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1 Introduction

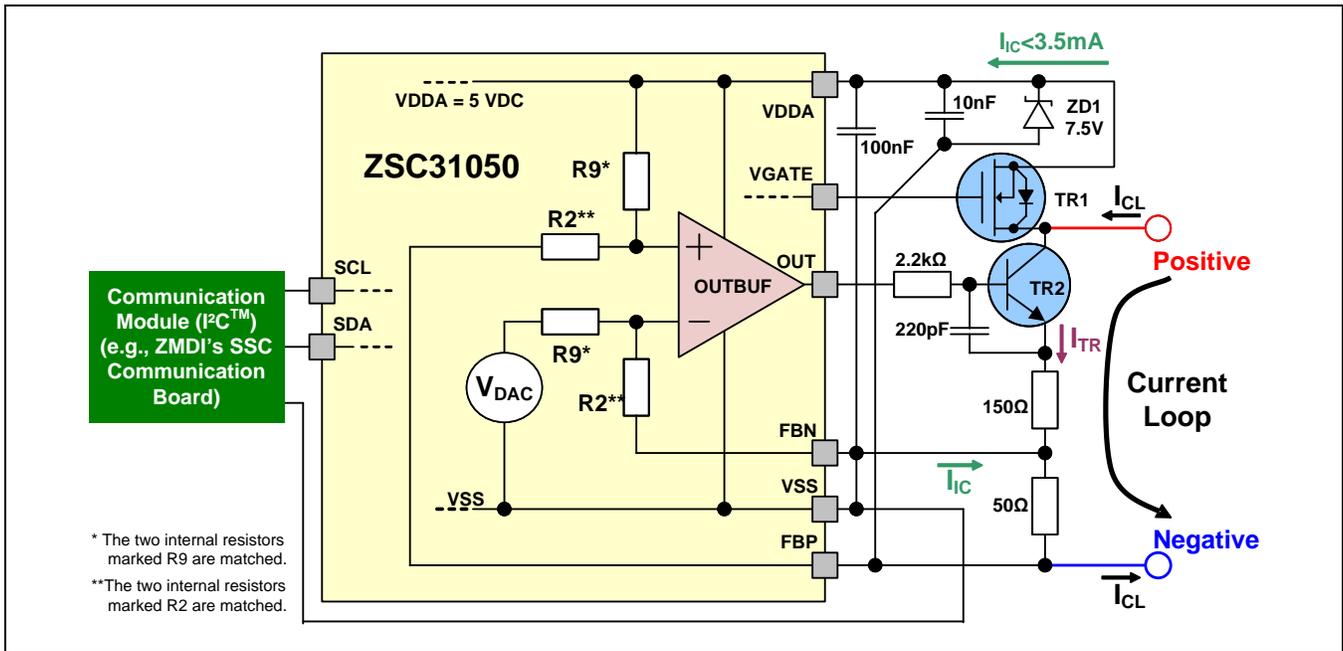
This application note covers the principles of a two-wire current-loop output for the ZSC31050 sensor signal conditioner IC and provides examples of output circuits and information about the calibration procedure. The analog current loop is a typical output signal configuration, especially for industrial sensors. Using only two wires, the sensor is supplied with power *and* transmits its output signal to the processing unit. This saves cost, offers a very robust signal transmission in terms of EMI, and provides a connection check of the sensor module via the “life zero” behavior of the output signal’s range of 4 to 20 mA.

When the ZSC31050 is used in current-loop mode, a buffer is used in the output signal path, which is not offset-compensated. Tolerances of the required external elements cause additional errors, especially for the 50Ω current sense resistor (see Figure 2.1). An “over-all” calibration can remove such errors.

2 The ZSC31050 with 4-to-20mA Current Loop Output

The ZSC31050’s analog output stage is configurable for controlling a current-loop output signal via EEPROM settings. As a result, fewer external parts are needed and the parts are less expensive. See Figure 2.1 for an illustration of the functionality of this configuration:

Figure 2.1 Schematic of the ZSC31050’s Current Loop Output Stage with Communication via I²C™ Interface



The 2.2kΩ resistor and the 220pF capacitor are not needed for the main functionality but are useful for protecting the ZSC31050’s analog output OUT from over-voltage (e.g., due to ESD) and for suppressing noise. The Zener diode ZD1 (7.5V) protects the VDDA line from positive over-voltage and protects the FBP input of the ZSC31050 from negative over-voltage (e.g., caused by the response time of the internal VDDA regulator after power-on). Recommended types for TR1 include the BSS169 or DN3545; for TR2, the BCX56-10 can be used.

The communication module's power supply must be isolated from the current loop for proper operation via the I²C™* interface.

The ZSC31050's 11-bit digital-to-analog converter (DAC) is controlled by an internal calibration microcontroller (CMC) using the *normalized and inverted* value $(1 - P_{11}/2^{11})$ of the digital 11-bit value P_{11} , which represents the 11 MSBs of the digital 15-bit output signal P . Therefore, its analog output voltage V_{DAC} can be calculated with equation (1).

$$V_{DAC} = VDDA * \left(1 - \frac{P_{11}}{2^{11}}\right) \quad (1)$$

Based on this equation and on the fact that all voltages are referenced to VSS, the loop current I_{CL} can be calculated with equation (2).

$$I_{CL} = \frac{P_{11}}{2^{11}} * \left(\frac{VDDA}{\frac{9}{2} * 50\Omega}\right) \quad (2)$$

To ensure that $I_{IC} < 3.5$ mA (includes supply current of the transducer to be conditioned) within the operational temperature range, the ZSC31050's bias current level is adjusted during final test to the optimal value for proper operation of the analog front-end before delivery. Therefore the individual default values stored in bits 4 to 6 of EEPROM register C1_{HEX}/28_{DEC} must be left unchanged to ensure operation in current loop mode within specifications. For more details, refer to the *ZSC31050 Technical Note – EEPROM Changes Bias Adjustment* (see section 8). Adjusting the clock to a frequency of <1.2MHz is recommended to minimize the current consumption of the ZSC31050's digital section to the required level in current-loop output mode.

