

Capacitive Touch Hardware Design Guide

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MSP430

ABSTRACT

Capacitive touch detection is sometimes considered more art than science. This often results in multiple design iterations before the optimum performance is achieved. There are, however, good design practices for circuit layout and principles of materials that need to be understood to keep the number of iterations to a minimum. This design guide describes a process for creating and designing capacitive touch solutions, starting with the schematic, working through the mechanicals, and finally designing the electrodes for the application.

Contents

1	Introduction	2
2	Overview of Capacitive Touch Sensing	2
3	Schematic	6
4	Mechanicals	7
5	Layout	11
6	References	22

List of Figures

1	Sample Electrode Shapes	3
2	Equivalent Circuit	4
3	Typical Material Stackup	8
4	Sensitivity vs Thickness	9
5	Intentional Gaps Between Electrode and Overlay	11
6	Top and Cross-Sectional Views of Trace Line in PCB	12
7	Trace Without Copper Pouring Underneath in Multilayer PCB	13
8	Top View of Connector and Noise Source	14
9	Top View of Different Traces.....	15
10	Capacitance of the Electrode	16
11	Button Shape Examples, Dos and Don'ts	17
12	Incorrect Design of a Slider or Wheel for Desired Resolution	18
13	Designing Electrode Shapes to Support Desired Resolution	19
14	Ends of Sliders.....	19
15	Effective Area Example for Electrodes Larger Than Decal	20
16	Effective Area Example for Electrode Smaller Than Decal	20
17	Ground Separation	22
18	Example Hatched Ground Fill.....	22

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1 Introduction

Texas Instruments provides three major pieces of collateral for developing capacitive touch solutions:

1. This document, the *Capacitive Touch Hardware Design Guide*
2. Capacitive Touch Software Library ([CAPSENSELIBRARY](#))
3. Tuning guides:
Capacitive Touch Sensing, MSP430™ Button Gate Time Optimization and Tuning Guide ([SLAA574](#))
Capacitive Touch Sensing, MSP430™ Slider and Wheel Tuning Guide ([SLAA575](#))

Good sensor design is the foundation for a successful touch product. The purpose of this design guide is to provide guidance for the design and layout of capacitive touch sensors so that they can achieve maximum performance. By achieving maximum performance in the hardware, the capacitive touch software library can perform the capacitive touch measurements with the lowest power consumption. After the software library is implemented for the application, the tuning guides can be used to tune the performance of the capacitive touch application.

[Section 2](#) provides an overview of capacitive touch detection and describes its terms, concepts, and theory of operation. [Section 3](#) and following are organized like a product design—from schematic to mechanicals to layout. The schematic and mechanicals are treated as design requirements that influence the PCB layout. This guide first describes requirements that might be found in the schematic and mechanical requirements of the product. These requirements have an effect on the layout and must be considered first. After the requirements of the product are understood, then the PCB layout can begin.

2 Overview of Capacitive Touch Sensing

This overview is broken into two main parts. The first part is the theory of capacitive touch detection. In [Section 2.1](#), some basic terms are defined and discussed to give a basis for the description of capacitive touch detection provided in the equivalent circuit. The second portion of the overview in [Section 2.2](#) introduces figures of merit used in capacitive touch detection. These parameters are used to evaluate the performance and are referred to frequently in the document as the goal or reason for certain design rules.

2.1 Theory of Capacitive Touch Sensing

[Figure 2](#) shows an equivalent circuit that provides a basis for understanding how the different aspects of the design contribute to the overall performance. Before discussing the equivalent circuit, some basic terms are introduced: electrode, traces, and capacitance.

2.1.1 Terms: Electrodes, Traces, Capacitance

An *electrode* is the physical conductive structure that a person interacts with. This structure is typically thought of as the copper on a printed circuit board (PCB), but can also be made of transparent materials such as indium tin oxide (ITO) or other conductive materials like silver.

As shown in [Figure 1](#), the electrode shape can be very simple (for buttons) or very complex (for inter-digitation). The electrode does not necessarily need to be planar. One of the benefits of capacitive touch detection is that it allows an application to use buttons, wheels, or sliders that conform to the shape of irregular surfaces.

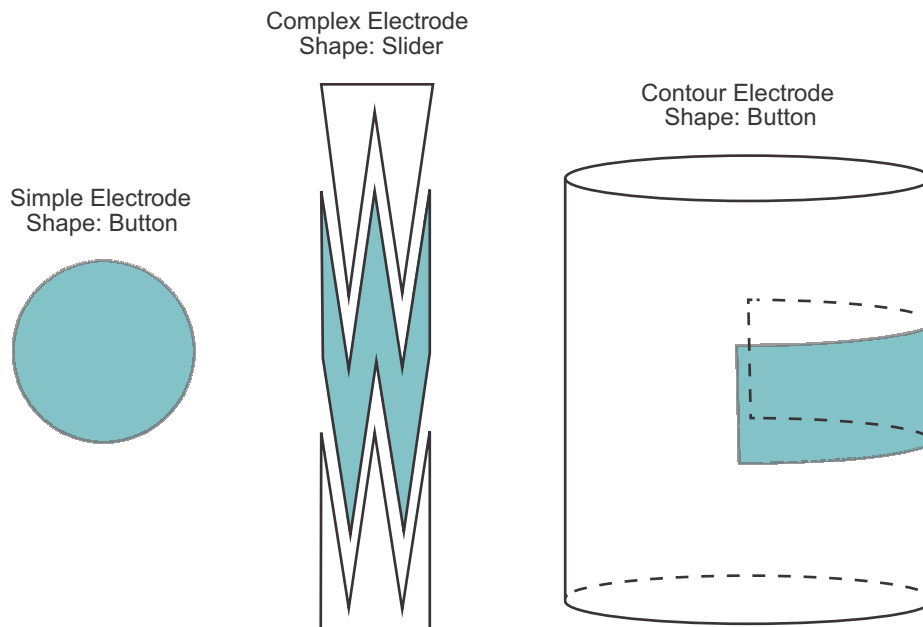


Figure 1. Sample Electrode Shapes

A *trace* is the conductive connection between the MSP430™ microcontroller and the electrode. Similar to the electrode, the trace is typically a copper trace on a PCB, but it could also be made of materials like ITO and silver. Connectors and cables between the microcontroller and electrode also affect performance and are described along with trace routing in [Section 5](#).

Capacitance is the ability of the electrode to store an electrical charge. In the context of capacitive touch detection, there are two common categories of capacitance: mutual capacitance and self capacitance. As the names imply, self capacitance refers to the capacitance of one electrode, while mutual capacitance refers to the capacitance between two electrodes. Self capacitance is the topic of this document, and the concepts described here pertain primarily to self-capacitance solutions.

An important concept within capacitive touch detection is baseline capacitance. This represents the steady-state no-interaction capacitance seen by the microcontroller. The baseline capacitance is the sum of the parasitic capacitances, which include the electrode, trace, and parasitic capacitances associated with the MSP430 pins, solder pads, and any discrete components associated with the circuit ⁽¹⁾. The baseline capacitance is important because sensitivity is a function of the relative change in capacitance. If the baseline capacitance is too large, then any change in capacitance caused by a touch or proximity event is very small and might not be distinguishable from the baseline.

2.1.2 Equivalent Circuit

When describing the various capacitances found in a capacitive touch solution, an equivalent circuit model can be helpful in visualizing the source of the different capacitances as well as the effect of each capacitance. [Figure 2](#) is an example of an equivalent circuit for a single self-capacitance button.

⁽¹⁾ For example, ESD current-limiting resistors.

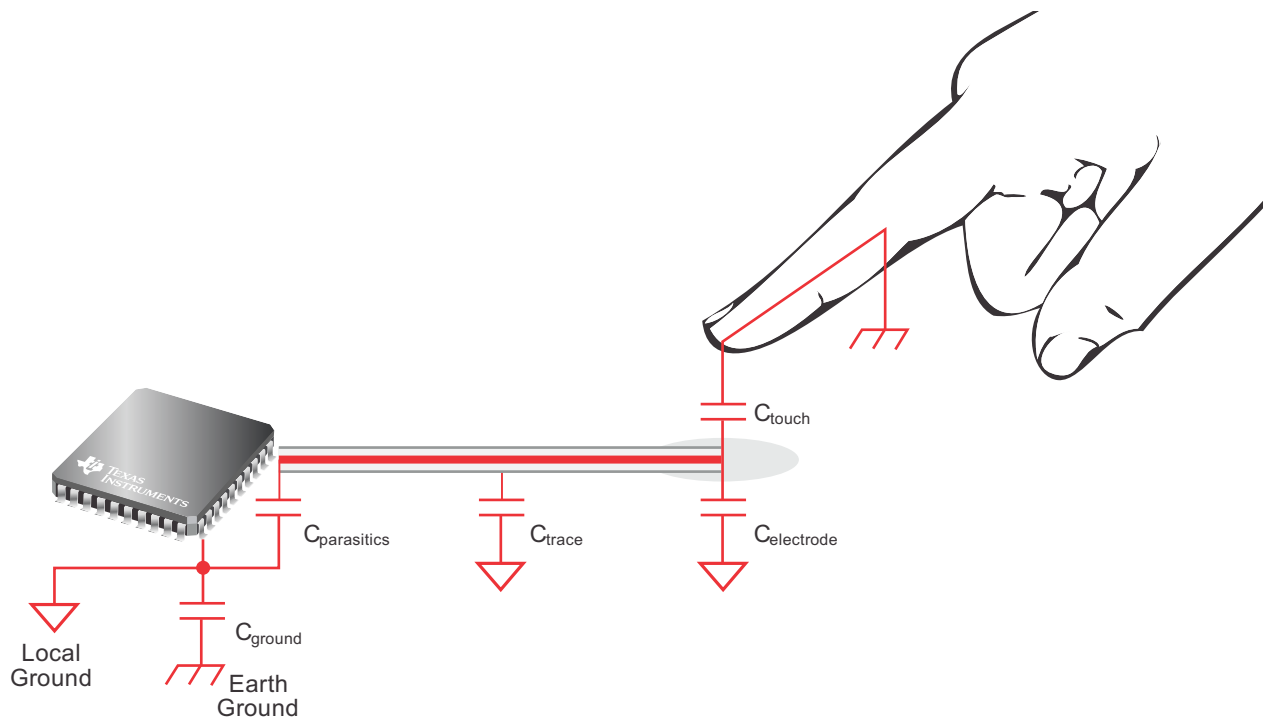


Figure 2. Equivalent Circuit

Five different capacitances are shown in [Figure 2](#). C_{ground} is the capacitance between the local device under test (DUT) ground and earth ground. In some applications, local and earth ground are connected when the DUT uses mains power, but typically the local ground is capacitive coupled back to earth ground.

