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12k 5 μm linescan CCD sensor with 320 MHz data rate

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Abstract

A linescan sensor suited for high image quality, high-resolution, high-speed imaging has been developed. The 12,288 pixel sensor has:

- 8 outputs each operating at 40 MHz to provide a high line scanning speed of 23.7 kHz,
- 5 μm pixels for shorter sensor length and simpler optical design,
- optimized pixel structure to maximize MTF (55% at ½ Nyquist) and minimize image lag (125 electrons),
- an exposure control and lateral antiblooming structure that does not produce imaging artifacts,
- 100% fill factor down to the deep UV (> 45% QE at 250 nm),
- highly linear output structures and amplifiers (<1% non-linearity),
- matched 3.3V 2-phase clocks, and
- output waveform shape that allows low noise and stable sampling at 40 MHz.

1. Introduction

Five years ago, we reported a 6,144 7 μm pixel linescan CCD sensor with a 160 MHz data rate [1]. The 6k pixel sensor was developed in response to demands from machine vision applications for higher resolution, higher speed, and better antiblooming and exposure control performance. At that time, this represented a generational increase over the 2k and 4k pixel cameras that were standard at that time. Since that report, the demand for higher resolution has continued as the push for a reduction in the number of cameras in multi-camera systems continues. To meet today's requirements, we developed the next generational advancement, a 12,288 5 μm pixel linescan CCD sensor with a data rate of 320 MHz and a scan rate of 23.7 kHz, with the antiblooming and exposure control capabilities required by machine vision applications.

The photograph and block diagram of the sensor are shown in Figs. 1 and 2. Measured specifications are listed in Table 1.

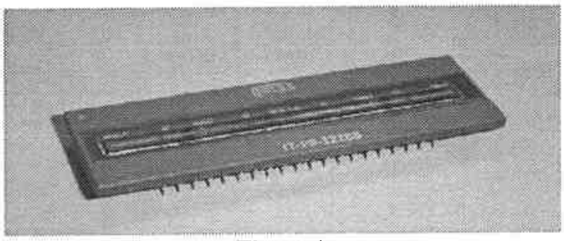

Figure 1.
Photograph of the IT-PB-12288
12K 5 μm 320 MHz CCD.

2. Device Details

2.1 Pixel

The 5 μm pixel pitch was chosen so that the aperture of the 12,288 5 μm pixel sensor is similar to the aperture of the 8,192 7 μm pixel sensor. This is an advantage, since lenses with good optical throughput, MTF, range of magnification, depth of field, and are reasonably priced have been available for 8,192 7 μm pixel linescan cameras for a number of years. In contrast to a 5 μm array, a 12,288 7 μm pixel sensor will require large lenses that push the envelope of lens technology. With lenses this large, one normally needs to trade-off performance for price. 4.7 μm linear array pixel pitches have been previously reported [2], [3]. However, they have fewer pixels, lack antiblooming and exposure control features, and do not achieve the scanning speed of this sensor.

The 5 μm pitch sensor was designed to achieve MTF performance that is close to the earlier generation 7 μm pixel sensor. We achieved this not by merely scaling down the 7 μm pixel features, but by optimizing the pixel implant parameters so that a greater fraction of charges are generated within the depletion region. Many machine vision applications require good infrared response (this sensor has a QE of 54% at 800 nm), which makes the task of optimizing MTF more challenging. The measured MTF is shown in Fig. 3.

The pixel is optimized so that image lag is close to being bulk trap limited. The exposed portion of the pixel surface is pinned, ensuring that surface states remain passivated and cannot contribute to lag. There are also no potential traps in the edges of the pinning implants that can contribute to lag. The image lag with blue illumination is almost the same as the image lag with green or red illumination. This confirms that traps in the silicon-oxide interface do not contribute significantly to image lag.

The 5 µm pixel sensor achieves the same photoresponse non-uniformity as the 7 µm pixel sensor, with or without the exposure control feature enabled. Unlike area arrays, this sensor is specified to have zero exclusion for pixel defects. The exposure control performance is worth noting because many sensors have inferior uniformity due to artifacts that can result from a poorly designed or a poorly manufactured lateral exposure control gate structure.

Despite having a smaller pixel pitch, the 5 µm pixel sensor has the same full well as the 7 µm pixel sensor, ensuring that photon shot noise performance can remain the same. A sensor with low levels of random noise when it is not illuminated has been reported [4]. However, this sensor has low full well and will be photon shot noise limited when illuminated.

