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Test Methodologies for Digital CMOS Camera-on-a-Chip Image Sensors

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CMOS camera-on-a-chip digital image sensors contain not only an array of (active) pixels, but also bias generators, analog signal processing circuits, programmable-gain amplifiers, analog-to-digital converters, timing generators, interface control logic and other digital and analog functions. Compared to a CCD, the complex system-on-a-chip with a full digital interface makes assessing intrinsic image sensor performance more difficult.

In this paper, we discuss some methodologies that we have developed for testing of our digital CMOS APS sensors. Some of them are applicable in sensor characterization, and others in large volume production testing. We will also present our digitally programmable light source, whose excellent linearity (to within 1% over three orders of magnitude), spatial uniformity (within 1% over several cm^2), and other interesting features prove very useful in both sensor characterization and production testing.

Since digital image sensors are a new entity in the marketplace, another purpose of presenting this paper is to define some new terms and measurables that are germane to sensors with on-chip ADCs. These measurables, for example, include digital responsivity (bits/lux-sec) as a function of on-chip gain, digital noise, digital dynamic range, etc. While characterization of a CMOS camera-on-a-chip is not so different from that of a CCD imaging system including an ADC, the limited resolution of on-chip ADCs and their imperfections complicate extraction of some key parameters such as conversion gain.

Production testing

The right approach to volume image quality testing of CMOS imagers has to be very cost efficient. Our production testing of image quality is performed on a PC-based test station equipped with a digital frame grabber, a multi-function board with programmable digital ports, DACs, and counter/timers, and a GPIB (IEEE-488) interface board for control of chip/wafer handling equipment. The test system also includes a LED-based, three-color, variable-intensity light source that will be described below. Photobit's proprietary imager testing application incorporates a number of test procedures highly optimized for real-time image processing. These procedures include test for uniformity of the imager response to uniform illumination, test of the color filter array quality, test for "hot" and "dead" pixels and their clusters, test of INL, DNL, and offset of on-chip ADCs, test of linearity of the imager response, measurement of dark signal under various operating modes, and a number of tests designed to check specific imager functions, such as autoexposure control. The imager testing application is controlled via a sophisticated graphic user interface, which allows one to schedule, monitor, and modify tests, archive test results, set sensor grading criteria through limit tables, and communicate with peripheral devices, such as the light source, chip/wafer handler, and tested imager. When run on a 450 MHz Pentium II platform this software performs comprehensive image quality testing of a 200,000 pixels imager in approximately 25 seconds.

Sensor characterization

All our measurement methods are first tested during in-depth image sensor characterization. If deemed suitable, a method may then be employed in large volume testing. Photobit's family of CMOS APS image sensors, including the PB-100, PB-159, PB-300, and PB-720 sensors, shares the same basic camera-on-the-chip architecture. The important features of this architecture affecting the sensor characterization and testing are on-chip analog-to-digital converters (ADCs), programmable on-chip amplifiers, and an extensive set of sensor function controls accessible via a serial host interface port (SHIP). The presence of these features creates a number of new problems and possibilities in methodology and implementation of sensor measurements. The characterization of the sensor's opto-electrical performance is essentially done by computerized statistical analysis of its digital output in various operating modes (dark, illuminated, and ADC test mode). The only measurement of analog signal that must complement this analysis is the measurement of ADC reference voltage via a dedicated test output. Fig.1 shows the typical set of characterization graphs for one of Photobit's digital CMOS APS.

We have tested several methods of characterization of the analog signal chain from a pixel to the ADC. For example, the standard technique of measuring the sensor response to an external test signal applied to ADC test input may be very well approximated by modulation of the pixel bias voltage. The ability to measure the gain in the analog signal chain and ADC reference voltages is necessary to calculate essential pixel characteristics (dark current, quantum efficiency, and conversion gain) from digital output data collected in dark and lighted conditions.

Digitally controlled light source

For our photoresponse measurements, we have developed a pulsed, variable-duty-cycle light source utilizing light-emitting diodes (LEDs). The high performance version of our light source consists of a high-density array of LEDs, an optical integrating sphere, and a digitally controlled LED driver. The LED array contains four types of LEDs emitting in the infrared, red, green, and blue regions of the electromagnetic spectrum. By powering same-color LEDs with a periodic, rectangular voltage waveform whose duty cycle is digitally programmed, we achieve a three-decade dynamic range of the exposure time for the sensor integration time of 1/30 sec. This result is equivalent to being able to linearly vary the intensity of a steady-state, monochromatic light source over a dynamic range of 1000. The 8 in. diam. integrating sphere of our light source produces spatially uniform faceplate illumination, with nonuniformity less than 1% within a circular area of 2 cm diameter. Less stringent uniformity requirements can be met by using a smaller diffusing element than an integrating sphere, which significantly reduces the size and cost of the entire light source.

The short response time, high emission efficiency, and low heat output of an LED-based light source give it a number of significant advantages over traditional incandescent light sources. Direct digital control allows one to rapidly vary the output of the source during an image sensor test and thus reduce the duration and/or increase the complexity of performed tests. Unlike most incandescent light sources, the LEDs require no forced cooling. The lack of moving parts, combined with the virtual lack of long-term thermal degradation in LEDs result in ruggedness and durability, which are very desirable in industrial applications. Since the operation of our light source is digitally controlled and can be synchronized with an external logic signal with accuracy on the order of 100 ns, the light source can be easily integrated with existing industrial VLSI testing systems.

Table 1 **Typical Digital CMOS APS Specification**

Parameter	Value	Unit
Pixel size	7.9 x 7.9	μm^2
Charge Conversion Gain	20	µV/e
Analog-to-Digital Conversion (ADC) Gain*	200 5.0 250	LSB/V mV/LSB e^-/LSB
8-bit ADC Dynamic Range	255 48	LSB dB
Linear Part of Dynamic Range*	200 1.0 50,000	LSB V e^-
Maximum Signal-to-Noise Ratio	220 47	 dB
Responsivity**	400 2.0 100,000	LSB/lux*s V/lux*s e^-/lux*s
Quantum Efficiency @ 470nm @ 525nm @ 660nm	 29 31 33	 % % %
Photo Response Non Uniformity (PRNU) @ 470nm @ 525nm @ 660nm	 0.5 0.6 1.0	 %, rms %, rms %, rms
Read Noise***	0.4 0.5 21	LSB, rms mV, rms e^-, rms$^-$
Fixed Pattern Noise***	0.8 1.0	LSB, rms mV, rms
Dark Signal	4 20 1000	LSB/s mV/s e^-/s
Dark Signal Non Uniformity (DSNU)	40	%, rms
Dark Signal Luminance Equivalent "Dark Lux"**	0.01	lux

* Analog signal chain gain setting = 4

** CIE Illuminant A Color Temperature 2854K with Schott S-8612 IR cutoff filter

*** Analog signal chain gain settting = 32