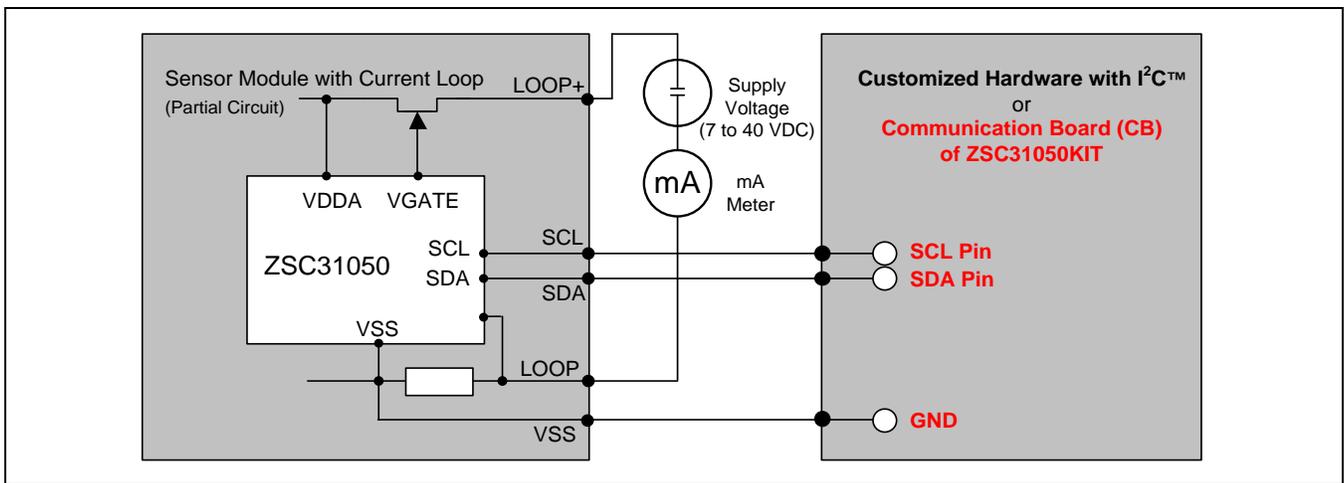
* I²C™ is a trademark of NXP.

3 Setup and Evaluation of Current Loop Configuration

The ZSC31050 current loop application can be verified with IDT's ZSC31050 SSC Evaluation Kit, user-provided customized hardware, or a combination. The user's customized ZSC31050-based sensor module can be connected directly to the kit's SSC Communication Board (SSC CB) to connect to the user's computer running the ZSC31050 Evaluation Software or user software. Alternately, the current loop configuration can be evaluated by mounting the ZSC31050 on the kit's SSC Evaluation Board (SSC EB) and communicating via the SSC CB.

The required additional user-customized hardware can be connected to the SSC EB or the SSC CB via the interface and GND pins on the boards (see the example in Figure 3.1).

Figure 3.1 Schematic of I²C™ Communication with a Current Loop Output Module



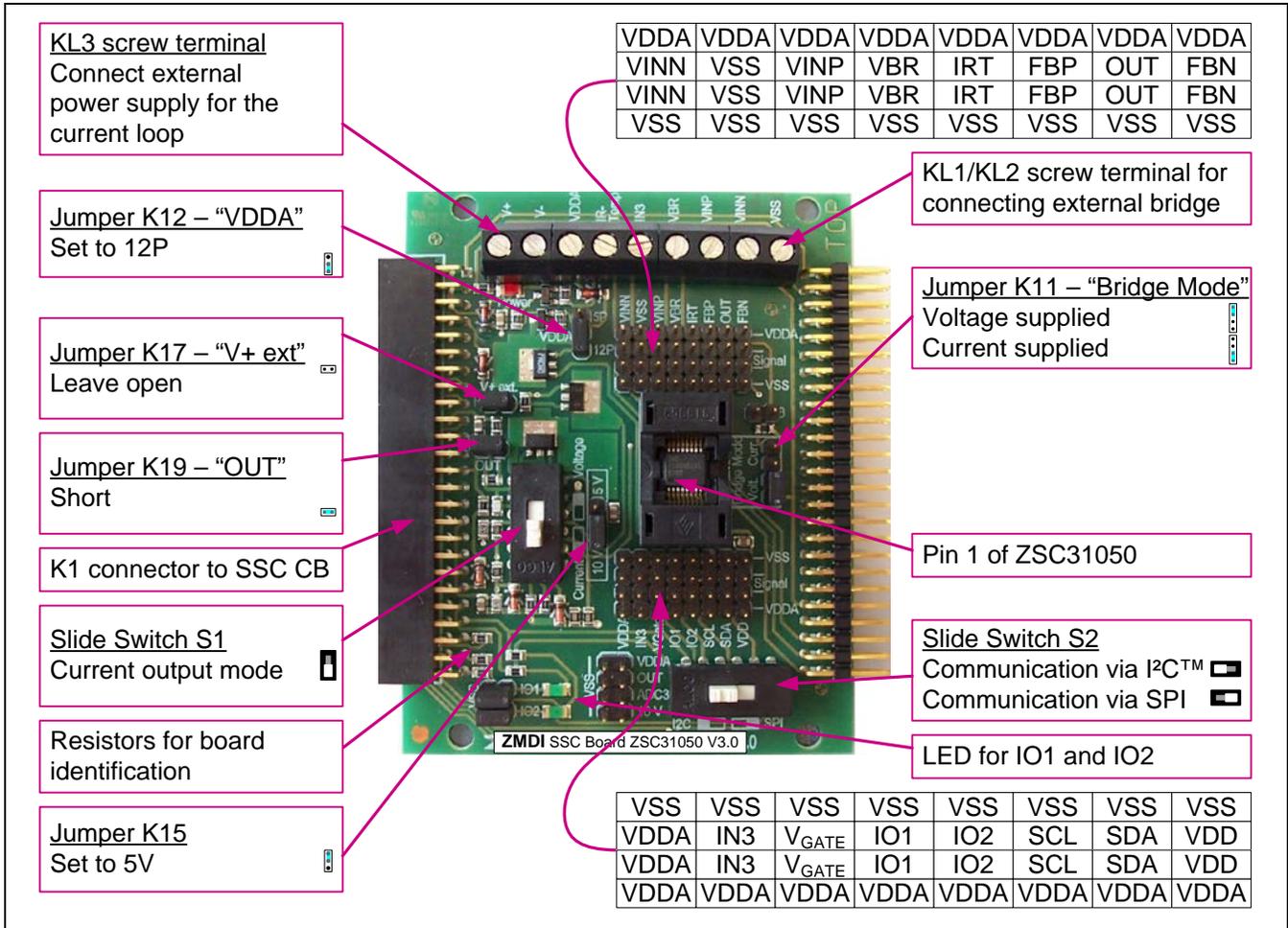
3.1. Setup for Two-Wire Current Loop Evaluation Using the ZSC31050 SSC Evaluation Kit

When using the ZSC31050 Evaluation Kit, an evaluation of the current loop configuration is supported by the kit's hardware directly. Only an external current loop supply and a mA-meter are needed to setup a current loop application. Refer to Table 3.1 and Figure 3.2 for the correct setup of the jumpers and switches on the ZSC31050 SSC Evaluation Board V3.0. Table 3.1 gives an overview of the settings on the ZSC31050 SSC Evaluation Board needed to enable the output mode to be evaluated. For this application, use the "2-Wire Current Loop" settings.

