A Wide Dynamic Range CMOS Image Sensor with Resistance to High Temperatures

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Abstract

A 1/4 inch VGA 5.6 μm pixel pitch wide dynamic range (WDR) CMOS image sensor with resistance to high temperatures has been developed using a very-low-dark-current front-end of line (VLDC FEOL), a metal hermetic seal package and/or the inorganic cap layer to suppress the degradation of the spectra response of the on-chip micro lens and color filter (OCML/OCCF). The dark current is reduced to 175 e^-/sec-pixel at 85˚C (25 e^-/sec-pixel at 60˚C) by the use of VLDC FEOL. Sensor chips with no cap and an inorganic cap onto the OCML were assembled into a metal seal package and a conventional package respectively. They were exposed to a 150˚C/ 500 hours thermal-stress test in the air. No degradation of the spectra response in any of R/G/B pixels for both samples is observed after the thermal stress test. The sample images captured by the WDR CMOS image sensor with and without the thermal stress show no significant degradation in image quality up to 85˚C. The image sensing performance results in a low noise and huge effective saturation voltage. The dynamic range is extended to 93 dB.

Introduction

A wide-dynamic-range (WDR) CMOS image sensor using a lateral overflow integration capacitor in each pixel demonstrated over-100 dB dynamic range (DR) in single exposure and over-200 dB DR in multiple exposures plus the current readout operation, keeping a high sensitivity and a high S/N ratio [1-4]. Automotive applications, for which this sensor best suits, require an operation temperature typically ranging from -40 to 85 ˚C or much higher. Security and medical applications also desire the extension of operation temperatures. In these hard conditions, especially at very high temperatures, the increase of dark current shot noise requires careful attention. Thermal decomposition of organic materials in the sensor chip and/or the package is also an issue. Several papers have reported dark current reduction approaches [5,6]. However a temperature-resistant image sensing solution has not been clearly reported as the discussion has just started [7]. This paper describes a WDR CMOS image sensor with resistance to high temperatures using a very-low-dark-current front-end of line (VLDC FEOL) and an inorganic cap on the on-chip micro lens (OCML) as well as a metal hermetic seal package to suppress thermal decomposition of both the OCML and the on-chip color filter (OCCF).

Dynamic Range Enhancement

Fig. 1 shows a pixel schematic circuit diagram adopted for the wide dynamic range solution. The pixel circuit consists of a fully depleted photodiode (PD), a floating diffusion to convert the charge to the voltage (FD), a charge transfer switch (M1), an overflow photoelectron integration capacitor (CS), a switch between the floating diffusion FD and the overflow capacitor CS (M3), a reset switch (M2), a source follower amplifier (M4) and a pixel select switch (M5). The basic concept in this pixel circuit is to use the switch M1 for a suitable overflow path of saturated photoelectrons and integrate overflowed photoelectrons in FD and CS during a charge integration period. The non-saturated photoelectrons are transferred from PD to FD and converted to the voltage as a high sensitivity low light signal (S1) as well as the conventional 4 transistors type CMOS image sensor. The dynamic range is extended by fully utilizing the photoelectrons integrated at and overflowed from PD for a bright light signal (S2).

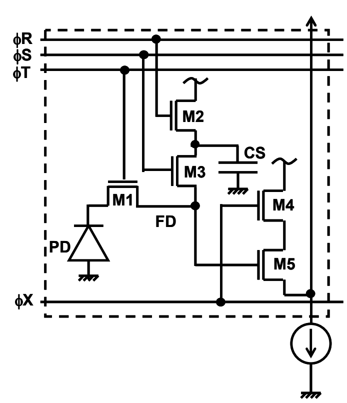

Fig.1 Pixel schematic of wide dynamic range (WDR) CMOS image sensor.

One of the advantages in this CMOS image sensor is high tolerance to reset noise and dark current in the signal S2 [4]. Since the signal S2 is a mixture of the non-saturated and the saturated overflow photoelectrons, the minimum number of photoelectrons in S2 is close to the number of the saturated photoelectrons in S1 for the case of S2 selected. Precisely speaking, the only N2 in the next frame (defined as N2') can be stored in the same horizontal blanking period, however the fixed pattern noise is removed by the subtraction of (S2+N2)-N2' in the same horizontal blanking period and a high S/N ratio can be realized in the region of S1/S2 switch. This noise reduction method offers the simple operation without the necessity of the off-chip frame memory.

