

FEATURES

Ultra low power: 25 to 130 μA at $V_S = 2.5 V$ (typ)
Power consumption scales automatically with bandwidth
User selectable fixed 10-bit resolution or 4mg/LSB scale factor in all g -ranges, up to 13-bit resolution at $\pm 16 g$
32 level output data FIFO minimizes host processor load
Built in motion detection functions

- Tap/Double Tap detection
- Activity/Inactivity monitoring
- Free-Fall detection

Supply and I/O voltage range: 1.8 V to 3.6 V
SPI (3 and 4 wire) and I²C digital interfaces
Flexible interrupt modes – Any interrupt mappable to either interrupt pin
Measurement ranges selectable via serial command
Bandwidth selectable via serial command
Wide temperature range (-40 to +85°C)
10,000 g shock survival
Pb free/RoHS compliant
Small and thin: 3 × 5 × 1 mm LGA package

APPLICATIONS

Handsets
 Gaming and pointing devices
 Personal navigation devices
 HDD protection
 Fitness equipment
 Digital cameras

GENERAL DESCRIPTION

The ADXL345 is a small, thin, low power, three-axis accelerometer with high resolution (13-bit) measurement up to $\pm 16 g$. Digital output data is formatted as 16-bit twos complement and is accessible through either a SPI (3- or 4-wire) or I²C digital interface.

The ADXL345 is well suited for mobile device applications. It measures the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion or shock. Its high resolution (4mg/LSB) enables resolution of inclination changes of as little as 0.25°.

Several special sensing functions are provided. Activity and inactivity sensing detect the presence or lack of motion and if the acceleration on any axis exceeds a user-set level. Tap sensing detects single and double taps. Free-Fall sensing detects if the device is falling. These functions can be mapped to interrupt output pins. An integrated 32 level FIFO can be used to store data to minimize host processor intervention.

Low power modes enable intelligent motion-based power management with threshold sensing and active acceleration measurement at extremely low power dissipation.

The ADXL345 is supplied in a small, thin 3 mm × 5 mm × 1 mm, 14-lead, plastic package.

FUNCTIONAL BLOCK DIAGRAM

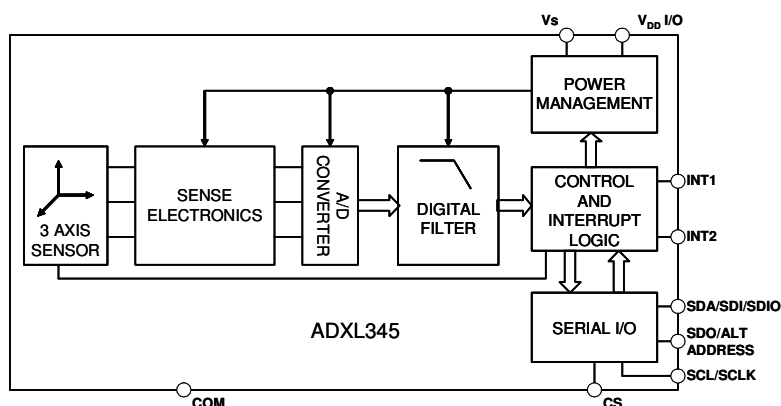


Figure 1. ADXL345 Simplified Block Diagram

SPECIFICATIONS

$T_A = 25^\circ\text{C}$, $V_S = 2.5\text{ V}$, $V_{DD I/O} = 1.8\text{ V}$, Acceleration = 0 g, unless otherwise noted.

Table 1. Specifications¹

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range	User Selectable		$\pm 2, 4, 8, 16$		g
Nonlinearity	Percentage of full scale		± 0.5		%
Inter-Axis Alignment Error			± 0.1		Degrees
Cross-Axis Sensitivity ²			± 1		%
OUTPUT RESOLUTION	Each axis				
All g-ranges	10-bit mode		10		Bits
$\pm 2\text{ g}$ range	Full-Resolution		10		Bits
$\pm 4\text{ g}$ range	Full-Resolution		11		Bits
$\pm 8\text{ g}$ range	Full-Resolution		12		Bits
$\pm 16\text{ g}$ range	Full-Resolution		13		Bits
SENSITIVITY	Each axis				
Sensitivity at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 2\text{ g}$ 10-bit or Full-Resolution	232	256	286	LSB/g
Scale Factor at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 2\text{ g}$ 10-bit or Full-Resolution	3.5	3.9	4.3	mg/LSB
Sensitivity at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 4\text{ g}$ 10-bit mode	116	128	143	LSB/g
Scale Factor at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 4\text{ g}$ 10-bit mode	7.0	7.8	8.6	mg/LSB
Sensitivity at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 8\text{ g}$ 10-bit mode	58	64	71	LSB/g
Scale Factor at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 8\text{ g}$ 10-bit mode	14.0	15.6	17.2	mg/LSB
Sensitivity at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 16\text{ g}$ 10-bit mode	29	32	36	LSB/g
Scale Factor at $X_{OUT}, Y_{OUT}, Z_{OUT}$	$V_S = 2.5\text{ V}$, $\pm 16\text{ g}$ 10-bit mode	28.1	31.2	34.3	mg/LSB
Sensitivity Change due to Temperature			± 0.02		%/ $^\circ\text{C}$
0 g BIAS LEVEL	Each axis				
0 g Output ($X_{OUT}, Y_{OUT}, Z_{OUT}$)	$V_S = 2.5\text{ V}$, $T_A = 25^\circ\text{C}$	-150	0	+150	mg
0 g Offset vs. Temperature			$< \pm 1$		mg/ $^\circ\text{C}$
NOISE PERFORMANCE					
Noise (x-, y-axes)	Data Rate = 100 Hz, $\pm 2\text{ g}$ 10-bit or Full-Res.		< 1		LSB RMS
Noise (z-axis)	Data Rate = 100 Hz, $\pm 2\text{ g}$ 10-bit or Full-Res.		< 1.5		LSB RMS
OUTPUT DATA RATE / BANDWIDTH	User Selectable				
Measurement Rate ³		0.1		3200	Hz
SELF TEST					
Output Change X		+0.31		+1.02	g
Output Change Y		-0.31		-1.02	g
Output Change Z		+0.46		+1.64	g
POWER SUPPLY					
Operating Voltage Range (V_S)		2.0	2.5	3.6	V
Interface Voltage Range ($V_{DD I/O}$)		1.7	1.8	V_S	V
Supply Current	Data Rate > 100 Hz		130	150	μA
Supply Current	Data Rate < 10 Hz		25		μA
Standby Mode Leakage Current			0.1	2	μA
Turn-On Time ⁴	Data Rate = 3200 Hz		1.4		ms
TEMPERATURE					
Operating Temperature Range		-40		85	$^\circ\text{C}$
WEIGHT					
Device Weight			20		mgrams

¹ All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

² Cross-axis sensitivity is defined as coupling between any two axes.

³ Bandwidth is half the output data rate.

⁴ Turn-on and wake-up times are determined by the user defined bandwidth. At 100 Hz data rate the turn-on/wake-up time is approximately 11.1 ms. For additional data rates the turn-on/wake-up time is approximately $\tau + 1.1$ in milliseconds, where τ is $1/(\text{Data Rate})$.

ABSOLUTE MAXIMUM RATINGS

Table 2. Absolute Maximum Ratings

Parameter	Rating
Acceleration (Any Axis, Unpowered)	10,000 <i>g</i>
Acceleration (Any Axis, Powered)	10,000 <i>g</i>
V_S	−0.3 V to 3.6 V
$V_{DD I/O}$	−0.3 V to 3.6
All Other Pins	−0.3 V to 3.6
Output Short-Circuit Duration (Any Pin to Ground)	Indefinite
Temperature Range (Powered)	−40°C to +105°C
Temperature Range (Storage)	−40°C to +105°C

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although this product features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.



