Technical note

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InGaAs area image sensors

Contents

InGaAs area image sensors detect near infrared rays invisible to the human eye and convert the light into images. They have a hybrid structure consisting of a two-dimensional back-illuminated InGaAs photodiode array and high-gain low-noise CMOS readout circuit (ROIC: readout integrated circuit) that are connected by In bumps. A pixel is made up of one InGaAs photodiode element and one ROIC. The ROIC has a built-in timing generator that makes it possible to produce analog video outputs with a simple application of an external master clock (MCLK) and master start pulse (MSP). The InGaAs area image sensors have the following features.

- Cutoff wavelength: to 2.55 μm
- High quantum efficiency: 65% max.
- High sensitivity: 1 μV/e⁻ min.
- Readout mode: global shutter mode, rolling shutter mode
- Simple operation: built-in timing generator
- Built-in TE-cooler

Hamamatsu InGaAs area image sensors

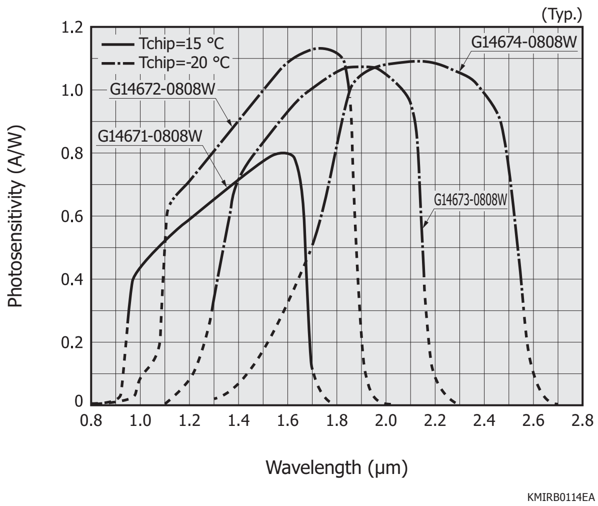
Type		Cutoff wavelength (μm)	Number of pixels [H × V]	Pixel pitch (μm)	ROIC	Metal package
Standard	Compact	1.7	64 × 64	50	CTIA	TO-8
			128 × 128	20	SF	
	High number of pixels		320 × 256	20	Differential CTIA	28L
			640 × 512		SF	
Long wavelength	Compact	1.9	64 × 64	50	CTIA	TO-8
	High number of pixels	1.9	320 × 256	20	Differential CTIA	28L
		2.15				
		2.55				

1. Structure

1 - 1 InGaAs photodiodes

The two-dimensional back-illuminated InGaAs photodiode array built into the InGaAs area image sensor provides high quantum efficiency in the near infrared region [Figure 1-1]. We also offer a type with built-in thermoelectric cooler for controlling the photodiode temperature.

[Figure 1-1] Spectral response



1 - 2 ROIC

The ROIC in the InGaAs area image sensor is manufactured to suit the characteristics of the InGaAs photodiode using CMOS technology. Multi-functionality and high performance as well as cost reduction in constructing systems are accomplished by mounting the analog circuit for signal processing and the digital circuit for generating timing signals on a single chip.

The ROIC comes in three types: CTIA (capacitive transimpedance amplifier), differential CTIA, and SF (source follower). The proper ROIC type must be selected according to the application. Figure 1-2 shows block diagrams of each type.

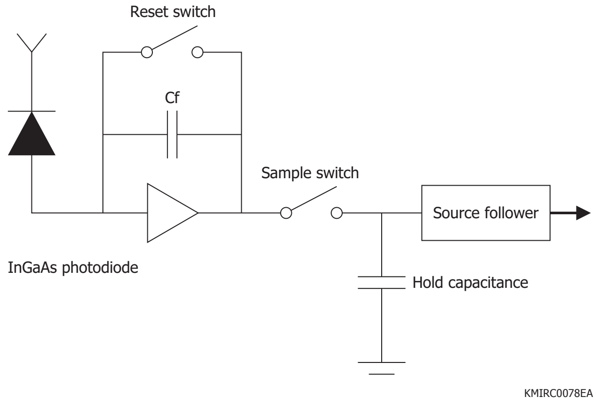
The advantages of the CTIA type are that (1) the charge-to-voltage converter takes on an amplifier structure and (2) it has superior linearity since the voltage applied to the InGaAs photodiodes can be kept constant. The disadvantages are that (1) the power consumption by the amplifier is large and (2) temperature control using the TE-cooler is necessary because of the temperature increase in the sensor caused by the large power consumption.

With the differential CTIA type, dark current can be reduced using the drive system, which brings voltage difference between the anode and cathode of the photosensitive area close to zero. It is suitable for low-light-level detection because of its high gain.

