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Line Array Sensor Comparison

Hamamatsu S11639
Sony ILX511B
Toshiba TCD1205DG

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Introduction

Linear image sensor arrays are critical components in a broad range of applications including spectroscopy, machine vision, barcode scanners, position detection, encoding and medical imaging.

Charge-coupled devices (CCDs) have historically been the dominant technology utilized in realizing linear imaging sensor arrays as well as two-dimensional sensing arrays for industrial and scientific applications. The Sony ILX511B has long been one of the primary linear image sensors employed in low-cost, diffractive UV-VIS spectrometers as well as numerous other industrial applications. The ILX511B is a front illuminated CCD device offering high sensitivity at a low cost. The TCD1205DG is a popular CCD sensor offered by Toshiba.

Complementary metal-oxide semiconductor (CMOS) based image sensor technology has advanced dramatically in the past 20 years, driven mainly by consumer and cost sensitive industrial imaging markets. The improvements in CMOS imager technology have resulted in these devices becoming viable options in many fields, which had previously been dominated exclusively by CCD technologies. In 2014 Hamamatsu released the S11639 linear array CMOS sensor, and in 2015 an improved version of the sensor, the S11639-01.

As in most real world cases there are some advantages and disadvantages to both CCD and CMOS technologies. It is beyond the scope of this technical note to discuss in detail these differences. However, it is worth noting that one of the most important differences is the fundamental way in which the sensors read out the conversion of photons to electrons. In a CCD device the converted charges are accumulated at the pixel level and then clocked out sequentially in order to be converted by a charge measurement circuit. In a CMOS sensor the charge to voltage conversion occurs at the pixel level. Many of the differences among and between available CCD and CMOS sensors are not apparent to the end user; however, they can translate into notable, or subtle, differences in the critical optical and electrical specifications of the sensor as well as available features.

It is a challenging task to make a direct comparison between imaging sensors based solely on the values and information provided in manufacturer's datasheets. This is partially because manufacturers may use different test conditions and setups, and also each application will have a unique set of tradeoffs that must be considered when selecting an imaging sensor. AdvancedMEMS has made side-by-side measurements comparing the ILX511B, TCD1205DG and S11639 sensors under standardized test conditions in order to provide a reference set of objective measurements and comparisons to assist our customers in determining which sensor may be more optimal for their specific application. Because the S11639-01 was released while these tests were being completed, we also evaluated it and included the results in this summary report.

The Sony ILX511B, Toshiba TCD1205DG and Hamamatsu S11639 (as well as the S11639-01) were chosen for this comparison because they are all popular linear sensor arrays and have the same basic form factor (22-pin or 24-pin DIP), 2048 effective pixels and a pixel size of 14μm × 200μm with a pitch of 14μm. As noted previously, the ILX511B and TCD1205DG are both CCD devices, while the S11639 and S11639-01 are CMOS-based devices.

Silicon-based linear sensor arrays are commonly used in the 200nm to 1000nm range. We noted that in order to operate at UV wavelengths the ILX511B and TCD1205DG were coated with a UV coating, while the S11639 and S11639-01 were used as provided from the manufacturer, without any additional UV coating applied.

The objective of AdvancedMEMS is to provide customers with an unbiased, independent evaluation and data to utilize when selecting an imaging sensor for a specific application. We work with our customers to select the ideal sensor for their specific application, and we incorporate image sensors and electronic components from Hamamatsu, Sony and Toshiba into our own products as well as designs for our customers.

Table 1 presents a summary of the parameters reviewed in this report. This is by no means an exhaustive list of parameters that may be of interest for a given application, but rather an attempt to address the most critical parameters that are a factor in the majority of all systems incorporating a linear image sensor.

