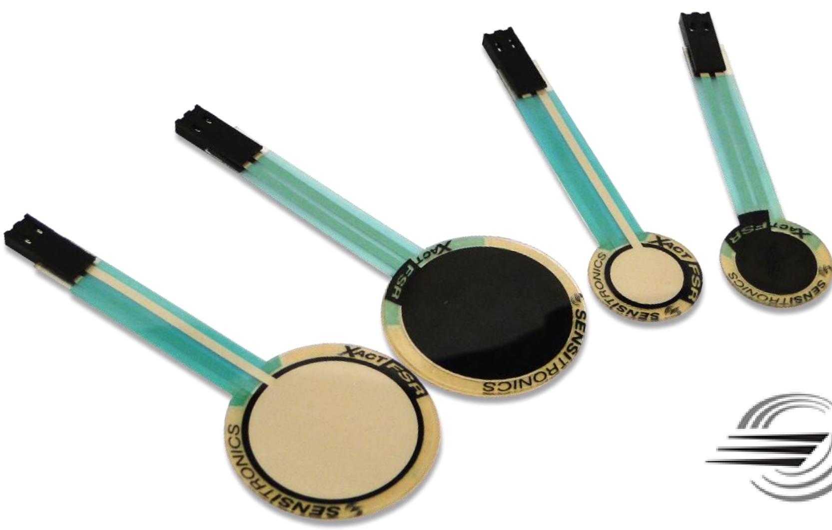

SENSITRONICS LLC

FSR 101

Force Sensing Resistor Theory and Applications

Revision 1.01

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Introduction

Principal of Operation

Force Sensing Resistors (FSRs) are resistive sensors exhibiting varying resistance that responds to force applied to the sensing area. As force on the sensor is increased, this resistance is decreased.

In the simplest layout configuration (Single-Zone), an FSR is a two-terminal device that can essentially be treated as a variable resistor whose value is controlled by applied force.

Construction: ShuntMode vs ThruMode

FSR construction can generally be categorized as one of two types: **ShuntMode** and **ThruMode**. Both FSR types are 2-terminal, 2-layer devices, and interchangeable in terms of basic functionality. However, the two types exhibit different Force vs. Resistance response curves, and are thus preferable for different design applications.

ShuntMode Construction

ShuntMode is the more common of the two construction types. In ShuntMode construction, the top layer of the FSR consists of a solid area of a semiconductive FSR element deposited on a flexible substrate. The bottom layer is comprised of conductive traces on a flexible substrate, arranged into two sets of **interdigitating fingers**.

Figure 1: ShuntMode FSR Top Layer

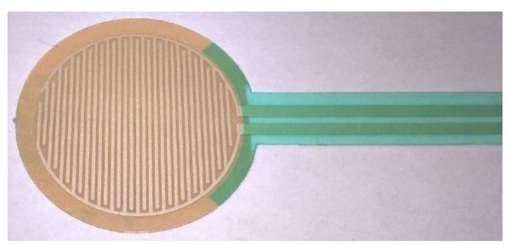


Figure 2: ShuntMode FSR Bottom Layer

When the two layers are pressed together, the semiconductive FSR element on the top layer **shunts** the traces on the bottom layer (hence the name **ShuntMode**), varying the resistance seen across the output terminals.

In custom designs, conductive traces can be laid out directly on a PCB, replacing the bottom substrate. The semiconductive FSR element layer is placed over top, aligned by mounting hardware or adhesives. The XactFSR is the most consistent FSR element to date.

ThruMode Construction

In ThruMode construction, a solid semiconductive FSR element is deposited on top of a solid conductive area (rather than **interdigitating fingers**), completely covering the conductor. This is done identically on both the top and bottom layers, which are then affixed facing one another.