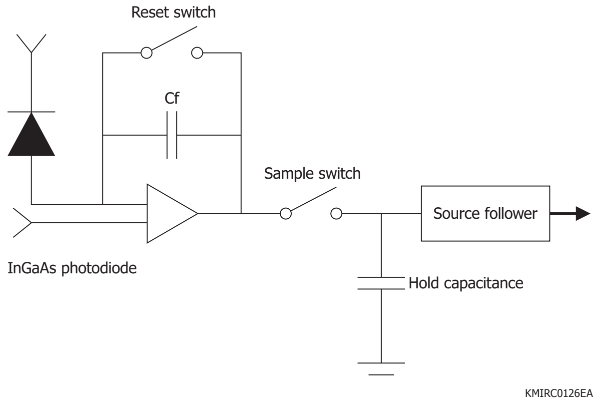
The SF type has a simply structured charge-to-voltage converter, and has low power consumption compared to the CTIA type, but comes with the disadvantage of a narrow linearity range.

[Figure 1-2] Block diagram of one pixel

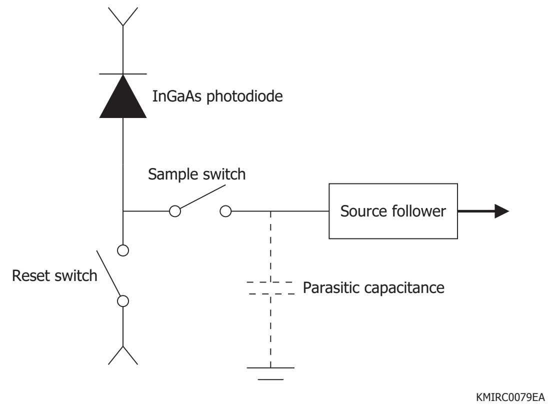
(a) CTIA type



(b) Differential CTIA type



(c) SF type



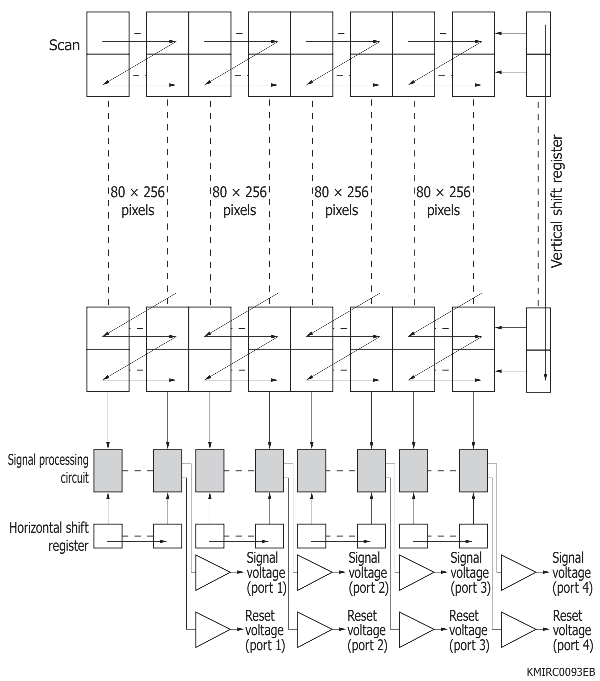
A global shutter mode is used for signal readout. A specific product (G12242-0707W) is capable of switching readout modes between the global shutter mode and the rolling shutter mode. In global shutter mode, all pixels are reset simultaneously, and integration of all

pixels begin at the same time. Therefore, data integrated over the same time duration is output from all pixels. In rolling shutter mode, a reset occurs every line, the data is output, and then integration starts immediately. If you want to prioritize the frame rate, select the rolling shutter mode. If you want to prioritize the the synchronization of imaging, select the global shutter mode.
The series of operations of the readout circuit (G14671 to G14674-0808W) are described below.
The integration time is equal to the low period of the master start pulse (MSP), which is a frame scan signal, and the output voltage is sampled and held simultaneously at all pixels. Then, the pixels are scanned, and the video is output.
The vertical shift register scans from top to bottom while sequentially selecting each row. The following operations ① to ③ are performed on each pixel of the selected row.

① Transfers the optical signal information sampled and held in each pixel to the signal processing circuit as a signal voltage, and samples and holds the signal voltage.
② Resets each pixel after having transferred the signal, transfers the reset signal voltage to the signal processing circuit, and samples and holds the reset signal voltage.
③ The horizontal shift register performs a sequential scan to output the signal voltage and reset signal voltage as serial data. The offset voltage in each pixel can be eliminated by finding a difference between the signal voltage and the reset signal voltage with a circuit outside the sensor.

Then the vertical shift register shifts by one row to select the next row and the operations ① to ③ are repeated.
When the MSP, which is a frame scan signal, goes low after the vertical shift register advances to the 256th row, the reset switches for all pixels simultaneously turn off and the next frame integration begins.

