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Capacitive Touch Button

IQS127D

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<p>This thesis project aimed to achieve the best possible touch event on a touch button by selecting a suitable material to fill the gap between PCB and casing that is implemented on the company's latest analog watch.</p> <p>All tests on the pre-designed watch were carried out in the laboratory on the premises of the company. The materials tested as well as the professional supervision were provided by the company's team of engineers.</p> <p>One part of the thesis work was to design a test circuitry and software to meet the project requirements and facilitate the testing process. Another part was to test different types of materials in order to select the most suitable fit that meets the criteria and provides the desired sensitivity for the touch button.</p> <p>As a result of this project, the material to fill the gap between the PCB and the casing was selected, in order to obtain the desired sensitivity for the new watch.</p>	
Keywords	Touch button, watch, capacitance, Gasket, conductive foam

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Abbreviations

MCU	MicroController Unit
PCB	Printed Circuit Board
IC	Integrated Circuit
OTP	One Time Programmable
ATI	Antenna Tuning Implementation
LED	Light Emitting Diode
SI	International System of Units
DUT	Device Under Test

1 Introduction

The company is a caring company that provides industry benchmark services and wearable wellbeing products used by active elderly but also older adults needing support. Wearable product users are supported by family and friends as well as professional care providers.

The latest product of the company, a wristwatch, has two touch buttons which contribute to the controlling of the user interface display. Those touch buttons utilize the capacitive touch switch principle.

The buttons have a gap of around 0,55 mm between the casing and the printed circuit board, the reason behind this thesis project was to select the best filling material that can combine high sensitivity to different human finger types and durability.

The material that was first used as filler had two problems, the first problem was from production perspective which is the assembling of the material in the device, the second problem was that the material was not durable. So the purpose of the thesis project was to solve those problems and dig deeper into the functionality and working principle of the capacitive buttons, as well as to research the theory behind it. [5.]

Different materials were already available in the company lab. They were used for other purposes than the touch button gap filling, but because of their electrical features, they were possible candidates for this task, so they could be tested first, then if needed new materials could be ordered.

One main key element in this thesis project was the IC used as a sensor, which is the IQS127D. Understanding the functionality of this chip and understanding the possible configurable outputs is vital to selecting the filling material, so there is a dedicated section for it in the background part of this document to give more details.

2 Background

2.1 Capacitance Theory

Since this project is heavily related to capacitance change, it is wise to start the subject by explaining some theory about capacitance and the way capacitors work.

Physically, capacitance is a measure of the capacity of storing electric charge for a given potential difference ΔV . The SI unit of capacitance is the farad (F) [8,5-4].

A metal plate not connected to any external force would have equal amount of positive and negative charge meaning electrons and holes. When an external force or a voltage source is applied directly to a plate, the electrons start to get inside the plate, but the same electron that has accumulated already in the plate will start repelling the new coming electrons, which results in the plate going back to its negative equals positive charge state.

When another metal plate gets closer to the first plate, the result we got from the early mentioned experiment will be different. Now when an external force is applied, the electrons getting inside the first plate will this time repel the electrons on the other plate, resulting in more positive charge on the other plate than negative, which leads to allow more electrons into the first plate until no more electrons can be taken, because again the new coming electrons will be repelled by the already accumulated electrons. So this time with the external force we got equally charge plates with different charge on each plate.

To achieve bigger amount of charge on the plate, there are many solutions. Bigger external force can achieve this task, this force will let more electrons accumulate in the first plate leading to more amount of charge as explained before. Formula (2) describes this process.

Increasing the capacitance by increasing the area of the two plates with the same external force will also allow more electrons to accumulate into the first plate, leading to more positive charge accumulated on the other plate, resulting in higher amount of charge on both plates (case A in figure 1).

The distance between the plates, if decreased, that will increase the capacitance as well, which will lead to bigger attraction force between the positively charged and negatively charged plate (case B in figure 1), then allowing more charge to accumulate on both plates. Formula (1) explains how capacitance is related to other parameters that are shown in figure 1.

Finally, changing the filling material in the gap between the plates will affect the field between the positively and negatively charged plate, which also will cause if chosen correctly, a bigger capacitance and more accumulated charges on the plates (case C in figure 1). This last solution will be deeply engaged with the research of this thesis project. [1.]

Formulas below explain mathematically the processes mentioned in the text earlier:

$$C = \varepsilon \frac{A}{D} \quad (1)$$

Where: ε is absolute permittivity, A area of plates, D is distance between plates.

$$Q = C \times V \quad (2)$$

Where: Q is charge on plates, C capacitance, V voltage applied across plates.

$$I = \frac{dQ}{dT} \quad (3)$$

Where: I is current, dQ is change in charge, dT is time duration. [6,109.]

Figure 1 is visualization of formula (1) that showed the relation between capacitance on one side dielectric material used between plates and plate dimensions and spacing on the other side.

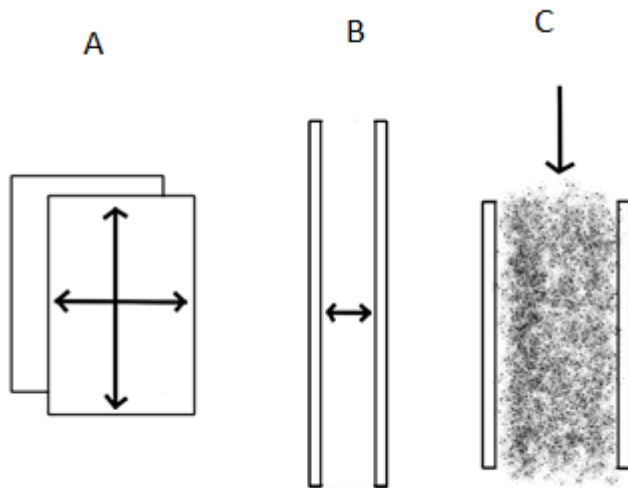


Figure 1. Capacitance relation with physical dimensions and dielectric.

The capacitance changes of the plates, no matter resulted from what option previously mentioned, is the principle on which the capacitive sense chip is designed. As we are about to find out next, the different filling materials tested on our device will affect the capacitance of the sensing plate, hence affecting the output of the sensor and the functionality of the overall device's circuit.

To understand the affect a material on the capacitance change, this requires better understanding and knowledge of the electrical characteristics of those materials in order for us to have better results selecting the suitable filling material.

It is worth mentioning at this point, that since the finger and the human body is not completing our circuit in which the sensor chip is placed, then in our situation the two plates are connected to two different grounds. This does not mean any difference in the working principle of the sensor, the capacitance change scenarios mentioned earlier and the affecting factors are the same with this sensor as they are in a capacitor, more details about this will be in the following section.

2.2 Basic Concept of Capacitive Touch Sensor

In practice there are many types of touch sensors used for different applications, each differs in their working principle and suits specific tasks more than others. Below are two of them.

Resistance touch sensor, which needs for working two plates, when a finger is placed on the button it provides electrical path for current and closes the circuit.

When an object such as a finger, presses down on a point on the panel's outer surface the two conductive layers become connected at that point producing a switch closing in the circuit. See figure 2. The panel then behaves as a pair of voltage dividers with connected outputs. This causes a change in the electrical voltage which is registered as a touch event and sent to the controller for processing.

The touch screen controller gets the alternating voltages between the two layers and converts them into the digital X and Y coordinates of the activated area. Once the coordinates are known, a special software driver translates the touch into something that the operating system can understand. [3,9.]

