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MAX30112

Optimized Pulse-Oximeter and Heart Rate AFE for Wearable Health

General Description

The MAX30112 is a complete optical pulse oximetry and heart rate detection integrated analog front-end. The MAX30112 has a high-resolution, optical readout signal-processing channel with built-in ambient light cancellation, as well as high-current LED driver DACs, to form a complete optical readout signal chain. With external LED(s) and photo diode(s), the MAX30112 offers the lowest power, highest performance heart rate detection solution for wrist applications.

The MAX30112 operates on a 1.8V main supply voltage, with a separate 3.1V to 5.25V LED driver power supply. The device supports a standard I^2C compatible interface, as well as shutdown modes through the software with near-zero standby current, allowing the power rails to remain powered at all times.

Applications

- Wrist-Worn Wearable Devices
- In-Ear Wearable Devices
- SpO_2 Monitoring Devices
- Fitness Wearable Devices

Benefits and Features

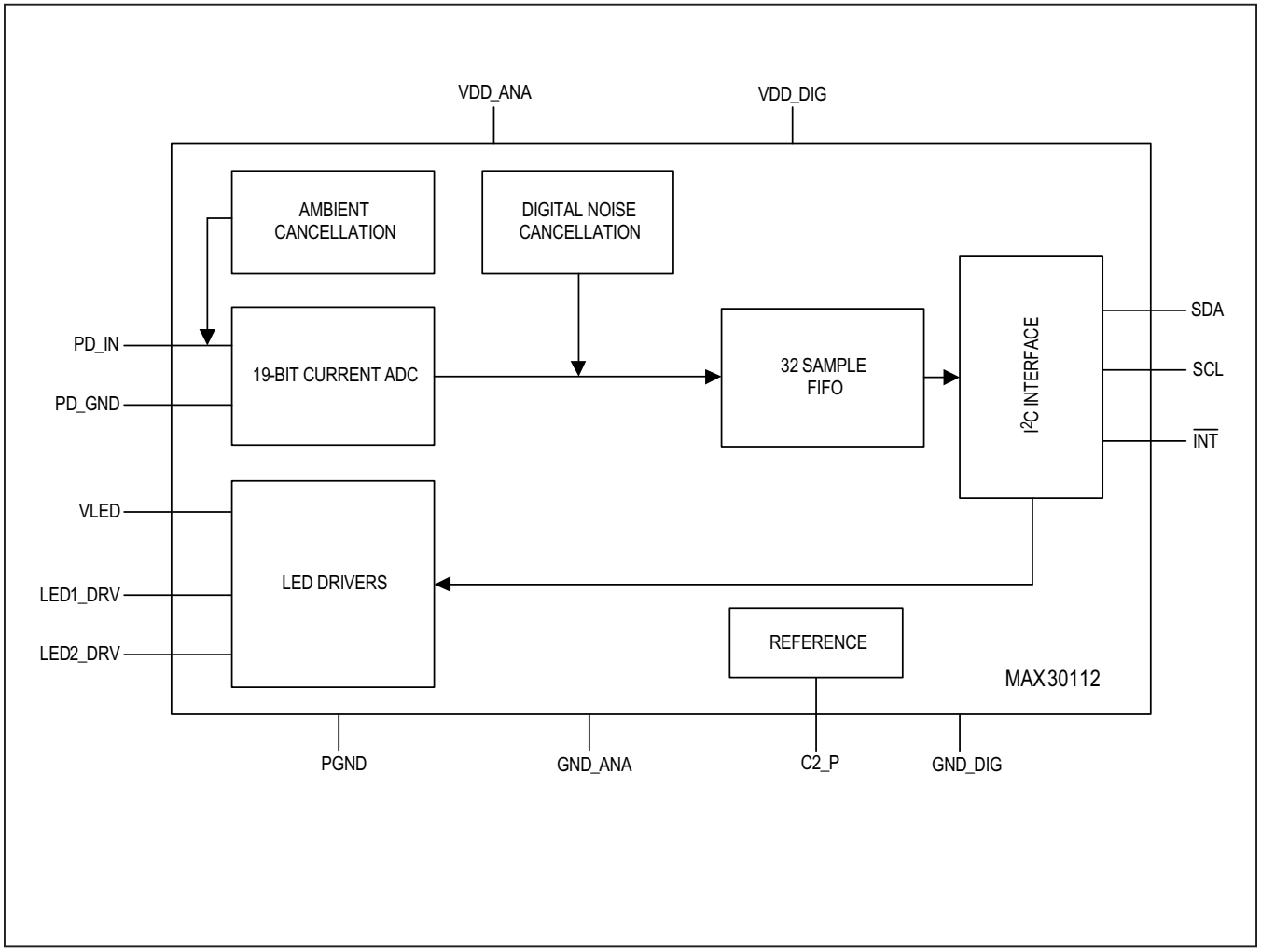
- Reflective or Transmissive Heart Rate, Heart Rate Variability, or SpO_2 Monitoring
- Transmit Section
  - Two 8-bit LED Current DACs
  - Four Current Ranges 50mA, 100mA, 150mA, 200mA
  - Low Noise Current Sources for High Peak Transmit to Receive Dynamic Range
  - Low 160mV Dropout to Support Direct Drive From Rechargeable Li Battery
  - High Output Impedance and High Supply Rejection to Support Unregulated Supply or Direct Drive From Boost Switcher Supply
- Receive Section
  - 19-bit Optical ADC Path to Support the Lowest Perfusions Situations
  - Low 25pA-RMS Input Referred Noise to Minimize LED Power Under Most Conditions
  - High Ambient Light Input Range of 200µA and to Support Extraction of HRM Signal in the Most Adverse Lighting Conditions
  - Built-in Front And Back End Ambient Light Cancellation, Improving Rejection and Eliminating System Complexity of Dealing with Ambient Light
  - Short Exposure Pulse Widths of 52µs, 104µs, 206µs, 417µs for Efficient Uses of LED Light
  - Multiple Sample Rate Options from 20sps to 3.2ksps
- Ultra-Low-Power Operation for Mobile and Body-Wearable Device
  - Dynamic Power Down Modes to 100sps for Low-Power Consumption
  - Full AFE Power Consumption of Less Than 25µA (typ) at 25sps
  - Large 32 Sample FIFO to Support Batch Processing in the Microcontroller
  - Variety of System Monitors Mappable to Interrupts to Off-Load System Monitoring Functions From the Microcontroller
  - Low Shutdown Current = 1.4µA (typ)
- I^2C interface
- Supports a Single 1.8V Supply with Separate 3.1V to 5.25V LED Supply
- Miniature 2.8mm x 2.0mm, 6x4, 0.4mm Ball Pitch WLP Package
- -40°C to +85°C Operating Temperature Range

Ordering Information *appears at end of data sheet.*

19-8749; Rev 0; 5/17

maxim integrated™

Simplified Block Diagram



Absolute Maximum Ratings

VDD_ANA to GND_ANA .....-0.3V to +2.2V
VDD_DIG to GND_ANA .....-0.3V to +2.2V
VDD_ANA to VDD_DIG.....-0.3V to +0.3V
PGND to GND_ANA.....-0.3V to +0.3V
GND_DIG to GND_ANA.....-0.3V to +0.3V
VLED to PGND.....-0.3V to +6.0V
LED1_DRV to PGND .....-0.3V to V_{LED} + 0.3V
LED2_DRV to PGND .....-0.3V to V_{LED} + 0.3V
PD_GND to GND_ANA.....Internally Shorted
SDA, SCL, $\overline{INT}$ to GND_ANA.....-0.3V to +6.0V
All other pins to GND_ANA.....-0.3V to +2.2V
Output Short-Circuit Duration.....Continuous
Continuous Input Current Into Any Pin (except LEDx_DRV Pins).....±20mA
Continuous Power Dissipation, WLP (T_A = +70ºC, derate 5.5mW/°C above +70°C).....440mW
Operating Temperature Range..... -40°C to +85°C
Storage Temperature Range..... -40°C to +105°C
Soldering Temperature (reflow).....+260°C

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Package Information

24-Bump WLP

PACKAGE CODE	W241C2+1
Outline Number	21-100088
Land Pattern Number	Refer to Application Note 1891
THERMAL RESISTANCE, FOUR-LAYER BOARD:	
Junction to Ambient (θ_{JA})	49°C/W

For the latest package outline information and land patterns (footprints), go to www.maximintegrated.com/packages. Note that a "+", "#", or "-" in the package code indicates RoHS status only. Package drawings may show a different suffix character, but the drawing pertains to the package regardless of RoHS status.

Package thermal resistances were obtained using the method described in JEDEC specification JESD51-7, using a four-layer board. For detailed information on package thermal considerations, refer to www.maximintegrated.com/thermal-tutorial.

Electrical Characteristics

(V_{DD} = VDD_ANA = VDD_DIG = 1.8V, V_{LED} = 3.3V, C_{LOAD} = 10pF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.) (Note 1))

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
POWER SUPPLY							
Power Supply Voltage	V_{DD}	Guaranteed by V_{DD} DC PSR		1.7	1.8	2.0	V
LED Supply Voltage	V_{LED}	Guaranteed by V_{LED} DC PSR		3.1	3.3	5.25	V
V_{DD} Supply Current	I_{DD}	Low Power = Off, LED1 or LED2 (FD1 = 0x01 or FD1 = 0x02, PPG_TINT = 0x0, LP_MODE = 0x0), Note 2	Sample Rate = 100sps, single pulse (PPG_SR = 0x4)		241	308	µA
		Low Power = On, LED1 or LED2 (FD1 = 0x01 or FD1 = 0x02, PPG_TINT = 0x0, LP_MODE = 0x1), Note 2	Sample Rate = 100sps, single pulse (PPG_SR = 0x4)		72		
			Sample Rate = 50sps, single pulse (PPG_SR = 0x2)		40		
			Sample Rate = 25sps, single pulse (PPG_SR = 0x1)		24	43	
			Sample Rate = 50sps, dual pulse (PPG_SR = 0xD)		94		
	I_{DD}		Sample Rate = 25sps, dual pulse (PPG_SR = 0xC)		51		µA

Electrical Characteristics (continued)

(V_{DD} = VDD_ANA = VDD_DIG = 1.8V, V_{LED} = 3.3V, C_{LOAD} = 10pF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.) (Note 1))