PIN CONFIGURATION AND DESCRIPTIONS

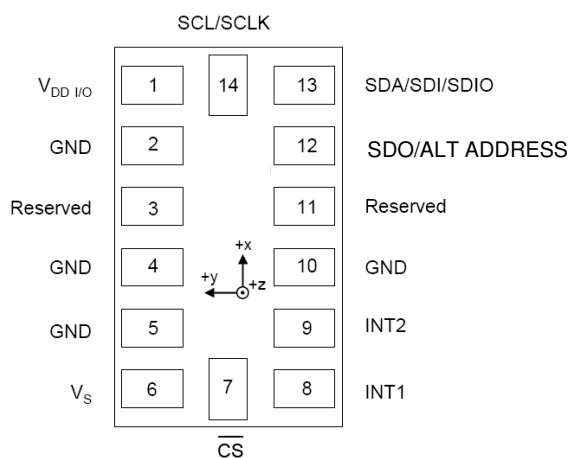


Figure 2. Pin Configuration (TOP VIEW)

Figure 2. Pin Configuration (Top View)

Table 3. Pin Descriptions

Pin No.	Mnemonic	Description
1	$V_{DD\ I/O}$	Digital Interface Supply Voltage
2	GND	Must be connected to ground
3	Reserved	Reserved, must be connected to V_S or left open
4	GND	Must be connected to ground
5	GND	Must be connected to ground
6	V_S	Supply Voltage
7	\overline{CS}	Chip Select
8	INT1	Interrupt 1 Output
9	INT2	Interrupt 2 Output
10	GND	Must be connected to ground
11	Reserved	Reserved, must be connected to GND or left open
12	SDO/ALT ADDRESS	Serial Data Out, Alternate I ² C Address Select
13	SDA/SDI/SDIO	Serial Data (I ² C), Serial Data In (SPI 4-Wire), Serial Data In/Out (SPI 3-Wire)
14	SCL/SCLK	Serial Communications Clock

FUNCTIONAL DESCRIPTION

DEVICE OPERATION

The ADXL345 is a complete three-axis acceleration measurement system with a selectable measurement range of either $\pm 2g$, $\pm 4g$, $\pm 8g$, or $\pm 16g$. It measures both dynamic acceleration resulting from motion or shock and static acceleration, such as gravity, which allows it to be used as a tilt sensor. The sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using differential capacitors that consist of independent fixed plates and plates attached to the moving mass. Acceleration deflects the beam and unbalances the differential capacitor, resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation is used to determine the magnitude and polarity of the acceleration.

POWER SEQUENCING

Power may be applied to V_S or $V_{DD I/O}$ in any sequence without damaging the ADXL345. All possible power on states are summarized in Table 4. The interface voltage level is set with the interface supply voltage $V_{DD I/O}$, which must be present to ensure that the ADXL345 does not create a conflict on the communications bus. For single-supply operation, $V_{DD I/O}$ can be the same as the main supply, V_S . Conversely, in a dual-supply application, $V_{DD I/O}$ can differ from V_S to accommodate the desired interface voltage. Once V_S is applied, the device enters standby state, where power consumption is minimized and the device waits for $V_{DD I/O}$ to be applied and a command to enter measurement state (setting the MEASURE bit in the **POWER_CTL** register). Clearing the MEASURE bit returns the device to standby state.

Table 4. Power Sequencing

Condition	V_S	$V_{DD I/O}$	Description
Power Off	Off	Off	Completely off, potential for communications bus conflict.
Bus Enabled	Off	On	No functions available, but will not create conflict on communications bus.
Standby or Measurement	On	On	At power up the device is in Standby mode awaiting a command to enter measurement mode and all sensor functions are off. Once instructed to enter Measurement mode, all sensor functions are available.

POWER SAVING

Power Modes

The ADXL345 automatically modulates its power consumption proportionally with its output data rate as shown in Table 5. If

additional power savings is desired, a lower power mode is available. In this mode, the internal sampling rate is reduced allowing for power savings in the 12.5 to 400Hz data rate range at the expense of slightly greater noise. To enter lower power mode, set the LOW_POWER bit(D4) in the **BW_RATE** register.

Table 5. Current Consumption versus Data Rate

Output Data Rate (Hz)	Bandwidth (Hz)	Rate Code	I_{DD} (μA)
3200	1600	1111	130
1600	800	1110	80
800	400	1101	130
400	200	1100	130
200	100	1011	130
100	50	1010	130
50	25	1001	80
25	12.5	1000	55
12.5	6.25	0111	37
6.25	3.125	0110	25
3.125	1.563	0101	25
1.563	0.782	0100	25
0.782	0.39	0011	25
0.39	0.195	0010	25
0.195	0.098	0001	25
0.098	0.048	0000	25

The current consumption in Low Power Mode is shown in Table 6. Cases where there is no advantage to using Low Power Mode are shaded.

Table 6. Current Consumption versus Data Rate in Low Power Mode

Output Data Rate	Bandwidth (Hz)	Rate Code	I_{DD} (μA)
3200	1600	1111	130
1600	800	1110	80
800	400	1101	130
400	200	1100	80
200	100	1011	55
100	50	1010	37
50	25	1001	30
25	12.5	1000	25
12.5	6.25	0111	25
6.25	3.125	0110	25
3.125	1.563	0101	25
1.563	0.782	0100	25
0.782	0.39	0011	25
0.39	0.195	0010	25
0.195	0.098	0001	25
0.098	0.048	0000	25

SERIAL COMMUNICATIONS

I²C and SPI digital communications are available. In both cases, the ADXL345 operates as a slave. I²C mode is enabled if the \overline{CS} pin is tied high to $V_{DD1/O}$. In SPI mode, the \overline{CS} pin is controlled by the bus master. In both SPI and I²C modes of operation, data transmitted from the ADXL345 to the master device should be ignored during writes to the ADXL345.

SPI

For SPI, either 3-wire or 4-wire configuration is possible, as shown in the connection diagrams in Figure 3 and Figure 4. Clearing the SPI bit in the **DATA_FORMAT** register selects 4-wire mode while setting the SPI bit selects 3-wire mode. The maximum SPI clock speed is 5 MHz, with 12 pF maximum loading and the timing scheme follows CPOL = 1, CPHA = 1.

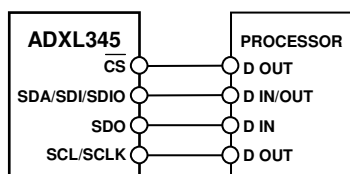


Figure 3. 4-Wire SPI connection

\overline{CS} is the serial port enable line, and is controlled by the SPI master. It must go low at the start of transmissions and back

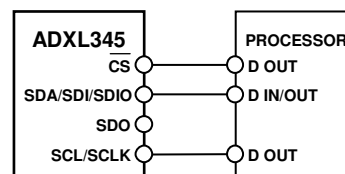


Figure 4. 3-Wire SPI connection

high at the end as shown in Figure 5. SCLK is the serial port clock and is supplied by the SPI master. It is stopped high when \overline{CS} is high, during period of no transmission. SDI and SDO are the serial data in and out respectively. Data should be sampled at the rising edge of SCLK.

To read or write multiple bytes in a single transmission, the Multi-Byte bit, located after the R/W bit in the first byte transfer, must be set. After the register addressing and the first byte of data, continued clock pulses will cause the ADXL345 to point to the next register for read or write. Continued clock pulses will continue to shift the register that is pointed to until the clock pulses are ceased and \overline{CS} is de-asserted. To perform reads or writes on different, non-sequential registers, \overline{CS} must be de-asserted between transmissions and the new register must be addressed separately.