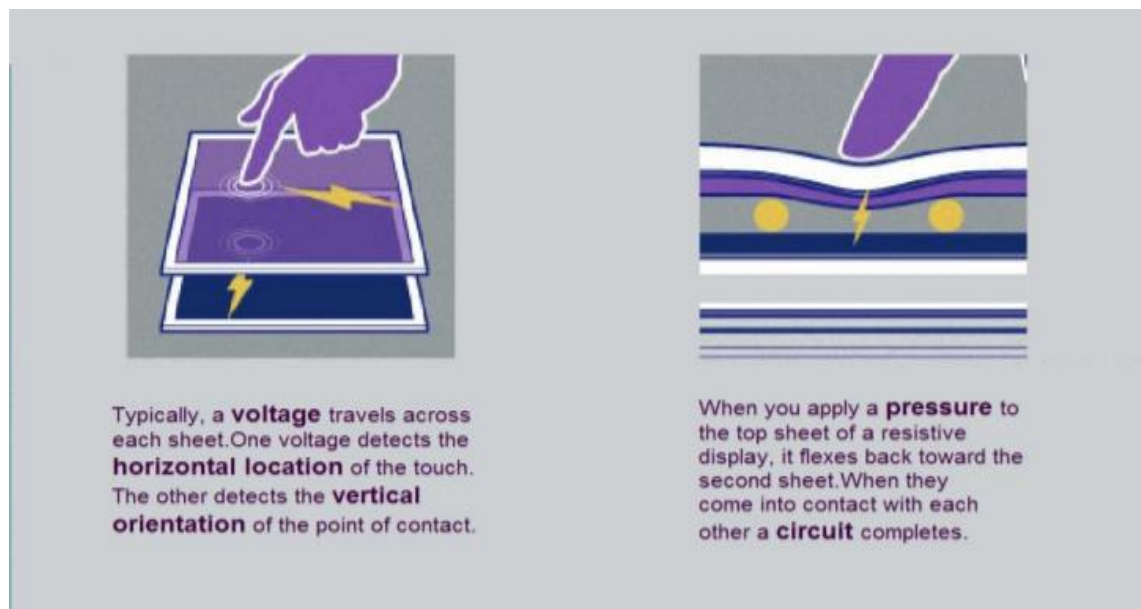


Figure 2. Resistance touch sensor principle, Reprinted from Touch Screen Technologies [3,9].

Capacitance touch sensor, this type of sensors works with one plate only, which functions as sensing plate separated from the outer world by non-conductive layer such as glass or plastic. The plate gets charged and discharged frequently in order to sense any nearing object, this type of sensors also works as proximity sensor for short distances.

Capacitance sensors usually are more complicated to implement than the resistance counterparts, since they usually require a separate chip with designated circuitry to do the task of sensing and triggering.

Figure 3 illustrates how a plate can gather more charge on the surface opposite to the finger which will result in a trigger in the IC sensor connected to it.

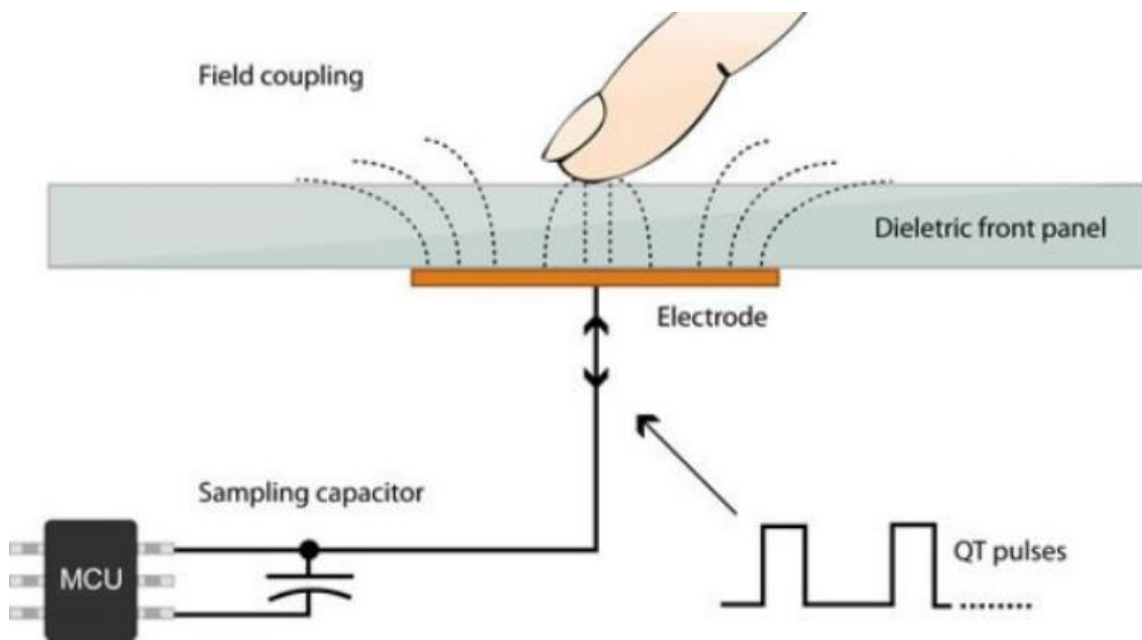


Figure 3. Basic concept of capacitance touch sensor, Reprinted from [2].

The MCU here will sense any change in the amount of transferred charge and will trigger the output accordingly.

2.2.1 Types of Capacitive Sensors

Self-Capacitance method: by measuring the increase in capacitance, the MCU is able to know the status of the sensor (Figure 4 shows the self-capacitance method of detecting a touch). Self-capacitive touch measures the capacitance the human body adds to capacitance already formed between itself (the electrode), and its surroundings. [7,4.]

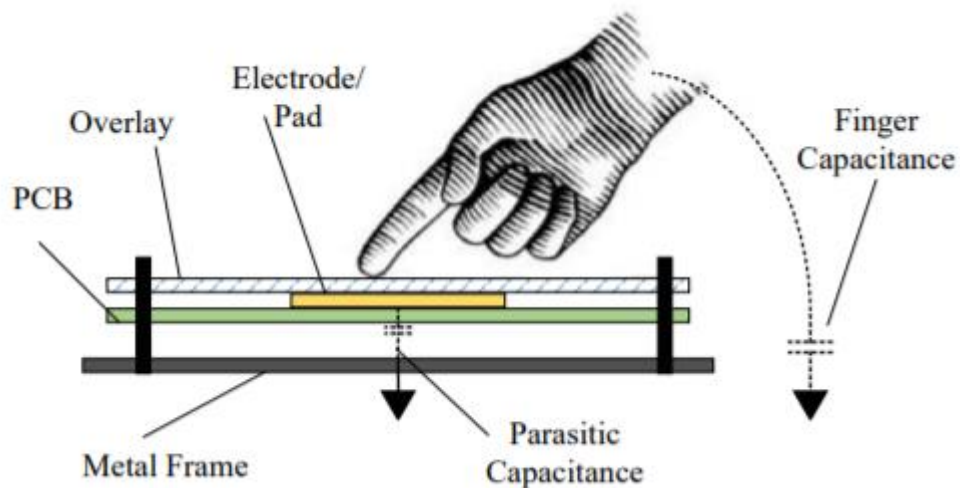


Figure 4. Self-Capacitance method, Reprinted from [7,4].

Mutual-capacitance method: in contrast to the self-capacitance method, this method drives a pair of touch sensing channels. These channels connect to corresponding electrodes to create an electric field. The electric field generates not only between the plates and the environment, but also between the two plates themselves. The result of a touch in this mode is a decrease in capacitance in the system. Since the sensor is measuring the finger's interaction with the field between the two plates, this results a more complicated electrode shape. Figure 5 shows the interlocking pattern between a transmitting electrode and a receiving electrode. [7,4.]

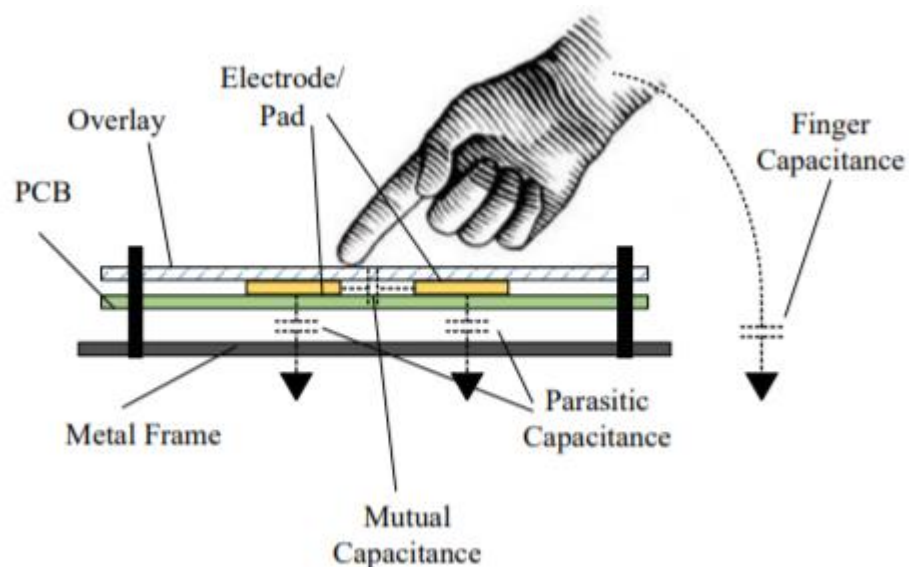


Figure 5. Mutual-capacitance method, Reprinted from [7,4].

