HYPERSPECTRAL CMOS IMAGER

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I. INTRODUCTION

CCDs have been used for many years for Hyperspectral imaging missions and have been extremely successful. These include the Medium Resolution Imaging Spectrometer (MERIS) [1] on Envisat, the Compact High Resolution Imaging Spectrometer (CHRIS) on Proba and the Ozone Monitoring Instrument operating in the UV spectral region. ESA are also planning a number of further missions that are likely to use CCD technology (Sentinel 3, 4 and 5). However CMOS sensors have a number of advantages which means that they will probably be used for hyperspectral applications in the longer term.

There are two main advantages with CMOS sensors: First a hyperspectral image consists of spectral lines with a large difference in intensity; in a frame transfer CCD the faint spectral lines have to be transferred through the part of the imager illuminated by intense lines. This can lead to cross-talk and whilst this problem can be reduced by the use of split frame transfer and faster line rates CMOS sensors do not require a frame transfer and hence inherently will not suffer from this problem. Second, with a CMOS sensor the intense spectral lines can be read multiple times within a frame to give a significant increase in dynamic range

We will describe the design, and initial test of a CMOS sensor for use in hyperspectral applications. This device has been designed to give as high a dynamic range as possible with minimum cross-talk. The sensor has been manufactured on high resistivity epitaxial silicon wafers and is be back-thinned and left relatively thick in order to obtain the maximum quantum efficiency across the entire spectral range

II. DESIN REQUIREMENTS

A Hyperspectral sensor is effectively an array of many linear imaging devices each targeted at a different spectral band, as shown in Fig. 1. The satellite scans the ground with the spectrum from a narrow strip being split across the imager. The row data from the device then provides spatial information and the column data provides spectral information. Wavelengths of interest generally range from the ultra-violet to near infra-red. Hyperspectral imaging differs from multispectral imaging in that the entire spectrum is distributed across the device and may be divided into bands as required, whereas in multispectral imaging discrete spectral bands are viewed using separate linear arrays.

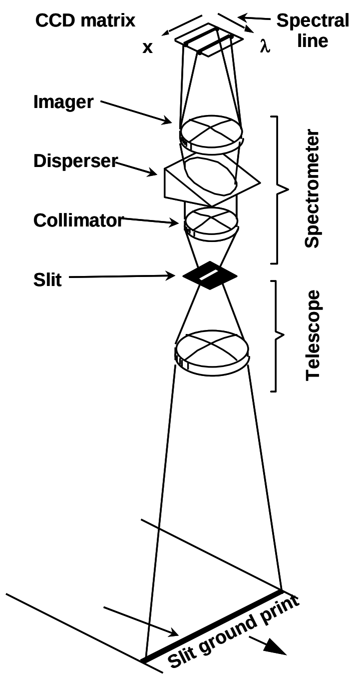
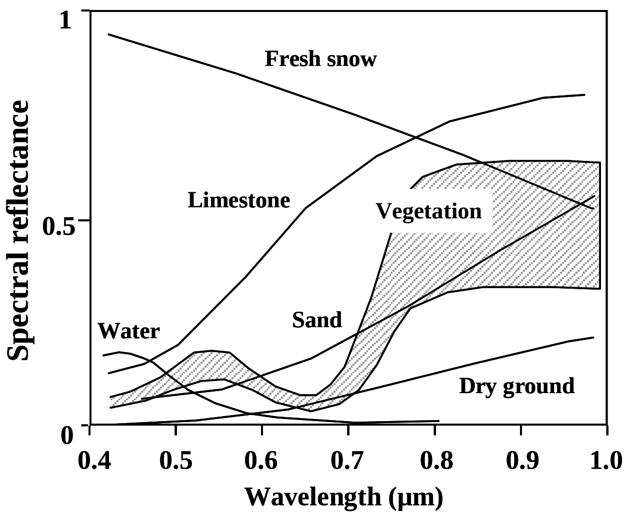


Fig.1. Schematic of Hyperspectral imager

The challenge for Hyperspectral imaging is that there is a large variation in intensity between the different spectral bands that may be defined across the spectral range, as shown in figure 2. This causes two significant problems; firstly the detector must be able to operate with a large range of signal intensities and secondly care must be taken to avoid cross-talk of the high intensity spectral bands with those which are less bright. This difference in intensities between the spectral lines becomes significantly more sever if shorter wavelengths are used (for example in Sentinel 4).

