

Technical Note

MT9V024 Slave Exposure Mode Operation

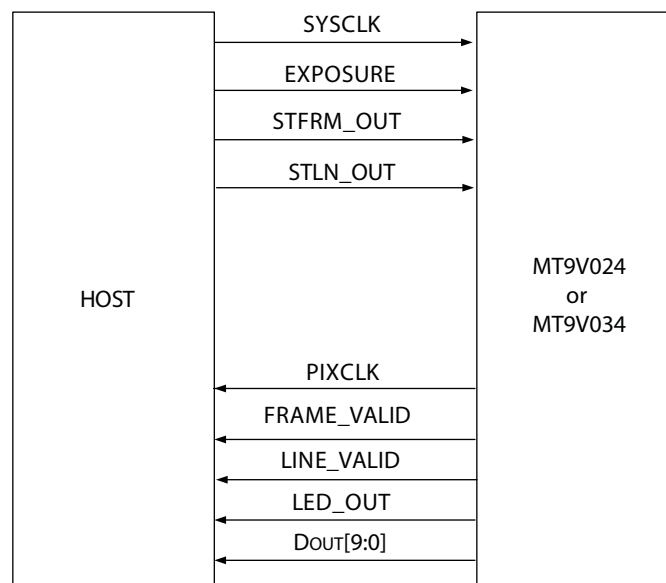
Introduction

Aptina's MT9V024 CMOS image sensor is designed to have exposure time synchronized to an external control source. This feature, called slave exposure, coupled with the global shutter mode of operation, is ideal for supporting the demands of machine vision systems and interior and exterior automotive environments.

Operation Details

While many imaging applications, such as broadcast television, operate according to a video standard, there also exist many machine vision and automotive applications that need to operate in a nonstandard manner where the exposure of the image sensor is synchronized to an external event. For example, the exposure of the image sensor may need to be limited to the time that a product is at a specific point on a conveyor belt, or to be synchronous with the flash of a light source. The MT9V024 offers the ability to control the exposure of the image sensor through the use of two trigger signals—the first signal (EXPOSURE) starts the exposure and the second (STFRM_OUT) stops the exposure. Additionally, the image sensor allows control of the image data flow through the use of a trigger signal (STLN_OUT) that enables the readout of each row of image data. This technical note addresses only the single image sensor (non-stereoscopic) slave mode of operation.