Table 1: Primary parameters relevant in most systems employing a linear image sensor

	Parameter	Note
1	Sensor Type	From manufacturer's datasheet
2	Pixel Format	From manufacturer's datasheet
3	Sensor Structure	From manufacturer's datasheet
4	UV Coating	Vendor supplied
5	Electronic Shutter	From datasheet and test as applicable
6	Power Supply	From manufacturer's datasheet
7	Conversion Efficiency	Measurement
8	Maximum Data Rate	From manufacturer's datasheet
9	Full Well Capacity	Measurement
10	Readout Noise	Measurement
11	Dark Current	Measurement
12	Dynamic Range	Measurement
13	Linearity	Measurement
14	Spectral Response	Measurement
15	Cross Talk	Measurement
16	Image Lag	Measurement
17	Sensitivity	Measurement

Test Conditions

A primary objective of this work was to evaluate the image sensors under identical, controlled conditions. In order to accomplish this objective, AdvancedMEMS designed test setups for each parameter and executed the tests under identical, or as closely matched as possible, conditions for each sensor. For many of the completed tests, similar hardware and components were employed. Variations will be noted for each test as appropriate.

To minimize performance variations between the sensors due to different designs of the electronic or software interfaces, we used OEM boards and drivers from a common vendor, Spectronic Devices (http://www.spectronicdevices.com). Interface boards for the ILX511B and TCD1205DG were purchased from Eureca Messtechnik (http://www.eureca.de), while the board for the S11639 was provided directly by Spectronic Devices. The OEM boards are relatively simple with a fixed clock period of 2µs for the Sony and Toshiba, and 1µs for the Hamamatsu sensors; the boards are USB powered with a 12bit A/D converter. The electronic gains of the boards are fixed with an adjustable offset subtraction. The frame start trigger may be provided via software or an external TTL signal.

A minimum of two of each sensor type was tested. If no significant variation was noted, a nominal test result was reported. Table 2 provides a summary of the sensors utilized in this test, as well as the supplier.

Table 2: Sensors summary

Sensor	Vendor	Note
ILX511B	Eureca Messtechnik	
ILX511B-UV	Eureca Messtechnik	with UV coating
TCD1205DG	Eureca Messtechnik	
TCD1205DG-UV	Eureca Messtechnik	with UV coating
S11639	Spectronic Devices	
S11639	Hamamatsu	
S11639-01	Hamamatsu	

The primary test setup for this work employed a Princeton Instruments (Acton) SP2150i monochromator with an order sorting filter and a xenon light source. Light was delivered through a fiber optic cable and then passed through a series of optics in sealed lens tubes to project a uniform light field onto the sensor array. A reference diode was placed in the optical path to allow continuous monitoring of the light intensity. Calibrated (NIST traceable) photodiodes were utilized to provide reference measurements as well as validation for each test.

Mounts for the line sensor arrays and calibrated reference photodiodes were fabricated to allow the device under test (DUT) to be placed in lens tubes and mounted in the light sealed test setup. Signals from the reference diodes were measured with a Gamma Scientific Flex Optometer (http://www.gamma-sci.com. The Flex Optometer was controlled by the same test program interfacing with the monochromator and the DUT.

The monochromator and light source provided a wavelength range of 380nm to 830nm. For wavelengths of interest outside this range, and for tests requiring a stable, variable intensity light source, a stabilized LED interfaced to the test program was used.

Completed Tests and Parameter Summaries

1. Sensor Type

The type of sensor was determined from a review of the manufacturer's provided datasheet, summarized in Table 3.

Table 3: Sensors Type

Sensor	Type
ILX511B	CCD
TCD1205DG	CCD
S11639, S11639-01	CMOS

2. Pixel Format

All the sensors in this study have the same pixel size. A summary is given in Table 4.

Table 4: Pixel Format

Sensor	Pixel Width	Pixel Height
ILX511B	14µm	200µm
TCD1205DG	14µm	200µm
S11639, S11639-01	14µm	200µm

The sensors share a common pixel form factor. The narrow, long form factor is optimal for many spectroscopy and other machine vision applications where a larger pixel area may be desired, combined with good spatial resolution.

3. Sensor structure

A summary of the sensor structure for each device is presented in Table 5. The most notable difference is the pixel type.

The Sony and Toshiba sensors are packaged in 22-pin DIP packages, while the Hamamatsu devices are housed in 24-pin DIP LCP packages.

The sensors all have the same number of active pixels as well as the same active area.