Additionally the spectral response of the detector also tends to be lower at the edges of the spectral band which gives a further increase in the ratio of the signal level obtained in different spectral bands A typical plot of quantum efficiency (QE) of silicon sensors are shown below in figure 3.

This difference in signals means that the device must cope with a large dynamic signal range and is therefore very susceptible to cross-talk. Cross-talk can have both optical and electrical components. The electrical cross-talk is a much less significant issue for CMOS imagers where there is no frame transfer required as part of the read-out process



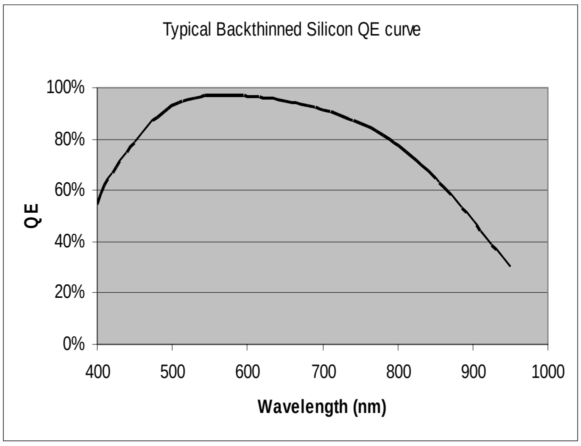


Fig.2. Ground Reflectance spectra. Fig.3. Typical Back-thinned Silicon QE curve.

II. DESIGN

The intention of this development was to produce a generic CMOS hyperspectral imager that could be readily adapted for different applications the main specification targets are as shown below. The design has been covered in detail before [2] and so only a brief description is included here.

Parameter	**Value**	**Comments**
Number of rows (spectral lines)	256	
Number of columns (spatial resolution)	1024	Any multiple of 512 columns can be made.
Pixel size	24 µm square	
Frame rate (full frame)	250 fps	Windowing can allow faster rates.
Windowing (ROI)	Spectral direction only.	Rows can be randomly selected.
Peak signal, "full well charge", Q_{FW}	100k or 300k electrons	Run time programmable, either global or row-by-row.

Shutter type	Global pipelined snapshot or rolling or row-by-row randomly addressed.	Snapshot gives best motion-stopping. Rolling shutter can include CDS to reduce kTC noise. Row-by-row allows both read-with-reset or NDR (non-destructive readout.
Charge to Voltage conversion gain at 100k electrons Q_{FW} setting	13 µV/electrons at photodiode.	10 µV/electrons at imager output pin.
Output type	Analogue	12 bit external ADC recommended.
Number of output channels	8	One output channel for each group of 128 columns.
Read-out Noise	~ 15 electrons $_{RMS}$	At 100k electrons setting with CDS.

A. Pixel design

There is some debate as to whether a global shutter is required for a hyperspectral CMOS imager. As the conclusion is somewhat unclear the pixel for this device has been designed to operate as a baseline in global shutter mode but with an option to run with CDS with a rolling shutter.

As a low cost 0·35 µm CMOS process was chosen for this imager, the snapshot shutter must be implemented by using switches and capacitors rather than a pinned photodiode and transfer gate. This leads to the use of two source followers in each pixel, in turn requiring a level shifter to give an output voltage range suitable to read the desired full-well through the analogue chain. The circuit of each pixel is:

