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TCS3771

Color Light-To-Digital Converter with Proximity Sensing

General Description

The TCS3771 family of devices provides red, green, blue, and clear (RGBC) light sensing and proximity detection (when coupled with an external IR LED). They detect light intensity under a variety of lighting conditions and through a variety of attenuation materials. The proximity detection feature allows a large dynamic range of operation for use in short distance detection behind dark glass such as in a cell phone or for longer distance measurements for applications such as presence detection for monitors or laptops. The programmable proximity detection enables continuous measurements across the entire range. In addition, an internal state machine provides the ability to put the device into a low power mode in between RGBC and proximity measurements providing very low average power consumption.

The TCS3771 is directly useful in lighting conditions containing minimal IR content such as LED RGB backlight control, reflected LED color sampler, or fluorescent light color temperature detector. With the addition of an IR blocking filter, the device is an excellent ambient light sensor, color temperature monitor, and general purpose color sensor.

The proximity function is targeted specifically towards battery-powered mobile devices, LCD monitor, laptop, and flat-panel television applications. In cell phones, the proximity detection can detect when the user positions the phone close to their ear. The device is fast enough to provide proximity information at a high repetition rate needed when answering a phone call. It can also detect both close and far distances so the application can implement more complex algorithms to provide a more robust interface. In laptop or monitor applications, the product is sensitive enough to determine whether a user is in front of the laptop using the keyboard or away from the desk. This provides both improved *green* power saving capability and the added security to lock the computer when the user is not present.

Ordering Information and Content Guide appear at end of datasheet.

Key Benefits & Features

The benefits and features of the TCS3771 are listed below:

Figure 1:
Added Value of using TCS3771

Benefits	Features
• Single Device reduces board space	• RGB Color Sensing and Proximity Detection in a Single Device

• Enables both Correlated Color Temperature and Ambient Light Sensing across wide range of lighting condition applications	• Color Light Sensing
	  • Programmable Analog Gain, Integration Time, and Interrupt Function with Upper and Lower Thresholds
	  • Resolution Up to 16 bits
	  • Very High Sensitivity - Ideally Suited for Operation Behind Dark Glass
	  • Up to 1,000,000:1 Dynamic Range

• Enables versatile Infra-red proximity based object detection	• Proximity Detection
	  • Programmable Number of IR Pulses, Current Sink for the IR LED - No Limiting Resistor Needed, and Interrupt Function with Upper and Lower Thresholds
	  • Covers a 2000:1 Dynamic Range

• Low power wait state programmability reduces average power consumption	• Low Power Wait State
	  • 65µA Typical Current
	  • Wait Timer is Programmable from 2.4ms to > 7 seconds

• Digital interfaces are less susceptible to noise	• I^2C Interface Compatible • Up to 400kHz (I^2C Fast Mode)
• Reduces micro-processor Interrupt Overhead with both up persist and no-persist interrupt thresholds	• Dedicated Interrupt Pin
• Enables drop-in and foot-print compatible solutions	• Pin and Register Set Compatible with the TCS3x7x Family of Devices
• Reduces board space requirements while simplifying designs	• Small 2mm × 2.4mm Dual Flat No-Lead Package
• Low power sleep state reduces average power consumption	• Sleep Mode - 2.5µA Typical Current

Applications

The applications of TCS3771 include:

- RGB LED Backlight Control
- Ambient Color Temperature Sensing
- Cell Phone Touch Screen Disable
- Notebook/Monitor Security
- Automatic Menu Popup

- Industrial Process Control
- Medical Diagnostics

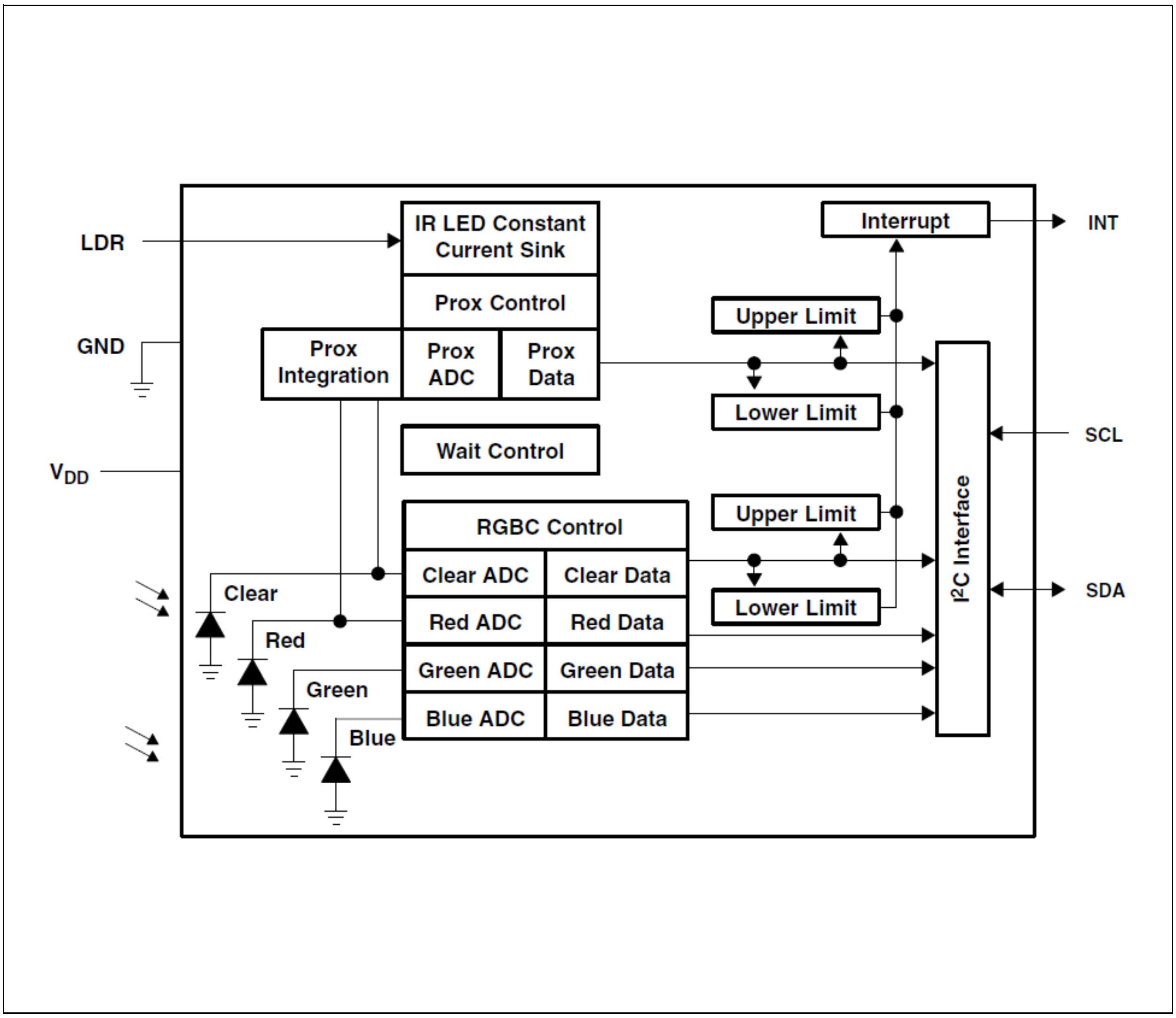
End Products and Market Segments

- HDTVs, Mobile Handsets, Tablets, Laptops, Monitors, PMP (Portable Media Payers)
- Medical and Commercial Instrumentation
- Consumer Toys
- Industrial/Commercial Lighting

Block Diagram

The functional blocks of this device for reference are shown below:

Figure 2:
TCS3771 Block Diagram



Detailed Description

The TCS3771 light-to-digital device contains a 4 × 4 photodiode array, integrating amplifiers, ADCs, accumulators, clocks, buffers, comparators, a state machine, and an I^2C interface. The 4 × 4 photodiode array is composed of red-filtered, green-filtered, blue-filtered, and clear photodiodes - four of each type. Four integrating ADCs simultaneously convert the amplified photodiode currents to a digital value providing up to 16 bits of resolution. Upon completion of the conversion cycle, the conversion result is transferred to the data registers. The transfers are double-buffered to ensure that the integrity of the data is maintained. Communication to the device is accomplished through a fast (up to 400kHz), two-wire I^2C serial bus for easy connection to a microcontroller or embedded controller.