The timing diagram for 3-wire SPI reads or writes is shown in Figure 5. The 4-wire equivalents for SPI reads and writes are shown in Figure 6 and Figure 7 respectively.

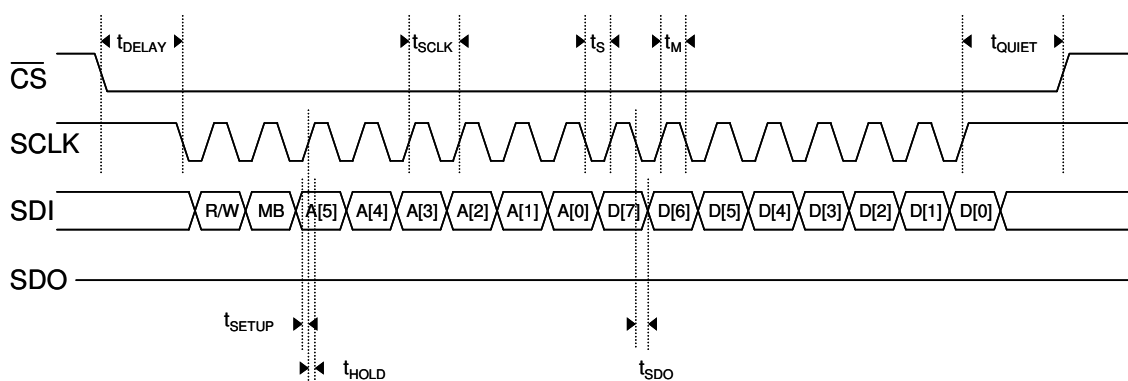


Figure 5. SPI 3-wire Timing Diagram

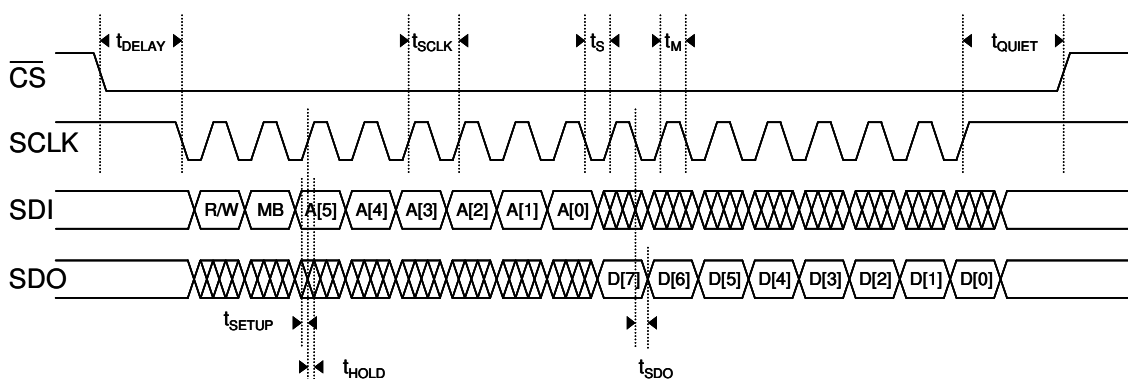


Figure 6. SPI 4-wire Read Timing Diagram

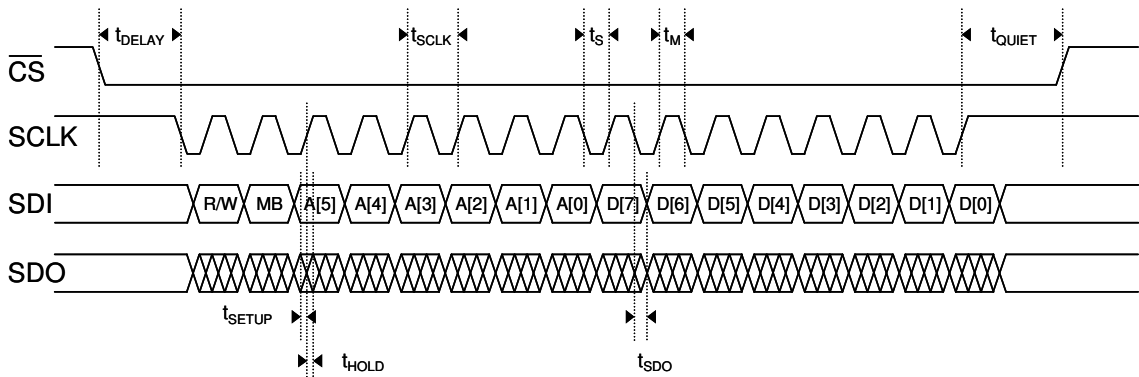


Figure 7. SPI 4-wire Write Timing Diagram

Table 7. SPI Timing Specifications
(TA = 25°C, VS = 2.5V, VDD I/O = 1.8V)

Parameter	Limit	Unit	Description
fSCLK	5	MHz max	SPI clock frequency
tSCLK	200	ns min	1/(SPI clock frequency) Mark/space ratio for the SCLK input is 40/60 to 60/40
tDELAY	200	ns min	falling edge to SCLK falling edge
tQUIET	200	ns min	SCLK rising edge to rising edge
tS	0.4 × tSCLK	ns min	SCLK low pulse width (space)
tM	0.4 × tSCLK	ns min	SCLK high pulse width (mark)
tSDO	8	ns max	SCLK falling edge to SDO transition
tSETUP	10	ns min	SDI valid before SCLK rising edge
tHOLD	10	ns min	SDI valid after SCLK rising edge

for the device is 0x1D, followed by the read/write bit. This translates to 0x3A for write, 0x3B for read. An alternate I²C address of 0x53 (followed by the read/write bit) may be chosen by grounding the SDO pin (pin 12). This translates to 0xA6 for write, 0xA7 for read.

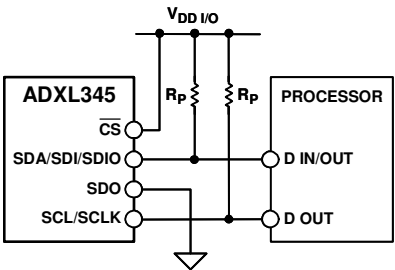
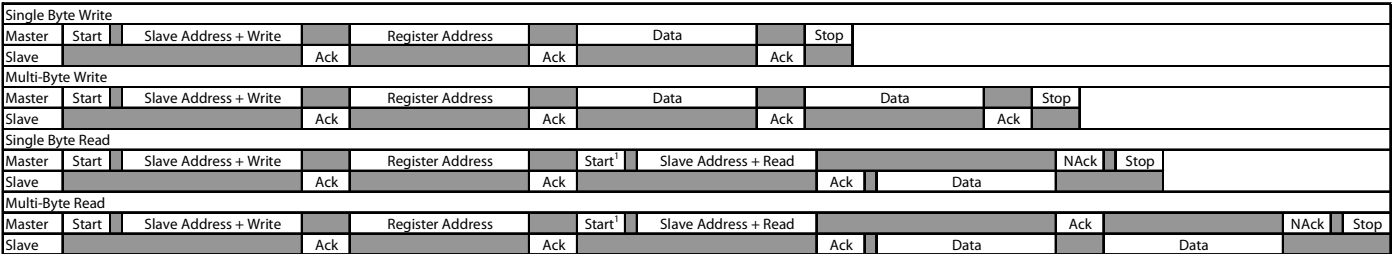


Figure 8. I²C Connection Diagram (Address = 0x53)

I²C

With CS tied high to VDD I/O, the ADXL345 is in I²C mode, requiring a simple 2-wire connection as shown in Figure 8. The ADXL345 conforms to *The I²C Bus Specification*, Version 2.1, January 2000, available from Phillips Semiconductor. It supports standard (100 kHz) and fast (400 kHz) data transfer modes. Single or multiple byte read/writes are supported as shown in Figure 9. With the SDO pin high the 7 bit I²C address

If other devices are connected to the same I²C bus, the nominal operating voltage level of these other devices cannot exceed VDD I/O by more than 0.3 V. Pull-up resistors, RP, should be in the range of 1k to 20kΩ.



