APPLICATION NOTES
AVAILABLE
AN20 • AN42 • AN44–48 • AN50 • AN52 • AN53 • AN73

Terminal Voltage ±5V, 64 Taps

X9221

Dual E²POT™ Nonvolatile Digital Potentiometer

FEATURES

- Two E²POTs in One Package
- Two-Wire Serial Interface
- Register Oriented Format
  - —Directly Write Wiper Position
  - —Read Wiper Position
  - —Store as Many as Four Positions per Pot
- Instruction Format
  - —Quick Transfer of Register Contents to Resistor Array
- Low Power CMOS
- Direct Write Cell
  - —Endurance - 100,000 Writes per Register
  - —Register Data Retention - 100 years
- 8 Bytes of E²PROM memory
- 3 Resistor Array Values
  - —2KΩ to 50KΩ Mask Programmable
- Resolution: 64 Taps each Pot
- 20-Lead Plastic DIP and 20-Lead SOIC Packages

DESCRIPTION

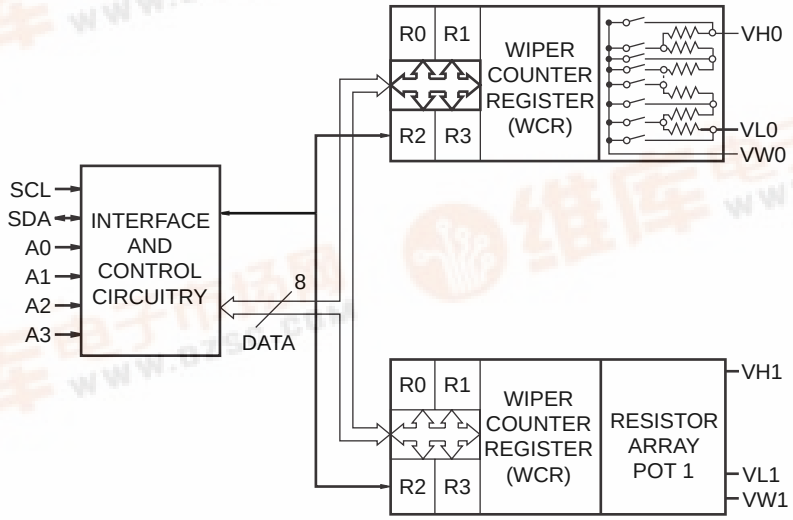
The X9221 integrates two nonvolatile E²POT™ digitally controlled potentiometers on a monolithic CMOS micro-circuit.

The X9221 contains two resistor arrays, each composed of 63 resistive elements. Between each element and at either end are tap points accessible to the wiper elements. The position of the wiper element on the array is controlled by the user through the two-wire serial bus interface.

Each resistor array has associated with it a wiper counter register and four 8-bit data registers that can be directly written and read by the user. The contents of the wiper counter register control the position of the wiper on the resistor array.

The data register may be read or written by the user. The contents of the data registers can be transferred to the wiper counter register to position the wiper. The current wiper position can be transferred to any one of its associated data registers.

FUNCTIONAL DIAGRAM



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PIN DESCRIPTIONS

Host Interface Pins

Serial Clock (SCL)

The SCL input is used to clock data into and out of the X9221.

Serial Data (SDA)

SDA is a bidirectional pin used to transfer data into and out of the device. It is an open drain output and may be wire-ORed with any number of open drain or open collector outputs. An open drain output requires the use of a pull-up resistor. For selecting typical values, refer to the guidelines for calculating typical values on the bus pull-up resistors graph.

Address

The Address inputs are used to set the least significant 4 bits of the 8-bit slave address. A match in the slave address serial data stream must be made with the Address input in order to initiate communication with the X9221

Potentiometer Pins

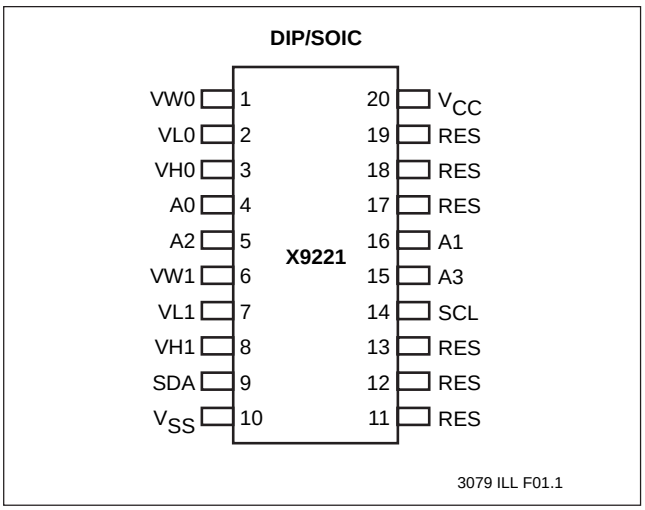
V_H (V_{H0} – V_{H1}), V_L (V_{L0} – V_{L1})

The VH and VL inputs are equivalent to the terminal connections on either end of a mechanical potentiometer.

V_W (V_{W0} – V_{W1})

The wiper outputs are equivalent to the wiper output of a mechanical potentiometer.

PIN CONFIGURATION



PIN NAMES

Symbol	Description
SCL	Serial Clock
SDA	Serial Data
A0–A3	Address
V_{H0}–V_{H1}, V_{L0}–V_{L1}	Potentiometers (terminal equivalent)
V_{W0}–V_{W1}	Potentiometers (wiper equivalent)
RES	Reserved (Do not connect)

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PRINCIPLES OF OPERATION

The X9221 is a highly integrated microcircuit incorporating two resistor arrays, their associated registers and counters and the serial interface logic providing direct communication between the host and the E²POT potentiometers.

Serial Interface

The X9221 supports a bidirectional bus oriented protocol. The protocol defines any device that sends data onto the bus as a transmitter and the receiving device as the receiver. The device controlling the transfer is a master and the device being controlled is the slave. The master will always initiate data transfers and provide the clock for both transmit and receive operations. Therefore, the X9221 will be considered a slave device in all applications.

Clock and Data Conventions

Data states on the SDA line can change only during SCL LOW periods (t_{LOW}). SDA state changes during SCL HIGH are reserved for indicating start and stop conditions.

Start Condition

All commands to the X9221 are preceded by the start condition, which is a HIGH to LOW transition of SDA while SCL is HIGH (t_{HIGH}). The X9221 continuously monitors the SDA and SCL lines for the start condition and will not respond to any command until this condition is met.

