AN2934

Capacitive Touch Sensor Design Guide

Introduction

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The process for designing products that use touch controls is a complex process with many decisions to be made, such as what materials will be used in their construction and how the mechanical and electrical requirements will be met. The key to this process is the design of the actual sensors (specifically buttons, sliders, wheels and touch screens) that form the interface with the user.

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1. Self-Capacitance Sensors

1.1 Self-Capacitance Measurement

Self-capacitance touch sensors use a single sensor electrode to measure the apparent capacitance between the electrode and the DC ground of the touch sensor circuit.

Figure 1-1. Self-Capacitance Sensor Model
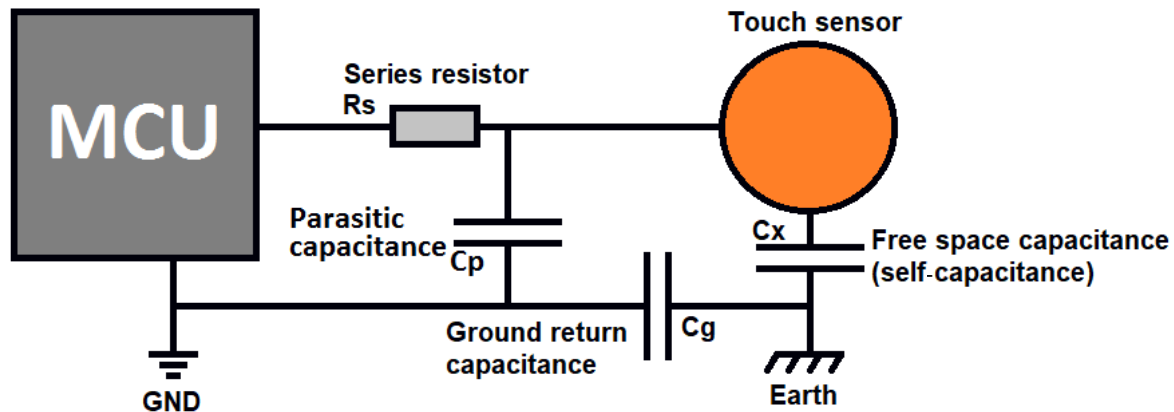
The base capacitance is formed by the combination of parasitic, sensor and ground return capacitance. In combination, these form the 'untouched' capacitance that is measured during calibration and used as reference to detect a capacitance change indicating touch contact.

Figure 1-2. Self-Capacitance Model with Touch Contact

When a touch contact is applied, the apparent sensor capacitance is increased by the introduction of a parallel path to earth through t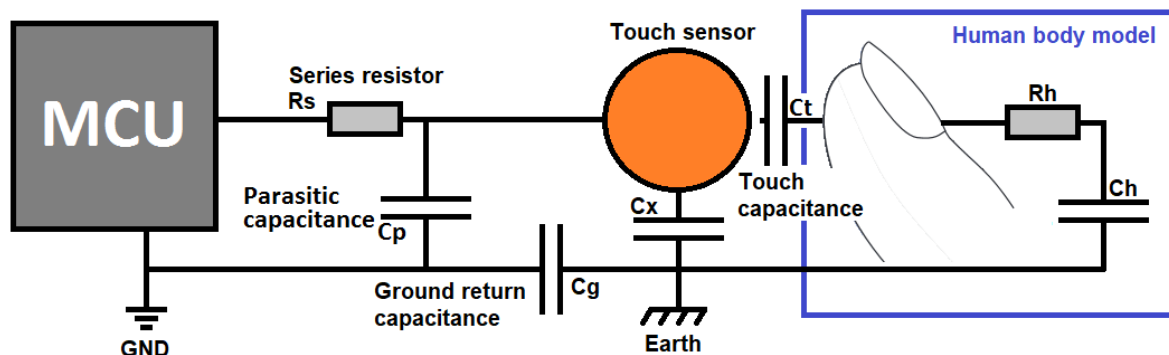he 'Human Body Model'. The touch capacitance C_t forms a series combination with the HBM capacitance C_h and ground to earth capacitance C_g. This increase is referred to as the 'Touch Delta'.

Note: The HBM resistance R_h does not affect touch sensitivity.

C_t

• May be approximated as a parallel plate capacitor

- A user's fingertip placed onto a solid surface may be approximated as a disc with the diameter between 5-10 mm. 8 mm is estimated as a typical user's fingertip diameter and is used in the examples in this document.
- Capacitor plates are the touch sensor electrode and the user fingertip
- Electrolyte is the touch cover
- 0.1 pF up to 5 pF depending on sensor size and touch cover thickness/material

Ch

- Human body model capacitance
- Self-capacitance of the human body with respect to earth
- 100 pF to 200 pF for an adult depending on physique

Cg

- Capacitance of the coupling between the application DC ground and earth
- Depends on application type and power system
- As little as ~1 pF in a small battery powered device
- Infinite capacitance/short circuit where the DC ground is connected directly to earth

In series capacitors, the dominant effect is that of the smallest capacitor.

Equation 1-1. Series Capacitor Combination

$$Ct = \frac{C_1 C_2}{C_1 + C_2}$$

Ct is much smaller than Ch, and in most applications Ct is also much smaller than Cg, so Ct determines the change in measured capacitance.

For example:

Ct = 1 pF, Ch = 100 pF, Cg = 100 pF

→ C$_{Total}$ = 0.98 pF

→ C$_{Total}$ is almost equal to Ct

But in an application where Cg is very low, e.g., 2 pF, sensitivity will be reduced significantly.

Ct = 1 pF, Ch = 100 pF, Cg = 2 pF

→ C$_{Total}$ = 0.662 pF

→ Measured touch delta is reduced by ~33%

1.2   Sensor Design

1.2.1   Touch Capacitance Model
When designing sensors, a simple approximation of Ct may be derived from the parallel plate capacitor formula.

Note: This approximation loses accuracy where the area dimensions are less than an order of magnitude greater than the distance dimension.

Equation 1-2. Parallel Plate Capacitor

$$C = \frac{\epsilon\, A}{d} = \frac{\epsilon_0\; \epsilon_r\, A}{d}$$

Where 'A' is the parallel area, 'ε' is the permittivity of the electrolyte, i.e., vacuum permittivity ϵ_0 x Relative permittivity ϵ_r and 'd' is the thickness of the touch cover.

→ The strongest touch delta is achieved with a large sensor electrode, thin touch cover and high permittivity cover material.

Example:

Touch sensor electrode: 12 mm diameter disc

Touch cover: 1 mm plastic with relative permittivity ϵ_r = 2

Touch contact: 8 mm diameter disc

→ Use the area of the smaller plate – the user fingertip – to calculate the capacitance

$$Ct = ((8.85E - 12) \times (2) \times (0.00005027))/(0.001) = -.89\, pF$$

1.2.2 Button Sensor Design

The simplest implementation of a capacitive sensor is a button, where the sensor consists of a single node and is interpreted as a binary state: In Detect or Out of Detect. When the touch delta – the digitized measurement of touch capacitance Ct – exceeds the touch threshold the sensor is In Detect.

The sensor is characterized by a user touch or touch emulator such as a conductive bar, which is connected to earth via a human body model circuit. The threshold is set to a proportion – often 50% – of the maximum touch delta.

Figure 1-3. Button Sensor Delta and Threshold
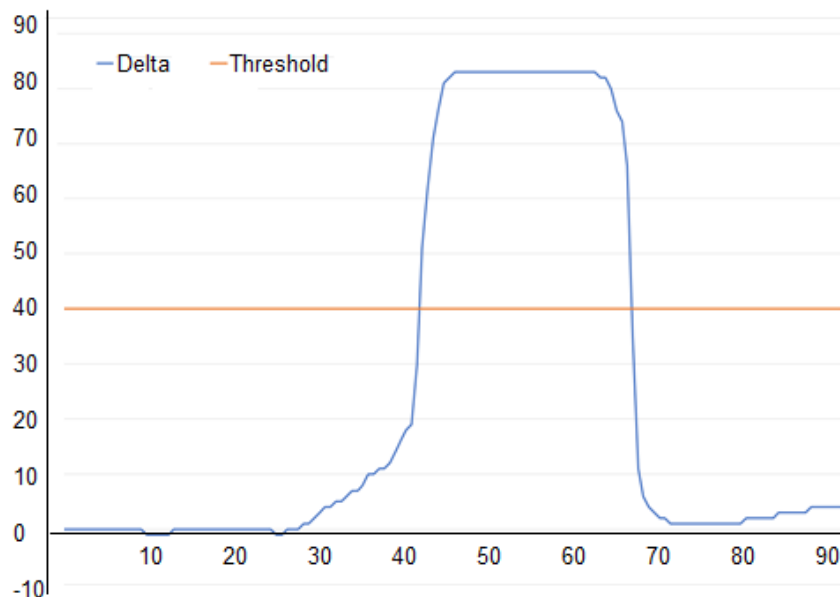
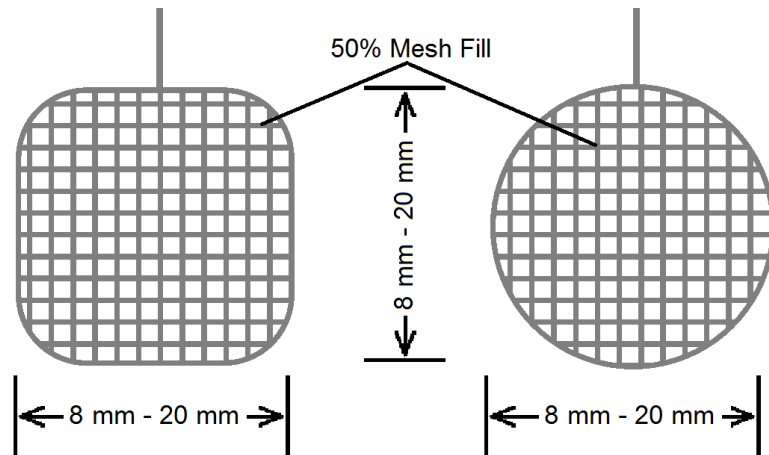## Electrode Shapes

An electrode is simply the patch of conductive material on the substrate that forms the sensor. Common shapes are round or rectangular solid areas although any shape with sufficient touch contact area may be used. Corners should be rounded to reduce the concentration of electric fields which may increase the occurrence of Electrostatic Discharge (ESD) to the sensor pad.

Figure 1-4. Standard Button Shapes
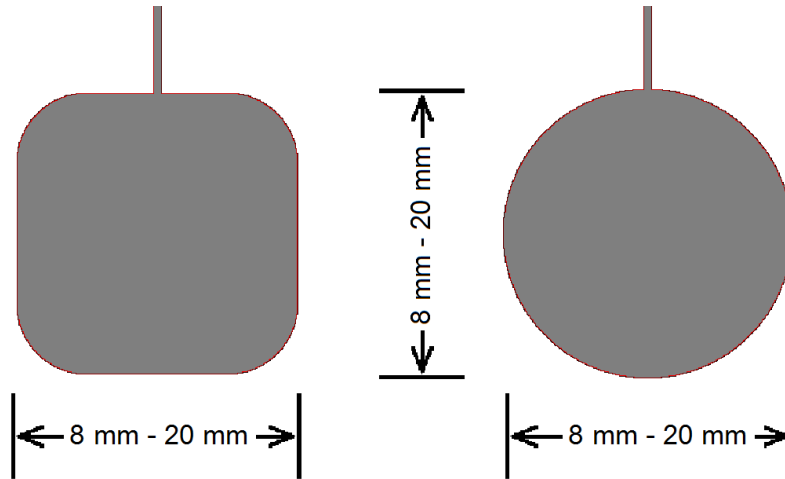
It is also possible to use a hatched pattern (such as a 50% mesh fill) for the electrode if desired. This tends to reduce the load capacitance of the sensor electrode, but also reduces the area interacting with the touch so there is a proportional drop in sensitivity.

Figure 1-5. Standard Buttons with Mesh Fill

Touch Target Size

The touch sensor electrode should be large enough that a touch contact does not need to be precisely placed to activate the sensor. If the sensor electrode is smaller than the user's fingertip, then sensitivity is reduced by the smaller effective area. For example, an 8 mm touch sensor with an 8 mm touch contact will only show maximum delta when the contact is placed directly at the center of the electrode.

Figure 1-6. 8 mm Touch Sensor
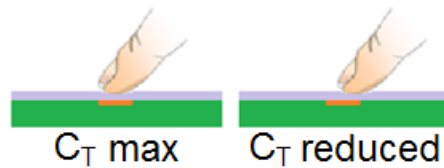
By increasing the size of the sensor, the user may place a contact anywhere over the sensor area with no loss in sensitivity. The effective parallel area of the touch contact is limited by the size of the user's fingertip, not the sensor area.

Figure 1-7. 12 mm Touch Sensor

Hand Shadow

An unnecessarily large sensor electrode will show an unintended proximity effect due to coupling to an approaching hand before the fingertip makes contact.
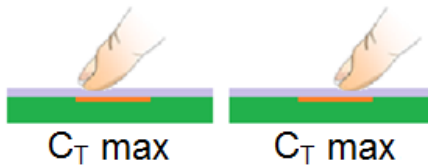
Pin Loading

Large sensors have higher self-capacitance, and the effect is increased if the sensor is located close to other circuitry including other sensors.