¹This Start is either a restart or a Stop followed by a Start

Figure 9. I²C Timing Diagram

INTERRUPTS

The ADXL345 provides two output pins for driving interrupts: INT1 and INT2. Each of the interrupt functions are described in detail below. All functions can be used simultaneously, with the only limiting feature being that some functions may need to share interrupt pins. Interrupts are enabled by setting the appropriate bit in the **INT_ENABLE** register and are mapped to either the INT1 or INT2 pins based on the contents of the **INT_MAP** register. It is recommended that interrupts be configured with the interrupts disabled, preventing interrupts from being accidentally triggered during configuration. This can be done by writing a value of 0x00 to the **INT_ENABLE** register.

DATA_READY

DATA_READY is set when new data is available and cleared when no new data is available.

SINGLE_TAP

SINGLE_TAP is set when single acceleration event that is greater than the value in the **THRESH_TAP** register occurs for a time shorter than specified in the **DUR** register.

DOUBLE_TAP

DOUBLE_TAP is set when two acceleration events that are greater than the value in the **THRESH_TAP** register occur that are shorter than the time specified in the **DUR** register, with the second tap starting after the time specified by the **LATENT** register and within the time specified in the **WINDOW** register. See the Tap Detection description in the Application section for more details.

ACTIVITY

ACTIVITY is set when acceleration greater than the value stored in **THRESH_ACT** is experienced.

INACTIVITY

INACTIVITY is set when acceleration of less than the value stored in the **THRESH_INACT** register is experienced for longer than the time specified in the **TIME_INACT** register. The maximum value for **TIME_INACT** is 255 s.

FREE_FALL

FREE_FALL is set when acceleration of less than the value stored in the **THRESH_FF** register is experienced for longer than the time specified in the **TIME_FF** register. The FREE_FALL interrupt differs from INACTIVITY interrupt in that all axes always participate, the timer period is much smaller (1.28 s maximum) and it is always DC coupled.

WATERMARK

WATERMARK is set when the FIFO has filled up to the value stored in **SAMPLES**. It is cleared automatically when the FIFO is read and its content emptied below the value stored in **SAMPLES**.

OVERRUN

OVERRUN is set when new data has replaced unread data. The precise operation of OVERRUN depends on the FIFO mode. In Bypass Mode, OVERRUN is set when new data replaces unread data in the **DATA_X**, **DATA_Y**, and **DATA_Z** registers. In all other modes, OVERRUN is set when the FIFO is filled. OVERRUN is cleared by reading the FIFO contents, and is automatically cleared when the data is read.

FIFO

The ADXL345 contains a 32 level FIFO that can be used to minimize host processor intervention. The FIFO has four modes as described in Table 15 in the Register Definitions section. Mode selection is made by setting the appropriate **MODE** bits in the **FIFO_CTL** register. Each FIFO mode is described below.

Bypass Mode

In Bypass Mode the FIFO is not operational and remains empty.

FIFO Mode

In FIFO Mode data from X, Y, and Z measurements go into the FIFO. When the FIFO is filled to the level specified in **SAMPLES** (in the **FIFO_CTL** register), the **WATERMARK** interrupt is set. The FIFO will continue filling until it is full (32 X, Y, and Z samples) and then stop collecting data. After the FIFO has stopped collecting data the device still continues to operate, so features like Tap detection, for example, may still be used once the FIFO is full. The **WATERMARK** interrupt will continue to occur until the number of samples in the FIFO is less than the value of **SAMPLES** in the **FIFO_CTL** register.

Stream Mode

In Stream Mode data from X, Y, and Z measurements go into the FIFO. When the FIFO is filled to the level specified in **SAMPLES** (in the **FIFO_CTL** register), the **WATERMARK** interrupt is set. The FIFO will continue filling, and will hold the latest 32 X, Y, and Z samples, discarding older data as new data arrives. The **WATERMARK** interrupt will continue to occur until the number of samples in the FIFO is less than the value of **SAMPLES** in the **FIFO_CTL** register.

Trigger Mode

In Trigger Mode, the FIFO fills and holds the latest 32 X, Y, and Z samples. Once a trigger event occurs (as described by the **TRIG_SOURCE** bit in the **FIFO_CTL** register), the FIFO will keep the last *n* samples (where *n* is the value specified by **SAMPLES** in the **FIFO_CTL** register) and then operate in FIFO mode, collecting new samples only when the FIFO is not full. Additional trigger events will not be recognized until Trigger Mode is reset. This can be done by setting the device in Bypass Mode, reading the **FIFO_STATUS** register and then setting the device back into Trigger Mode. The FIFO data should be read first, as placing the device into Bypass Mode will clear the FIFO.

Retrieving Data from the FIFO

FIFO data is read through the **DATA_X**, **DATA_Y** and **DATA_Z** registers. When the FIFO is in FIFO, Stream, or Trigger Modes, reads to the **DATA_X**, **DATA_Y**, and **DATA_Z** registers read data stored in the FIFO. Each time any data is read from the FIFO the oldest X, Y, and Z data is placed into the **DATA_X**, **DATA_Y** and **DATA_Z** registers. If a single byte read operation is performed, the remaining bytes worth of data will be lost. Therefore, all axes of interest should be read in a burst (or multi-byte) read operation. To ensure that the FIFO has completely popped, there must be at least 5 μ s between the end of reading the data registers, signified by the transition to register 0x38 from 0x37 or the CS pin going high, and the start of new reads of the FIFO or reading the **FIFO_STATUS** register. For SPI operation at 1.5 MHz or lower, the register addressing portion of the transmission is sufficient delay to ensure the FIFO has completely popped. It is necessary for SPI operation greater than 1.5 MHz to de-assert the $\overline{\text{CS}}$ pin to ensure a total of 5 μ s, which is at most 3.4 μ s at 5 MHz operation. This is not a concern when using I²C, as the communication rate is low enough to ensure a sufficient delay between FIFO reads.

SELF TEST

The ADXL345 incorporates a Self Test feature that effectively tests both its mechanical and electronic systems. When the Self Test function is enabled (via the **SELF_TEST** bit in the **DATA_FORMAT** register), an electrostatic force is exerted on the mechanical sensor. This electrostatic force moves the mechanical sensing element in the same manner as acceleration, and it is additive to the acceleration experienced by the device. This added electrostatic force results in an output change in the X, Y, and Z-axes. Because the electrostatic force is proportional to V_s^2 , the output change varies with V_s .

The Self Test feature on the ADXL345 exhibits a bi-modal behavior which depends upon which phase of the clock Self Test is enabled. Due to this, a typical value for Self Test is not reported; however, the limits shown in Table 1 and below are valid for both potential values.