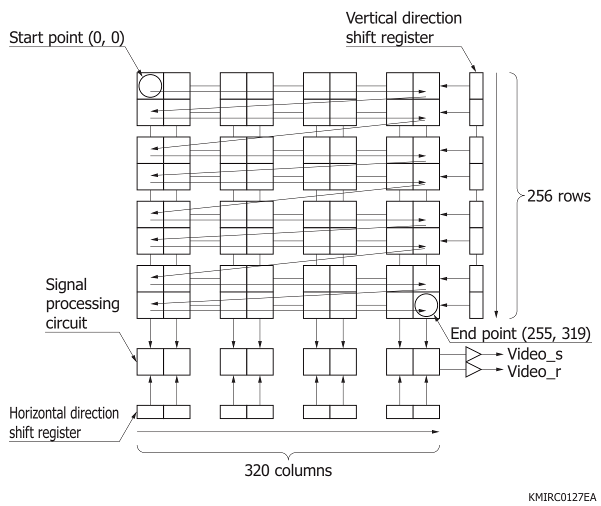
[Figure 1-3] Block diagram (G14671 to G14674-0808W)



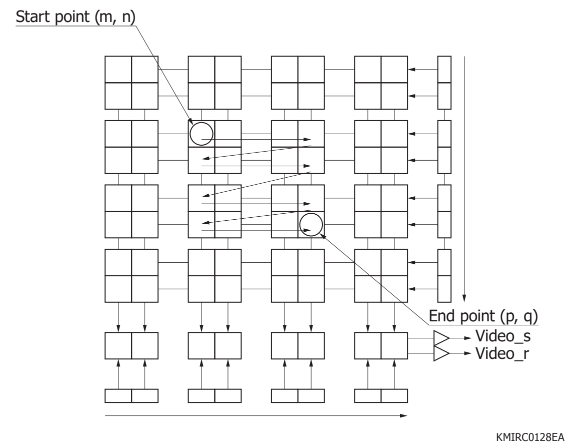
The G14671 to G14674-0808W have the partial readout function. The number of readout region is one per frame. Specify the readout region with a start coordinate (m, n) and end (p, q) [Figure 1-4 (b)]. When there is a small number of readout pixels, the frame rate is higher. The G14671 to G14674-0808W have a function for switching the number of readout ports (four ports or one port). The partial readout function is effective only for one port.
The figure 1-5 shows the relationship between the frame rate and the readout pixels for one port. The frame rate, with one port and 149 × 149 pixels readout, corresponds to the frame rate with four ports and all-pixel readout.

[Figure 1-4] Readout region (G14671 to G14674-0808W)

(a) All-pixel readout: 256 × 320 pixels



(b) Partial readout: (m, n) to (p, q)



[Figure 1-5] Frame rate vs. number of readout pixels (G14671 to G14674-0808W)

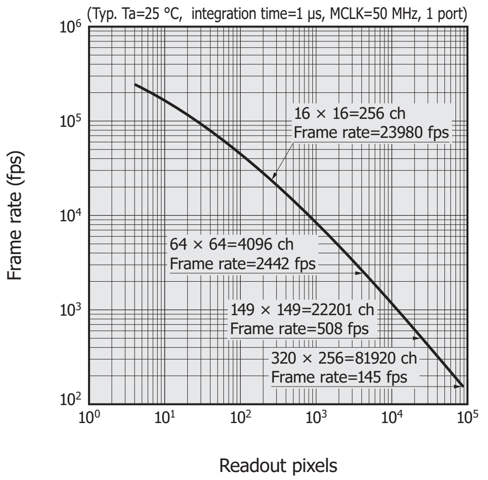


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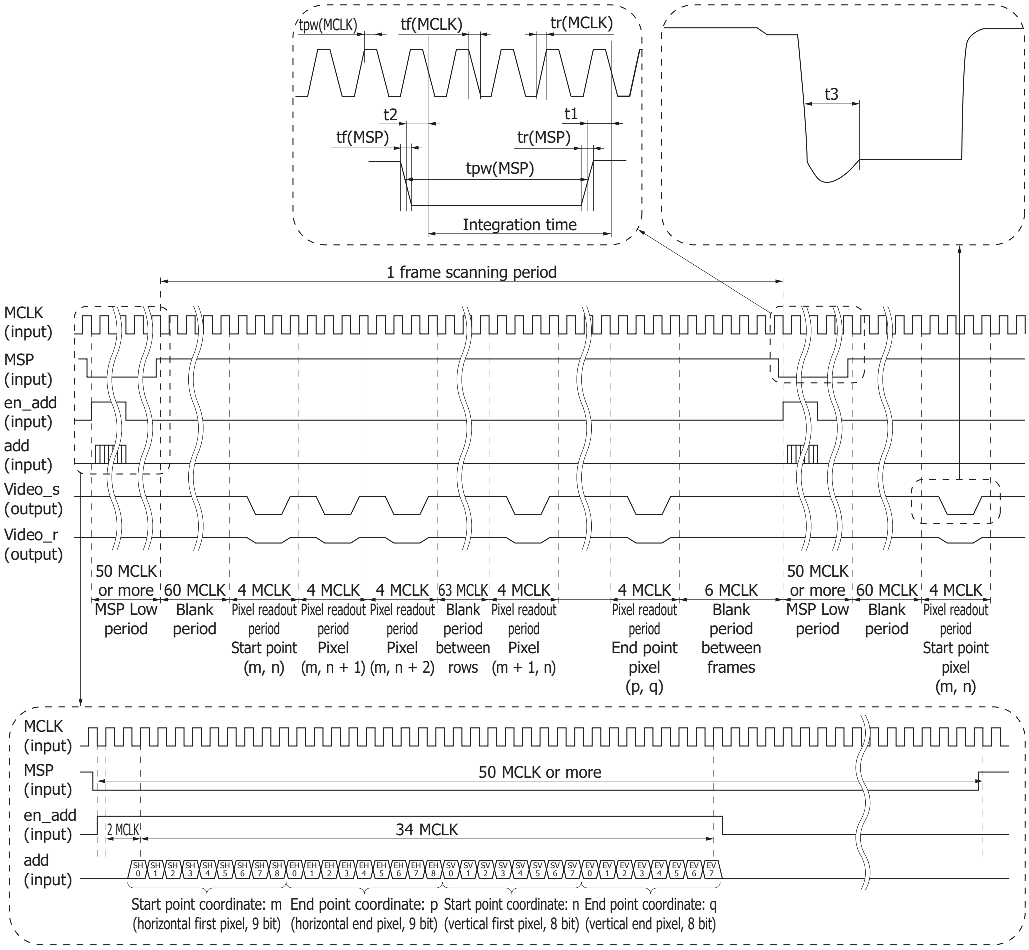
Figure 1-6 shows the partial readout timing chart. Input the control signal [Table 1-1] from the pulse generator to the G14671 to G14674-0808W.