The TCS3771 provides a separate pin for level-style interrupts. When interrupts are enabled and a preset value is exceeded, the interrupt pin is asserted and remains asserted until cleared by the controlling firmware. The interrupt feature simplifies and improves system efficiency by eliminating the need to poll a sensor for a light intensity or proximity value. An interrupt is generated when the value of an RGBC or proximity conversion exceeds either an upper or lower threshold. In addition, a programmable interrupt persistence feature allows the user to determine how many consecutive exceeded thresholds are necessary to trigger an interrupt. Interrupt thresholds and persistence settings are configured independently for both RGBC and proximity.

Proximity detection requires only a single external IR LED. An internal LED driver can be configured to provide a constant current sink of 12.5mA, 25mA, 50mA or 100mA of current. No external current limiting resistor is required. The number of proximity LED pulses can be programmed from 1 to 255 pulses. Each pulse has a 14µs period. This LED current coupled with the programmable number of pulses provides a 2000:1 contiguous dynamic range.

Pin Assignments

The TCS3771 pin assignments are described below:

Figure 3:
Pin Diagram of Package FN Dual Flat No-Lead (Top View)

Package drawing not to scale.

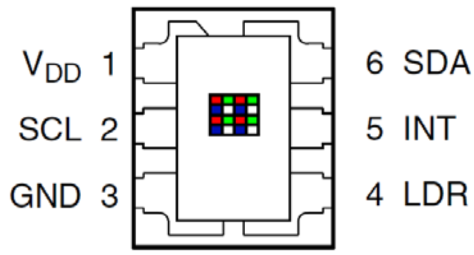


Figure 4:
Terminal Functions

Terminal		Type	Description
Name	No		
V_{DD}	1		Supply voltage
SCL	2	I	I^2C serial clock input terminal - clock signal for I^2C serial data
GND	3		Power supply ground. All voltages are referenced to GND.
LDR	4	O	LED driver for proximity emitter - up to 100mA, open drain
INT	5	O	Interrupt - open drain (active low)
SDA	6	I/O	I^2C serial data I/O terminal - serial data I/O for I^2C

Absolute Maximum Ratings

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only. Functional operation of the device at these or any other conditions beyond those indicated under Recommended Operating Conditions is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Figure 5:
Absolute Maximum Ratings over Operating Free-Air Temperature Range (unless otherwise noted)

Symbol	Parameter	Min	Max	Unit
V_{DD}	Supply voltage [1]		3.8	V
V_O	Digital output voltage range	-0.5	3.8	V
I_O	Digital output current	-1	20	mA
T_{stg}	Storage temperature range	-40	85	°C
	ESD tolerance, human body model		2000	V

Note(s):

1. All voltages are with respect to GND.

Electrical Characteristics

All limits are guaranteed. The parameters with min and max values are guaranteed with production tests or SQC (Statistical Quality Control) methods.

Figure 6:
Recommended Operating Conditions

Symbol	Parameter	Min	Nom	Max	Unit
V_{DD}	Supply voltage	2.7	3	3.3	V
T_A	Operating free-air temperature	-30		70	°C

Figure 7:
Operating Characteristics, V_{DD} = 3V, T_A = 25°C (unless otherwise noted)

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
I_{DD}	Supply current	Active - LDR pulses off		235	330	µA
		Wait mode		65		
		Sleep mode - no I^2C activity		2.5	10	
V_{OL}	INT, SDA output low voltage	3mA sink current	0		0.4	V
		6mA sink current	0		0.6	
I_{LEAK}	Leakage current, SDA, SCL, INT pins		-5		5	µA
I_{LEAK}	Leakage current, LDR pin		-10		+10	µA
V_{IH}	SCL, SDA input high voltage	TCS37715	0.7 V_{DD}			V
		TCS37717	1.25			
V_{IL}	SCL, SDA input low voltage	TCS37715			0.3V_{DD}	V
		TCS37717			0.54	

Figure 8:
Optical Characteristics, V_{DD} = 3V, T_A = 25°C, Gain = 16, ATIME = 0xF6 (unless otherwise noted) [1]

	Parameter	Test Conditions	Red Channel			Green Channel			Blue Channel			Clear Channel			Unit
			Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
R_e	Irradiance responsivity	λ_D = 465nm, [2]	0%		15%	10%		42%	65%		88%	19.2	24	28.8	Counts/ (μW/cm^2)
		λ_D = 525nm, [3]	6%		25%	60%		85%	9%		35%	22.4	28	33.6	
		λ_D = 625nm, [4]	85%		110%	0%		15%	5%		25%	27.2	34	40.8	

Note(s):

1. The percentage shown represents the ratio of the respective red, green, or blue channel value to the clear channel value.
2. The 465nm input irradiance is supplied by an InGaN light-emitting diode with the following characteristics: dominant wavelength λ_D = 465nm, spectral halfwidth $\Delta\lambda½$ = 22nm, and luminous efficacy = 75lm/W.
3. The 525nm input irradiance is supplied by an InGaN light-emitting diode with the following characteristics: dominant wavelength λ_D = 525nm, spectral halfwidth $\Delta\lambda½$ = 35nm, and luminous efficacy = 520lm/W.
4. The 625nm input irradiance is supplied by a AlInGaP light-emitting diode with the following characteristics: dominant wavelength λ_D = 625nm, spectral halfwidth $\Delta\lambda½$ = 9nm, and luminous efficacy = 155lm/W.