C_{trace} and $C_{\text{electrode}}$ is the capacitance between the trace and electrode structures back to the local ground. This capacitance is most directly affected by surrounding structures, typically ground pours, that are either on the same layer or on adjacent layers. Not shown is the capacitance between the trace and electrode structures and earth ground. These capacitances are not without merit; however, for simplicity and in the context of this document, the design guidelines are given with the principle of affecting the local capacitance (that is, separation between local ground and the traces and electrodes). The capacitance $C_{\text{parasitics}}$ is a combination of the internal parasitic capacitance of the microcontroller and any components within the circuit. This capacitance is also referenced to local ground. The touch capacitance, C_{touch} , is the parallel plate capacitance formed between the touch interaction and the electrode. In the example of a touch, as the finger presses against the overlay, the flattened surface of the finger forms the upper plate and the electrode forms the lower plate. The capacitance is a function of the area of the two plates, the distance between them, and the dielectric of the material that separates them.

[Section 3](#), [Section 4](#), and [Section 5](#) describe how the physical attributes of a design affect the capacitances found in the equivalent circuit. The goal is to address these capacitances with layout and mechanical design guidelines and maximize the performance. [Section 2.2](#) addresses performance parameters associated with signal and noise.

2.2 Signal and Noise

Capacitive touch detection is a type of analog-to-digital converter (ADC), specifically a capacitance-to-digital converter. As with most ADCs, the terms of interest are resolution, signal-to-noise ratio (SNR), and linearity, in the specific cases of wheels and sliders. Throughout this document, the design guidance helps to maximize signal, minimize noise, and address when these two goals are at odds.

2.2.1 Signal

As mentioned in [Section 2.1.1](#), the basis of capacitive touch detection is the ability to measure a change in capacitance. This change in capacitance is the signal that the capacitive touch solution identifies. The term sensitivity is often used to describe the signal strength—a more sensitive solution has a stronger signal.

Sensitivity is measured in capacitance per counts. In the context of capacitive touch detection, the magnitude of change introduced by a touch is on the order of picofarads or hundreds of femtofarads. It is not uncommon for a solution to see a touch introduce 1 pF of change and be measured as 300 counts. And while the sensitivity might be 3.3 fF/count, this should not be considered until the noise is factored in (see [Section 2.2.2](#)).

Sensitivity can be controlled within firmware, but the goal is to provide good sensitivity with the hardware, so that the lowest sensitivity settings can be used in firmware, which provides the lowest-power solution. Referring to the equivalent circuit in [Figure 2](#), C_{touch} must be maximized, while the other four capacitances must be minimized. The capacitances of the trace and electrode are approximated as parallel plate capacitances. [Equation 1](#) serves as the basis for layout recommendations.

$$C = \epsilon_r \times \epsilon_0 \times A/d \quad (1)$$

The dielectric constant (ϵ_r), area (A), and distance (d) are described throughout this document with the intent of positively influencing the capacitance for a touch system.

2.2.1.1 Parasitic Capacitance

Although parasitic capacitance is presented separately, it is a part of the sensitivity and signal. As already mentioned, the capacitance of interest is the relative change in capacitance. The change in capacitance is based upon the touch interaction, but this change is perceived relative to the parasitic capacitance of the system. The parasitic capacitance is also called the steady-state capacitance or baseline capacitance. If the introduced change is 100 fF, then the sensitivity, which is the relative change in capacitance, can be increased by decreasing the parasitic capacitance.

The capacitances C_{trace} , $C_{\text{electrode}}$, and $C_{\text{parasitics}}$ are generically referred to as parasitic capacitance.

2.2.1.2 Resolution

The term resolution can be used in several different contexts in capacitive touch detection. In the broadest sense, resolution is sensitivity and defined in terms of capacitance. A measurement system may be designed to resolve changes in capacitance in 0.1-pF steps and, therefore, the resolution is 0.1 pF.

In applications, the term resolution can refer to distance for wheels, sliders, and proximity. In these applications, the goal is to resolve changes in distance along a slider or above a proximity electrode. The capacitance is inversely proportional to the distance but, in the context of sliders, wheels, and proximity sensors, resolution is more clearly expressed in terms of distance than capacitance.

Resolution is directly limited by sensitivity. The hardware design must provide the maximum amount of sensitivity, and any additional sensitivity that is needed to support the required resolution must be gained in firmware (typically at the cost of higher power consumption).

2.2.1.3 Linearity

The term linearity is often used to describe the performance of capacitive touch wheels and sliders. Similar to the linearity performance of ADC or digital to analog converter (DAC), the linearity is how well the reported position matches with the actual position. A wheel or slider can have poor linearity which are flat or 'dead spots' or missing codes, because of the design and shape of the electrodes. [Section 5.2.1.3](#) provides some good and poor examples of linearity.

Linearity is related to sensitivity. By increasing sensitivity, the flat or dead spots can be reduced or eliminated, but this is typically done in conjunction with shaping of the electrodes.

2.2.1.4 Range

Range applies to proximity sensors. The range or distance is directly proportional to the sensitivity. The more sensitive the hardware design, the greater the distance or range can be achieved with a proximity sensor.

2.2.2 Noise

The signal is the change in capacitance that results in a meaningful change in counts. Noise, on the other hand, is any disturbance that does not change the capacitance but does change the counts. Most often these disturbances are the result of power supply switching noise, electrostatic discharge (ESD), electrically fast transients (EFTs), radiated noise, or some other type of electrical noise that couples into the system.

A general aggressor-victim approach is taken to address noise. Obviously, the capacitive touch circuit is the victim, but what is not so obvious are the media through which the noise travels from the aggressor to the victim. Common media are the V_{CC} rail, the V_{SS} rail, and the capacitive coupling between traces (crosstalk). Typically, the aggressor is anything within the same operating (frequency) band as the capacitive touch circuit. These should be avoided when possible. If an aggressor at the same frequency cannot be avoided, the medium between the aggressor and victim should be addressed. This is done by maximizing the distance between the aggressor and victim, which is a common theme in [Section 5.1.2](#).

2.2.3 Signal-to-Noise Ratio (SNR)

The SNR is a system-level specification and needs to be tested at the system level. Good layout alone is not adequate but is part of the overall design to achieve an acceptable SNR. The main idea in providing good sensitivity is to maximize the capacitance associated with a touch and minimize the parasitic capacitance. The noise must be mitigated and reduced with good design practices for noise immunity (from, for example, ESD, RF, or EMC).

In achieving an acceptable level of SNR, the competing requirements for noise and signal must be addressed. The most common example of competing requirements is seen with guard channels or guard rings. These structures help reduce susceptibility to radiated emissions, and the closer these structures are to the circuit being protected, the more effective they are. However, moving these structures closer to the capacitive touch circuit has an unwanted effect of increasing the parasitic capacitance and consequently lowering the sensitivity.

In addition to managing the competing goals of sensitivity and noise immunity, these goals need to be managed within the overall requirements of the end product. This can mean trying to achieve a solution in a limited space, under a large aesthetic housing, or in the presence of other electrical activity (noise). [Section 3](#), [Section 4](#), and [Section 5](#) describe the development process of the schematic, mechanicals, and PCB layout, respectively, to identify how the PCB layout can be modified to support different requirements for touch products.

3 Schematic

At the schematic stage of development, the two key elements are noise and parasitic capacitances associated with components.

3.1 Components

External components are not ideal with capacitive touch solutions because of the additional parasitic capacitance associated with any component. Therefore, components selected to be part of the capacitive touch circuit should have the smallest footprint area possible. Capacitance is directly proportional to area, so any reduction in footprint reduces capacitance. Typically, these external components are related to ESD protection such as current-limiting resistors placed between the MSP430 microcontroller and the electrode. The concept of minimizing footprint also applies to connectors or any other component in the capacitive touch circuit.

Ideally, any component would have a very low drift factor with temperature and time. While this is not a necessity, because the software has drift compensation, it is preferred to keep the touch circuit and all associated components as stable as possible over time and temperature.

3.2 ESD Protection

ESD protection should be designed with consideration of the laminate material that acts as a barrier between potential ESD strikes and the PCB ⁽²⁾. Relying on the high-dielectric breakdown voltage of the overlay is preferred to adding ESD components to the touch solution, because these components add parasitic capacitance to the circuit and reduce sensitivity.

If additional ESD protection is required, small current-limiting resistors and low-capacitance clamps are recommended.

3.3 Power

The drift compensation found within the capacitive touch software library accounts for drift in V_{CC} over time (this drift may be associated with battery decay in portable applications). More spurious shifts in V_{CC} , such as those associated with noise spikes or ripple, can affect the measurement and even the drift compensation if the noise lasts for a long period of time.

The most common method of reducing power supply noise is the use of filters. A PI filter is typically the filter of choice. An LDO can also be used to reduce power supply noise.

