Concept of Capacitance with application to Smartphones

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INTRODUCTION

Capacitors are devices used in almost every circuit, these components can be made of different materials or different sizes or shapes, and the main use of these devices is to store energy temporally, this energy can be used to provide energy to the circuit for a certain time in case the power source is removed, they can be used in other applications such as convert Alternating Current (AC) into Direct Current (DC), where this device will help to provide the energy required in the conversion after the AC voltage has been passed through the bridge rectifier.

The capacitance of these devices can be obtained by multiplication of the charge and voltage, however, there are more factors that can affect the capacitance of the capacitor, different experiments have been carried out, with different insulator materials and the capacitances of these produced will be analysed in this report, in order to understand the importance of these devices, and how they are implemented in new devices such as touchscreens.

CAPACITANCE LAB

THEORY

A capacitor is a device used to store electrical charge temporally, these devices have a simple structure, consisting of two plates of a conducting material placed near each other separated by an insulator material, these devices are charged by using a battery or another power source, once the capacitor is connected to the power source, the two plates quickly became charge, one of the plates acquires a negative charge and the other plate obtain a positive charge when the capacitor is connected in parallel with the power source, the capacitor will acquire the same voltage than the power source, and once the power source is removed from the circuit the capacitor will discharge very quick providing to the circuit the charge that was stored in it, there is a proportional relation between the charge (Q) acquire for each plate and the voltage (V) applies in the circuit and the result of this proportionality is called capacitance (C) and can be obtained by dividing the charge over the voltage (Eq.1)

$$\frac{Q}{V} = C$$

Equation 1: Capacitance formula

The unit obtained from this formula is coulombs per volt, this unit is usually called farad (F), the capacitance not only depends on Q or V, but it can also be affected by different factors such as dimensions of the capacitor, shape, or the material that is used as an insulator [1] These factors provide a new formula that can be used to obtain the capacitance of a capacitor (Eq.2).

$$\varepsilon * \frac{A}{d} = C$$

Equation 2:Capacitance formula

PROCEDURE

This laboratory aims to measure a capacitor's capacitance using different dielectric materials, using different components and devices such as a Digital Storage Oscilloscope (DSO), a resistance box, and metal plates.

To obtain the actual capacitance created by the capacitors it is required to obtain the capacitance of the ODS and the one produced by the cable, these capacitances need to be measured first because they are the source of error when measuring the capacitance of the capacitors.

Once the previous capacitances have been obtained, it is required to analyse the capacitance produced by the different dielectric materials, using the capacitance formula (Eq.2) and the dimensions of the dielectric materials, will be possible to obtain the capacitance that each material will produce, this data can be used to identify the name of the dielectric material used for these experiments.

RESULTS

Digital Storage Oscilloscope capacitance.

Stray capacitance is the unintentional and unwanted capacitance in a circuit, it can appear when two surfaces or components at different electric potentials are closed enough to produce an electric field, it is important to calculate the stray capacitances that the components and materials that are going to be used have, to obtain a more precise result, the capacitance can be obtained by using the time rise (Eq. 3)

$$Rise\,Time\ (10\% - 90\%) = 2.2 * R * C$$

Equation 3: Capacitance and rise time

To obtain the stray capacitance of the circuit, the oscilloscope was connected with a 20 kΩ resistance, with no test capacitance, the time rise obtained from this experiment was 6.6µs, this value was obtained by measuring the 10% and 90% of the voltage that was set up in the oscilloscope, replacing the values used in this experiment in the capacitance equation it is possible to obtain the stray capacitance in the circuit (Eq.4).

$$2.2 * 20k * C = 6.6\mu$$

Equation 4: Stray capacitance

Making the capacitance the subject of the equation a capacitance of 150 pF (Eq.5), this value is the unwanted capacitance produced in the circuit.

$$C = \frac{6.6\mu}{2.2 * 20k}\ ;\ C = 150\rho F$$

Equation 5: Capacitance value

Coaxial cable capacitance.