In order to prove the shrink-ability of the WDR pixel concept, the pixel pitch is reduced from 7.5 μm (in the previous work) to 5.6 μm in this work. Fig.2 shows the chip micrograph of the 1/4 inch VGA 5.6μm-pixel-pitch WDR-CMOS image sensor fabricated through a 0.18μm 2P3M process.

Operation Temperature Range Extension

Very Low Dark Current Front End of Line

Very-low-dark-current (VLDC) approaches are implemented to the front-end of line (FEOL) of the 0.18μm 2P3M process. These include: the reduced plasma etching damage at the transfer gate formation, the modified channel doping profile under the transfer gate, the pinned photodiode with smaller electrical field and furnace temperature process for re-crystallization. Fig.3 compares the dark current of the VLDC FEOL and the conventional flow. Dark current is reduced to 175 e^-/sec-pixel at 85˚C (25 e^-/sec-pixel at 60˚C) by the use of the VLDC FEOL. The activation energy of the dark current for VLDC FEOL is about 0.62eV and should be the generation dominated.

Thermal Resistant On-chip Micro Lens & Color Filter

The chemical aspects of the thermal decomposition of the OCML/OCCF material (phenol resin) have been analyzed with a Fourier transform infrared spectrophotometer (FTIR) as shown in Fig.4. Fig.5 shows the CO_2 (2362 cm^{-1}) absorbance as the result of thermal decomposition in the varied O_2 concentration from 0% to 1% in O_2/N_2 mixed gases. It is also found that CO_2 over 100 ppb is detected at 222˚C for 1 % O_2/N_2, 237˚C for 1000 ppm O_2/N_2 and 282˚C for 100 ppm. No CO_2 over 100 ppb is found under 300˚C for the case of <10 ppm O_2/N_2. By preventing the OCML/OCCF from oxidation, the thermal decomposition is suppressed. In order to prevent the oxidative decomposition of the OCML/OCCF, two approaches, an inorganic (SiO_2 /SiN) cap onto the OCML and a metal hermetic seal package with low residual oxygen concentration in N_2 gas ambient are adopted. Fig.6 shows the schematic of the inorganic cap

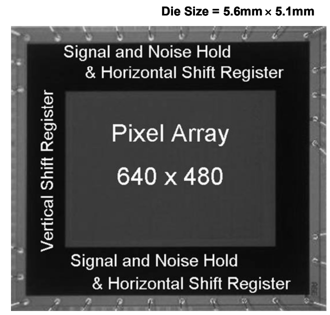

Fig.2 Chip micrograph of the 1/4 inch VGA WDR CMOS image sensor with 5.6 μm pixel pitch.

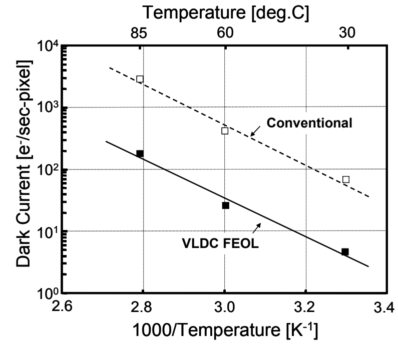

Fig.3 Dark current comparison between the VLDC FEOL and the conventional flows.

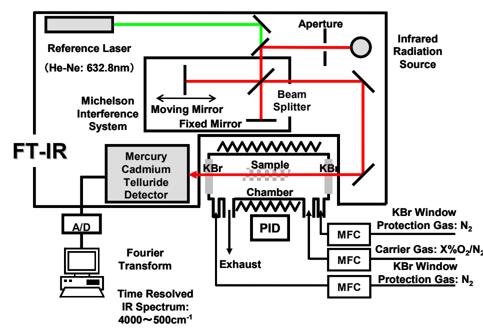

Fig.4 Schematic drawing of Fourier transform infrared spectrophotometer (FTIR).