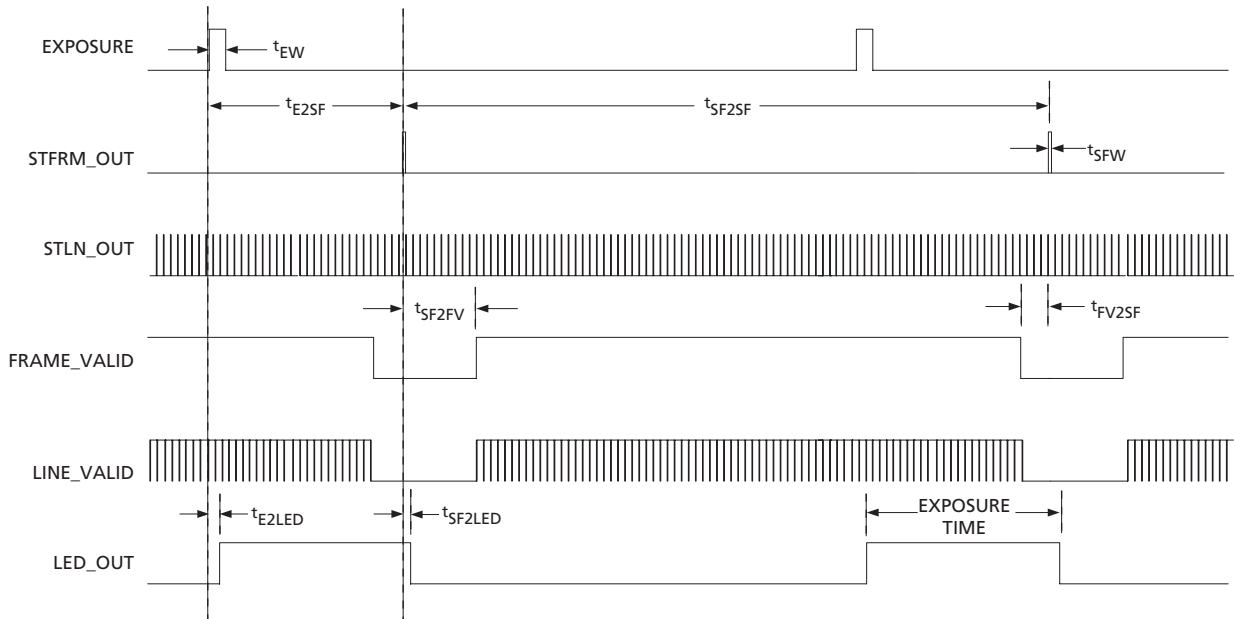
Figure 1: Block Diagram



Exposure Mode Overview

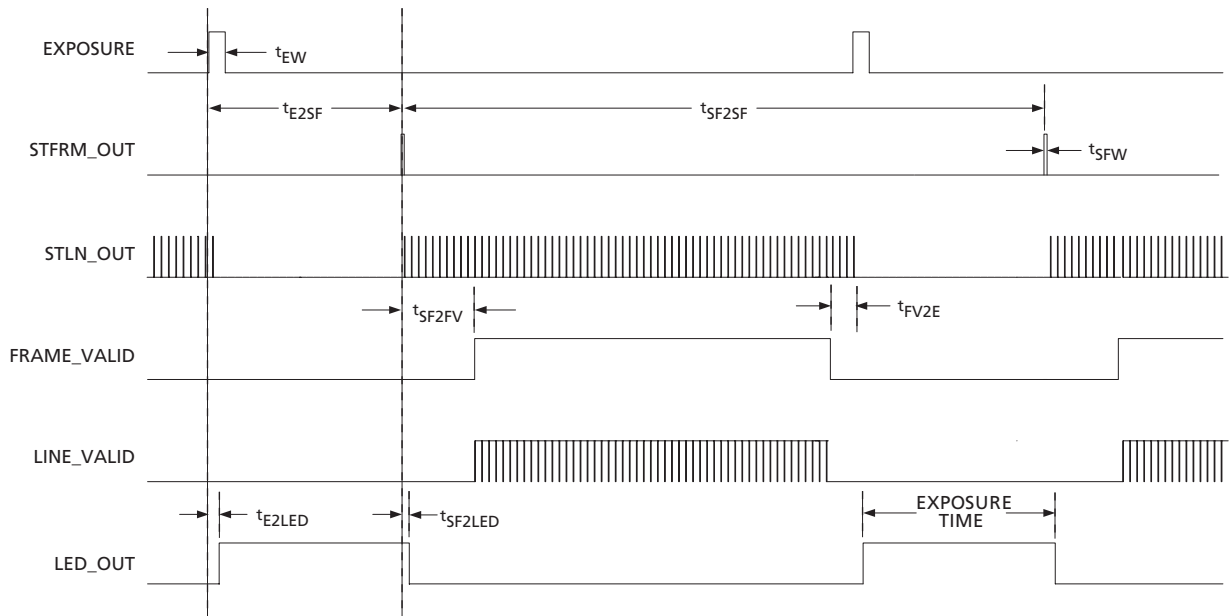
When the image sensor is set to slave mode (R0x07, bits[4:3] = 0), the beginning and end of the exposure time are controlled by the host system. The global shutter feature allows all pixels to be exposed in parallel—all pixels start exposing (integrating charge) simultaneously and stop exposing simultaneously. When exposure stops, the per-pixel integrated charges are digitized and read out of the chip.

Figure 2: Exposure and Readout Timing (Simultaneous Mode)



- Notes:
1. Not drawn to scale.
 2. Frame readout shortened for clarity.
 3. Simultaneous progressive scan readout mode shown.

Figure 3: Exposure and Readout Timing (Sequential Mode)



- Notes:
1. Not drawn to scale.
 2. Frame readout shortened for clarity.
 3. STLN_OUT pulses are optional during exposure time.
 4. Sequential progressive scan readout mode shown.

Table 1: Exposure and Readout Timing Limits

Symbol	Name	Minimum	Typical	Maximum
t_{EW}	EXPOSURE width	1 SYSCLK-cycle	1 SYSCLK-cycle	
t_{E2SF}	EXPOSURE to STFRM_OUT (Approximate exposure time)	t_{E2SL}		
t_{SF2SF}	STFRM_OUT period (frame period or reciprocal frame rate)	Refer to text		
t_{SFW}	STFRM_OUT width	1 SYSCLK-cycle	1 SYSCLK-cycle	1 SYSCLK-cycle
t_{SF2FV}	STFRM_OUT to FRAME_VALID		$t_{SF2SL} + [R0x06]$ row-times + 26 SYSCLK-cycles	
t_{FV2SF}	FRAME_VALID to STFRM_OUT (simultaneous mode)	4 SYSCLK-cycles		
t_{FV2E}	FRAME_VALID to EXPOSURE (sequential mode)	2 row-times + 4 SYSCLK-cycles		
t_{E2LED}	EXPOSURE to LED_OUT		t_{E2SL}	
t_{SF2LED}	STFRM_OUT to LED_OUT		2 SYSCLK-cycles	
t_{E2SL}	EXPOSURE to STLN_OUT	129 SYSCLK-cycles	1 row-time	
t_{RW}	Pixel reset duration		128 SYSCLK-cycles	
t_{SF2SL}	STFRM_OUT to STLN_OUT	660 SYSCLK-cycles		
t_{TW}	Pixel transfer duration		1 row-time	