Table 8. Self Test output in LSB for 2 g and Full-Resolution

	$V_s = 2.5 \text{ V}$			$V_s = 3.3 \text{ V}$		
	Min.	Typ.	Max.	Min.	Typ.	Max.
X-Axis	+80		+260	+140		+455
Y-Axis	-80		-260	-140		-455
Z-Axis	+120		+420	+210		+730

Table 9. Self Test output in LSB for 4 g 10-bit

	$V_s = 2.5 \text{ V}$			$V_s = 3.3 \text{ V}$		
	Min.	Typ.	Max.	Min.	Typ.	Max.
X-Axis	+40		+130	+70		+225
Y-Axis	-40		-130	-70		-225
Z-Axis	+60		+210	+105		+365

Table 10. Self Test output in LSB for 8 g 10-bit

	$V_s = 2.5 \text{ V}$			$V_s = 2.5 \text{ V}$		
	Min.	Typ.	Max.	Min.	Typ.	Max.
X-Axis	+20		+65	+35		+113
Y-Axis	-20		-65	-35		-113
Z-Axis	+30		+105	+52		+183

Table 11. Self Test output in LSB for 16 g 10-bit

	$V_s = 2.5 \text{ V}$			$V_s = 2.5 \text{ V}$		
	Min.	Typ.	Max.	Min.	Typ.	Max.
X-Axis	+10		+33	+17		+57
Y-Axis	-10		-33	-17		-57
Z-Axis	+15		+53	+26		+92

REGISTER MAP

Table 12. Register Map

Hex	Dec	Name	Type	Reset Value	Description
0	0	DEVID	R	11100101	Device ID.
1	1	Reserved			Reserved. Do not access.
to					Reserved. Do not access.
1C	28	Reserved			Reserved. Do not access.
1D	29	THRESH_TAP	R/W	00000000	Tap threshold
1E	30	OFSX	R/W	00000000	X axis offset
1F	31	OFSY	R/W	00000000	Y axis offset
20	32	OFSZ	R/W	00000000	Z axis offset
21	33	DUR	R/W	00000000	Tap duration
22	34	LATENT	R/W	00000000	Tap latency
23	35	WINDOW	R/W	00000000	Tap window
24	36	THRESH_ACT	R/W	00000000	Activity threshold
25	37	THRESH_INACT	R/W	00000000	Inactivity threshold
26	38	TIME_INACT	R/W	00000000	Inactivity time
27	39	ACT_INACT_CTL	R/W	00000000	Axis enable control for ACT/INACT
28	40	THRESH_FF	R/W	00000000	Free-fall threshold
29	41	TIME_FF	R/W	00000000	Free-fall time
2A	42	TAP_AXES	R/W	00000000	Axis control for Tap/Double Tap
2B	43	ACT_TAP_STATUS	R	00000000	Source of Tap/Double Tap
2C	44	BW_RATE	R/W	00001010	Data Rate and Power Mode control
2D	45	POWER_CTL	R/W	00000000	Power Save features control
2E	46	INT_ENABLE	R/W	00000000	Interrupt enable control
2F	47	INT_MAP	R/W	00000000	Interrupt mapping control
30	48	INT_SOURCE	R	00000000	Source of interrupts
31	49	DATA_FORMAT	R/W	00000000	Data format control
32	50	DATA_X0	R	00000000	X axis data
33	51	DATA_X1	R	00000000	
34	52	DATA_Y0	R	00000000	Y axis data
35	53	DATA_Y1	R	00000000	
36	54	DATA_Z0	R	00000000	Z axis data
37	55	DATA_Z1	R	00000000	
38	56	FIFO_CTL	R	00000000	FIFO control
39	57	FIFO_STATUS	R/W	00000000	FIFO status

REGISTER DEFINITIONS**0x00 DEVID (read-only)**

D7	D6	D5	D4	D3	D2	D1	D0
1	1	1	0	0	1	0	1

DEVID holds a fixed device ID code of 0xE5 (345 octal).

0x1D THRESH_TAP (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

THRESH_TAP holds the threshold value for tap interrupts.

The data format is unsigned, so the magnitude of the tap event is compared to THRESH_TAP. The scale factor is 62.5 mg/LSB (i.e. 0xFF = +16 g). A zero value may result in undesirable behavior if Tap/Double Tap interrupts are enabled.

0x1E, 0x1F, 0x20 OFSX, OFSY, OFSZ (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

OFSX/OFSY/OFSZ offer user offset adjustments in two's-complement form with a scale factor of 15.6 mg/LSB (i.e. 0x7F = +2 g).

0x21 DUR (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

DUR is an unsigned time value representing the maximum time that an event must be above the THRESH_TAP threshold to qualify as a tap event. The scale factor is 625 μ s/LSB. A zero value will prevent Tap/Double Tap functions from working.

0x22 LATENT (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

LATENT is an unsigned time value representing the wait time from the detection of a tap event to the opening of the time window WINDOW for a possible second tap event. The scale factor is 1.25 ms/LSB. A zero value will disable the Double Tap function.

0x23 WINDOW (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

WINDOW is an unsigned time value representing the amount of time after the expiration of LATENT during which a second tap can begin. The scale factor is 1.25 ms/LSB. A zero value will disable the Double Tap function.

0x24 THRESH_ACT (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

THRESH_ACT holds the threshold value for activity detection.

The data format is unsigned, so the magnitude of the activity event is compared to THRESH_ACT. The scale factor is 62.5 mg/LSB. A zero value may result in undesirable behavior if Activity interrupt is enabled.

0x25 THRESH_INACT (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

THRESH_INACT holds the threshold value for inactivity detection. The data format is unsigned, so the magnitude of the inactivity event is compared to THRESH_INACT. The scale factor is 62.5 mg/LSB. A zero value may result in undesirable behavior if Inactivity interrupt is enabled.

0x26 TIME_INACT (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

TIME_INACT is an unsigned time value representing the amount of time that acceleration must be below the value in THRESH_INACT for inactivity to be declared. The scale factor is 1 second/LSB. Unlike the other interrupt functions, which operate on unfiltered data (See Threshold description in Application section), the inactivity function operates on the filtered output data. At least one output sample must be generated for the inactivity interrupt to be triggered. This will result in the function appearing un-responsive if the TIME_INACT register is set with a value less than the time constant of the Output Data Rate. A zero value will result in an interrupt when the output data is below THRESH_INACT.

0x27 ACT_INACT_CONTROL (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
ACT AC/DC	ACT_X Enable	ACT_Y Enable	ACT_Z Enable	INACT AC/DC	INACT_X Enable	INACT_Y Enable	INACT_Z Enable

X/Y/Z Enable: A '1' enables X, Y, or Z participation in activity or inactivity detection. A '0' excludes the selected axis from participation. If all of the axes are excluded, the function is disabled.

AC/DC: A '0' = DC coupled operation and a '1' = AC coupled operation. In DC coupled operation, the current acceleration is compared with **THRESH_ACT** and **THRESH_INACT** directly to determine whether activity or inactivity is detected. In AC coupled operation for activity detection, the acceleration value at the start of activity detection is taken as a reference value. New samples of acceleration are then compared to this reference value and if the magnitude of the difference exceeds **THRESH_ACT** the device will trigger an activity interrupt. In AC coupled operation for inactivity detection, a reference value is used again for comparison and is updated whenever the device exceeds the inactivity threshold. Once the reference value is selected, the device compares the magnitude of the difference between the reference value and the current acceleration with **THRESH_INACT**. If the difference is below **THRESH_INACT** for a total of **TIME_INACT**, the device is considered inactive and the inactivity interrupt is triggered.

0x28 THRESH_FF (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

THRESH_FF holds the threshold value for Free-Fall detection. The data format is unsigned. The root-sum-square(RSS) value of all axes is calculated and compared to the value in **THRESH_FF** to determine if a free fall event may be occurring. The scale factor is 62.5 mg/LSB. A zero value may result in undesirable behavior if Free-Fall interrupt is enabled. Values between 300 and 600 mg (0x05 to 0x09) are recommended.

0x29 TIME_FF (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
MSB	D6	D5	D4	D3	D2	D1	LSB

TIME_FF is an unsigned time value representing the minimum time that the RSS value of all axes must be less than **THRESH_FF** to generate a Free-Fall interrupt. The scale factor is 5 ms/LSB. A zero value may result in undesirable behavior if Free-Fall interrupt is enabled. Values between 100 to 350 ms (0x14 to 0x46) are recommended.