Table 5: Sensor Structure

Sensor	Pixel Pitch	Number of Pixels	Active Area	Illumination	Package	Pixel Type
ILX511B	14µm	2048	200µm × 28.672mm	Frontside	22-pin DIP	CCD
TCD1205DG	14µm	2048	200µm × 28.672mm	Frontside	22-pin DIP	CCD
S11639, S11639-01	14µm	2048	200µm × 28.672mm	Frontside	24-pin DIP	CMOS, Active Pixel

4. UV Coating

Typically in front illuminated CCD devices light must pass through a polysilicon gate, which results in significant absorption (there are also reflection losses resulting from index of refraction difference) of short wavelength light. Therefore, in order to achieve photo response in the UV region a coating is required. The CMOS device in this technical note does not require a coating and is natively sensitive in the UV range.

Table 6: UV Coating

Sensor	UV Coating
ILX511B	Required for UV sensitivity
TCD1205DG	Required for UV sensitivity
S11639, S11639-01	Not Required for UV sensitivity

5. Electronic Shutter

Electronic shutter capability in linear image sensor arrays can be very useful to implement variable integration times, automated correction of sensitivity variability, or in applications where corrections of variable input light levels are required.

Table 7 summarizes which of the characterized sensors have an electronic shutter function.

Table 7: Electronic Shutter

Sensor	Electronic Shutter
ILX511B	No
TCD1205DG	Yes
S11639, S11639-01	Yes

6. Power Source

All the tested image sensors were designed to operate from a single 5V supply, allowing straightforward integration into low cost systems. A summary of the typical power requirements for the characterized sensors is provided in Table 8.

Table 8: Power Supply – nominal operating conditions at 25°C

Sensor	Nominal Operating Voltage	Operating Current	Clock Frequency	Note
ILX511B	5V	5mA	1MHz	Data sheet value
TCD1205DG	5V	5mA	Not Specified	Not listed directly in datasheet
S11639	5V	10mA	1MHz	Manufacturer data
S11639-01	5V	10mA	1MHz	Manufacturer data

It should be noted that increased clock frequency typically leads to higher current requirements.

7. Conversion Efficiency

We did not design the electronic interfaces to the devices, so the conversion gain was calculated in two steps. A 660nm, stabilized LED was employed to generate a uniform, variable intensity light source. Multiple images were taken at each intensity level and processed to remove flat field effects over the set of pixels used in the calculations. As the photon shot noise signal follows a Poisson distribution, the gain can be determined from the noise and signal levels, provided other noise sources do not significantly contribute. Following processing the signal was plotted against the calculated variance, and the gain (in terms of e- and digital counts) is calculated from the slope. The electronic gain can then be used to calculate the conversion efficiency in μV/e-.

Table 9: Conversion Efficiency

Sensor	e-/DC	Electronic Conversion (V/DC)	Conversion Efficiency (μV/e-)
ILX511B	11.5	2.995E-4	26.04
TCD1205DG	17.0	1.485E-4	8.74
S11639	20.5	4.970E-4	23.94
S11639-01	19.5	4.970E-4	25.16

8. Maximum Data Rate

The data rate for each sensor is proportional to the clock frequency. Since the clock frequency on the OEM Spectronic Devices interface boards is not adjustable, the typical, test and maximum clock frequency for each device is listed in table 10.

Table 10: Clock Frequencies

Sensor	Typical f_{clock}	Test f_{clock}	Maximum f_{clock}
ILX511B	1.0 MHz	0.5 MHz	2.0 MHz
TCD1205DG	0.5 MHz	0.5 MHz	1.0 MHz
S11639	5.0 MHz	1.0 MHz	10 MHz
S11639-01	5.0 MHz	1.0 MHz	10 MHz

The typical frequency is the frequency used in the manufacturer's data sheet when reporting frequency dependent parameters; the test frequency is the frequency of the Spectronic Devices interface board clock; and the maximum frequency is the maximum clock supported by the device, as reported by the manufacturer.

9. Full Well Capacity

Our test for full well capacity used a uniform, stable light source (in this case a 565nm stabilized LED). The illumination level was held constant while the integration time was ramped from a minimum value until saturation occurred. Full well capacity was then calculated from the conversion efficiency.