Table 1: Exposure and Readout Timing Limits (continued)

Symbol	Name	Minimum	Typical	Maximum
t_{SL2SL}	STLN_OUT period (Row time)	$[R0x04 + R0x05]$ SYSCLK-cycles		$[R0x04 + (2 \times R0x05) - 23]$ SYSCLK-cycles
t_{SLW}	STLN_OUT width	1 SYSCLK-cycle	1 SYSCLK-cycle	1 SYSCLK-cycle
t_{SL2FVH}	STLN_OUT to FRAME VALID rising edge		26 SYSCLK-cycles	
$t_{FVH2LVH}$	FRAME_VALID rising edge to LINE_VALID rising edge		$[R0x05 - 22]$ SYSCLK-cycles	
t_{SL2LVH}	STLN_OUT to LINE_VALID rising edge		$[R0x05 + 4]$ SYSCLK-cycles	
t_{LVL2SL}	LINE_VALID falling edge to STLN_OUT	-4 SYSCLK-cycles		$[R0x05 - 27]$ SYSCLK-cycles
t_{SL2FVL}	STLN_OUT to FRAME VALID falling edge		27 SYSCLK-cycles	
$t_{LVL2FVL}$	LINE_VALID falling edge to FRAME VALID falling edge		23 SYSCLK-cycles	

- Notes:
1. See "Row-Time Definition" on page 7 for row-time unit definition.
 2. SYSCLK-cycle unit is defined as the reciprocal of the SYSCLK input frequency.
 3. To change exposure time, change the t_{E2SF} value by changing the EXPOSURE pulse location (do not change t_{SF2SF}).
 4. To change frame rate, change the t_{SF2SF} value.

Register Settings

The slave mode of operation requires that certain automatic functions of the image sensor be disabled or set to fixed values, as shown in Table 2.

Table 2: Slave Mode Register Settings

Register	Register Name	Bit	Bit Name	Bit Description	Value in Dec (Hex)
0x07	Chip control	4:3	Sensor master/slave mode	0 = slave mode 1 = master mode 3 = snapshot mode	0
0x07	Chip control	5	Stereoscopy mode	0 = stereoscopy disabled 1 = stereoscopy enabled	0
0x07	Chip control	6	Stereoscopic master/slave mode	0 = stereoscopic master 1 = stereoscopic slave	0
0xAF	AGC/AEC enable	0	AEC enable	0 = disable automatic exposure control 1 = enable automatic exposure control	0

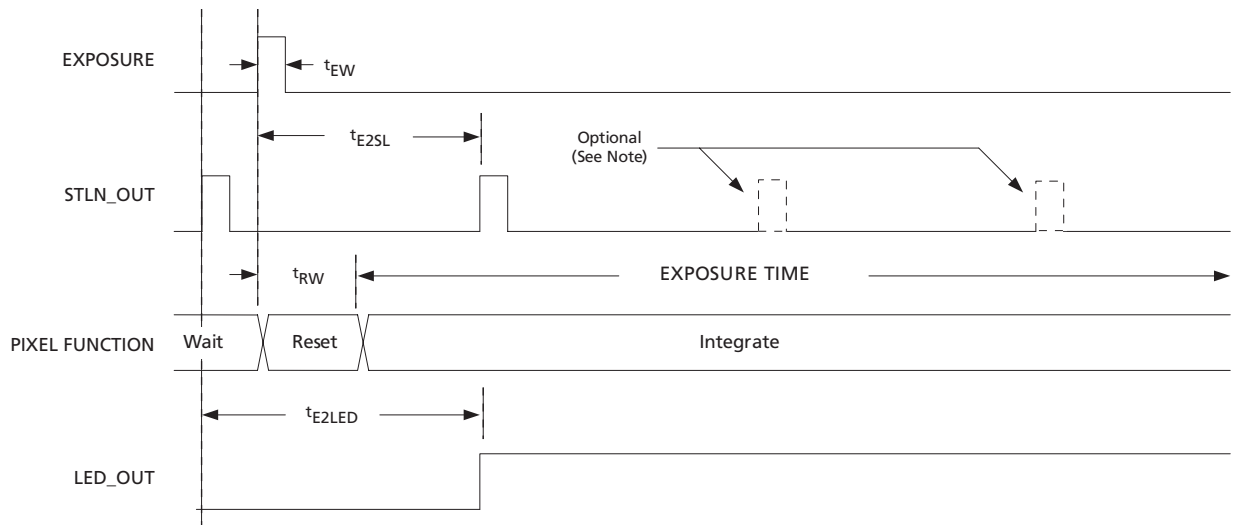
Automatic black level correction and automatic gain correction functions are optimized to work in an imaging system where the frame rate, exposure time, and scene dynamic range can be considered to remain constant. Therefore, for best performance in slave mode, it is recommended to disable these functions. The automatic black level correction is disabled by setting R0x47 bit 0 to "1;" the automatic gain correction is disabled by setting R0xAF bit 1 to "0."