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
V_{LED} Supply Current	I_{LED}	Low Power = On, LED1 or LED2, LED driver 0mA (FD1 = 0x01 or FD1 = 0x02, PPG_TINT = 0x0, LP_MODE = 0x1, LEDx_DRV = 0x00)	Sample Rate = 100sps, single pulse (PPG_SR = 0x4)		0.1	±1	µA
		Low Power = On, LED1 or LED2, LED driver full scale (FD1 = 0x01 or FD1 = 0x02, PPG_TINT = 0x0, LP_MODE = 0x1, LEDx_DRV = 0xFF)	Sample Rate = 100sps, single pulse (PPG_SR = 0x4)		308		
			Sample Rete = 50sps, single pulse (PPG_SR = 0x2)		155		
			Sample Rate = 25sps, single pulse (PPG_SR = 0x1)		74	110	
		Low Power = On, LED1 and LED2, LED driver full scale (FD1 = 0x1, FD2 = 0x2, FD3 = 0x0, PPG_TINT = 0x0, LP_MODE = 0x1, LEDx_DRV = 0xFF)	Sample Rate = 100sps, single pulse (PPG_SR = 0x4)		616		µA
			Sample Rate = 50sps, single pulse (PPG_SR = 0x2)		304		
			Sample Rate = 25sps, single pulse (PPG_SR = 0x1)		149		
V_{DD} Current in Shutdown		T_A = +25°C, Note 2			1.6	5	µA
V_{LED} Current in Shutdown		T_A = +25°C				1	µA
V_{DD} Undervoltage Interrupt Threshold		T_A = +25°C			1.64		V
V_{DD} Overvoltage Interrupt Threshold		T_A = +25°C			2.0		V
OPTICAL RECEIVE CHANNEL							
ADC Resolution					19		bits
ADC Full-Scale Input Current		PPG_ADC_RGE = 0x0			6.0		µA
ADC Full-Scale Input Current (Including DC Offset DAC)		PPG_ADC_RGE = 0x1			12.0		µA
		PPG_ADC_RGE = 0x2			24.0		
		PPG_ADC_RGE = 0x3			48.0		
ADC Integration Time	t_{PPG_TINT}	LED_SETLNG = 0x3	PPG_TINT = 0x0		52		µs
			PPG_TINT = 0x1		104		
			PPG_TINT = 0x2		208		
			PPG_TINT = 0x3		417		

Electrical Characteristics (continued)

(V_{DD} = VDD_ANA = VDD_DIG = 1.8V, V_{LED} = 3.3V, C_{LOAD} = 10pF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.) (Note 1))

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Minimum PPG Sample Rate		PPG_SR = 0x0			20		sps
Maximum PPG Sample Rate		PPG_SR = 0xA			3200		sps
Sample Rate Error		From nominal as indicated in the PPG_SR table		-2		+2	%
DC Ambient Light Input Range	ALR	T_A = +25°C			200		µA
Total Integrated Input Referred Noise Current		PPG_ADC_RGE = 0x0, T_A = +25°C	PPG_TINT = 0x0		71		pArms
			PPG_TINT = 0x1		50		
			PPG_TINT = 0x2		35		
			PPG_TINT = 0x3		25		pArms
Maximum Photodiode Input Capacitance					1000		pF
Transmit and Receive Channel V_{DD} DC PSR		Loopback test, exposure current = 1.6µA nominal, PPG_TINT = 0x3, V_{LED} = 3.3V, V_{DD} = 1.7V to 2.0V	PPG_ADC_RGE = 0x0		2420		LSB/V
			PPG_ADC_RGE = 0x1		2010		
			PPG_ADC_RGE = 0x2		1790		
			PPG_ADC_RGE = 0x3		1664		
LED TRANSMIT DRIVER							
LED Current Resolution					8		Bits
Driver DNL					1		LSB
Driver INL					1		LSB
Full-Scale LED Current	I_{LED}	LEDx_PA = 0xFF	LEDx_RGE = 0x0	45	50	55	mA
			LEDx_RGE = 0x1		100		
			LEDx_RGE = 0x2		150		
		LEDx_PA = 0xF2, LEDx_RGE = 0x3			190		
	I_{LED}	LEDx_PA = 0xFF, LEDx_RGE = 0x3 (Note 3)			200		mA
Minimum Output Voltage		LEDx_PA = 0xFF, V_{DD} = 1.8V, V_{LED} = 3.3V, 95% of the desired LED current	LEDx_RGE = 0x0		0.16	0.25	V
			LEDx_RGE = 0x1		0.32		
			LEDx_RGE = 0x2		0.49		
		LEDx_RGE = 0x3 LEDx_PA = 0xF2, V_{DD} = 1.8V, V_{LED} = 3.3V, 95% of the desired LED current			0.64		

Electrical Characteristics (continued)

(V_{DD} = VDD_ANA = VDD_DIG = 1.8V, V_{LED} = 3.3V, C_{LOAD} = 10pF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.) (Note 1))

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Transmit Driver V_{LED} DC PSR		LEDx_PA = 0xFF, V_{DD} = 1.8V, V_{LEDx_DRV} = 0.9V, V_{LED} = 3.1V to 5.25V	LEDx_RGE = 0x0	-0.9	-0.04	+0.9	mA/V
			LEDx_RGE = 0x1		-0.06		
			LEDx_RGE = 0x2		-0.02		
		LEDx_PA = 0xF2, V_{DD} = 1.8V, V_{LEDx_DRV} = 0.9V, V_{LED} = 3.1V to 5.25V	LEDx_RGE = 0x3		-0.025		
Transmit Driver V_{DD} DC PSR		LEDx_PA = 0xFF, V_{LED} = 3.3V, V_{LEDx_DRV} = 0.9V, V_{DD} = 1.7V to 2.0V	LEDx_RGE = 0x0	-4	±0.08	+4	mA/V
			LEDx_RGE = 0x1		0.014		
			LEDx_RGE = 0x2		0.16		µA/V
		LEDx_PA = 0xF2, V_{LED} = 3.3V, V_{LEDx_DRV} = 0.9V, V_{DD} = 1.7V to 2.0V	LEDx_RGE = 0x3		0.02		mA/V
LED Driver Compliance Interrupt	LED_{COMP}	LEDx_RGE = 0x0, LED1_DRV only			170		mV
DIGITAL / I/O CHARACTERISTICS							
Output Low Voltage	V_{OL}	SDA, $\overline{INT}$, I_{SINK} = 6mA				0.4	V
I²C Input Voltage Low	V_{IL_I2C}	SDA, SCL				0.4	V
I²C Input Voltage High	V_{IH_I2C}	SDA, SCL		1.4			V
Input Hysteresis	V_{HYS}	SDA, SCL			200		mV
Pin Capacitance	C_{PIN}	SDA, SCL, $\overline{INT}$ (when inactive)			10		pF
Pin Leakage Current	I_{PIN}	SDA, SCL, $\overline{INT}$ (when inactive), T_A = +25°C			±0.01	±1	µA
DIGITAL / I²C TIMING CHARACTERISTICS, NOTE 3							
I²C Write Address					C0		Hex
I²C Read Address					C1		Hex
Serial Clock Frequency	f_{SCL}			0		400	kHz
Bus Free Time Between STOP and START Conditions	t_{BUF}			1.3			µs
Hold Time START and Repeat START Condition	$t_{HD,STA}$			0.6			µs
SCL Pulse-Width Low	t_{LOW}			1.3			µs
SCL Pulse-Width High	t_{HIGH}			0.6			µs
Setup Time for a Repeated START Condition	$t_{SU,STA}$			0.6			µs

Electrical Characteristics (continued)

(V_{DD} = VDD_ANA = VDD_DIG = 1.8V, V_{LED} = 3.3V, C_{LOAD} = 10pF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Typical values are at T_A = +25°C.) (Note 1))

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Data Hold Time	$t_{HD,DAT}$		0		900	ns
Data Setup Time	$t_{SU,DAT}$		100			ns
Setup Time for STOP Condition	$t_{SU,STO}$		0.6			µs
Pulse Width of Suppressed Spike	t_{SP}		0		50	ns
Bus Capacitance	CB				400	pF
SDA and SCL Receiving Rise Time	t_R		20 + 0.1CB		300	ns
SDA and SCL Receiving Fall Time	t_F		20 + 0.1CB		300	ns
SDA Transmitting Fall Time	t_{TF}		20 + 0.1CB		300	ns

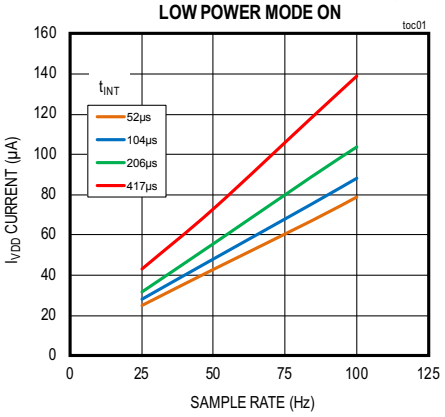
Note 1: Limits are 100% tested at T_A = +25°C. Limits over the operating temperature range and relevant supply voltage range are guaranteed by design and characterization.

Note 2: Limit assumes that all user-programmable memory is programmed. If user programmable memory is left unprogrammed, currents can exceed the limit shown.

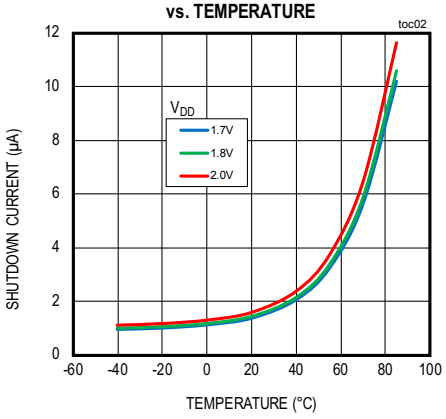
Typical Operating Characteristics

VDD_ANA = VDD_DIG = 1.8V, VLED = 3.3V, GND_ANA = GND_DIG = PGND = 0V, T_A = +25°C, min/max are from T_A = -40°C to +85°C, unless otherwise noted. (Note 2)

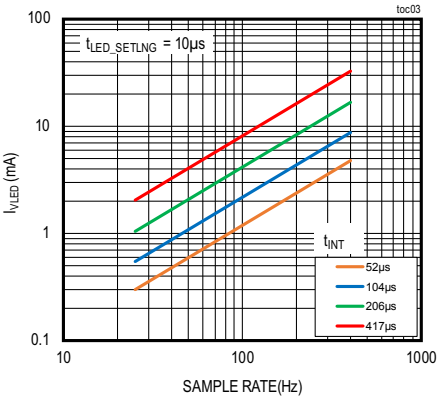
I_{VDD} vs. SAMPLE RATE FOR DIFFERENT INTEGRATION TIMES, LOW POWER MODE ON



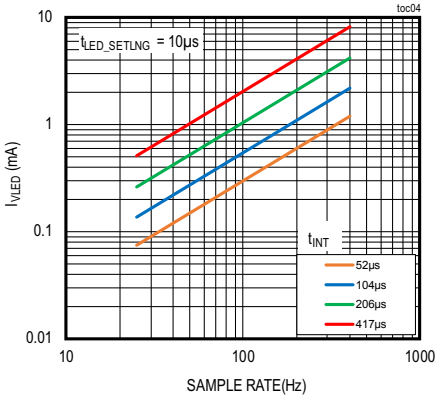
V_{DD} SHUDTOWN CURRENT vs. TEMPERATURE



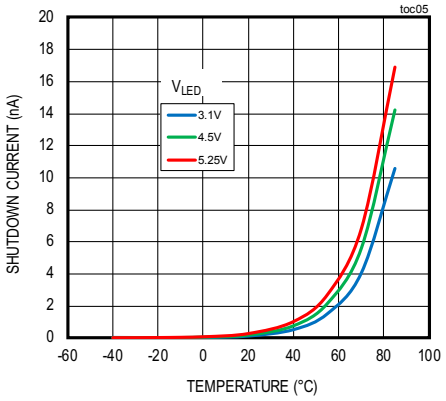
AVERAGE I_{VLED} vs. f_{SAMPLE} FOR DIFFERENT INTEGRATION TIMES AT 200mA PEAK LED DRIVER CURRENT



