A Light Source for Testing CMOS Imagers

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Abstract

Testing the optical properties of complementary metal oxide (CMOS) imagers requires a light source. The light source must produce stable uniform light with calibrated wavelength and intensity. Available commercial light source units are costly and often unalterable to a custom test setup. The proposed light source is designed to be affordable and adaptable while maintaining the necessary optical quality. The design consists of an array of light emitting diodes (LED), an infrared (IR) cut-off filter, and holographic diffusers—all of which are encased in an anodized aluminium housing. Initial experimental results have shown that the light source has lasting stability and a light uniformity above 90 percent. Applications for this light source include the experimentation and testing of imagers, photo cells, and other optoelectronic devices.

Introduction

All imaging systems have the same basic functions: optical collection of photons, wavelength discrimination of photons, detector for conversion of photons to electrons, and a method to read out the detectors. Due to low system cost, low power usage, and integration of additional circuitry on chip, CMOS imagers are rapidly gaining popularity in the digital camera market.

NASA's need for highly miniaturized imaging systems is greatly responsible for the recent motivation to produce CMOS image sensors with charge coupled device (CCD) resolution. The development of low power instrument imaging systems for next-generation deep-space exploration spacecraft is driven by performance—not cost. This effort, along with the exponential improvement in CMOS technology, has enhanced the future of CMOS image sensors in space applications and consumer markets (digital still cameras, camcorders, etc.) [1].

CMOS imagers offer the opportunity of having a complete imaging system on a single silicon chip. Timing control, drive electronics, color and signal processing, analog to digital conversion, and interface electronics can all be integrated into one device. A system on chip (SOC) architecture is operated with standard logic supply voltages, consumes power in the range of a few hundred milliwatts, and is extremely small when compared to other imaging systems.

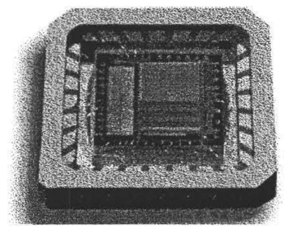

Figure 1. Micron CMOS imager with system on chip architecture

The pixel (photo-detector) array dictates the optical performance of the CMOS imager. The quality of the pixel array is characterized by such parameters as quantum efficiency, conversion gain, responsivity, noise, and image lag. Measuring these optical properties requires illuminating the imager while under test. The focus of the research is to develop a cost effective light source with the necessary properties for testing a CMOS sensor array. The proposed light source can be used to test the CMOS imager die while still at wafer level, thus speeding development time and lowering manufacturing cost.

Light Source Specifications

By understanding the CMOS pixel array and the spectral characteristics that define it, the specifications for the proposed light source can be derived. Figure 2 is a schematic of a 3 transistor (3T) active pixel. Active pixel sensor (APS) arrays function in integrating mode. Light incident on the photodiode generates electron hole pairs, thus producing a photocurrent. The photocurrent is then integrated, creating an amount of charge that is stored on the capacitive node of the floating diffusion. The photo-generated charge is then converted to a voltage by the source follower transistor; the resulting voltage is then read out by the row select transistor for further processing.

Through the analysis and characterization of this optoelectronic process, the illumination criteria for the light source will be defined.

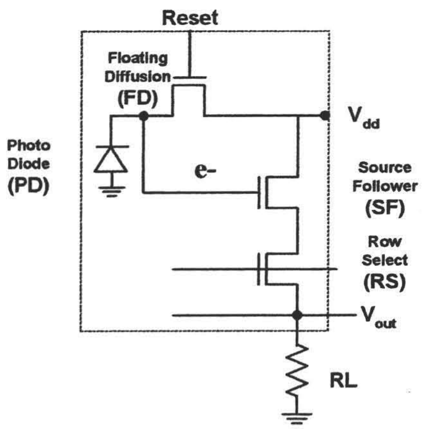

Figure 2. 3T pixel design

Intensity and Wavelength Control

The optical responsivity of the pixel is a function of the power and wavelength of the incident light. The pixel output voltage is determined by the amount of charge accumulated on the floating diffusion. In turn, the accumulated charge is determined by the energy of the incident light. Conversion gain ($Cgain$) is a measure of the electrons accumulated on the floating diffusion converted to volts ($\mu V / e-$). The quantum efficiency is a measure of the effectiveness of the photodiode to generate electron-hole pairs from incident photons. The overall responsivity of the pixel is related to both the conversion gain and the quantum efficiency (η) by the following relationship:

$$R = Cgain * \eta$$

$$= (\frac{\mu V}{e-}) * (\frac{e-}{photons})$$

$$= \frac{\mu V}{photon}$$

Using Planck's constant, the energy of a photon is related to the wavelength by:

$$E = hv = \frac{hc}{\lambda}$$

Quantum efficiency is then defined as a function of wavelength and/or photon energy and is denoted by the following equation:

$$\eta = \frac{\#of\_e-h\_pairs}{\#of\_photons} = \frac{(Ip/q)}{(Po/hv)}$$

where IP is the average photocurrent generated by a steady-state average optical power Po incident on the pixel and q is the electron charge [2].