2.3 Capacitance Touch Sensors and Charge Transfer (CT) Theory

As mentioned earlier capacitance touch sensors are more complicated than other types of sensors, since they require extra circuitry to perform the desired task. The sensor's package has other components that co-operate to perform the capacitance change measurements. A process called charge transfer is usually used in such sensors.

Shortly, CT method determines the capacitance of a capacitor C_x by using a reference capacitor C_r with known capacitance. The capacitor C_x gets charged using a reference voltage source V_{reg} and then discharged to the capacitor C_r . The charging and discharging happen with the help of switch that switches with predetermined frequency. The number of trips or charge transfers required to fill C_r is called current sample C_s , knowing C_s is the key to know the capacitance of C_x .

The sensing plate or antenna is connected to a voltage reference through a switch. This switch has another pole that is connected to a reference capacitor which works as a container.

The switch changes position in a predetermined frequency, when the plate is free, meaning not nearing any charge carrying object, it contains low amount of charge near the surface. So when it discharges, in other words, the charge gets transferred to the reference capacitor, it takes known amount of trips or transfers to fill up the reference capacitor. This capacitor is called reference capacitor because it has precalculated capacitance.

When an object such as finger gets closer to the sensing plate, the charge on its surface attracts more opposite charge to the surface of the sensing plate. Now the amount of charge to be transferred to the reference capacitor is different, therefore, the number of transfers to fill up the reference capacitor is different.

In fact, when there is a finger placed it takes a smaller number of trips to fill the container capacitor. Hence the sensor is able to recognise that an object has touched the antenna, which in turn caused the change of capacitance and as a result the output of this sensor will change, indicating a touch event. Figure 6 is a visual description of the process.

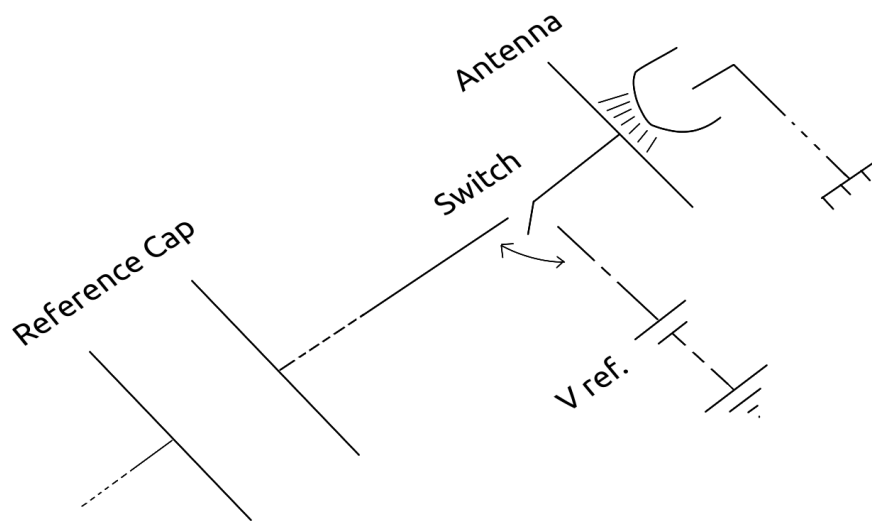


Figure 6. Process of charge transfer in touch sensor, Data gathered from [4,7].

Often capacitive touch sensors also work as proximity sensors, meaning that there is another dedicated output in the sensors that indicates a proximity event has happened. This is because the working principle of proximity sensor is the same as touch sensor, since they both rely on the same capacitance changed sensing mechanism.

In this thesis project we did not pay attention to the proximity or distance sensing feature of those sensors.

2.3.1 Parasitic Capacitance

Parasitic capacitances have the effect of decreasing the effect of a user's touch in the system. This is a result of the fact that we are measuring change in capacitance. A typical user's touch adds between 1 pF to 10 pF to the electrode (sensing plate). [10.]

If a change in capacitance is measured due to a touch of 5 pF, then we get a 25% increase in capacitance if our parasitic capacitance is only 20 pF. If our parasitic capacitance is 100 pF, then a touch only causes a 5% increase in capacitance. As a result, the change is more difficult to measure. [10.]

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 7 is an example of an equivalent circuit for a single self-capacitance button. [10.]

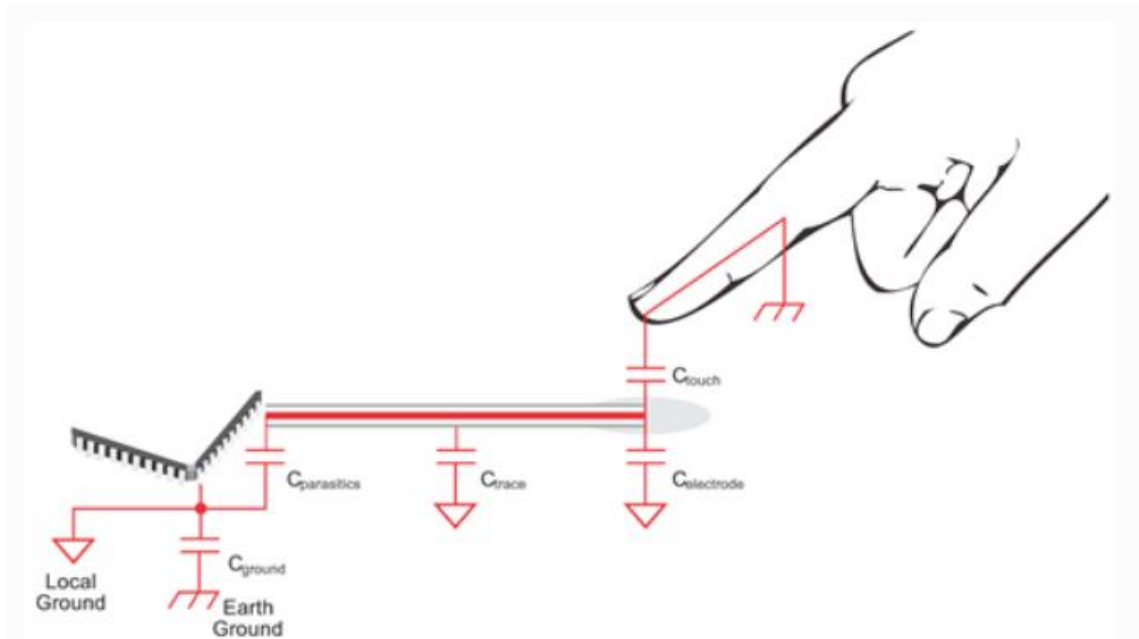


Figure 7. Equivalent circuit for self-capacitance button. Reprinted from [10].

Five different capacitances are shown in figure 7. 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. [10.]

C_{trace} and $C_{electrode}$ 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. [10.]

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. [10.]

The effect of parasitic capacitance goes beyond just a reduction in percent change. From a physics perspective, having ground structures in close proximity of the electrode will cause the field lines projected out from the electrode to concentrate between the electrode and ground, rather than penetrating up through the overlay into the area of interaction. [10.]

2.4 IQS127D Touch and Proximity Sensor

This sensor is one of the most commonly used sensors for this purpose in many different applications. What makes it desirable is that it can be programmed to serve variety of touch applications as wanted.

Two registers inside this IC are responsible for setting the desired configuration of this sensor. Many parameters like touch threshold, sensitivity level, power mode, halt time, communication protocol and other similar parameters for the proximity are there, each parameter or each bit of those two registers can be programmed one time only, so this chip is One Time Programmable or OTP chip.

2.4.1 Programmable Bits and Halt Feature

As stated earlier, the halt time bits exist in one of the two programmable registers inside the chip. Halt time is a feature implemented in this chip that helps adapting to new environments.

For example, if the chip is placed in a new environment, which results in a capacitance change in the sensing plate, this will trigger the output of the sensor. So even though it is new and permanent environment and not a touch or proximity event, the sensor would not be able to know the difference.

To help solving this issue the halt time feature comes and ensure that the output of the sensor is not triggered permanently, when the predetermined halt time has elapsed the output changes back to idle state or no event state.