Not only circuit produces a stray capacitance, but the leads of the components can also produce a stray capacitance, this means that many components used in a circuit or used in electrical connections such as cables can produce capacitance, even though this capacitance is usually small if it is not studied and take it into account, the results obtained when a capacitor is connected will not be accurate, following the same process used to obtain the stray capacitance in the previous experiment a time rise of 12.2µ was obtained, applying this values will be possible to obtain the capacitance (Eq.6).

$$2.2 * 20k * C = 12.2\mu$$

Equation 6: Capacitance

Obtaining a value of 277 pF (Eq.7), however, the value obtained is the result of the cable capacitance plus the capacitance of the oscilloscope because the cable was added in parallel to the stray capacitance.

$$C = \frac{12.2\mu}{2.2 * 20k}\ ;\ C = 277\rho F$$

Equation 7: Total capacitance

To obtain the cable capacitance is required to subtract the capacitance of the digital oscilloscope of 150 pF minus the total capacitance of 277 pF obtaining a capacitance of 127 pF (Eq.8)

$$C = 277\rho F - 150\rho F\ ; C = 127\rho F$$

Equation 8: Cable capacitance

Commercial coaxial cables usually provide the capacitance per unit length produced by the cable, this helps to achieve a better result by using cables with lower capacitance, the cable used for this experiment had a length of 1.2m approximately this means that the capacitance of the cable per unit length is 105 pF/m (Eq. 9).

$$C = 105\rho F/m$$

Equation 9: Capacitance per unit length

RG58 cables usually have a capacitance of 100 pF/m [2] This value is close to the one obtained from the cable used in the experiment with an error of 5 pF/m

Dielectric Constance of FR4

The dielectric constant is the ability of a material to store electrical energy, another important factor that will affect the capacitance is the permittivity of the material, this factor will increase the capacitance produced, the first step is finding the capacitance produced, a parallel plate was used with a large area on one side (terminal G), with two smaller half size areas (terminal A and B) connecting the terminal A with G, a capacitance is obtained (Eq.10)

$$C = \frac{18.2\mu}{2.2 * 20k}\ ;\ C = 414\rho F$$

Equation 10: Total capacitance

The capacitance obtained includes the capacitance of the cable and the stray capacitance of the circuit, this means that those capacitances must be subtracted to obtain the actual capacitance produced by terminals A and G with a value of 137 pF (Eq. 11).

$$C = 414\rho F - 277\rho F\ ; C = 137\rho F$$

Equation *11: A-G Capacitance*

Once the capacitance has been found, it is possible to obtain the permittivity of the material by using the capacitance formula (Eq.2) something important that has to be taken into account is the size of the plates used, once all the data has been placed in the formula, the permittivity can be obtained with a value of 31.3pF/m (Eq.12)

$$\varepsilon = \frac{137\rho * 1.6m}{0.1 * 0.07}\ ;\ \varepsilon = 31.3\ \rho$$

Equation 12: Permittivity

Using the permittivity of the material it is possible to obtain the relative permittivity or dielectric constant (Eq.13).

$$K = \varepsilon_R = \frac{\varepsilon}{\varepsilon_0}$$

Equation 13: Relative permittivity

The permittivity of the material is divided by the permittivity of the vacuum that has a value of 8.854p, the relative permittivity of the FR4 obtained was 3.54 (Eq.14) the value obtained from the calculations it is close to the value of the commercial FR4 that range from 3.8 to 4.8 [3]

$$\frac{31.3p}{8.854p} = \varepsilon_R\ ;\ K = \varepsilon_R = 3.54$$

Equation 14: FR4 Dielectric constant.