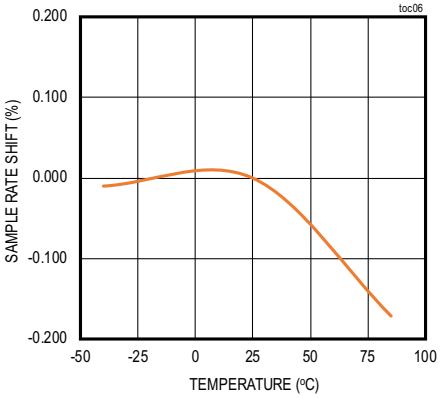
AVERAGE I_{VLED} vs. f_{SAMPLE} FOR DIFFERENT INTEGRATION TIMES AT 50mA PEAK LED DRIVER CURRENT



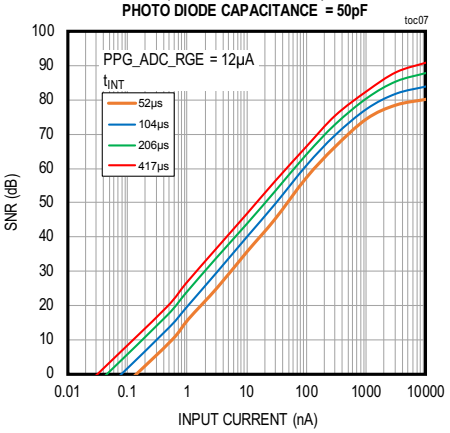
V_{LED} SHUTDOWN CURRENT vs. TEMPERATURE



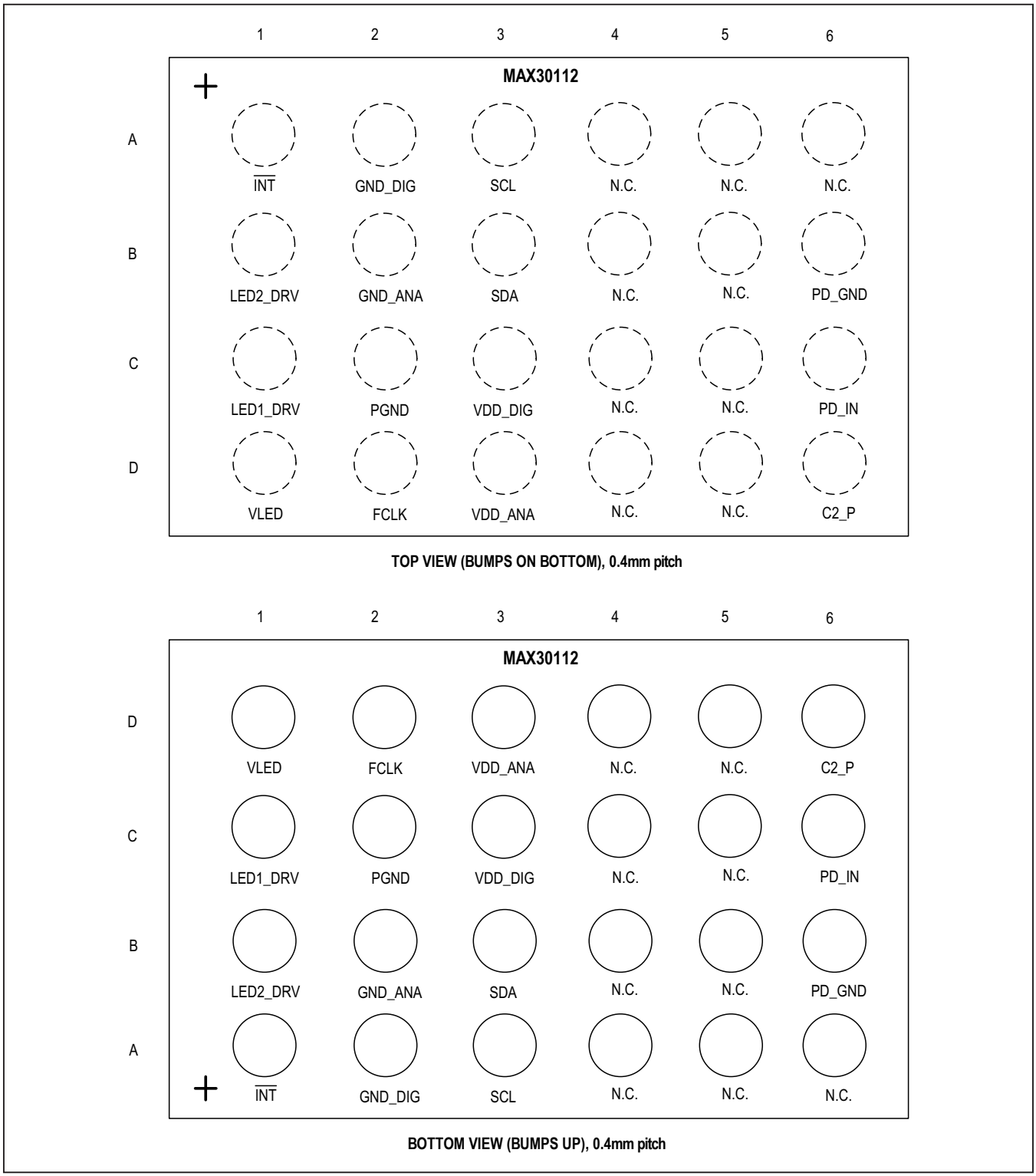
SAMPLE RATE SHIFT WITH TEMPERATUE



SIGNAL TO NOISE vs. INPUT CURRENT (NYQUEST BANDWIDTH) PHOTO DIODE CAPACITANCE = 50pF



Pin Configurations



TOP VIEW (BUMPS ON BOTTOM), 0.4mm pitch

BOTTOM VIEW (BUMPS UP), 0.4mm pitch

Pin Description

PIN	NAME	FUNCTION
POWER		
C3	VDD_DIG	Digital Logic Supply. Connect to externally-regulated supply. Suggest to connect to VDD_ANA.
A2	GND_DIG	Digital Logic and Digital Pad Return. Suggest to connect to common PCB ground.
D3	VDD_ANA	Analog Supply. Connect to externally-regulated supply. Bypass with a 0.1µF as close as possible to bump and a 10µF capacitor to GND_ANA.
B2	GND_ANA	Analog Power Return. Suggest to connect to common PCB ground.
D1	V_{LED}	LED Power Supply Input. Connect to external voltage supply. Bypass with a 10µF capacitor to PGND.
C2	PGND	LED Power Return.
CLOCK		
D2	FCLK	Optional External Clock input. Leave FCLK unconnected/floating, if external clock is not used.
I²C CONTROL INTERFACE		
A3	SCL	SCL Input. I²C clock input
B3	SDA	SDA Input/Output. I²C data I/O
A1	$\overline{INT}$	Interrupt. Programmable Open-Drain Interrupt output signal pin (Active Low)
OPTICAL		
C6	PD_IN	Photodiode Cathode Input. Keep traces as short as possible, shield with PD_GND.
B6	PD_GND	Photodiode Anode. Connect to PCB GND plane only at PD_GND pin. Use as shield trace for PD_IN.
C1	LED_DRV1	LED Driver Output 1. Connect the LED cathode to LED_DRV1 output and its anode to the V_{LED} supply.
B1	LED_DRV2	LED Driver Output 2. Connect the LED cathode to LED_DRV2 output and its anode to the V_{LED} supply.
REFERENCE		
D6	C2_P	Internal Reference Decoupling Point. Bypass with a 10µF capacitor to GND_ANA
N.C.		
A4, A5, A6, B4, B5, C4, C5, D4, D5	N.C.	No Connection. Internally connected, leave N.C. unconnected.

Detailed Description

The MAX30112 is a complete optical pulse oximetry and heart rate detection integrated analog front-end readout circuit designed for the demanding requirements of mobile and wearable devices. Minimal external hardware components are necessary for integration into a mobile device. The MAX30112 is fully adjustable through software registers, with the digital output data being stored in a 32-samples FIFO within the IC.

Optical Subsystem

The optical subsystem in MAX30112 is composed of ambient light cancellation (ALC), a continuous-time, sigma-delta ADC, and proprietary discrete time filter. ALC incorporates a proprietary scheme to cancel ambient-light-generated photo diode current up to 200µA, allowing the sensor to work in high ambient light conditions. The ADC has programmable full-scale ranges of between 6µA and 48µA. The internal ADC is a continuous-time oversampling sigma-delta converter with 19-bit resolution. The ADC output data rate can be programmed from 20sps (samples per second) to 3200sps. The MAX30112 includes a proprietary discrete time filter to reject 50Hz/60Hz interference and changing residual ambient light from the sensor measurements.

MAX30112 supports Dynamic Power Down mode (Low Power mode) in which the power consumption is decreased between samples. This mode is only supported for sample rates 100sps and below. For more details on the power consumption at each sample rates, refer to the *Electrical Characteristics* table.

LED Driver

The MAX30112 integrates two precision LED-driver-current DACs that modulate LED pulses for both SpO_2 and HR measurements. The LED current DACs have 8-bits of dynamic range with four programmable full-scale ranges of 50mA, 100mA, 150mA, and 200mA. The LED drivers are low-dropout current sources, allowing for low-noise, power-supply independent LED currents to be sourced at the lowest supply voltage possible; thus minimizing LED power consumption. The LED pulse width and the LED settling time can be programmed to allow the algorithms to optimize SpO_2 and HR accuracy at the lowest dynamic power consumption dictated by the application.

I²C/SMBus Compatible Serial Interface

The MAX30112 features an I²C/SMBus™ compatible, 2-wire serial interface consisting of a serial data line (SDA) and a serial clock line (SCL). SDA and SCL facilitate communication between the MAX30112 and the master at clock rates up to 400kHz.

Figure 1 shows the 2-wire interface timing diagram. The master generates SCL and initiates data transfer on the bus. The master device writes data to the MAX30112 by transmitting the proper slave address followed by the register address and then the data word. Each transmit sequence is framed by a START (S) or REPEATED START (Sr) condition and a STOP (P) condition. Each word transmitted to the MAX30112 is 8-bits long and is followed by an acknowledge clock pulse. A master reading data from the MAX30112 transmits the proper slave address followed by a series of nine SCL pulses. The MAX30112 transmits data on SDA in sync with the master-generated SCL pulses. The master acknowledges receipt of each byte of data. Each read sequence is framed by a START (S) or REPEATED START (Sr) condition, a not acknowledge, and a STOP (P) condition. SDA operates as both an input and an open-drain output. A pullup resistor is required on SDA. SCL operates only as an input. A pullup resistor is required on SCL if there are multiple masters on the bus, or if the single master has an open-drain SCL output. Series resistors in line with SDA and SCL are optional. Series resistors protect the digital inputs of the MAX30112 from high voltage spikes on the bus lines, and minimize crosstalk and undershoot of the bus signals.

Detailed I2C Timing Diagram

The detailed timing diagram of various electrical characteristics is shown in Figure 1.

Bit Transfer

One data bit is transferred during each SCL cycle. The data on SDA must remain stable during the high period of the SCL pulse. Changes in SDA while SCL is high are control signals (see the *START and STOP Conditions* section).

START and STOP Conditions

SDA and SCL idle high when the bus is not in use. A master initiates communication by issuing a START condition. A START condition is a high-to-low transition on SDA with SCL high. A STOP condition is a low-to-high transition on SDA while SCL is high (Figure 2). A START condition from the master signals the beginning of a transmission to the MAX30112. The master terminates transmission, and frees the bus, by issuing a STOP condition. The bus remains active if a REPEATED START condition is generated instead of a STOP condition.