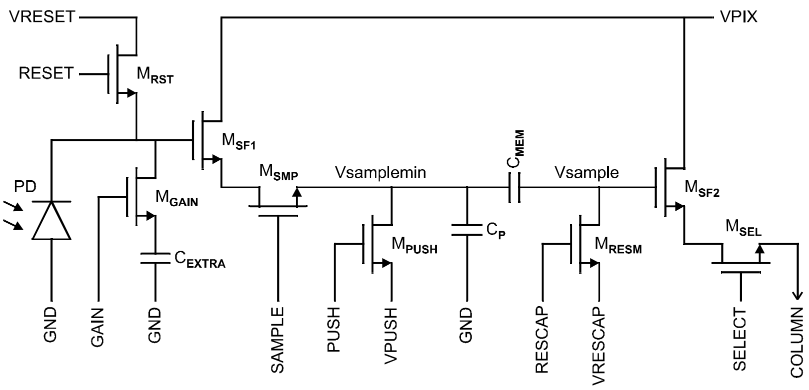


Fig. 4 7T (8T) pixel design

An n-well in p-epi diode is used for the photodiode PD and to give the choice of two conversion gains, extra capacitance can be added by setting GAIN to high to connect C_{EXTRA} in parallel with PD. This gives a 3 × factor on maximum charge and a ⅓ × factor on conversion gain. Each row of pixels has an individual GAIN signal to allow any pattern of high and low gain rows. All actions from reset, through integration to driving Vsample can be simultaneous on all pixels, giving a snapshot shutter. Levels will stay on Vsample nodes to allow a rolling readout of the stored image while the next image is integrating.

If preferred the pixels can be read in a rolling shutter mode by setting line-by-line operation of the pixel controls in place of global operation. This mode can include CDS to reduce noise.

In addition rows can be randomly addressed and so rows where the signal level is high can be read out at an increased frequency. For example the sensor could be operated with an overall frequency of 100Hz for faint spectral lines but at 500Hz for the most intense spectral lines giving a further factor of x5 (or more if required) in the ratio of the peak signal in different rows. When combined with the capacitance switch this would accommodate for a peak signal ratio of x15.

III MANUFACTURE

A. Wafer Fabrication

As the pixel size is relatively large and there is not high speed digital in the device this sensor was made using 0.35µm technology. In order to be able to obtain good quantum efficiency at the NIR end of the spectrum thick epitaxial silicon with a resistivity of approximately 1000Ω.cm was used for the device manufacture with standard 10Ω.cm. material as a backup. This enables the silicon to be depleted to a depth of greater than 10µm meaning that the overall thickness can give a QE close to what can be achieved with a CCD (made on standard material).

B. Back Thinning

CMOS sensors have already been successfully thinned [3] and these sensors will us a very similar process. Backthinning has started although results are not yet available. The 1000Ω.cm material has a starting thickness of 14µm and is being thinned to approximately 10µm. Samples of the backthinned versions of these devices should be available by the end of 2010. Pictures of a backthinned wafer are shown in Fig 5.

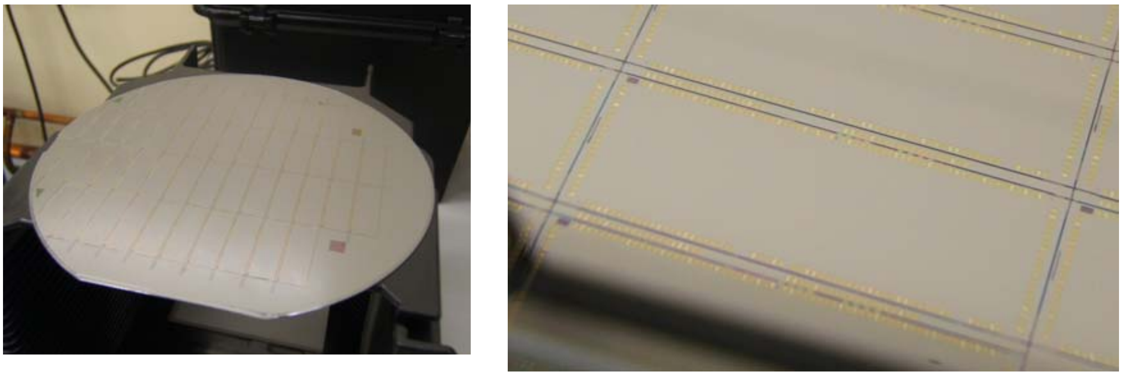


Fig.5. Backthinned Hyperspectral Wafer

C. Assembly

Devices have been assembled in simple PCB packages as the main objective of this programme is to determine the electrical and electro-optical performance. An image of an assembled device is shown in Fig. 6.

IV TEST

A custom test set has been manufactured with the control signals provided by an Altera FPGA through a Visual Basic interface. Data collection is carried out using Labview software via a Cameralink interface. The test set operates all 8 analogue channels in parallel at 11MHz each giving a total data rate of 88MHz to enable a maximum frame rate of 250Hz. The custom test board used to drive the sensor is shown in Fig 7.