Figure 9:
RGBC Characteristics, V_{DD} = 3V, T_A = 25°C, AGAIN = 16, AEN = 1 (unless otherwise noted)

Parameter	Test Conditions	Min	Typ	Max	Unit
Dark ADC count value	E_e = 0, AGAIN = 60×, ATIME = 0xD6 (100ms)	0	1	5	Counts
ADC integration time step size	ATIME = 0xFF	2.27	2.4	2.56	ms
ADC number of integration steps		1		256	Steps
ADC counts per step		0		1024	Counts
ADC count value	ATIME = 0xC0 (153.6ms)	0		65535	Counts
Gain scaling, relative to 1× gain setting	4×	3.8	4	4.2	%
	16×	15	16	16.8	
	60×	58	60	63	

Figure 10:
Proximity Characteristics, V_{DD} = 3V, T_A = 25°C, Gain = 16, PEN = 1 (unless otherwise noted)

	Parameter	Test Conditions	Condition	Min	Typ	Max	Unit
I_{DD}	Supply current	LDR pulse on			3		mA
	ADC conversion time step size	PTIME = 0xFF		2.27	2.4	2.56	ms
	ADC number of integration steps			1		256	Steps
	ADC counts per step			0		1023	Counts
	IR LED pulse count			0		255	Pulses
	LED pulse period	Two or more pulses			14		µs
	LED pulse width - LED on time				6.3		µs
	LED drive current	I_{SINK} sink current @ 600mV, LDR pin	PDRIVE = 0	80	106	132	mA
			PDRIVE = 1		50		
			PDRIVE = 2		25		
			PDRIVE = 3		12.5		
	Dark count value	E_e = 0, PTIME = 0xFB, PPULSE = 2				900	Counts
	Red channel	λ_P = 850nm, E_e = 45.3µW/cm^2, PTIME = 0xFB, PPULSE = 2 (1)		1000		3000	Counts
	Clear channel	λ_P = 850nm, E_e = 45.3µW/cm^2, PTIME = 0xFB, PPULSE = 2 (1)		1000		3000	Counts
	Operating distance (2)				30		Inches

Note(s):

1. The specified light intensity is 100% modulated by the pulse output of the device so that during the pulse output low time, the light intensity is at the specified level, and 0 otherwise.
2. Proximity Operating Distance is dependent upon emitter properties and the reflective properties of the proximity surface. The nominal value shown uses an IR emitter with a peak wavelength of 850nm and a 20° half angle. The proximity surface used is a 90% reflective (white surface) 16 × 20-inch Kodak Gray Card. 60mw/SR, 100mA, 64 pulses, open view (no glass). **Greater distances are achievable with appropriate system considerations.**

Figure 11:
Wait Characteristics, V_{DD} = 3V, T_A = 25°C, Gain = 16, WEN = 1 (unless otherwise noted)

Parameter	Test Conditions	Channel	Min	Typ	Max	Unit
Wait step size	WTIME = 0xFF		2.27	2.4	2.56	ms
Wait number of steps			1		256	Steps

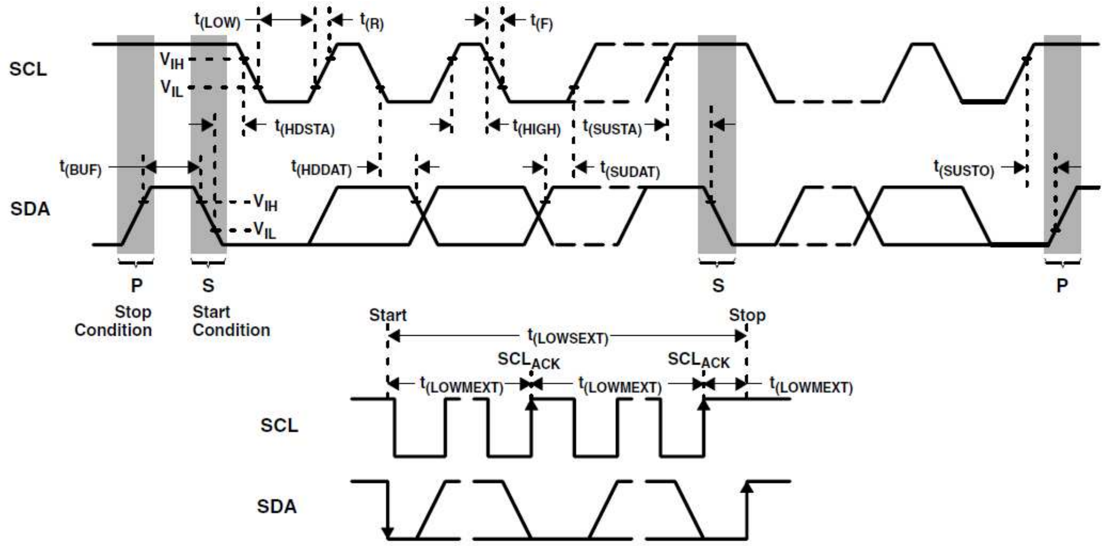
Figure 12:
AC Electrical Characteristics, V_{DD} = 3V, T_A = 25°C (unless otherwise noted)

Symbol	Parameter [1]	Test Conditions	Min	Typ	Max	Unit
$f_{(SCL)}$	Clock frequency (I^2C only)		0		400	kHz
$t_{(BUF)}$	Bus free time between start and stop condition		1.3			µs
$t_{(HDSTA)}$	Hold time after (repeated) start condition. After this period, the first clock is generated.		0.6			µs
$t_{(SUSTA)}$	Repeated start condition setup time		0.6			µs
$t_{(SUSTO)}$	Stop condition setup time		0.6			µs
$t_{(HDDAT)}$	Data hold time		0			µs
$t_{(SUDAT)}$	Data setup time		100			ns
$t_{(LOW)}$	SCL clock low period		1.3			µs
$t_{(HIGH)}$	SCL clock high period		0.6			µs
t_F	Clock/data fall time				300	ns
t_R	Clock/data rise time				300	ns
C_i	Input pin capacitance				10	pF

Note(s):
1. Specified by design and characterization; not production tested.