Early STOP Conditions

The MAX30112 recognizes a STOP condition at any point during data transmission unless the STOP condition occurs in the same high pulse as a START condition. For proper operation, do not send a STOP condition during the same SCL high pulse as the START condition.

Slave Address

The slave address is defined as the seven most significant bits (MSBs), followed by the read/write bit. For the MAX30112, the seven most significant bits are 0b1100000. For read mode, set the read/write bit to 1 (slave address = 0xC1). For write mode, set the read/write bit to 0 (slave address = 0xC0). The address is the first byte of information sent to the IC after the START condition.

Acknowledge Bit

The acknowledge bit (ACK) is a clocked 9th bit that the MAX30112 uses to handshake receipt each byte of data when in write mode (Figure 3). The MAX30112 pulls down SDA during the entire master-generated 9th clock pulse if the previous byte is successfully received. Monitoring ACK allows for detection of unsuccessful data transfers. An unsuccessful data transfer occurs if a receiving device is busy or if a system fault has occurred. In the event of an unsuccessful data transfer, the bus master will retry communication. The master pulls down SDA during the 9th clock cycle to acknowledge receipt of data when the MAX30112 is in read mode. An acknowledge is sent by the master after each read byte to allow data transfer to continue. A not-acknowledge is sent when the master reads the final byte of data from the MAX30112, followed by a STOP condition.

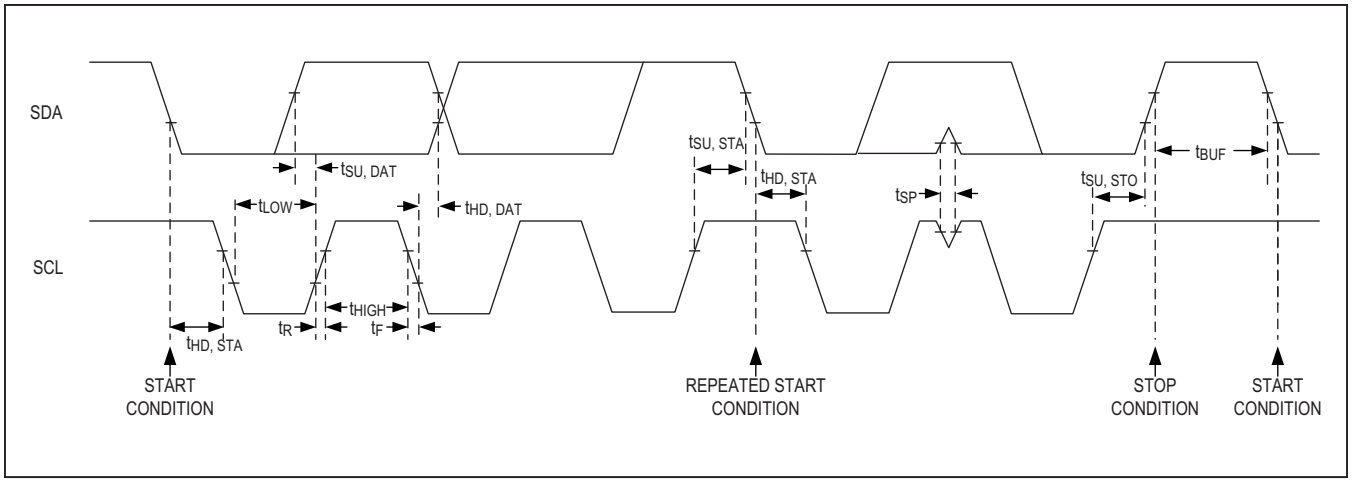


Figure 1. Detailed I2C Timing Diagram

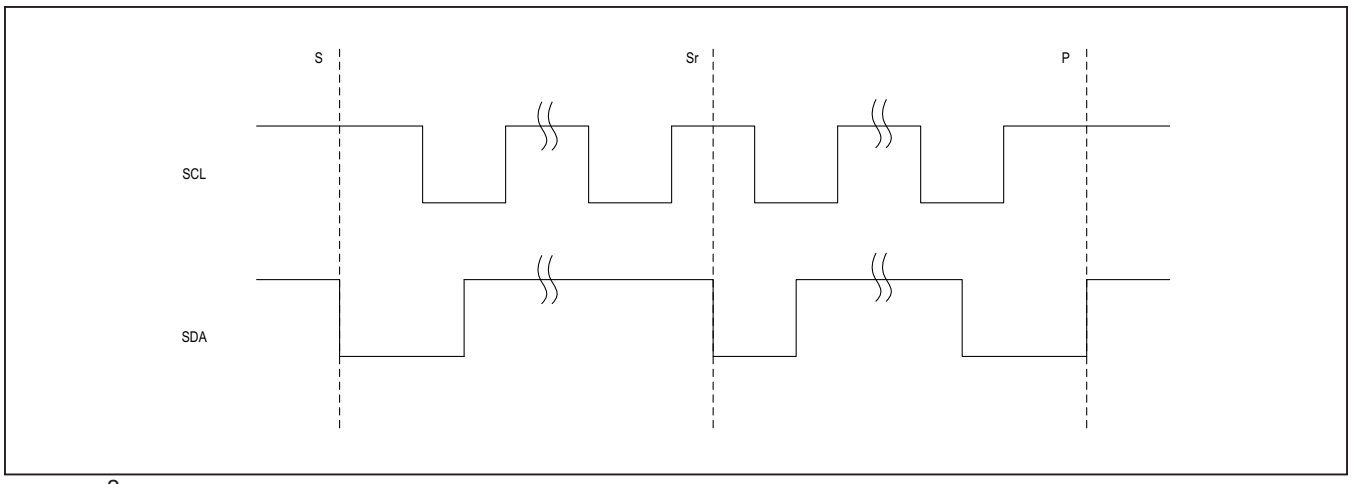


Figure 2: I²C START, STOP, and REPEATED START Condition

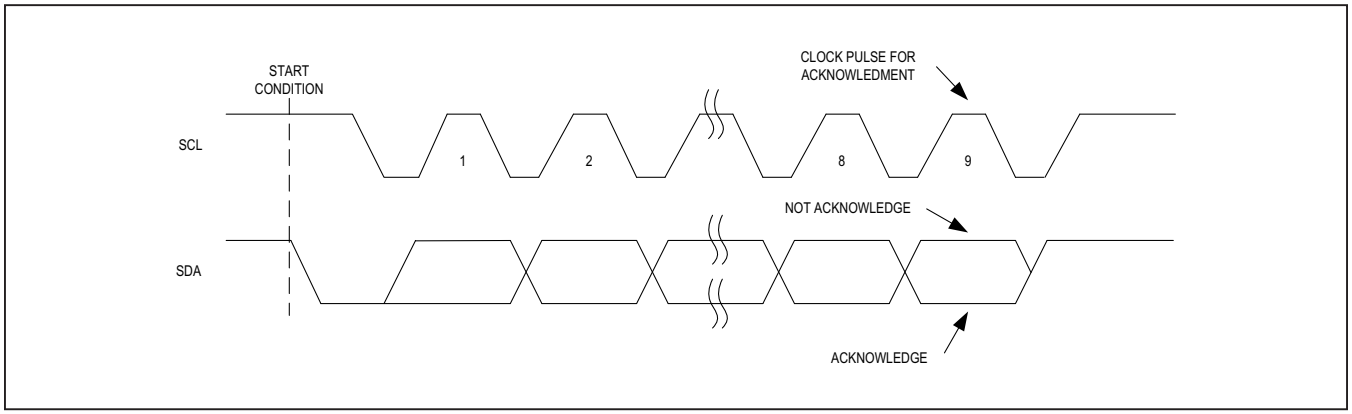


Figure 3. I²C Acknowledge Bit

I²C Write Data Format

A write to the MAX30112 includes transmission of a START condition, the slave address with the R/$\overline{W}$ bit set to 0, one byte of data to configure the internal register address pointer, one or more bytes of data, and a STOP condition. Figure 4 illustrates the proper frame format for writing one byte of data to the MAX30112. Figure 5 illustrates the frame format for writing n-bytes of data to the MAX30112.

The slave address with the R/$\overline{W}$ bit set to 0 indicates that the master intends to write data to the MAX30112. The MAX30112 acknowledges receipt of the address byte during the master-generated 9th SCL pulse.

The second byte transmitted from the master configures the MAX30112's internal register address pointer. The pointer tells the MAX30112 where to write the next byte of data. An acknowledge pulse is sent by the MAX30112 upon receipt of the address pointer data.

The third byte sent to the MAX30112 contains the data that will be written to the chosen register. An acknowledge pulse from the MAX30112 signals receipt of the data byte. The address pointer auto increments to the next register address after each received data byte. This auto-increment feature allows a master to write to sequential registers within one continuous frame. The master signals the end of transmission by issuing a STOP condition. The auto_increment feature is disabled when there is an attempt to write to the FIFO_DATA register.