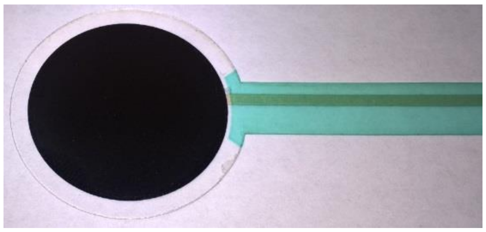


Figure 3: ThruMode FSR Top Layer

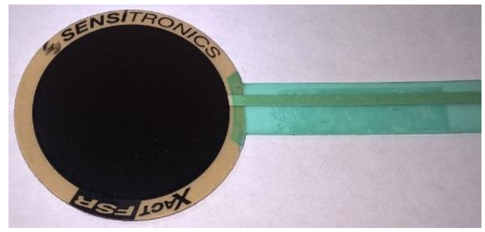


Figure 4: ThruMode FSR Bottom Layer

The solid conductor on each layer runs to a single output terminal, and any excitation current passes **through** one layer to the other, hence the name **ThruMode**.

Because **ThruMode** sensors use two semiconductive regions to form an FSR element-on-element junction, the response curve is steeper for a given ink, and less linear than **ShuntMode** devices.

Layout Configurations / Grouping

Multiple FSRs can be grouped on a single substrate. While custom layouts allow for limitless patterns / combinations, FSR layout configuration can be generally be classified into three types: Single-Zone FSRs, Discrete Arrays, and MatrixArrays.

For simplicity, theory and circuit examples in this document are discussed in terms of Single-Zone sensors, but can be scaled to multi-sensor layouts -- the same general principles apply.

Single-Zone FSR

A single sensing element, with two terminals.

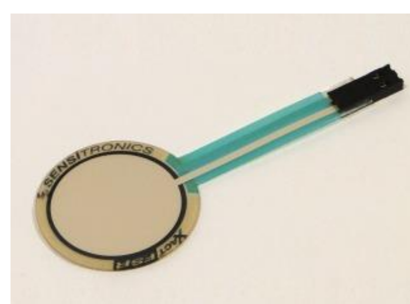


Figure 5: Single-Zone FSR

Discrete Array

A discrete array is simply a collection of any number of **Single-Zone** elements, printed together on a single substrate. The two terminals of each sensor element may be pinned out individually, or connected to a common trace at one end to reduce connector contacts.

Figure 6: Discrete Array

MatrixArray

In a MatrixArray, a large quantity of sensing elements are arranged in a grid, with each sensor element (or "**sensel")** located at the intersection of a row and column. Rows and columns are pinned out, rather than individual sensors (as in a **Discrete Array**).

MatrixArrays require multiplexed scanning electronics, but allow for very high sensor counts (often 10000+ sensor cells) using limited I/O pins.

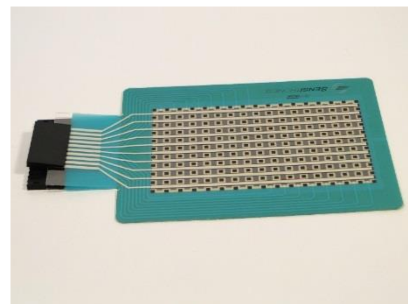


Figure 7: MatrixArray

FSR Characteristics

The relationship between input force and output resistance of a Force Sensing Resistor is determined by sensor shape, trace geometry, and ink formulation used in the manufacturing process. This section describes how parameters are characterized, and common sources of error / variance.

Characteristic Curve: Resistance vs. Force

Force Sensing Resistors are characterized primarily by a Resistance vs. Force curve, in which sensor resistance is plotted as a function of applied force. Curves vary according to sensor model, but can generally be well-approximated by some function of the form $y = \mathrm{ax}^{-b}$.

The following plot shows an example response curve, using test data from a Single-Zone FSR actuated by a force sweep on an automated dynamic test fixture.