Stop Condition

All communications must be terminated by a stop condition, which is a LOW to HIGH transition of SDA while SCL is HIGH.

Acknowledge

Acknowledge is a software convention used to provide a positive handshake between the master and slave devices on the bus to indicate the successful receipt of data. The transmitting device, either the master or the slave, will release the SDA bus after transmitting eight bits. The master generates a ninth clock cycle and during this period the receiver pulls the SDA line LOW to acknowledge that it successfully received the eight bits of data. See Figure 7.

The X9221 will respond with an acknowledge after recognition of a start condition and its slave address and once again after successful receipt of the command byte. If the command is followed by a data byte the X9221 will respond with a final acknowledge.

Array Description

The X9221 is comprised of two resistor arrays. Each array contains 63 discrete resistive segments that are connected in series. The physical ends of each array are equivalent to the fixed terminals of a mechanical potentiometer (V_H and V_L inputs).

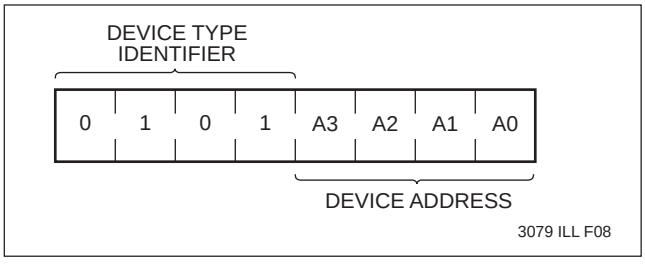
At both ends of each array and between each resistor segment is a FET switch connected to the wiper (V_W) output. Within each individual array only one switch may be turned on at a time. These switches are controlled by the Wiper Counter Register (WCR). The six least significant bits of the WCR are decoded to select, and enable, one of sixty-four switches.

The WCR may be written directly, or it can be changed by transferring the contents of one of four associated data registers into the WCR. These data registers and the WCR can be read and written by the host system.

Device Addressing

Following a start condition the master must output the address of the slave it is accessing. The most significant four bits of the slave address are the device type identifier (refer to Figure 1 below). For the X9221 this is fixed as 0101[B].

Figure 1. Slave Address

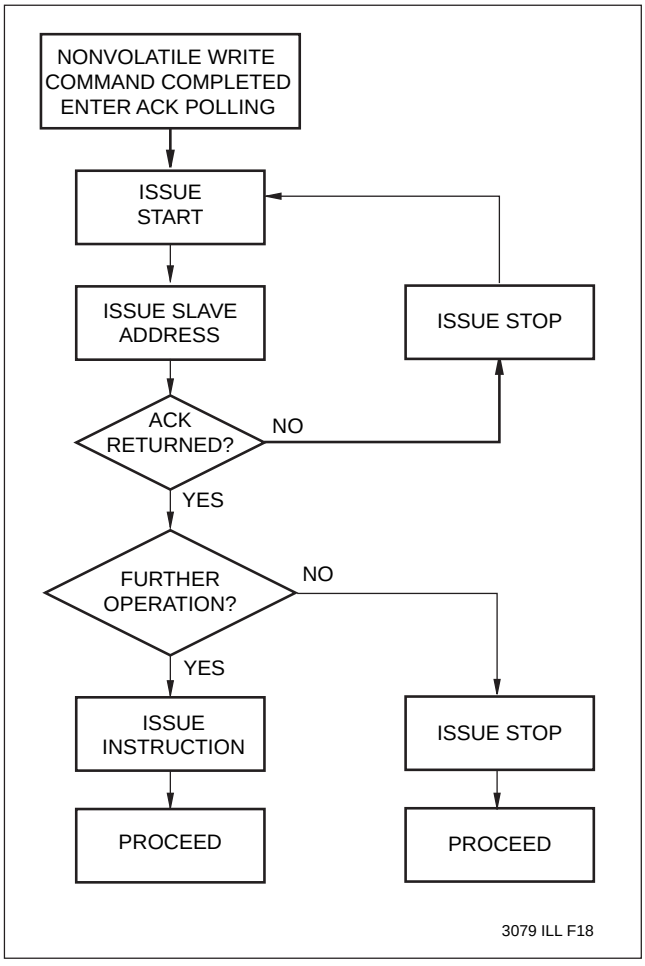


The next four bits of the slave address are the device address. The physical device address is defined by the state of the A0-A3 inputs. The X9221 compares the serial data stream with the address input state; a successful compare of all four address bits is required for the X9221 to respond with an acknowledge.

Acknowledge Polling

The disabling of the inputs, during the internal nonvolatile write operation, can be used to take advantage of the typical 5ms E^2PROM write cycle time. Once the stop condition is issued to indicate the end of the nonvolatile write command the X9221 initiates the internal write cycle. ACK polling can be initiated immediately. This involves issuing the start condition followed by the device slave address. If the X9221 is still busy with the write operation no ACK will be returned. If the X9221 has completed the write operation an ACK will be returned and the master can then proceed with the next operation.

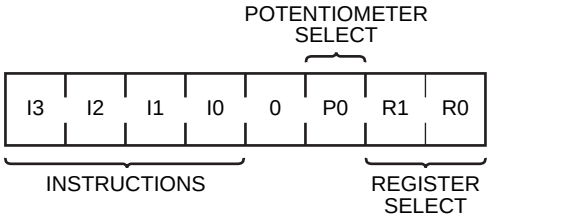
Flow 1. ACK Polling Sequence



Instruction Structure

The next byte sent to the X9221 contains the instruction and register pointer information. The four most significant bits are the instruction. The next four bits point to one of two pots and when applicable they point to one of four associated registers. The format is shown below in Figure 2.

Figure 2. Instruction Byte Format



The four high order bits define the instruction. The sixth bit (P0) selects which one of the two potentiometers is to be affected by the instruction. The last two bits (R1 and R0) select one of the four registers that is to be acted upon when a register oriented instruction is issued.

Four of the nine instructions end with the transmission of the instruction byte. The basic sequence is illustrated in Figure 3. These two-byte instructions exchange data between the WCR and one of the data registers. A transfer from a data register to a WCR is essentially a write to a static RAM. The response of the wiper to this action will be delayed t_{STPWV}. A transfer from WCR's current wiper position to a data register is a write to nonvolatile memory and takes a minimum of t_{WR} to complete. The transfer can occur between either potentiometer and their associated registers or it may occur between both of the potentiometers and one of their associated registers.