[Table 1-1] Control signals from pulse generator (G14671 to G14674-0808W)

Control signal	Description
MCLK	Master clock. The video data rate (12.5 MHz max.) is determined by clock pulse frequency.
MSP	The MSP is a signal that starts each control signal to perform frame scan. When the MSP goes from low (0 V) to high (3.3 V) and the MCLK falls, each control signal is started. The frame scan is performed when the MSP is in the high (3.3 V) period. The MSP low period needs to be set 50 MCLK or more during partial readout.
en_add	Enable signal voltage of address input signal pulse
add	Address input signal pulse. Input a start coordinate (m, n) and end coordinate (p, q) of readout region while en_add is in the high period. m: horizontal direction (0 to 319), input with 9-bit (SH0 to SH8) n: vertical direction (0 to 255), input with 8-bit (SV0 to SV7) p: horizontal direction (0 to 319, m or more), input with 9-bit (EH0 to EH8) q: vertical direction (0 to 255, n or more), input with 8-bit (EV0 to EV7)

[Figure 1-6] Timing chart (partial readout)



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Parameter	Symbol	Min.	Typ.	Max.	Unit
Clock pulse rise/fall times	tr(MCLK)	0	5.5	6	ns
	tf(MCLK)				
Clock pulse width	tpw(MCLK)	4	-	-	ns
Start pulse rise/fall times	tr(MSP)	0	5.5	6	ns
	tf(MSP)				
Start pulse width	tpw(MSP)	1	-	-	μs
Reset (rise) timing*	t1	4	-	-	ns
Reset (fall) timing*	t2	4	-	-	ns
Output settling time	t3	-	-	30	ns

* Setting these timings shorter than the minimum value may delay the operation by one MCLK pulse and cause malfunction.

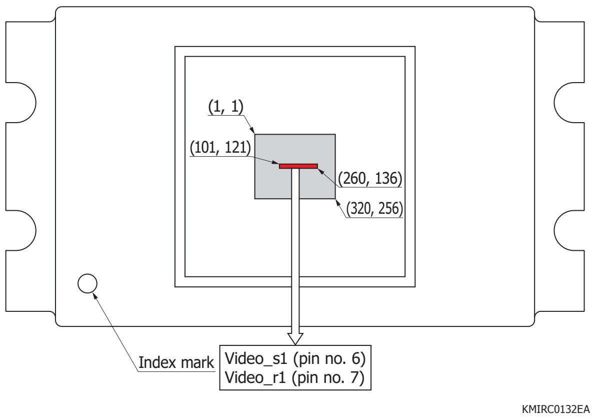
Partial readout example [number of readout pixels: 2560 (160 columns × 16 rows)]

m=100 (column 101), n=120 (row 121),
p=259 (column 260), q=135 (row 136)

Readout region

When the index mark of the G14671 to G14674-0808W is set to the lower left [Figure 1-7], the upper left is the starting point and the lower right is the ending point. [gray: effective pixel region (320 × 256 pixels), red: partial readout region (160 × 16 pixels)]. The signal of the partial readout region is output from one port [Video_s1 (pin no. 6), Video_r1 (pin no. 7)].

[Figure 1- 7] Readout region



Calculating the frame rate

The frame rate of the G14671 to G14674-0808W is calculated as follows.