Larger load capacitance causes increased time constant and so the sensor takes longer to charge, discharge and measure. This can lead to deterioration in touch detect latency and power consumption.

Depending on measurement technology, high capacitance sensors may have reduced sensitivity or may exceed the range of the analog front-end compensation circuitry.

Note: See 8. Appendix A for device specific information on maximum sensor capacitance.

Electrode Separation

Individual sensor electrodes should be sufficiently separated so that touching one key does not cause an unintentional capacitance change on the neighboring keys, which could be misidentified as another touch contact. Recommended spacing between sensor electrodes is 4 mm + touch cover thickness. In many cases it is necessary to trade off sensor size and sensor separation for a dense UI.

Table 1-1. Touch Key Dimensions

|	Min	Typical	Max
Key Size	8 mm	12 mm	20 mm
Separation	3 mm	6 mm	—

1.2.3   Slider Sensor Design

A slider is simply a row of two or more touch sensor electrodes which are measured as individual sensors. The measured touch deltas are combined to determine the position of a touch contact with increased resolution by interpolation between the sensors.

With large sensors and no spatial interpolation, the consistency of the reported touch position vs actual position is very poor. As a contact moves across the slider, most of the time there is a touch contact only on one of the four electrodes. Position interpolation can only occur while the contact is crossing from one sensor to the next.

Figure 1-8. Slider Position without Interpolation
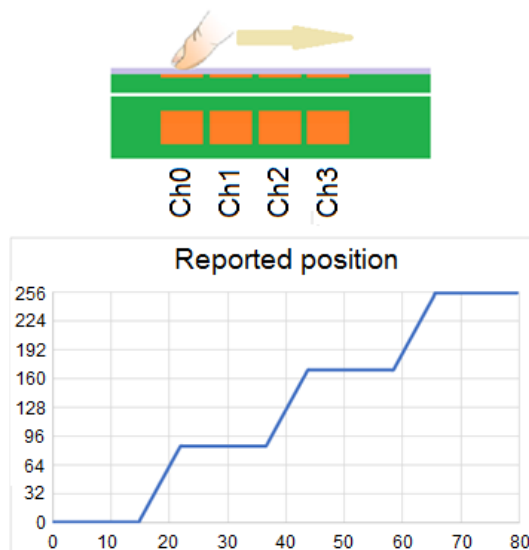
This may be improved by reducing the sensor size and increasing the number of sensors. If the sensor pitch is reduced to ~ ½ the width of a touch contact (i.e., sensor pitch ~4 to 5 mm) then there will always be two to three sensor electrodes under the touch contact and several touch deltas are available for interpolation wherever the contact is placed.

Figure 1-9. Slider Position with Interpolation
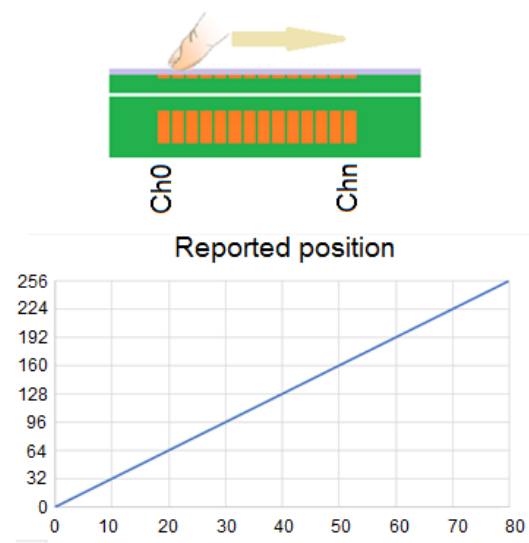
However, this is not always the optimal solution; for a long slider, the required number of sensor electrodes may be more than the touch sensor controller supports or take longer to measure leading to an unacceptable touch latency.

An alternative is to use spatial interpolation to 'stretch' the crossover position from one slider electrode to the next. One example is the electrode shape illustrated below. This design has tapered overlapping

edges to ensure that a touch contact anywhere along the length of the slider will always have contact area with at least two sensor electrodes.

Figure 1-10. Slider with Extended Interpolation

Make all sections equal width, repeating sections as required for desired total width

Adjust taper angle to fill remaining space

4-6 mm per section
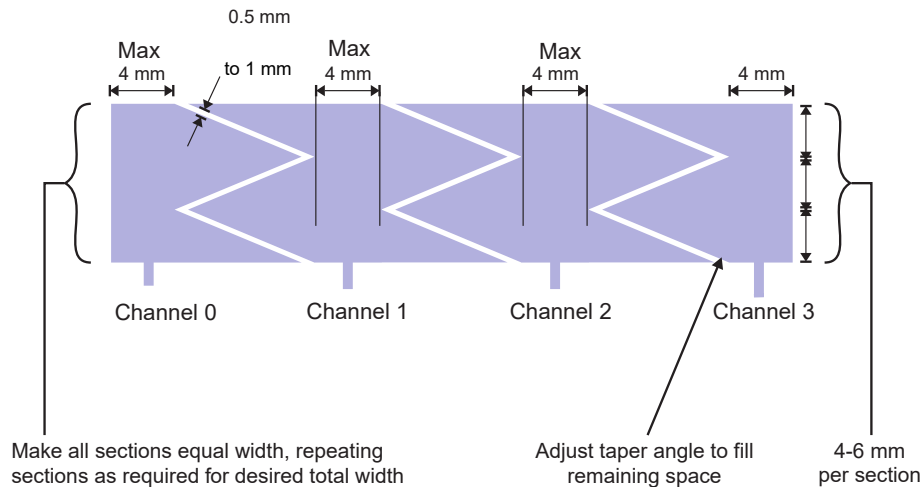
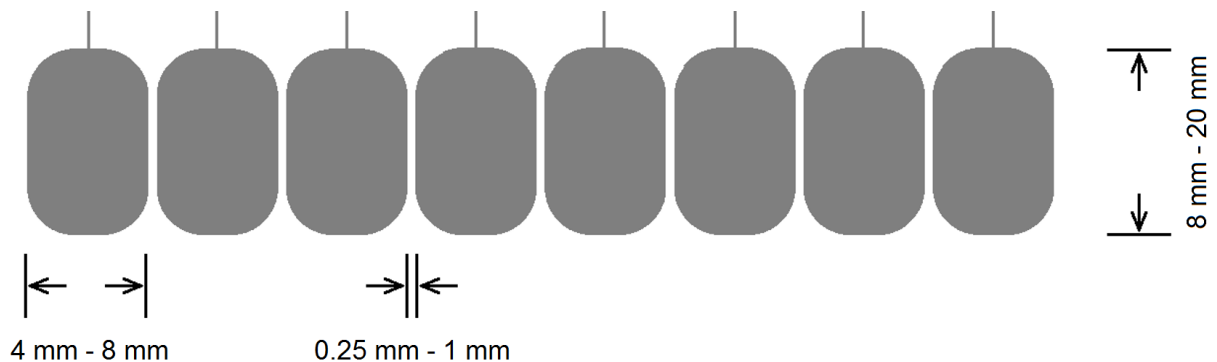### Spacing of Slider Electrodes

Each element of the slider is loaded by its own self-capacitance and by the capacitance between it and its neighboring electrodes as other electrodes are usually driven to a static DC level while a particular sensor is being measured.

Note: The exception to this is the implementation of 'Driven Shield+'. See 3. Shielding for further details.

Recommended separation between the sensor electrodes depends on the size of the electrodes and their overlap lengths.

A slider consisting of small keys without extended interpolation should have separation of 0.5 mm between electrodes. This improves touch delta consistency as the contact moves from one element to the next, without the occurrence of reduced touch delta in between.

Figure 1-11. Eight-Channel Slider/No Interpolation

4 mm - 8 mm

0.25 mm - 1 mm

8 mm - 20 mm

A slider consisting of large electrodes with long overlap lengths must have increased separation between the sensor electrodes to avoid excess sensor load capacitance. In such a design, the separation may be increased to 1 mm or more.

Figure 1-12. Six-Channel Slider with Interpolation
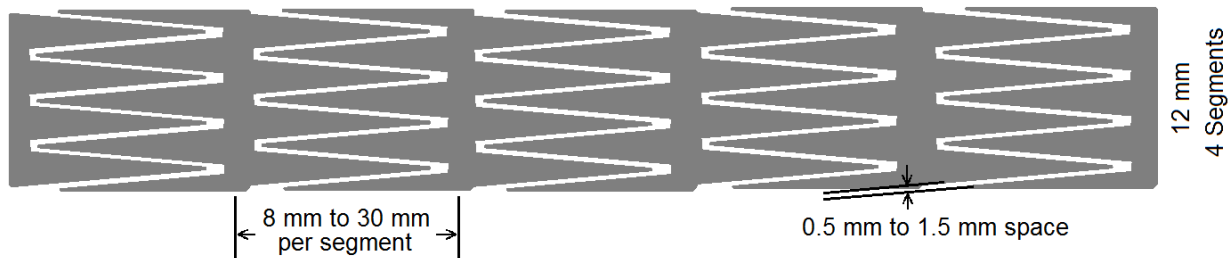
As with the button sensor design, sharp corners in the slider electrodes should be rounded to minimize susceptibility to ESD. The points of the triangles forming the interpolated slider should be truncated to a rounded end of ~2 mm diameter.

The electrodes must be close together for continuous sensitivity, but too little separation can cause increased loading capacitance, as each sensor electrode has a parasitic load against its neighboring electrodes. The spacing should be increased to maximum 1.5 mm in the cases when there are long parallel edges between electrodes due to extensive interpolation.

Table 1-2. Button Slider Dimensions

	Min	Typical	Max
Slider width	8 mm	12 mm	20 mm
Electrode length	4 mm	6 mm	8 mm
Electrode separation	0.25 mm	0.5 mm	1 mm

Table 1-3. Interpolated Slider Dimensions

	Min	Typical	Max
Slider width	8 mm	12 mm	20 mm
Electrode length	8 mm	16 mm	30 mm
Electrode separation	0.5 mm	1 mm	1.5 mm

1.2.4 Wheel Sensor Design

A wheel sensor consists of a row of three or more sensor electrodes which are arranged into a circle.

Note: At least three electrodes are needed as position calculation requires unique crossover regions.

A wheel sensor operates in the same way as a slider sensor, with the single exception being that it is wrapped around from Channel n to Channel 0 so there are no end electrodes in the design.

As with a slider, the simplest implementation is to arrange buttons in a circle. At least three electrodes are used.

Figure 1-13. Simple Three-Channel Wheel
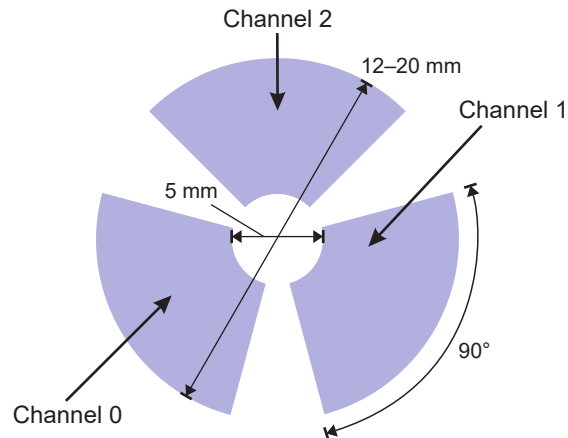
A larger wheel may be implemented by increasing the number of sensor keys used or by increasing the segment interpolation, as in the case of the slider.

Figure 1-14. Eight-Electrode Wheel without Extended Interpolation
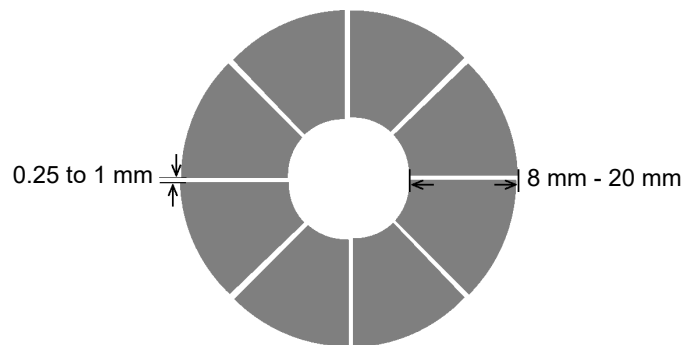
Figure 1-15. Three-Electrode Wheel with Extended Interpolation
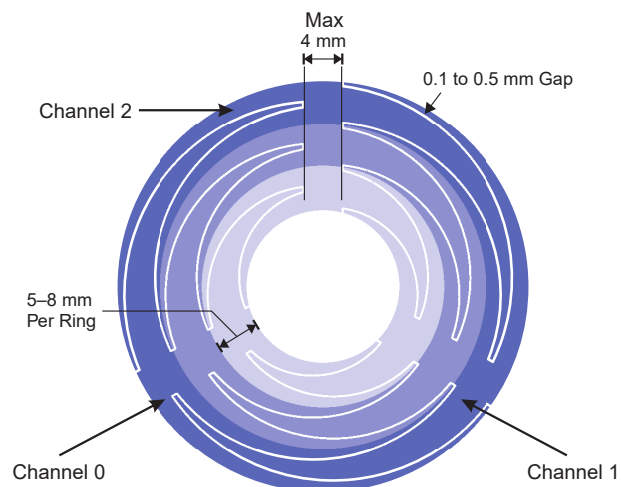
As with other sensors, sharp corners in the electrodes need to be rounded to minimize susceptibility to ESD. The points of the triangles forming the interpolation should be truncated to a rounded end of ~2 mm diameter.