Unfortunately the gain of the Spectronic Devices boards is fixed. In the case of the TCD1205 and the S11639 (and S11639-01), the analog to digital converter reached saturation (4095 counts) prior to saturation of the output voltage of the sensors (see Figure 1). Therefore the saturation voltage (V_{sat}) was measured using an external high speed 16bit ADC monitoring the output voltage through a voltage follower. The saturation voltages and calculated full well capacities are presented in Table 11.

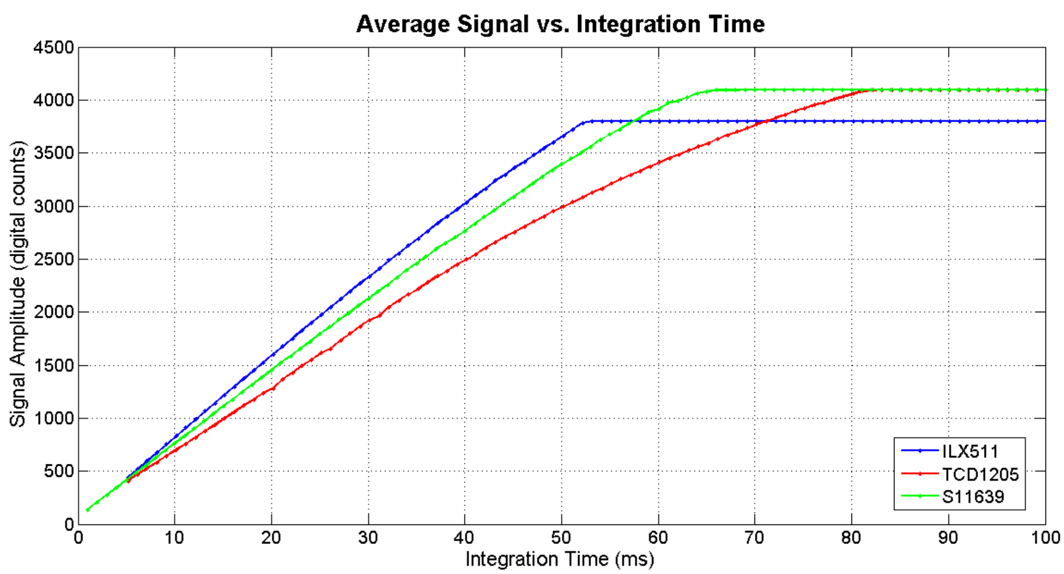

Figure 1: Signal level as a function of integration time for each sensor: the ILX511B (*blue*), the TCD1205DG (*red*) and the S11639 (*green*). The plots for the S11639 and S11639-01 are visually the same.

Table 11: Saturation voltage and full well capacity

Sensor	Saturation Voltage	Full Well Capacity
ILX511B	1.14V	43.77×10^3 e^-
TCD1205DG	0.776V	88.84×10^3 e^-
S11639	1.94V	81.05×10^3 e^-
S11639-01	2.05V	81.47×10^3 e^-

Full well capacity and saturation voltage are important characteristics when compared to the dark current level and the read noise of the sensor since these ratios will define a bound on the dynamic range of the sensor.

10. Readout Noise

Readout noise is the noise associated with reading the signal from each pixel. It is a measure of the variability that is seen when data is read under identical conditions.

Our test for read noise required minimum integration time. Because the shortest integration time for the ILX511B and TCD105DG with the Spectronic Devices interface board is 5ms, the S11639 and S11639-01 were also set to an integration time of 5ms. We will refer to a minimum integration length frame, taken in the dark, as a bias frame. After establishing equilibrium conditions of the camera in the test setup nine bias frames were taken in succession. Each frame was verified to be free of artifacts. The pixel mean of the bias frames was then subtracted from the middle frame, and the resulting image was utilized to compute the RMS noise level in digital counts. The measured read noise in digital counts, as well as the calculated read noise in mV (rms), is presented in Table 12.

