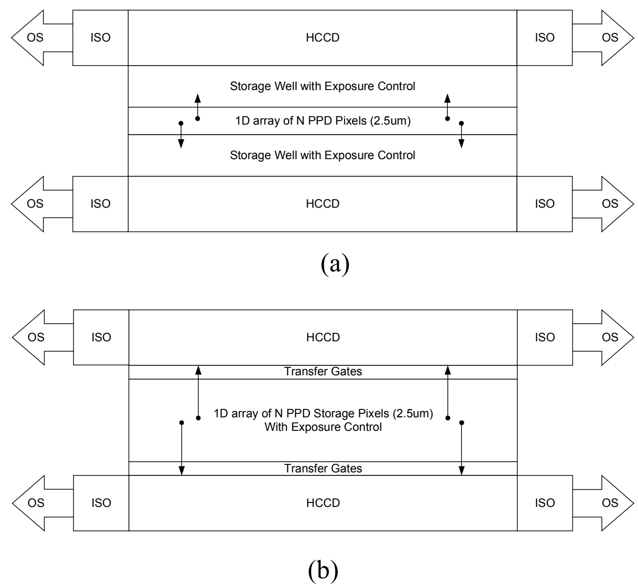
2. Sensor Architecture

We have fabricated and tested two variants of the 2.5 μm pixel sensor. The architectures of sensors are shown in Fig. 1. Alternate pixels or pixel blocks are read out using separate shift registers. Although Fig. 1 indicates four corner outputs, the sensor is fabricated in a CCD process that permits structural blocks to be stitched [3]. The blocks can be patterned during wafer processing to produce sensors of different lengths and with more outputs.

Although the 2.5 μm pixel sensor is functionally similar to sensors with larger pixels, there are a number of new considerations that arise in the new sensor.

3. Full Well and Antiblooming

The first consideration is the full well capacity. Unlike area imagers, reducing the pixel size in linescans does not necessarily result in lower full well. In linear sensors, photogenerated charges can either be stored in a storage gate adjacent to the photosensitive area (see Fig. 2) or stored in an elongated pinned photodiode (see Fig. 3). Both types of storage structures can be sized to store the same amount of charge as larger pixel sensors. Our 2.5 μm pixel sensor has a full well of at least 60,000 electrons. The 2.5 μm pixel sensor has the same full well as the 5 μm pixel sensor.



OS = Output Structure, ISO = Isolation Registers, HCCD = Horizontal CCD

Figure 1
Sensor Block Diagram with Two Pixel Variants (a) and (b)

Each of the two pixel structures has its advantages and disadvantages.

The storage gate pixel structure allows a more precise control of the full well capacity since the full well capacity can be adjusted using the storage gate bias. In applications where very high level of antiblooming (> 100x) is required, the pixel capacity can be reduced to increase the headroom between pixel saturation and the onset of blooming. The level of antiblooming can be adjusted by at least an order of magnitude using this method. The mere presence of an antiblooming drain does not automatically result in an arbitrarily high level of antiblooming because the charge draining capacity of the antiblooming gate and drain can determine an antiblooming limit. This limit is more evident in 2.5 μm pixels since the dimensions of the antiblooming drains are very small. As a result, the current density through the antiblooming drain can be quite high.

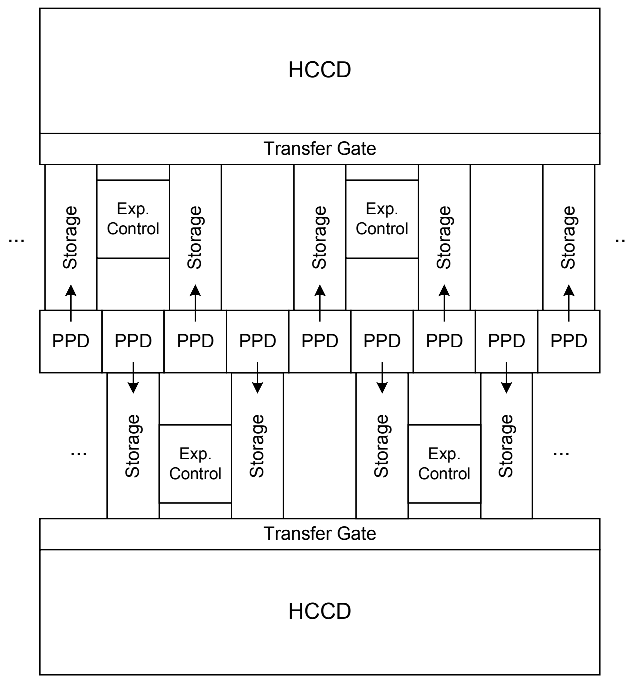


Figure 2
Block Diagram of the Storage Gate Pixel Structure

The pinned photodiode storage pixel structure has lower dark current and is more tolerant of exposure to high energy radiation. The full well capacity of this structure is fixed by geometry and by the channel potential of the pinned photodiode. To achieve at least 60,000 electrons of pixel capacity in a 2.5 μm pixel size, the pinned photodiode portion of the pixel has to be quite long. When charges are read out from the pixel, the charges move primarily because of charge diffusion. Because the diffusion time is proportional to the square of the distance, a larger full well results in a longer or an incomplete readout.