Wheel electrodes must be close together for continuous sensitivity, but too little separation can cause increased loading capacitance, as each sensor electrode has a parasitic load against its neighboring electrodes. The spacing should be increased up to max 1.5 mm in the cases when there are long parallel edges between electrodes due to extensive interpolation.

Table 1-4. Button Wheel Dimensions

	Min	Typical	Max
Wheel width	8 mm	12 mm	20 mm
Electrode length	4 mm	6 mm	8 mm
Electrode separation	0.25 mm	0.5 mm	1 mm

Table 1-5. Interpolated Wheel Dimensions

	Min	Typical	Max
Slider width	8 mm	12 mm	20 mm
Electrode length	8 mm	16 mm	30 mm
Electrode separation	0.5 mm	1 mm	1.5 mm

1.2.5 Surface Sensor Design

A self-capacitance touch surface consists of 'row' and 'column' electrodes whose measurements are used to implement slider functionality in both the horizontal and vertical directions.

The simplest pattern is the 'diamond' pattern shown below. In this example, sensors H0 to H5 provide the horizontal location of a touch contact, while V0 to V4 provide the vertical location.

Figure 1-16. Touch Surface Diamond Pattern

Horizontal sensors to measure vertical position

Vertical sensors to measure horizontal position
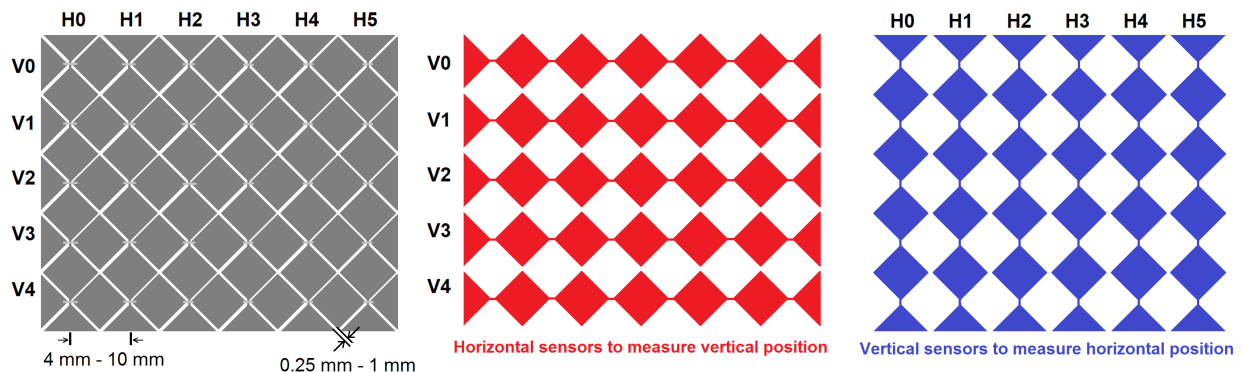
The sensor is characterized by its pitch and separation:

- Horizontal/vertical sensor pitch is the distance between column/row electrode centers.
- Sensor separation is the perpendicular distance between the parallel edges of adjacent diamonds.

Each sensor electrode is formed by chains of squares (symmetrical node pitch) or diamonds (asymmetrical pitch) which are turned 45° to provide improved interpolation in the horizontal and vertical directions.

Electrode Pitch

The ideal electrode pitch is approximately 5 mm for a user contact of 8 mm. This ensures that a contact placed anywhere on the surface will include an overlap area with at least two sensor electrodes in each dimension; thus, the contact permits the best interpolation of the touch position.

For larger touch surface designs many sensor electrodes are required to maintain optimum linearity. More sensors require more time to measure and increased power consumption. In many cases the designer must compromise between sensor linearity and the number of sensors.

Extended Interpolation

As with sliders and wheels, it is possible to design electrodes for a surface sensor with increased interpolation between adjacent sensors. This allows the designer to increase the electrode pitch while maintaining linearity.

One example is the 'flower' pattern, where each element of the sensor array has increased spatial interpolation with its neighbors.

Figure 1-17. Touch Surface Flower Pattern
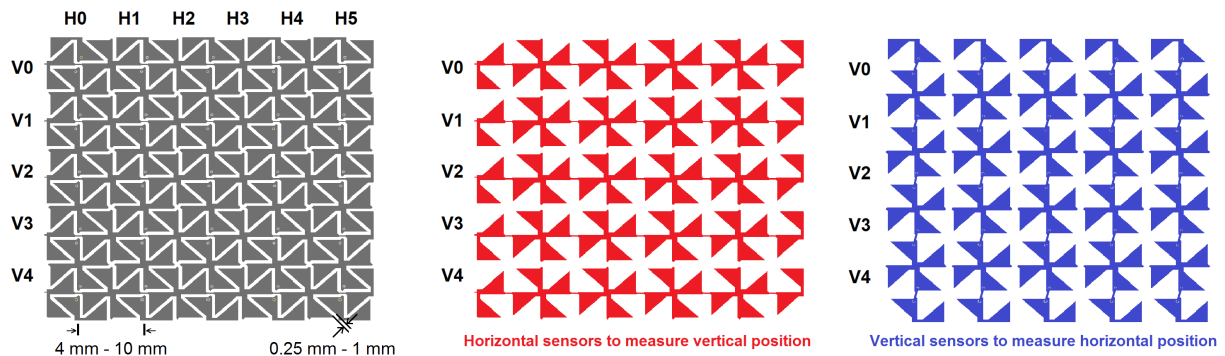
As with other sensors, sharp corners in the electrodes have to be rounded to minimize susceptibility to ESD. The points of the triangles forming the interpolation should be truncated to a rounded end of ~2 mm diameter.

Note: Two-touch detection requires separation of at least 2x sensor pitch between contact centers.

Table 1-6. Diamond Patten Dimensions

Type	Min	Typical	Max
Electrode pitch	4 mm	6 mm	10 mm
Electrode separation	0.25 mm	0.5 mm	1 mm

Table 1-7. Flower Patten Dimensions

Type	Min	Typical	Max
Electrode pitch	4 mm	6 mm	10 mm
Electrode separation	0.5 mm	1 mm	1.5 mm

2. Touch Cover Effect

A thicker touch cover increases the distance between the user's fingertip and the sensor electrode. This causes reduced capacitance between the user and the sensor electrode, and a proportional decrease in touch sensitivity.

This can be compensated by increasing the size of the electrode. A thicker cover also has the effect of diffusing the electric field formed between the fingertip and electrode, and thus a larger electrode can effectively increase the contact area.

For maximum sensitivity each sensor electrode should be designed to extend beyond the touch contact by at least the thickness of the touch cover.

All types of sensors should be wide enough to extend beyond the dimensions of a touch contact by at least the thickness of the touch cover on both inside and outside. See examples below:

- 1 mm touch cover/8 mm contact: recommended width = 10 mm
- 3 mm touch cover/8 mm contact: recommended width = 14 mm
- 6 mm touch cover/8 mm contact: recommended width = 20 mm

In an interpolation sensor (slider, wheel, or surface), the diffusion of the electric fields results in an extended crossover area between adjacent electrodes and improved accuracy in the reported contact position.

3.   Shielding

In many applications it is necessary to shield the touch sensors to prevent incorrect activation. This may be caused by Electromagnetic Interference (EMI) or by touch contact at a location that is not intended to be touch sensitive.

A variety of shield types may be used with self-capacitance sensors depending on the measurement technology.

These may be generally classed into 'passive' shield, where a shielding electrode is driven to a DC level, and 'active' shield, where a sequence of different voltage levels is driven to the shield during the measurement cycle.

Note: See 9. Appendix B for device specific availability.

3.1   Passive Shield

A shield electrode may be placed around the sensor electrode, or between the sensor and sources of interference, that may impair correct operation. A passive shield is an implementation where the shield electrode is driven to a constant DC level during the sensor measurement.

- Usually connected to DC ground
- May also use V_{DD} or any ground referenced DC level
- Rear flood prevents touch or EMI from behind
- Coplanar flood provides better isolation of touch sensors
- May be hatched to reduce capacitive load
- Detrimental to moisture tolerance

Effect of Ground Loading
DC or ground loading adds directly to the sensor base capacitance thus increasing the time constant.

Note: Ground in this context includes any conductor close to the sensor or its trace that is referenced to DC ground. This encompasses any circuit element or signal track that is nearby.

Idle sensors are usually driven to a DC level and the traces to these idle channels behave as though connected to ground. If a trace leading to key 1 is routed past key 2, then key 2 is loaded as though to a ground trace.

Where the ground referenced electrodes or traces are close to the touch sensor there is a reduction in touch sensitivity as the electric field emitted by the sensor electrode is attracted to the ground plane. This reduces the strength of the electric field available to interact with the user touch contact.

Rear Ground Shield
Sometimes it is desirable to shield an electrode on its rear side to prevent false detection from moving parts to the rear, or to prevent interference from switching signals, for example, from backlighting or driver circuitry.

If a driven shield is not possible, then a ground plane may be used. This should be connected directly to the circuit ground at a single point.

A rear ground plane may significantly reduce the sensitivity of the touch sensors, as the DC ground attracts the electric field emitted by the touch sensor electrode. This should be taken into consideration

particularly where the touch cover may be thicker than the separation between electrode and ground layers.

To alleviate this problem the electrode and ground plane should be separated by the maximum distance possible. For example, on a multilayer PCB, touch sensors should be on the top layer and ground on the bottom.

Additionally, the ground shield may be reduced to 50% or 25% hatched fill, which reduces the sensor loading while still providing the shield effect.

If the application does not risk accidental touch contact from the rear of the sensor board, the rear ground plane may be cut out behind the sensor keys. This reduces capacitive loading of the sensors while providing sensor isolation from other circuit components or EMI.

Coplanar Ground Shield

A coplanar ground shield may be implemented to improve isolation between touch sensors, to reduce EMI to the touch sensors and to reduce the interference caused by common mode noise when a touch contact is present.

As a coplanar shield does not overlap the area of the touch sensors, a solid pour should be used.
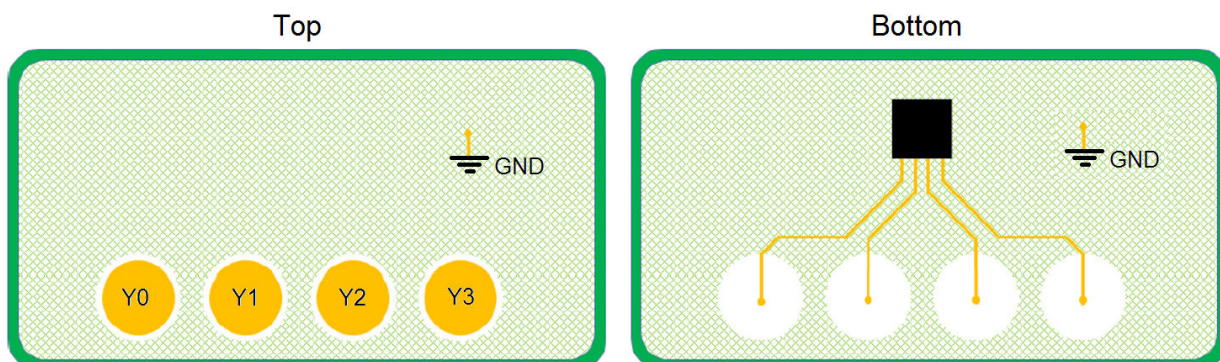
To minimize the loss in sensitivity, the ground shield should be kept at a distance from any touch sensor of approximately 2 mm, which may be increased for large sensor electrodes.

Figure 3-1. Coplanar Ground Plane Separation
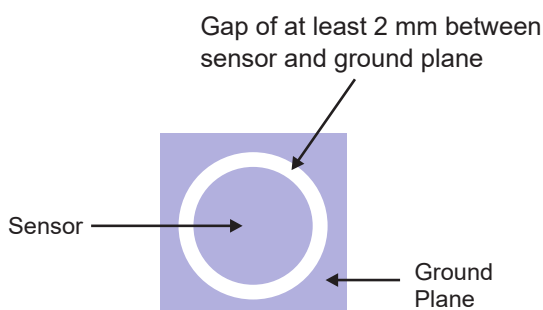
Example Layout
Figure 3-2. Sensor Layout with Front and Rear Hatched Ground Plane

Table 3-1. Sensor to Ground Separation

Min	Typical	Max
1 mm	2 mm	3 mm

Larger electrodes should have increased ground separation to avoid too much load capacitance on the sensor electrodes.

3.2 Active Shield

3.2.1 Driven Shield

- Drives 'shield' electrode with a sequence of DC levels synchronized to the sensor measurement
- Requires a dedicated shield electrode
- Reduces or eliminates loading of sensors due to capacitance with neighbors
- Rear shield prevents touch from behind
- Improved water tolerance

Any ground referenced trace near a sensor will load that sensor, reduce its sensitivity and may even produce false touches in certain environmental conditions, such as specifically wet or very humid conditions.