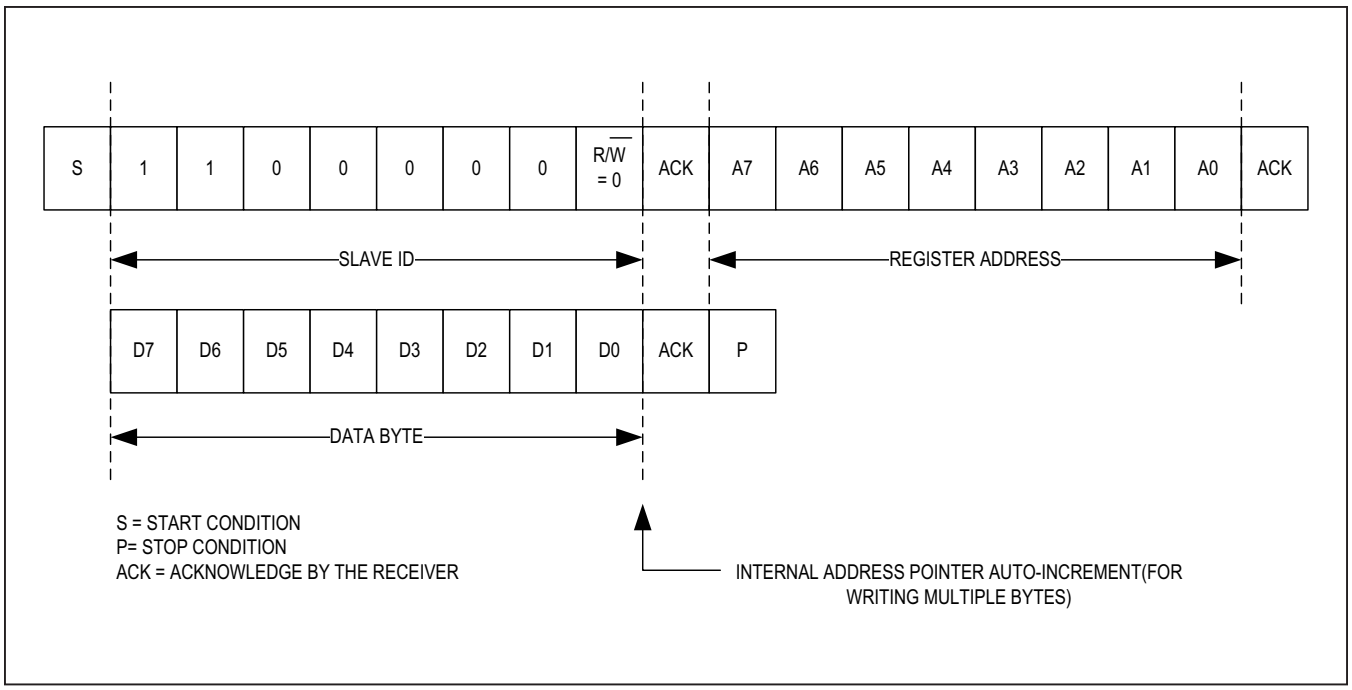


Figure 4. I²C Single-Byte Write Transaction

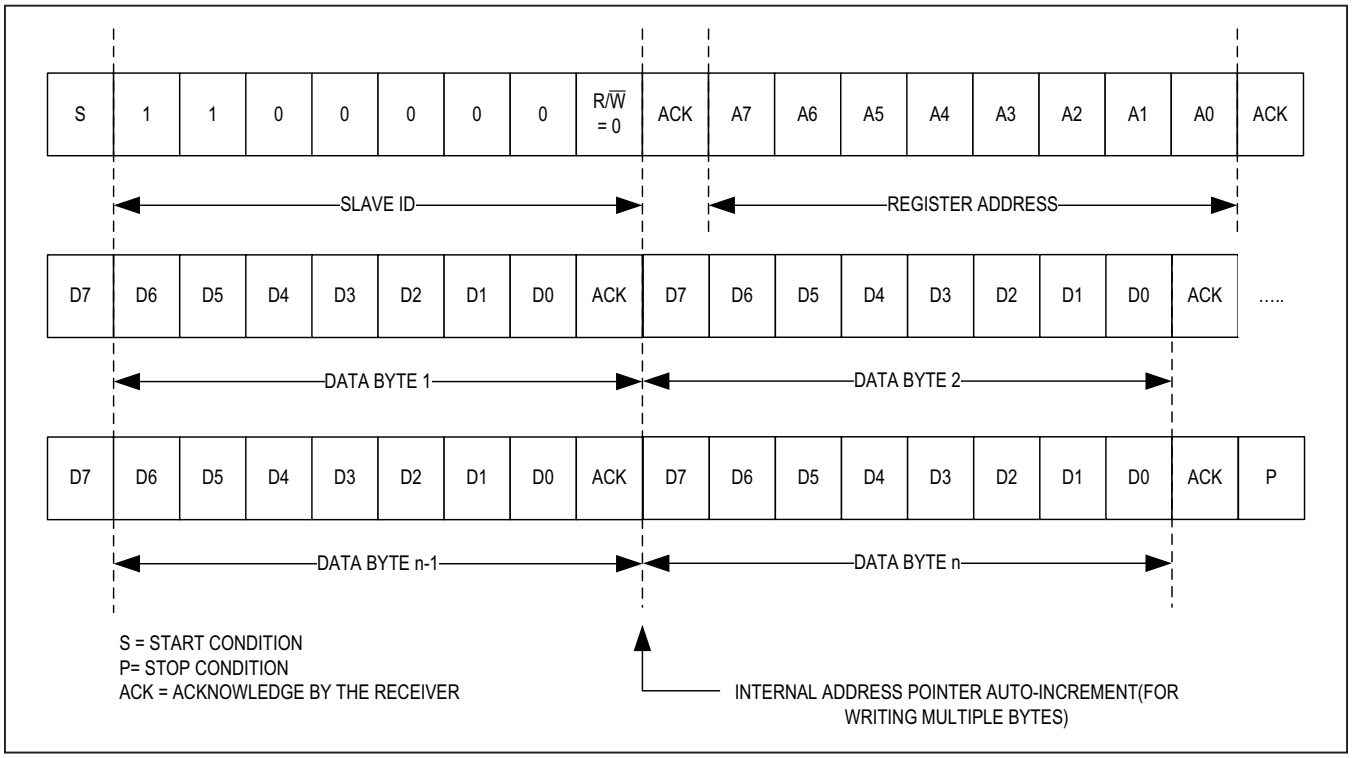


Figure 5. I²C Multi-Byte Write Transaction

I²C Read Data Format

Send the slave address with the R/$\overline{W}$ bit set to 1 to initiate a read operation. The MAX30112 acknowledges receipt of its slave address by pulling SDA low during the 9th SCL clock pulse. A START command followed by a read command resets the address pointer to register 0x00.

The first byte transmitted from the MAX30112 will be the contents of register 0x00. Transmitted data is valid on the rising edge of SCL. The address pointer auto-increments after each read data byte. This auto-increment feature allows all registers to be read sequentially within one continuous frame. The auto_increment feature is disabled when there is an attempt to read from the FIFO_DATA register. A STOP condition can be issued after any number of read data bytes. If a STOP condition is issued followed by another read operation, the first data byte to be read will be from register 0x00.

The address pointer can be preset to a specific register before a read command is issued. The master presets the address pointer by first sending the MAX30112 slave address with the R/$\overline{W}$ bit set to 0 followed by the register address. A REPEATED START condition is then sent followed by the slave address with the R/$\overline{W}$ bit set to 1. The MAX30112 then transmits the contents of the specified register. The address pointer auto-increments after transmitting the first byte.

The master acknowledges receipt of each read byte during the acknowledge clock pulse. The master must acknowledge all correctly received bytes except the last byte. The final byte must be followed by a not acknowledge from the master and then a STOP condition. Figure 6 illustrates the frame format for reading one byte from the MAX30112. Figure 7 illustrates the frame format for reading multiple bytes from the MAX30112.

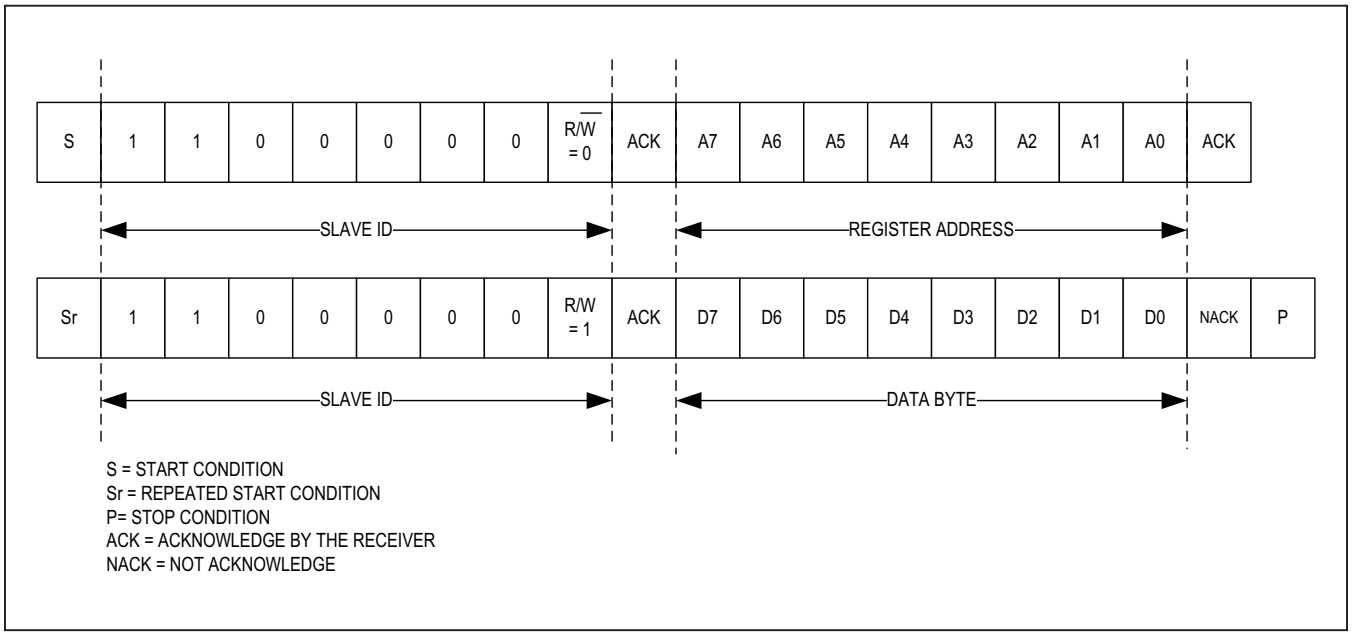


Figure 6. I²C Single-Byte Read Transaction

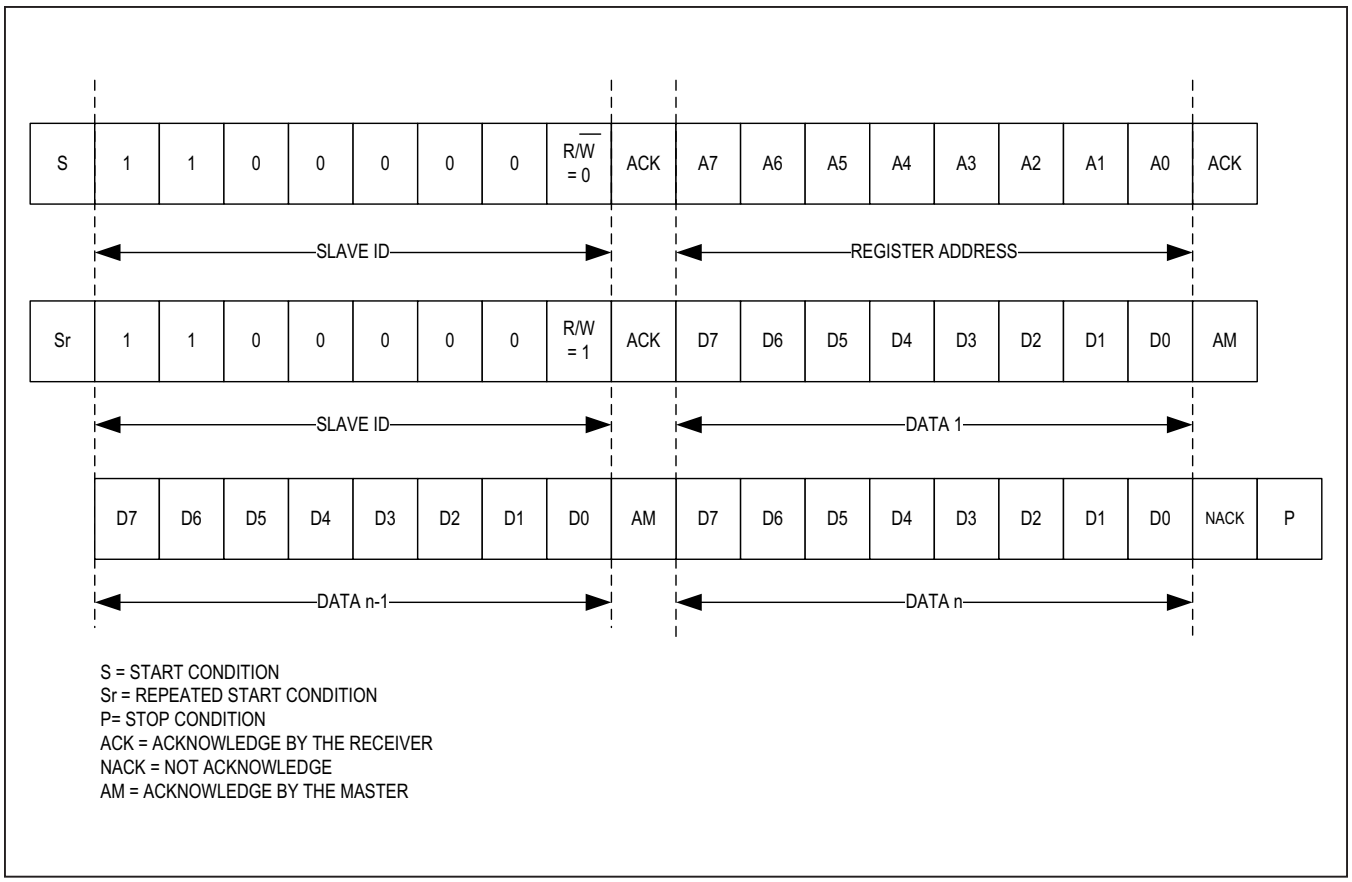


Figure 7. I^2C Multi-Byte Read Transaction

FIFO Configuration

The FIFO can hold up to 32 samples of data, with each sample comprised of up to 4 data Items (time slots). Each data item is 3 bytes. The content of each data item is programmed through register FD1 to FD4 (FIFO data control).These data items are ADC counts from the analog front-end of this device. The FIFO supports the following features:

- Maximum 32 samples (depth)
- Supports up to four data items in each sample
- FIFO roll-on full
- Different interrupt modes based on watermark

There are seven registers that control how the FIFO is configured and read out. These registers are illustrated below.