4. Exposure Control

Exposure control is important in many machine vision applications because it allows the number of signal electrons collected to remain constant while the web speed is ramping up or down, or when the arrival time of the object to be scanned is indeterminate. Because the exposure control and pixel transfer gates generate different fringing electric field distribution to the charge storage area, the two gates have different effects on traps in the storage area. These exposure control traps result in isolated pixels exhibiting nonlinear pixel response. The nonlinear behaviour cannot normally be removed by calibration or software correction.

In the new 2.5 μm pixel process, we made significant improvements to passivation and gettering steps in the fabrication process to minimize the number of traps. We have reduced the number of traps by at least an order of magnitude. The same processing steps have also yielded dark current levels that are lower by an order of magnitude.

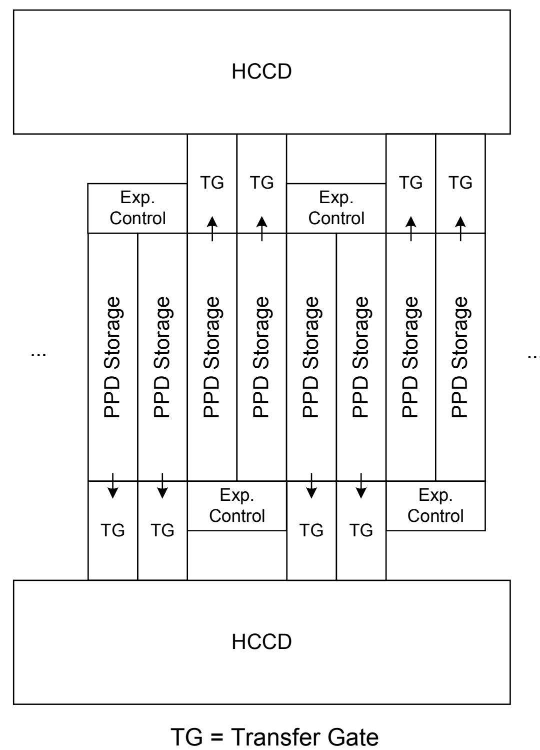


Figure 3
Block Diagram of the PPD Storage Pixel Structure

Exposure control traps can also appear as a result of pixel design, even without material non-idealities. The 2.5 μm storage gate pixel structure introduced unique design challenges since we had to incorporate a pinned photodiode photosite, a storage gate, an exposure control/antiblooming gate, an antiblooming drain, and a pixel readout gate in a very confined space. Each of these gates is affected by short and narrow channel effects, both of which become significantly more prominent at 2.5 μm pixel dimensions, where gate dimensions can be as small as 0.5 μm. We have carefully designed the pixel so that the short and narrow channel effects do not form unintended design traps in the charge transfer path.

5. MTF and QE

Linescans are normally fabricated in a relatively thick (15 to 20 µm) p- epitaxial layer grown on top of a p+ silicon substrate. Photoelectrons are generated throughout the p-epi. This thick charge generation region ensures good quantum efficiency in the red and near infrared. This is advantageous since the tungsten halogen bulbs commonly used in industrial inspection have significant red and infrared outputs.

The depletion region of the pinned photodiode does not normally extend much deeper than 5 µm from the silicon-oxide interface. Electrons diffuse randomly in the field free region underneath this depletion layer. The charge diffusion in the field free region of the epi results in the degradation of the modulation transfer function (MTF). Despite this MTF degradation, in 5 µm pixel sensors, the trade-off still favors thick epi because the effect in red and infrared sensitivity is large while the degradation in MTF is small.

In a 2.5 µm pixel imager however, the degradation in MTF due to charge diffusion becomes a lot more significant. We calculated the MTF for 650 nm illumination for 5, 3.5, and 2.5 µm pinned photodiode pixels with a 17 µm thick epi, using a model [4] that has been corroborated by measurements on a 5 µm pixel. The results are shown in Fig. 4.

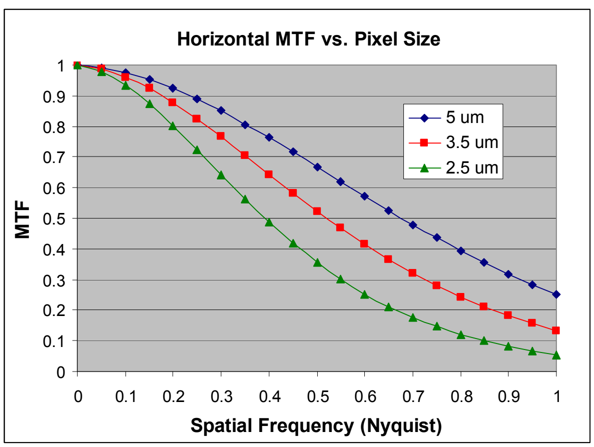


Figure 4
Linescan Horizontal MTF as a Function of Pixel Size

If we choose an acceptable MTF threshold of 30%, the 5 µm pixel is usable up to 93 lp/mm (93% of Nyquist), the 3.5 µm pixel is usable up to 103 lp/mm (72% of Nyquist), and the 2.5 µm pixel is usable up to 110 lp/mm (55% of Nyquist). These numbers suggest that there is no resolution benefit in using pixels that are smaller than 5 µm with a 17 µm thick epi. The spatial resolution benefit of a smaller pixel is negated by the degradation in MTF due to charge diffusion.