Figure 3-3. Driven Shield Circuit
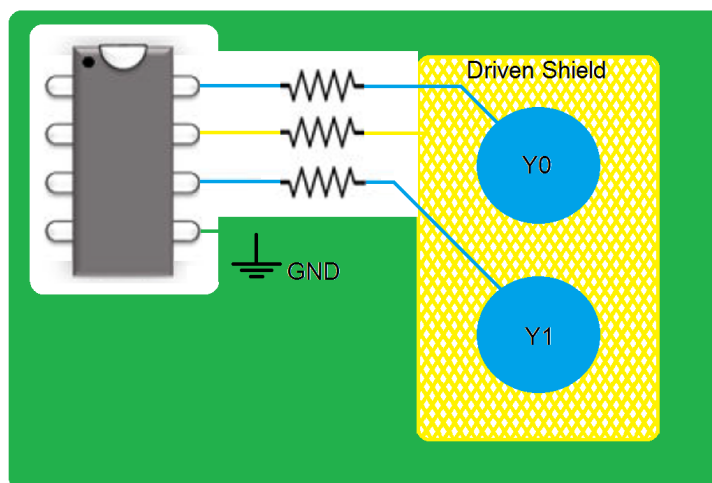
Two classes of driven shield are available on Microchip touch sensor devices: three-level shield and two-level shield.

Three-Level Shield

The shield is driven through a sequence of voltages matching the electrode potential at each stage in the measurement. This effectively decouples the touch sensor from the ground, reducing the capacitive loading and provides an electrical shield to EMI improving the Signal to Noise Ratio (SNR) of the sensor. By placing the shield between the sensor and other circuit components, the operation in the presence of moisture is greatly improved.

Table 3-2. Sensor to Shield Separation – Three-Level Shield

Min	Typical	Max
0.2 mm	0.5 mm	3 mm

Two-Level Shield

Drives a charge pulse during the sensor measurement which shields the sensor from outside influence while additionally boosting the sensitivity of the sensor.

The shield electrode is driven with pulses synchronized to the measurements. These pulses have the effect of boosting the self-capacitance measurement by injection of additional charge to the sensor capacitance. Greater touch sensitivity is achieved as a user touch contact interacts with the electric field between shield and sensor as well as the electric field between sensor and shield and the electric field between sensor and ground.
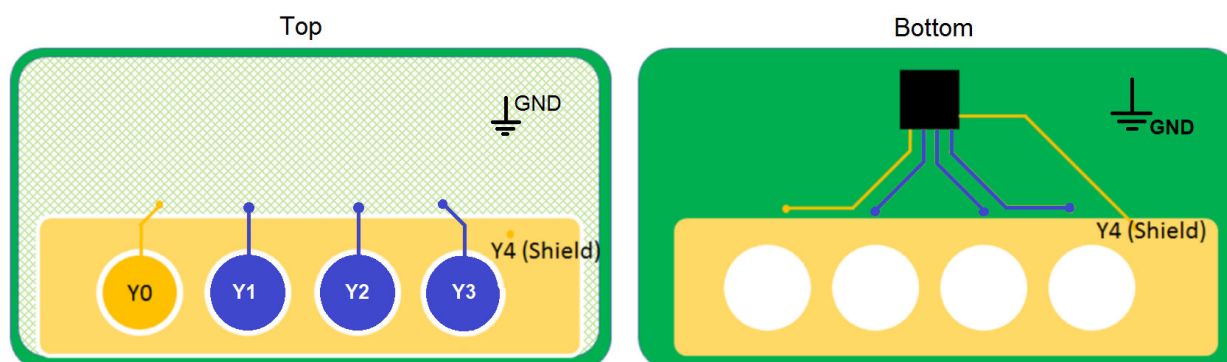
Sensor load capacitance is reduced as the shield isolates the sensor from nearby ground referenced circuit components.

Table 3-3. Separation between Sensor and Shield Electrodes

| Min	Typical	Max
1 mm	2 mm	3 mm

Driven Shield Examples
Figure 3-4. Driven Shield Layout

Alternatively, a 'ring shield' may be used to isolate each of the sensor electrodes from each other and the ground plane. The ring shield consists of a shield electrode wrapped around each touch sensor. The electrode should be at least 2 mm wide and separated from the touch sensor by approximately 2 mm.

Note: The shield should not form a complete ring around the sensor electrode as this may lead to problems with RF noise. Breaking the ring also allows simplified routing and enables a single layer sensor design.

Figure 3-5. Ring Shield Layout
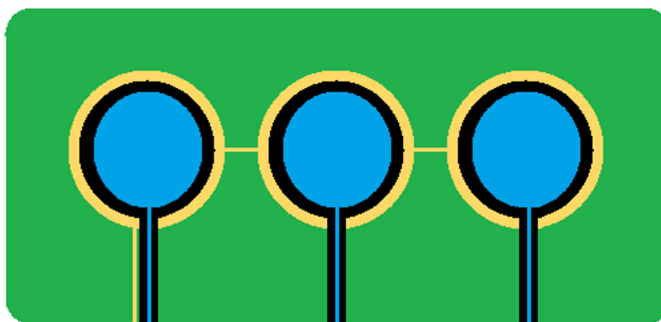

3.2.2 Driven Shield+

Some devices have the facility to drive the 'shield' signal – three-level or two-level – not only to a dedicated shield electrode but also to other touch sensor electrodes on the UI.

Even in the case where all pins are used as touch sensors and there are no pins available for a shield, Driven Shield+ can be used to drive the other sensors as shield. In the application examples shown in Figure 3-6, Y0 is the active sensor and all other electrodes are driven as shield.

Figure 3-6. Driven Shield + Examples
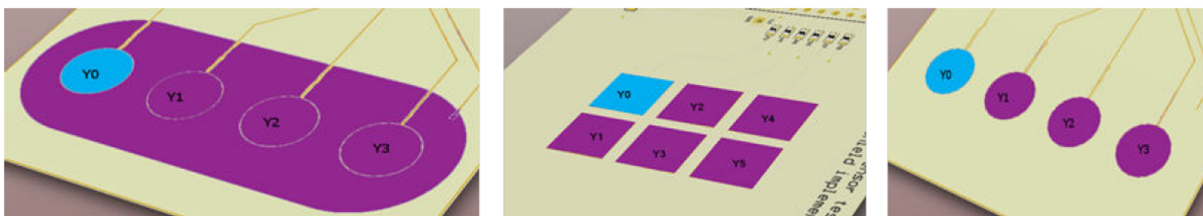
Figure 3-7. Sensors with Ground in Close Proximity
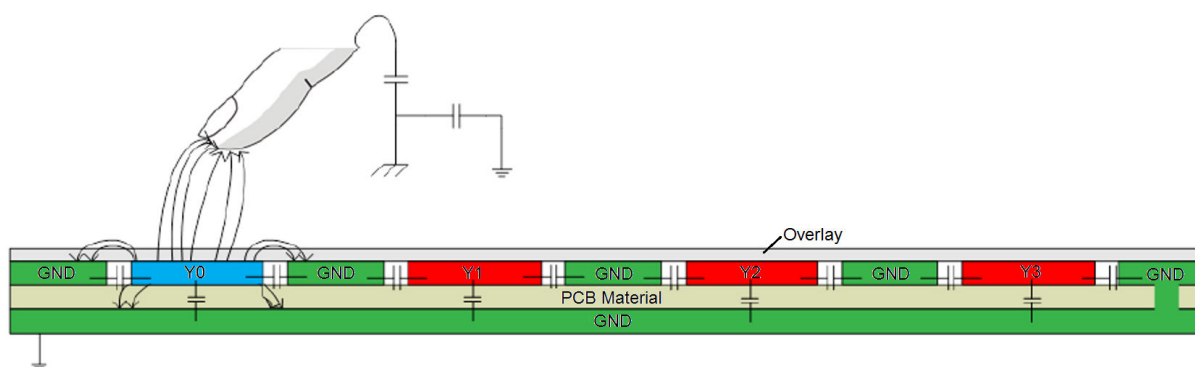
In Figure 3-7, sensor Y0 is measured while all other sensors are held static at V_{DD}. There is also a ground flood or signal near the sensors. In this scenario, additional capacitance exists between Y0 and ground. Charge driven into Y0 will be shared with ground, reducing the electric field at the touch surface and so reducing touch sensitivity. As discussed in section 3.1 Passive Shield, this may be mitigated by increasing the space between the sensor and the ground shield but this is not always possible in UI design with high sensor density.

Figure 3-8. Sensors with Driven Shield+
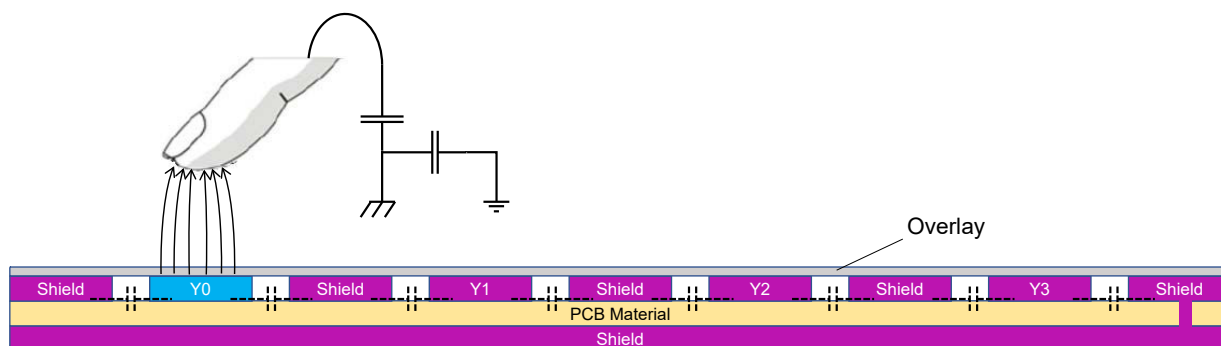
With Driven Shield+ there is little capacitive loading between Y0 and the other electrodes as they are driven to the same potential. There is a stronger electric field between the sensor and the user, which increases sensitivity and SNR.

This effect of using Driven Shield+ allows greater field projection and improved performance in proximity sensor applications.

Moisture Tolerance

With Driven Shield+, water coupling between a sensor and the shield does not create a touch delta because the shield and sensor are driven to the same potential. Where a driven shield is used but adjacent keys are not shielded, water can potentially cause a false touch detection due to coupling to neighboring keys.

Care should be taken when designing systems where the touch sensor may be exposed to water. If water is to bridge across the shield signal and over a ground, then some field from the touch sensor will couple to ground through the water which may cause false touch detection.

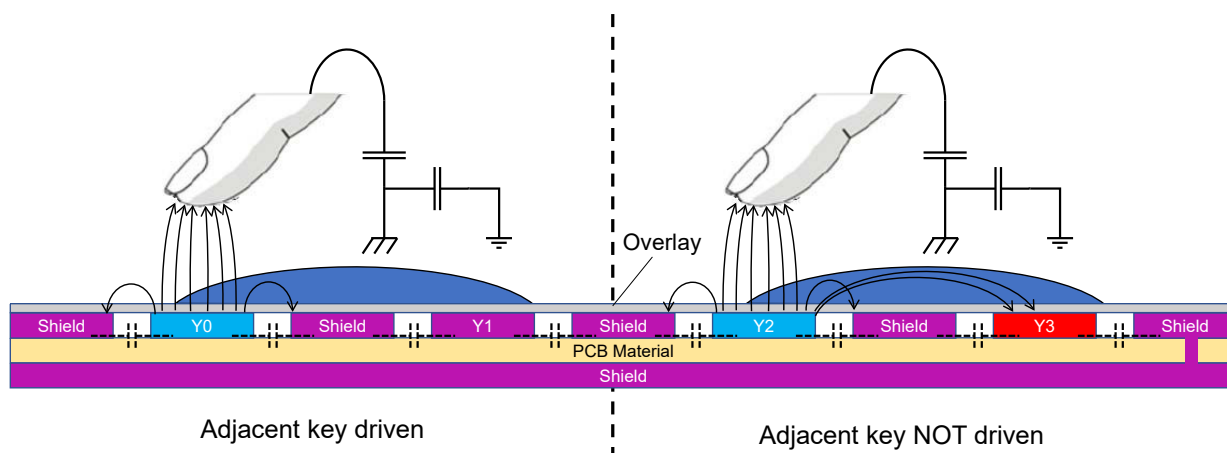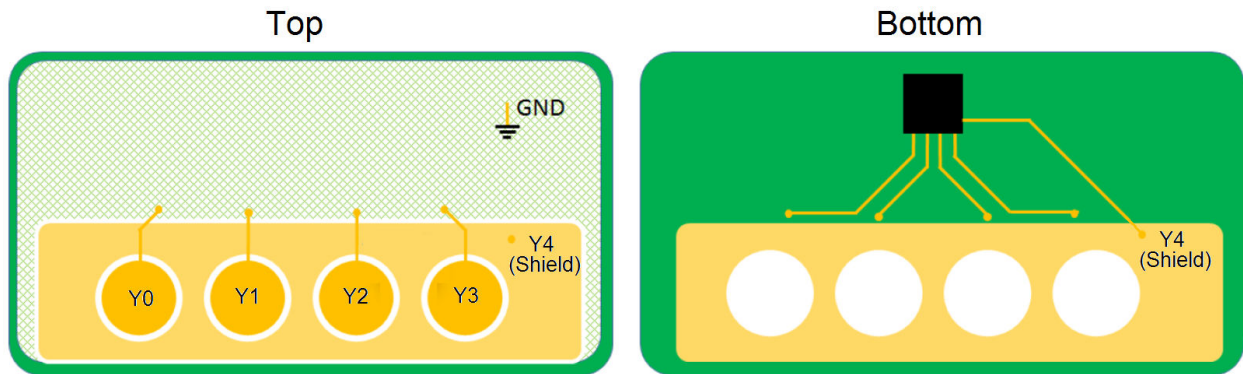**Figure 3-9. Effect of Water on Touch Sensors**

Figure 3-10. Driven Shield + Layout Example

3.3 Radiated Emissions

Depending on the application and its environment, the use of Active Shield may cause excessive radio frequency emissions. This is caused by high speed switching of large area electrodes and can lead to products failing to achieve required RFI standards.