Table 3.1 Settings on the Board Needed to Enable the Output Mode

ZSC31050 Output Mode	Power Supply			Jumper Settings				Slide Switch S1 Position
	CB-KS5V	CB-KS12V	ext.	K12	K15	K17	K19	
2-Wire Current Loop (4 to 20 mA)			Via KL3	12P-VDDA	OUT-5V	Open	Shorted	Current
Ratiometric	Via K1			5P-VDDA	OUT-5V	Open	Open	Voltage
Non-ratiometric (0-5)V		Via K1	Via KL3	12P-VDDA	OUT-5V	Shorted if CB-KS12V Open if ext.	Open	Voltage
Non-ratiometric (0-10)V		Via K1	Via KL3	12P-VDDA	OUT-10V	Shorted if CB-KS12V Open if ext.	Shorted	Voltage

Figure 3.2 Evaluation of a Current Loop Output Module using the ZSC31050 Evaluation Board V3.0

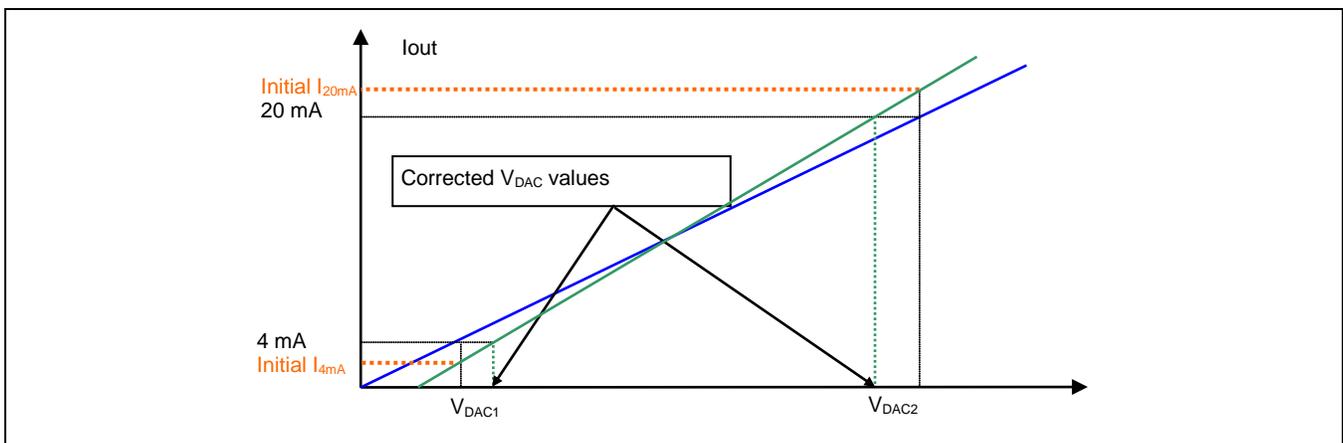


4 Calibration of the Current Loop

The ZSC31050 calibration procedure performed via the digital interfaces removes all errors of the front-end and achieves the adaptation of gain, offset, and non-linearity correction for the sensor element within the temperature range. For calibrating a sensor module with current-loop output configuration, an additional 2-point calibration is needed to remove the tolerances of the external parts.

To use the same calibration method as used for the voltage-output mode, a recalculation of the calibration target values TG_x [%VDDA] for the output voltage can be used to remove the tolerances of the external parts. Figure 4.1 illustrates how to calculate these corrected target values for TG_x [%VDDA].

Figure 4.1 4mA to 20mA Interface Fine Tuning



The blue line shows the ideal function. The green line is the error line (with 2 initial measurement points: I_{4mA} and I_{20mA}).

This transfer function for the measured currents I_{4mA} and I_{20mA} is given by equation:

$$I_{x \text{ mA}} = \frac{V_{DAC} + \Delta V_{Offset}}{R + \Delta R} \quad (3)$$

Where:

$$V_{DAC} = VDDA * \left(1 - \frac{P_{11}}{2^{11}}\right) = VDDA * TG_x \text{ [%]}$$

ΔV_{Offset} = Offset error

$$R = \frac{9}{2} * 50\Omega = 225\Omega$$

ΔR = Resistor and gain error

R = Current loop resistance

Both error values provide a good indication of the physical behavior of the circuitry:

- The offset error of the uncompensated amplifier
- The tolerance errors of the resistors

Using a VDDA voltage of 5V is recommended for the ZSC31050 current loop application. The resulting “free-of-error” target values TG_{4mA} and TG_{20mA} for the MIN and MAX values of the loop current I_{CL} can be calculated by equations (4) and (5):

$$I_{CL_min} = 4mA = \frac{V_{DAC_4mA}}{225\Omega} = \frac{VDDA * TG_{4mA}}{225\Omega} \quad \Rightarrow TG_{4mA} = 18\% \quad (4)$$

$$I_{CL_max} = 20mA = \frac{V_{DAC_20mA}}{225\Omega} = \frac{VDDA * TG_{20mA}}{225\Omega} \quad \Rightarrow TG_{20mA} = 90\% \quad (5)$$

However, the offset of the operational amp and the tolerances of the resistors cause different values of I_{CL} when setting the DAC of the ZSC31050 to these “free-of-error” target values via the *SET_DAC* command (see the *ZSC31050 Functional Description*). Based on the resolution of the 11-bit DAC (DAC-IN = 0 to 2047), a decimal value of 368 at $TG_{4mA} = 18\%$ and of 1843 at $TG_{20mA} = 90\%$ can be calculated. After setting the DAC to each value, the resulting currents I_{4mA} and I_{20mA} must be measured. Based on equation (3) and on the calculated target values of equations (4) and (5), the error values ΔV_{Offset} and ΔR can be determined with equations (6) and (7):

$$\Delta R = \frac{VDDA * (90\% - 18\%)}{I_{20mA} - I_{4mA}} - 225\Omega \quad (6)$$

$$\Delta V_{Offset} = (I_{4mA} * (225\Omega + \Delta R)) - 18\% * VDDA = (I_{20mA} * (225\Omega + \Delta R)) - 90\% * VDDA \quad (7)$$

These error values can be used to re-calculate the target values TG_{4mA} and TG_{20mA} via equations (8) and (9):

$$TG_{4mA} = \frac{4mA * (225\Omega + \Delta R) - \Delta V_{Offset}}{VDDA} \quad (8)$$

$$TG_{20mA} = \frac{20mA * (225\Omega + \Delta R) - \Delta V_{Offset}}{VDDA} \quad (9)$$

The Excel™ spreadsheet *ZSC31050 Current Loop Calibration* can be used to perform this calculation (see section 8). The ZSC31050 SSC Evaluation Software Revision 1.5.0.9 or higher for the ZSC31050 Evaluation Kit also supports this calibration step as demonstrated in Figure 4.2 through Figure 4.6. Refer to the *ZSC31050 Evaluation Kit Description* for setup instructions.