4 Mechanicals

The mechanicals are the mechanical characteristics of the design. The mechanicals include the overlay material, ink on top of the overlay, any adhesives used to bond the electrode to the overlay or enclosure, and any transition materials used to remove air gaps between the electrode and the overlay. Mechanicals also include the types of materials used for the electrodes. The mechanicals affect both the signal and the parasitic capacitance.

The goal of this section is threefold:

1. To understand the benefits in terms of both aesthetics and robustness
2. To understand how the materials on top of the electrode and the electrode material itself influence the layout of the electrodes
3. To avoid mistakes in the mechanicals that are detrimental to the electrical performance

4.1 Typical Stackup

Figure 3 shows a typical stackup for a capacitive touch solution. One of the main goals of this stackup is to reduce (or eliminate, if possible) any low-dielectric (air) gaps between the electrode and the area where the touch takes place. The capacitance associated with the stackup has a very strong effect on the signal (change in capacitance from a touch). The signal is directly proportional to the dielectric of the materials. If possible, high-dielectric materials should be used, but at a minimum the stackup should eliminate any air gaps ⁽³⁾.

⁽²⁾ Charge can spread over the laminate and find an entry point. Be aware of events that go around the barrier instead of through it.

⁽³⁾ Air gaps can also contain moisture, which can influence performance or even damage the stackup as temperatures vary and the contents of the gap expand and contract.

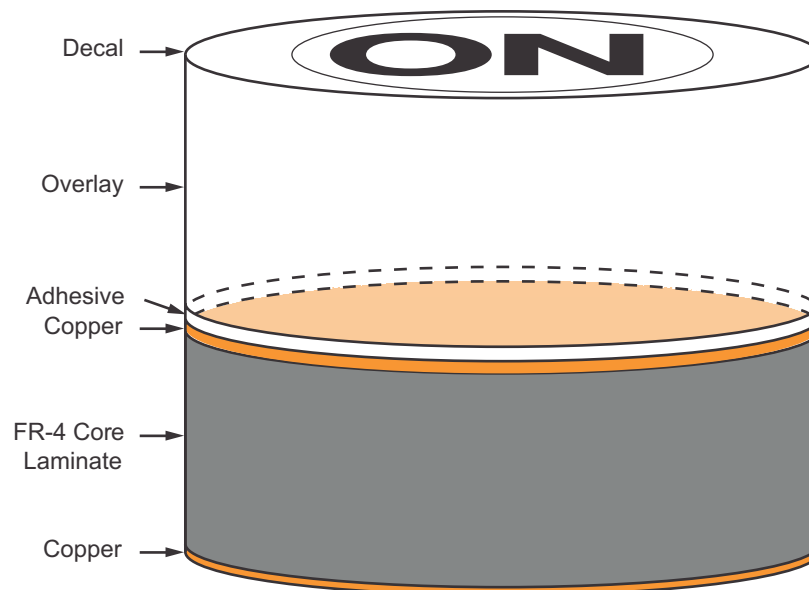


Figure 3. Typical Material Stackup

Another critical attribute of the stackup is that it should be nonconductive. This is not usually a problem with the overlay material but can be overlooked when choosing adhesives, labels, or inks. Popular adhesives for capacitive touch solutions include 200MP products from 3M™ such as 467MP and 468MP.

4.1.1 Overlay

The capacitance of the stackup is a superposition of all of the material, but the overlay is often the dominant material. The type and dimension of the overlay material that is used is determined by the desired aesthetic and from the required amount of protection. A common requirement is rugged (scratch or puncture resistant) and yet lightweight.

[Figure 4](#) (also see [reference \[4\]](#)) shows the relationship between the thickness of the overlay and the sensitivity of the circuit. From the parallel plate capacitance equation, the capacitance is inversely proportional to the material thickness ($C \approx 1/d$).

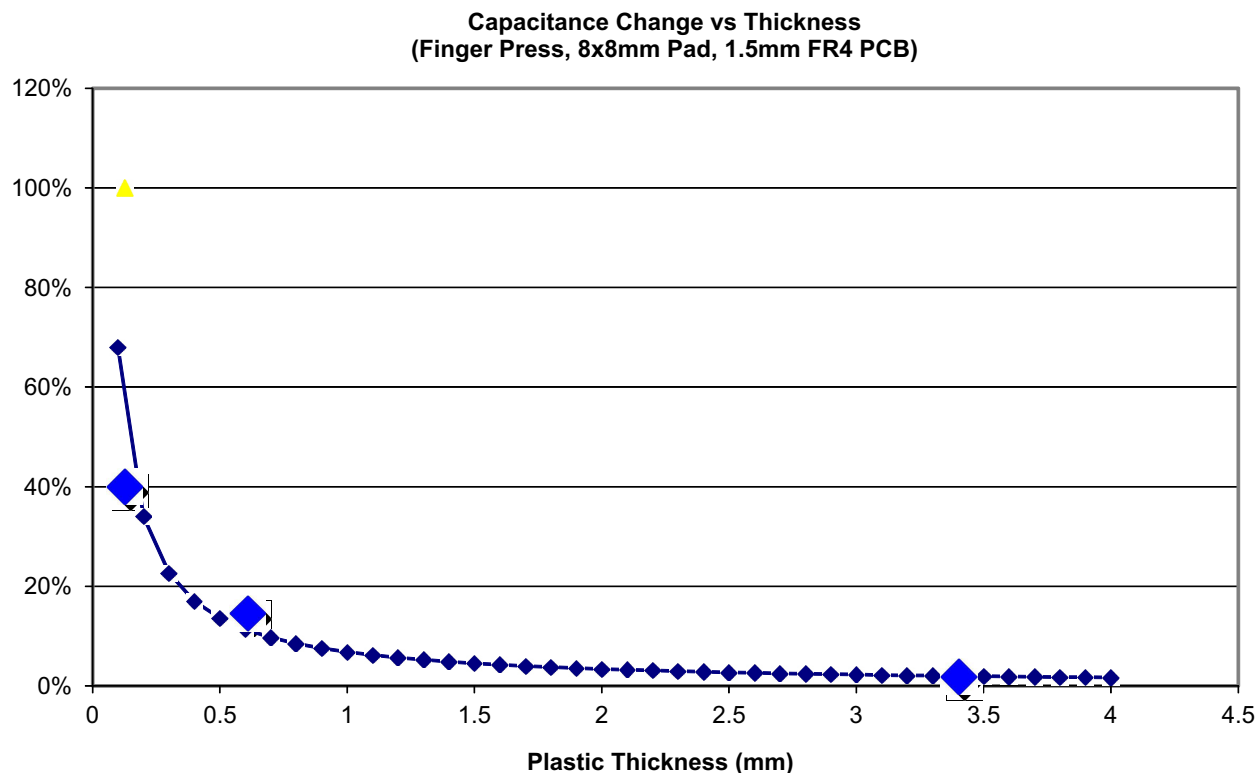


Figure 4. Sensitivity vs Thickness

The thickness and dielectric of the material influence the electrode design. The electrode area is a function of the area of interaction (a fingertip or the palm of the hand) while the spacing (to adjacent electrodes or ground fill) is related to the thickness of the overlay. For example, with a 2-mm overlay that has a dielectric of 3, the spacing should be approximately 1 mm (half of the thickness). Using a higher dielectric material (for example, $\epsilon_r = 6$) the thickness could be doubled while maintaining the same level of performance. Table 1 shows dielectric values for various materials used as overlays.

Table 1. Material Dielectric and Breakdown Voltage

Material	Dielectric Constant ⁽¹⁾ (ϵ_r)	Breakdown Voltage (V/mm)
Air	1.0	3300 (STP)
FR-4	4.8	20000
Glass	7.6 to 8.0	7900
Gorilla® Glass	7.2 to 7.6	See Manufacturer ⁽²⁾
Polycarbonate	2.9 to 3.0	16000
Acrylic	2.8	13000
ABS	2.4 to 4.1	16000

⁽¹⁾ Relative permittivity

⁽²⁾ <http://www.corninggorillaglass.com>

[Table 1](#) also includes the breakdown voltage for different overlay materials. This should be considered when designed for ESD protection. ESD solutions should be system solutions, and any additional components should complement the protection provided by the overlay.

4.1.2 Electrode and Trace Materials

The performance is affected by the conductive materials that are used for the electrode and for the trace between the electrode and the microcontroller. Most applications use copper on a PCB, and copper has a resistivity of 1.7×10^{-6} Ohm-cm ⁽³⁾. As the resistivity of the conductor increases, the ability to move charge to and from the electrode decreases. This has the same effect as an increase in parasitic capacitance. This increase in resistivity, like an increase in parasitic capacitance, reduces the system sensitivity. [Table 2](#) shows the resistivity for materials that are commonly used in touch applications.

⁽³⁾ Resistivity is given in Ohm-cm so that resistance is equal to the resistivity times the length divided by the cross-sectional area :
 $R = \rho \times L / A$.

Table 2. Resistivity of Materials

Material	Resistivity, ρ (Ohm-cm)
Copper	1.68×10^{-6}
Silver	1.59×10^{-6}
Tin	1.09×10^{-5}
Indium Tin Oxide	1.05×10^{-3} ⁽¹⁾

⁽¹⁾ This resistivity is for a film thickness of 270 nm. Typically, vendors provide sheet resistance instead of resistivity for ITO, which is on the order of 10 to 100 Ohms per square.

Use of high-resistivity materials is addressed in [Section 5](#), but generally the recommendation is to increase the area of traces to reduce the resistance (at the cost of capacitance). ITO solutions provide lower sensitivity, which must be compensated for in the capacitance measurement algorithm by longer measurement times.

4.2 Other Situations

Not all applications fit into the typical category, and this section describes two special cases. The first is intentional air gaps that are greater than 2 mm between the electrode and the overlay material, and the second is the use of gloves.