High emissions are particularly prevalent not at the switching frequency of the touch sensors, but at higher frequencies dependent on the MCU core speed and the I/O pin slew rate.

Mitigation

Add or increase the series resistor to the shield electrode:

- By increasing the series resistance, the time constant of the RC shield is increased and the amount of energy available at high frequencies is reduced.
  Note: The resistor package has a parasitic capacitance which at RF frequencies may be lower impedance than the resistor itself.

Reduce the area of active shield:

- Instead of a full flood, consider using patches of shield electrodes behind each touch sensor, extending only 2-5 mm beyond the edge of each sensor.
- The patches have to be joined together at a single physical point and connected to the resistor in a 'star' formation.

Figure 3-11. Minimum Driven Shield Area
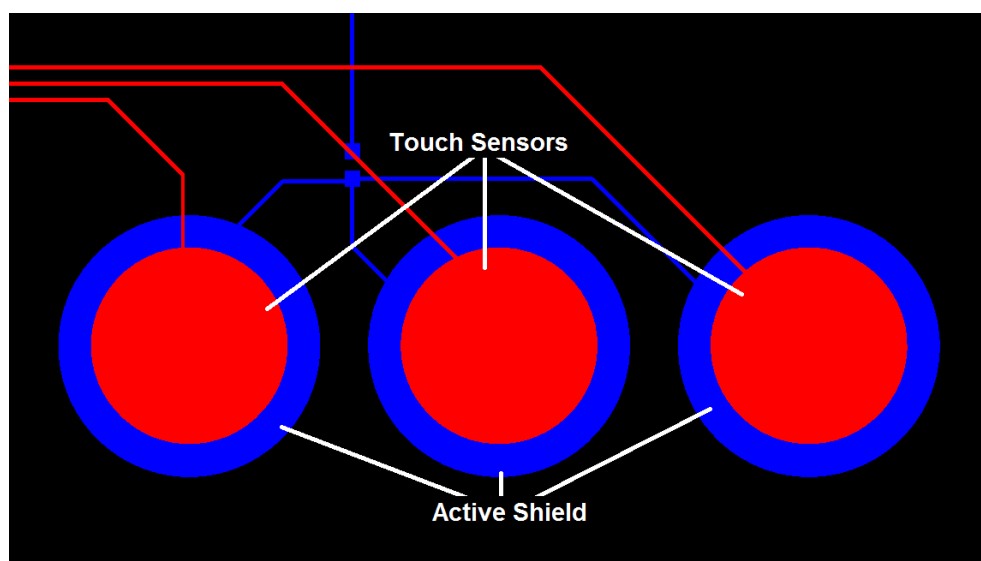
4. Mutual Capacitance Sensors

4.1 Mutual Capacitance Measurement

Mutual capacitance touch sensors use a pair of electrodes for each sensor node, measuring the capacitance between them. The sensor is formed where the electrode pair is placed close together, usually with interdigitated segments to optimize the length of parallel conductors forming the base capacitance of the sensor node.

Figure 4-1. Mutual Capacitance Sensor
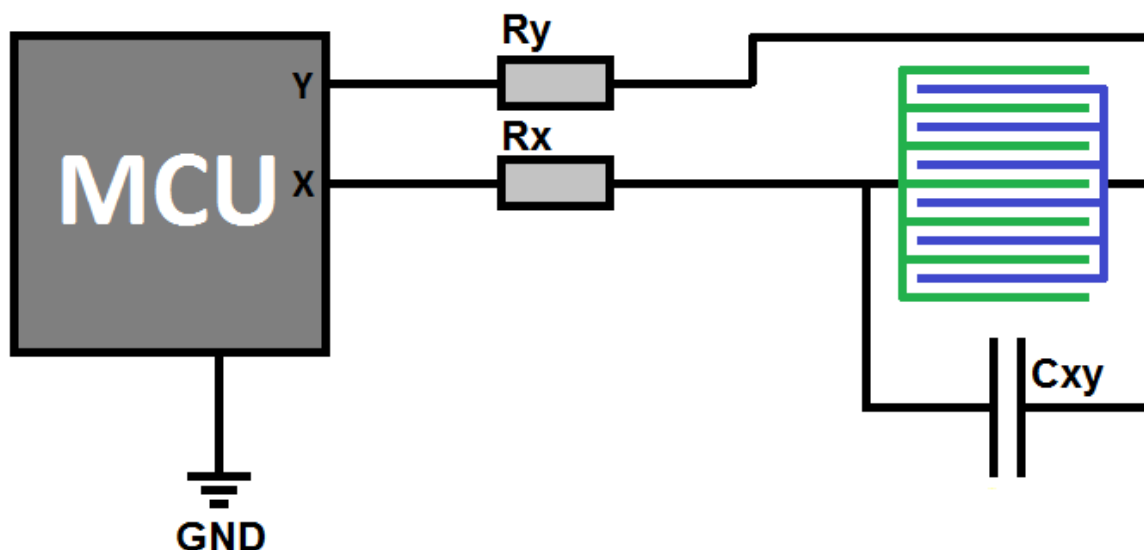
When a touch contact is placed over the sensor, the user's fingertip interacts with the electric field between the X (transmit) and Y (receive) electrodes.

Figure 4-2. Mutual Capacitance Sensor with Touch Contact
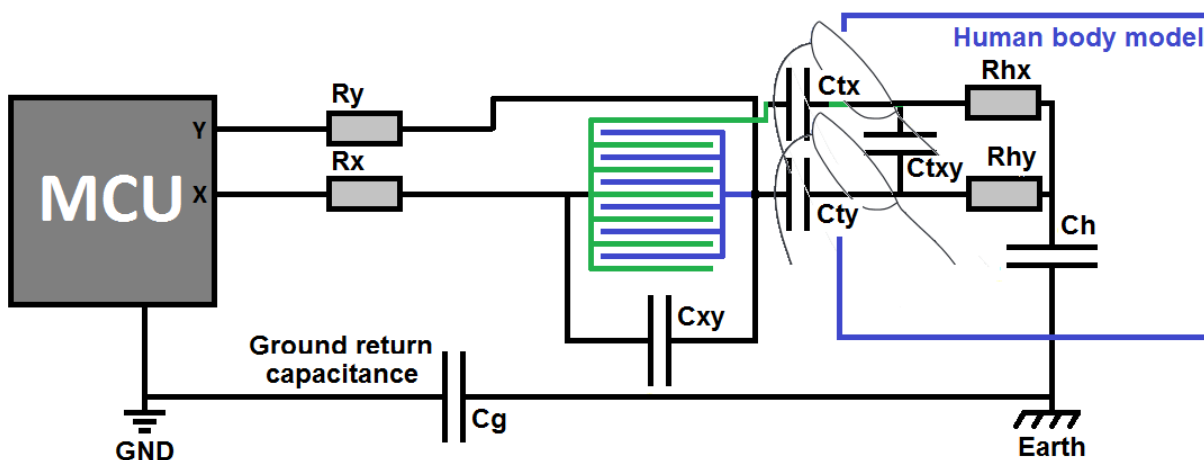
This is a complex interaction of two competing effects:

- Forming an extra 'plate' in the XY capacitance increases the coupling between X to Y by the addition in parallel of the series combination Ctx and Cty.
- Providing a ground return path via Ch (human body model capacitance) and Cg (ground to earth capacitance) reduces the amount of charge transferred from X to Y, thus causing an apparent decrease in the X – Y capacitance.

Note: The HBM resistance Rh (here shown as Rhx and Rhy) does not affect touch sensitivity.

Ct

- Overall reduction in XY capacitance due to touch contact
- 0.1 pF up to 2 pF depending on sensor design and touch cover thickness/material

Ch

- Human body model
- 100 pF to 200 pF

Cg

- Coupling between the application DC ground and earth
- Depends on application type and power system
- As little as ~1 pF in a small battery powered device
- Infinite capacitance/short circuit where the DC ground is connected directly to earth

As in self-capacitance sensors, Ct is much smaller than Ch or Cg for most applications; the measured touch delta is dominated by Ct, which is controlled by the sensor design.

5. Sensor Design

5.1 Touch Capacitance Model

Unlike self-capacitance measurements, there is no simple approximation of the expected touch capacitance for a given mutual sensor layout. The parallel plate approximation is not applicable as the 'plates' in this case are segments of the X and Y electrodes which are much smaller than the touch cover. The user's touch contact is dominated by edge and point fields between the electrode pair and the fingertip.

When designing mutual capacitance sensors, the node layout may be optimized to suit application requirements.

For example:

- Strongest touch delta
- Best noise tolerance
- Best water rejection
- Minimum sensor capacitance
- Minimum power consumption
- Minimum touch latency

In many applications it is necessary to compromise between requirements.

For example, the strongest touch delta is achieved with high interdigitation of electrodes, but minimum sensor capacitance requires larger spacing between X and Y.

Increasing XY separation reduces XY capacitance, but also reduces the lengths of parallel segments between the electrodes.

Figure 5-1. 0.5 mm vs 1 mm XY Spacing

12.5 mm square key
with 0.5 mm spacing

12.5 mm square key
with 1 mm spacing
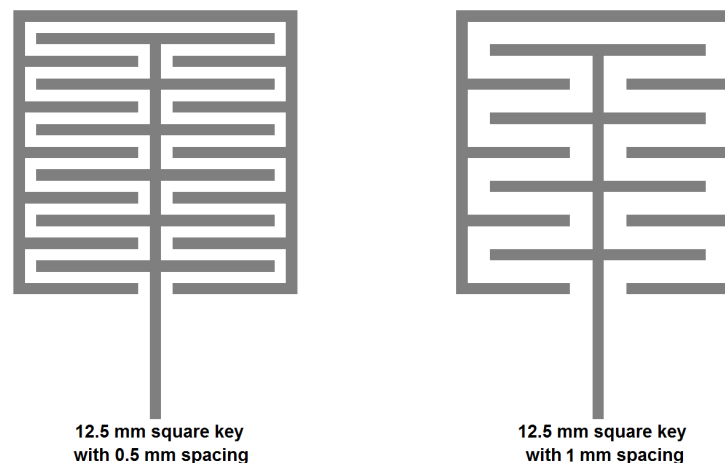
When a user places a touch contact, a much smaller total length of parallel segments is covered. As these lengths are the location of the user's interaction with the XY field, the reduction of length causes a proportional reduction in touch sensitivity.

Figure 5-2. Touch Contact 12 mm Key

Fingertip placed on key

12.5 mm square key
with 0.5 mm spacing

12.5 mm square key
with 1 mm spacing
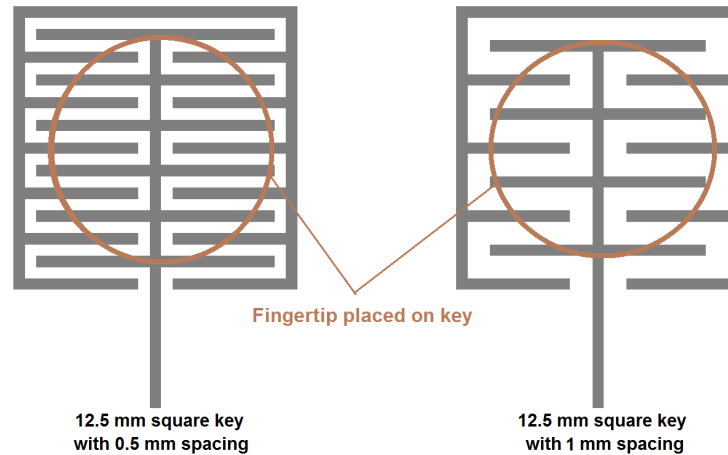
5.2   Button Sensor Design

The simplest implementation of a capacitive sensor is a button, where the sensor consists of a single XY node and is interpreted as a binary state: In Detect or Out of Detect. When the touch delta – the digitized measurement of touch capacitance C_t – exceeds the touch threshold, then the senor is In Detect.

Note: C_t is negative in the case of mutual capacitance sensors, but in many implementations the signal data is inverted so a normalized increase in signal is observed on contact.

Electrode Shapes

A sensor node is present where the electrodes form an area of coupling between X and Y. Common buttons are round or rectangular although any shape with parallel segment coupling of X and Y electrodes may be used.

Interdigitated Key

The simplest sensor layout is a coplanar interdigitated key. See figure below.