Note that references to “...Pressure” in the software are for the measurand of any sensor type, not just pressure.

Figure 4.2 Step 1: Configuration and Pre-Adjustment of Current-Loop Output Mode

1. Select "I2C – Comm Bd." in the "Interface & Settings" section for this example.

2. Set the analog front-end (AFE) of the ZSC31050 according to the sensor element's parameters.

3. Select "Current" under "Output Mode."

4. Adjust the clock frequency to the minimum level = 1MHz.

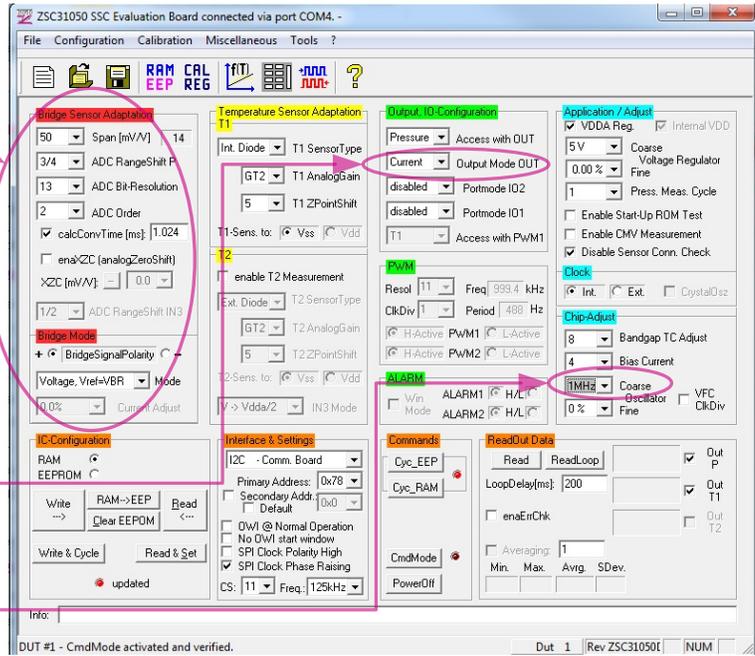
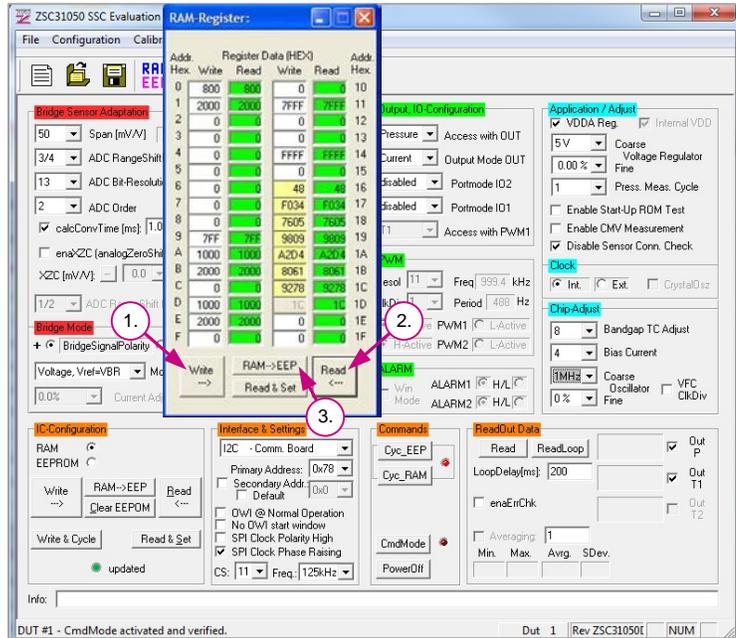


Figure 4.3 Step 2: Transfer the Pre-Adjustments to the RAM and EEPROM

1. Write the adjustments to RAM by clicking the "Write" button.
2. Verify the WRITE_RAM operation. (If ok, then all READ cells become green.)
3. Copy RAM to EEPROM by clicking the "RAM --> EEP" button.



For the third step, there is the option to use a programmable digital multimeter (DMM) to import the actual current measurement into the SSC Evaluation Software. If using a non-programmable multimeter, follow step 3a below in Figure 4.4. If using a programmable multimeter, follow step 3b in Figure 4.5 instead.

Figure 4.4 Step 3a: Adjustment of the External Current-Loop Circuitry

1. Complete the fields for VDDA, RSens, I(min) and I(max) in the “Current Loop Output Adjust & Measurement” dialog menu accessed by clicking on “Current Loop Adjust” under the “Tools” menu at the top.
2. Set the analog output of ZSC31050 to the “ideal” 4mA value, measure the actual loop current via a milliamp meter, and input this in the “SetMin” field.
3. Set the analog output of ZSC31050 to the “ideal” 20mA value, measure the actual loop current via the milliamp meter, and input this in the “SetMax” field.
4. Check the “cpy2Cal” function box.
5. Calculate the calibration target values based on the measured parameters of the external parts by clicking the “Calculate Adjust” button.
6. Verify the calculated target values at up to four current values (Tmin, Tmid, T_3rd, and Tmax).
7. Verify the limits for the loop current (Lmin and Lmax).

	Lmin	Tmin	Tmid	T_3rd	Tmax	Lmax
Initial[mA]:	4	4	12	16	20	20
Targets[%]						
Initial:	18	18	54	72	90	90
Adjusted:	18.08	18.08	53.821	71.687	89.553	89.55

Figure 4.5 Step 3b: Adjustment of the External Current-Loop Circuitry with External DMM Readout

Note: Implementing an external digital multimeter’s (DMM) readout requires a user-program that communicates with the DMM and reads out the data.