Frame rate = 1/(MSP low period [s] + 1 frame scanning period [s]) ········ (1-1)

1 frame scanning period [MCLK] = {MSP blank period from rising edge to start point pixel 60 [MCLK]} + (Pixel readout period 4 [MCLK] × Number of readout pixels [ch]) + (Blank period between rows 63 [MCLK]/row) × (Number of rows − 1) + Blank period between frames 6 [MCLK] ········ (1-2)

1 frame scanning period [s] = 1 frame scanning period [MCLK] × MCLK frequency [s] ········ (1-3)

- m=100 (column 101), n=120 (row 121), p=259 (column 260), q=135 (row 136) [number of readout pixels: 2560 (=160 columns × 16 rows), MCLK=50 MHz (0.02 μs), MSP low period=1 μs]

1 frame scanning period = 60 [MCLK] + (4 [MCLK] × 2560 [ch])+ {63 [MCLK] × (16 − 1)} + 6 [MCLK]=11251 [MCLK]

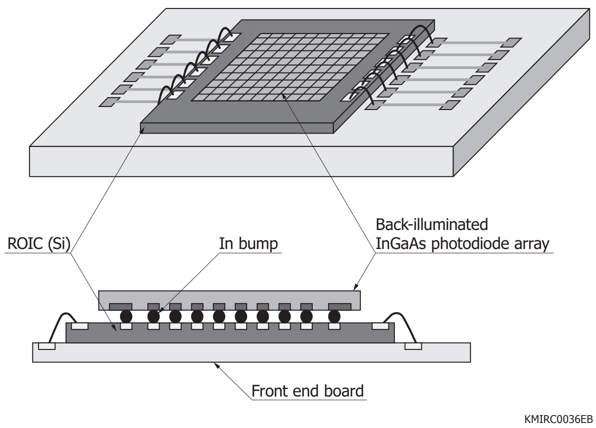
1 frame scanning period = 11251 [MCLK] × 0.02[μs] = 225.02 [μs]

Frame rate = 1/(1 [μs] + 225.02 [μs]) = 4424.38 fps

1 - 3 In (indium) bumps

In bumps electrically connect the InGaAs photodiode and ROIC. Since the Young's modulus of In is lower than that of Au, Cu, and Al and the melting point is 157 °C, distortion caused by heat can be suppressed. Thus, In is suitable for connecting metals and semiconductors with different thermal expansion coefficients.

[Figure 1-8] Schematic of InGaAs area image sensor



[Table 1-2] Input signal arrangement of add signals

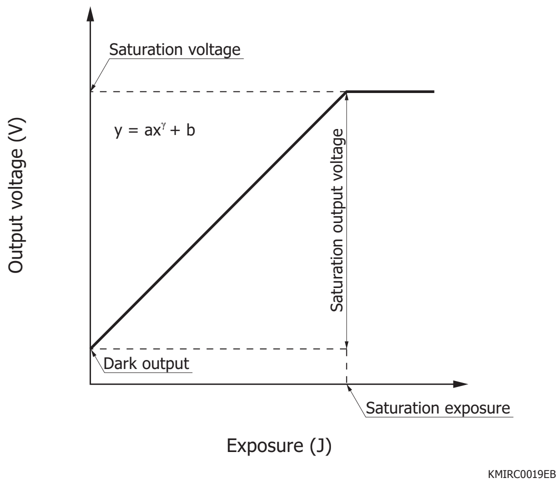
SH0	SH1	SH2	SH3	SH4	SH5	SH6	SH7	SH8	EH0	EH1	EH2	EH3	EH4	EH5	EH6	EH7	EH8	SV0	SV1	SV2	SV3	SV4	SV5	SV6	SV7	EV0	EV1	EV2	EV3	EV4	EV5	EV6	EV7
0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	1	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	1
m=100									p=259									n=120								q=135							

2. Characteristics

2 - 1 Input/output characteristics

The input/output characteristics express the relation between the light level incident to the image sensor and the signal output. Since InGaAs area image sensors operate in charge amplifier mode, the incident light exposure (unit: J) is expressed by the product of light level (unit: W) and integration time (unit: s). Figure 2-1 shows a schematic diagram of the input/output characteristics. The slope in the figure can be expressed by equation (2-1).

[Figure 2-1] Schematic graph of input/output characteristics (log graph)



$$y = ax^{\gamma} + b \quad \cdots\cdots\cdots (2\text{-}1)$$

y: output voltage
a: sensitivity (ratio of output with respect to the exposure)
x: exposure
γ: slope coefficient
b: dark output (output when exposure=0)

Since the upper limit of the output voltage is determined by the output voltage range of the ROIC, the input/output characteristics will have an inflection point. The incident light exposure at this inflection point is referred to as the saturation exposure, the output voltage as the saturation output voltage, and the amount of charge stored in the charge amplifier as the saturation charge.
In our InGaAs linear image sensor datasheets, the saturation output voltage (Vsat) is defined as the saturated output voltage from light input minus the dark output. The saturation charge is calculated from the equation Q=CV based on the saturation output voltage. If the integration capacitance (Cf) is 0.1 pF and the saturation output voltage is 2.0 V, then the saturation charge will be 0.2 pC.