In order to compute the quantum efficiency of the photodiode and the overall pixel responsivity, the wavelength and intensity of the light must be a known value. It can be concluded that the light source used to test the overall responsivity of the CMOS APS pixel must have the ability to control intensity and wavelength.

The light source must also be controlled by the test acquisition system in order to identify the response time of the photodiode. After the photoelectric charge is sampled, the photo diode is reset to begin integrating charge once again. If the photo diode fails to completely reset, image lag will occur. Image lag can be tested by reading a dark pixel value, completely saturating the pixel with a pulse of light, and then reading the dark frame following the pulse of light. By subtracting the first dark reading from the dark reading taken after the pulse of light, the image lag of the pixel can be quantified. The light source needs to be controlled so that it can be in sync with the tester; it must also produce enough light to completely saturate the pixels.

Uniformity

CMOS imagers are very susceptible to noise. The fixed pattern noise (FPN) is caused because of the mismatches in transistor gain, dark current, and the physical layout of the pixel array. Since most imaging applications are extremely sensitive to non-uniformity, it is important that the signal transfer characteristic of every pixel in the CMOS array is uniform [3].

The ability to uniformly illuminate the entire CMOS imager is perhaps the most important requirement of the light source because the light incident on the surface of the detector array must be uniform to measure the effects of FPN. Each pixel must also be exposed to the same amount of light so that the quantum efficiency and conversion gain of neighbouring pixels can be compared and calibrated.

Proposed Light Source Design

The light source design is tailored to illuminate an imager at a conjugate distance of 50 millimeters (mm). The conjugate area (or surface area) that must be uniformly illuminated is 25.4 square mm. The proposed light source design consists of an array of LEDs, an IR cut-off filter, and holographic diffusers. The light source unit was designed to be very adaptable to a variety of test situations while maintaining a low cost. The proposed design also allows the intensity and wavelength to easily be controlled to their desired values.

LED Array

The LED array consists of 31 LEDs mounted in a 50 mm diameter, two layer printed circuit board (PCB). To enhance uniformity, the LEDs are spatially placed in a circular array (as shown in Figure 3). The amount of light that each individual LED radiates is dependant upon the amount of current flowing through it. To increase the probability that each LED receives identical amounts of current, each LED is placed in series with a one-percent-tolerant 200 ohm resistor. The user can set the light intensity of the source by controlling the current through LED array. The power to the LED ring can be provided by any stable, controllable voltage source.

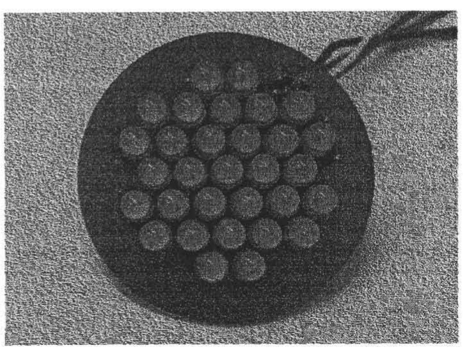

Figure 3. LED Ring

The LEDs used in the light source unit are red/green/blue (RGB) LEDs made by Nichia. The emission spectrum of the RGB LEDs is shown in Figure 4. The RGB LEDs enable the tester to have three selectable wavelengths of light with one LED ring. The LEDs have four leads: a common anode and three separate cathodes. The colors red, green, and blue can be selected by simply grounding the desired lead.

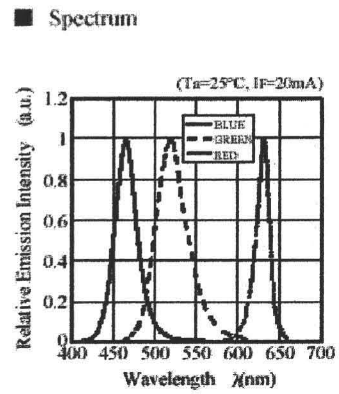

Figure 4. Emission spectrum of Nichia RGB LEDs

Different LED arrays containing LEDs with other desirable wavelengths can easily be designed and inserted into the light source unit. LED specifications such as emission angle, lens cap, intensity, and emission spectrum should be considered when selecting LEDs for a particular application. For example, in order to produce a more uniform light, one might select LEDs with a wide emission angle. However, a wider emission angle comes at the cost of decreased luminous intensity.