Improved performance for simultaneous mode ($R0x07[8] = 1$) is obtained by setting $R0x20 = 0x3C5$ or $0x3C7$. Improved performance for sequential mode ($R0x07[8] = 0$) is obtained by setting $R0x20 = 0x3C5$ or $0x3C7$. In simultaneous mode, where exposure time exceeds readout time, the vertical blanking is internally extended, but the vertical blank register ($R0x06$) is not updated.

Start of Exposure

The start of exposure is controlled by the EXPOSURE input on the image sensor. Normally, EXPOSURE is held in a LOW state. To start exposing, two input pulses are needed. First, an STLN_OUT pulse must be applied. Then, EXPOSURE is changed to a HIGH state. This HIGH state is then sampled on the rising edge of the master clock (SYSCLK) of the image sensor. Thus, EXPOSURE must be held HIGH for at least one master clock cycle. The exposure period does not begin immediately. Any residual signal charge in the pixel cleared (that is, the pixel is reset). This pixel reset period lasts 128 master clock cycles.

Figure 4: Start of Exposure Detail

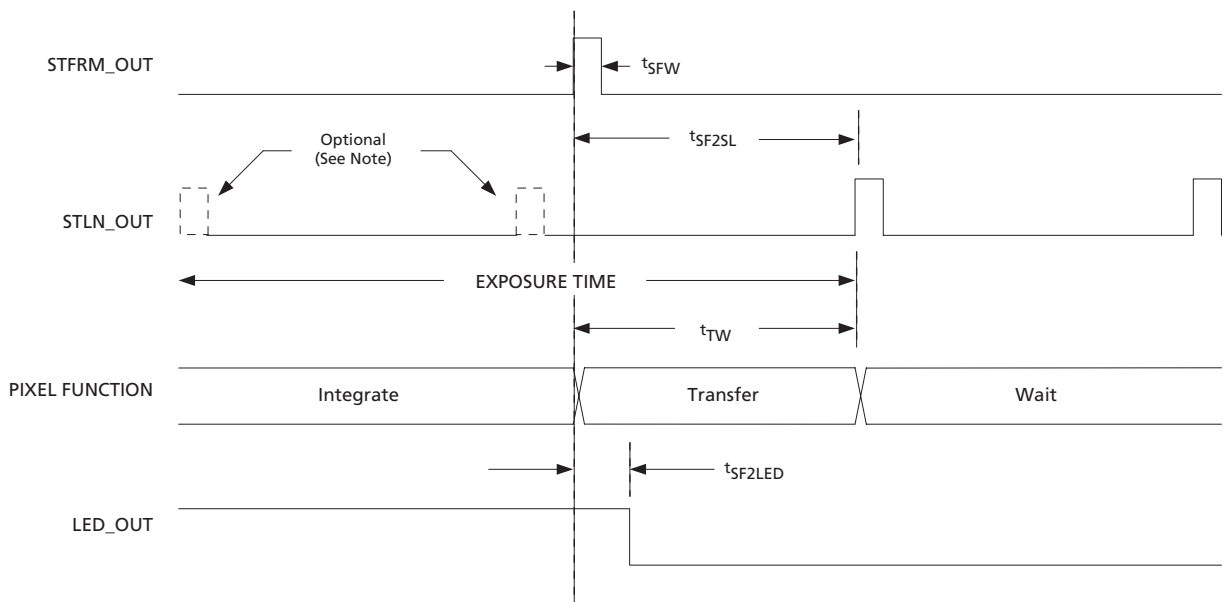


- Notes:
1. Not drawn to scale.
 2. STLN_OUT pulses during integration are optional for linear sequential operation only.

End of Exposure

The end of exposure is controlled by the STFRM_OUT input on the image sensor. This STFRM_OUT signal is usually an output of the image sensor; however, in slave mode it is converted to an input pin. Normally, STFRM_OUT is held in a LOW state. To stop exposing, this signal is changed to a HIGH state. This HIGH state is then sampled on the rising edge of the master clock of the image sensor. Thus, STFRM_OUT must be held HIGH for one master clock cycle. This change to a HIGH state causes the per-pixel integrated charges to be transferred from the pixel to the readout structure. For proper operation, STFRM_OUT HIGH state should be limited to one master clock cycle only. The exposure period does not end immediately. During the time where the per-pixel charges are being transferred, incident photons continue to be captured and transferred. This transfer time is typically one row-time.

Figure 5: End of Exposure Detail



- Notes:
1. Not drawn to scale.
 2. STLN_OUT pulses during integration are optional for linear sequential operation only.