DMM readout is applicable for ZSC31050 software version 1.5.3 or later. Connect the DMM according to the manufacturer’s instructions.

1. Complete the fields for VDDA, RSens, I(min) and I(max) in the “Current Loop Output Adjust & Measurement” dialog menu accessed by clicking on “Current Loop Adjust” under the “Tools” menu at the top.
2. Check the box to activate “Serial DMM” mode. “MMin” and “MMax” are enabled.
3. Set the analog output of the ZSC31050 to the “ideal” 4mA value with “SetMin.”
4. Read the measurement results from the DMM by clicking the “MMin” button. The result is input by the software in the correlating input field.
5. Set the analog output of the ZSC31050 to the “ideal” 20mA value with “SetMax.”
6. Read the measurement results from the DMM by clicking the “MMax” button. The result is input by the software in the correlating input field.
7. Continue as described for step 3a from paragraph 4.

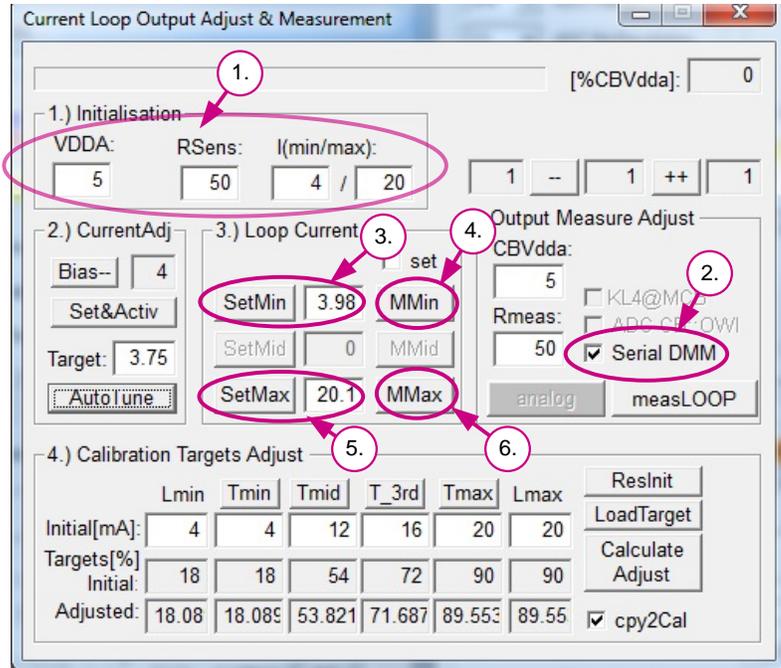
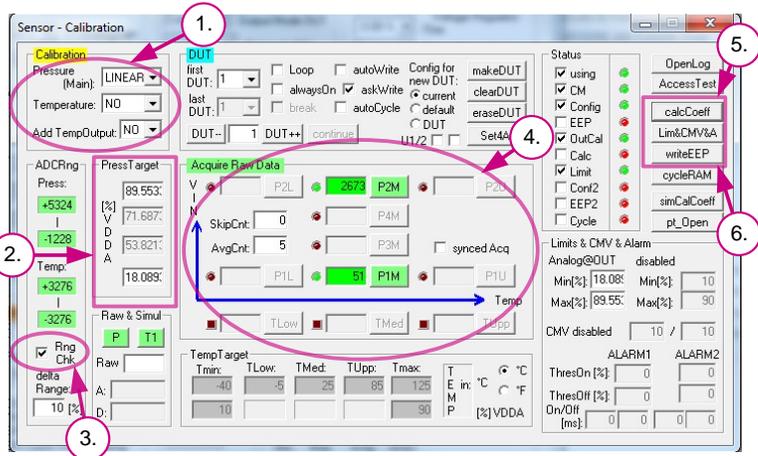


Figure 4.6 Step 4: Calibration using the Re-calculated Target Values

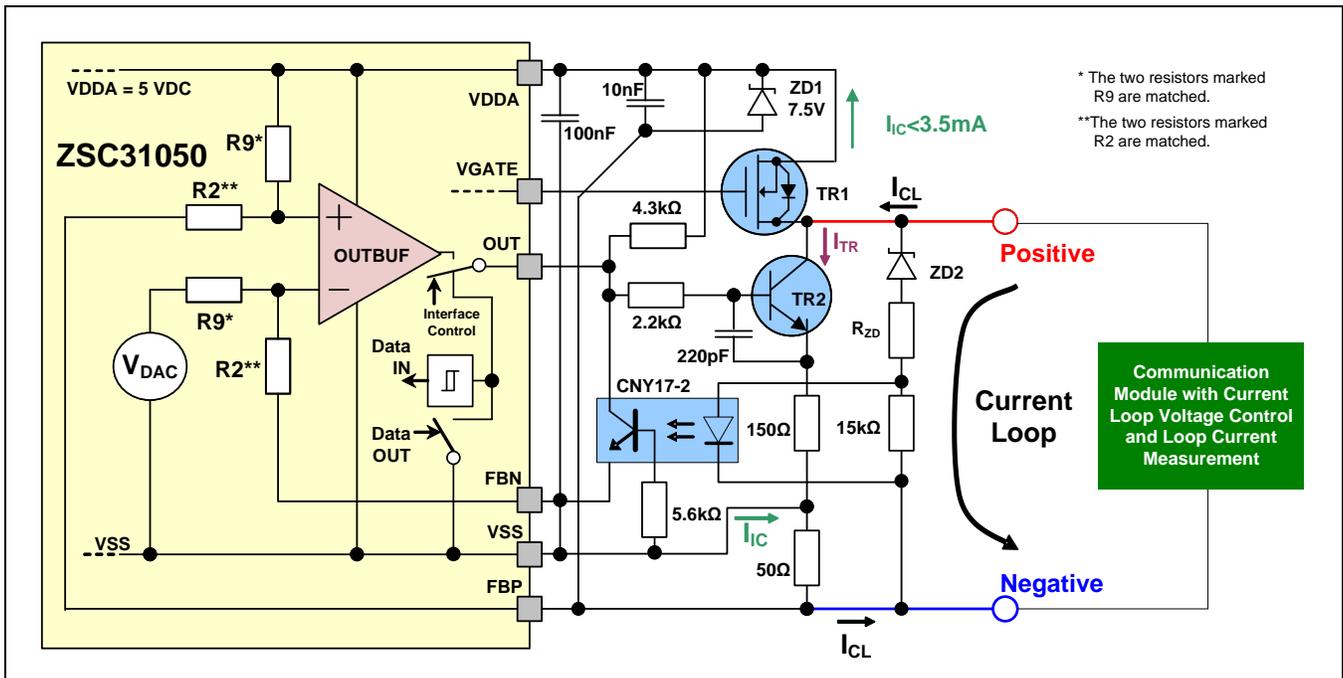
1. Adjust the calibration setup based on the characteristics vs. measurand and temperature of the sensor element to be conditioned.
2. Enter recalculated calibration "Pressure" targets (refer to step 5 illustrated in Figure 4.4 or step 4 Figure 4.5).
3. Check the box to activate the "RngChk" function to avoid saturation of the ADC input.
4. Acquire raw values stepwise according to the adjusted setup.
5. Calculate coefficients (and limits and alarm values, if needed).
6. Write all coefficients to EEPROM.
7. Start the Normal Operating Mode (NOM) based on the new EEPROM data (main software window).