Four instructions require a three-byte sequence to complete. These instructions transfer data between the host and the X9221; either between the host and one of the data registers or directly between the host and the WCR. These instructions are: Read WCR, read the current wiper position of the selected pot; Write WCR, change current wiper position of the selected pot; Read Data Register, read the contents of the selected nonvolatile register; Write Data Register, write a new value to the selected data register. The sequence of operations is shown in Figure 4.

The Increment/Decrement command is different from the other commands. Once the command is issued and the X9221 has responded with an acknowledge, the master can clock the selected wiper up and/or down in one segment steps; thereby, providing a fine tuning capability to the host. For each SCL clock pulse (t_{HIGH}) while SDA is HIGH, the selected wiper will move one resistor segment towards the V_H terminal. Similarly, for each SCL clock pulse while SDA is LOW, the selected wiper will move one resistor segment towards the V_L terminal. A detailed illustration of the sequence and timing for this operation are shown in Figures 5 and 6 respectively.

Figure 3. Two-Byte Command Sequence

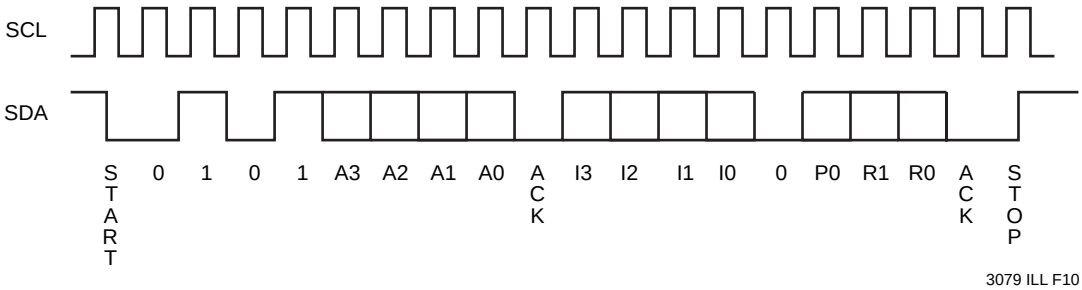


Figure 4. Three-Byte Command Sequence

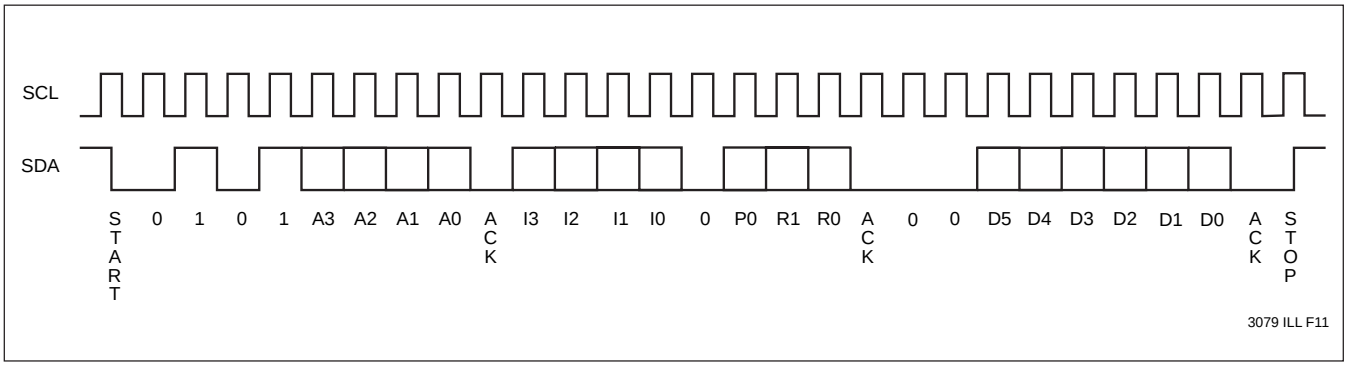


Figure 5. Increment/Decrement Command Sequence

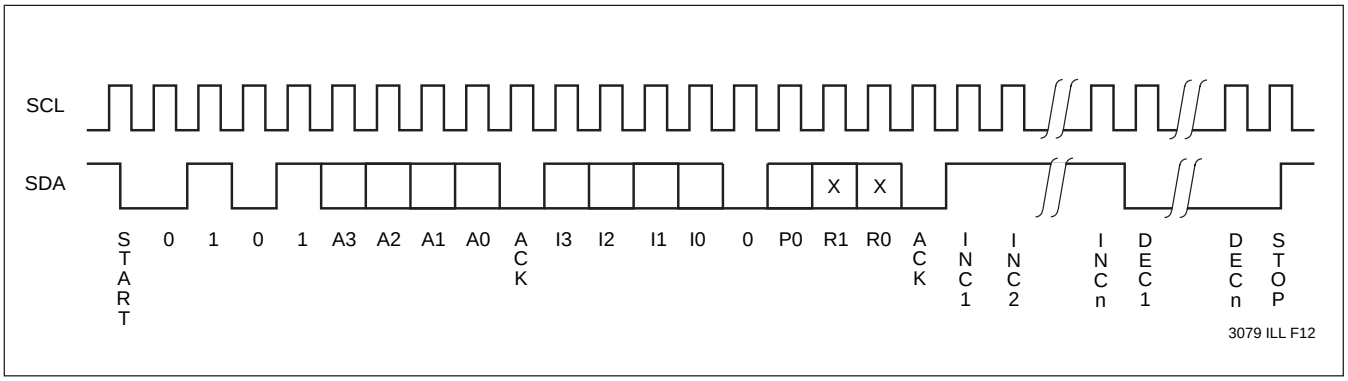


Figure 6. Increment/Decrement Timing Limits

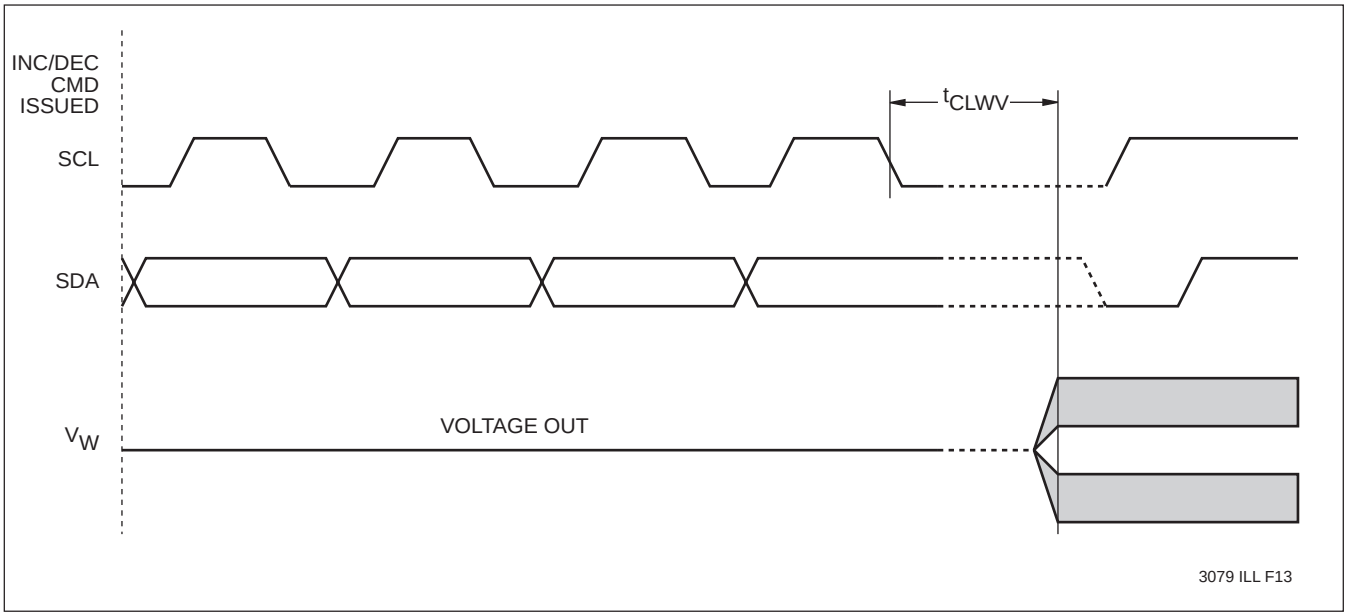


Table 1. Instruction Set

Instruction	Instruction Format								Operation
	I_3	I_2	I_1	I_0	0	P_0	R_1	R_o	
Read WCR	1	0	0	1	0	1/0	N/A(7)	N/A	Read the contents of the Wiper Counter Register pointed to by P_0
Write WCR	1	0	1	0	0	1/0	N/A	N/A	Write new value to the Wiper Counter Register pointed to by P_0
Read Data Register	1	0	1	1	0	1/0	1/0	1/0	Read the contents of the Register pointed to by P_0 and R_1–R_0
Write Data Register	1	1	0	0	0	1/0	1/0	1/0	Write new value to the Register pointed to by P_0 and R_1–R_0