Parameter Measurement Information

Figure 13:
Timing Diagrams



Typical Characteristics

Figure 14:
Photodiode Spectral Responsivity

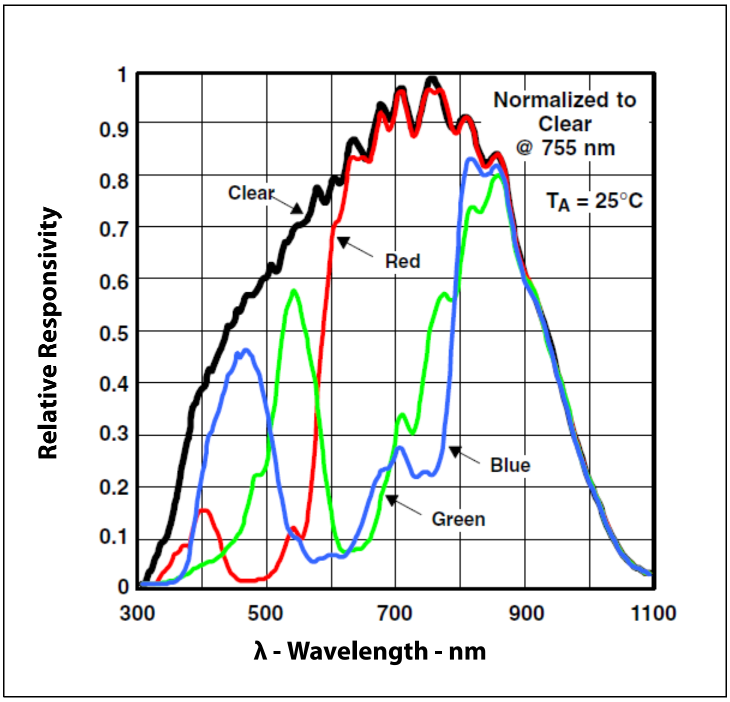


Figure 15:
Typical LDR Current vs. Voltage

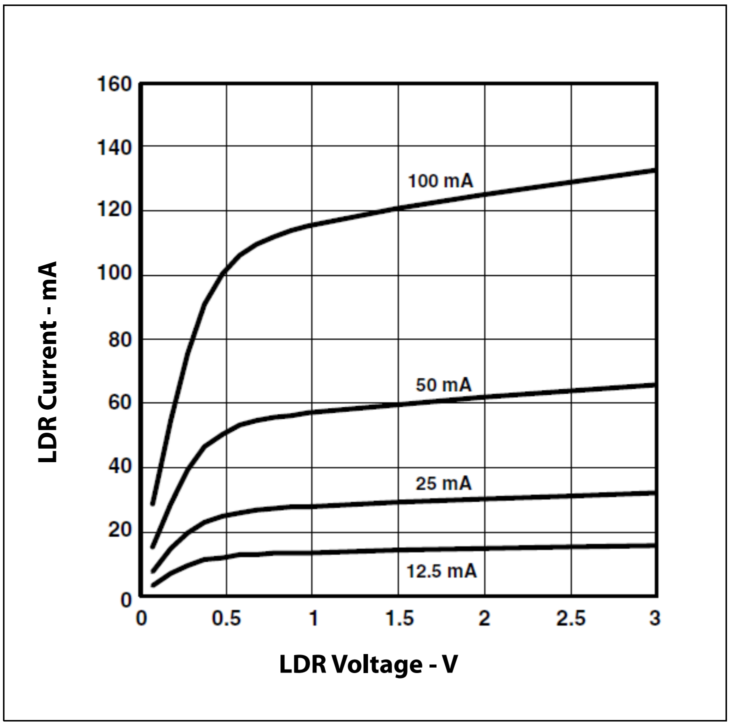


Figure 16:
Normalized I_{DD} vs. V_{DD} and Temperature

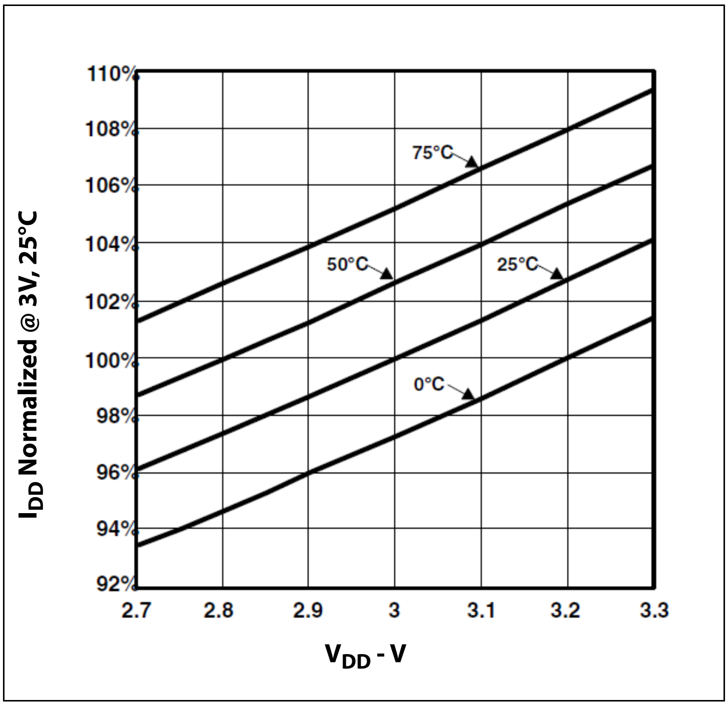


Figure 17:
Normalized Responsivity vs. Angular Displacement

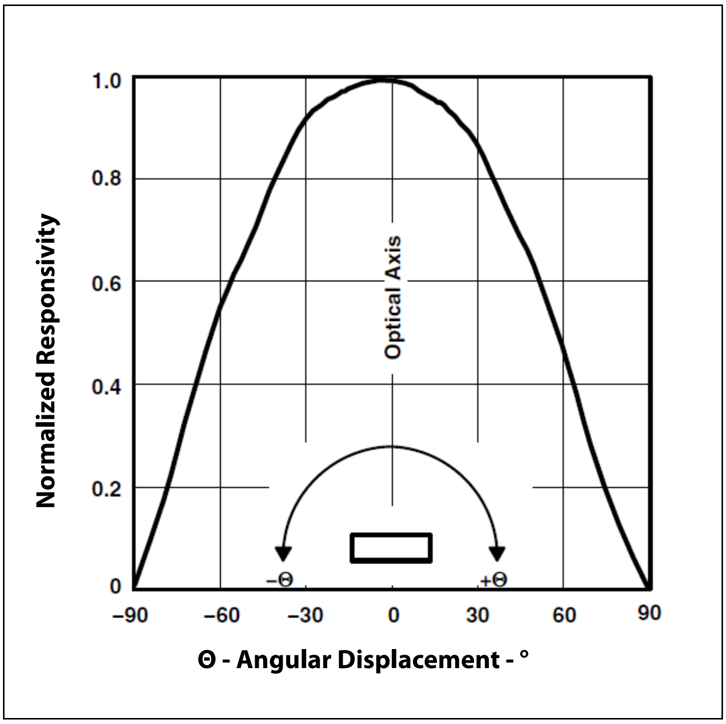
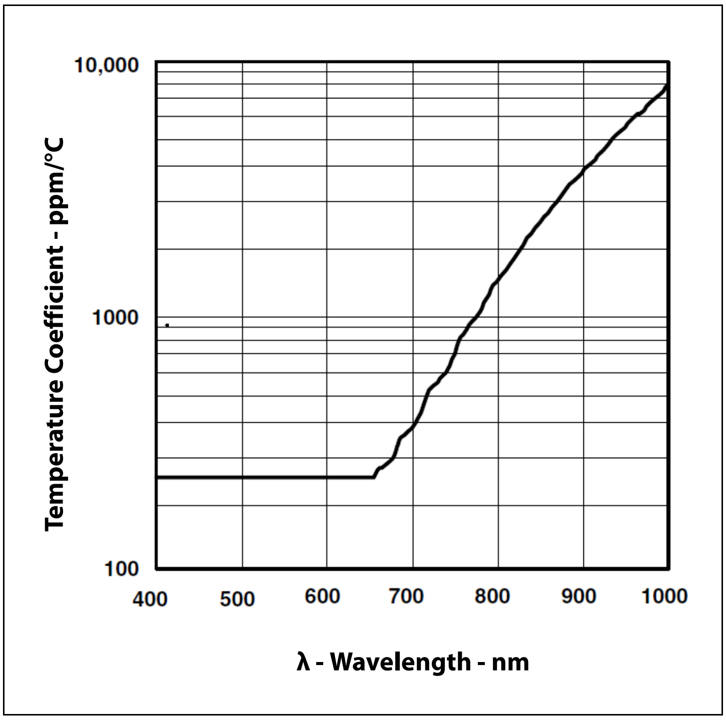