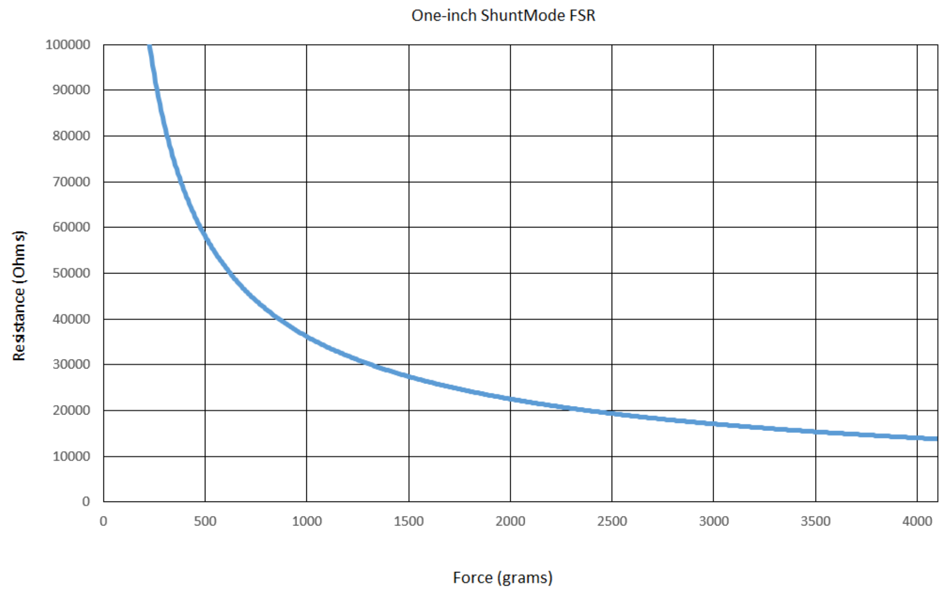


Figure 8: Example FSR Characteristic Curve (Resistance vs. Force)

Clearly, the relationship plotted above is non-linear. However, when the same data set is replotted on a logarithmic scale (both axes), the result is near-linear, as shown in the chart below.

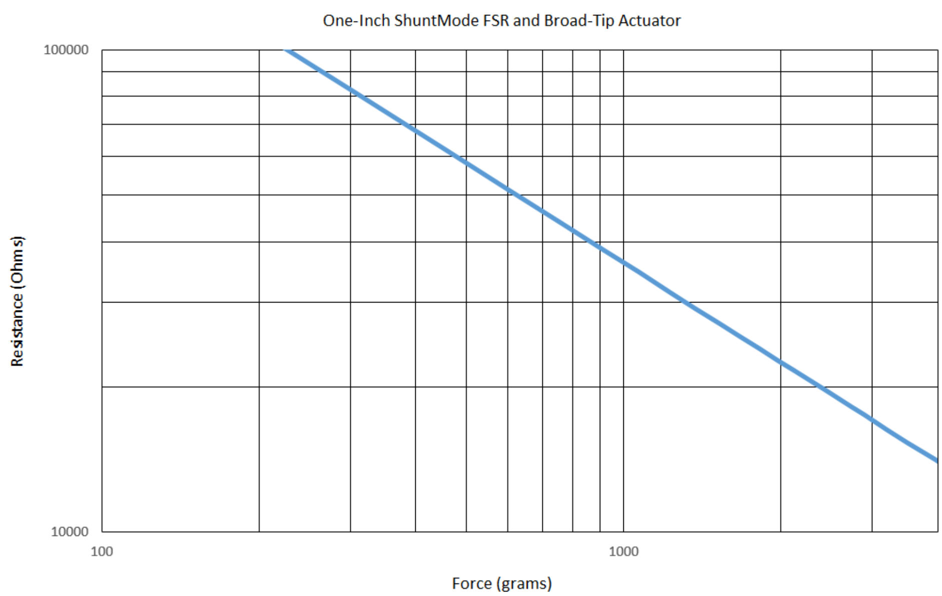


Figure 9: Same Characteristic Test Data, Replotted on a Log-Log Scale

While curve data values vary widely with sensor model, the approximate shape of this example curve is inherent to Force Sensing Resistors, and will generally describe the response of any given FSR.

It is important to note that mounting and actuation can significantly alter characteristic curves. So, while datasheet curves for bare sensors (without spacers) are useful as design guidelines, in-system characterization and calibration is required to achieve good accuracy.

Accuracy Limitations

Force vs. Resistance accuracy varies by sensor model, but is generally limited to a ballpark figure around +/- 10%, even in a well-designed mechanical system with consistent actuation.