Exposure Time Calculation

The exposure time is approximately the time between the rising edge of the EXPOSURE input signal and the rising edge of the STFRM_OUT input signal. To calculate the actual exposure time, the pixel reset time and the pixel transfer time, as well as the relative times between the input signals and the STLN_OUT input, are taken into account. The following equation applies:

$$exposure_time = t_{E2SF} - t_{RW} + t_{SF2SL} \quad (EQ 1)$$



Row-Time Definition

One row-time is equal to the sum of the number of active pixels (columns) (R0x04) and the number of horizontal blanking pixels (R0x05) divided by the pixel readout rate:

$$row_time = \frac{active_pixels + horizontal_blank_pixels}{SYSCLK_frequency} \quad (EQ\ 2)$$

$$row_time\ default_settings = \frac{752 + 94}{26.67\ MHz} = 31.72\ \mu s \quad (EQ\ 3)$$

Column binning does not affect the row-time (column binning factor applies equally to both the numerator and denominator of the row-time equation, thereby canceling itself out).

Note: Proper operation of the image sensor requires that the sum of the number of active pixels and the number of horizontal blanking pixels (R0x04 + R0x05) must be a value greater than or equal to 704.

Data Readout Overview

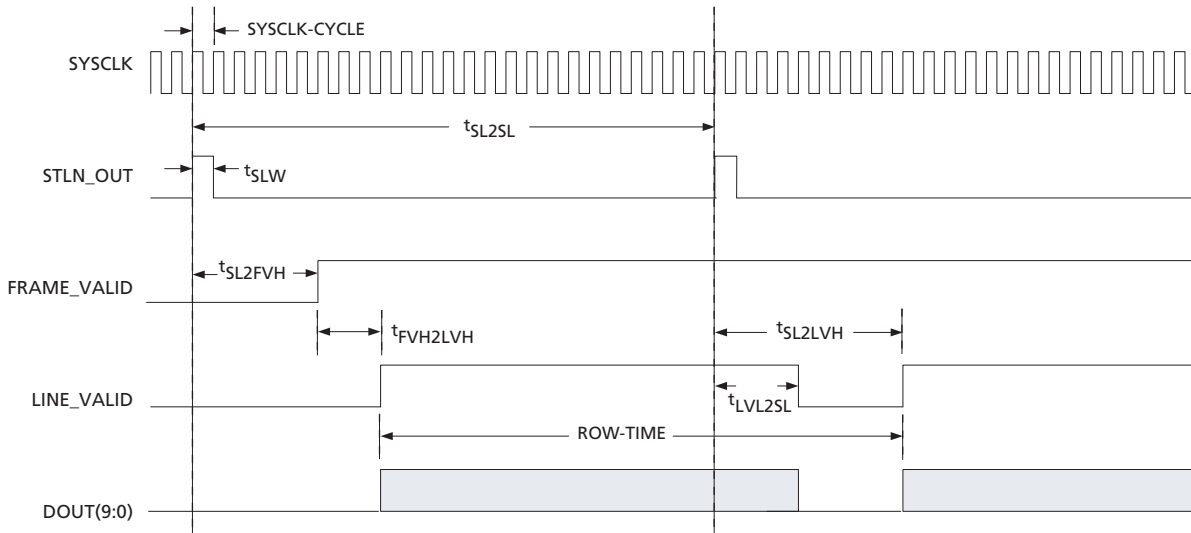
In slave mode, the image data flow is controlled by a trigger signal (STLN_OUT) that enables the readout of each row of image data. This control allows the slow-down of the data flow (that is, slow-down of the frame rate) should the host system not be able to process the image data fast enough. It also allows the synchronization of the host system's row-by-row image processing routines with the collection of new rows of image data.

Horizontal Row Read Enable

After exposure is complete and the per-pixel integrated charges have been transferred to the readout structure, the image sensor is ready to digitize and/or process the pixel data and to present this digital video data to the host system. The data is read to the host system in a horizontal row (line) by horizontal row manner. In slave mode, each row of video digital data must be individually enabled before it is read out.