4.2.1 Gaps

In some applications, components are on the same layer as the electrode. This prevents the overlay from being directly applied to the electrode. A common example of this is when an LCD is mounted near the electrode (see [Figure 5](#)). Another scenario is when the overlay material is not a uniform surface and, therefore, the electrode cannot make direct contact with the overlay.

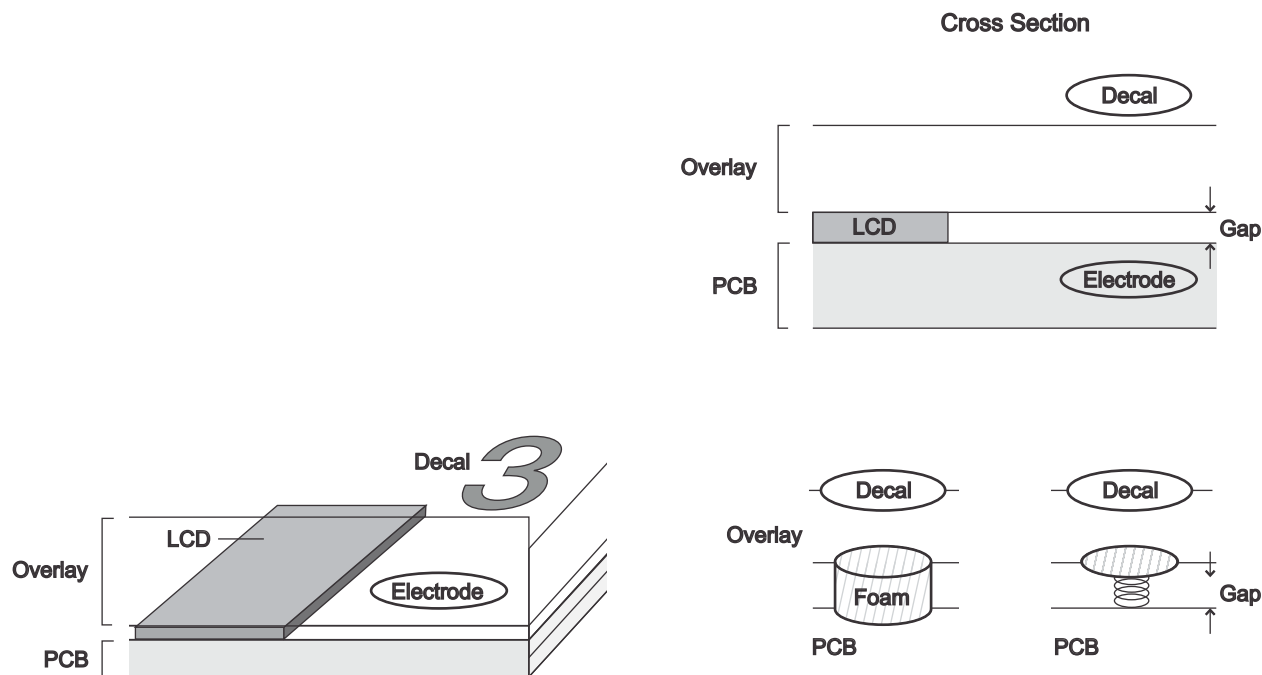


Figure 5. Intentional Gaps Between Electrode and Overlay

In either case, the gap must be filled or bridged with a nonconductive filler (typically adhesive) or a conductive extension. When the gap is in excess of 2 mm, then a conductive extension, either foam or metal, should be used. The metal or foam must be malleable to conform to the shape of the surfaces and prevent the formation of gaps. As shown in [Figure 5](#), the area created by the foam or metal in contact with the overlay is now the area that influences the capacitance.

4.2.2 Gloves

Gloves are simply another layer of medium between the electrode and the finger, and the same principles of thickness and dielectric apply. The challenges with glove applications include the ability to support both gloved and ungloved hands as well as the variation in the types of gloves the application might require. Typical leather or plastic gloves have a dielectric constant in the range of 2 to 4, and fabric gloves and gloves with insulation can have a dielectric constant less than 2.

5 Layout

After the mechanicals are understood, the electrodes can be sized and designed to provide the most signal. Independent of the mechanicals, the layout design is affected by the distance between the microcontroller and the electrodes, the PCB stackup (for example, one layer, two layer, or four layer), and other electrical circuits on the PCB.

The first item to consider relates to the schematic and the placement of any external components that are associated with the capacitive touch solution. This is typically found with the comparator solutions, and the resistor is part of the feedback path that creates the oscillator. Other examples are of ESD protection components. In all cases, the components should be kept as close as possible to the microcontroller. As the components move farther away from the microcontroller, the increased area correlates to an increased risk of noise or ESD conducting into the device.

5.1 Routing

The parasitic capacitance of the trace comprises several major and minor capacitance contributors. For simplicity, C_{trace} represents the major capacitances formed between the trace line and the ground pour on the bottom side and surrounding it. The top and cross-sectional views of a typical two layer PCB are shown in Figure 6. The capacitance, C_{trace} , is determined by the trace line width (W), dielectric thickness (H), trace thickness (T), and the relative permittivity of the PCB material (ϵ_r).

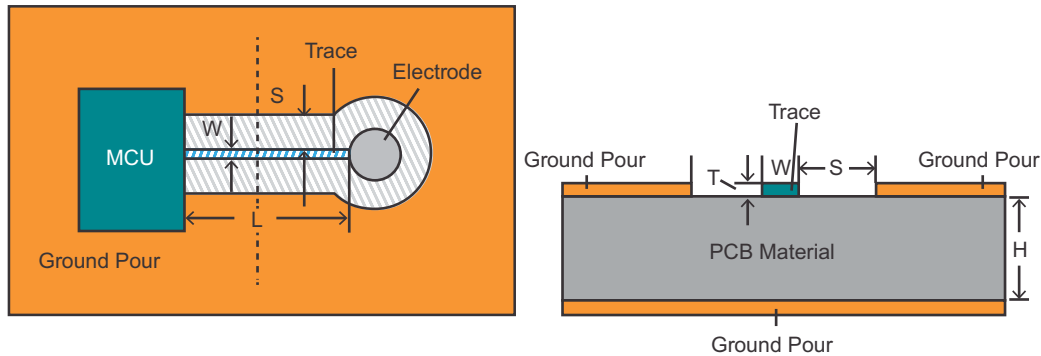


Figure 6. Top and Cross-Sectional Views of Trace Line in PCB

The capacitance per unit length of the trace is an important concept to emphasize the need for short traces. Increasing the distance of the trace increases the parasitic capacitance associated with the trace. Increasing the trace length can also increase susceptibility to noise. Therefore, the trace routing between the microcontroller and the electrode should be kept as short as possible. This is not always possible, so it is important to understand the increase in parasitic capacitance associated with the trace routing.

5.1.1 Capacitance per Unit Length

The capacitance per unit length should be kept as small as possible to minimize the parasitic capacitance (C_{trace}) and ultimately maximize sensitivity. As previously mentioned, the dominant capacitance in C_{trace} is the parallel plate capacitance between the trace and the surrounding ground pour. The ability to reduce this capacitance is a direct function of the PCB manufacturing capabilities. Tighter tolerances and smaller minimum dimensions (trace width and separation) allow for thinner traces and larger separation, which result in lower capacitance per unit length. These manufacturing capabilities typically come at a higher cost.

Table 3 shows how the capacitance per unit length changes with the variation of different dimensions. (These are taken from Reference 4 in the *Coplanar Waveguide Analysis/Synthesis Calculator*.)

Table 3. Calculating Results of Capacitance per Unit Length

W (mm)	S (mm)	T (mm)	H (mm)	ϵ_r	C (pF/cm)
0.152	0.152	0.036	1.6	4.6	0.633
0.152	0.254	0.036	1.6	4.6	0.555
0.152	0.381	0.036	1.6	4.6	0.496
0.203	0.152	0.036	1.6	4.6	0.692
0.203	0.254	0.036	1.6	4.6	0.602
0.203	0.381	0.036	1.6	4.6	0.543
0.254	0.152	0.036	1.6	4.6	0.74
0.254	0.254	0.036	1.6	4.6	0.641
0.254	0.381	0.036	1.6	4.6	0.578
0.254	0.152	0.036	2.54	4.6	0.736
0.254	0.254	0.036	2.54	4.6	0.637
0.254	0.381	0.036	2.54	4.6	0.566

Table 3 shows that increasing the space, S , between the trace line and the ground is an effective way to reduce the parasitic capacitance. However, increasing the separation can have negative effects that need to be understood. One effect is simply increased board space. Increasing the dimensions can lead to larger PCBs and higher cost. Another effect is related to noise. The larger separation makes traces more sensitive to touch events (touching the trace instead of the electrode) and more susceptible to radiated emissions.

In practice, the designer should choose a balanced S value, and a value of $1/8$ of the overlay thickness is typically acceptable. Additionally, a hatched ground is commonly used instead of solid fill near the trace lines to reduce the area and consequently the parasitic capacitance (see Section 5.3.2).

Table 3 also shows that as H gets smaller, the parasitic capacitance increases, which results in a decrease in sensitivity. In most applications, a two-layer PCB is used, and a standard FR4 PCB with the thickness of 1 mm to 1.6 mm is recommended. If a multilayer board is used, it is recommended to keep the H as large as possible. With complex multilayer boards (more than six layers), it is important to recognize that the absence of copper in the internal layers can cause issues and the height, H , between the top layer and the bottom may be smaller than predicted.

Figure 7 shows an example of a four-layer PCB, which may be desired in applications with limited board space. To reduce parasitic capacitance, the ground pour is usually placed on the lowest layer underneath the trace to provide the largest H . If it is difficult to achieve the maximum height, then a narrower W , a larger S , or even a hatched ground fill (see Section 5.3.2) are alternatives to reducing the parasitic capacitance.