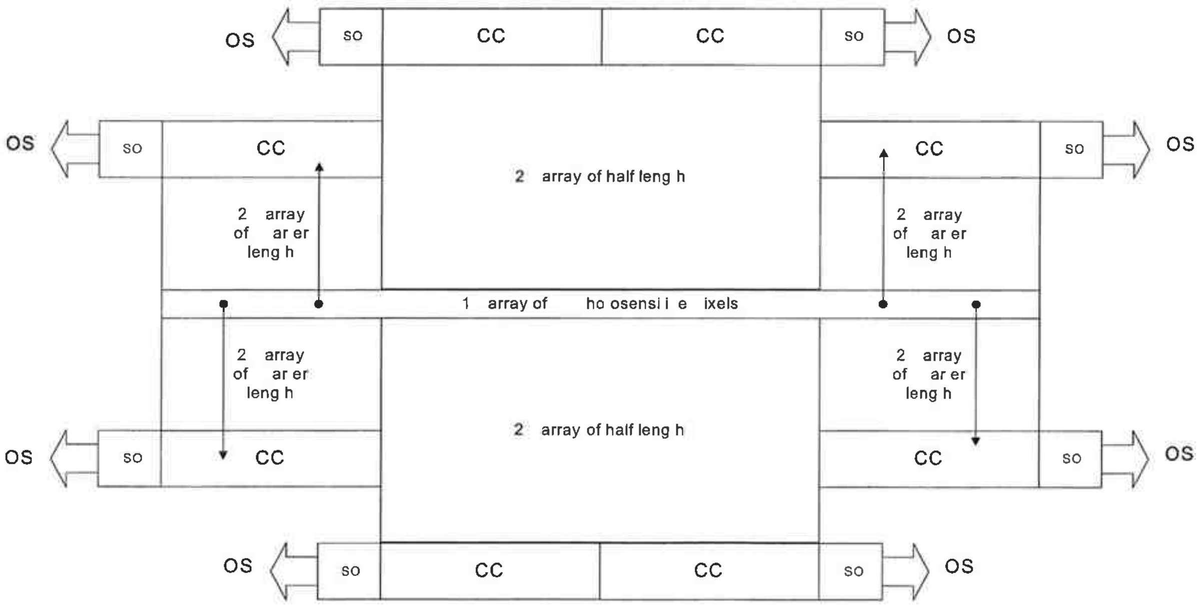

Figure 2.
Bi-directional Centre Tap Array Architecture.

Equally important is the fact that the 5 µm pixel sensor achieves the same level of antiblooming uniformity as the 7 µm pixel sensor. The uniformity of the onset of lateral antiblooming is important because a non-uniform onset will result in spatial variations in the level of antiblooming achieved.

2.2 Output Structure

The 320 MHz data rate is achieved through the use of 8 outputs each operating at 40 MHz; 4 placed in the traditional corner positions for a bi-linear linescan and 4 at central locations along the array.

The horizontal CCD can operate with 5V or 3.3V clocks.

The 62dB of dynamic range is achieved at the full 320 MHz data rate, after the outputs have been sampled by A/D converters. Many sensors are designed to achieve very low noise performance, but are unable to maintain the noise performance at high speed, because the lack of a stable sampling region in the analog video at high speed makes the sampled output susceptible to sampling jitter. The amplifier of this sensor has been optimally damped to maximize the sampling region in the analog video. Substrate noise is minimized through the appropriate routing of substrate current. Clocks signals are routed in the die with signal integrity considerations in mind to minimize the effects of signal feedthroughs and reflections.

An output structure and amplifier optimized for high sensitivity and high speed A/D sampling require a significant amount of chip area adjacent to the end of the horizontal CCD shift register. The use of vertical stages for the centre-taps secures the area required. The vertical stages employ delay gates previously reported in [5]. The delay gates are multi-pinned-phase (MPP) two-phase registers to allow high-speed bussing layout in a single metal layer and to keep dark current to a minimum. The vertical stages operate at a frequency of 3.3 MHz. To simplify image capture, the timing of the charge transfer has been implemented so that the charge related to a single common line from the image is clocked horizontally from the centre and outer taps simultaneously.

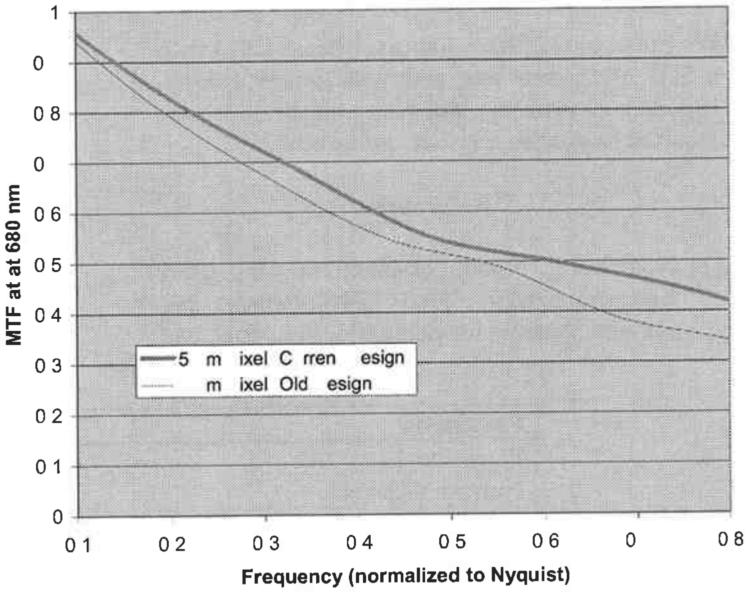

Figure 3.
MTF at 680nm.