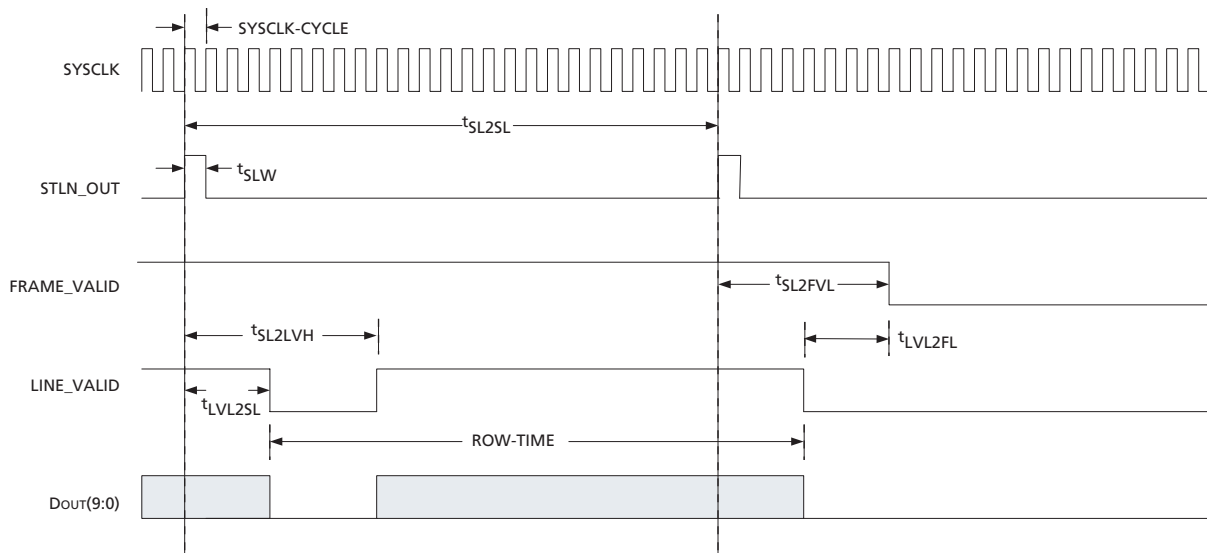
This row readout enabling is performed by the STLN_OUT input. This STLN_OUT signal is usually an output of the image sensor; however, in slave mode it is converted to an input pin. Normally, STLN_OUT is held in a LOW state. To enable the readout of one horizontal row, this signal is changed to a HIGH state. This change to a HIGH state causes the per-pixel integrated charges in the readout structure to be shifted to the analog-to-digital converters and through to the image data pipeline. For best performance, STLN_OUT must be held HIGH for one master clock cycle, and LOW for the remainder of the row-time.

Figure 6: Start of Readout Detail



Note: Not drawn to scale.

Figure 7: End of Readout Detail



Note: Not drawn to scale.



STLN_OUT Signal Restrictions

Because all pixels in the row (both active and blanking) must be read out before the next row readout can be started, the minimum period of STLN_OUT (shown as ⁴SL2SL) is forced to be greater than or equal to the calculated row-time. The minimum allowable STLN_OUT period is set by the following equation:

$$STLN_OUT_period_{minimum} = \frac{active_pixels + horizontal_blank_pixels}{SYSCLK_frequency} \quad (EQ\ 4)$$

$$STLN_OUT_period_{minimum@default_settings} = \frac{752 + 94}{26.67\ MHz} = 31.72\ \mu s \quad (EQ\ 5)$$

where the number of active pixels is the value stored in R0x04 and the number of horizontal blanking pixels is the value stored in R0x05.

The maximum allowable STLN_OUT period is set by the following equation:

$$STLN_OUT_period_{maximum} = \frac{(2 \times horizontal_blank_pixels) + active_pixels - 23}{SYSCLK_frequency} \quad (EQ\ 6)$$

$$STLN_OUT_period_{maximum@default_settings} = \frac{(2 \times 94) + 752 - 23}{26.67\ MHz} = 34.38\ ms \quad (EQ\ 7)$$

Enabling the next row readout (next STLN_OUT pulse) can occur no earlier than four master clock cycles prior to the falling edge of LINE_VALID. An STLN_OUT pulse that is applied any sooner will terminate the current row readout and begin the next row readout. For best operation, it is recommended that the period of STLN_OUT be set to one row-time.

STFRM_OUT Signal Restrictions

Because all pixels in a frame (both active and blanking) must be read out before the next frame readout can be started, the minimum period of STFRM_OUT (shown as ⁴SF2SF) is forced to be greater than or equal to the calculated frame time. The frame time is dependent on two variables: the number of rows read out per frame (both active and blanking) and the row-time (STLN_OUT signal period). The number of rows per frame is equal to the sum of the number of active rows (R0x03) and the number of vertical blanking rows (R0x06) divided by a row-binning factor (see the MT9V024 data sheet definitions for R0x0D bits [1:0]) (row-binning factor equals 1 for no binning, 2 for 2X binning, or 4 for 4X binning):

$$row_per_frame = \frac{active_rows + vertical_blank_rows}{row_binning_factor} \quad (EQ\ 8)$$

$$row_per_frame_{default_settings} = \frac{480 + 45}{1} = 525\ rows \quad (EQ\ 9)$$



The frame time is equal to the product of the number of rows per-frame and the row-time.

$$frame_time = (rows_per_frame) \times (STLN_OUT_period) \quad (EQ\ 10)$$

$$frame_time_{default_settings} = (525\ rows) \times \left(\frac{31.72\ \mu s}{row} \right) = 16.65\ ms \quad (EQ\ 11)$$

For accuracy, a small overhead time of four SYSCCLK-cycles should be added to the frame time. It has been omitted from Equation 10 for clarity.

Moreover, the minimum time between two successive STFRM_OUT pulses must be greater than or equal to this calculated frame time. In the event that STFRM_OUT is applied before the readout is complete (FRAME_VALID is asserted), the current readout will be aborted and all data lost.