Figure 18:
Responsivity Temperature Coefficient

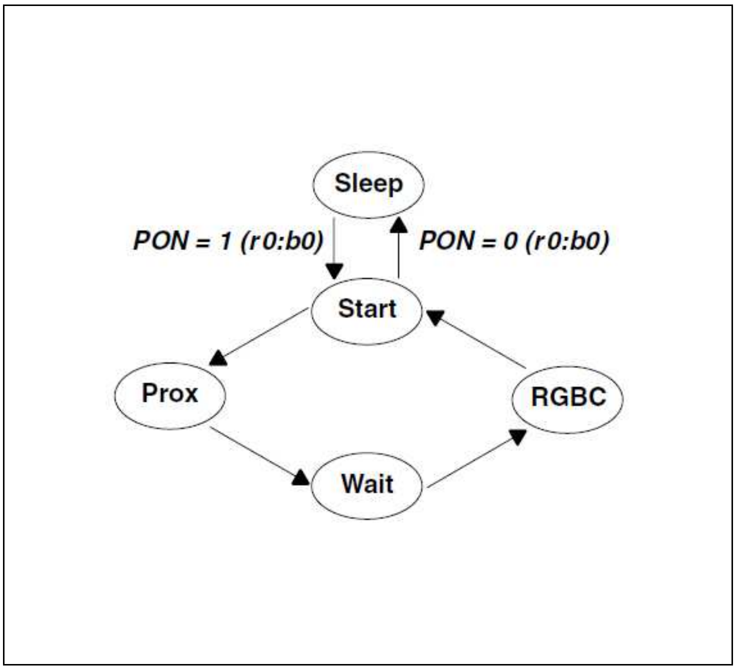


Principles of Operation

System State Machine

The TCS3771 provides control of RGBC, proximity detection, and power management functionality through an internal state machine (Figure 19). After a power-on-reset, the device is in the sleep mode. As soon as the PON bit is set, the device will move to the start state. It will then continue through the Prox, Wait, and RGBC states. If these states are enabled, the device will execute each function. If the PON bit is set to 0, the state machine will continue until all conversions are completed and then go into a low power sleep mode.

Figure 19:
Simplified State Diagram

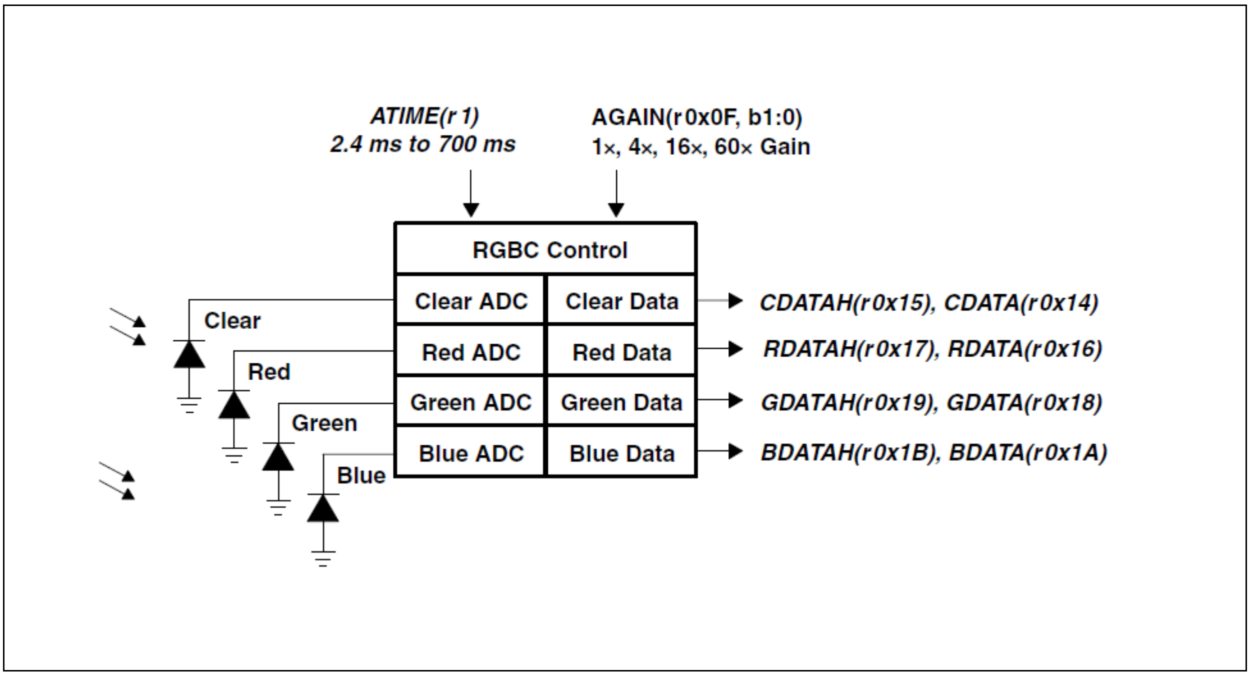


Note(s): In this document, the nomenclature uses the bit field name in italics followed by the register number and bit number to allow the user to easily identify the register and bit that controls the function. For example, the power on (PON) is in register 0, bit 0. This is represented as *PON (r0:b0)*.

RGBC Operation

The RGBC engine contains RGBC gain control (AGAIN) and four integrating analog-to-digital converters (ADC) for the RGBC photodiodes. The RGBC integration time (ATIME) impacts both the resolution and the sensitivity of the RGBC reading. Integration of all four channels occurs simultaneously and upon completion of the conversion cycle, the results are transferred to the color data registers. This data is also referred to as channel count. The transfers are double-buffered to ensure that invalid data is not read during the transfer. After the transfer, the device automatically moves to the next state in accordance with the configured state machine.

Figure 20:
RGBC Operation



The registers for programming the integration and wait times are a 2’s compliment values. The actual time can be calculated as follows:

ATIME = 256 - Integration Time / 2.4ms

Inversely, the time can be calculated from the register value as follows:

Integration Time = 2.4ms × (256 - ATIME)

For example, if a 100-ms integration time is needed, the device needs to be programmed to:

256 - (100 / 2.4) = 256 - 42 = 214 = 0xD6

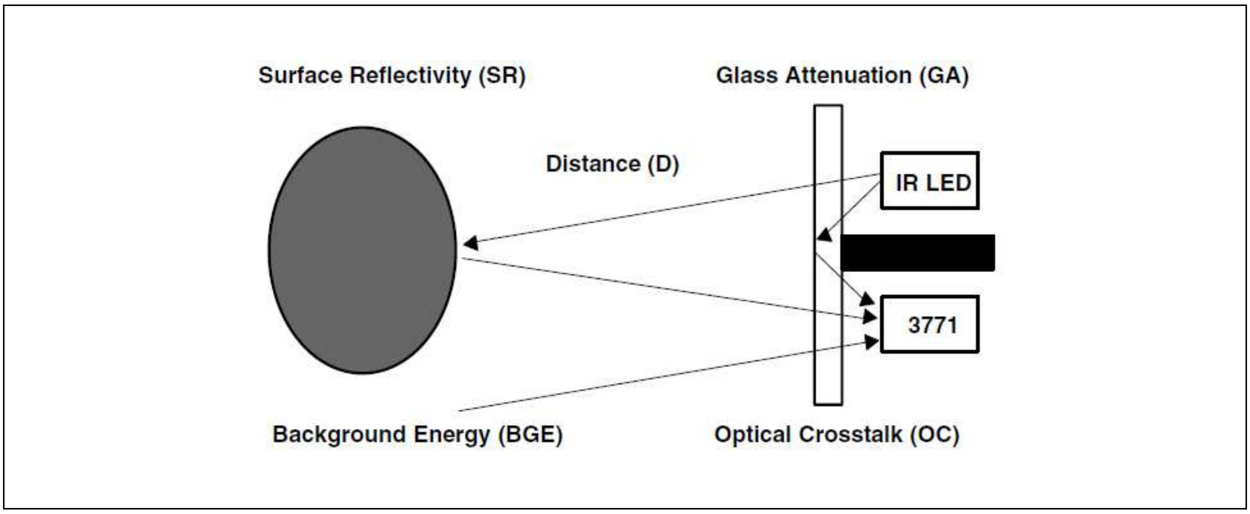
Conversely, the programmed value of 0xC0 would correspond to:

(256 - 0xC0) × 2.4 = 64 × 2.4 = 154ms

Proximity Detection

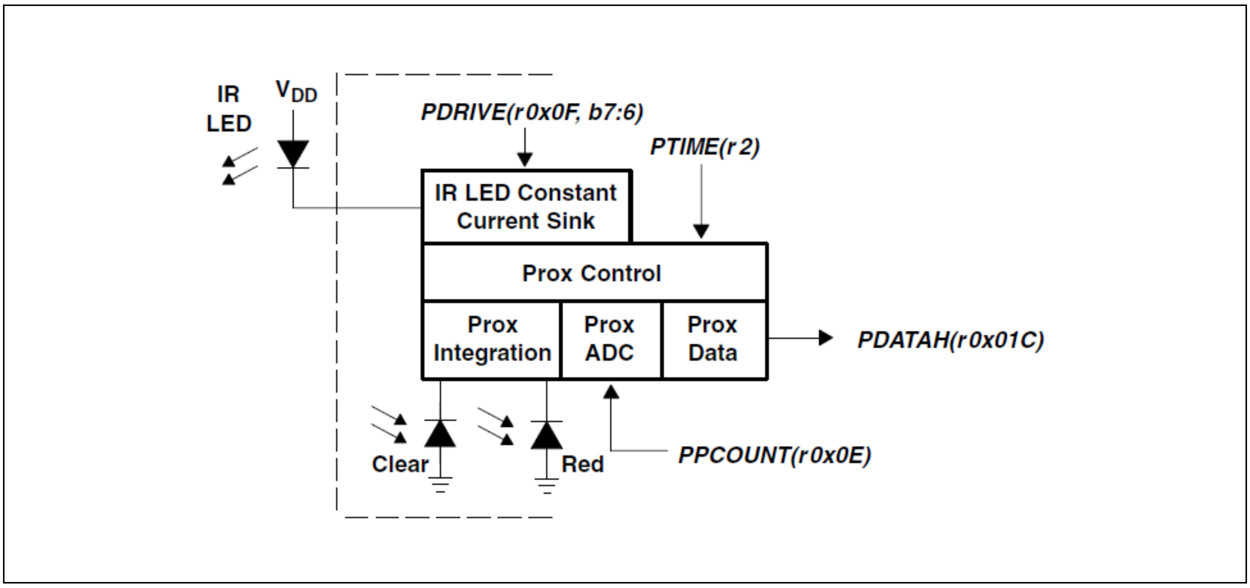
Proximity sensing uses an external light source (generally an infrared emitter) to emit light, which is then viewed by the integrated light detector to measure the amount of reflected light when an object is in the light path (Figure 21). The amount of light detected from a reflected surface can then be used to determine an object's proximity to the sensor.

Figure 21:
Proximity Detection



The TCS3771 has controls for the number of IR pulses (PPCOUNT), the integration time (PTIME), the LED drive current (PDRIVE) and the photodiode configuration (PDIODE). The photodiode configuration can be set to red diode (recommended), clear diode, or a combination of both diodes. At the end of the integration cycle, the results are latched into the proximity data (PDATA) register.

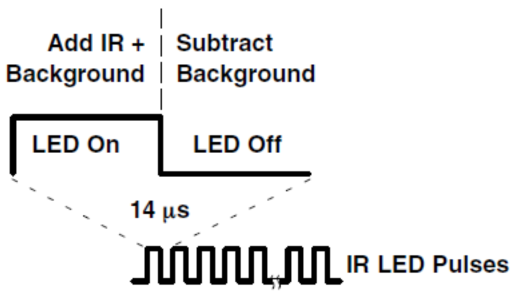
Figure 22:
Proximity Detection Operation



The LED drive current is controlled by a regulated current sink on the LDR pin. This feature eliminates the need to use a current limiting resistor to control LED current. The LED drive current can be configured for 12.5mA, 25mA, 50mA, or 100mA. For higher LED drive requirements, an external P-FET transistor can be used to control the LED current.

The number of LED pulses can be programmed to any value between 1 and 255 pulses as needed. Increasing the number of LED pulses at a given current will increase the sensor sensitivity. Sensitivity grows by the square root of the number of pulses. Each pulse has a 14µs period.

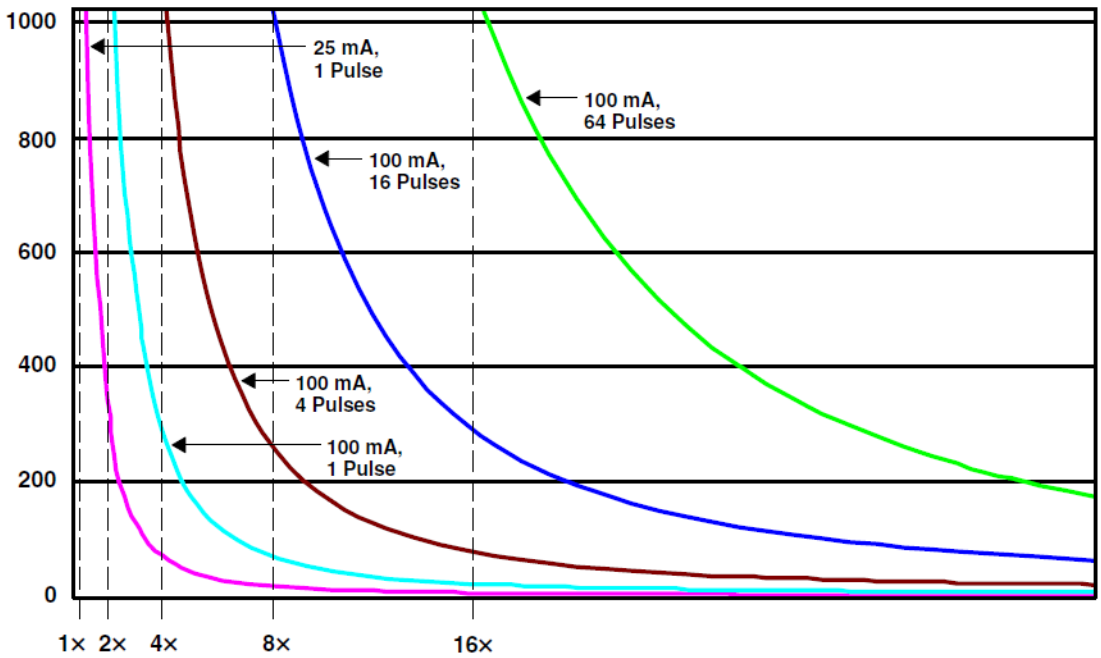
Figure 23:
Proximity IR LED Waveform



The proximity integration time (PTIME) is the period of time that the internal ADC converts the analog signal to a digital count. It is recommend that this be set to a minimum of PTIME = 0xFF or 2.4ms.

The combination of LED power and number of pulses can be used to control the distance at which the sensor can detect proximity. Figure 24 shows an example of the distances covered with settings such that each curve covers 2× the distance. Counts up to 64 pulses provide a 16× range.