The amount of illumination incident on the device under test is measured in terms of lux, which is the density of luminous flux on a surface. The distance between the device under test and the light source must be taken into consideration when designing the illuminator because enough illumination must be supplied to the device under test to completely saturate the image sensor.

The proposed light source is designed to illuminate a CMOS imager die at a distance of 50 mm from the light source. The Nichia RGB LEDs produce more than enough light to saturate the sensor; each color is capable of producing more than 100 lux of illumination at a distance of 50 mm. The Nichia RGB LED has an emission angle of 80 degrees with a diffused lens cap. The RGB LED specifications are listed in Table 1.

Electrical-Optical Characteristics	Red	Green	Blue
Luminous intensity (candela)	0.18	0.6	0.13
Forward voltage	1.9	3.5	3.6
Forward current (max.)	50	30	3
Emission angle (degrees)	80	80	80
Lens cap	Diffused		

Table 1. RGB LED specifications

IR Cut-off Filter

Figure 5 illustrates the relative responsivity of silicon and the human eye in terms of wavelength. Visible light ranges in wavelength from approximately 450 to 700 nanometers. As can be seen in Figure 5, silicon is responsive to light in the IR region (light with wavelengths greater than 700 nanometers), while the human eye is not. The CMOS imagers that will be tested with the proposed illuminator are intended for applications in the visible spectrum; therefore, the light source must radiate visible light only.

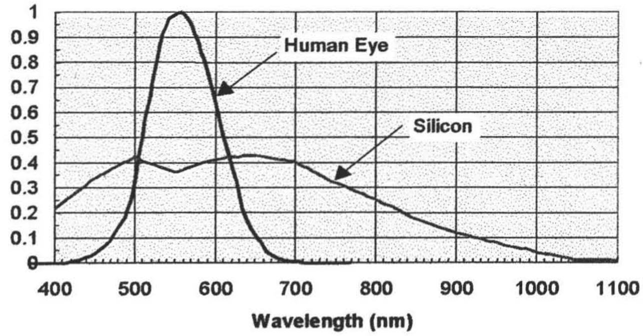

Figure 5. Responsivity of human eye vs. silicon

Although blue and green LEDs emit very little IR light, red LEDs produce a substantial amount. To eliminate the effects of the presence of near-IR light incident upon the detector, a cut-off filter was purchased from Edmund Optics. Figure 6 shows the response of the cut-off filter attenuating light with wavelengths greater than 700 nanometers.

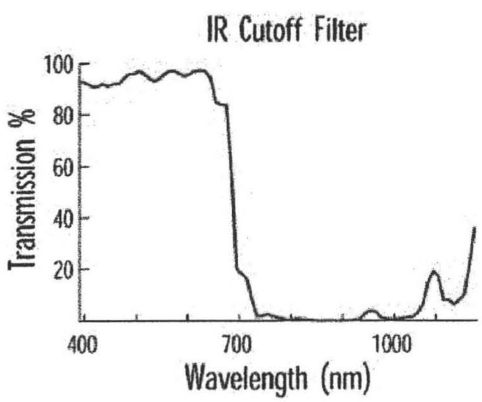

Figure 6. Response of IR cut-off filter.

Holographic Diffuser

To further spread the light emitted by the LED array, the proposed light source is designed with a series of holographic diffusers that use diffraction to spread out the incident light. Holographic diffusers are characterized by transmission efficiency, wavelength range, and diffusing angle. The holographic diffusers purchased at Edmunds Optics are wide-angle circular diffusers with a transmission efficiency slightly above 90 percent [4].

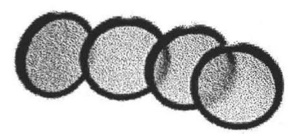

Figure 7. Holographic Diffusers

Light Source Mount

The light source mount was designed using Auto-cad and then created at CNA Precision Machining in Ogden, Utah. The top side of the mechanical housing has a male c-mount optic thread so that it can be placed in a semiconductor probe station to illuminate the imager die under test at wafer level (see Figure 8). The mechanical housing can also be placed on a test platform to characterize packaged parts. The light source housing is made of anodized aluminum and has an inside diameter of 50 mm. The barrel of the source unit is 40 mm long and the total length of the housing is 60 mm.

The design of the light source provides liberty in adjusting the distance between the LED array and the diffusers. Nylon spacers ranging in sizes from 5 to 20 mm long are used to set the distance between the LED ring and the diffusing optics. By changing the distance between the LED array and the diffusers, one can investigate which size spacer and which combination of diffusers will produce the most uniform light output. As shown in Figure 8, the LED array is placed in the back of the light source. Following the LED ring, spacers are slid in the barrel of the light source to separate the LED ring from the IR cut-off filter. Then, other spacers are placed between the IR cut-off filter and the diffusers. The spacers are made out of nylon and can easily be cut to any length. The complete illuminator system is then held in place by a retaining ring placed at the end of the barrel.