Note: For proper operation, the STFRM_OUT and STLN_OUT input signals cannot be simultaneous. There must be at least three master clock cycles between the rising edges of these two input pulses.

Exposure and Data Synchronization Outputs

The MT9V024 image sensor offers an output synchronization signal (LED_OUT) that can be used to control the flash of a light source. The timing of this signal in slave mode is similar to the other exposure modes. The signal is normally held in a LOW state. LED_OUT will change to a HIGH state either one row-time after EXPOSURE goes HIGH or immediately after the first STLN_OUT pulse is applied, whichever happens first. LED_OUT will return to the normal LOW state typically two master clock cycles after the STFRM_OUT input is changed to HIGH.

To indicate that a valid frame of video data is being output from the image sensor, FRAME_VALID switches to a HIGH state. This change of state occurs at approximately R0x06 row-times after the exposure ends (LED_OUT changes to a LOW state). This change of state will only occur if the host system has issued an appropriate number of STLN_OUT pulses. This number of pulses equals the number of rows stored in the vertical blanking register (R0x06) (the default value is 45). FRAME_VALID will return to a LOW state after the host system has issued an additional number of STLN_OUT pulses equivalent to the number of rows in the window height register (R0x03) (the default value is 480).

During the valid video frame state, LINE_VALID switches to a HIGH state to indicate a valid row of video data is being presented. LINE_VALID switches to a HIGH state a set number of master clock cycles after the STLN_OUT pulse is applied. This number of cycles is set to be equal to four cycles plus the number of pixels stored in the horizontal blanking register (R0x05) (the default register value is 94). Thus, under default settings, the LINE_VALID signal switches to a HIGH state 98 master clock cycles after STLN_OUT has been asserted. LINE_VALID returns to a LOW state after a set number of master clock cycles equal to the number of pixels stored in the window width register (R0x04) (the default value is 752).

For complete information on these and other synchronization signals, refer to the MT9V024 data sheet.

Calculating the Frame Rate

Slave exposure mode supports both simultaneous and sequential readout modes. The actual frame rate is always the reciprocal of the STFRM_OUT period. Depending on the readout mode selected, the maximum allowable frame rate can be calculated.

In simultaneous readout mode, the reciprocal of the frame time is the maximum frame rate achievable by the image sensor. The maximum allowable frame rate is the reciprocal of the larger of either the frame time or the sum of the exposure time and an overhead factor.

$$frame_rate_{simultaneous} = \frac{1}{\text{larger of } [frame_time] \text{ or } [exposure_time + overhead]} \quad (\text{EQ 12})$$

If the exposure time is 33.27ms and default register settings are used, the maximum frame rate that is achievable is 30Hz ($1 / (33.27 + 0.06)ms$) —because 33.33ms is greater than the default register setting frame time of 16.65ms. Further, if the exposure time is 8.33ms and default register settings are used, the maximum frame rate that is achievable is 60Hz ($1 / 16.65ms$) because 8.33ms is less than the default register setting frame time of 16.65ms.

Note: The overhead factor, which represents the minimum time between the end of current exposure [n] and start of next exposure [$n+1$], is $2 \text{ row-times} + 4 \text{ SYSCLK-cycles}$, which equals 63.56μs under default settings.

In sequential readout mode, the maximum allowable frame rate is the reciprocal of the sum of the frame time, the exposure time, and the overhead factor.

$$frame_rate_{sequential} = \frac{1}{[frame_time] + [exposure_time + overhead]} \quad (\text{EQ 13})$$

A faster frame rate can only be achieved by reducing the number of active or blanking pixels (columns), by reducing the number of active or blanking rows, or by shortening the exposure time.



Example Frame Rate Calculations

Two examples follow on performing frame rate calculations for the MT9V024 image sensor. Table 3 below and Table 4 on page 14 show the settings used in the calculations.

Table 3: Example 1: Simultaneous Readout Frame Rate
(with a smaller image window and an approximate 6.15ms exposure time)

Image Sensor Condition	Setting Description	Register [Bits] = Value
Exposure mode	Slave	0x07[4:3] = 0
Exposure time	6.15ms	N/A
Readout mode	Simultaneous	0x07[8] = 1
Clock frequency	26.67 MHz	N/A
Window height	450	0x03[8:0] = 450
Window width	730	0x04[9:0] = 730
Horizontal blanking	87	0x05[9:0] = 87
Vertical blanking	20	0x06[14:0] = 20
Shutter width	200	0x0B[14:0] = 200
Row bin	No binning	0x0D[1:0] = 0

Step 1: Calculate the row-time.

$$row_time = \frac{active_pixels + horizontal_blank_pixels}{SYSCLK_frequency} \quad (EQ\ 14)$$

$$row_time = \frac{730 + 87}{26.67\ MHz} = 30.63\ \mu s \quad (EQ\ 15)$$

Step 2: Calculate the rows-per-frame read out.