Table 12: Read noise

Sensor	Read Noise (digital counts)	Read Noise (mV)
ILX511B	2.1159 rms	0.63mV rms
TCD1205DG	12.6864 rms	1.89mV rms
S11639	1.5224 rms	0.76mV rms
S11639-01	0.6190 rms	0.31mV rms

It is important to note that the Sony and Toshiba device read noise is characterized at 500kHz, while the Hamamatsu device is at 1MHz due to the fixed clock frequencies of the OEM interface boards used in this study.

11. Dark Current

Dark current is a critical parameter, limiting the performance of photodiodes and image sensors in many applications. In our test dark current was measured at 25°C in a light sealed environment after the sensor was installed into the test system and allowed to reach steady state conditions. An image frame is taken at increasing exposure times, and a center window of pixels is averaged to determine the average dark current at each integration time. The resulting value, in digital counts, is plotted as a function of integration time. The dark output signal (in mV) is derived from this plot.

Plots of the dark signal level as a function of integration time are provided in Figure 2.

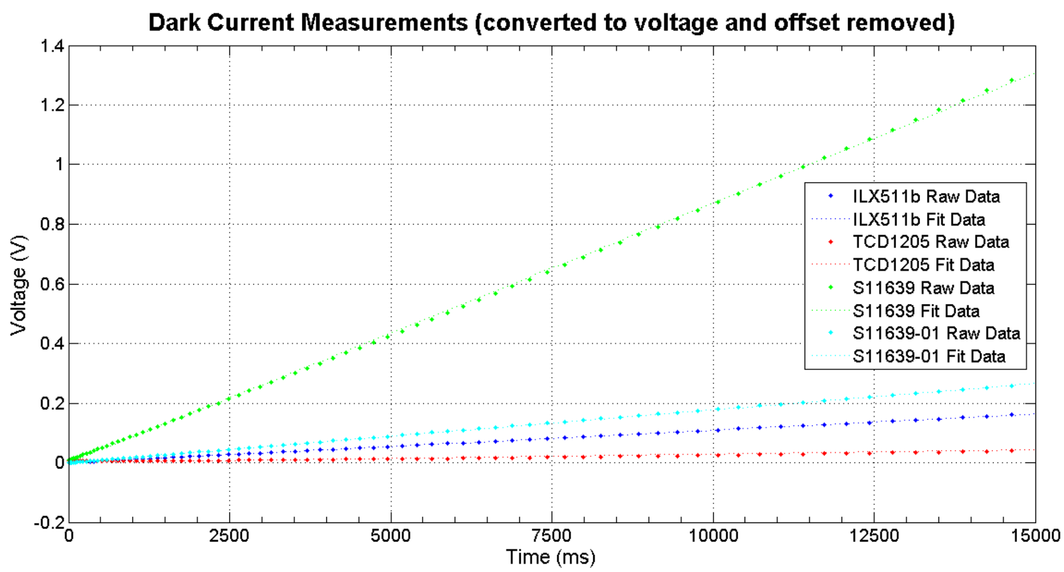

Figure 2: Dark output level in volts for each sensor (ILX511B, TCD1205DG, S11639 and S11639-01) as a function of integration time, including the linear fit curve. In this plot the digital counts have been converted to a voltage, and the initial offset has been removed.

Because the dark output voltage is a function of integration time, results for all sensors are reported in Table 13 as a slope in digital counts per millisecond and output voltage per millisecond. The output voltage resulting from an integration period of 10ms is also presented for each sensor, and this voltage does not include any initial output offset voltage. We also compute the dark current density for each sensor from the measured conversion efficiency in picoamps per square cm.

Table 13: Dark output

Sensor	Slope Fit (DC/ms)	Dark Output Rate mV/ms	$\Delta V_{DarkOut}$ per 10ms	Dark Current pA per cm^2
ILX511B	0.0363	0.011	0.11 mV	2.41 pA/cm^2
TCD1205DG	0.0166	0.002	0.02 mV	2.11 pA/cm^2
S11639	0.1041	0.051	0.51 mV	11.69 pA/cm^2
S11639-01	0.0361	0.018	0.18 mV	4.11 pA/cm^2

The dark current and associated dark output levels vary significantly with temperature. In most applications, the ratio of the dark output to the minimum signal level as well as the saturation level are critical parameters.