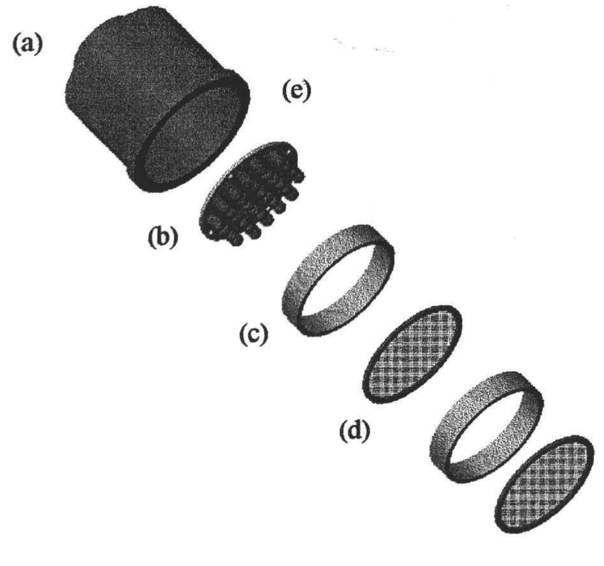

Figure 8. Light Source Mount. (a) c-mount threads, (b) LED array, (c) spacer, (d) holographic diffuser, (e) retaining ring

Experimental Results

The light source has been used to illuminate a surface area of 25.4 square mm at a distance of 50 mm. The intensity of the illumination at the incident surface is monitored by a TAOS TSL253 light-to-voltage converter. The TSL253 is a point source detector that outputs a voltage directly corresponding to the intensity and wavelength of the incident light. Using a spectrometer and a monochromator, the TSL253 has been calibrated to define a conversion between voltage output and lumens per square meter in order to define the illumination levels imposed on the imager in terms of lux.

The uniformity of the light source has been tested by placing the point source detector at multiple locations throughout the 25.4 square mm illuminated surface. After the minimum and maximum values of intensity are found, uniformity is calculated by dividing the minimum illumination value by the maximum illumination value and multiplying that ratio by 100. Reporting the uniformity in terms of a percentage accurately describes the variation of illuminous intensity across the intended surface area. Table 2 reports illumination uniformity for the colors red, green, and blue using different wide-angle holographic diffusers placed 30 mm from the LED array. During the experiment the 25.4 square mm surface was exposed to 40 lux of illumination.

Diffusing Angle	Red	Green	Blue
30 °	*85%*	*87%*	*85%*
60°	*87%*	*88%*	*87%*
80°	*92%*	*90%*	*89%*
80° and 60°	*94%*	*92%*	*95%*

Table 2. Light source uniformity comparisons

The data in Table 2 shows that the uniformity increases as the light source is used with greater diffusing angle optics.

Figure 9 is a graph of the uniformity of the light source over an area of 35 square mm at a distance of 50mm. Each point in the mesh plot represents the intensity value at that particular spatial location as reported by a grid of TAOS TSL253 light-to-voltage converting sensors. The mesh plot demonstrates the uniformity of red light at approximately 50 lux using an 80 degree holographic diffuser. As can be seen in the plot, the center of the grid demonstrates a uniform distribution of intensity, but the perimeter area suffers.

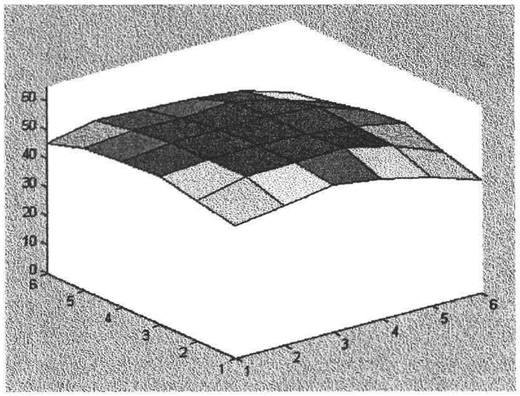

Figure 9. Uniformity plot

Conclusions and Future Work

Research will continue to refine and improve the quality of the developed light source. A major focus of future research will be implementing ideas to overcome the technical challenge of creating a uniform illumination.

An opal glass diffuser will be used with the holographic diffusers to identify the effects of greater diffusion. Different LEDs and LED arrays have already been designed and will be tested. Future research will also focus on finding other methods to test the uniformity of the light source.

This research has concluded that an LED light source can be created to test the optical properties of CMOS image sensors. Initial experimentation has proven that a uniform distribution of light can be created from LEDs by using diffractive optics. It is believed that the proposed light source design will find applications in the testing and calibration of other optoelectronic devices.

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