$$rows_per_frame = \frac{active_rows + vertical_blank_rows}{row_binning_factor} \quad (EQ\ 16)$$

$$row_per_frame = \frac{450 + 20}{1} = 470\ rows \quad (EQ\ 17)$$

Step 3: Calculate the frame period.

$$frame_period = (rows_per_frame) \times (row_time) \quad (EQ\ 18)$$

$$frame_period = (470\ rows) \times \left(\frac{30.63\ \mu s}{row} \right) = 14.40ms \quad (EQ\ 19)$$



Step 4: Use the approximate exposure time.

$$exposure_time = 6.15ms \quad (EQ\ 20)$$

Step 5: Calculate the overhead factor.

$$overhead = [2x(row_time)] + \left[\frac{4}{SYSCLK_frequency} \right] \quad (EQ\ 21)$$

$$overhead = [2x(30.63\mu s)] + \left[\frac{4}{26.67\ MHz} \right] \quad (EQ\ 22)$$

$$overhead = [61.26\mu s] + [0.15\mu s] = 61.41\mu s \quad (EQ\ 23)$$

Step 6: Compare frame period with sum of actual exposure time and overhead factor.

$$frame_period \Leftrightarrow [exposure_time + overhead] \quad (EQ\ 24)$$

$$14.40ms \Leftrightarrow [6.15ms + 61.41\mu s] \quad (EQ\ 25)$$

$$14.40ms > 6.15ms \quad (EQ\ 26)$$

Step 7: Use larger value from Step 6 to calculate frame rate.

$$frame_rate_{simultaneous} = \frac{1}{larger\ of\ [frame_period]\ or\ [exposure_time + overhead]} \quad (EQ\ 27)$$

$$frame_rate = \frac{1}{14.40ms} \quad (EQ\ 28)$$

$$frame_rate = 69.44Hz \quad (EQ\ 29)$$



Table 4: Example 2: Sequential Readout Frame Rate
(with a smaller image window and an approximate 6.15ms exposure time)

Image Sensor Condition	Setting Description	Register [Bits] = Value
Exposure mode	Slave	0x07[4:3] = 0
Exposure time	6.15ms	N/A
Readout mode	Sequential	0x07[8] = 0
Clock frequency	26.67 MHz	N/A
Window height	450	0x03[8:0] = 450
Window width	730	0x04[9:0] = 730
Horizontal blanking	87	0x05[9:0] = 87
Vertical blanking	20	0x06[14:0] = 20
Shutter width	200	0x0B[14:0] = 200
Row bin	No binning	0x0D[1:0] = 0

Step 1: Calculate the row-time.

$$row_time = \frac{active_pixels + horizontal_blank_pixels}{SYSCLK_frequency} \quad (EQ\ 30)$$

$$row_time = \frac{730 + 87}{26.67\ MHz} = 30.63\ \mu s \quad (EQ\ 31)$$

Step 2: Calculate the rows-per-frame read out.

$$rows_per_frame = \frac{active_rows + vertical_blank_rows}{row_binning_factor} \quad (EQ\ 32)$$

$$row_per_frame = \frac{450 + 20}{1} = 470\ rows \quad (EQ\ 33)$$

Step 3: Calculate the frame period.

$$frame_period = (rows_per_frame) \times (row_time) \quad (EQ\ 34)$$

$$frame_period = (470\ rows) \times \left(\frac{30.63\ \mu s}{row} \right) = 14.40ms \quad (EQ\ 35)$$

Step 4: Use the approximate exposure time.

$$exposure_time = 6.15ms \quad (EQ\ 36)$$

Step 5: Calculate overhead factor.

$$overhead = [2x(row_time)] + \left[\frac{4}{SYSCLK_frequency} \right] \quad (EQ 37)$$

$$overhead = [2x(30.63\mu s)] + \left[\frac{4}{26.67\text{ MHz}} \right] \quad (EQ 38)$$

$$overhead = [61.26\mu s] + [0.15\mu s] = 61.41\mu s \quad (EQ 39)$$

Step 6: Calculate frame rate.

$$frame_rate_{sequential} = \frac{1}{[frame_period] + [exposure_time + overhead]} \quad (EQ 40)$$

$$frame_rate = \frac{1}{[14.40ms] + [6.15ms + 61.41\mu s]} \quad (EQ 41)$$

$$frame_rate = \frac{1}{20.61ms} \quad (EQ 42)$$

$$frame_rate = 48.52Hz \quad (EQ 43)$$

Conclusion

The slave exposure mode of the MT9V024 image sensor supports imaging applications where it is necessary to synchronize the exposure time of the image sensor with an external event or when the host system needs to control the flow of image data.

For more information on this and other features, refer to the MT9V024 data sheet located at Aptina's Web site at www.aplina.com



Revision History

Rev. A	11/16/12
• Initial release.	

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