FIFO Data Control (Address 0x09 and 0x0A)

The data format in the FIFO, as well as the sequencing of exposures, are controlled by the FIFO Data Control registers through FD1 through FD4. There are four FIFO data items available, each holding up to 32 samples. The exposure sequence cycles through the FIFO data bit fields, starting from FD1 to FD4. The first FIFO data field set to NONE (0000) ends the sequence.

Table 1. FIFO Information, Control and Configuration Registers

ADDRESS	REGISTER NAME	DEFAULT VALUE	B7	B6	B5	B4	B3	B2	B1	B0
0X04	FIFO Write Pointer	00	-	-	-	FIFO_WR_PTR[4:0]				
0X05	Overflow Counter	00	-	-	-	OVF_COUNTER[4:0]				
0X06	FIFO Read Pointer	00	-	-	-	FIFO_RD_PTR[4:0]				
0X07	FIFO Data Register	00	FIFO_DATA[7:0]							
0X08	FIFO Configuration	0F	-	FIFO_STAT_CLR	A_FULL_TYPE	FIFO_RO	FIFO_A_FULL[3:0]			
0x09	FIFO Data Control 1	00	FD2[3:0]				FD1[3:0]			
0x0A	FIFO Data Control 2	00	FD4[3:0]				FD3[3:0]			

Table 2: Data Items Type for FIFO Control Registers

FDX[3:0]*	DATA TYPE	FIFO DATA CONTENT	NOTE
0000	NONE	-	-
0001	LED1	PPG_DATA[18:0]	MS bits should be masked
0010	LED2	PPG_DATA[18:0]	MS bits should be masked
0011	Reserved	-	-
0100	Reserved	-	-
0101	PILOT LED1	PPG_DATA[18:0]	MS bits should be masked
0110	Reserved	-	-
0111	Reserved	-	-
1000	Reserved	-	-
1001	Reserved	-	-
1010	Reserved	-	-
1011	Reserved	-	-
1100	DIRECT_AMBIENT	PPG_DATA[18:0]	MS bits should be masked
1101	LED1 and LED2	PPG_DATA[18:0]	MS bits should be masked
1110	Reserved	-	-
1111	Reserved	--	-

** Note: In FDx, x is 1, 2, 3, or 4 for the corresponding FIFO bank.*

Write Pointer (Register 0X04)

FIFO_WR_PTR[4:0] points to the FIFO location where the next sample will be written. This pointer advances for each sample pushed on to the FIFO by the internal conversion process. The write pointer is a 5-bit counter and will wrap around to count 0x00 on the next sample after count 0x1F.

Overflow Counter (Register 0X05)

OVF_COUNTER[4:0] logs the number of samples lost if the FIFO is not read in a timely fashion. This counter holds at count value 0x1F. When a complete sample is popped from the FIFO (when the read pointer advances), and OVF_COUNTER is reset to zero. This counter is essentially a debug tool. It should be read immediately before reading the FIFO in order to check if an overflow condition has occurred.

Read Pointer (Register 0X06)

FIFO_RD_PTR[4:0] points to the location from where the next sample from the FIFO will be read through the interface. This advances each time a sample is read from the FIFO. The read pointer can be both read and written to. This allows a sample to be reread from the FIFO if it has not already been overwritten. The read pointer is updated from a 5-bit counter and will wrap around to count 0x00 from count 0x1F.

FIFO Data (Register 0X07)

FIFO_DATA[7:0] is a read-only register used to retrieve data from the FIFO. The format and data type of the data stored in the FIFO is determined by the FIFO data control register. Readout from the FIFO follows a progression defined by the FIFO data control register as well. This configuration is best illustrated by a few examples.

Assume it is desired to perform an SpO_2 measurement simultaneously with monitoring the ambient level on the photodiode to adjust the IR and red LED intensity. To perform this measurement, config the following registers,

FIFO Data Control field

```
FD1[3:0] = 0x1 (LED1)
FD2[3:0] = 0x2 (LED2)
FD3[3:0] = 0xC  (DIRECT_AMBIENT)
FD4[3:0] = 0x0 (NONE)
```

PPG Configuration

```
PPG_ADC_RGE[1:0] (Gain Range Control)
PPG_SR[3:0]      (Sample Rate Control)
PPG_TINT[1:0]    (Integration Time)
```

LED Pulse Amplitude

```
LED1_PA[7:0] (LED1 Current Pulse Amplitude)
LED2_PA[7:0] (LED2 Current Pulse Amplitude)
```

When done, the sample sequence and the data format in the FIFO will follow the following time/location sequence.

```
LED1 sample 1
LED2 sample 1
DIRECT_AMBIENT sample 1
LED1 sample 2
LED2 sample 2
DIRECT_AMBIENT sample 2
.
.
.
LED1 sample n
LED2 sample n
DIRECT_AMBIENT sample n
```

where:

LED1 sample x = ambient light corrected photodiode ADC count exposure data from LED1 for the sample x

LED2 sample x = ambient light corrected photodiode ADC count exposure data from LED2 for the sample x

DIRECT_AMBIENT sample x = direct ambient sample x

n is the number of samples in the FIFO, which can be up to 32 samples.

For a second example, assume it is desired to pulse LED1 and LED2 simultaneously while also monitoring the ambient level. In this case, set the following registers,

FIFO Data Control field

```
FD1[3:0] = 0xD (LED1 and LED2)
FD2[3:0] = 0xC (DIRECT_AMBIENT)
FD3[3:0] = 0x0 (NONE)
FD4[3:0] = 0x0 (NONE)
```

The sequencing in the FIFO will then be,

```
LED1 and LED2 sample1
DIRECT_AMBIENT sample 1
LED1 and LED2 sample2
DIRECT_AMBIENT 2
.
.
.
LED1 and LED2 sample n
DIRECT_AMBIENT n
```

where:

LED1 and LED2 sample x = ambient light corrected photodiode ADC count exposure data when both LED1 and LED2 are active simultaneuously

DIRECT_AMBIENT sample x = direct ambient corrected sample x

The number of bytes of active data samples is given by: 3 x K x N,

where:

K = the number of active sampled channels as defined in the FIFO_Data_Control register 0x09 and 0x0A

N = the number of active data samples in the FIFO

The number of active data samples in the FIFO is directly readable by subtracting the FIFO_RD_PTR[4:0] from the FIFO_WR_PTR[4:0], and taking wrap around of the pointers into consideration. It is typically controlled in the system by generating an interrupt on the $\overline{INT}$ line when the FIFO reaches a watermark level computed from the FIFO_A_FULL[3:0] field in the FIFO Configuration register (0x08). In this case, when the active data samples in the FIFO reach a level given by 32 - FIFO_A_FULL[3:0], an A_FULL interrupt is generated.

To calculate the number of active samples when the $\overline{INT}$ signal is asserted, execute the following pseudo-code:

```
read the OVF_COUNTER register
read the FIFO_WR_PTR register
read the FIFO_RD_PTR register
if (OVF_COUNTER == 0), then // no overflow
occurred
  if (FIFO_WR_PTR > FIFO_RD_PTR) then
    NUM_AVAILABLE_SAMPLES = FIFO_WR_PTR
- FIFO_RD_PTR
else
    NUM_AVAILABLE_SAMPLES = FIFO_WR_PTR
+ 32 - FIFO_RD_PTR
endif
else
    NUM_AVAILABLE_SAMPLES = 32 // overflow
    occurred and data has been lost
endif
```

FIFO data format depends on the data type being stored. Optical data, whether ambient-corrected LED exposure, ambient-corrected proximity, or direct ambient-sampled data is as shown in the Table 3. The ADC data is left-justified at FIFO_DATA[18] and the MSBs (FIFO_DATA[23:18]) are don't care and should be masked as shown in Table 3. In other words, the MSB bit of the ADC data is always in the bit 18 position.

The ADC resolution is set by the PPG_LED_PW[1:0] in the PPG Configuration 1 Register. This field generates an ADC resolution of 19, 18, 17, or 16 bits and is tied to the selected integration time of 417µs, 206µs, 104µs, or 52µs, respectively. In lower ADC resolutions, the unused LSBs should be masked.

Table 3. Integration Pulse Width, Resulting ADC Resolution, and FIFO Data Format

		FIFO DATA FORMAT (FIFO_DATA[23:0])																							
Integration Pulse Width	**ADC Res**	**ADC Value**																							
		F23	F22	F21	F20	F19	F18	F17	F16	F15	F14	F13	F12	F11	F10	F9	F8	F7	F6	F5	F4	F3	F2	F1	F0
417µs	19-bits	X	X	X	X	X	O18	O17	O16	O15	O14	O13	O12	O11	O10	O9	O8	O7	O6	O5	O4	O3	O2	O1	O0
206µs	18-bits	X	X	X	X	X	O18	O17	O16	O15	O14	O13	O12	O11	O10	O9	O8	O7	O6	O5	O4	O3	O2	O1	X
104µs	17-bits	X	X	X	X	X	O18	O17	O16	O15	O14	O13	O12	O11	O10	O9	O8	O7	O6	O5	O4	O3	O2	X	X
52µs	16-bits	X	X	X	X	X	O18	O17	O16	O15	O14	O13	O12	O11	O10	O9	O8	O7	O6	O5	O4	O3	X	X	X

FIFO Almost Full (Watermark)

The FIFO_A_FULL[3:0] register in the FIFO_Configuration register (0x08) determines when the A_FULL bit in the Interrupt_Status 1 register (0x00) gets asserted. The FIFO is almost full when it has 32 minus FIFO_A_FULL[3:0] samples. Then, if A_FULL_EN mask bit in the Interrupt_Enable 1 register (0x02) is set, the A_FULL bit in the Interrupt Status 1 will be set and routed to the $\overline{INT}$ pin on the MAX30112 interface. This condition prompts the Application Processor to read samples from the FIFO before it gets filled. The A_FULL bit is cleared and $\overline{INT}$ is deasserted when the status register is read, or when the FIFO_DATA register (0x07) is read and FIFO_STAT_CLR (0x08) bit is set.