Figure 5-3. Standard Coplanar Layouts

X Electrode

0.25 mm to 2 mm

0.25 mm to 1 mm

0.25 mm to 1.5 mm

0.25 mm to 1.5 mm

8 mm to 20 mm

Y Electrode

8 mm to 20 mm

8 mm to 20 mm
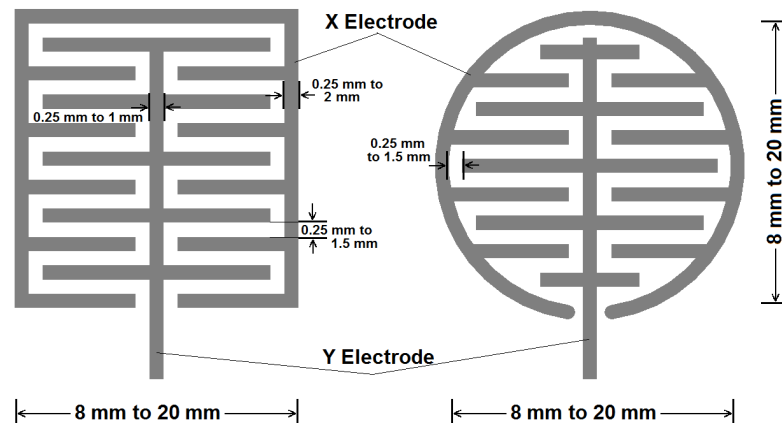
Table 5-1. Interdigitated Key Dimensions

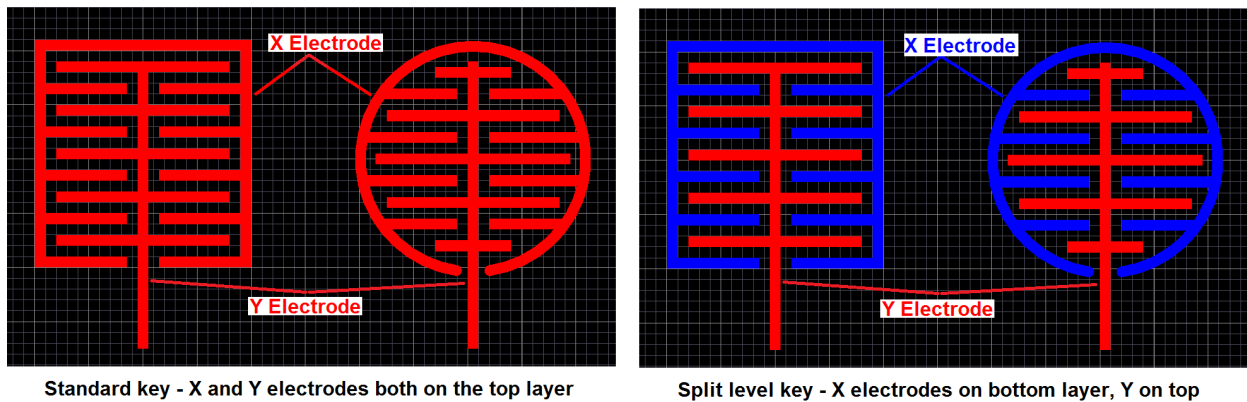|	Min	Typical	Max
Key size	8 mm	12 mm	20 mm
X electrode width	0.25 mm	0.5 mm	2 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
XY spacing	0.25 mm	0.5 mm	1.5 mm

The interdigitated key is typically implemented on a single PCB layer but may be split between two layers with the X electrodes on the layer furthest from the touch surface. This design has the advantage of keeping the maximum length of parallel segment under the touch contact while increasing the XY separation and thus reducing the sensor capacitance.
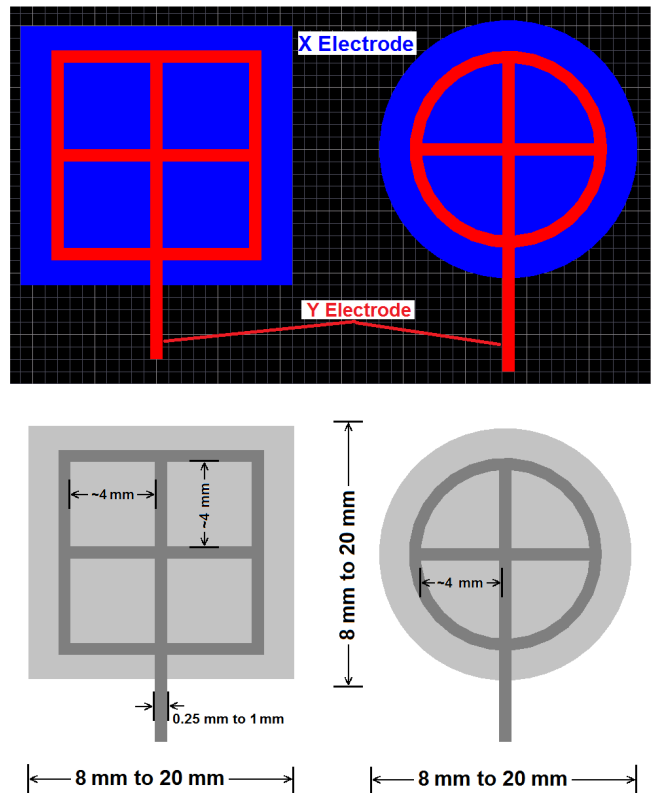
Figure 5-4. Split Level Layout

Standard key - X and Y electrodes both on the top layer

Split level key - X electrodes on bottom layer, Y on top

Flooded X Key

An alternative layout is 'flooded X', where the X electrode is a solid area behind a segmented Y electrode. The X area should extend beyond the Y electrode by at least 2 mm on each side.

Figure 5-5. Flooded X Layout

Table 5-2. Flooded X Key Dimensions

	Min	Typical	Max
Key size	8 mm	12 mm	20 mm
X electrode width	8 mm	12 mm	20 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
Gaps in Y grid	4 mm	4 mm	4 mm

This layout has the advantage that the X area shields the Y sensor from circuit noise. However, in an application requiring a thicker touch cover, flooded X sensors suffer from poor sensitivity.

Generally, flooded X sensors should only be used where the touch cover is thinner than the substrate. With standard 1.6 mm FR4, no touch cover > 1.6 mm thick should be considered.

Note: Flooded X sensors are generally not suitable for implementation on flex PCB, as the thin substrate requires an equally thin touch cover. Flooded X sensors are not suitable for use with some devices. See 10. Appendix C for device specific information.

5.3 Slider Sensor Design

A slider may be implemented on a row of two or more sensors placed together. Measurements of the sensor group are combined to determine the position of a touch contact with increased resolution by interpolation between the sensors.

As noted in the previous chapter, using large sensors without interpolation leads to poor matching of the calculated contact position vs the actual position. The sensor count may be increased to improve interpolation, but at the cost of total measurement time.

Interdigitated Slider

Spatial interpolation may be applied using an interdigitated layout, where the sensor nodes are formed by alternating X and Y electrodes. Typically, a single Y line is used with multiple X lines as this allows for the easiest sensor routing.

Figure 5-6. Interdigitated Slider Layout
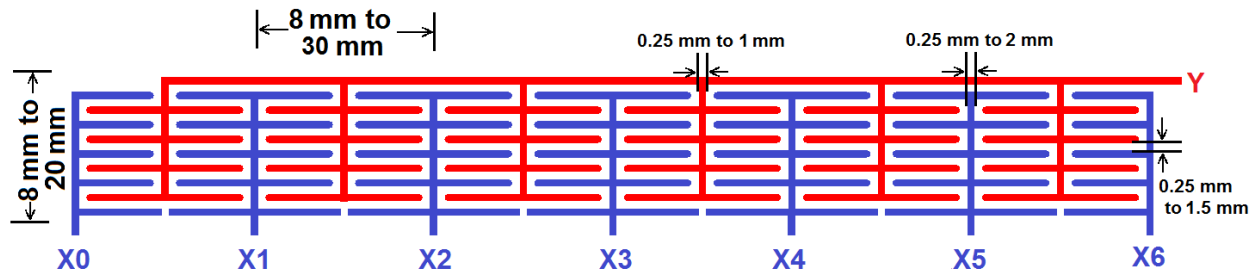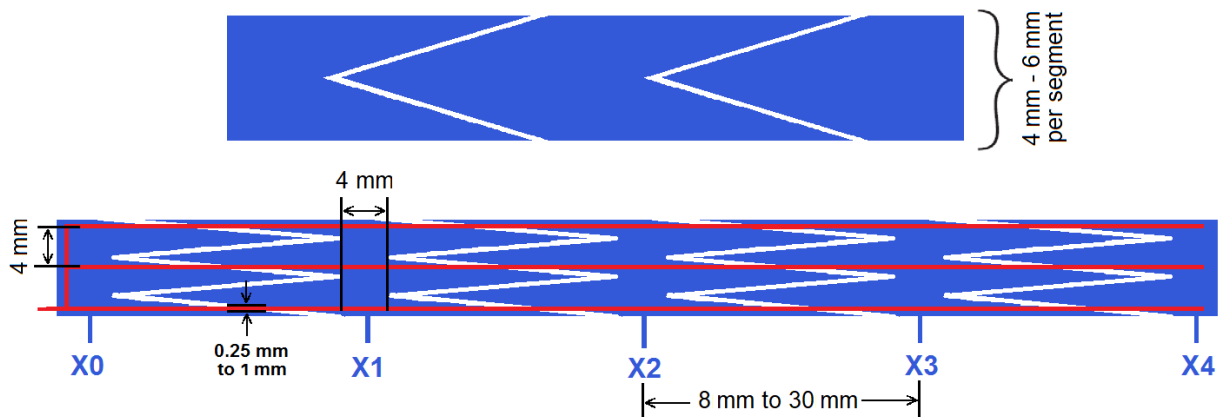

Table 5-3. Interdigitated Slider Dimensions

	Min	Typical	Max
Slider width	8 mm	12 mm	20 mm
Segment width	8 mm	12 mm	30 mm
X electrode width	0.25 mm	0.5 mm	2 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
XY spacing	0.25 mm	0.5 mm	1.5 mm

The interdigitated slider may be formed as a coplanar sensor, with X and Y electrodes on the same layer or split to different layers with X on the layer further from the touch surface.

Flooded X Slider

A flooded X slider provides improved linearity as the X electrodes are on a separate PCB layer. Spatial interpolation may be extended without complex routing around the Y electrodes. The X layer pattern for a flooded X slider is identical to the interpolated self-capacitance slider presented in the previous chapter.

Figure 5-7. Flooded X Slider Layout

Table 5-4. Flooded X Slider Dimensions

	Min	Typical	Max
Slider width	8 mm	12 mm	20 mm
X electrode width	8 mm	15 mm	30 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
Gaps between Y segments	3 mm	4 mm	5 mm

Resistive Interpolation

In both interdigitated and flooded X slider designs it is possible to reduce the number of sensor node measurements while maintaining linearity by resistive interpolation of some sensor nodes.

Figure 5-8. Sliders with Resistive Interpolation
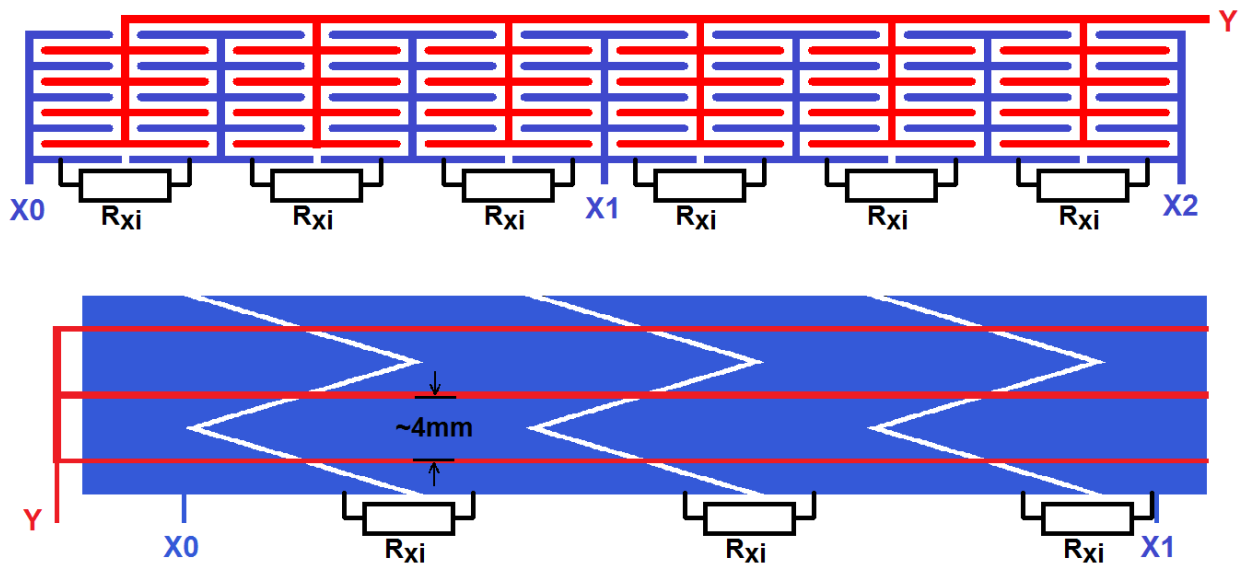
At least two directly routed X electrodes are required, placed at either end of the slider. Intermediate nodes are joined with a series of resistors, forming a resistive divider driving each intermediate node at a

fraction of the X drive voltage. A touch contact on an intermediate node causes a proportional touch delta on each of the direct nodes, facilitating interpolation along the length of the slider.