XFR Data Register to WCR	1	1	0	1	0	1/0	1/0	1/0	Transfer the contents of the Register pointed to by P_0 and R_1–R_0 to its associated WCR
XFR WCR to Data Register	1	1	1	0	0	1/0	1/0	1/0	Transfer the contents of the WCR pointed to by P_0 to the Register pointed to by R_1–R_0
Global XFR Data Register to WCR	0	0	0	1	N/A	N/A	1/0	1/0	Transfer the contents of all four Data Registers pointed to by R_1–R_0 to their respective WCR
Global XFR WCR to Data Register	1	0	0	0	N/A	N/A	1/0	1/0	Transfer the contents of all WCRs to their respective data Registers pointed to by R_1–R_0
Increment/Decrement Wiper	0	0	1	0	0	1/0	N/A	N/A	Enable Increment/decrement of the WCR pointed to by P_0

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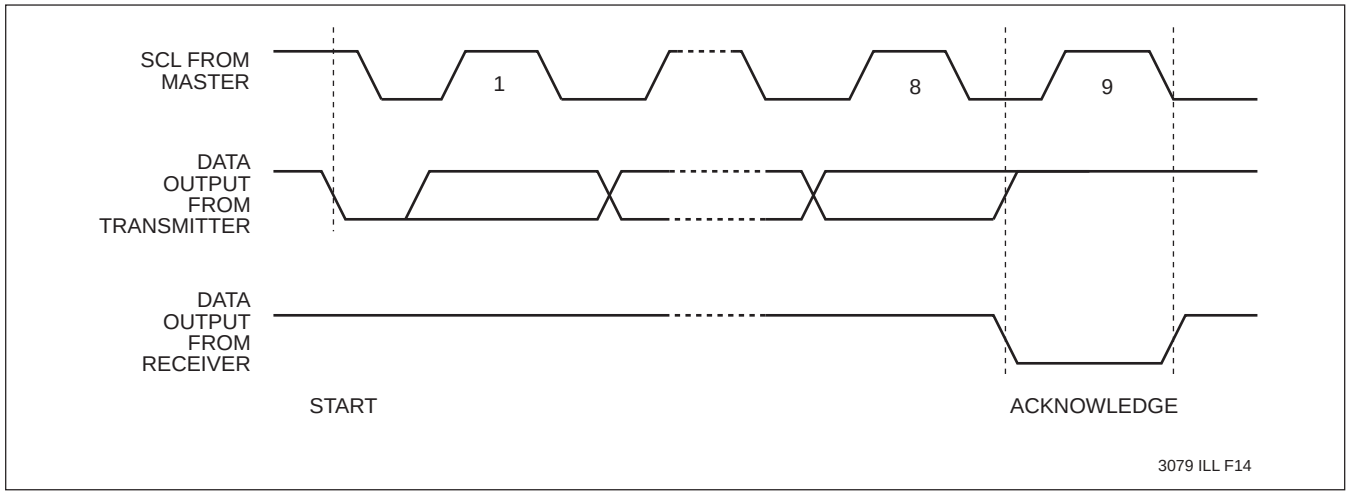
Notes: (7) N/A = Not applicable or don't care; that is, a data register is not involved in the operation and need not be addressed (typical)

Figure 7. Acknowledge Response from Receiver



DETAILED OPERATION

Both E²POT potentiometers share the serial interface and share a common architecture. Each potentiometer is comprised of a resistor array, a wiper counter register and four data registers. A detailed discussion of the register organization and array operation follows.

Wiper Counter Register

The X9221 contains two wiper counter registers (WCR), one for each E²POT potentiometer. The WCR can be envisioned as a 6-bit parallel and serial load counter with its outputs decoded to select one of sixty-four switches along its resistor array. The contents of the WCR can be altered in four ways: it may be written directly by the host via the Write WCR instruction (serial load); it may be written indirectly by transferring the contents of one of four associated data registers via the XFR Data Register instruction (parallel load); it can be modified one step at a time by the Increment/ Decrement instruction; finally, it is loaded with the contents of its data register zero (R0) upon power-up.