FSRs are not intended to replace strain gauges or load cells in designs where high absolute accuracy is required. FSRs do, however, provide significant advantages over load cells in terms of low physical profile and cost-effectiveness (no need for bridge circuits or instrumentation amplifiers), in applications where relative or course absolute force measurements are acceptable.

FSRs excel, for instance, in a wide variety of human touch applications, where 10% variance in absolute force is virtually imperceptible. The relative accuracy of FSRs is quite good, so they're also ideal in force mapping applications, in which the distribution of force is of interest, but absolute force / weight is not particularly relevant.

Loading Hysteresis

Loading Hysteresis describes the effect of previously applied forces on the current FSR resistance.

Here's an example: *An FSR is sitting at rest for some time. When a 100 gram weight is placed on top, the resistance of the FSR is measured it 10kohms. Next, a large 5kg weight is placed on the FSR. After several hours, the 5kg weight is removed, and the original 100 gram weight is set back on the sensor. This time, the sensor resistance measures 6kohms, and slowly creeps up toward 10k.*

While it may be possible to characterize and compensate for loading hysteresis in (very complex) software algorithms, it is often sufficient to simply limit load magnitude and duration to values which will not impose excessive hysteresis.

Thermal Drift

Like any resistive sensor, FSRs are affected to a certain extent by ambient temperature.

In general, FSRs become increasingly resistive as ambient temperature increases. The exact relationship of resistance vs. temperature depends on ink composition and surface area of the specific FSR, and must be characterized / compensated in low drift applications.

Distinguishing Force and Pressure

In a strict technical sense, Force Sensing Resistors sense pressure (Force x Area), rather than force. Applying equal quantities of force with say, a finger vs a stylus tip, will result in completely different resistance response.

The effect of **actuation** variance is illustrated in the example plots below, which show identical force sweeps applied to the same sensor, using two different actuators (broad vs narrow tip).

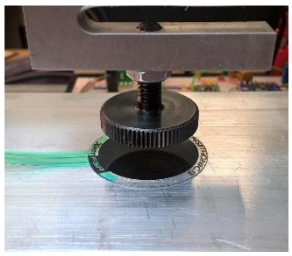


Figure 13: Broad Tip Actuator

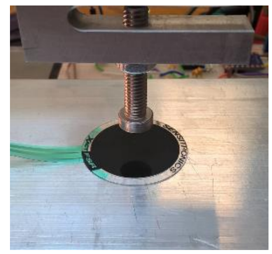


Figure 12: Narrow Tip Actuator

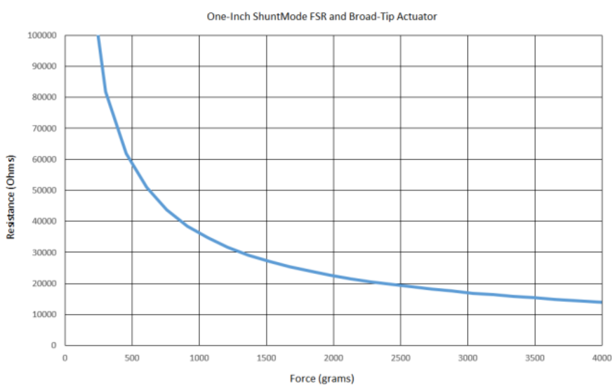


Figure 11: Broad Tip Actuator Results

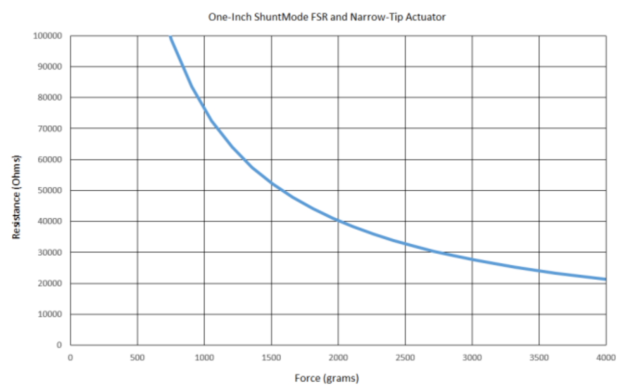


Figure 10: Narrow Tip Actuator Results

The significant difference in responses demonstrates the importance of **consistent mechanical actuation** in isolating force from pressure response.