Segment interpolation resistors Rxi should be selected so that the total series combination between each pair of directly connected X lines is approximately between 10-20 kOhm.

5.4 Wheel Sensor Design

A wheel sensor consists of a row of three or more sensor nodes which are arranged into a circle.
Note: At least three electrodes are required as position calculation needs unique crossover regions.

A wheel sensor operates in the same way as a slider sensor, with the single exception being that it is wrapped around from Channel n to Channel 0 so there are no end electrodes in the design.

Interdigitated Wheel
Like the interdigitated slider, the simplest implementation is a coplanar interdigitated wheel. X and Y electrodes are formed on the same PCB layer. The design may also be split across two PCB layers to reduce sensor capacitance, with the X electrodes on the layer further from the touch cover.

Figure 5-9. Interdigitated Wheel Layout
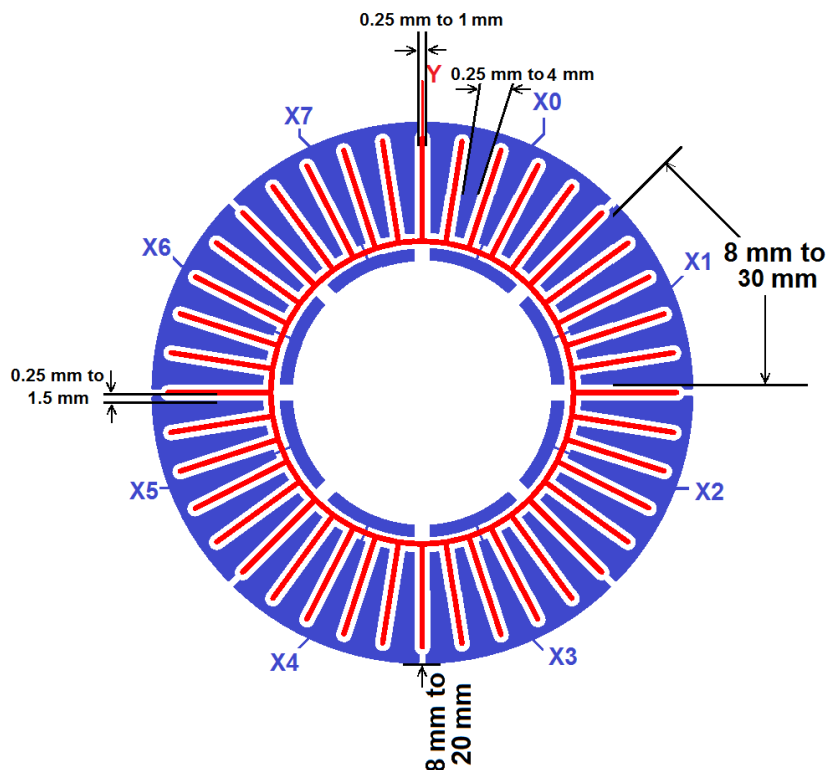
Table 5-5. Interdigitated Wheel Dimensions

	Min	Typical	Max
Wheel width	8 mm	12 mm	20 mm
Segment width	8 mm	12 mm	30 mm
X electrode width	0.25 mm	0.5 mm	4 mm*

..........continued	Min	Typical	Max
Y electrode width	0.25 mm	0.5 mm	1 mm
XY spacing	0.25 mm	0.5 mm	1.5 mm

Note: * Taper needs to be within this range at both ends.

Flooded X Wheel

As the X electrodes are on a separate PCB layer, spatial interpolation may be extended without complex routing around the Y electrodes. This allows the flooded X design to provide improved linearity over the interdigitated layout. The X layer pattern for a flooded X slider is identical to the interpolated self-capacitance wheel presented in the previous chapter.

Figure 5-10. Flooded X Wheel Layout
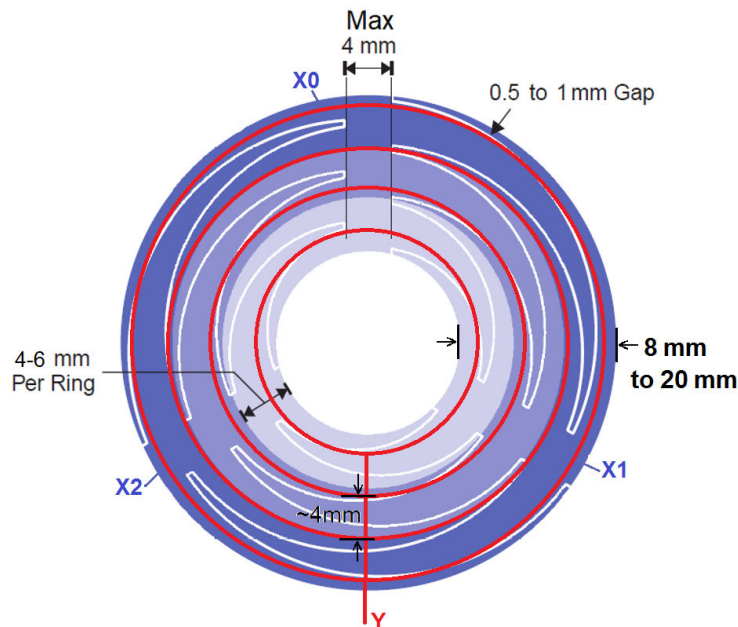
Table 5-6. Flooded X Wheel Dimensions

	Min	Typical	Max
Wheel width	8 mm	12 mm	20 mm
X electrode width	8 mm	15 mm	30 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
Gaps between Y segments	3 mm	4 mm	5 mm

Resistive Interpolation

In both wheel designs, it is possible to reduce the number of sensor node measurements while maintaining linearity by resistive interpolation of some sensor nodes.

Figure 5-11. Wheel with Resistive Interpolation
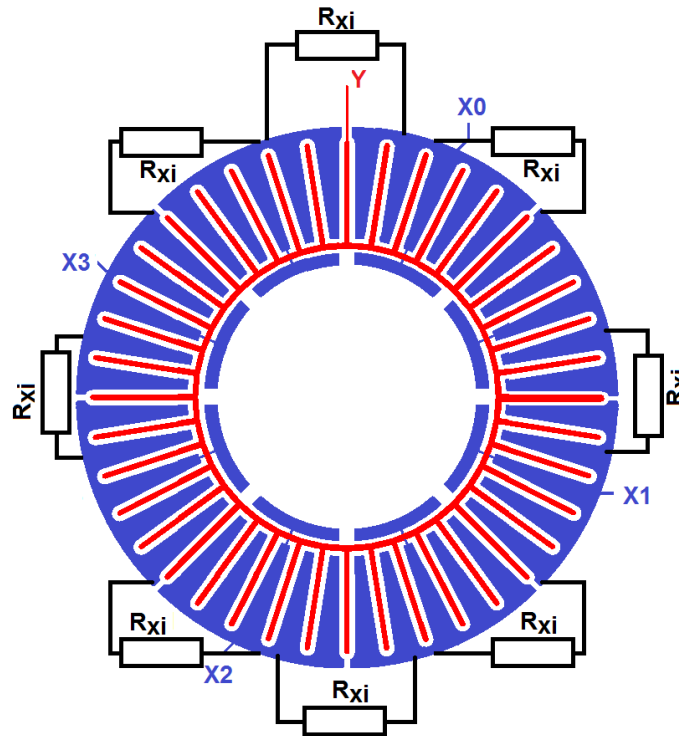
At least three directly routed X electrodes are required and need to be placed symmetrically around the wheel. Intermediate nodes are joined with a series of resistors, forming a resistive divider driving each intermediate node at a fraction of the X drive voltage. A touch contact on an intermediate node causes a proportional touch delta on each of the direct nodes, facilitating interpolation around the circumference of the wheel.

Segment interpolation resistors Rxi should be selected so that the total series combination between each pair of directly connected X lines is approximately between 10-20 kOhm.

5.5   Surface Sensor Design

A mutual capacitance touch surface consists of 'row' and 'column' electrodes which are implemented as X and Y, respectively. Each row or column is measured and the data are combined to implement slider functionality in both the horizontal and vertical directions.

Note: Two-touch detection requires separation of at least 2x sensor pitch between contact centers.

Interdigitated Surface

The interdigitated slider pattern may be extended to two dimensions to form an interdigitated surface sensor. The surface pattern requires two electrode layers to allow crossover as each row must be joined from left to right and each column from top to bottom.

The sensor may be formed on a single layer with connections only on the second layer, or as a split-level design with X electrodes on the layer further from the touch cover, Y electrodes on the closer layer.

Figure 5-12. Interdigitated Surface Layout
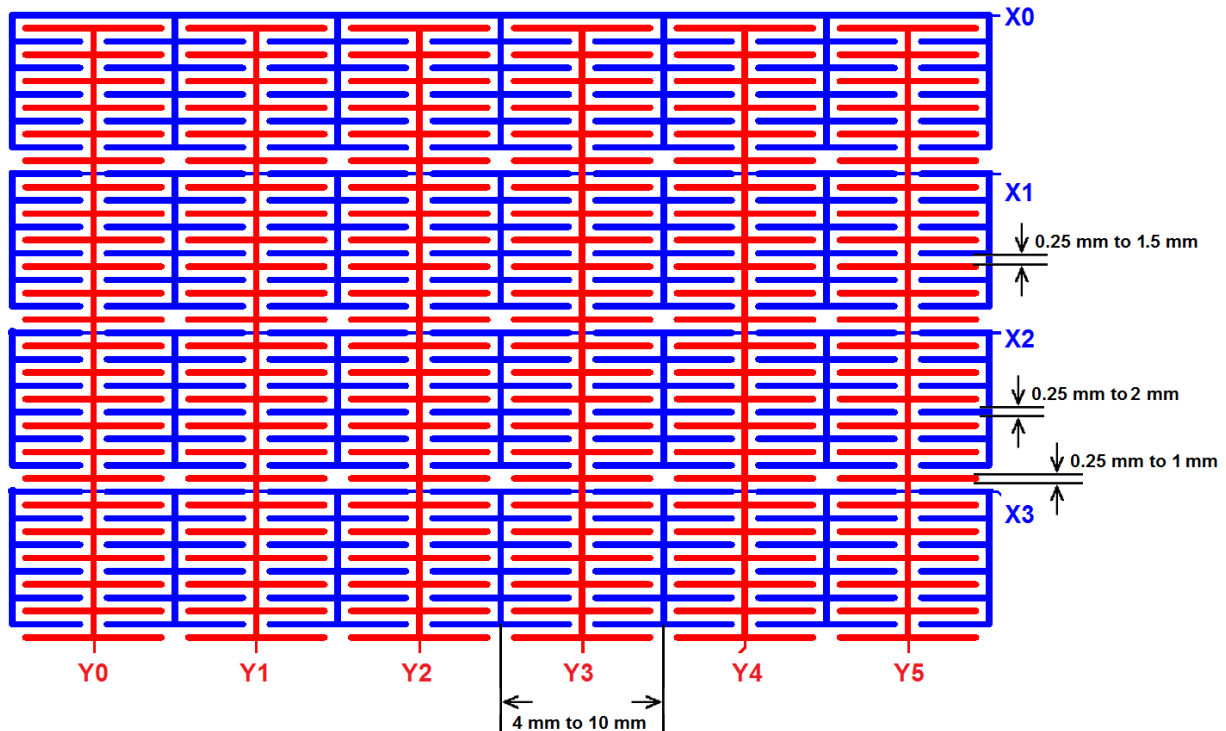
Table 5-7. Interdigitated Surface Parameters

	Min	Typical	Max
Row/column pitch	4 mm	6 mm	10 mm
X electrode width	0.25 mm	0.5 mm	2 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
XY spacing	0.25 mm	0.5 mm	1.5 mm

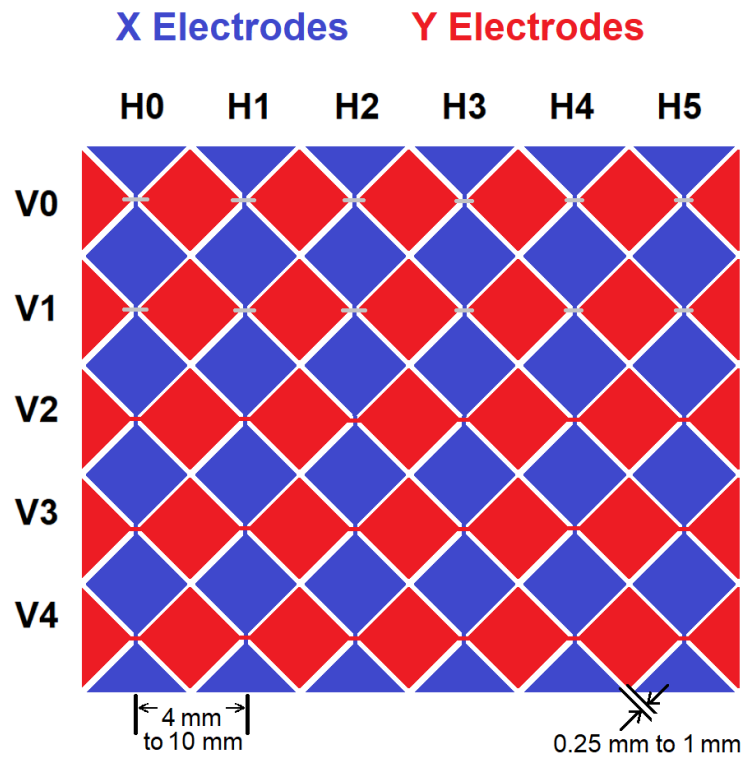**Diamond Pattern**

The Diamond Pattern presented in 5.5 Surface Sensor Design for self-capacitance surface may also be implemented as a mutual capacitance sensor.