2 - 2 Photoresponse nonuniformity

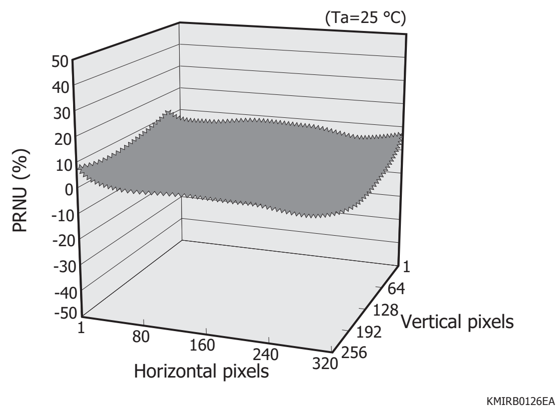
InGaAs area image sensors contain a large number of InGaAs photodiodes arranged in an array, yet sensitivity of each photodiode (pixel) is not uniform. This may result from crystal defects in the InGaAs substrate and/or variations in the processing and diffusion in the manufacturing process as well as inconsistencies in the ROIC gain. For our InGaAs area image sensors, variations in the outputs from all pixels measured when the effective photosensitive area of each photodiode is uniformly illuminated are referred to as photoresponse nonuniformity (PRNU) and defined as shown in equation (2-2).

$$\text{PRNU} = (\Delta X/X) \times 100\ [\%] \quad \cdots\cdots\cdots (2\text{-}2)$$

X : average output of all pixels
ΔX: absolute value of the difference between the average output X and the output of the maximum (or minimum) output pixel

In our outgoing product inspection for photoresponse nonuniformity, the output is adjusted to approx. 50% of the saturation output voltage and a halogen lamp is used as the light source. Since InGaAs area image sensors use a compound semiconductor crystal for photoelectric conversion, the photodiode array may contain crystal defects, resulting in abnormal output signals from some of the pixels (defective pixels). Moreover, scratches and stain on the light input window may also cause the sensitivity uniformity to deteriorate. So caution should be exercised on this point when handling image sensors. Figure 2-2 shows typical example of photoresponse nonuniformity (random sampling).

[Figure 2-2] Photoresponse nonuniformity (G14671-0808W, typical example)



2 - 3 Dark output

The dark output is the output generated even when no incident light is present. This output is the sum of the dark current (sum of diffusion current, recombination current, and surface leakage current) of the photodiode and the ROIC offset voltage. Since the upper limit of the video output is determined by the saturation output voltage, a large dark output narrows the dynamic range of the output signal. The output signal is the sum of the output generated by light and the dark output, so the purity of the output signal can be improved by using signal processing to subtract the dark output from each pixel. The dark output is given by equation (2-3). The integration time must be determined by taking the magnitude of the dark output into account.

$$V_d = I_D \times (T_s/C_f) + V_{off} \cdots\cdots\cdots (2\text{-}3)$$

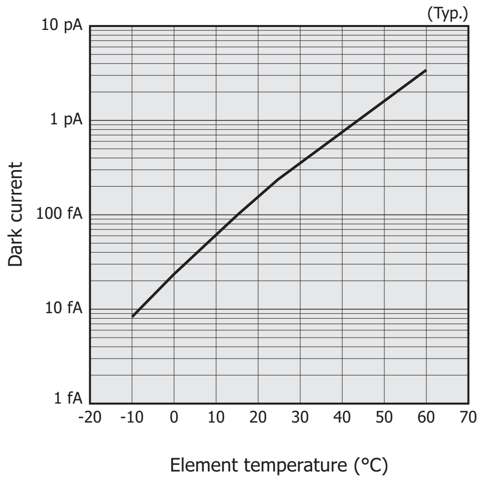
V_d : dark output [V]
I_D : dark current [pA]
T_s : integration time [s]
C_f : integration capacitance [pF]
V_{off}: ROIC offset voltage [V]

The band gap widens as the temperature decreases, so the number of carriers thermally excited into the valence band from the conduction band decreases, causing the dark current to reduce exponentially. In our InGaAs area image sensors, the temperature coefficient β of the dark current is 1.06 to 1.1. If the dark current at temperature T_1 (unit: °C) is I_{DT1} (unit: A), then the dark current I_{DT} at temperature T is expressed by equation (2-4).

$$I_{DT} = I_{DT1} \times \beta^{(T - T_1)} \text{ [A]} \cdots\cdots\cdots (2\text{-}4)$$

Figure 2-3 shows the temperature characteristics of the G14671-0808W dark current (random sampling).