0x2A TAP_AXES (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
0	0	0	0	SUPPRESS	TAP_X Enable	TAP_Y Enable	TAP_Z Enable

TAP_X/Y/Z Enable: A '1' in TAP_X, Y, or Z Enable enables X, Y, or Z participation in Tap detection. A '0' excludes the selected axis from participation in Tap detection.

Setting the SUPPRESS bit suppresses Double Tap detection if acceleration greater than **THRESH_TAP** is present between taps. See Tap Detection in the Application Section for more details.

0x2B ACT_TAP_STATUS (read)

D7	D6	D5	D4	D3	D2	D1	D0
X	ACT_X Source	ACT_Y Source	ACT_Z Source	ASLEEP	TAP_X Source	TAP_Y Source	TAP_Z Source

X/Y/Z Source: Indicate the first axis involved in a Tap or Activity event. A '1' corresponds to involvement in the event and a '0' corresponds to no involvement. They are not cleared, but overwritten by new data. **ACT_TAP_STATUS** should be read before clearing the interrupt. Disabling an axis from participation will clear the corresponding Source bit when the next Activity or Tap/Double Tap event occurs.

ASLEEP: A '1' indicates that the part is in the Auto Sleep Mode. A '0' indicates that the part is not using Auto Sleep Mode. See the **POWER_CTL** description for more information on Auto Sleep Mode.

0x2C BW_RATE (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
X	X	X	LOW_POWER	RATE			

LOW_POWER: A '0' = Normal operation and a '1' = Reduced power operation with somewhat higher noise. (See Power Modes section for details).

RATE: Selects device bandwidth and output data rate. See Table 5 and Table 6 for details. Default value is 0x0A, or 100 Hz Output Data Rate. An Output Data Rate should be selected that is appropriate for the communication protocol and frequency selected. Selecting too high of an Output Data Rate with a low communication speed will result in samples being discarded.

0x2D POWER_CTL (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
X	X	LINK	AUTO_SLEEP	MEASURE	SLEEP	WAKEUP	

LINK: A '1' with both the activity and inactivity functions enabled will delay the start of the activity function until inactivity is detected. Once activity is detected, inactivity detection will begin and prevent the detection of activity. This bit serially links the activity and inactivity functions. When '0' the inactivity and activity functions are concurrent. Additional information can be found in the Application section under Link Mode.

AUTO_SLEEP: A '1' sets the ADXL345 to switch to Sleep Mode when inactivity (acceleration has been below THRESH_INACT for at least TIME_INACT) is detected and the LINK bit is set. A '0' disables automatic switching to Sleep Mode. See SLEEP for further description.

MEASURE: A '0' places the part into standby mode and a '1' places the part into measurement mode. The ADXL345 powers up in standby mode with minimum power consumption.

SLEEP: A '0' puts the part into a normal mode of operation. A '1' places the part into Sleep Mode. This suppresses DATA_READY, stops sending data to the FIFO, and switches the sampling rate to one specified by the WAKEUP bits. In Sleep Mode, only the Activity function can be used.

When clearing the LINK, AUTO_SLEEP, or SLEEP bits, it is recommended that the part be placed into Standby when clearing the bits and then re-enabling Measurement mode during a following write. This is done to ensure the device is properly biased if Sleep mode is manually disabled. Not toggling Measurement mode may result in the first few after LINK, AUTO_SLEEP, or SLEEP is cleared having additional noise, especially if the device was asleep when the bits were cleared.

WAKEUP: Controls the frequency of readings in Sleep Mode as shown in

Table 13 below:

Table 13. WAKEUP Rates

D1	D0	Frequency (Hz)
0	0	8
0	1	4
1	0	2
1	1	1

0x2E INT_ENABLE (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
DATA_READY	SINGLE_TAP	DOUBLE_TAP	ACTIVITY	INACTIVITY	FREE_FALL	WATERMARK	OVERRUN

Setting bits with a value of '1' in this register to enable their respective functions and generate interrupts. A value of '0' will prevent the functions from generating an interrupt. DATA_READY, WATERMARK, and OVERRUN bits only enable the interrupt output; the functions are always enabled. It is recommended that interrupts be configured before enabling their outputs.

0x2F INT_MAP (read/Write)

D7	D6	D5	D4	D3	D2	D1	D0
DATA_READY	SINGLE_TAP	DOUBLE_TAP	ACTIVITY	INACTIVITY	FREE_FALL	WATERMARK	OVERRUN

Any '0' bits in this register send their respective interrupts to the INT1 pin. Bits set with a '1' send their respective interrupts to the INT2 pin. All selected interrupts for a given pin are ORed.

0x30 INT_SOURCE (read)

D7	D6	D5	D4	D3	D2	D1	D0
DATA_READY	SINGLE_TAP	DOUBLE_TAP	ACTIVITY	INACTIVITY	FREE_FALL	WATERMARK	OVERRUN

Bits set with a '1' in this register indicate that their respective functions have triggered. A value of '0' indicates that the corresponding event has not occurred. DATA_READY, WATERMARK and OVERRUN bits will always be set if corresponding event occurs, regardless of INT_ENABLE, and are cleared by reading data from the DATA_X/Y/Z registers. DATA_READY and WATERMARK may require multiple reads, as per the FIFO Mode descriptions in the FIFO section. Other bits are cleared by reading INT_SOURCE.

0x31 DATA_FORMAT (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
SELF_TEST	SPI	INT_INVERT	X	FULL_RES	JUSTIFY	RANGE	

DATA_FORMAT controls the presentation of data at registers 0x32 to 0x37. All data, except ± 16 g range, must be clipped to avoid rollover.

SELF_TEST: A '1' applies a Self Test force to the sensor causing a shift in the output data. A value of '0' disable Self Test.

SPI: A value of '1' sets the device to 3-wire SPI and a value of '0' sets the device to 4-wire SPI.

INT_INVERT: A value of '0' sets the interrupts to Active High while a value of '1' sets the interrupts to Active Low.

FULL_RES: When this bit is set with a value of '1' the device is in Full-Resolution Mode, where the output resolution increases with RANGE to maintain a 4 mg/LSB scale factor. When this bit is '0' the device is in 10-bit Mode and RANGE determine the maximum g-Range and scale factor.

JUSTIFY: A '1' = Left (MSB) justified and a '0' = Right justified with sign extension.

RANGE: Sets the g-Range based on Table 14 below.

Table 14. g-Range Setting

D1	D0	g-Range
0	0	± 2 g
0	1	± 4 g
1	0	± 8 g
1	1	± 16 g

0x32, 0x33 DATA0, DATA1 (read only)

D7	D6	D5	D4	D3	D2	D1	D0

0x34, 0x35 DATAY0, DATAY1 (read only)

D7	D6	D5	D4	D3	D2	D1	D0

0x36, 0x37 DATAZ0, DATAZ1 (read only)

D7	D6	D5	D4	D3	D2	D1	D0

These six bytes hold the output data for each axis. The output data is two's complement with **DATAx0** as the LSByte and **DATAx1** as the MSByte. The **DATA_FORMAT** register (0x31) controls the format of the data. It is recommended that a burst read of all of the registers is performed to prevent the change of data between reads of sequential registers.

0x38 FIFO_CTL (read/write)

D7	D6	D5	D4	D3	D2	D1	D0
FIFO_MODE	TRIGGER	SAMPLES					

FIFO_MODE: Corresponds to the FIFO Mode as shown in Table 15 below.

TRIGGER: A value of '0' sets the trigger event of Trigger Mode to INT1 and a value of '1' sets the trigger event to INT2.