3. Eliminating Seam Artifacts

Ideally, when the image is reconstructed from the eight output channels, the channel boundaries should not be visible. There are a number of artifacts that can produce visible seam boundaries. Minimizing these artifacts is particularly important for this sensor, since the start of the outputs of the centre taps correspond to pixels in central regions of the image.

Differences in gain and offset among the channels are not an issue, since DALSA cameras are equipped with per pixel gain (PRNU) and offset (FPN) correction.

Differences in linearity are an issue, particularly if different channels have different non-linear characteristics. The sensor has been designed so that not only is non-linearity less than 1% of saturation, the non-linearity of the difference between any two channels is also less than 1% of saturation.

Significant differences in analog waveform can result in non-linearity in the sampled output. The sensor is designed so that stable sampling regions are available at the maximum data rate of 40 MHz.

All outputs incorporate a number of isolation CCD cells between the output node diffusion and the first photoresponsive pixel. This allows the high-speed horizontal CCD clocks to stabilize before the first photoresponsive pixel is read out, ensuring that clock startup artifacts are not visible in the image. The use of the vertical delay gates in this sensor secures the area needed to incorporate these isolation CCD cells.

If the analog signal chain is not optimally damped, if there is spurious charge injection, or if charge transfer is not close to perfect, the output video will exhibit a non-ideal transient response. During dark to light transitions in the video, the first bright pixel can either droop or overshoot. When the sensor is exposed to uniform illumination, this first pixel droop or overshoot, if present, will be visible along the output channel boundaries. We have optimized the sensor design so that the first pixel of each tap has the same linear response as the other pixels, and so that any small deviation from the mean response is within the FPN and PRNU specification.

When present, non-ideal exposure control related artifacts are most noticeable as a highly non-linear response at very low signal levels (usually within the first 500 electrons of signal). This cannot be corrected by gain and offset correction and can be visible as mismatch between output channels at high camera gain, if different channels are affected to different degrees. This sensor does not exhibit this type of channel mismatch since there is near perfect charge transfer from the storage region in each pixel to both the exposure control and the pixel readout gates.

4. Conclusions

We present a 12,288 5 μm pixel linear CCD with a 320 MHz data rate and with image quality, exposure control and anti-blooming performance required for machine vision applications.

5. References

[1] N. O and C. Flood, "6k-pixel 160-MHz CCD Linescan Sensor", Proc. SPIE: Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications, vol. 3965, May 2000, pp. 50-57.

[2] NEC μPD8670A datasheet (http://www.necel.com/partic/display/english/ccdlinear/d8670a.html)

[3] Toshiba TCD1707D datasheet (http://www.semicon.toshiba.co.jp/openb2b/websearch/productDetails.jsp?partKey=TCD1707D)

[4] B. Fowler, J. Balicki, D. How, S. Mims, J. Canfield and M. Godfrey, "An Ultra Low Noise High Speed CMOS Scientific Linescan Sensor for Scientific and Industrial Applications," 2003 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors, May 15-17, 2003, Elmau, Germany.

[5] N. O, "Dual Linescan Architecture for High Responsivity and Low Photon Shot Noise," 2001 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors, Jun 7-9, 2001, Lake Tahoe, NV.

Parameter	Value
Pixel size	5 μm x 5 μm
Number of pixels	12,288
Number of outputs	8
Frequency of horizontal clocks	40 MHz
Pixel output rate	40 MHz x 8 = 320 MHz
Horizontal clock swing	3.3V
Line scan rate	Up to 23.7 kHz
Charge conversion efficiency	12 μV/e
Responsivity at 700 nm	7.6 V/(μJ/cm^2)
Quantum efficiency at 700 nm	71%
Responsivity at 400 nm	3.6 V/(μJ/cm^2)
Quantum efficiency at 400 nm	59%
Full well capacity	56,000 electrons
Saturation voltage	670 mV
Dynamic range	62 dB
Fixed pattern noise	8 electrons at 35°C
Global PRNU	12% of signal peak-to-peak
Local PRNU (8 pixel window)	6% of signal peak-to-peak
Exclusion pixels	Zero
Antiblooming	100x
MTF	55% at ½ Nyquist, λ = 680 nm
Image Lag	125 electrons average

Table 1.
Device Parameters and Measured Performance Characteristics.