[Figure 2-3] Temperature characteristics of dark current (G14671-0808W)



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2 - 4 Noise

InGaAs area image sensor noise can be largely divided into fixed pattern noise and random noise. Fixed pattern noise includes ROIC DC offset voltage and photodiode dark current which is current noise from the DC component. The fixed pattern noise can be canceled by using an external signal processing circuit. Random noise, on the other hand, results from fluctuations in voltage, current, or charge that are caused in the signal output process in the sensor. When the fixed pattern noise has been canceled by external signal processing, the random noise will then determine the InGaAs area image sensor's detection limit for low-level light or lower limit of dynamic range. Random noise includes the following four components:

① Dark current shot noise (Nd)
② Signal current shot noise at light input (Ns)
③ Charge amplifier reset noise (Nr)
④ CMOS charge amplifier readout noise (N_R)

Dark current shot noise ① results from erratic fluctuation in charge. This noise becomes larger as the output charge due to dark current increases, and therefore varies depending on operating conditions such as integration time and temperature. Signal current shot noise ② is caused by fluctuations due to incident photons arriving randomly at the sensor. The total noise (N) is expressed by equation (2-5).

$$N = \sqrt{Nd^2 + Ns^2 + Nr^2 + N_R^2} \cdots\cdots\cdots (2\text{-}5)$$

We specify the noise level (unit: V rms) in InGaAs area image sensors as fluctuations in the output voltage of each pixel.

3. Driver circuit

Figure 3-1 shows the recommended driver circuit for the InGaAs area image sensors G14671 to G14674-0808W.

Precautions on circuit preparation

(1) Bias generation circuit

- We recommend using a circuit structure that applies the voltage buffered by the amplifiers. Noise can be suppressed by limiting the bandwidth of the amplifiers appropriately. We recommend inserting an RC filter after the amplifier output (e.g., 10 Ω, 0.1 μF, f=approx. 160 kHz).
- The InGaAs image sensor can be driven using only the voltage generated by resistance voltage divider. However, we do not recommend this, because characteristics such as linearity will degrade due to the response speed and impedance.
- Use an op amp with adequate phase margin (AD8031, etc.). If the phase margin is inadequate, the op amp may oscillate depending on the bypass capacitor.
- We do not recommend linear regulators because they have insufficient ability to draw current and degrade characteristics such as linearity.
- The stability of the bias voltage affects the sensor noise, so make sure to check with an oscilloscope.
- A relatively large current may flow momentarily through the bias generation circuit. Use a voltage source that can supply at least 10 times the supply current shown on the datasheet.

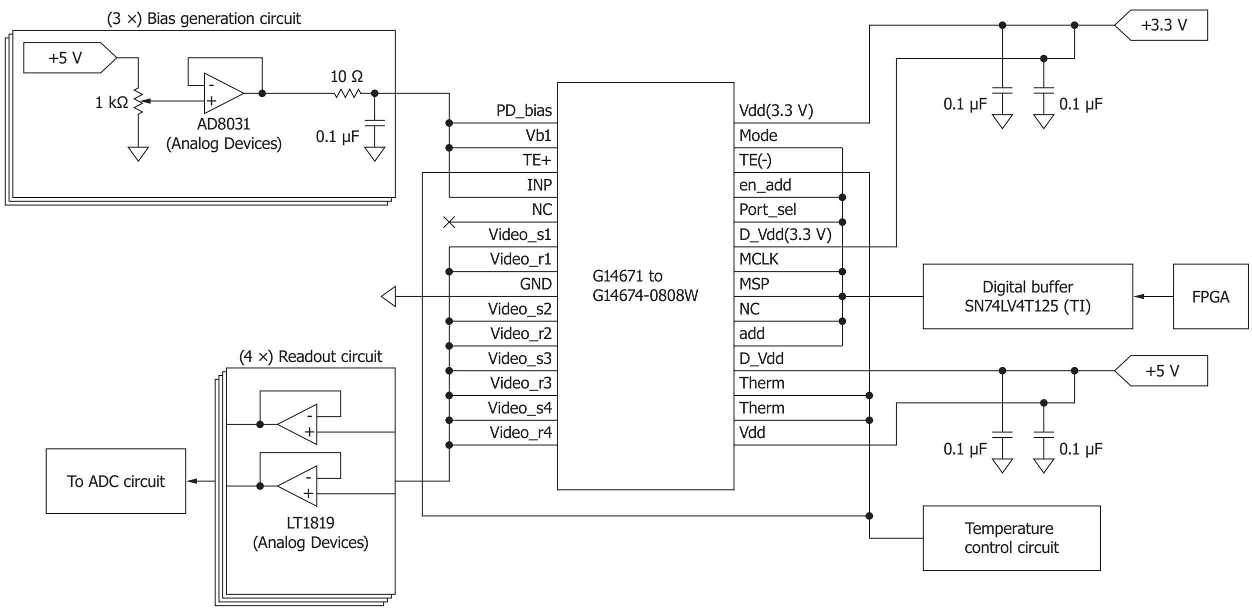
(2) Power supply

- Supply power from a stable external power supply or power supply circuit.
- Decouple with a capacitor (0.1 μF) near the sensor terminal.
- Be careful, as a relatively large current may flow momentarily, and if a choke coil is used, then a voltage drop may occur.