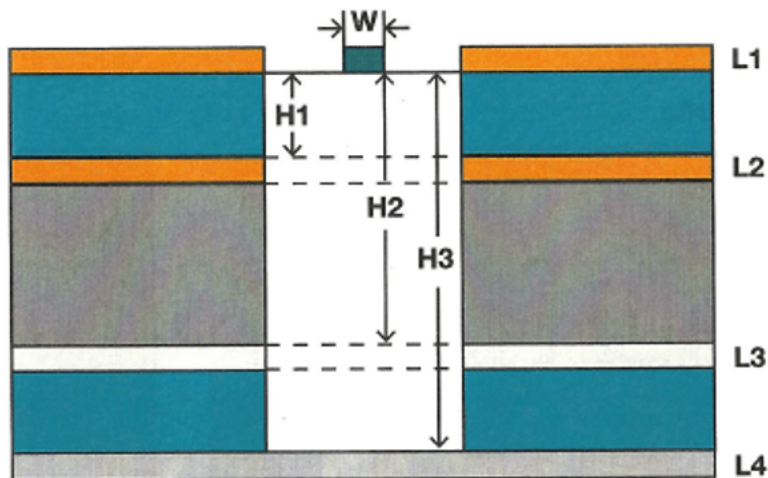


Figure 7. Trace Without Copper Pouring Underneath in Multilayer PCB

To determine the maximum trace length from the capacitance per unit length, some additional information is needed. The following example is used to calculate the maximum distance for a trace with a capacitance per unit length of 0.58 pF/cm . The capacitance introduced by a touch, C_{touch} , is assumed to be approximately 1 pF . To make sure that the capacitance induced by a finger is large relative to the parasitic capacitance, the total parasitic capacitance ($C_{\text{parasitics}}$, C_{trace} , and $C_{\text{electrode}}$) should be in the range of 10 pF to 20 pF (the change is at least a 5% change). Assuming that the $C_{\text{electrode}}$ is approximately 3 pF , the $C_{\text{parasitics}}$ is 5 pF , and the capacitance per unit length is 0.58 pF/cm , so the trace line length L should be no longer than 210 mm . If the electrode is larger (for a proximity application), the capacitance itself is larger (assume approximately 8 pF for this example), so the maximum trace line length L is reduced to 120 mm .

Generally speaking, the trace width W should be as thin as the PCB technology allows, because a short and narrow trace line is preferred. The trace thickness T and the relative permittivity of the material ϵ_r also have significant influence on capacitance per unit length, but they are determined by PCB manufacture process and are usually difficult to change.

5.1.2 Connectors

Some designs require the electrode to be off-board, and consequently a connector is used to transition the trace from the PCB to a cable or to another PCB. Connectors are generally not desired because like any component there is an associated parasitic capacitance with connector PCB footprint and structure.

In terms of parasitic capacitance and sensitivity, the connector is treated as a parasitic capacitance reducing the sensitivity of the solution. Because the connector is treated as a lumped capacitance, the placement is irrelevant to the sensitivity. However, the placement is important with respect to noise.

Figure 8 shows that if the aggressor (noise source, N1) is located on the PCB, then the preferred placement of the connector is near the MSP430 microcontroller. The parasitic capacitance associated with the connector shunts high-frequency noise ($Z \approx 1/j\omega C$) and increases the noise immunity of the circuit. Conversely, if the aggressor is located off-board (noise source, N2), then the connector should be placed farther from the microcontroller and closer to the electrode. This arrangement minimizes the off-board trace and cable length (which acts like an antenna). When multiple aggressors exist as is shown in Figure 8, it is recommended to reduce the effect of the radiators that most closely match the operating frequency of the touch detection circuit.

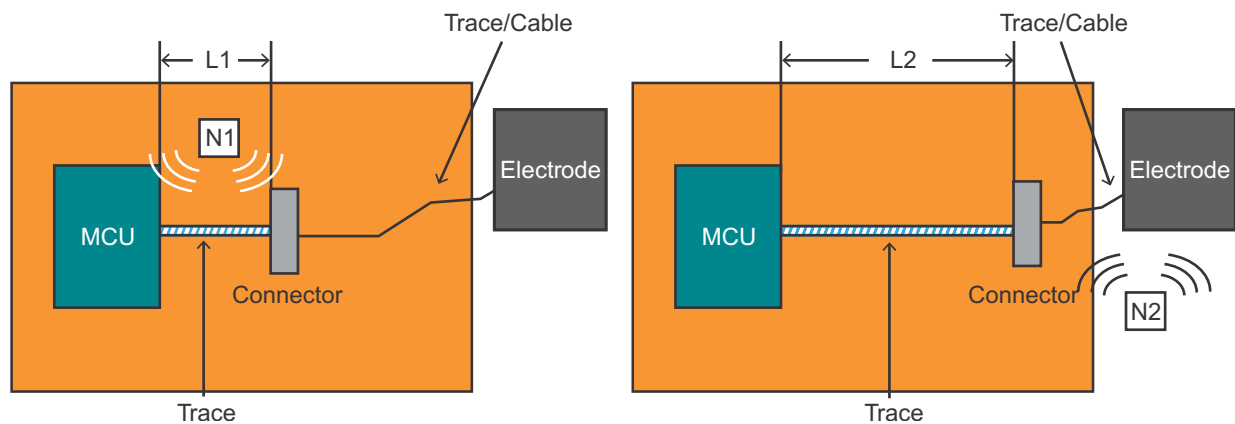


Figure 8. Top View of Connector and Noise Source

When deciding the position of the connector, the designer must balance the length of the trace and the cable while considering parameters like the background noise.

5.1.3 Routing Material

The routing is typically done with copper, but other materials like silver and ITO can be used. Silver is similar to copper and similar performance can be expected (if the thickness of the materials are also equivalent). ITO is very different from copper, and the difference in resistivity degrades the sensitivity of the solution. Lowering the impedance of the trace (by increasing the width) should be a high priority in the design, even though this comes at the cost of increased parasitic capacitance and reduced noise immunity. Ultimately, the use of materials like ITO requires more processing by the MSP430 microcontroller to adjust to lower sensitivity and increased noise.

5.1.4 Crosstalk

In Section 5.1.2, the aggressor is assumed to be a point source of noise. In this section, the aggressors are different signals that are routed in close proximity to the capacitive touch sensor trace. These aggressors can be another capacitance sensor trace or noncapacitance sensor lines. Examples of noncapacitance sensor lines include digital signals, analog signals, and high-current signals used to drive LEDs.

5.1.4.1 Other Capacitive Touch Traces

Capacitive sensor traces influence neighboring capacitive touch sensor traces. The space between capacitance sensor trace lines, S_{cs} , should be kept as a safe distance (see Figure 9).

The Capacitive Touch Software Library ([CAPSENSELIBRARY](#)) uses sequential scanning, and the recommended default state for all capacitive touch I/Os is output low. Using the library and the recommended default state allows traces to be treated similarly to ground pour, so that the same spacing recommendation applies, which is 1/8 of the laminate thickness.

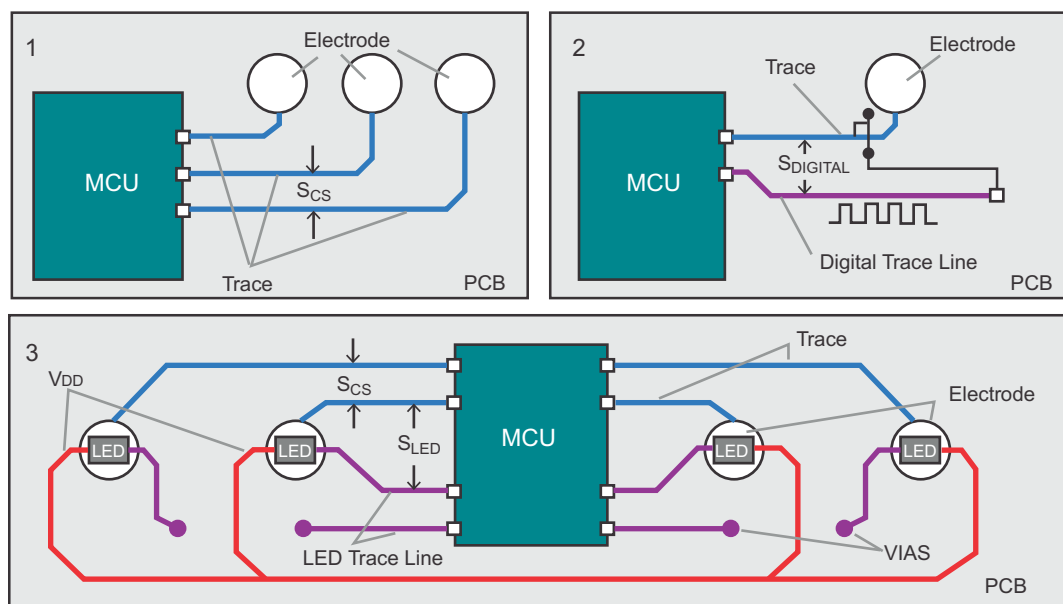


Figure 9. Top View of Different Traces

5.1.4.2 Digital Signals

Digital signals are typically PWM signals or communications like I2C or SPI. Unlike the capacitive traces described in [Section 5.1.4.1](#), these signals can act as aggressors and can be active during a capacitance measurement. It is recommended to keep these types of signals at least 4 mm away from the capacitive touch trace. If the digital signal and the capacitive touch trace must cross, then it is recommended to keep the crossing at a 90° angle.

5.1.4.3 LED Signals

Signals used to drive LEDs (unless the LEDs require high-strength drivers) are similar to other digital signals. Therefore, as with digital signals, a distance of at least 4 mm is strongly recommended for S_{LED} , as shown in [Figure 9](#).