Figure 24:
Proximity ADC Count vs. Relative Distance



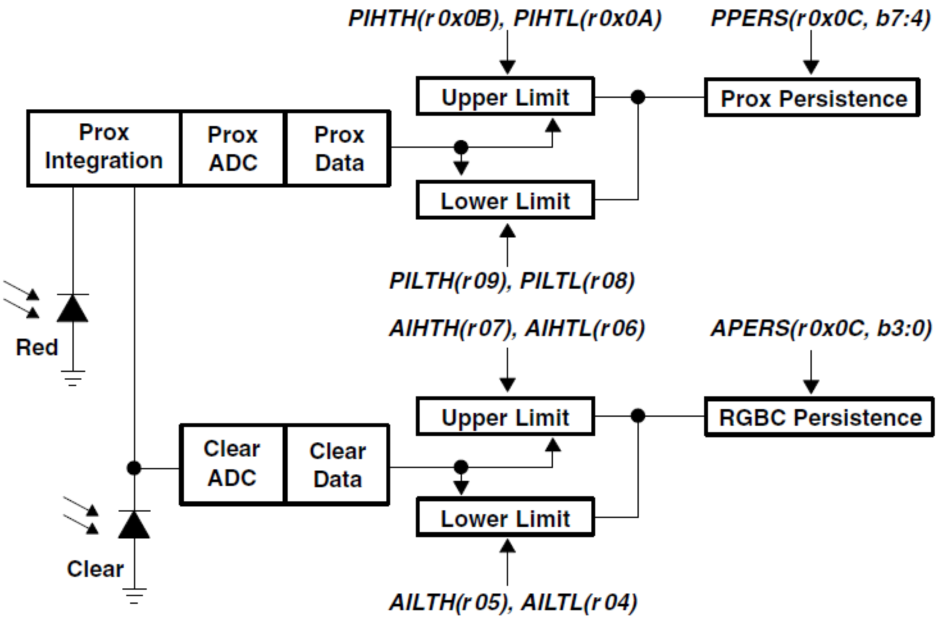
Interrupts

The interrupt feature simplifies and improves system efficiency by eliminating the need to poll the sensor for light intensity or proximity values outside of a user-defined range. While the interrupt function is always enabled and it's status is available in the status register (0x13), the output of the interrupt state can be enabled using the proximity interrupt enable (PIEN) or RGBC interrupt enable (AIEN) fields in the Enable Register (0x00).

Four 16-bit interrupt threshold registers allow the user to set limits below and above a desired light level and proximity range. An interrupt can be generated when the RGBC Clear data (CDATA) falls outside of the desired light level range, as determined by the values in the RGBC interrupt low threshold registers (AILTx) and RGBC interrupt high threshold registers (AIHTx). Likewise, an out-of-range proximity interrupt can be generated when the proximity data (PDATA) falls below the proximity interrupt low threshold (PILTx) or exceeds the proximity interrupt high threshold (PIHTx). It is important to note that the low threshold value must be less than the high threshold value for proper operation.

To further control when an interrupt occurs, the device provides a persistence filter. The persistence filter allows the user to specify the number of consecutive out-of-range RGBC or proximity occurrences before an interrupt is generated. The persistence register (0x0C) allows the user to set the RGBC persistence (APERS) and the proximity persistence (PPERS) values. See the persistence register for details on the persistence filter values. Once the persistence filter generates an interrupt, it will continue until a special function interrupt clear command is received (see Command Register).

Figure 25:
Programmable Interrupt



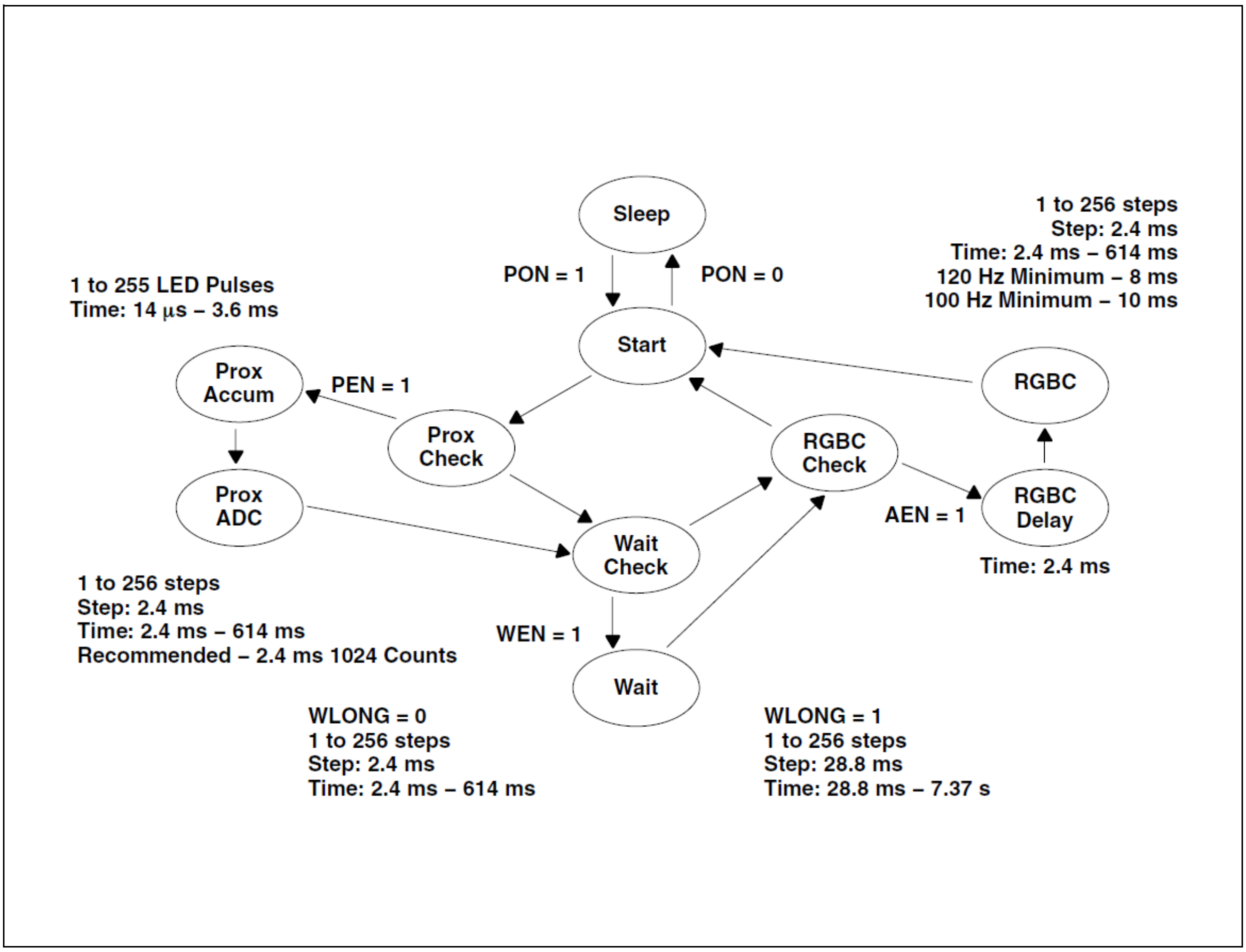
State Diagram

Figure 26 shows a more detailed flow for the state machine. The device starts in the sleep mode. The PON bit is written to enable the device. A 2.4ms delay will occur before entering the start state. If the PEN bit is set, the state machine will step through the proximity states of proximity accumulate and then proximity ADC conversion. As soon as the conversion is complete, the state machine will move to the following state.

If the WEN bit is set, the state machine will then cycle through the wait state. If the WLONG bit is set, the wait cycles are extended by 12× over normal operation. When the wait counter terminates, the state machine will step to the RGBC state.