Actuator design considerations are discussed in the next section.

Actuation

As illustrated previously, consistent actuation is a critical factor in achieving consistent FSR readings. Actuator geometry is largely application-specific, but some generalized types and their advantages are discussed in the examples below.

The actuator system is critical for improving the part-to-part reproducibility of the device incorporating the FSR. The actuator refers to the device or the means by which the FSR is "touched" or actuated. As the flexible upper substrate deflects and yields to the force applied by the actuator, initially there is a small area of contact between the FSR element and the circuit. As the force is increased, the area of contact also increases and the output becomes more conductive. The ink used, the rigidity of the substrates, and other features of the FSR's construction influence the relationship between applied force and resistance.

As long as the force is applied consistently, cycle-to-cycle repeatability is maintained. A thin elastomer, such as silicone rubber, placed between the actuator and the sensor, can be used to absorb some error from inconsistent force distribution

The actuator should be 20% smaller than the ID (inside diameter) of the spacer so that the spacer does not interfere with the applied force.

Spacer Height and Inner Diameter (ID)

As with a typical membrane switch, the two substrates can be spaced using various thicknesses of material like 3M 467 double stick adhesive. The spacer height or thickness of the spacer, the open area (ID) of the spacer, as well as the thickness of the top or deflecting film, will mechanically determine the amount of force required for the two surfaces to come into contact.

A typical conductive membrane switch is fully conductive when force is applied and contact is made. A force-sensing resistor can be in contact and maintain a high resistive state with light force in a "preloaded" condition. A threshold circuit can be used to set the limit at which the device is considered "in contact".

Dielectric Dots

Dielectric dot patterns can also be used for spacing the two layers apart. The frequency or spacing and height of the dots determine the amount of force needed for actuation. The closer the dots are to each other, the more force is required to activate the sensor.

Actuator Examples

Disc Actuators are ideally shaped to cover 80% of the FSRs sensing area. Disc-type actuators are typically made of rubber or other semi-flexible material. Silicone rubber has excellent memory is a very good actuator. Other materials, like Rogers urethane rubber ("Poron") or their foam silicone ("Bisco"), have also been used with success.

Figure 14: Example of a Disc Actuator – Metal With Foam Pad

Dome Actuators are similar to disc actuators, but are domed or radiused. Shaping the dome can help linearize the FSR.

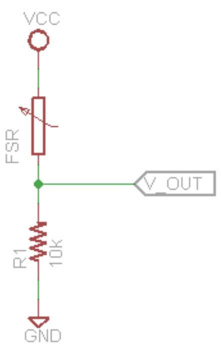
Figure 15: Example of a Dome Actuator

Overlay Actuators use some large pad (foam, rubber, or other flexible material) to cover one or multiple FSRs, including any inactive areas between sensor elements.

Basic FSR Circuit Examples

Voltage Divider

In the simplest measurement circuit, a reference resistor (R1) is placed in series with the FSR. A known supply voltage is applied, and output voltage is measured across R1.



Output is given by:

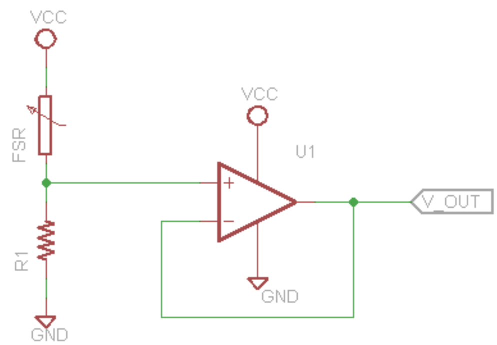
$$V_{OUT} = \frac{V_{CC} \times R1}{R1 + R_{FSR}}$$

The resistance to voltage relationship is, of course, non-linear. R1 can be calculated for optimal resolution over the desired measurement range, but generally speaking, a value near the midpoint of the FSR's resistance range (on a logarithmic scale) works well. In this example, the FSR has a resistance range of 1k-100k, so R1 = 10k is a reasonable choice.