Without this feature, many applications would be impossible to implement using this sensor chip. However, this feature can be disabled by programming the same bit to the “never halt” option.

Below are figure 8 and figure 9 taken from the datasheet of the IQS127D describing all programmable bits with their available different options [4,5].

Table 4-1: User Selectable Configuration Options: Bank 0

T_{THR1}	T_{THR0}	P_{THR1}	P_{THR0}	FUNC1	FUNC0	LOGIC	~
bit 7							bit 0
Bank 1: bit 0, Bank 0: bit 7-6		$T_{THR}<2:0>$: Touch Thresholds				-Section 6.4	
		000 = 1/16					
		001 = 1/32					
		010 = 2/16					
		011 = 3/16					
		100 = 4/16					
		101 = 6/16					
		110 = 8/16					
		111 = 10/16					
Bank0: bit 5-4		$P_{THR}<1:0>$: Proximity Thresholds				-Section 6.3	
		00 = 2					
		01 = 4					
		10 = 8					
		11 = 16					
Bank0: bit 3-2		$FUNC<1:0>$: OUTPUT Pins' functions				-Section 6.2	
		00 = POUT active, TOUT active					
		01 = POUT latch, TOUT active					
		10 = POUT active, TOUT toggle					
		11 = POUT latch, TOUT toggle					
Bank0: bit 1		LOGIC: Output logic select -				-Section 6.1	
		0 = Active Low					
		1 = Active High					
Bank0: bit 0		Not Used					

Figure 8. Configurable bits in bank 0, Reprinted from [4,5].

For this project, the bank 0's most important bits are T_{THR1} and T_{THR0} , together with T_{THR2} from bank 1 form the touch threshold or touch sensitivity. In other words, those bits have tested with different values as more details will be in the results sections.

P_{THR1} and P_{THR0} were not in use in this project and left as 00, $FUNC<1:0>$ were 00 throughout the project and LOGIC was 0.

Table 4-2: User Selectable Configuration Options: Bank 1

STREAMING	-	SHORT STREAMING	t_{HALT1}	t_{HALT0}	P_{MODE1}	P_{MODE0}	T_{THR2}
bit 7							bit 0
Bank 1: bit 7	STREAMING: 1-wire streaming mode 0 = disabled 1 = enabled				-Section 7		
Bank 1: bit 6	Not used						
Bank 1: bit 5	SHORT STREAMING: Short word streaming enable (Function enabled if this bit together with STREAMING bit is set) –Section 7						
Bank 1: bit 4-3	$t_{\text{HALT}}<1:0>$: Halt time of Long Term Average 00 = 18.6 seconds 01 = 74.5 seconds 10 = Never 11 = Always				-Section 6.6		
Bank 1: bit 2-1	$P_{\text{MODE}}<1:0>$: Power Modes 00 = Boost Mode 01 = Normal Power Mode 10 = Low Power Mode 1 11 = Low Power Mode 2				-Section 6.5		
Bank 1: bit 0	$T_{\text{THR}}<2:0>$: Touch Thresholds See Table 4-1				-Section 6.4		

Figure 9. Configurable bits in bank 1, Reprinted from [4,6].

Bank 1's most important bits are $t_{\text{HALT}}<1:0>$ and $T_{\text{THR}2}$, those were tested with different values, while STREAMING was not used and left as 0, $P_{\text{MODE}}<1:0>$ was set to 00 or boost mode.

To explain more about the functionality of the halt feature in the IQS127D let us start with figure 10, which is a screenshot that was taken from the oscilloscope while testing the functionality of the chip sensor.

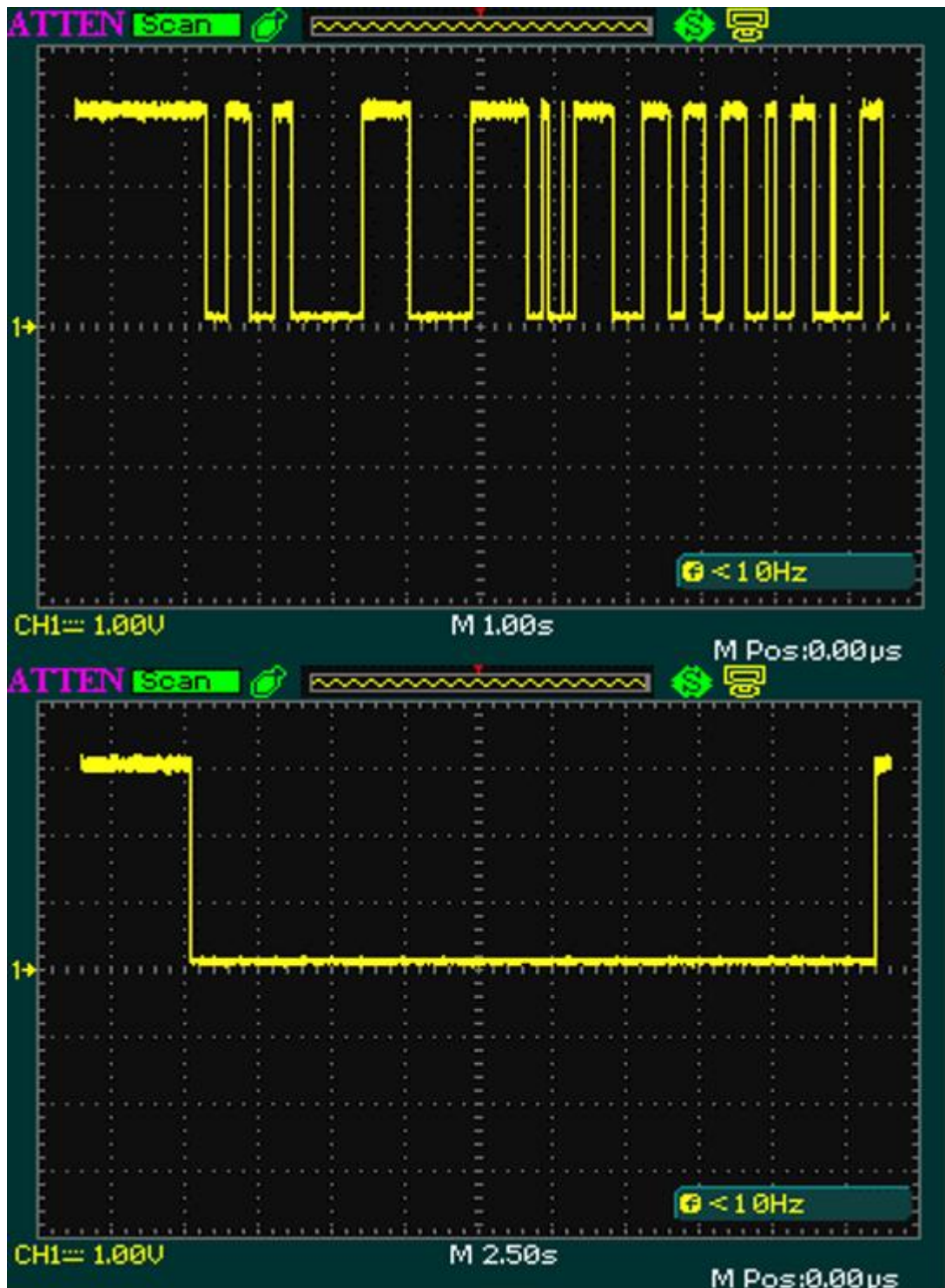


Figure 10. Oscilloscope image during halt process in lower side and normal process upper side.

So here in the upper side of the figure, normal process of the chip is monitored with frequent touch events. It is good here to point out that the chip configuration during those shots was the default configuration, so the bits of bank 0 were 0b00000000 and bank 1

were 0b00000000, the halt time was set to 18,6 seconds as also can be noticed from figure 10 (2,5 seconds/division).

During the halt event a metal object was placed on the antenna pin continuously, until the sensor reached halt time after about 18 seconds. Then the output changes from low to high, even though the metal object was still on the antenna.

One issue worth mentioning, that was noticed during the tests, is the unpredictable behavior of the chip directly after start-up. The sensor, sometimes, would not respond to touch events for uncertain period of time. Figure 11 is a screenshot from the oscilloscope and will help illustrating this issue.