5 Communication via Current Loop for Calibration

In the application, communication for configuring and calibrating the sensor module can be completed via its two terminals for the current loop while in Command Mode (not an option during Normal Operating Mode). In this case, an additional communication module with special features is needed (see Figure 5.1). A galvanic isolation is needed for external access to the ZSC31050's analog output pin for ZACwire™ communication via the current loop terminals. A common optocoupler (e.g., CNY17-2) can be used for short-circuiting the ZSC31050's analog output OUT pin to VSS (signals a logic "L" is to be written).

Figure 5.1 Schematic of the ZSC31050's Current Loop Output Stage with Communication via ZACwire™



The principle of communication is simple using the four possible signal codes shown in Table 5.1, which are color coded for the signal levels illustrated in Figure 5.2. Communication must be initiated by sending the command 72_{HEX} (switches the ZSC31050 into the Command Mode) within the ZACwire™ start window of 20ms after the power supply has been turned on for the circuit in Figure 5.2.

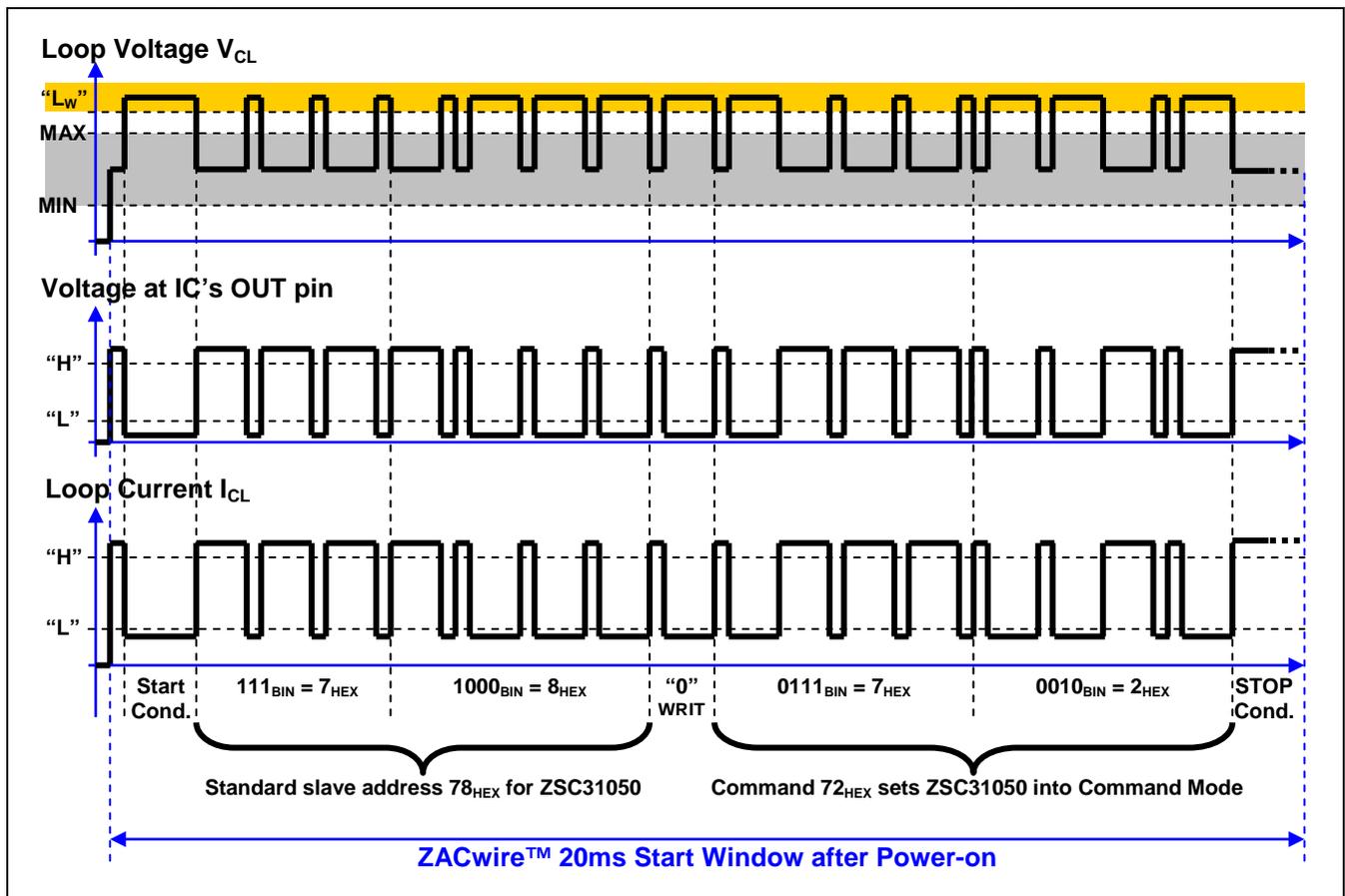
Table 5.1 Signal Coding

Operation	Current Loop Voltage [VDC]	Loop Current [mA]	Remarks
WRITE "L"	> Maximal NOM voltage level	< 5mA	Data from master to slave (coded by loop voltage)
WRITE "H"	Within NOM voltage range	> 15mA	
READ "L"	Within NOM voltage range	< 5 mA	Data from slave to master (coded by loop current)
READ "H"	Within NOM voltage range	> 15 mA	

The ZACwire™ communication is initiated by increasing the current loop voltage above its maximal value for the Normal Operation Mode. The WRITE “L” level is determined by the Zener voltage of **ZD2**. The 15kΩ resistor avoids unintended switching of the optocoupler caused by leakage current. Because the 5.6kΩ resistor significantly decreases the switch-OFF time of the optocoupler’s transistor, a low-speed/low-cost part can be used for this application. The 4.3kΩ pull-up-resistor at the ZSC31050’s OUT pin is needed for communication for the WRITE and READ “H” operations.