(3) Readout circuit

- The sensor has a relatively high output impedance, so buffer it near the sensor output end.
- To reduce noise, keep the bandwidth of the readout circuit at three to ten times the pixel rate (we recommend five times).

[Figure 3-1] Recommended driver circuit (analog front end circuit)



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4. Application examples

InGaAs area image sensors used for infrared detection significantly increase the information obtained through detection as compared to single-element InGaAs PIN photodiodes or InGaAs linear image sensors. Its field of application is expanding including night vision for security purposes, plastic sorting (pet bottles and other disposables), farm produce sorting (e.g., grains), semiconductor analyzers, and academic research (astronomy and satellite).
4-1 to 4 below show near infrared images taken using an InGaAs camera (Hamamatsu C12741-03U) equipped with the InGaAs area image sensor G13393-0909W and using a near infrared LED.

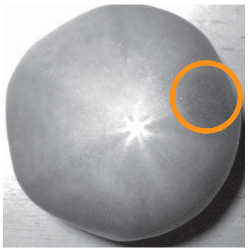
4 - 1 Farm product inspection

The bruised part of the tomato has high moisture content. Using the fact that the wavelength of the absorption spectrum of water is 1.45 μm, "bruised parts" can be detected that are difficult to see visually.

[Figure 4-1] Detecting the bruised part on a tomato that has been pressed

(a) Visible

(b) Near infrared
(LED's peak emission wavelength: 1.45 μm)



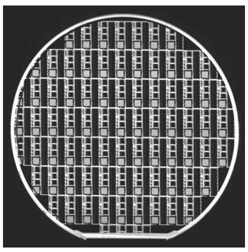
4 - 2 Semiconductor inspection

Visible light does not pass through silicon wafers, but near infrared rays (1.1 μm and above) do pass. Using this property, it is possible to detect alignment marks on silicon wafer pattern surfaces, which cannot be seen with visible light on bonded wafers.

[Figure 4-2] Silicon wafer pattern detection

(a) Visible

(b) Near infrared
(LED's peak emission wavelength: 1.2 μm)



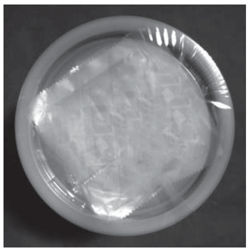
4 - 3 Instant noodle inspection

Using the fact that near infrared rays pass through the cup, it is possible to check for presence/absence of gunpowder and contaminants in the cup.

[Figure 4-3] Check for presence/absence of gunpowder and contaminants in the cup

(a) Visible

(b) Near infrared
(LED's peak emission wavelength: 1.2 μm)



4 - 4 Security

Near infrared light has longer wavelengths than visible light, so it is less susceptible to diffused reflection caused by fine particles, such as fog and smoke. InGaAs area image sensors are used in monitoring cameras because they can easily capture near infrared images even when there is fog or smoke.

[Figure 4-4] Check the target object while it is full of smoke

(a) Visible

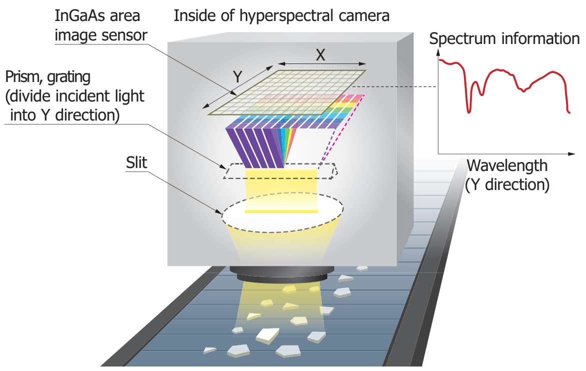
(b) Near infrared
(LED's peak emission wavelength: 1.55 μm)

4 - 5 Hyperspectral imaging

Hyperspectral imaging is a method by which pixel-level spectrum information is acquired simultaneously with capturing images of the target object. It is a useful method to isolate materials that are difficult to distinguish by eyesight.
Just like a normal line camera, you move the object (or camera) to do scan imaging. An area image sensor is used because incident light passes through the slit, then is separated by a prism and a grating in the Y axis direction of the sensor. Highly accurate identification is made possible using a camera equipped with a near infrared area image sensor, because a characteristic

near infrared spectrum can be obtained according to the type of plastic (PVC, acrylic, PET, PS).

[Figure 4-5] Hyperspectral camera



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Information described in this material is current as of December 2020.
Product specifications are subject to change without prior notice due to improvements or other reasons. This document has been carefully prepared and the information contained is believed to be accurate. In rare cases, however, there may be inaccuracies such as text errors. Before using these products, always contact us for the delivery specification sheet to check the latest specifications.
The product warranty is valid for one year after delivery and is limited to product repair or replacement for defects discovered and reported to us within that one year period. However, even if within the warranty period we accept absolutely no liability for any loss caused by natural disasters or improper product use.

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