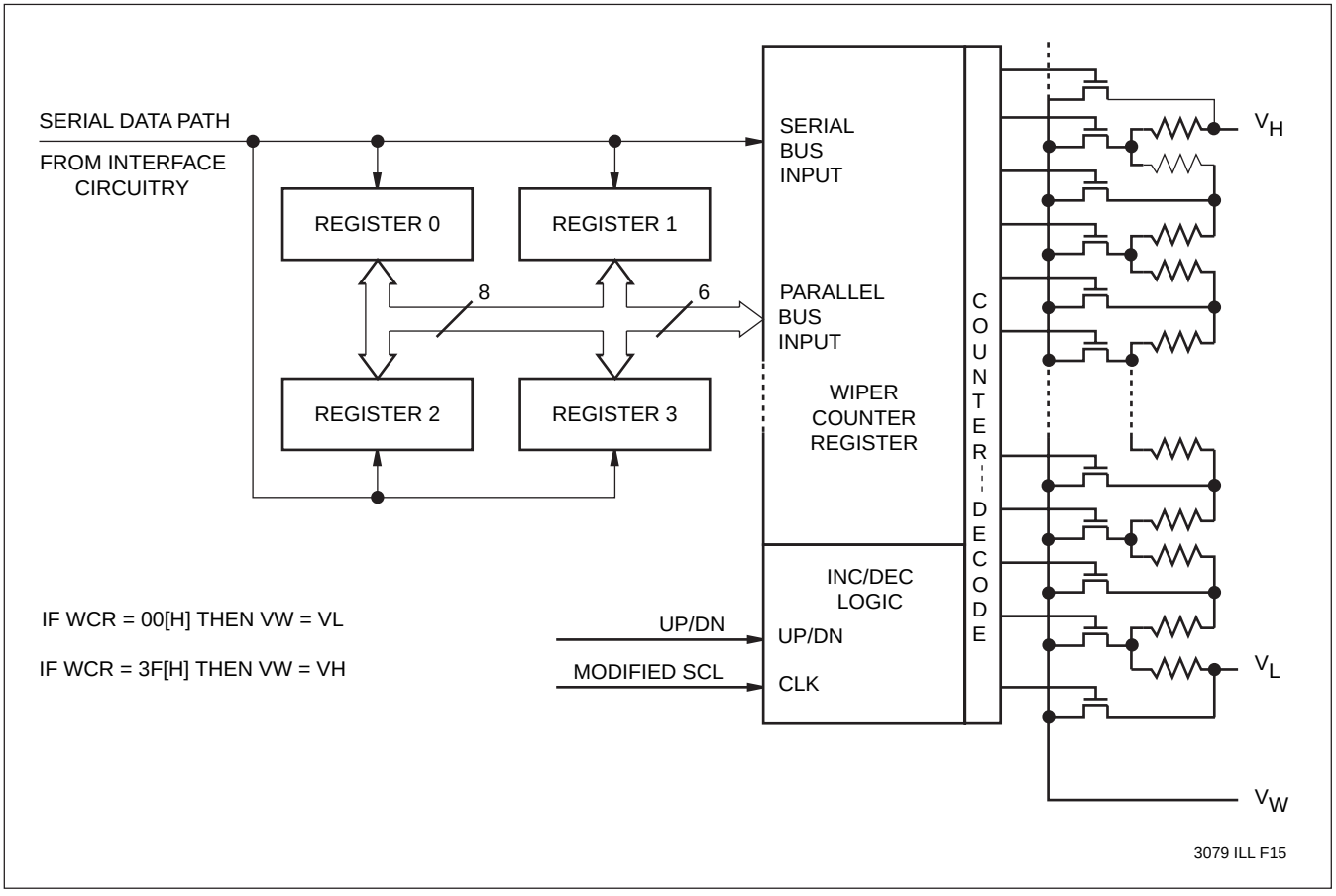
The WCR is a volatile register; that is, its contents are lost when the X9221 is powered-down. Although the register is automatically loaded with the value in R0 upon power-up, it should be noted this may be different from the value present at power-down.

Data Registers

Each potentiometer has four nonvolatile data registers. These can be read or written directly by the host and data can be transferred between any of the four data registers and the WCR. It should be noted all operations changing data in one of these registers is a nonvolatile operation and will take a maximum of 10ms.

If the application does not require storage of multiple settings for the potentiometer, these registers can be used as regular memory locations that could possibly store system parameters or user preference data.

Figure 8. Detailed Potentiometer Block Diagram



ABSOLUTE MAXIMUM RATINGS*

Temperature under Bias ..... –65°C to +135°C
Storage Temperature ..... –65°C to +150°C
Voltage on SCK, SCL or any Address Input with Respect to V_{SS} ..... –1V to +7V
Voltage on any V_H or V_L Referenced to V_{SS} ..... ±8V
$\Delta V = |V_H - V_L|$ 16V
Lead Temperature (Soldering, 10 seconds) ..... 300°C

***COMMENT**

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

RECOMMENDED OPERATING CONDITIONS

Temperature	Min.	Max.
Commercial	0°C	+70°C
Industrial	–40°C	+85°C
Military	–55°C	+125°C

3079 PGM T02

Supply Voltage	Limits
X9221	5V ±10%

3079 PGM T03.1

ANALOG CHARACTERISTICS (Over recommended operating conditions unless otherwise stated.)

Symbol	Parameter	Limits				Test Conditions
		Min.	Typ.	Max.	Units	
R_{TOTAL}	End to End Resistance	–20		+20	%	
	Power Rating			50	mW	25°C, each pot
I_W	Wiper Current	–1		+1	mA	
R_W	Wiper Resistance		40	100	Ω	Wiper Current = ± 1mA
V_{TERM}	Voltage on any V_H or or V_L Pin	–5		+5	V	
	Noise		≤120		dB/$\sqrt{Hz}$	Ref: 1V
	Resolution			1.6	%	
	Absolute Linearity (1)	–1		+1	MI(3)	$V_{w(n)(actual)} - V_{w(n)(expected)}$
	Relative Linearity (2)	–0.2		+0.2	MI(3)	$V_{w(n+1)} - [V_{w(n)} + MI]$
	Temperature Coefficient		±300		ppm/°C	

3079 PGM T04.2

D.C. OPERATING CHARACTERISTICS (Over recommended operating conditions unless otherwise stated.)