During normal operation, the ZSC31050’s current consumption must be $I_{IC} < 3.5\text{mA}$ (including the transducer supply current and additional pull-up-current of less than 1mA). Refer to section 2 for a detailed description.

Figure 5.2 Example for Initialization of ZACwire™ Communication via the Current Loop Interface

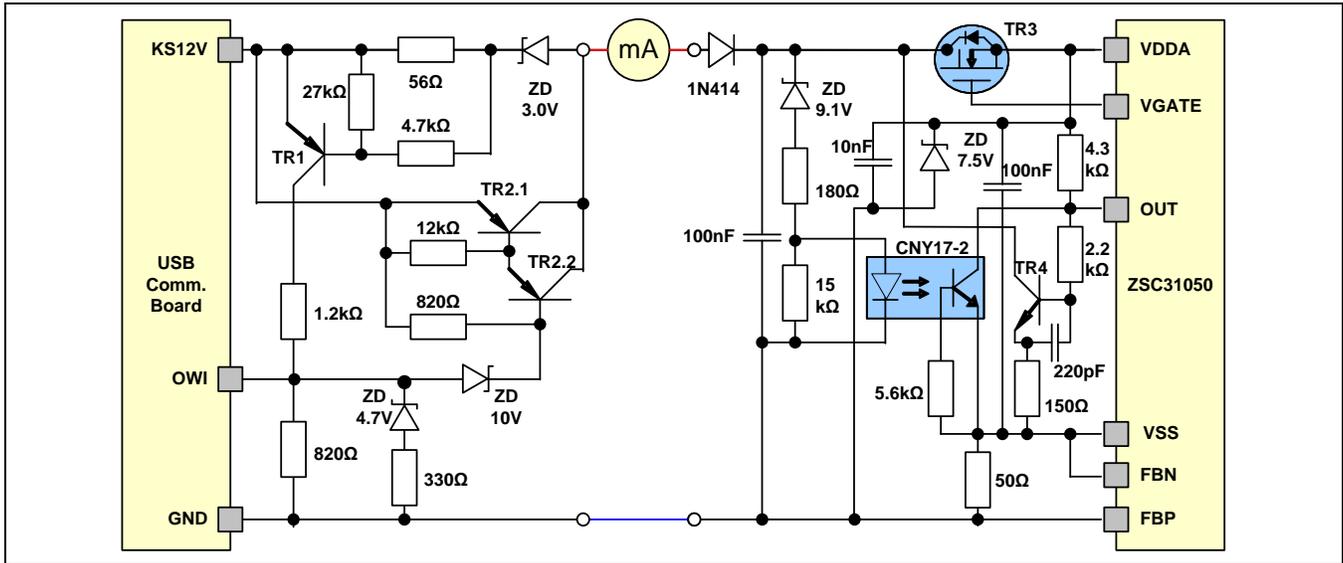


6 Test of Communication via Current Loop

For testing ZACwire™ communication with the ZSC31050 via the two wires of the current loop, the SSC Communication Board (CB) and the application circuitry in Figure 5.1 can be used to communicate using the CB's OWI interface. To adapt the CB for signal coding (see Figure 5.2), the circuitry shown in Figure 6.1 can be used.

For WRITE operations (i.e., data from the CB to the ZSC31050), the OWI pin of the CB is driven by its internal microcontroller to 0V = "L" or to 5V = "H." This turns the PNP-transistor TR2 on (at "L") or off (at "H") and changes the supply voltage of the sensor module from < 9VDC when off to > 11VDC when on. If the supply voltage of the sensor module is below 9VDC, then the optocoupler stays off and the collector of its NPN-transistor is at high impedance. Via the 4.3kΩ pull-up resistor, the ZSC31050's OUT pin is set to "H" potential. If the supply voltage increases approximately 11 VDC, then the optocoupler is turned on and its NPN-transistor shorts the OUT pin of the ZSC31050 to VSS, which indicates "L."

Figure 6.1 Schematic for the Adaptation Circuitry for Current Loop Communication



For READ operations (i.e., data from the ZSC31050 to the CB), the OWI pin of the CB is at high impedance ("tri-state"). The logic level "L" is determined by the 820Ω resistor relative to GND; however the voltage at OWI is approximately 1 VDC. This cannot turn on transistor TR2 because its emitter-to-base-saturation voltage is > 1VDC (Darlington transistor), so TR2 stays off during a READ operation. If the ZSC31050's ZACwire™ interface transmits a logic "L," then the voltage at the OUT pin = 0VDC. As a result, the loop current is < 5mA and the voltage drop across the 56Ω resistor is smaller than the emitter-to-base-saturation voltage of TR1. Its collector stays in the high impedance state, and the voltage at the OWI pin on the CB is 1VDC.

If the ZSC31050's ZACwire™ interface transmits a logic "H," then the voltage at the OUT pin = 5VDC. Therefore the loop current is > 15mA and the voltage drop across the 56Ω resistor becomes greater than the emitter-to-base-saturation voltage of TR1. Its collector shorts the 1.2kΩ resistor with KS12V = 12 VDC and the voltage at the OWI pin of the CB is > 4.7VDC, which indicates a logic "H."

Important: This circuitry is designed for the 12V supply line of IDT's Communication Board only and can be used for evaluations of the principle of ZACwire™ communication only via the current loop.

7 Schematics for Three-Wire Current-Loop Applications

The ZSC31050 must be configured for voltage output for three-wire current-loop applications. If the load of the current loop is referenced to GND (see Figure 7.1), then the characteristic of the output voltage must be inverted (negative gradient); otherwise, the standard characteristic must be used (see Figure 7.2). This can be achieved by setting the target values for calibration according to the required output characteristics.