Fig. 6 Packaged Hyperspectral Imager

Fig.7 Hyperspectral Test Board

V TEST RESULTS

Preliminary testing has been carried out and shows that the sensor functions to the design requirements. An initial image is shown in Fig.8 together with an image operating with the rows accessed in a non linear order in Fig. 9 to show the random access capability. These images so far are with front illuminated operation which is non-ideal as the sensor has a full mirror over the front surface to give maximum response when operated in back illuminated mode.

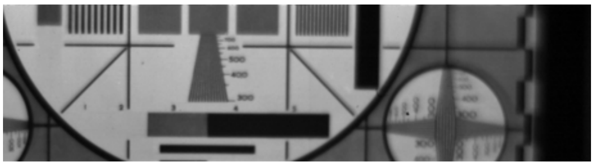


Fig 8. Chart Image.

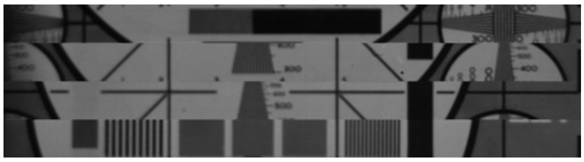


Fig.9. Chart image with “random” row access.

A dark frame shows a good uniformity with a Gaussian distribution (see Fig 10) with few defective ‘hot’ pixels. The total dark Signal Non Uniformity (DSNU) is approximately 9% of the mean dark signal Preliminary measurements indicate that the mean dark signal is approximately 100 electrons per pixel image at 250Hz and +20°C. Fig.11 shows a histogram from a flat field image (with dark image subtraction) to give an indication of photo response non uniformity (PRNU). As can be seen the total PRNU including both gain and photo response non uniformity has a standard deviation of 2.7%. As the front surface of the device is covered by a reflecting mirror giving very low detection efficiency this result seem surprisingly good.

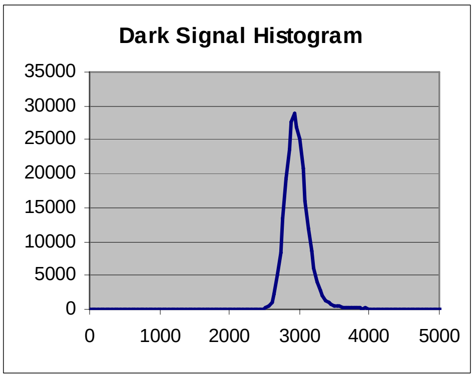


Fig.10 Dark Image Histogram

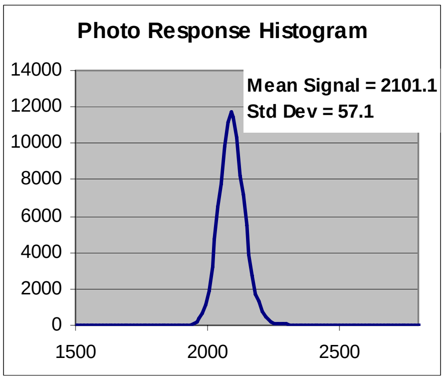


Fig.11. Photo Response Non-Uniformity

The variation of dark signal with temperature and with integration time is as expected for a non-pinned surface. Plots of dark signal variation with time are shown in Fig 12 at +20°C and +25°C. An increase of dark signal of 50% between these temperatures is as expected. Also note that at these signal levels the linearity appears to be reasonably good although detailed measurements of this have not yet been made. One count corresponds to approximately 1.8 electrons.

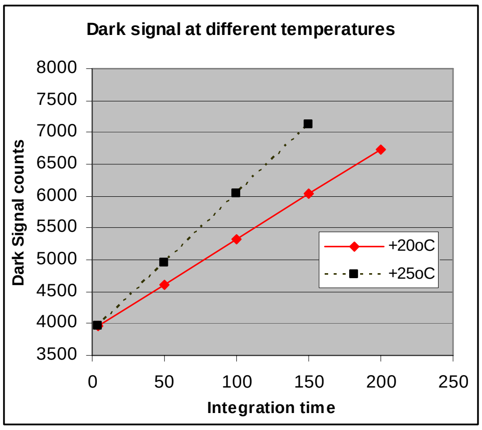


Fig.11. Variation of Dark signal with Temperature

VI CONCLUSIONS

A Custom CMOS sensor has been designed for Hyperspectral Imaging and shown to perform as expected although further characterization is required. It is anticipated that this type of sensor once fully proven will take the place of CCDs for Hyperspactral Imaging applications

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