When the application processor receives an interrupt, there are at least 32 minus FIFO_A_FULL[3:0] samples available in the FIFO. It is not necessary to read the FIFO_WR_PTR and FIFO_RD_PTR registers. The Application Processor may read all the available samples in the FIFO, or only a portion of it. At high sample rates, it is recommended that only a portion of the available samples are read on an A_FULL interrupt, to ensure that FIFO reading does not happen when the next sample conversion is in progress. The remaining samples will be read on the next interrupt.

If the A_FULL interrupt is not enabled, the Application Processor has to read the FIFO in polling mode. In this mode the Application Processor has to read the FIFO_WR_PTR and FIFO_RD_PTR registers to calculate the number of samples available in the FIFO, and then decide how many samples to read. However, polling mode is not recommended, because in this mode an interface transaction will inevitably overlap an optical sample, potentially adding noise to the optical data. Because of this concern, the interface transaction should occur during the dead time between optical samples to avoid adding additional noise.

FIFO_RO (FIFO Rollover)

The FIFO_RO bit in the FIFO_Configuration register (0x08) determines whether samples get pushed on to the FIFO when it is full. If push is enabled when FIFO is full, old samples are lost. If FIFO_RO is not set, the new sample is dropped and the FIFO is not updated.

A_FULL_TYPE

The A_FULL_TYPE bit defines the behavior of the A_FULL interrupt. If the A_FULL_TYPE bit is set low, the A_FULL interrupt gets asserted when the A_FULL condition is detected and cleared by status register read, but reasserts for every sample if the A_FULL condition persists.

If A_FULL_TYPE bit is set high, the A_FULL interrupt gets asserted only when the A_FULL condition is detected. The interrupt gets cleared on status register read, and does not re-assert for every sample until a new A_FULL condition is detected.

FIFO_STAT_CLR

The FIFO_STAT_CLR bit defines whether the A-FULL interrupt should get cleared by FIFO_DATA register read. If FIFO_STAT_CLR is set low, A_FULL and DATA_RDY interrupts do not get cleared by FIFO_DATA register read but get cleared by status register read. If FIFO_STAT_CLR is set high, A_FULL and DATA_RDY interrupts get cleared by a FIFO_DATA register read or a status register read.

Optical Timing

The AFE can be configured to make a variety of measurements which involves the following options:

- LED1
- LED2
- LED1 + LED2
- Direct Ambient Measurement

For more details on the available modes, refer to *FIFO Configuration* section.

The “LED Ambient Sample” is integrated without turning on the LED, while “LED Exposure Sample” is integrated with LED illumination driven by the on-chip LED driver. Each “LED Exposure Sample” output is then compensated by the “LED Ambient Sample” at the front-end before the ADC conversion. The final FIFO exposure value for each LED mode represents an ambient corrected LED exposure signal.

The controller is also configurable to measure direct ambient level for every exposure sample. The direct ambient measurement can be used to adjust the LED drive level to compensate for increased noise levels when high interfering ambient signals are present.

The following optical timing diagrams illustrate the possible measurement configurations.

Sequential LED1 and LED2 Pulsing with Direct Ambient Sampling

The optical timing diagram in Figure 8 illustrates the optical timing when both LED1 and LED2 are enabled to pulse sequentially followed by a direct ambient measurement. This timing mode is an example of when measuring SpO_2 with IR and red LEDs. The converted values of the optical measurements made by each LED followed by the converted direct ambient value will appear successively in the FIFO.

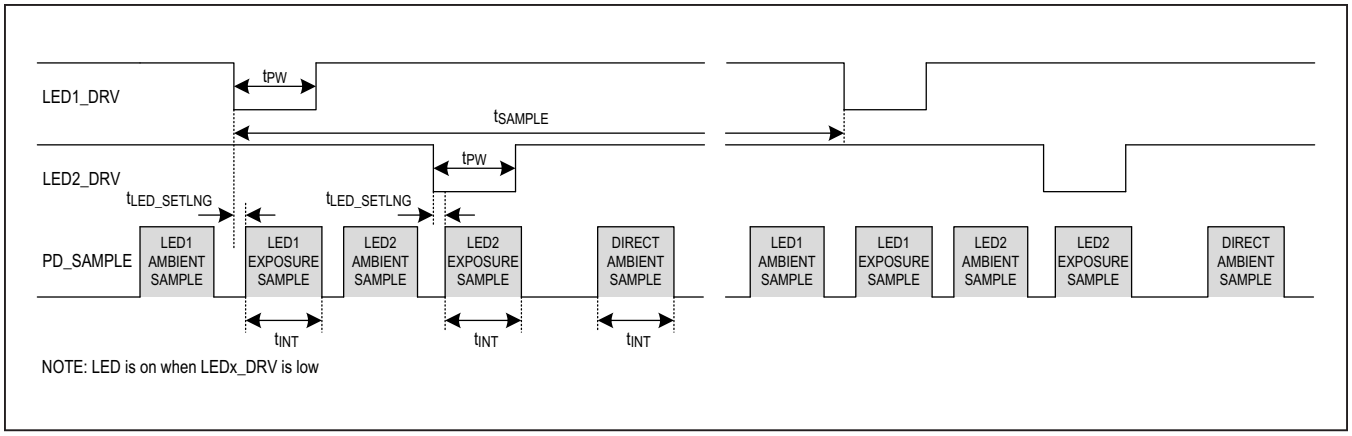


Figure 8. Timing for LED1 and LED2 Firing with Direct Ambient Sampling

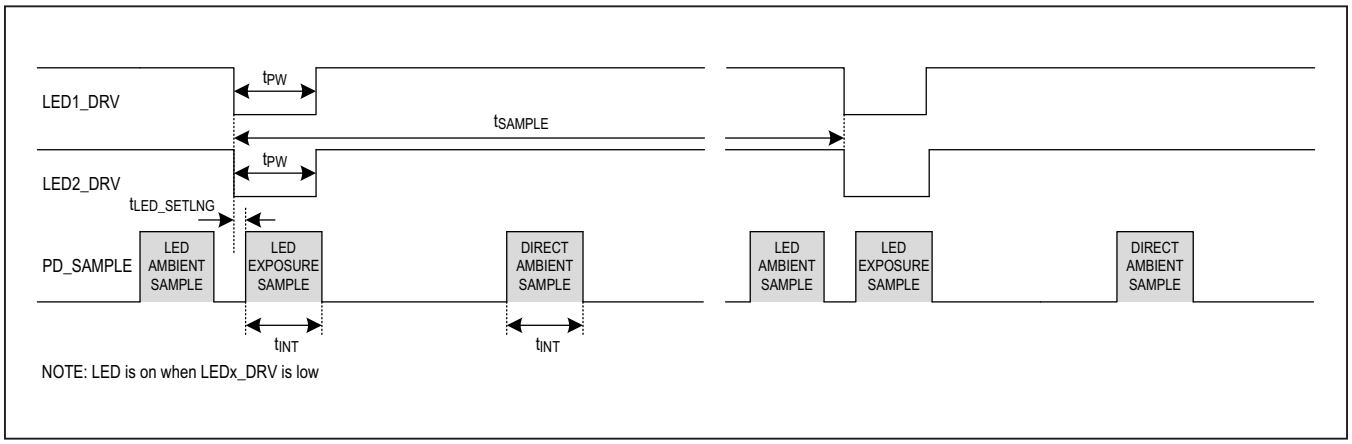


Figure 9: Timing for Dual LED Pulsing with Direct Ambient Sampling

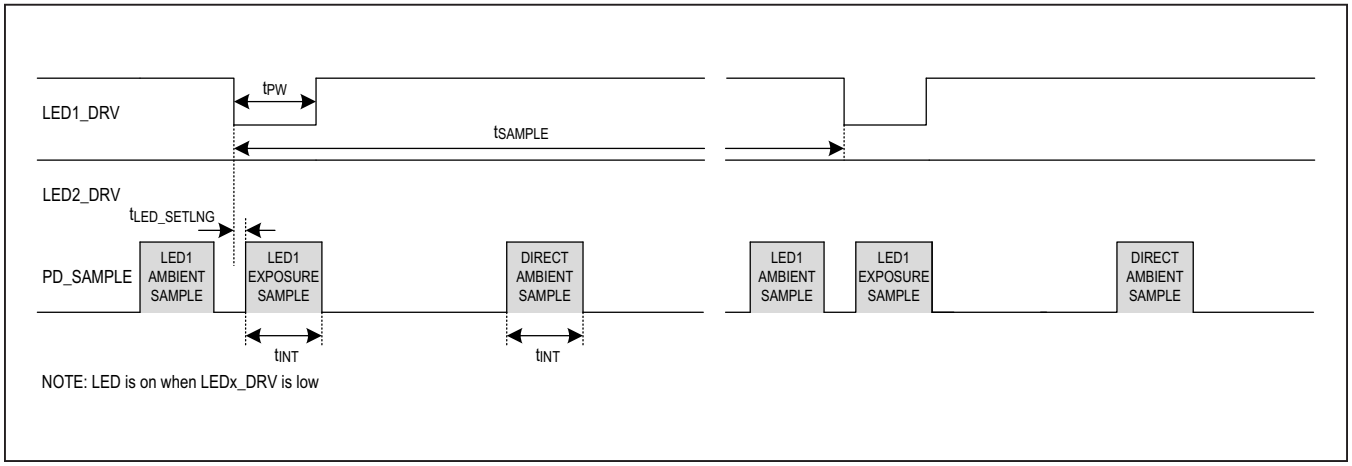


Figure 10: Timing for LED1 Pulsing with Direct Ambient Sampling

Dual-LED Pulsing with Direct Ambient Sampling

The optical timing diagram in Figure 9 represents both LED1 and LED2 pulsing simultaneously with direct ambient sampling enabled. This timing mode would be used when heart rate is being measured with two green LEDs. In this mode, a single optical sampled value followed by the ambient sampled value will appear in successive the FIFO locations.

LED1 Pulsing with Direct Ambient Sampling

The optical timing diagram in Figure 10 represents only LED1 pulsing during the data sampling time with direct ambient sampling enabled. This timing mode would be used when heart rate is being measured with a single green LED. In this mode, a single optical-sampled value, followed by the ambient sampled value, will appear successively in the FIFO.