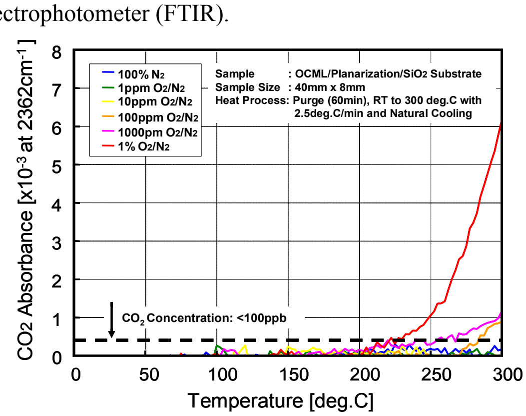

Fig.5 CO_2 absorbance measured by Fourier transform infrared spectrophotometer as the result of the thermal decomposition of the micro lens in O_2 (=0 to 1%)/N_2 ambient.

onto the OCML. In addition to the passivation effect, optical performance is taken into account to select the inorganic cap. The optical simulation results in improved quantum efficiency for the SiO_2 /SiN cap on the OCML, as shown in Fig.7. Sensor chips with and without the inorganic cap onto the OCML were assembled into a conventional package or the metal hermetic seal package, as shown in Fig.8. They were exposed to a 150˚C/ 500 hours thermal stress test in the air. Fig.9 shows the sensitivities of R/G/B pixels under a certain illumination, tested every 100 hours. The sensor chip under the thermal stress with the conventional package shows a drastic drop of sensitivity, especially in B/G pixels. However, the other two samples (the inorganic cap onto the OCML and the metal hermetic-sealed package) show no significant degradation of the spectral response in any of R/G/B pixels. The surface of the OCML is found to be protected from oxidative decomposition in both cases.

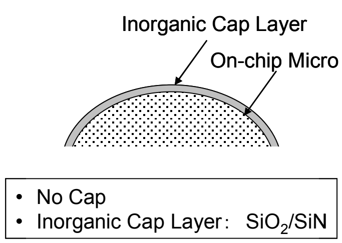

Fig.6 Inorganic cap layer onto on-chip micro lens.

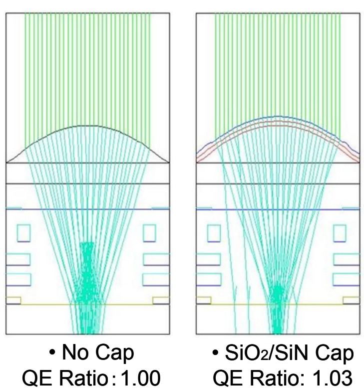

Fig.7 Optical performance of the inorganic cap layer to on-chip micro lens.

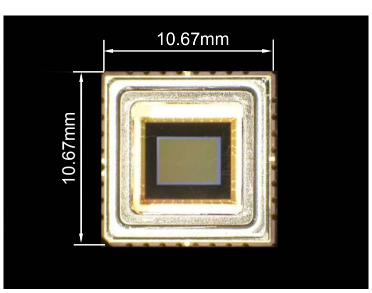

Fig.8 The WDR CMOS image sensor with the metal hermetic seal package.

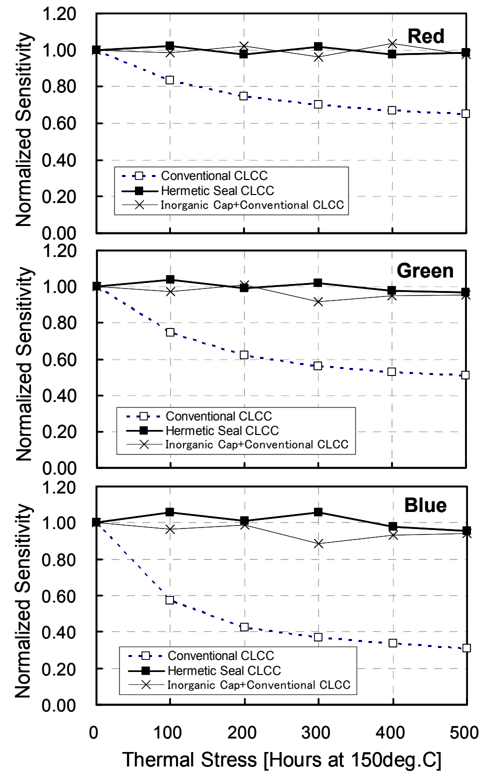

Fig.9 R, G and B sensitivities of the WDR CMOS image sensors with the hermetic seal package and the conventional package after the thermal stress test.