Symbol	Parameter	Limits				Test Conditions
		Min.	Typ.	Max.	Units	
I_{CC}	Supply Current (Active)			3	mA	f_{SCL} = 100KHz, SDA = Open, Other Inputs = V_{SS}
I_{SB}	V_{CC} Current (Standby)		200	500	µA	SCL=SDA=V_{CC}, Addr.= V_{SS}
I_{LI}	Input Leakage Current			10	µA	$V_{IN} = V_{SS}$ to V_{CC}
I_{LO}	Output Leakage Current			10	µA	$V_{OUT} = V_{SS}$ to V_{CC}
V_{IH}	Input HIGH Voltage	2		V_{CC} + 1	V	
V_{IL}	Input LOW Voltage	–1		0.8	V	
V_{OL}	Output LOW Voltage			0.4	V	I_{OL} = 3mA

3079 PGM T05.3

Notes: (1) Absolute Linearity is utilized to determine actual wiper voltage versus expected voltage as determined by wiper position when used as a potentiometer.
(2) Relative Linearity is utilized to determine the actual change in voltage between two successive tap positions when used as a potentiometer. It is a measure of the error in step size.
(3) MI = RTOT/63 or $(V_H - V_L)/63$, single pot

ENDURANCE AND DATA RETENTION

Parameter	Min.	Units
Minimum Endurance	100,000	Data Changes per Register
Data Retention	100	Years

3079 PGM T06.2

CAPACITANCE

Symbol	Parameter	Max.	Units	Test Conditions
$C_{I/O}$(5)	Input/Output Capacitance (SDA)	8	pF	$V_{I/O}$ = 0V
C_{IN}(5)	Input Capacitance (A0, A1, A2, A3 and SCL)	6	pF	V_{IN} = 0V

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POWER-UP TIMING

Symbol	Parameter	Max.	Units
t_{PUR}(6)	Power-up to Initiation of Read Operation	1	ms
t_{PUW}(6)	Power-up to Initiation of Write Operation	5	ms

3079 PGM T08

A.C. CONDITIONS OF TEST

Input Pulse Levels	V_{CC} x 0.1 to V_{CC} x 0.9
Input Rise and Fall Times	10ns
Input and Output Timing Levels	V_{CC} x 0.5

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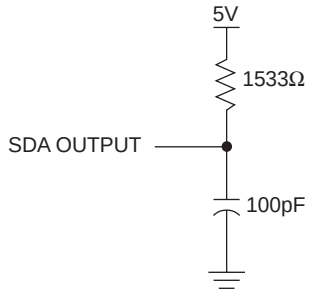
Notes: (5) This parameter is periodically sampled and not 100% tested.

(6) t_{PUR} and t_{PUW} are the delays required from the time VCC is stable until the specified operation can be initiated. These parameters are periodically sampled and not 100% tested.

EQUIVALENT A.C. TEST CIRCUIT



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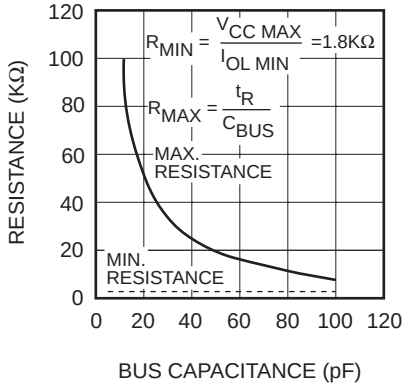
SYMBOL TABLE

WAVEFORM	INPUTS	OUTPUTS
	Must be steady	Will be steady
	May change from LOW to HIGH	Will change from LOW to HIGH
	May change from HIGH to LOW	Will change from HIGH to LOW
	Don't Care: Changes Allowed	Changing: State Not Known
	N/A	Center Line is High Impedance

Guidelines for Calculating Typical Values of Bus Pull-Up Resistors



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A.C. CHARACTERISTICS (Over recommended operating conditions unless otherwise stated)

Symbol	Parameter	Limits		Units	Reference Figure
		Min.	Max.		
f_{SCL}	SCL Clock Frequency	0	100	KHz	10
t_{LOW}	Clock LOW Period	4700		ns	10
t_{HIGH}	Clock HIGH Period	4000		ns	10
t_R	SCL and SDA Rise Time		1000	ns	10
t_F	SCL and SDA Fall Time		300	ns	10
Ti	Noise Suppression Time Constant (Glitch Filter)		100	ns	10
$t_{SU:STA}$	Start Condition Setup Time (for a Repeated Start Condition)	4700		ns	10 & 12
$t_{HD:STA}$	Start Condition Hold Time	4000		ns	10 & 12
$t_{SU:DAT}$	Data in Setup Time	250		ns	10
$t_{HD:DAT}$	Data in Hold Time	0		ns	10
t_{AA}	SCL LOW to SDA Data Out Valid	300	3500	ns	11
t_{DH}	Data Out Hold Time	300		ns	11
$t_{SU:STO}$	Stop Condition Setup Time	4700		ns	10 & 12
t_{BUF}	Bus Free Time Prior to New Transmission	4700		ns	10
t_{WR}	Write Cycle Time (Nonvolatile Write Operation)		10	ms	13
t_{STPWV}	Wiper Response Time From Stop Generation		1000	µs	13
t_{CLWV}	Wiper Response From SCL LOW		500	µs	6
$t_R V_{CC}$	V_{CC} Power-up Rate	0.2	50	mV/µs	