12. Dynamic Range

Dynamic range is most commonly defined as the saturation level divided by the read noise, or full well capacity over read noise in electron units. However, dynamic range is also sometimes defined as the saturation level divided by the dark level at a specific integration time; this is done by some manufacturers (e.g. Toshiba) and end users.

In Table 14, the dynamic range for each sensor is presented.

Table 14: Dynamic Range

Sensor	Dynamic Range V_{sat}/V_{read}
ILX511B	1810
TCD1205DG	411
S11639	2553
S11639-01	6839

13. Linearity

Linearity of the sensor response is an important characteristic of image sensors. In our characterization we measured linearity of the output signal for each sensor as a function of exposure time under conditions where the sensor was illuminated by a constant, uniform light field. In these tests a 565nm, stabilized LED was used as the light source.

The output level of the sensor was plotted against integration time. Standard error of the percent error from a linear fit prior to saturation was used as a metric of linearity.

Table 15 presents a summary of the relative linearity of each sensor.

Table 15: Linearity

Sensor	Linearity
ILX511B	Better
TCD1205DG	Good
S11639	Best
S11639-01	Best

14. Spectral Response

Spectral response is a characterization of how an image sensor responds to photons at different wavelengths. An ideal image sensor would have a flat spectral response across all wavelengths of interest. In the real world this is of course not feasible, and spectral response is a critical parameter for designers to consider when selecting an optical sensor.

In our characterization of spectral response the monochromator setup (previously described) was configured to sweep from 380nm to 830nm. The output of the monochromator was passed through an aperture to illuminate the center region of the image sensors as well as the calibrated reference diode. The reference diode was then employed to calibrate a reference in-line monitor diode. The image sensors were then tested and characterized, using the calibrated in-line diode as a real-time reference.

The relative spectral responses of the sensors are plotted in Figure 3.

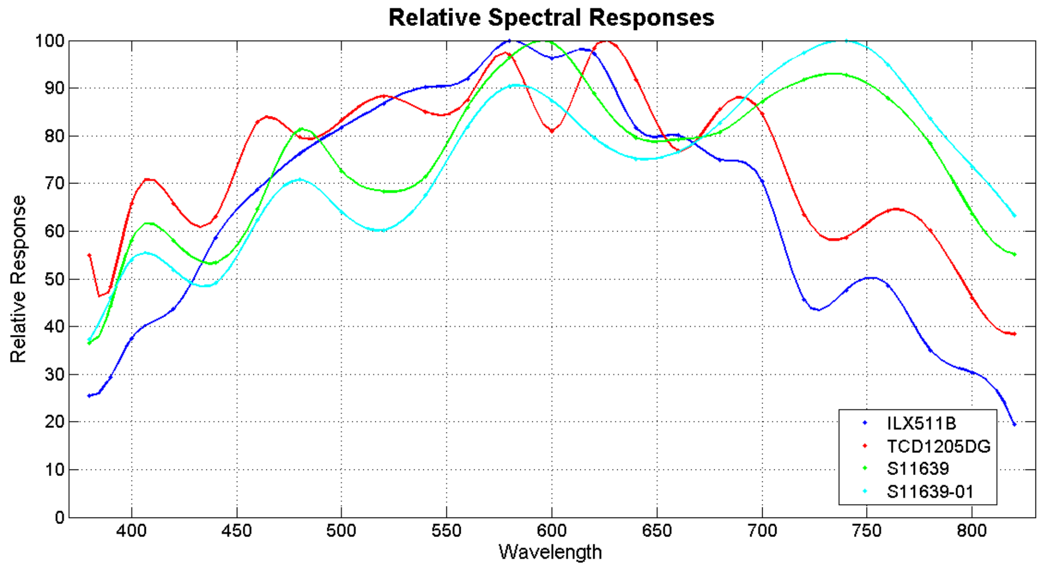

Figure 3: Relative spectral response of the Sony ILX511B, Toshiba TCD1205DG, Hamamatsu S11639 and S11639-01.

In addition, a stabilized, filtered, LED UV source at 265nm and a near IR source at 970nm were employed to characterize the spectral responses in the UV and near IR ranges. Table 18 provides a summary of the sensors' response in the UV and near IR ranges.