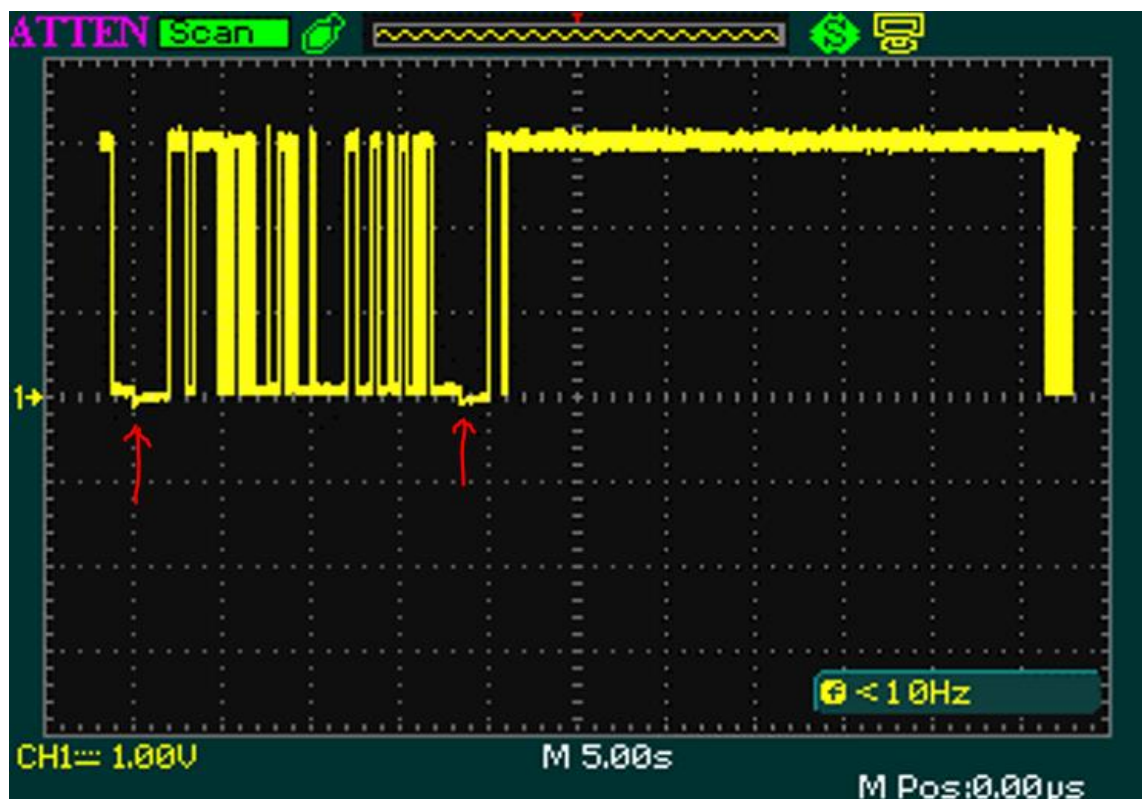


Figure 11. Unpredictable behavior of IQS127D after start-up.

The arrows in figure 11 indicates the moment the chip was powered. To explain the events in the figure in details, let us start from the low output that precedes the arrows, this low output indicates that the power is cut from the chip, then the dip is the moment the power is turned ON then it takes a while for the output to go to the idle or no event states which is here the high level.

In figure 11, keep in mind that during the whole period that covers the screen, there were continuous touch events happening. So the whole screen was supposed to show constant shifting from high level to low then back to high, exactly as it shows during the period between the two arrows.

Here, in fact, we have two scenarios, one was that the output responded almost immediately to the touch events and the other was no response for uncertain period of time.

There are many possible reasons to why the sensor behaved this way: ATI (Auto Tuning Implementation) feature could be one reason (see next section). Insufficient supply current or voltage from unstable source and sudden changes in parasitic capacitance in the system are other possible explanations to this behavior.

2.4.2 Antenna Tuning Implementation (ATI)

It is a necessity to mention the Antenna Tuning Implementation ATI used in the latest generations of the sensor, as it affects radically the way the sensing device functions during operation and on start-up of the device.

Briefly, the ATI is a complicated algorithm implemented in the chip to help adapt it to sudden changes in the surrounding environment, when the amount of charge taken frequently from the sensing antenna is not within the predetermined range.

This adaption relies on two factors: ATI multiplier and ATI compensation. The multiplier will be best described as course adjustment, whilst the compensation as fine adjustment.

In IQS127D an Automatic ATI is in use. The main purpose is to optimise the sensing antenna's physical connection to the device and to minimize the effect of the parasitic capacitance. ATI algorithm is executed as mentioned earlier on start-up and also when the charge samples are not within the range.

The Automatic ATI is in the favour of the best performance of our sensor, but it has also its downsides that will affect the sensing operation at some points. While the algorithm is being executed the chip loses sense temporarily for a very short period of time. In most cases it is not noticeable.

One scenario where the chip executes this algorithm would be on start-up, when the device performs the automatic tuning. Another scenario is the Automatic re-tuning that happens during device operation when a relatively large sensitivity reduction is detected. [4,13.]

The ATI effects on the functionality of the device had to be taken into consideration during the testing of the sensor with different filling materials.

2.4.3 Long Term Average (LTA)

LTA is the average value calculated from the current sample C_s . It uses an IIR (Infinite Impulse Response) type of filter, which tracks slow changes in the environment and forms a dynamic reference for the sensor.

Long Term Average is the key to determine touch and proximity events, as well as to enable the use of halt timer. A halt timer starts when an event occurs and expires after the user specified amount of seconds $t_{\text{HALT}} < 1:0 >$ which results in recalibrating of the LTA filter (see bank 1 in figure 9). [9,1.]

Below are formulas (4) and (5) that show the relation between Long Term Average LTA and both Current Sample C_s and Touch Threshold T_{THR} :

$$T_{\text{THR}} = \text{User selected touch threshold} * \text{LTA} \quad (4)$$

Where user selected touch threshold are the bits $T_{\text{THR}1}$ and $T_{\text{THR}0}$ from bank 0 and $T_{\text{THR}2}$ from bank 1 (see figure 8 and figure 9).

$$T_{\text{THR}} \leq \text{LTA} - C_s \quad (5)$$

The above condition must hold for at least three consecutive current samples in order for a touch event to be triggered in IQS127D.

Next is an example scenario to explain how a touch event is triggered in IQS127D, starting by calculating LTA from T_{THR} and C_s .

2.4.4 Example

Assumption: Suppose in case of no finger placed that Current Sample $C_s = 100$. In case of finger placed $C_s = 50$. User selected Touch Threshold = $1/50$. Number of current samples taken so far is 5. No touch event yet.

Also suppose that C_s is the same during the whole period of a touch event and the same during the period of no touch event.

Scenario: At this point $LTA = (5 \cdot 100)/5 = 100$ then $T_{THR} = 100/50 = 2$ then $(2) \nless (100 - 100 = 0)$ this means finger not placed (see formulas (4) and (5)).

Now finger placed. After one more sample, $LTA = (5 \cdot 100 + 50)/6 = 91.6$ then $T_{THR} = 91.6/50 = 1.8$ then $(1.8) < (91.6 - 50 = 41.6)$ **holds**, there is finger placed. If the finger is continuously placed for two more samples, then a touch event will be triggered.

3 Testing and Results

3.1 Additional Circuitry for Testing Purposes

Before starting to test different materials to fill the gap between the PCB and the casing of the device, the chip itself needed to be tested in order to understand its functionality and how it behaves in reality. This test aimed to put the chip within similar environment or surrounding to the one that it was supposed to be implemented inside.

A simple testing circuit was made to achieve this goal, taking into consideration two important parameters, how fast the chip responds to touch events and how stable the output was going to be during one complete touch event.

A 7-segment display was included in the circuit, to show whether one touch event will trigger an increment by one or more on the display. This means that the output of the sensor can be monitored to see whether it is stable or not.

Additional purpose of the 7-segments display was to show if quick and predetermined number of presses on the sensing plate would result in the same amount of counts on the display, meaning that the sensor sensed all the touch events and gave reliable stable output, which prompted the microprocessor to show the correct number of presses.