SAMPLES: Function depends on the FIFO Mode as shown in Table 16 below. Entering a value of zero in SAMPLES will immediately set the WATERMARK status bit in **INT_SOURCE**, regardless of FIFO mode. Undesirable operation may occur if a value of zero is used for SAMPLES when Trigger Mode is used.

Table 15. FIFO Modes

D7	D6	MODE	Function
0	0	Bypass	The FIFO is bypassed
0	1	FIFO	FIFO collects up to 32 values then stops collecting data
1	0	Stream	FIFO holds the last 32 data values. Once full, the FIFO's oldest data is lost as it is replaced with newer data
1	1	Trigger	When triggered by the TRIGGER the FIFO holds the last 32 data values and stops when full.

Table 16. SAMPLES Functions

FIFO Mode	Samples Function
Bypass	None
FIFO	Specifies how many FIFO entries are need to trigger a Watermark interrupt
Stream	Specifies how many FIFO entries are need to trigger a Watermark interrupt
Trigger	Specifies how many FIFO samples <i>before</i> the trigger event are retained in the FIFO buffer

0x39 FIFO_STATUS (read)

D7	D6	D5	D4	D3	D2	D1	D0
FIFO_TRIG	X	ENTRIES					

FIFO_TRIG: A '1' corresponds to a trigger event occurring while a '0' means that a FIFO trigger event has not yet occurred.

ENTRIES: Reports how many data values are stored in the FIFO. To collect the data from the FIFO, access is through the standard **DATAx**, **DATAY**, and **DATAZ** registers. FIFO reads must be done in burst, or multi-byte, mode as each FIFO level is cleared after any read, single- or multi-byte, of the FIFO. The FIFO stores a maximum of 32 entries, which equates to a maximum of 33 entries available at any given time, due to the fact that an additional entry is available at the output filter of device.

APPLICATION

POWER SUPPLY DECOUPLING

In many applications, a 0.1 μF capacitor at V_S and $V_{DD\text{ I/O}}$ placed close to the ADXL345 supply pins adequately decouples the accelerometer from noise on the power supply. However, in applications where noise is present at the 50 kHz internal clock frequency, or any harmonic thereof, additional care in power supply bypassing is required because this noise may cause errors in acceleration measurement. If additional decoupling is necessary, a 10 Ω resistor or ferrite in series with V_S and an additional larger bypass capacitor (2.2 μF or greater) at V_S may be helpful.

Care should be taken that the connection from the ADXL345 ground to the power supply ground be low impedance because noise transmitted through ground has an effect similar to noise transmitted through V_S .

MECHANICAL CONSIDERATIONS FOR MOUNTING

The ADXL345 should be mounted on the PCB in a location close to a hard mounting point of the PCB to the case. Mounting the ADXL345 at an unsupported PCB location (that is, at the end of a “lever,” or in the middle of a “trampoline”), as shown in Figure 10, may result in large apparent measurement errors because the accelerometer will see the resonant vibration of the PCB. Locating the accelerometer near a hard mounting point ensures that any PCB resonances at the accelerometer are above the accelerometer’s mechanical sensor resonant frequency and, therefore, effectively invisible to the accelerometer.

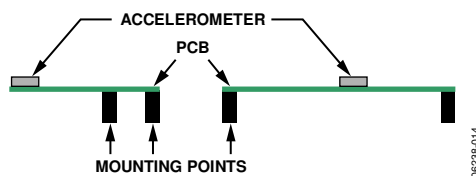


Figure 10. Where Not to Mount an Accelerometer

TAP DETECTION

The tap interrupt function is capable of detecting either single or double taps. The following parameters are shown graphically in Figure 11 for a valid single and valid double tap event:

- Tap detection threshold is defined by the **THRESH_TAP** register.
- Maximum tap duration time is defined by the **DUR** register.
- Tap latency time is defined by the **LATENT** register and is the waiting period from the end of the first tap

until the opening of the time window, whose value is contained in the **WINDOW** register, for a possible second tap.

- The interval time after the expiration of **LATENT** is defined by the **WINDOW** register and is the period of time during which a second tap must begin. The second tap need not finish before the end of **WINDOW**.

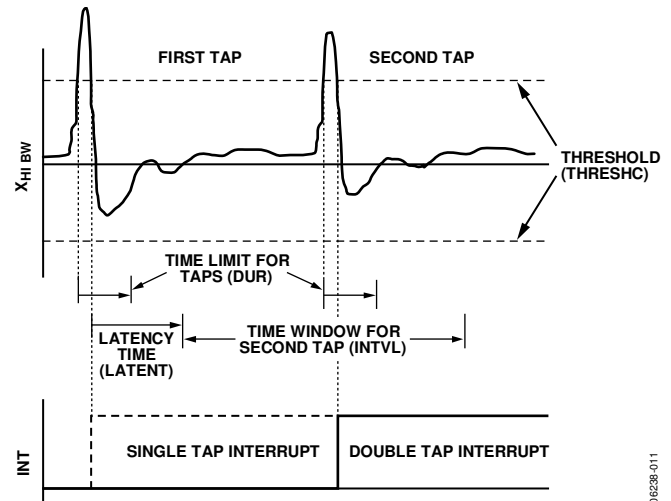


Figure 11. Tap Interrupt Function with Valid Single and Double Taps

If only the single tap function is in use, the single tap interrupt will trigger at the point that the acceleration goes below the threshold as long as **DUR** is not exceeded. If both single and double tap functions are in use the single tap interrupt will trigger once the double tap event has been either validated or invalidated.

Several events can occur to invalidate the second tap of a double tap event. First, if the **SUPPRESS** bit in the **TAP_AXES** register is set, any acceleration spikes above the threshold during the **LATENT** time window will invalidate the double tap as seen in Figure 12.

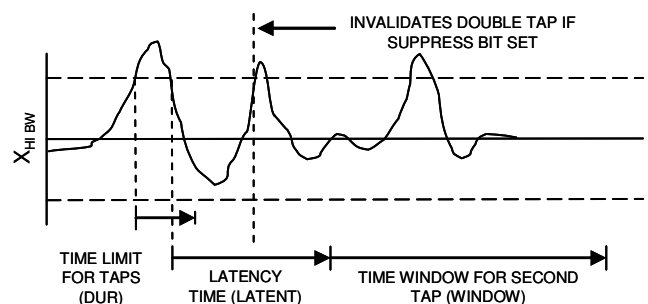


Figure 12. Double Tap event invalid due to high-g event with **SUPPRESS** set

A double tap event can also be invalidated if an acceleration above the threshold is detected at the start of **WINDOW**, resulting in an invalid double tap at the start of **WINDOW**, shown in Figure 13. Additionally, a double tap event can be invalidated by having an acceleration exceed **DUR**, resulting in an invalid double tap at the end of **DUR** for the second tap event, also seen in Figure 13.

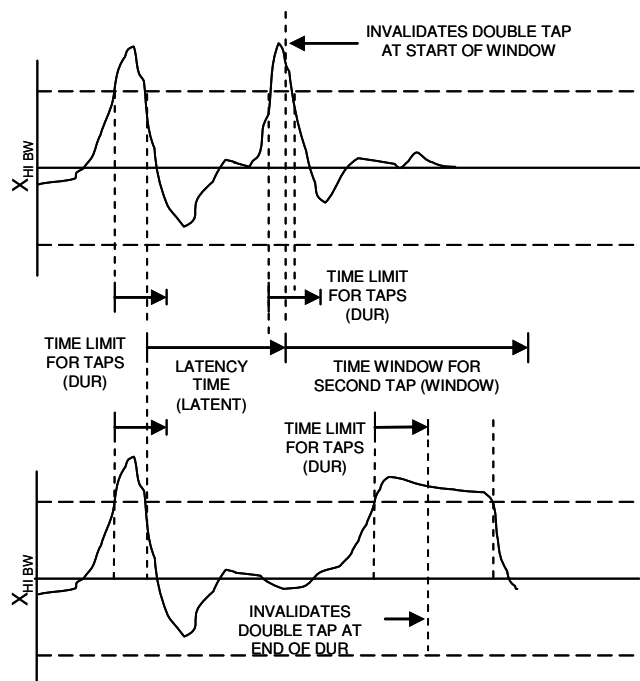


Figure 13. Tap Interrupt Function with Invalid Double Taps

Single taps, double taps, or both may be detected by setting their respective bits in the **INT_ENABLE** register. Control over participation of each of the three axes in tap/double tap detection is exerted by setting the appropriate bits in the **TAP_AXES** register. For the double tap function to operate, both **LATENT** and **WINDOW** must be non-zero.