Horizontal sensor nodes may be driven as X lines, while vertical nodes are measured as Y or vice versa. The X and Y electrodes may be coplanar or split level with X to the rear, as described above for buttons, sliders and wheels.

Note: Implementations using reversible XY electrodes should be located on a single layer.

Figure 5-13. Mutual Surface Diamond Pattern

**Table 5-8. Surface Diamond Pattern Dimensions**

	Min	Typical	Max
Row/column pitch	4 mm	6 mm	10 mm
XY separation	0.25 mm	0.5 mm	1 mm

Similarly, the flower pattern surface may be used for mutual capacitance surface.

Flooded X Surface

The sensor is formed with X electrodes as vertical bars to the rear, and Y electrodes as narrow traces horizontally spaced on the top layer. Interpolation along Y nodes provides either vertical position, interpolation along X nodes the horizontal.

Figure 5-14. Flooded X Pattern
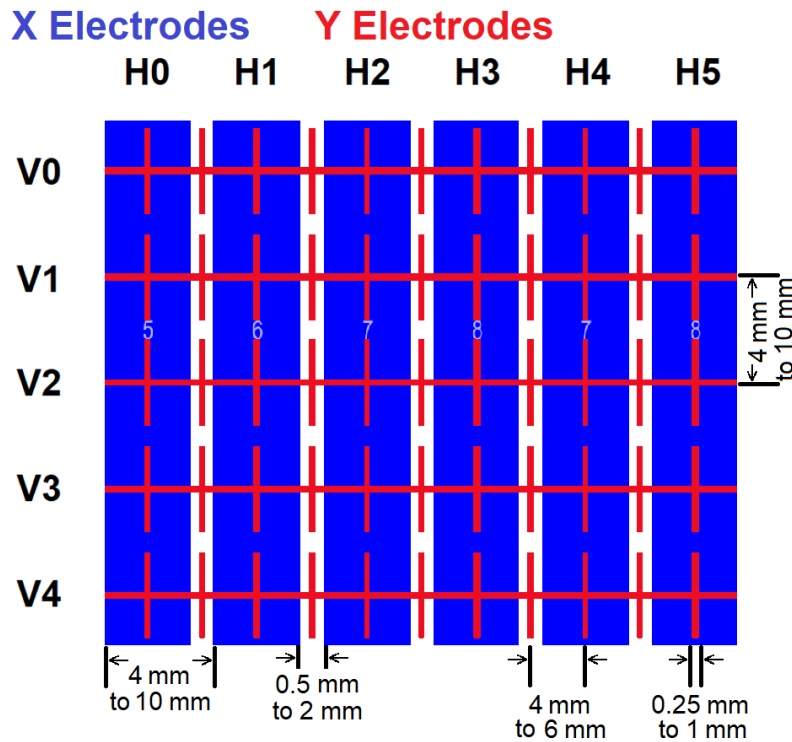
Table 5-9. Flooded X Pattern Parameters

	Min	Typical	Max
Row/column pitch	4 mm	6 mm	10 mm
XX separation	0.5 mm	1 mm	2 mm
Y electrode width	0.25 mm	0.5 mm	1 mm
Y electrode spacing	3 mm	4 mm	5 mm

6. Touch Cover Effects

A thicker touch cover increases the distance between the user's fingertip and the sensor electrodes and has the effect of diffusing the electric field formed between them. There is a reduction in touch contact capacitance, but this can be compensated by increasing the size of the electrode and the amount of digitization.

For maximum sensitivity each sensor should be designed to extend beyond the touch contact by at least the thickness of the touch cover.

For a 1 mm touch cover the smallest touch button or narrowest slider/wheel should be $(8\,mm + (2 \times 1\,mm) = 10\,mm.$

For a 3 mm cover this is increased to $(mm + (2 \times 3\,mm) = 14\,mm.$

In an interpolated sensor (slider, wheel or surface), a thicker cover benefits from an extended crossover area between adjacent electrodes and thus improved accuracy in the reported contact position.

For flooded X sensors, a thicker cover leads to a more pronounced reduction in sensitivity. It is recommended not to use a touch cover thicker than the XY layer separation.

7. Shielding

In many applications it is necessary to shield the touch sensors to prevent incorrect activation. This may be caused by EMI or by touch contact at a location which is not intended to be touch sensitive.

Mutual capacitance sensors may be isolated with a passive shield.

7.1 Passive Shield

- Usually connected to DC ground
- May also use V_{DD} or any ground referenced DC level
- Rear flood prevents touch or EMI from behind
- Coplanar flood provides better isolation of touch sensors
- May be hatched to reduce capacitive load
- Detrimental to moisture tolerance

Rear Ground Shield

Sometimes it is desirable to shield an electrode on its rear side to prevent false detection from the rear, or to prevent interference from switching signals from, e.g., backlighting or driver circuitry.

A ground plane may be used. This should be connected directly to the circuit ground at a single point.

For mutual capacitance sensors, the effect of a ground area behind the sensor node has the effect of reducing the overall capacitance of the sensor node. This can be beneficial in some applications as it allows more keys to be lumped together. However, the sensor's time constant may be increased due to loading of the Y line electrode.

A rear ground plane may significantly reduce the sensitivity of the touch sensors, as the DC ground attracts the electric field emitted by the X electrode. This should be taken into consideration particularly where the touch cover may be thicker than the separation between sensor and ground layers.

The electrode and ground plane should be separated by the maximum distance possible. For example, on a multi-layer PCB, touch sensors should be on the top layer and ground on the bottom.

The ground shield may be reduced to 50% or 25% hatched fill, which alleviates the reduction in sensitivity while still providing the shield effect.

If the application does not risk accidental touch contact from the rear of the sensor board, the rear ground plane may be cut out behind the sensors. This eliminates desensitization of the sensors while providing isolation from other circuit components or EMI.
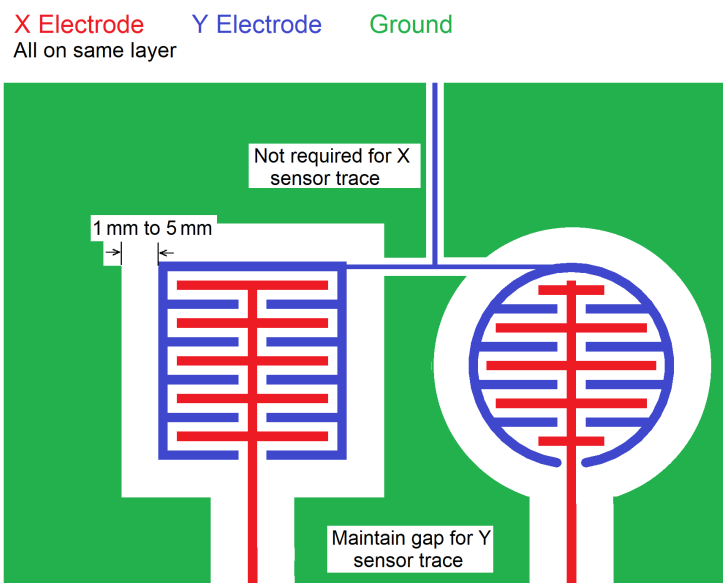
Coplanar Ground Shield

A coplanar ground shield may be implemented to improve isolation between touch sensors, to reduce EMI and common mode noise effects.

As a coplanar shield does not overlap the area of the touch sensors, a solid pour may be used.

To minimize the loss in sensitivity, the ground shield should be kept at a distance from any touch sensor of approximately 2 mm, which may be increased for large sensor electrodes or better moisture tolerance.

**Figure 7-1. Coplanar Ground Plane Separation**

X Electrode   Y Electrode   Ground
All on same layer

Not required for X sensor trace

1 mm to 5 mm

Maintain gap for Y sensor trace

Table 7-1. Sensor to Ground Separation

Min	Typical	Max
1 mm	2 mm	5 mm

7.2   Moisture Tolerance

With mutual mapacitance sensors, moisture droplets on an isolated sensor node will not cause accidental touch detection. In fact, the sensor will show an 'away from touch' delta, as the droplets increase the XY coupling – via the capacitance formed between the water and the X line Cwx and that between water and Y line Cwy – but do not provide a significant ground return path.

Figure 7-2. Droplet on Isolated Sensor

C_{xy}

C_{xy}

C_{wx} C_{wy}
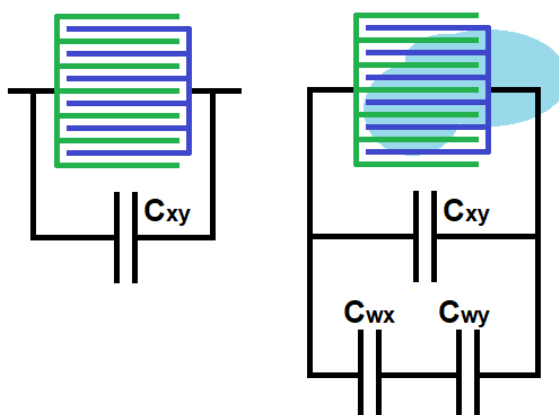
Usually, the sensor is one of a group of sensors in close proximity and shares the PCB with many components and signals. In this case, a water droplet which crosses from the sensor node to any other circuit component will cause an increase in ground return coupling. In this case, the net result may be towards touch delta and false touch detection.

Figure 7-3. Droplet Crossing to Ground Flood
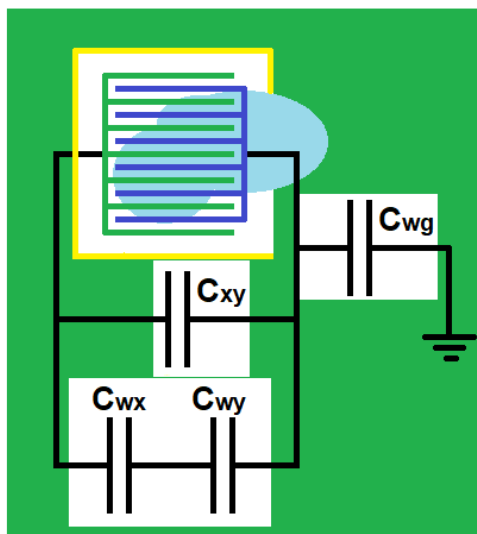
8.   Appendix A

Device family	Maximum self-capacitance sensor capacitance (pF)	Maximum mutual capacitance sensor capacitance (pF)
ATtiny81X/161X/321X	53	32
ATmega324PB/ATmega328PB	32	32
ATSAML10/L11	63	32
ATSAML22	32	32
ATSAMC20/C21	32	32
ATSAMD10/D11	32	32
ATSAMD20/D21/DA1/ ATSAMHA1	32	32
ATSAML21	32	32
ATSAMD51/ATSAME51/ ATSAME53/ATSAME54	63	32

9.   Appendix B

Device Family	Active Shield Support
ATtiny81X/161X/321X	Driven Shield+ (Three Level)
ATSAML1X	
ATSAMD2X/ATSAMDA1/ATSAMHA1	Driven Shield (Two Level)
ATSAMC2X/ATSAML2X	
ATSAME5X/ATSAMD5X	
PIC® MCU without HCVD	
ATmega328PB/ATmega324PB	Active Shield not supported
PIC MCU with dual ADC	Driven Shield+ (Two Level)
PIC MCU with ADCC	Driven Shield+ (Two Level)

10. Appendix C

Device Family	Suitable for Flooded X Design[1]
ATtiny81X/161X/321X	Yes
ATmega324PB/ATmega328PB	No
ATSAML10/L11	Yes
ATSAML22	No
ATSAMC20/C21	No
ATSAMD10/D11	No
ATSAMD20/D21/DA1/ATSAMHA1	No
ATSAML21	No
ATSAMD51/ATSAME51/E53/E54	Yes

Note: 1. Yes = devices support I/O drive for X lines

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PART NO.   [X]⁽¹⁾   –X   /XX

Device   Tape   Temperature   Package
           and Reel   Range

Device:	Device A, Device B, etc	
Tape and Reel Option:	Blank	= Standard packaging (tube or tray)
	T	= Tape and Reel[1]
Temperature Range:	I	= -40°C to +85°C (Industrial)
	E	= -40°C to +125°C (Extended)
Package:[2]	JQ	= UQFN
	P	= PDIP
	ST	= TSSOP
	SL	= SOIC-14
	SN	= SOIC-8
	RF	= UDFN
Pattern:	QTP, SQTP^{SM} (Serial Quick Turn Programming capability), Code or Special Requirements (blank otherwise)	

- Device A - I/P Industrial temperature, PDIP package
- Device B - E/SS Extended temperature, SSOP package

Note:
1. Tape and Reel identifier only appears in the catalog part number description. This identifier is used for ordering purposes and is not printed on the device package. Check with your Microchip Sales Office for package availability with the Tape and Reel option.
2. Small form-factor packaging options may be available. Please check http://www.microchip.com/packaging for small-form factor package availability, or contact your local Sales Office.

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