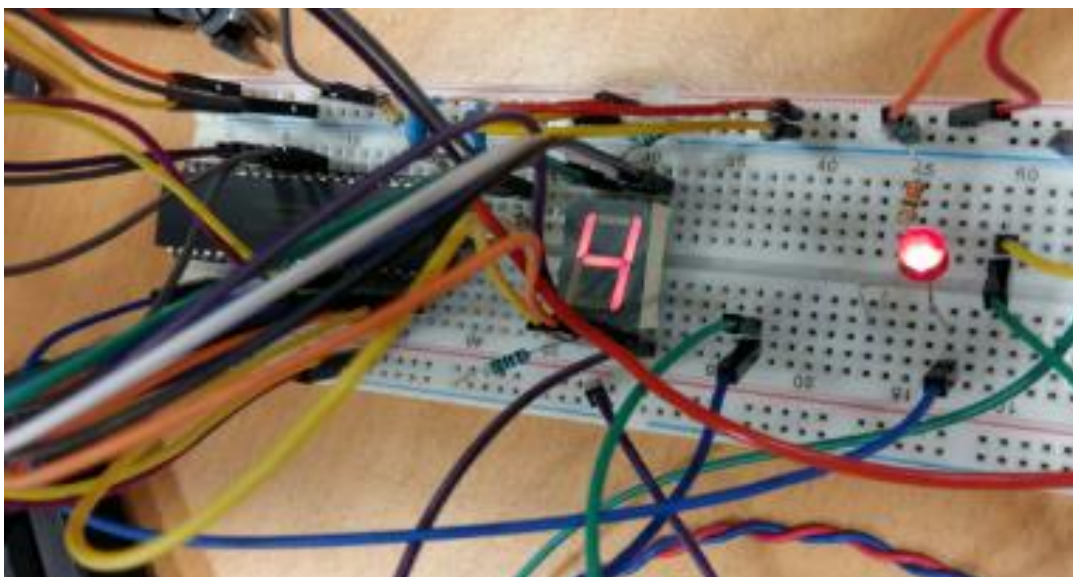


Figure 13. The actual test circuit.

The microcontroller used in this circuit was selected to be operative on high frequencies, in order to achieve reliable performance for our testing purposes. The frequency on which the MCU operates was 6 MHz. This frequency is provided by a crystal oscillator. In this case when very quick changes occur on the output of the sensor, the MCU can detect them and give a response accordingly.

The following summarises the functionality of the circuit briefly: when a fingertip is placed on the sensing antenna of the IC, the sensor changes its output signal. This signal triggers the MCU to turn off the red led and increment the 7-segment display by one.

The output of the MCU stays in the same state as long as the state of its input is the same. This means that as long as a finger is placed on the sensing plate, the LED is OFF and the display shows the same value. On the other hand, when there is no touch event, the LED is ON and the display keeps its value. The increment on the display and the changing in the state of the LED happens when there is a level change on the input of the MCU from 0 to 1 or the opposite.

The usage of high speed MCU gives our circuit both fast response and reliable result for the task assigned to it. The whole code on which the MCU runs was written in C language. Listing 1 has just the while loop that executes continuously, which is part of the main function of the code, the rest of the code can be found from appendix 1.

```
while(1) {
```

```

while (PORTB.B0==1)
    {display1 (m);
    PORTC.B4=1;}
if (PORTB.B0==0)
    {m++;
    if (m==10)
        m=0;
    while (PORTB.B0==0)
        {PORTC.B4=0;
        display1 (m);}
    }
}

```

Listing 1. Continuously running loop.

In addition to the hardware testing circuit, a software for testing purposes was made by one of the company's engineers. It aims to flash an LED in two different colours, indicating which touch button was pressed.

The advantage of this method of testing was that it does not require any additional physical connections or wires to be added to the main circuit, which means that the PCB, that includes the sensors, can be placed inside the case and the device can be fully assembled, as if it was intended for normal use. Here the testing environment is identical to the one in reality.

The downside in this method of testing was that the human eye can not capture the incident where the output of the touch event is not stable, because the LED flashes too quickly.

In fact, both testing methods were used throughout the whole pre-production period of the device, using one of them was not sufficient. The testing process was as follows:

At the beginning of the project the testing circuit was used for testing the functionality of the sensor alone and then to test the PCB that has the sensor in it. Then after fully assembling the device, the software was used in order to monitor the behaviour of the filling material on the long run.

Below is table 1 that illustrates the advantages of each method and the stage where it was used.

Table 1. Test methods and their positive and negative sides.

	Test circuit	Test software
Phase of project	first	last
Advantage	ability to observe the number of output changes during one touch event	testing takes place within the casing in similar scenario to actual use
Disadvantage	the tested device had to be modified and connected to the external circuit	LED flashing could be too fast to be possible to capture by naked eye

3.2 Tested Materials

The materials tested for this project are handful. Mainly they were available at the company and were used for other purposes, but it was wise to start searching for the filling material among those first.

Theoretically we have two types of materials that might be candidates for the filling purpose, non-conductive and conductive. Since the casing of the device is made of plastic and is non-conductive, this poses already an insulator layer of about 2.5 mm, in addition to the already existing 0.55 mm gap between the PCB and the case.

So the question was, will a non-conductive material work as a gap filler? Is the antenna going to sense a finger placed beyond the 2.5 mm insulator layer of plastic plus 0.55 mm layer of non-conductive material?

Well, the answer was NO. The non-conductive material will not work for us, so only conductive materials were to be tested. The materials that were available on the premises are the following: Conductive metal sheet, conductive foam, conductive rubber, conductive cloth, conductive shielding Gasket and Gasket fabric/foam.

One important aspect that had to be taken into consideration when selecting the best material was not only how well the antenna senses the touching finger, but also how

difficult was placing the material in the gap in production point of view. So when producing the device in masses, the procedure of placing the filling material in the gap has to be doable with least amount of time and effort.

Below are the tested materials, with each material's advantages and disadvantages and why it was or was not chosen.

Conductive metal sheet (see figure 14): this material has the least ohmic resistance among all tested materials and thus is the most conductive. In theory this metal sheet would work best for such purposes as filling material, since it extends the area of the sensing antenna and have the least impedance difference with the conductive material of the sensing antenna on the PCB.

One problem with this metal sheet was physical flexibility, it does not bend easily to match the shape of the gap we have, thus hard to implement from production point of view.

Another problem was that there had to be an added layer of glue between the surface of the casing and the metal, so it could stay in place. This posed another difficulty for production process.



Figure 14. Conductive metal sheet.

Conductive foam (see figure 15): this material was the one used with the first set of sample devices produced for testing. The material worked nicely at the beginning, but after a while, it was noticed that the surface of this material, which has a hairy structure, would lose its shape and form an air gap between the material and the PCB.

This issue was also noticed during production, the PCB would destroy the hairy structure on the material when placing it inside the casing.

Based on the previously mentioned issues, this material has short durability and not suitable for production.



Figure 15. Conductive foam.

Conductive rubber (see figure 16): this rubber is physically flexible in structure, so it would bend to form the wanted shape, which is a desired feature. The thickness of the material on the other hand and the lack of adhesive layer of glue to make it stick on the surface, made it unsuitable material for the filling purpose.



Figure 16. Conductive rubber.

Conductive cloth (see figure 17): the idea of an ideal material was that in addition of its electrical characteristics, the material has to be flexible and not hard in structure. So when it is in place, the shape of this material would deform slightly while installing the PCB, after that the material would regain its original shape to fully fill the gap between the sensing antenna on the PCB and the case.

Unfortunately, after ordering this material from an online dealer, the actual thickness of the material did not match the 1 mm thickness that was mentioned among the dimensions of this material on seller's web page. This posed the same problems faced with the conductive rubber, the material had to be folded many times to fit the gap. Besides, the lack of adhesive layer, all together made it not suitable as filling material.