Table 18: UV and IR Response

Sensor	UV Response 280nm	IR Response 970nm
ILX511B	NO	YES
TCD1205DG	NO	YES
S11639	YES	YES
S11639-01	YES	YES

15. Cross-talk

Cross-talk is a characterization of the signal level observed by adjacent pixels when their neighbor pixel is illuminated. To provide a measure of cross talk for these sensors, which all have 14µm x 200µm pixels, a continuous wave 660nm laser, delivered by a single mode fiber source, was focused to a 10µm spot and the illumination of a single pixel was optimized. The laser power was set to achieve 50% saturation. The average cross-talk to the adjacent pixels was measured.

Table 17 presents a summary of cross-talk, measured as a percentage of counts from the adjacent pixel relative to the illuminated pixel, for each sensor.

Table 17: Cross-talk

Sensor	Cross-Talk
ILX511B	3.5%
TCD1205DG	4.1%
S11639	3.2%
S11639-01	3.1%

16. Image Lag

Image lag describes what percent of a signal can remain from the previous image scan. To measure image lag the sensors were configured in the previously described default states. A red LED (660nm) uniformly illuminated each sensor, and the LED power was adjusted to achieve 50% saturation of the sensor.

The LED was then switched off and data was collected during the subsequent scan. The average percent of remaining signal was measured and is reported in Table 18.

Table 18: Image Lag

Sensor	Image Lag
ILX511B	0.15%
TCD1205DG	0.45%
S11639	0.13%
S11639-01	0.12%

17. Sensitivity

Sensitivity is a measure of the voltage output of a sensor per lux second. In our characterization setup employed to measure the photosensitivity of the sensors, a stabilized, 2796K light source was used to provide illumination and a calibrated, NIST-traceable detector was used to measure the photon flux.

The previously presented conversion factor was utilized to convert the output level in digital counts to voltage. The measured sensitivity of each sensor is provided in Table 19.

Table 19: Photo Sensitivity

Sensor	Sensitivity
ILX511B	780 V/(lx×s)
TCD1205DG	305 V/(lx×s)
S11639	1325 V/(lx×s)
S11639-01	1335 V/(lx×s)

18. Summary

As stated previously it is critical that the specific requirements of a given application be considered when selecting an image sensor, as each application will have unique specifications and different sets of tradeoffs in terms of the sensor parameters required to achieve optimal performance.

In this report, we have presented direct comparisons of important parameters used to evaluate the performance of line scan image sensors for the Sony ILX511B, Toshiba TCD1205DG, and Hamamatsu S11639 as well as S11639-01. Below we summarize a few recommendations based on these test results.

- In applications requiring native UV response, or high SNR and sensitivity in the UV and near IR ranges the Hamamatsu S11639 and S11639-01 offer superior performance.

- We also recommend the Hamamatsu S11639 or S11639-01 in applications where dynamic range (in particular the S11639-01 offers excellent dynamic range performance) or imaging speed are dominant parameters of concern.

- The Sony ILX511B and Toshiba TCD1205DG both offer high responsivity and sensitivity in the visible range as well as low absolute dark current levels.

- The Hamamatsu S11639 or S11639-01 should be considered if the highest degree of linearity is required.

It is important to state that Spectronic Devices interface boards were selected when compiling data for this report, as opposed to manufacturer's evaluation boards, setups from various vendors or custom designed AdvancedMEMS boards, in order to provide an independent, direct comparison. The Spectronic Devices boards provide a simple, low cost option for users wishing to explore different sensors. However, in most real world applications an optimized board will likely be required in order to provide higher resolution A/D conversion, adjustable gain or additional timing options.

Finally, we would like to emphasize that the characterized sensor parameters are expected to exhibit some production variation both sensor-to-sensor and lot-to-lot. Furthermore, differences in characterization setups as well as test methodology will significantly impact the value of measured device parameters. It is always recommended that end users evaluate image sensors for their specific applications using appropriate selected test conditions.

Contact AdvancedMEMS at info@advancedmems.com to discuss any of your imaging needs.