Figure 7.1 Load Referenced to GND

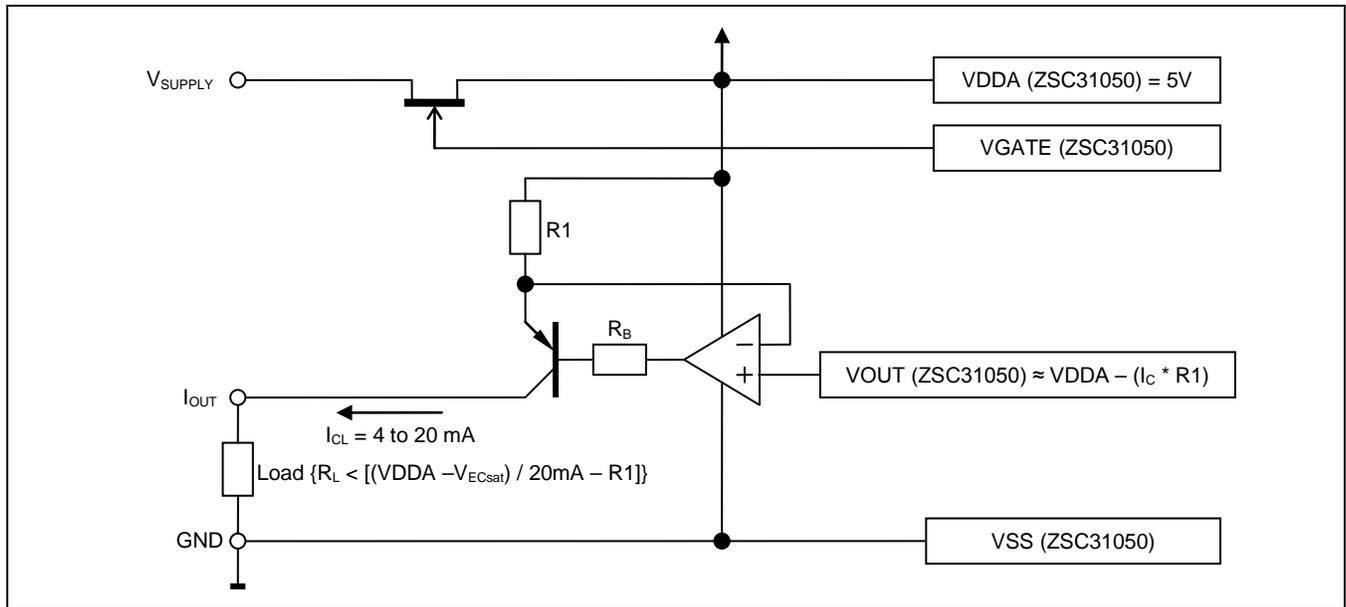
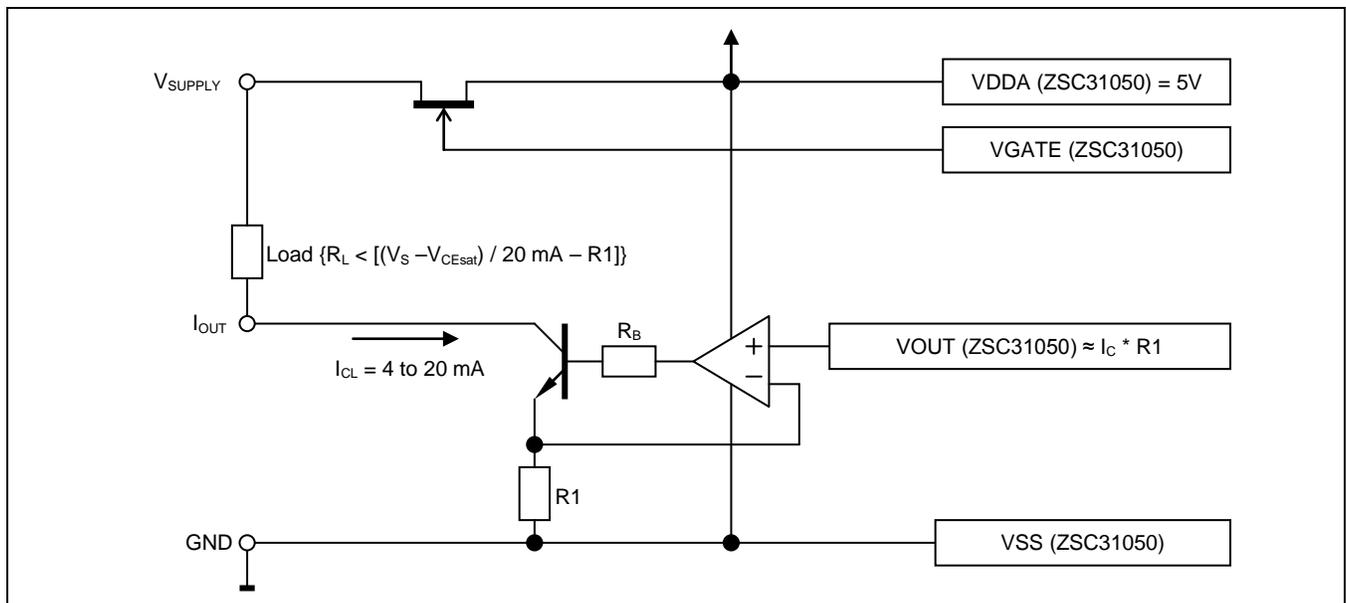


Figure 7.2 Load Referenced to Positive Supply V_S



8 Related Documents

Document
<i>ZSC31050 Data Sheet</i>
<i>ZSC31050 Functional Description</i>
<i>ZSC31050 Evaluation Kit Description</i>
<i>ZSC31050 Technical Note – EEPROM Changes Bias Adjustment *</i>
<i>ZSC31050 Current Loop Calibration Spreadsheet *</i>
<i>SSC Communication Board Data Sheet **</i>

Visit the ZSC31050 product page www.IDT.com/ZSC31050 or contact your nearest sales office for the latest version of these documents.

* Note: Documents marked with an asterisk (*) are available on request.

Note: Documents marked with two asterisks () are available at www.IDT.com/SSC-COMM-BD.

9 Glossary

Term	Description
ADC	Analog-to-Digital-Converter
AFE	Analog Front-End
CB	Communication Board
CMC	Calibration Microcontroller
DAC	Digital-to-Analog-Converter
EEPROM	Electrically Erasable Programmable Read Only Memory
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
IC	Integrated Circuit
NOM	Normal Operation Mode
MSB	Most Significant Bit
SDA	Serial Data (I ² C™ Interface)
SCL	Serial Clock (I ² C™ Interface)
SSC	Sensor Signal Conditioner

10 Document Revision History

Revision	Date	Description
1.00	August 8, 2011	First release of document.
1.02	July 9, 2015	Formula corrected on page 4. Updates for SSC Evaluation Software images and references to SSC Evaluation Kit hardware. Updates for procedures in Figure 4.2 through Figure 4.6. Minor edits for clarity. Update for contact information, related documents, and imagery.
	April 26, 2016	Changed to IDT branding.

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