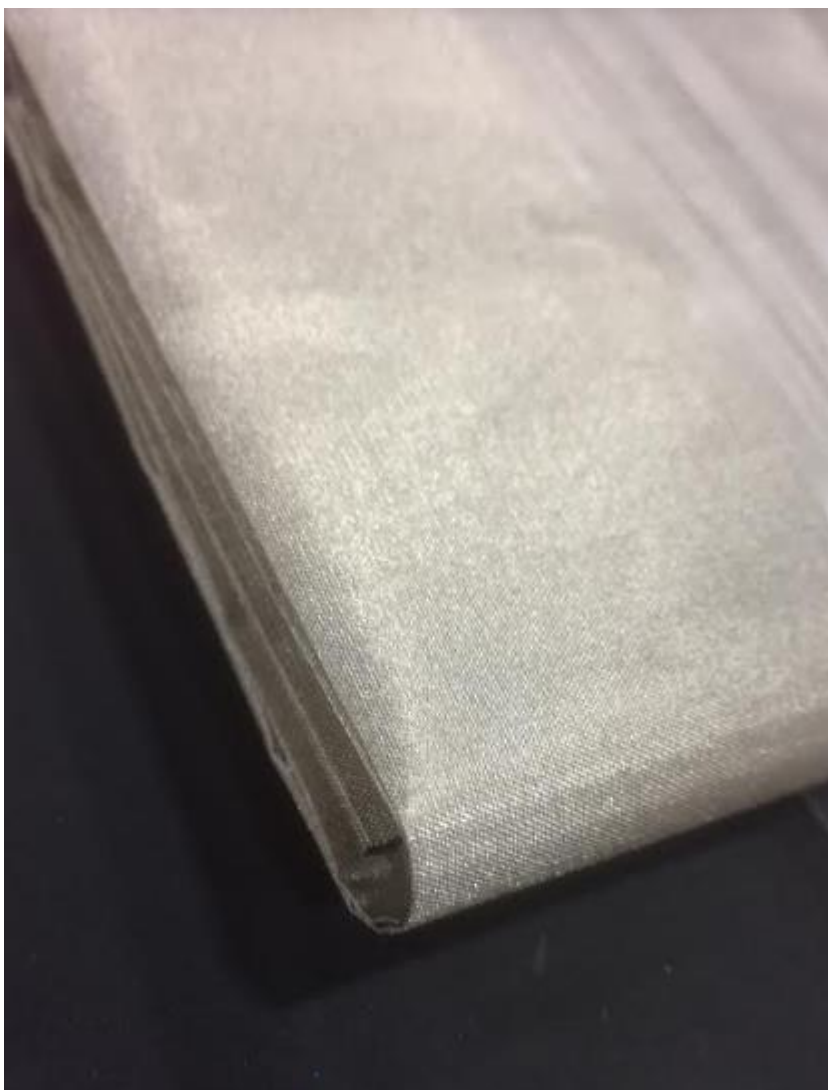


Figure 17. Conductive cloth

Conductive shielding Gasket (see figure 18): this material has almost cylindrical shape that makes it thicker than the available gap, but it can be compressed to fit the gap. The durability of this material is what makes it strong candidate. One more advantage was that it has readymade layer of glue that helps it stick to the surface firmly.

This material was tested with many sizes as gap filling. It functioned mostly just fine, but it was noticed that because of the unique shape, it would bend down when placing the PCB sometimes, and as a result the conductive side that meant to touch the antenna on the PCB would be away and the sensor would not work. This was not acceptable from production perspective and thus the material considered not suitable.



Figure 18. Conductive shielding gasket.

Gasket fabric/foam (see figure 19): the last material was tested and the one that proved best suitable as a filling material. This material came from the seller in many standard sizes and many glue layer heights as well. Many of those were available in the company. However, the focus of the tests was on two sizes of those which were most fit for filling purpose.

The thickness of this material which is about 0.55 mm together with the durable and strong structure were factors that made this material the best candidate. In addition to that, there is ready made layer of glue that comes on one side of the rectangle-shaped material which helped placing it on the inner side of the casing.

From production point of view, the process of placing the material in the gap was easy and fast. The rigid yet just enough flexible structure of this material made it easy to take the shape of the gap, but strong enough to bear the process of placing the PCB, without deforming the contact side with the PCB and causing an air gap between the material and the PCB.



Figure 19. Gasket fabric/foam.

Gasket fabric/foam material was widely tested with many different sizes, in order to find the best combination of touch-area and sensitivity. More about the results can be found in the 'Results' section, where different material width and height values were tested together with the material position on the case.

3.3 Results

The test results were saved in an excel document throughout the project time, the document was modified many times and each time new result came out of a test, it was added to the document.

This document is divided into three separate sheets, first sheet includes information about the materials with some notes regarding physical dimensions of the device's case and other notes for material behaviour, the second sheet has the executed tests on different materials with different sizes and their results, third sheet has the IQS127D sensor's observed output by the oscilloscope.

Let us start with table 2, that has information about the available materials with letters assigned to each material that will be used in the rest of the document.

Table 2. Different materials.

A	Conductive foam
B	Conductive rubber
C	Conductive metal sheet
D	Insulating rubber
E	Conductive shielding Gasket
F	Conductive cloth
G	Gasket Fabrik/Foam 5*457 RECT

Then table 3 will show some notes for each material and the design considerations in terms of durability and assembly point of view.

Table 3. Material notes.

Material	Resistor R _{Cx}			Assembly	Long term durability	Note
	330Ω	470Ω	680Ω			
A	X			Difficult	Poor	Good functional.
B	X			OK	Good	Didn't work due to gap thickness
C	X			Difficult	Excellent	Couldn't be installed properly because of the gap shape
D	X			OK	Good	Insulator will not work
E	X			OK	Good	Better response than conductive foam, but the size of material poses extra sensitive area.
F	X			Difficult	Good	Work fine but glue or sticker material needs to be put so it hold it on place
G	X			Good	Good	way better than conductive shielding gasket

In this table all the tests were done using a 470 Ω antenna resistor as recommended by the manufacturer.

Next are the test results table, but before the table is displayed there are many column titles that needs to be clarified. Hence we will start with figure 20 that shows the outer case with some markings to help understand the results table.

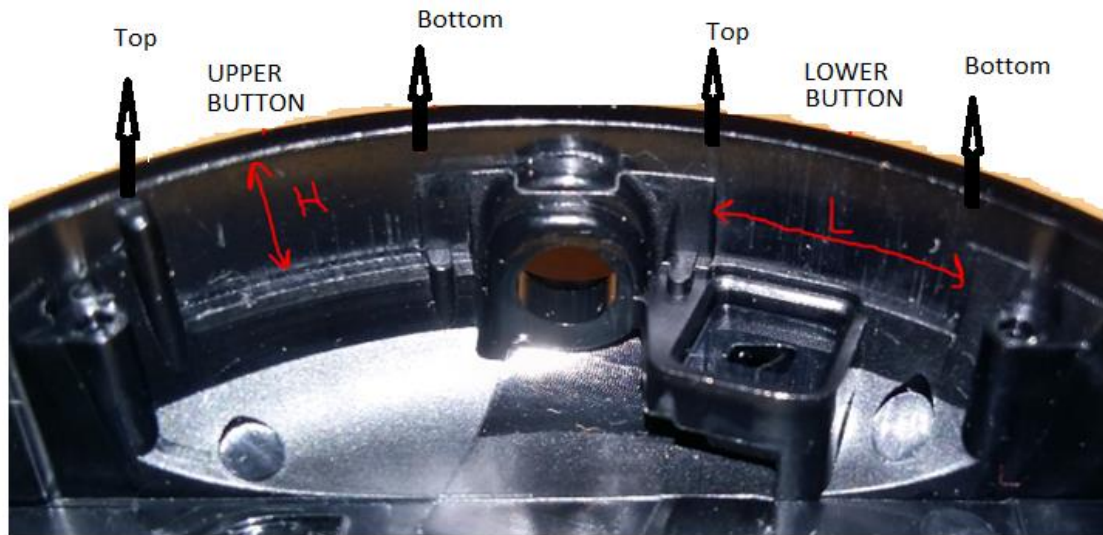


Figure 20. Case of the device from inside.

More notes regarding the physical dimensions and the available area on the casing can be found from table 4.

Table 4. Dimensions and notes for the available area on the case.

Dimension	Value (mm)	Note
height of area	5.07	all available button area
length of area	8.1	all available button area
height of frame	1.66	frame part covers the case from top
above the frame	0.85	above the frame available useless area
not usable height	$1.66+0.85=2.51$	whole area used by frame and above it
final useful height	$5.07-2.51=2.56$	the useful button area
thickness of gap	0.55	upper button
thickness of gap	0.6	lower button

Following is table 5, showing at the top the scale of grades used in the results table. Below that, in the middle, there is touch surface needed to trigger the sensor. Then at the bottom, there is crown press which indicates that when pressing the crown button (from figure 20, crown button is a push button placed between the upper in the lower touch buttons), will that affect either of the touch buttons and trigger their sensors or not.

Table 5. Grade, touch surface and crown press parameters.