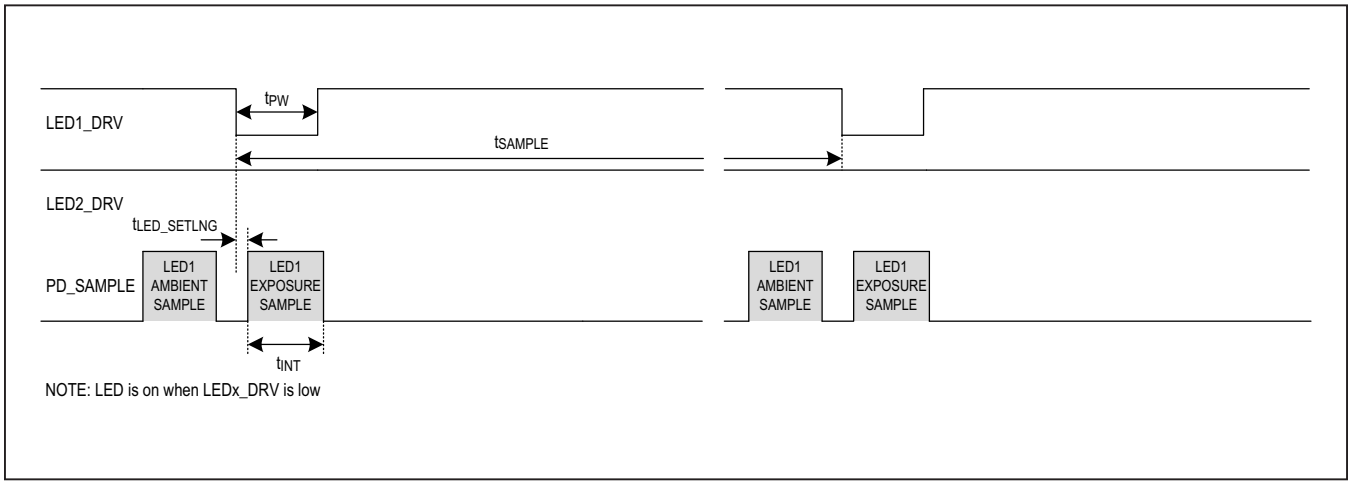


Figure 11: Timing for LED1 Pulsing with No Ambient Sampling

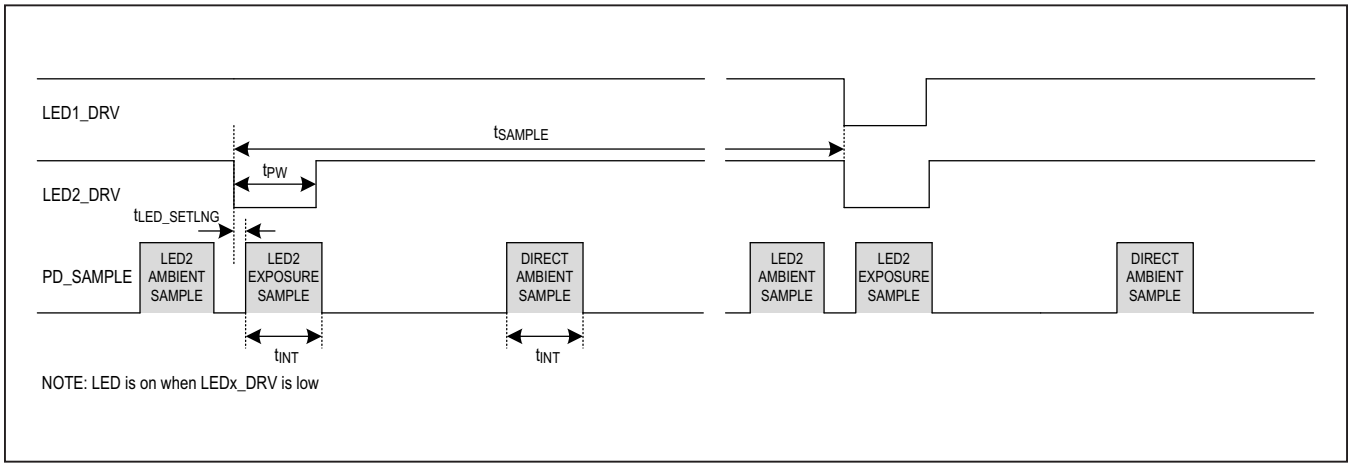


Figure 12: Timing for LED2 Pulsing with Direct Ambient Sampling

LED1 Pulsing with No Ambient Sampling

The optical timing diagram in Figure 11 represents only LED1 pulsing during the data sampling time with no direct ambient sampling enabled. This timing mode would be used when heart rate is being measured with a single green LED. In this mode, a single optical sampled value will appear successively in the FIFO.

LED2 Pulsing with Direct Ambient Sampling

The optical timing diagram in Figure 12 represents only LED2 firing during the data sampling time with direct ambient sampling enabled. This timing mode would be used when heart rate is being measured with a single green LED. In this mode, a single optical sampled value, followed by the ambient sampled value, will appear successively in the FIFO.

LED2 Pulsing with No Ambient Sampling

The optical timing diagram in Figure 13 represents only LED2 firing during the data sampling time with no direct ambient sampling enabled. This timing mode would be used when heart rateis being measured with a single

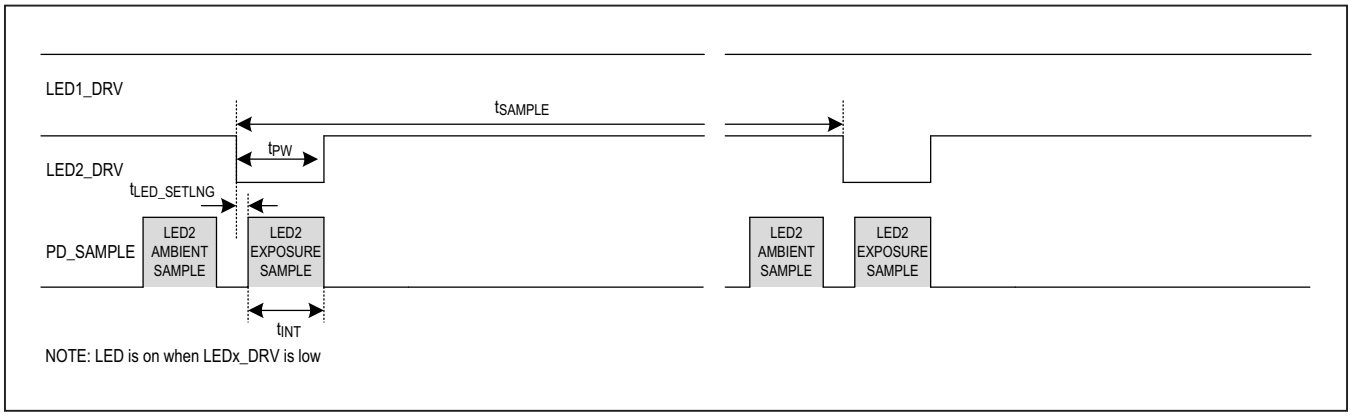


Figure 13: Timing for LED2 Pulsing with No Ambient Sampling

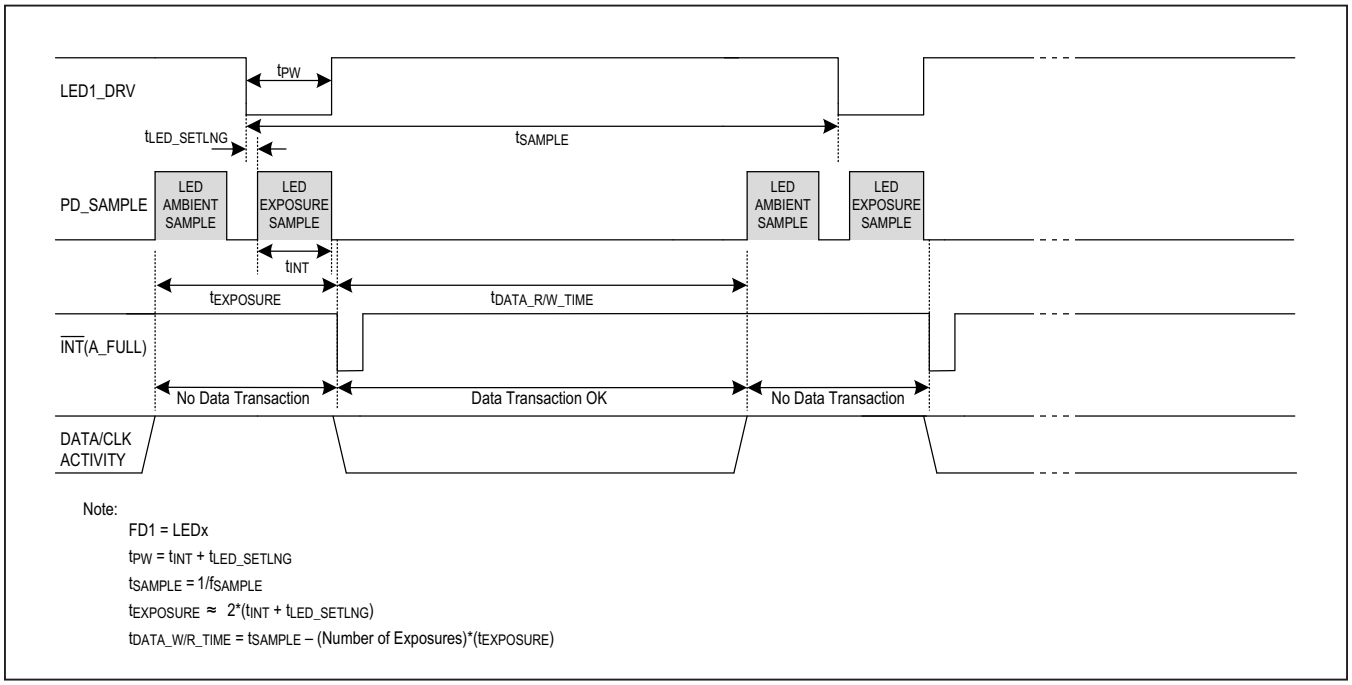


Figure 14. Readout Window for FIFO Read

green LED. In this mode, a single optical sampled value will appear successively in the FIFO.

FIFO Data Read Synchronization

Activity on the interface pins can bounce the on-chip GND potential, disturbing an optical sample, resulting in higher noise. Therefore, during a FIFO read event, it is recommended to time the FIFO read to occur between optical samples. This can be accomplished by reading the FIFO when the FIFO_A_FULL interrupt occurs and then limit the number of samples in the FIFO to those that can be read out during the time between samples. Figure 14 illustrates how to place this read relative to the FIFO_A_FULL interrupt and the chosen sample rate, integration pulse width and LED settling time.

Proximity Function

The MAX30112 features proximity mode, which could significantly reduce energy consumption and extend battery life. In proximity mode, LED1 is pulsing at a lower current. When an object is present, the ADC count will exceed the preset threshold (PROX_INT_THRESH) and trigger the interrupt (PROX_INT). This functionality is only available when the FD1 timing slot is assigned to LED1. To use this function, it is necessary to set four register/bit fields correctly. These variables are the normal state LED current on LED1, LED1_PA (0x11), the proximity LED current, LED_PILOT_PA (0x15), the threshold code, PROX_INT_THRESH (0x10) and the proximity mode enable bit (Interrupt Enable1 (0x02, bit 4). Note that the threshold value is the code in register PROX_INT_THRESH (0x10) times 2048.

If the proximity feature is enabled, it will be switched to proximity mode when the LED1 ADC count drops below the threshold code, PROX_INT_THRESH(0x10). At this point, the LED1 drive current will be set from LED1_PA(0x11) to LED_PILOT_PA(0x15). Note that the threshold value is the code in register PROX_INT_THRESH (0x10) times 2048. This drop in LED current should generate sufficient hysteresis to guarantee that the MAX30112 does not toggle back and forth between proximity and normal mode operation.

Once in proximity mode, the MAX30112 will return to normal operating mode when the ADC count generated by the current programmed into the LED_PILOT_PA (0x15) register passes above the threshold in the PROX_INT_THRESH (0x10) register. When this occurs, the LED1 current will increase to the value assigned in LED1_PA (0x11) register, again providing sufficient hysteresis to guarantee a clean transition. Note that the threshold value is the code in register PROX_INT_THRESH (0x10) times 2048.

It is necessary to experiment with the specific optical geometry when configuring the proximity function. As a means of a starting point of this experimental work, it is recommended that the LED_PILOT_PA (0x15) register be set to about 1/10th the value of the LED1_PA (0x11) register. It is also recommended that the PROX_INT_THRESH (0x10) be set to roughly mid-way between the output code produced by the values of LED1_PA (0x11) and LED_PILOT_PA (0x15) when the optical device is correctly mounted to a subject.