In designs where coarse / relative measurements are acceptable, a simple divider will often suffice.

Buffered Voltage Divider

In this variation, a unity gain buffer (aka voltage follower) follows the divider.

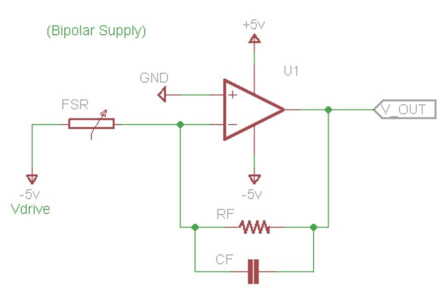


A buffer is required when sampling circuitry input impedance is low enough to impart loading error on the divider, or the output impedance of the voltage divider is otherwise greater than specified ADC requirements.

Using an Arduino, for example, although the input impedance of analog input configured pins is very high, the MCU datasheet recommends a maximum sensor output impedance of 10k. The input presents a capacitive load, which cannot charge quickly enough through the high-impedance divider for accurate sampling.

Part selection is not particularly critical, but the op-amp should at least be unity gain stable, with rail-to-rail input/output (RRIO).

I-V Converter (Transimpedance Amplifier)



A current-to-voltage converter, or transimpedance amplifier, exhibits a somewhat more uniform / ideal transfer function than voltage dividers. Unlike a divider, a transimpedance amp can allow a fixed voltage to be applied across a single FSR element, regardless of other parallel FSRs / resistances.

Applying ideal op-amp assumptions to the example circuit above, the voltage across the input terminals is zero, so V_{IN-} = 0v (virtual ground). Zero current flows in/out of the input terminals, so $I_{RF} = I_{FSR}$. From there, calculations are straightforward, and V_{OUT} is given by:

$$V_{OUT} = \frac{-V_{DRIVE}}{R_{FSR}} \times R_F$$

Provided that a rail-to-rail in/out op-amp is selected, the output swings from 0v to 5v.

A feedback capacitor (C_F) is optionally used to limit bandwidth and maintain stability. Optimal C_F value calculations are omitted here as they must account for FSR resistance, op-amp GBP, and stray capacitance. For the sake of experimentation, 10pF to 33pF is often a good starting point.

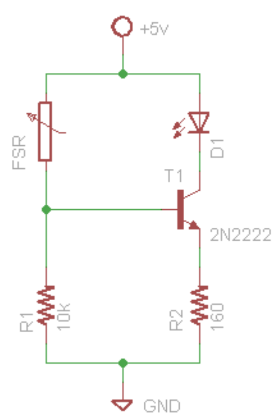
Generally, an op-amp is selected with:

- Very low input bias current (Ib in the range of nA or pA)
- JFET or CMOS inputs
- Bandwidth / Slew Rate selected to meet sample rate requirements
- Usually RRIO

Force-Sensitive Load Driver (LEDs, etc.)

When driving loads that require more than a couple milliamps, it may be tempting to simply place an FSR in series with the load. This is not a good idea, as most FSRs have a maximum current rating in the ballpark of 1mA to 10mA; exceeding this rating will damage the FSR.

Instead, the FSR should be used to control an output driver, i.e. BJT or FET. Here's an example circuit where an FSR controls base current of a BJT to drive an LED in common-emitter arrangement. The result is a force-dimmed LED flashlight, more or less.