3079 PGM T10.3

Figure 10. Input Bus Timing

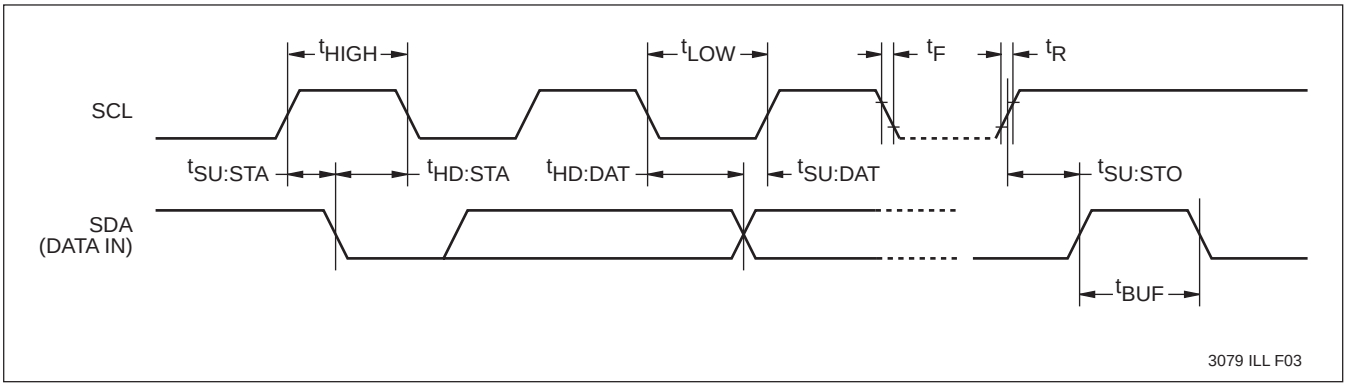


Figure 11. Output Bus Timing

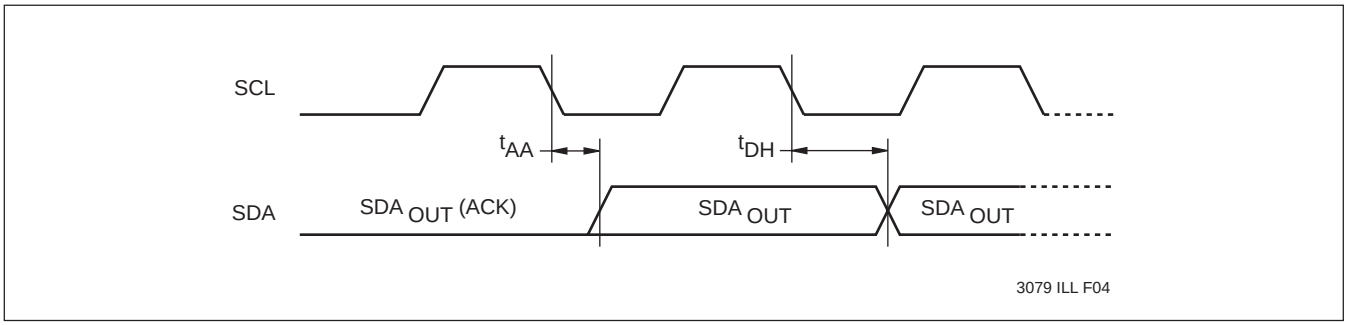


Figure 12. Start Stop Timing

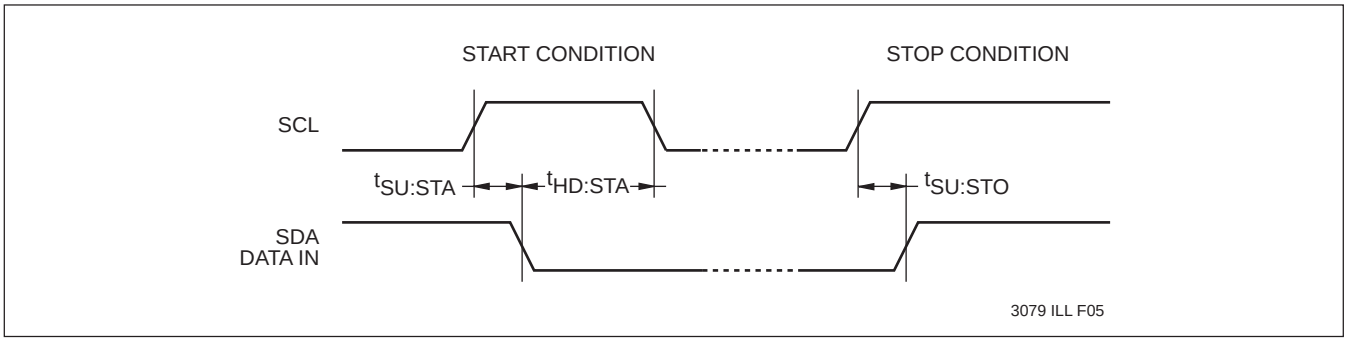
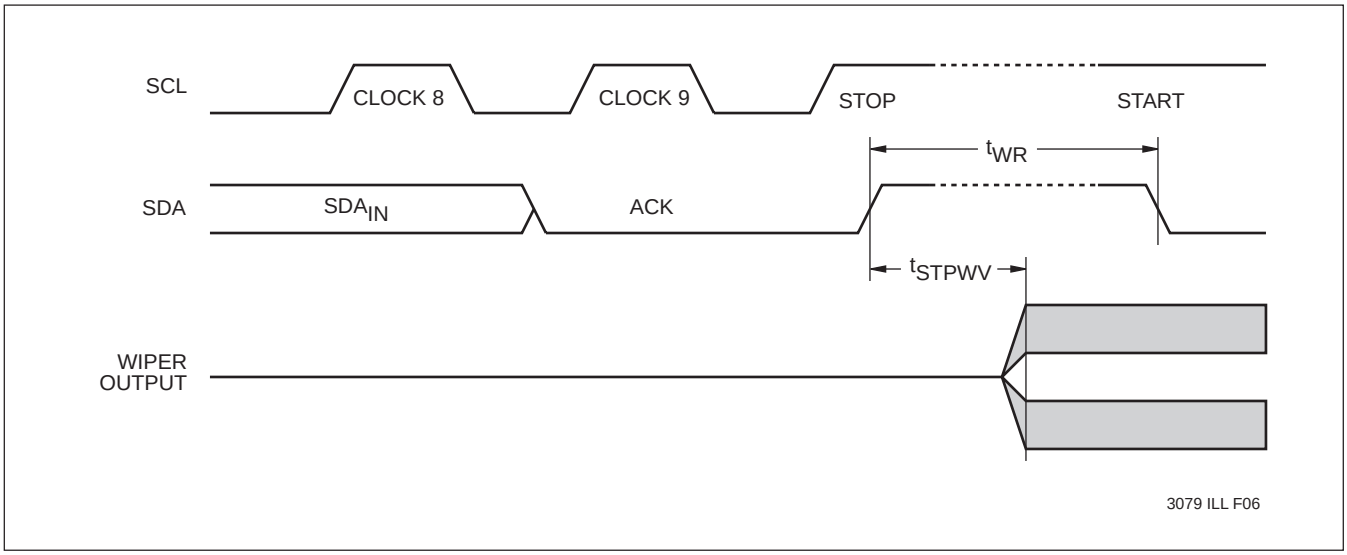
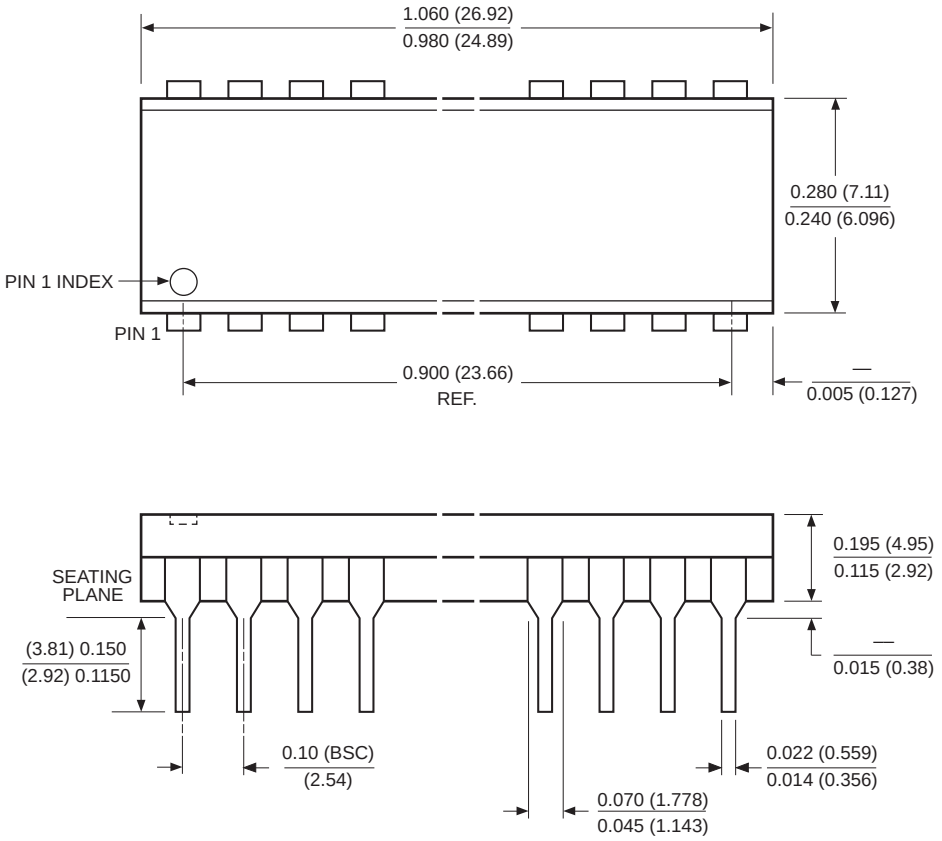