As a general rule, LEDs should be driven and the use of high-impedance states should not be used to control the LED. The use of a high impedance to prevent an LED from conducting can result in a significant difference between the on-state and off-state capacitances. This change in capacitance may be detected by the touch solution and treated as a change in the system capacitance, or even worse as a false detection. If the use of high-impedance control of the LED is unavoidable, a discrete capacitor (typically 1 nF is acceptable) in parallel with the LED is recommended.

5.2 Electrode Design

The electrode design must accomplish two goals. First, the design must provide sufficient signal (change in capacitance with interaction). The design must project the e-field up and out so that the appropriate level of sensitivity is achieved at the desired distance. Understanding the stackup, thickness and dielectric, the electrode can be sized and shaped to provide the maximum signal. Second, the electrode design needs to have a minimal parasitic capacitance.

In the following sections the shape and area of the electrode are discussed with the intent of maximizing the signal for different implementations (buttons, sliders, and wheels). The basis for controlling the parasitic capacitance is common to different sensor implementations and is discussed here.

Figure 10 shows an example PCB cross-section and the important parameters that influence the parasitic capacitance. Similar to Figure 6, the height, width, and separation have a direct effect on the parasitic capacitance of the electrode, $C_{\text{electrode}}$. The fundamental parameter *area* is not shown in Figure 10, because this has a direct effect on both the touch capacitance (C_{touch}) and the parasitic capacitance ($C_{\text{electrode}}$). This section describes how changes to the height and separation can minimize the parasitic capacitance. The following sections describe how changes to the area can maximize C_{touch} .

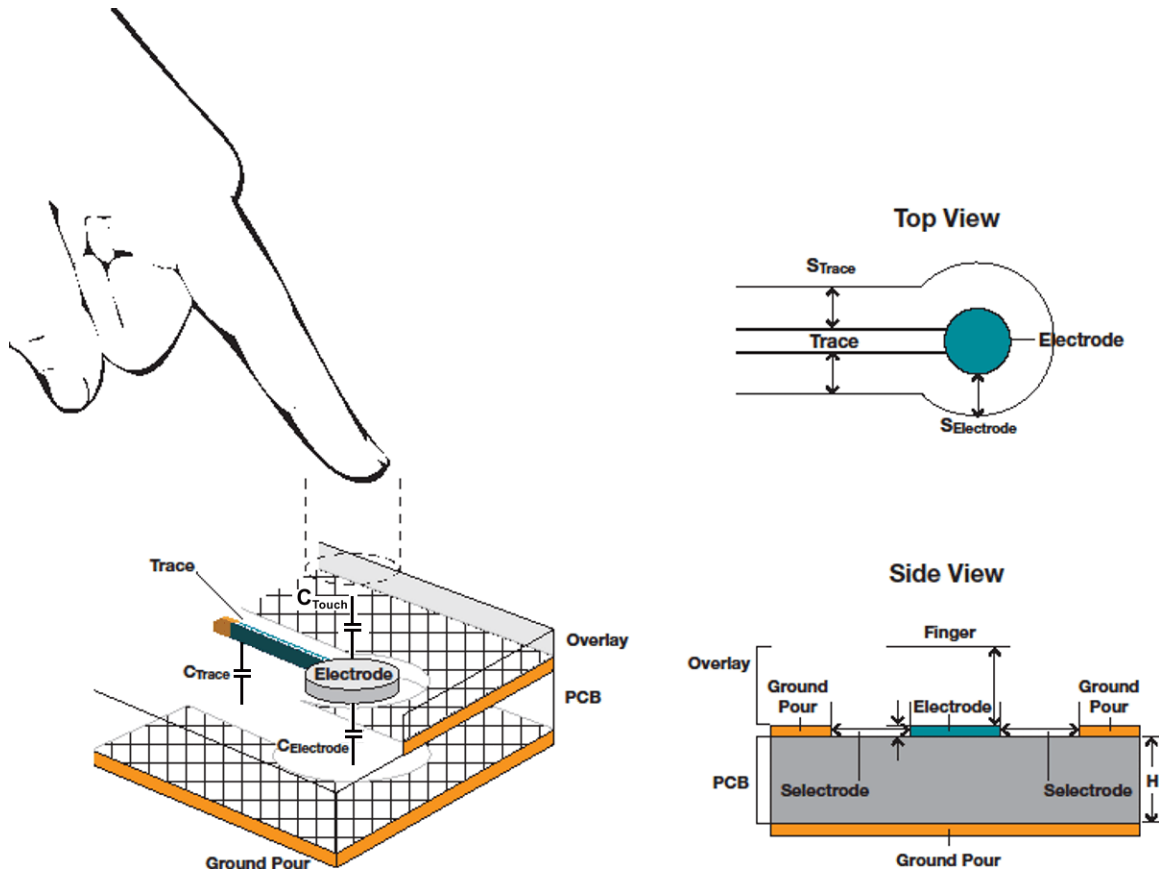


Figure 10. Capacitance of the Electrode

The separation ($S_{\text{Electrode}}$) is directly related to the height of the overlay as described in Section 4. The height is a function of the PCB and is not a parameter that can be easily controlled. The separation is typically the parameter with the most flexibility.

Table 4. Baseline Electrode Capacitance

Area (mm ²)	Height (mm)	Description	Separation (mm)	Capacitance (pF)
10x10, FR-4 ($\epsilon_r = 4.4$)	1.57	2 Layer PCB, L2	0.508	3.3
			1.02	3.2
			1.52	3.1
	1.30	4 Layer PCB, L2	0.508	3.8
	1.57	4 Layer PCB, L3	0.508	3.3

Table 4 shows that increasing the height (the distance between the electrode and the reference plane) decreases the capacitance. By decreasing the parasitic capacitance, the relative change in capacitance caused by a touch event is increased. For example, if the change in capacitance associated with a touch is 0.5 pF, the relative change is greater when the base capacitance is 11 pF instead of 12 pF, (5.5% instead of 4.2%).

5.2.1 Shape

The capacitance of the electrode is a function of area, but the shape is important to consider, because the shape can influence the area.

5.2.1.1 Buttons

For buttons, the electrode shape is typically round or rectangular. One common mistake is to make the electrode the same shape as the icons printed (in nonconductive ink) on the overlay. As shown in [Figure 11](#), this can lead to electrodes with odd shapes that create discontinuities and reduce surface area.

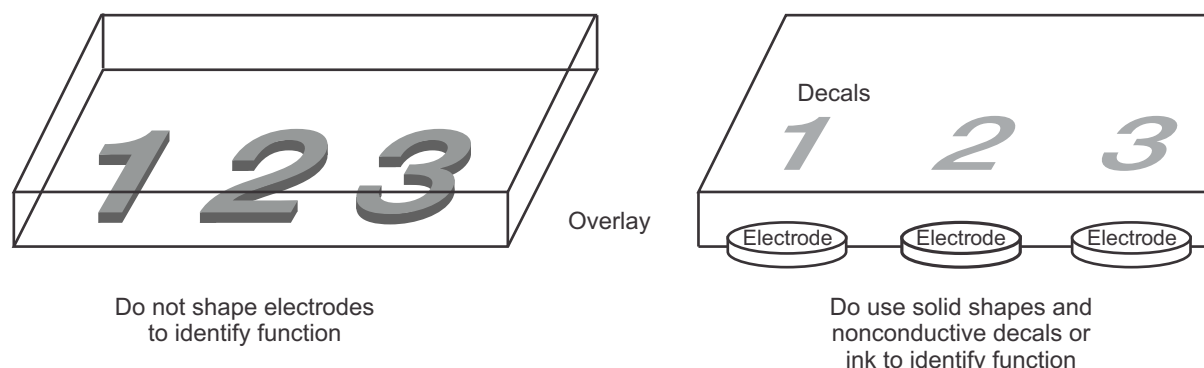


Figure 11. Button Shape Examples, Dos and Don'ts

5.2.1.2 Proximity

Proximity electrodes have a circular or square shape, the same as buttons. Proximity sensors require a higher degree of sensitivity than buttons, and this higher sensitivity is accomplished by increasing the area and the separation from other conductors.

5.2.1.3 Wheels and Sliders

The concept of a wheel is identical to a slider with the exception that the slider needs to be terminated at the ends. [Section 5.2.1.3.1](#) describes a wheel example, and [Section 5.2.1.3.2](#) describes the consideration for termination of a slider.

5.2.1.3.1 Wheels as an Example

The electrode shapes found in wheels are typically more elaborate than buttons to provide a desired number of points for a given number of electrodes over a given distance. In addition to these requirements, there are limitations imposed by the firmware implementation. The firmware expects the following to be true of the wheel:

- The minimum number of electrodes is three.
- At least two electrodes are being touched at one time. The firmware attempts to define the midpoint of each element and then uses the information from the neighbors to weight the position calculation. Ideally, in the center of an electrode the influence or 'weight' of each neighbor is equal and cancels out, which results in a calculated position that is at the center of the electrode. The exception to this is the endpoints of sliders (see [Section 5.2.1.3.2](#)).
- The coverage of the electrodes being touched should not exceed 100% of one electrode's area. Ideally the summation is always 100%. For example, if a finger is in the center between two electrodes, coverage is 50/50 on the two electrodes. As the finger moves in one direction, coverage of the two electrodes progresses through 40/60, 20/80, and so on to 0/100. As the finger moves in the other direction, coverage of the two electrodes progresses through 60/40, 80/20, and so on to 100/0.
- As a finger moves along the wheel, the coverage area on any one electrode is expected to increase linearly, reach a maximum, and then decrease linearly.

The firmware also has the following limitations and features which should be noted.

- The firmware uses integer math and, therefore, the number of points should be an even multiple (4, 6, 8, ...) of the number of electrodes.
- The '0' and 'numberOfElements' positions represent one-half of the resolution. For example, in [Figure 12](#), the position 64 is actually the other half of position 0. In this way, the number of positions is always 1 greater than the number of points.