The AEN should always be set, even in proximity-only operation. In this case, a minimum of 1 integration time step should be programmed. The RGBC state machine will continue until it reaches the terminal count at which point the data will be latched in the RGBC register and the interrupt set, if enabled.

Figure 26:
Expanded State Diagram



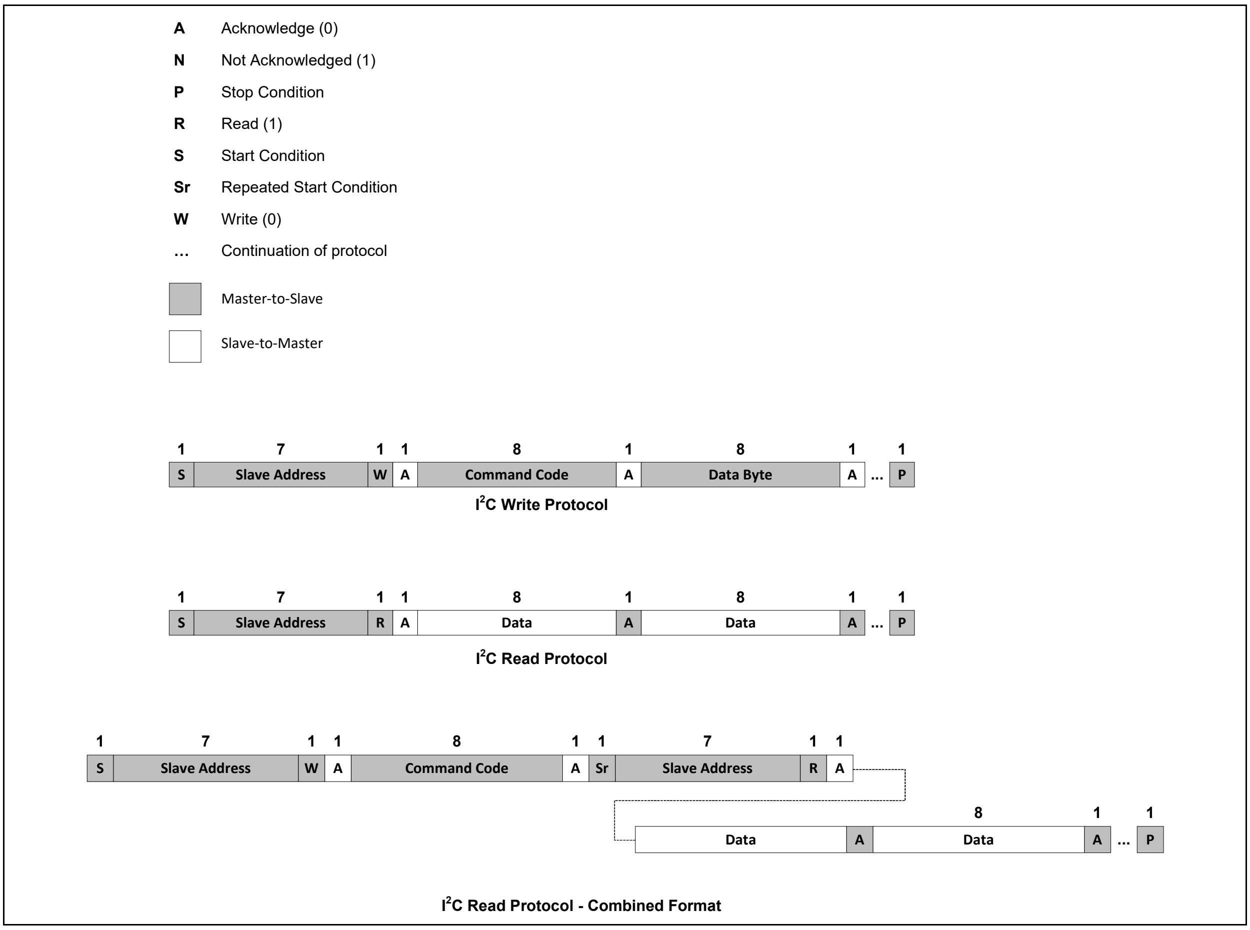
I²C Protocol

Interface and control are accomplished through an I²C serial compatible interface (standard or fast mode) to a set of registers that provide access to device control functions and output data. The devices support the 7-bit I²C addressing protocol.

The I²C standard provides for three types of bus transaction: read, write, and a combined protocol (Figure 27). During a write operation, the first byte written is a command byte followed by data. In a combined protocol, the first byte written is the command byte followed by reading a series of bytes. If a read command is issued, the register address from the previous command will be used for data access. Likewise, if the MSB of the command is not set, the device will write a series of bytes at the address stored in the last valid command with a register address. The command byte contains either control information or a 5-bit register address. The control commands can also be used to clear interrupts.

The I²C bus protocol was developed by Philips (now NXP). For a complete description of the I²C protocol, please review the NXP I²C design specification at http://www.i2c-bus.org/references.

Figure 27:
I²C Protocols



Register Set

The TCS3771 is controlled and monitored by data registers and a command register accessed through the serial interface. These registers provide for a variety of control functions and can be read to determine results of the ADC conversions. The Register Set is summarized in Figure 28.

Figure 28:
Register Address

Address	Register Name	R/W	Register Function	Reset Value
--	COMMAND	W	Specifies register address	0x00
0x00	ENABLE	R/W	Enables states and interrupts	0x00
0x01	ATIME	R/W	RGBC ADC time	0xFF
0x02	PTIME	R/W	Proximity ADC time	0xFF
0x03	WTIME	R/W	Wait time	0xFF
0x04	AILTL	R/W	RGBC interrupt low threshold low byte	0x00
0x05	AILTH	R/W	RGBC interrupt low threshold high byte	0x00
0x06	AIHTL	R/W	RGBC interrupt high threshold low byte	0x00
0x07	AIHTH	R/W	RGBC interrupt high threshold high byte	0x00
0x08	PILTL	R/W	Proximity interrupt low threshold low byte	0x00
0x09	PILTH	R/W	Proximity interrupt low threshold high byte	0x00
0x0A	PIHTL	R/W	Proximity interrupt high threshold low byte	0x00
0x0B	PIHTH	R/W	Proximity interrupt high threshold high byte	0x00
0x0C	PERS	R/W	Interrupt persistence filters	0x00
0x0D	CONFIG	R/W	Configuration	0x00
0x0E	PPCOUNT	R/W	Proximity pulse count	0x00
0x0F	CONTROL	R/W	Gain control register	0x00
0x12	ID	R	Device ID	ID
0x13	STATUS	R	Device status	0x00
0x14	CDATA	R	Clear ADC low data register	0x00
0x15	CDATAH	R	Clear ADC high data register	0x00
0x16	RDATA	R	Red ADC low data register	0x00
0x17	RDATAH	R	Red ADC high data register	0x00
0x18	GDATA	R	Green ADC low data register	0x00

Address	Register Name	R/W	Register Function	Reset Value
0x19	GDATAH	R	Green ADC high data register	0x00
0x1A	BDATA	R	Blue ADC low data register	0x00
0x1B	BDATAH	R	Blue ADC high data register	0x00
0x1C	PDATA	R	Proximity ADC low data register	0x00
0x1D	PDATAH	R	Proximity ADC high data register	0x00

The mechanics of accessing a specific register depends on the specific protocol used (See I2C Protocol).In general, the Command register is written first to specify the specific control/status register for following read/write operations.