Grade	Description
poor	Doesn't work
ok	Works but sensitivity low
good	Works but sensitivity good
Excellent	Works but sensitivity high
Touch surface:	Description
small	only tip of finger needed to activate sensor when touching the button area
big	tip of finger not enough
Crown press:	Description
yes	when press crown the corresponding button get pressed some times
no	doesn't get pressed

Now comes the main results table. This table is split into two tables, one for the upper button and another for the lower button. Table 6 is regarding the upper button.

Table 6. Upper button test results for filling material.

Gasket	Upper			Area [mm ²]	from top	from bottom	crown press	Touch surface	insulator layers	voters	grade	note/material
Default	Height mm	Length mm										
150 ms	2.50	8.00	20.00	0.00	0.00	yes	small	4.00	6.00	Good	E	
150 ms	3.20	7.00	22.40	0.00	1.00	No	small	4.00	6.00	Excellent	E	
150 ms	2.50	7.00	17.50	0.00	1.00	yes	small		5.00	Excellent	E	
90 ms	3.20	7.00	22.40	0.00	1.00	yes	small		4.00	Excellent	G	
50 ms	3.20	7.00	22.40	0.00	1.00	yes	small		1.00	Excellent	G	
90 ms	3.20	5.00	16.00	0.00	3.00	No	small		7.00	Excellent	G	
90 ms	3.10	5.50	17.05	0.00	2.50	No	small			Excellent	G	
90 ms	2.70	6.00	16.20									
90 ms	2.50	6.40	16.00	0	1.60		small			12.00	Excellent	G & B revision
90 ms	3.00	5.30	15.90									
90 ms	2.50	5.40	13.50									
Gasket												
1/32												
30 ms	2.50	5.00		0.00	3.00	no	small			4.00	Excellent	E
150 ms	2.50	5.00		0.00	3.00	no	small			2.00	Excellent	E

Next table 7 is for the lower button.

Table 7. Lower button test results for filling material.

Gasket	Lower		Area															
Default	Height mm	Length mm	[mm ²]	from top	from bottom	crown press	Touch surface	Insulator layers	voters	grade	note/material							
150 ms	2.50	8.00	20.00	0.00	0.00	no	big	1.00	6.00	Ok	E							
150 ms	2.50	9.00	22.50	1 (vii)	0.00	yes	small	2.00	3.00	Good	E							
150 ms	2.50	9.00	22.50	1 (vii)	0.00	yes	small	4.00		Good	E							
150 ms	2.50	7.00	17.50	1.00	0.00	no	big	1.00	6.00	Good	E							
90 ms	2.50	7.00	17.50	1.00	0.00	yes	small		4.00	Excellent	G							
50 ms	2.50	7.00	17.50	1.00	0.00	yes	small		1.00	Excellent	G							
90 ms	2.50	5.00	12.50	3.00	0.00	No	small		7.00	Excellent	G							
90 ms	3.20	5.00	16.00	3.00	0.00	No	small		1.00	Excellent	G							
90 ms	3.10	5.50	17.05	2.50	0.00	no	small			Excellent	G							
90 ms	2.70	6.00	16.20															
90 ms	2.50	6.40	16.00	1.60	0.00		small		12.00	Excellent	G							
90 ms	3.00	5.30	15.90															
90 ms	2.50	5.40	13.50															
Gasket																		
1/32																		
150 ms	2.50	7.00		1.00	0.00	yes	small		5.00	Excellent	E							
30 ms	2.50	5.00		3.00	0.00	no	small		4.00	Excellent	E							
150 ms	2.50	5.00		3.00	0.00	no	small		2.00	Excellent	E							

Voters column is the amount of people who tested the filling material and gave their grade. Then the average was considered the final grade and put in the grade column as the result. 'From top' and 'from bottom' columns indicate where the filling material was positioned in millimeters, where top and bottom are according to figure 20.

Default means that the sensor chip configuration bits were left as default value, which means that both bank 0 and bank 1 has the following bits 0b00000000, whereas 1/32 means that touch threshold was set to the most sensitive level (see figure 8).

The numbers 150 ms and 90 ms in the first column refer to the period of time that the touch event has to last, so the processor of the device considers this event as eligible touch and not coincidence. This feature is processor related and it has no relation with the IQS127D configurable bits.

Insulator layers refers to the amount of the electrical tape layers that can be placed between the touch area and the finger, so that the sensor can still sense the finger and trigger the output.

4 Conclusion

The chosen material for the filling purpose, according to tables 6 and 7, was Gasket fabric/foam with the following parameters: area is 16 mm², height is 2.5 mm, length is 6.4 mm and default chip configuration, for both upper and lower buttons.

This selection was based on 12 votes, most of which gave the excellent grade for the touch experience and the response on the user interface display.

Parasitic capacitance of the device's circuit still needs to be studied in more details, in order to have better understanding of how the surrounding is affecting the functionality of the sensor.

The testing process for the best filling material was not finished by the time of writing this conclusion. More materials can be tested with different register configurations. There is always better filling material for the touch buttons that has better characteristics than the chosen one.

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Source code for the test circuit

```
unsigned char m=0, num;
void display1 (unsigned char num)
{
  if (num == 0)
    {
      PORTB.B1=0;
      PORTB.B2=0;
      PORTB.B3=0;
      PORTB.B4=0;
      PORTB.B5=0;
      PORTD.B6=0;
      PORTD.B7=1;
    }
  else if (num == 1)
    {
      PORTB.B1=1;
      PORTB.B2=1;
      PORTB.B3=1;
      PORTB.B4=1;
      PORTB.B5=0;
      PORTD.B6=0;
      PORTD.B7=1;
    }
  else if (num == 2)
    {
      PORTB.B1=0;
      PORTB.B2=0;
      PORTB.B3=1;
      PORTB.B4=0;
      PORTB.B5=0;
      PORTD.B6=1;
      PORTD.B7=0;
    }
  else if (num == 3)
    {
      PORTB.B1=0;
      PORTB.B2=0;
      PORTB.B3=0;
```

```
        PORTB.B4=0;
        PORTB.B5=1;
        PORTD.B6=1;
        PORTD.B7=0;
    }
else if (num == 4)
    {
        PORTB.B1=1;
        PORTB.B2=0;
        PORTB.B3=0;
        PORTB.B4=1;
        PORTB.B5=1;
        PORTD.B6=0;
        PORTD.B7=0;
    }
else if (num == 5)
    {
        PORTB.B1=0;
        PORTB.B2=1;
        PORTB.B3=0;
        PORTB.B4=0;
        PORTB.B5=1;
        PORTD.B6=0;
        PORTD.B7=0;
    }
else if (num == 6)
    {
        PORTB.B1=1;
        PORTB.B2=1;
        PORTB.B3=0;
        PORTB.B4=0;
        PORTB.B5=0;
        PORTD.B6=0;
        PORTD.B7=0;
    }
else if (num == 7)
    {
        PORTB.B1=0;
        PORTB.B2=0;
        PORTB.B3=0;
```

```
        PORTB.B4=1;
        PORTB.B5=1;
        PORTD.B6=1;
        PORTD.B7=1;
    }
else if (num == 8)
    {
        PORTB.B1=0;
        PORTB.B2=0;
        PORTB.B3=0;
        PORTB.B4=0;
        PORTB.B5=0;
        PORTD.B6=0;
        PORTD.B7=0;
    }
else if (num == 9)
    {
        PORTB.B1=0;
        PORTB.B2=0;
        PORTB.B3=0;
        PORTB.B4=1;
        PORTB.B5=1;
        PORTD.B6=0;
        PORTD.B7=0;
    }
else
    {
        PORTB.B1=0;
        PORTB.B2=1;
        PORTB.B3=1;
        PORTB.B4=0;
        PORTB.B5=1;
        PORTD.B6=1;
        PORTD.B7=0;
    }
}

void main() {
```

```
TRISC.B4=0;
PORTC.B4=0;
TRISD.B6=0;
TRISD.B7=0;
TRISE.B4=0;
OPTION_REG.B7=0;
OPTION_REG.B6=0;
TRISB.B0=1;
TRISB.B1=0;
TRISB.B2=0;
TRISB.B3=0;
TRISB.B4=0;
TRISB.B5=0;
INTCON.B7=0;
INTCON.B4=0;
m=0;
display1(m);
while(1)
    {
        while(PORTB.B0==1){
            display1(m);
            PORTC.B4=1;
        }
        if(PORTB.B0==0)
            { m++;
              if (m==10)
                m=0;
              while(PORTB.B0==0)
                {
                    PORTC.B4=0;
                    display1(m);
                }
            }
    }
```