[Figure 12](#) shows an example in which the electrode size is too large for the target finger size, so there are locations where the finger touches only one electrode. In this example, the wheel circumference is 64 mm, divided into 64 1-mm segments (63 1-mm segments and 2 0.5-mm segments) and spaced over four electrodes. The electrodes are square and 13-mm long, and the finger shape is elliptical and 10-mm long ⁽¹⁾. This example assumes that when the finger area overlaps with 1 mm of the electrode, enough information is available to determine the next position. Due to the size of the electrode, this results in a 'dead zone' of 11 mm in which not enough information is available to update the position. The reported position remains unchanged within this region. The reported position brings attention to the concept of linearity that is often used to describe traditional ADCs. In this example, the performance is nonlinear, because many positions (codes) are missed in the 'dead zone' and codes are skipped when the finger moves from the electrode centered on 24 to the electrode centered on 40.

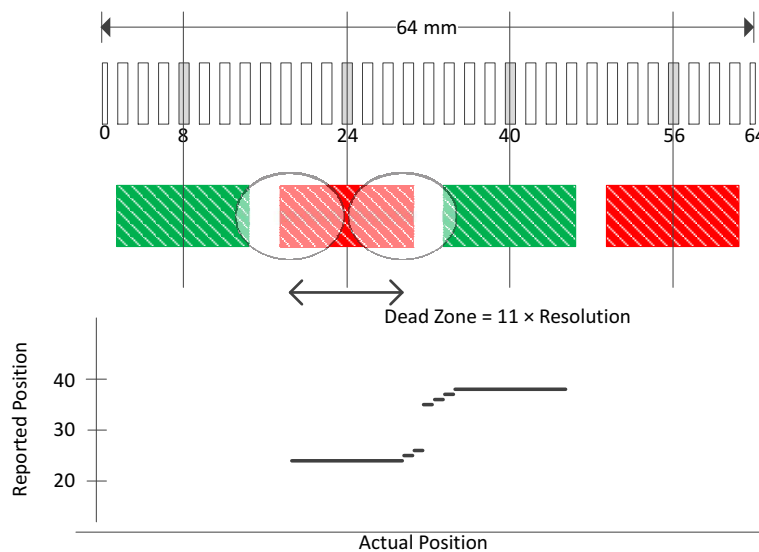


Figure 12. Incorrect Design of a Slider or Wheel for Desired Resolution

[Figure 13](#) has the same parameters as the slider in [Figure 12](#), but the electrode design has been changed so that the 'dead zone' is equivalent to the resolution of 1 mm. The electrodes are now 26-mm long, and this design overlaps the electrodes in three 10-mm long segments (11 to 21, 27 to 37, and 43 to 53). Because there is less area at the ends, the overlap between the finger area and the electrode must now be increased to provide enough information to adjust the position. It is important to note that this is a function of the sensitivity. Increasing the sensitivity by improving the layout per this section or by increasing the firmware performance, is typically needed in wheel applications to detect the smaller area.

⁽¹⁾ This discussion ignores the vertical size and considers only the horizontal position and dimensions.

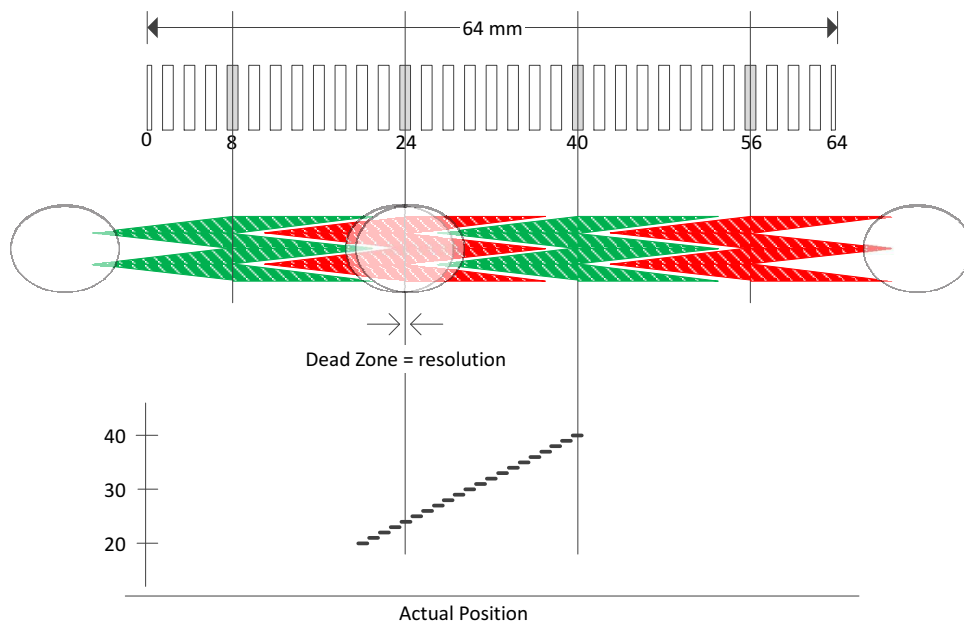


Figure 13. Designing Electrode Shapes to Support Desired Resolution

5.2.1.3.2 Slider Endpoints

The slider is a special case of the wheel in which the ends must be terminated. As shown in Figure 14, if the design is not adapted at the ends, then the position information exceeds the bounds of the design. The termination of the ends should create an equivalent area coverage that aligns with the intended ends of the slider.

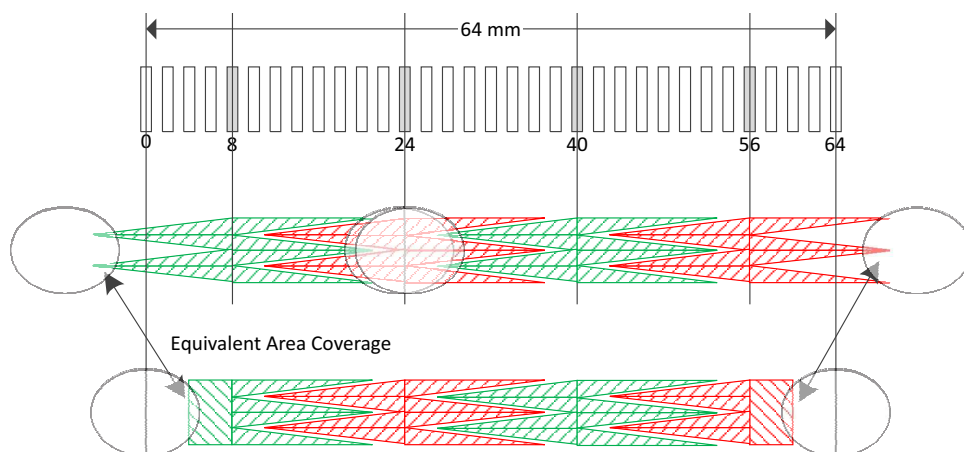


Figure 14. Ends of Sliders

5.2.2 Area

An important detail of designing the electrode shape is not to design shapes that have low surface area. The area of each electrode must provide the maximum C_{touch} , which in turn produces the most signal (the change in capacitance) when a touch event occurs.

5.2.2.1 Buttons

The goal of the button area is to provide sufficient signal when the user touches the overlay above the button electrode. Typically a nonconductive decal or ink is used to identify the touch area above the electrode. The relationship between the decal and the electrode can be varied so that contact with the outer edge of the decal registers a touch. Conversely, the electrode could be small to ensure that the button is activated only when the center of the decal is touched. Figure 15 and Figure 16 show how the effective touch area is a function of the electrode size and the size of the finger.