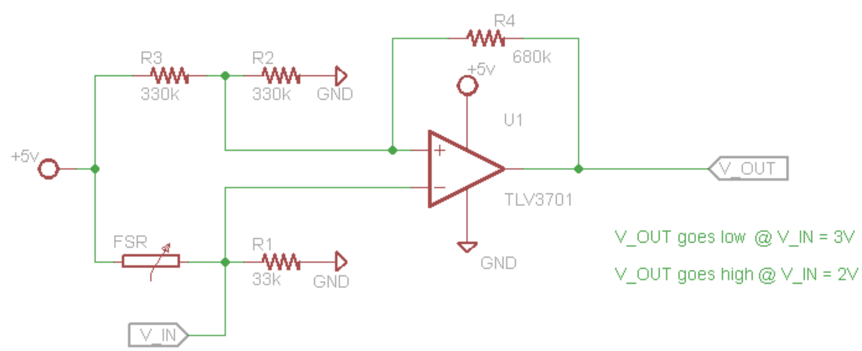
The datasheet for the LED used in this example lists a max continuous current of 20mA, and minimum forward voltage drop of 1.8v. We'll assume, conservatively, that minimum V_{CE} approaches 0v. So:

$$V_{R2}(\text{max}) = 5 - 1.8 - 0 = 3.2\text{v (max)}$$

$$R2 = 20\text{mA} / 3.2\text{v} = 160\Omega \text{ (min)}$$

R1 provides some control over force vs brightness. Without characterizing FSR response and the LED output curve, it's probably sufficient to select R1 experimentally here; 10k seems to work nicely.

Force Threshold Switch w/ Hysteresis



Another popular usage example of Force Sensing Resistors is threshold switching. The circuit above can be used to indicate when a specified force / weight is present, no ADC required. Hysteresis in this circuit effectively provides hardware debouncing. If debounced output is not desirable, R4 can be omitted.

In the example circuit, R2, R3, and R4 are selected for low/high thresholds at approximately $V_{TL} = 2$v and $V_{TH} = 3$v. Skipping derivation and arbitrarily selecting 330k for R3, R2 and R4 are calculated by:

$$\frac{R4}{R3} = \frac{V_{TL}}{V_{TH} - V_{TL}}$$

and

$$\frac{R3}{R2} = \frac{V_{TL}}{V_{CC} - V_{TH}}$$

Of course, R2+R3 and R4 can be replaced with two trimpots for variable threshold levels.

Any number of comparators will work fine, a TLV3701 is selected in this example for push-pull output and ultra-low current (I_Q). Alternatively, an op-amp can be used, but a comparator is usually preferable for faster propagation times at a lower cost.

Mounting / Physical Integration

Mounting Surface

Figure 17: FSR with Adhesive Backing

Best performance is achieved when FSRs are mounted on a flat, relatively rigid surface.

FSRs can usually be mounted on a gently curved surface (i.e. cylinder) without issue. However, actuation hardware must be designed and tested to ensure that the sensor responds predictably to all expected input forces.

Mounting custom FSRs to steeply curved or soft / conformal surfaces is possible in many cases, but entails higher cost due to the complexity of custom design, assembly, and testing.

It is also generally acceptable to gently bend (but not crease) the FSR tail at some angle well below 1/8" radius. Sharper angles can be accomplished with flexible conductors. Custom forming can be performed (at manufacturing time) if acute bends are required.

Mounting Adhesives

Sensitronics' Single-Zone FSRs are typically backed with a PSA adhesive.

Custom FSRs can be designed with or without adhesive backing. Sensors without included adhesive can be bonded to a mounting surface using PSA double-stick tape. When applying adhesives, care must be taken to ensure even adherence to the mounting surface. Trapped air bubbles or lumps in the adhesive will result in inconsistent FSR readings.

Connectors

FSRs should never be soldered manually; doing so will almost certainly melt the traces / substrate.

Sensitronics' off-the-shelf FSRs come pre-fitted with shrouded female header connectors (2.54mm/0.100" pitch). Custom FSRs can be manufactured with female headers, male pins, or bare printed traces, for use with FPC-type connectors. Virtually any desired pitch / spacing may be specified for custom FSRs.

Environmental Factors

Ambient Temperature

Unless otherwise specified, Sensitronics' FSRs are rated to operate within an absolute min/max temperature range of -15°F to + 200°F. Ambient / operating temperatures exceeding either limit may result in permanent damage to the sensor.

Moisture / Humidity

Standard FSRs are not fully sealed, and can be adversely affected by moisture and excessive humidity.

Custom FSRs can be made moisture resistant. Full submersion requires sonic welded design, or other sealant systems.