Image Sensing Performance

Fig.10 shows image samples captured by the temperature-resistant WDR CMOS image sensor with the metal hermetic seal package at 30, 60 and 85˚C before and after the thermal stress (150˚C / 500 hours). The WDR signal selecting either the non-saturated signal (S1) or the saturated overflow signal (S2) by pixel is reproduced and displayed as 8 bit resolution by applying the gamma correction ($\gamma \cong 0.15$) to 16 bit resolution data. The random noise is found to slightly increase as the temperature goes up, however no significant degradation of the image quality is observed even at 85˚C. Table 1 summarizes the image sensing performance of the temperature-resistant WDR CMOS image sensor with the metal hermetic seal package after 150˚C /500hours thermal stress test. The noise is 0.19 mV-rms, the effective saturation voltage of S2 is 8.8 V and the dynamic range is extended to 93 dB. The use of the metal hermetic package prevents the oxidative decomposition of the OCML/OCCF and leads to being thermally stable even after the thermal stress test.

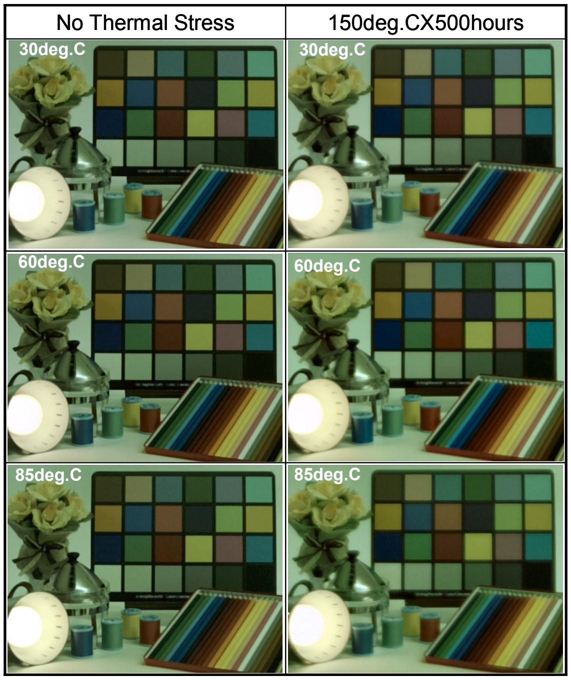

Fig.10 Image samples captured by no thermal stressed and 150˚C /500hours thermal stressed WDR CMOS image sensors with metal hermetic seal packages, at 30, 60 and 85˚C.

Table 1 Image sensing performance of the temperature-resistant WDR CMOS image sensor with the metal hermetic seal package (: after 150˚C /500hours).

Process technology	0.18μm 2P3M CMOS
Optical format	1/4 inch
Pixel size	5.6 x 5.6 μm^2
Number of effective pixels	640 x 480
Supply voltage	5 V
Frame rate	30 fps
Random Noise	0.19 mV_{rms}
Saturation of S1	700 mV
Saturation of S2	1100 mV
Effective saturation of S2 (saturation of S2 x 8)	8.8 V
Dynamic range	93 dB

Conclusion

The 1/4 inch VGA (5.6 μm pixel pitch) wide dynamic range (WDR) CMOS image sensor with resistance to high temperatures has been developed. The use of the very low dark current front-end of line (VLDC FEOL), the inorganic cap to the on-chip micro lens & color filter (OCML/OCCF) and the metal hermetic seal package enables the operation temperatures up to 85˚C. The VLDC approaches which include: reduced plasma etching damage at the transfer gate formation, modified channel doping profile under the transfer gate, pinned photodiode with smaller electrical field and furnace temperature process for re-crystallization achieves 175 e^-/sec-pixel of dark current at 85˚C (25 e^-/sec-pixel at 60˚C). The oxidative decomposition of the OCML/OCCF is completely suppressed, thus no significant degradation of the spectra response in any of R/G/B pixels is observed after the thermal stress test. The sample images captured by the WDR CMOS image sensor with and without the thermal stress test show no significant change in the image quality and keep a good noise performance up to 85 ˚C. The dynamic range is extended to 93 dB even after the thermal stress test.

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