Every mechanical system will have somewhat different tap/double tap response based on the system's mechanical characteristics, so some experimentation with values for the **LATENT**, **WINDOW**, and **THRESH_TAP** registers will be required. In general a good starting point is **LATENT**>0x10, **WINDOW**>0x10, and **THRESH_TAP**>3g. Setting very low values in the **LATENT**, **WINDOW**, and/or **THRESH_TAP** registers may result in unpredictable response due to the accelerometer picking up "echoes" of the tap inputs.

After a tap interrupt is received, the first axis to exceed the **THRESH_TAP** level is reported in the **ACT_TAP_STATUS** register. This register is never cleared, but overwritten with new data.

THRESHOLD

The lower Output Data Rates are achieved by decimation of a common sampling frequency inside the device. The activity, free-fall and tap/double tap detection functions are performed using the un-filtered data. Since the output data is filtered, the high frequency and high-g data that is used to determine activity, free-fall and tap/double tap events may not be present if the output of the accelerometer is examined. This may result in trigger events appearing to occur when acceleration does not appear to trigger an event, such as exceeding a threshold or remaining below a threshold for a certain period of time.

LINK MODE

The LINK function can be used to reduce the number of activity interrupts the processor must service by only looking for activity after inactivity. For proper operation of the link feature, the processor must still respond to the activity and inactivity interrupts by reading the **INT_SOURCE** register to clear them. If the activity interrupt is not cleared, the part will not go into Auto Sleep Mode. The **ASLEEP** bit in the **ACT_TAP_STATUS** register indicates if the part is in Auto Sleep Mode.

RECOMMENDED PWB LAND PATTERN

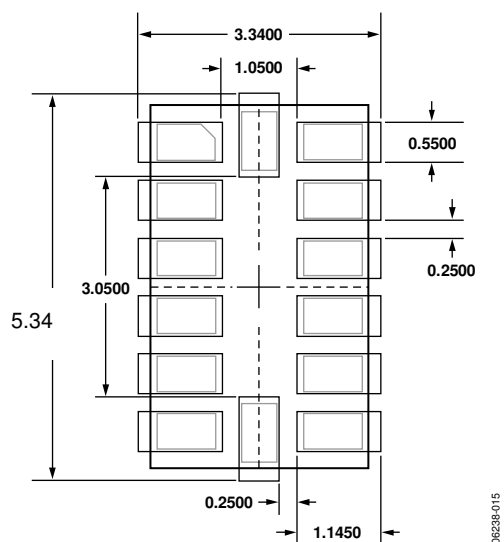


Figure 14. Recommended Printed Wiring Board Land Pattern
(Dimensions Shown in Millimeters)

RECOMMENDED SOLDERING PROFILE

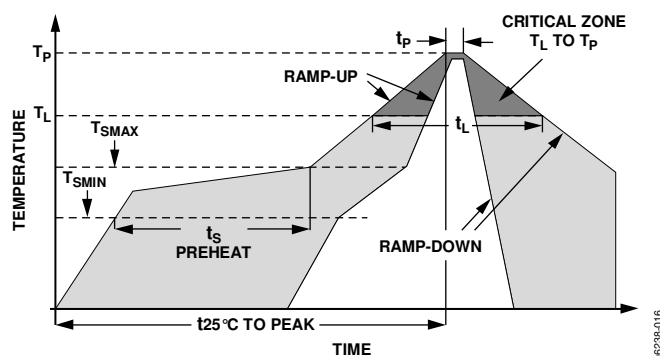
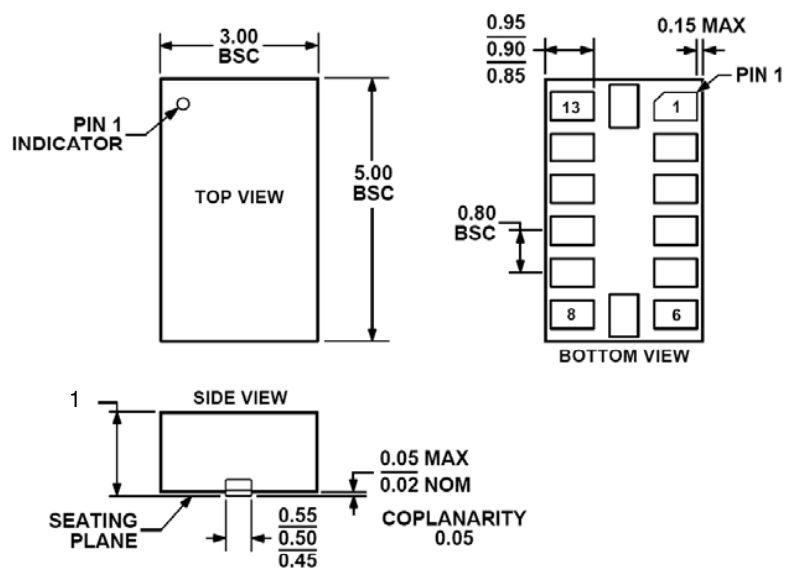


Figure 15. Recommended Soldering Profile

Table 17. Recommended Soldering Profile¹

Profile Feature	Condition	
	Sn63/Pb37	Pb-Free
Average Ramp Rate (T_L to T_P)	3°C/sec max	3°C/sec max
Preheat		
Minimum Temperature (T_{SMIN})	100°C	150°C
Maximum Temperature (T_{SMAX})	150°C	200°C
Time (T_{SMIN} to T_{SMAX})(t_s)	60 sec to 120 sec	60 sec to 180 sec
T_{SMAX} to T_L		
Ramp-Up Rate	3°C/sec max	3°C/sec max
Time Maintained Above Liquidous (T_L)		
Liquidous Temperature (T_L)	183°C	217°C
Time (t_L)	60 sec to 150 sec	60 sec to 150 sec
Peak Temperature (T_P)	240 + 0/-5°C	260 + 0/-5°C
Time Within 5°C of Actual Peak Temperature (t_P)	10 sec to 30 sec	20 sec to 40 sec
Ramp-Down Rate	6°C/sec max	6°C/sec max
Time 25°C to Peak Temperature	6 minutes max	8 minutes max

OUTLINE DIMENSIONS



ORDERING GUIDE

Model	Measurement Range	Specified Voltage (V)	Temperature Range	Package Description	Package Option
ADXL345BCCZ ¹	±2, 4, 8, 16g	2.5	−40°C to +85°C	14-Lead Land Grid Array Package [LGA]	TBD
ADXL345BCCZ-RL ¹	±2, 4, 8, 16g	2.5	−40°C to +85°C	14-Lead Land Grid Array Package [LGA]	TBD
ADXL345BCCZ-RL7 ¹	±2, 4, 8, 16g	2.5	−40°C to +85°C	14-Lead Land Grid Array Package [LGA]	TBD
EVAL-ADXL345Z ¹				Evaluation Board	

¹ Z = Pb-free part.