Figure 13. Write Cycle and Wiper Response Timing



PACKAGING INFORMATION

20-LEAD PLASTIC DUAL IN-LINE PACKAGE TYPE P



NOTE:

1. **ALL DIMENSIONS IN INCHES (IN PARENTHESES IN MILLIMETERS)**
2. **PACKAGE DIMENSIONS EXCLUDE MOLDING FLASH**

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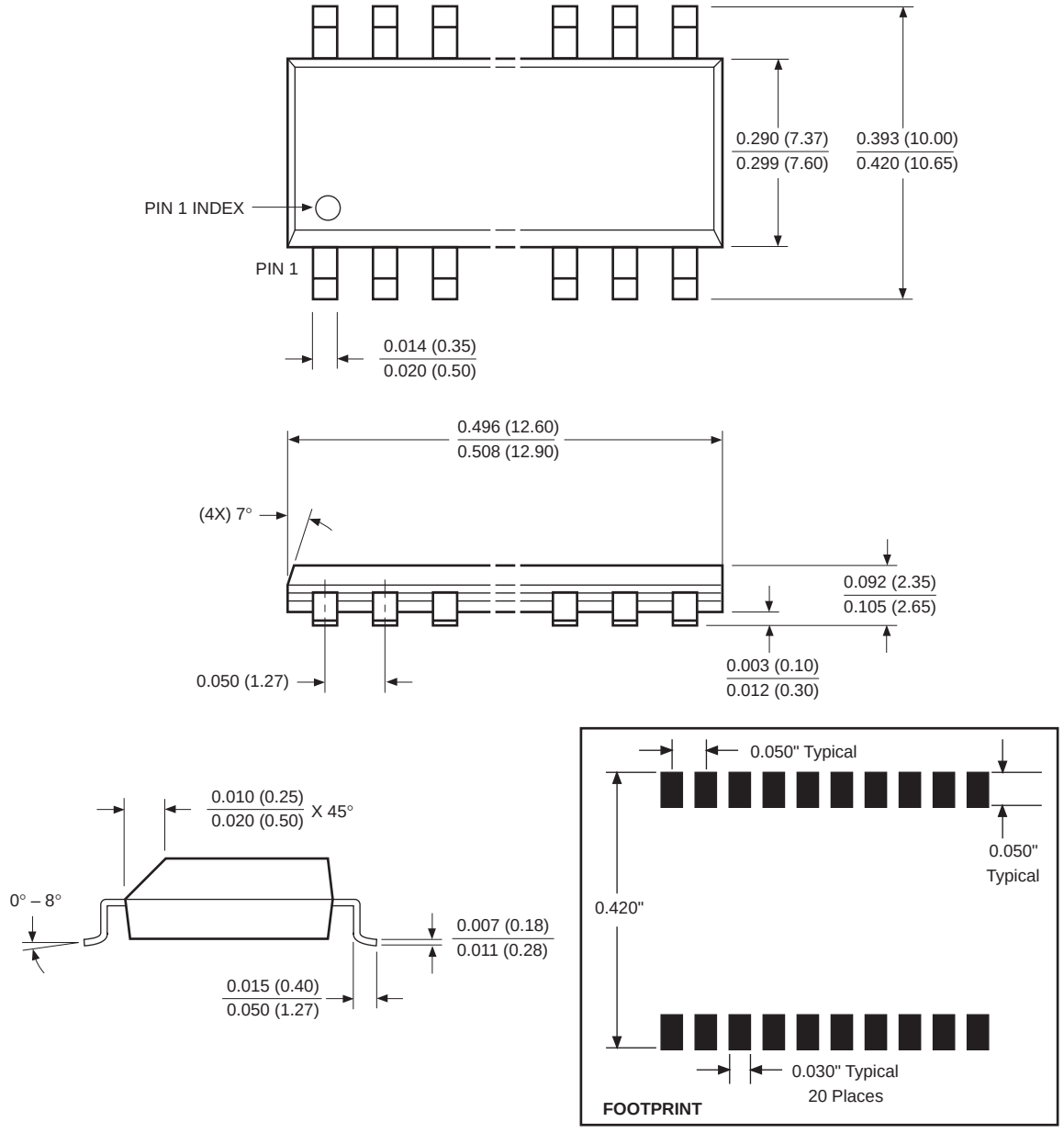
PACKAGING INFORMATION

20-LEAD PLASTIC SMALL OUTLINE GULL WING PACKAGE TYPE S



NOTE: ALL DIMENSIONS IN INCHES (IN PARENTHESES IN MILLIMETERS)

3926 FHD F23

ORDERING INFORMATION