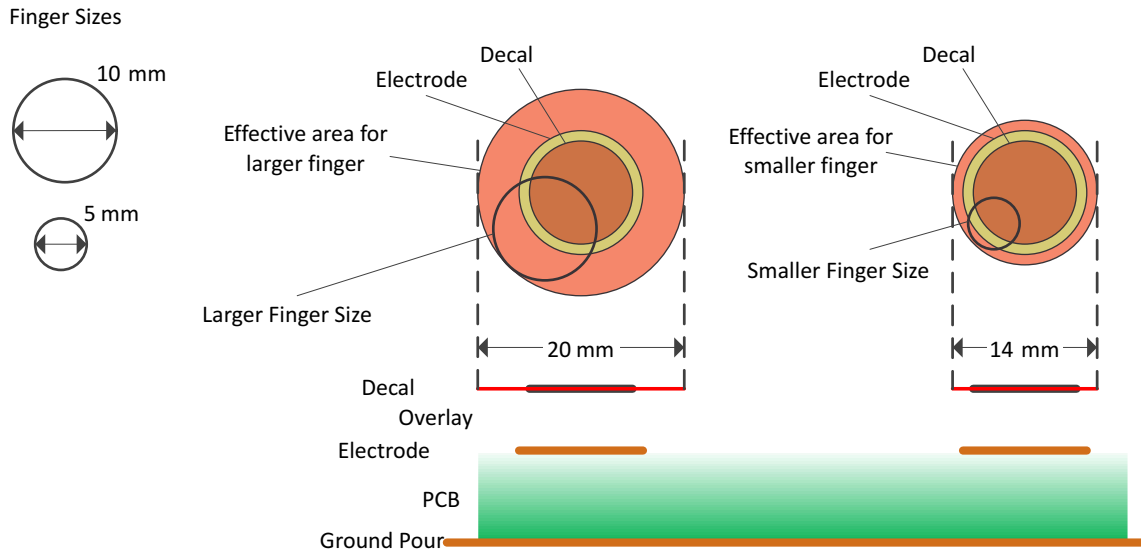


Figure 15. Effective Area Example for Electrodes Larger Than Decal

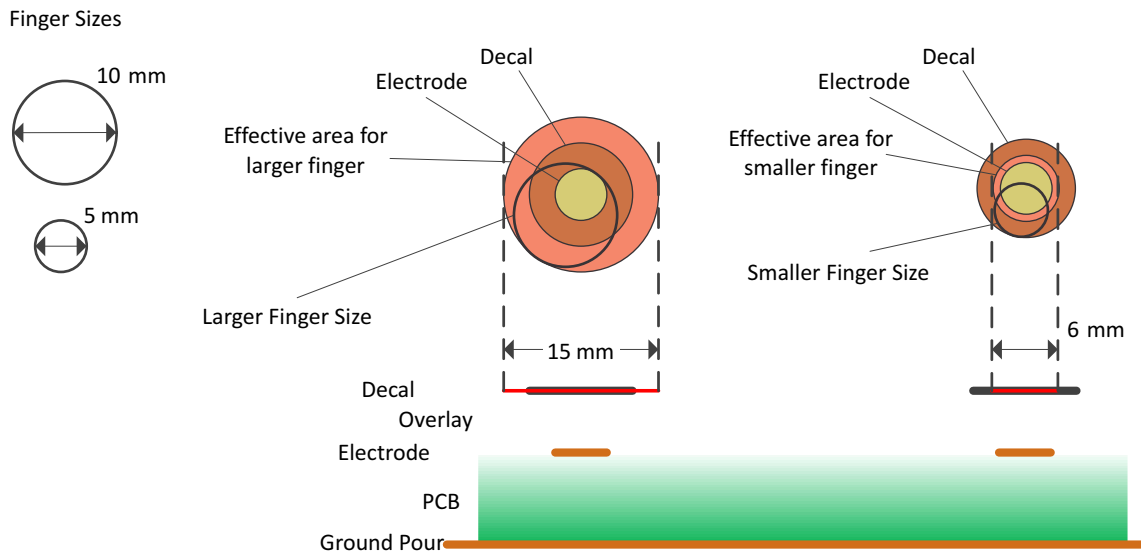


Figure 16. Effective Area Example for Electrode Smaller Than Decal

As the distance of the overlay increases, the effective area decreases. Therefore, it is important to keep the button electrode diameter at least three times the laminate thickness.

5.2.2.2 Proximity Sensors

Proximity sensors typically have a larger area in order to detect large surfaces (palm of the hand) at larger distances. In most applications the electrode size is limited by the end product dimensions. These applications depend heavily upon the measurement algorithm and longer measurement times to provide sufficient sensitivity. The longer measurement times translates into higher power consumption.

5.2.2.3 Sliders and Wheels

Sliders and wheels are different from buttons in that the interaction involves multiple electrodes. As shown in [Figure 13](#) the area of the electrode is not as critical as the percentage of coverage across multiple electrodes.

5.2.3 Electrode Material

As discussed in [Section 5.1](#), conductivity becomes an issue in more resistive materials like ITO. Although the transparency of ITO is very good, the resistivity is high when compared to materials like silver and copper. Typically the physical dimensions prohibit increasing the area of the ITO electrodes, and therefore any degradation in sensitivity must be compensated for in the firmware. This typically results in slightly longer measurement times and consequently increased power consumption.

5.2.4 Spacing Between Electrodes

As mentioned previously, one of the unique features of the capacitive touch software library, 1, is that the electrodes are scanned sequentially. This and following the recommendation to drive the signals to GND as the default state of the electrodes allows neighboring electrodes to be treated as an extension of the ground pour. Therefore, the spacing between the electrodes follows the same rules for spacing from ground. The goal is provide enough spacing so that the e-field propagates up and through the overlay material. A minimum spacing of one-half the laminate thickness has been found to provide sufficient signal (sensitivity).

5.3 Ground Planes

Surrounding ground planes affect the sensitivity of the electrode. This is seen primarily as an increase in base capacitance as the separation from the ground decreases and the area of the ground pour increases. This section looks at the placement of surrounding ground pours and the fill (percent hatch) of those pours.

Planes and pours near the electrode and trace must be connected to a potential and cannot be left floating or in a high impedance state. Such structures serve as a mechanism for noise coupling and are strongly discouraged.

5.3.1 Separation

Ground planes, both coplanar and on neighboring PCB layers, reduce noise. This is the same principle discussed in [Section 5.1](#). The ground or guard structures are placed as close as possible to reduce noise but also kept far enough away to minimize parasitic capacitance. This separation is a function of the thickness of the materials (overlay, adhesive, etc) on top of the trace. As mentioned in [Section 5.1](#), a good rule is one-eighth the thickness for separation between traces and ground. The separation between electrodes and ground should be at least one-half the thickness.

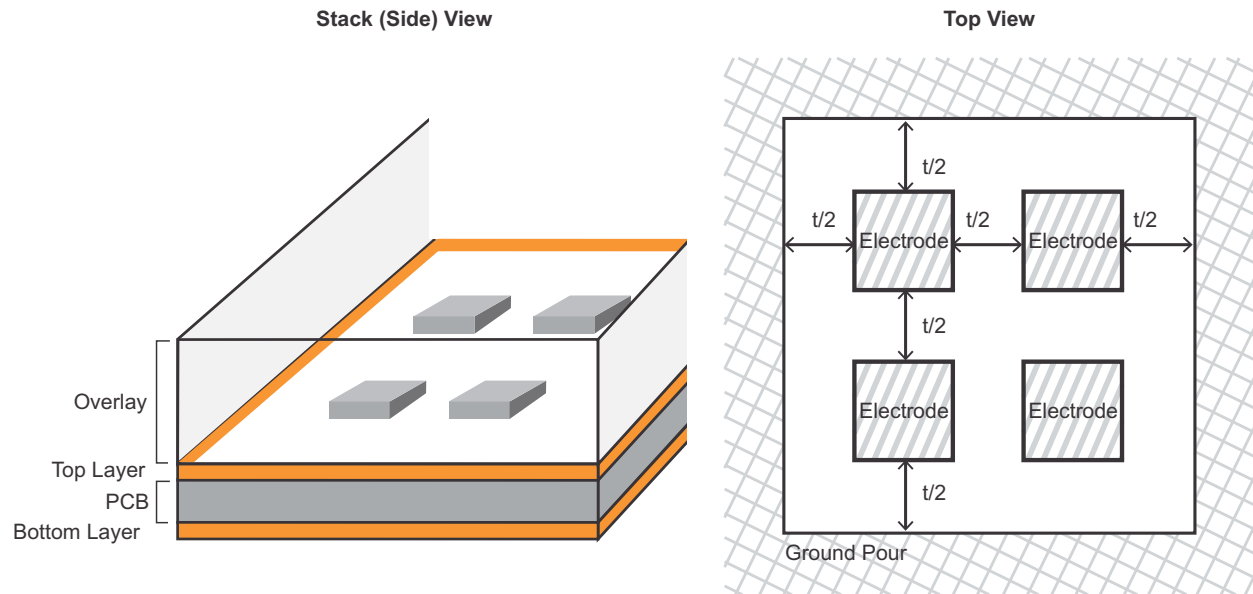


Figure 17. Ground Separation

As shown in [Figure 17](#), the separation between the electrode and the coplanar ground pour should be at least one half the height of the covering materials, t . Unused electrode should be held at a logic low level (V_{ss} potential) and not allowed to float. In this way the spacing between electrodes is the same as the ground and electrode distance.

5.3.2 Pour

The use of a hatched pour instead of a solid ground pour is a good design practice. This reduces the area and consequently the parasitic capacitance associated with both C_{trace} and $C_{electrode}$. Typically, a 25% fill hatch is sufficient, but this percentage can be increased or decreased to improve noise immunity or sensitivity, respectively.

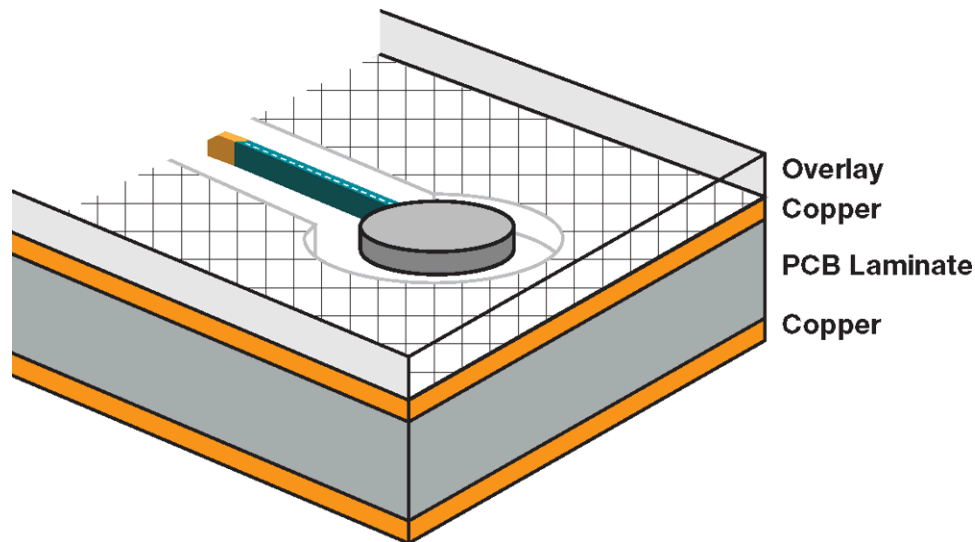


Figure 18. Example Hatched Ground Fill

6 References

1. *Capacitive Touch Software Library Programmer's Guide* (SLAA490)

2. *Capacitive Touch Sensing, MSP430™ Button Gate Time Optimization and Tuning Guide* ([SLAA574](#))
3. *Capacitive Touch Sensing, MSP430™ Slider and Wheel Tuning Guide* ([SLAA575](#))
4. *PCB-Based Capacitive Touch Sensing with MSP430* (SLAA363)
5. <http://wcalc.sourceforge.net/cgi-wcalc.html>

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