While it is theoretically also possible to improve the MTF of small pixels by increasing the depletion depth of the pinned photodiode using a more lightly doped epi, in practice, it is difficult to extend the depletion depth of the pinned photodiode without concurrently overextending the depletion region of the CCD photogates.

To bring the MTF of the 2.5 µm pixel back to around 30% at Nyquist, we have to limit the thickness of the field free region in the epi. We calculated that the epi of a 2.5 µm pixel should not be more than 5 µm thick.

The ratio of epi thickness to pixel size (17/5 = 3.4, 5/2.5 = 2) is smaller for smaller pixels. The pixel size dependence of the epi thickness required to achieve a minimum acceptable MTF is non-linear because the charge diffusion distance does not scale with pixel size. On smaller pixels, a higher percentage of photogenerated charges can diffuse to adjacent pixels.

A thinner epi will improve MTF but degrade the red and infrared response. The spectral response of a pinned photodiode pixel in 17 and 5 µm epi is shown in Fig. 5. The quantum efficiencies are calculated using a model that has been corroborated by measurements on 17 µm epi.

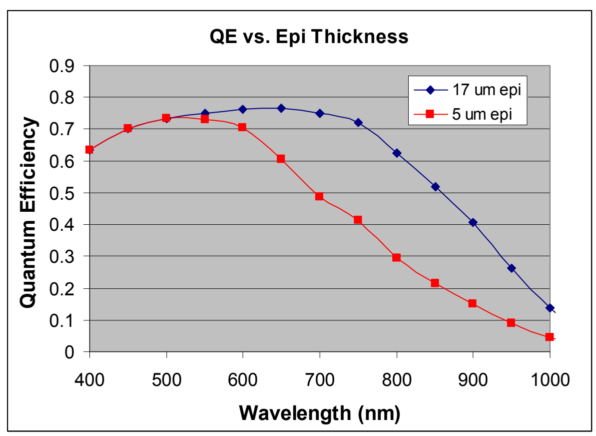


Figure 5
Spectral Response as a Function of Epi Thickness

The spectral response suggests that a transition to 2.5 µm linescan pixel needs to be accompanied by a reduction in the wavelength of illumination, perhaps through the use of high output LEDs.

6. Speed and Noise

Another important consideration is noise at high readout speeds. The odd and even pixels of the 2.5 μm pixel sensor read out in oppositely placed CCDs. As a result, the readout CCDs have 5 μm pitch. The 5 μm shift registers are two-phase CCDs with separately biased barrier and storage phases. The CCDs operate with 4.5V clocks.

Although the charge transfer efficiency of the sensor remains nearly ideal (> 0.99999) at readout speeds exceeding 60 MHz, we operate linescans at 40 MHz per output to strike a balance between noise, speed, electronic complexity, and temperature stability. Correlated double sampling becomes less effective at readout speeds that are greater than 40 MHz. In arrays with multiple outputs, crosstalk between outputs becomes more untenable at output speeds of over 40 MHz.

Machine vision systems have constantly pushed for faster inspection speeds, which we accommodate through the use of parallel outputs. Assuming no improvements in illumination, the increasing line rates will result in the push for lower readout noise.

One method of reducing the readout noise is by increasing the charge conversion efficiency (CCE) of the output node. While area CCDs have CCE's that routinely exceed 40 μV/e and CMOS imagers have CCE's with twice this value, machine vision linescans have CCE's that remain near 14 μV/e. This is mainly because the processes used to fabricate 60 mm long linescan arrays do not have the design rules necessary to achieve higher CCE. The use of a stitched process separated these two constraints and allowed us to break this barrier. We have achieved 18 μV/e in the new process and believe that a CCE between 20 to 25 μV/e is possible with optimization. While this number is admittedly below the state of the art for CCDs, it is the highest available in a high speed linescan CCDs. There are two factors that constrain the CCE in high speed linescans. The first is the large amplifier bandwidth requirement, which forces the dimensions of the input FET to be larger than the FET dimensions in slower speed devices. The second is p-epi substrate. Unlike processes with p-well on n-substrate, the substrate of the amplifier FETs cannot be connected to the source to mitigate the body effect. The body effect results in lower amplifier gain. We achieve an average readout noise of approximately 25 electrons rms at readout speed of 40 MHz.

7. Conclusions

We have successfully designed and fabricated a 2.5 μm pixel linear CCD. This represents the next step in the evolution towards smaller pixel sizes.

We discussed the various considerations and trade-offs associated with 2.5 μm pixel linescans, including the trade-off between full well capacity, antiblooming, and pixel readout duration; the need to consider short and narrow channel efforts in the exposure control structure; the system level trade-off between MTF, red quantum efficiency, and wavelength of illumination; and the trade-off between speed, noise, and sensitivity.

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