The next experiment consists in find the capacitance between terminal G and terminals A and B that are connected, using the time rise to find the capacitance it was possible to obtain a value of 550 pF (Eq.15).

$$C = \frac{24.2\mu}{2.2 * 20k}\ ;\ C = 550\rho F$$

Equation 15: Capacitance

The value obtained includes the total capacitance of the circuit and cable, this means that this capacitance must be removed to obtain the actual capacitance in the plates obtaining a value of 273pF (Eq. 16)

$$C = 550\rho F - 277\rho F\,; C = 273\rho F$$

Equation 16: Capacitance in the plates

A last connection has been done, for this test, terminals A and B are connected, but terminal G is left unconnected, using the time rise of 13.6µs a capacitance of 310pF (Eq.17)

$$C = \frac{13.6\mu}{2.2 * 20k}\,;\; C = 310\rho F$$

Equation 17: Capacitance

Removing the capacitance produced by the cable and the stray capacitance, the actual capacitance of their terminals is obtained with a value of 33 pF (Eq.18)

$$C = 310\rho - 277\rho F\,; C = 33\rho F$$

Equation 18: Capacitance in the plates

In order to prove the dielectric constant obtained in the previous experiments (3.54), the capacitance of the last experiments has been repeated by using the dielectric constant.

$$C = \frac{3.54 * 8.854\rho * 0.1 * 0.14}{1.6m}; C = 274\rho F$$

Equation 19: Capacitance

The value obtained (Eq19) when the dielectric constant was used, was almost the same value obtained in the experiment where terminals A and B were connected with terminal G (Eq19), the small difference in these results is caused for a bad measurement of the plates, or some electrical components was close enough to cause disturbance in the capacitance that was measure giving obtaining a wrong reading.

Dielectric Constance Unknown Material

Different materials have been used for this last experiment, and each material has a different time constant, which means they have a different capacitance as well, for the first time constant a capacitance of 773 pF was obtained (Eq.20).

$$C = \frac{34\mu}{2.2 * 20k}\,;\; C = 773\ \rho F$$

Equation 20: Capacitance

The capacitance obtained contains the capacitance of the cable and the stray capacitance, to obtain the capacitance of the material, these capacitances were removed obtaining a value of 496 pF (Eq.21)

$$C = 773\rho F - 277\rho F\,; C = 496\rho F$$

Equation 21: Capacitance of the material

Using the capacitance, a permittivity of 15.9 pF/m was obtained (Eq.22) using the value of the permittivity was possible to calculate the dielectric constant of the material with a value of 1.8 (Eq.23)

$$\varepsilon = \frac{496\rho * 1m}{0.24 * 0.13}\,;\; \varepsilon = 15.9\ \rho$$

Equation 22: Permittivity

$$\frac{15.9p}{8.854p} = \varepsilon_R\,;\; K = \varepsilon_R = 1.8$$

Equation 23: Dielectric constant

Repeating the same process for the second material, a capacitance of 1 nF was obtained (Eq.24), after subtracting the stray capacitances and the capacitance of the cable, the capacitance of the material was obtained having a value of 723 pF ((Eq.25).

$$C = \frac{44\mu}{2.2 * 20k}\,; C = 1\ nF$$

Equation 24: Capacitance

$$C = 1nF - 277\rho F\,; C = 723\ \rho F$$

Equation 25: Capacitance of the material

Using the capacitance of the material, it was possible to use the capacitance formula to obtain the permittivity produced, obtaining a value of 23.2 pF/m (Eq.26) using this value, the dielectric constant of the material was obtained, achieving a value of 2.62 (Eq.27)

$$\varepsilon = \frac{723\rho * 1m}{0.24 * 0.13}\,;\; \varepsilon = 23.2\ \rho$$

Equation 26: Permittivity

$$\frac{23.2p}{8.854p} = \varepsilon_R\,;\; K = \varepsilon_R = 2.62$$

Equation 27: Dielectric constant of the material

For the last material, a capacitance of 864 pF was obtained (Eq.28), and after subtracting the stray capacitance and the cable capacitance, the capacitance of the material obtained was 587 pF (Eq.29)

$$C = \frac{38\mu}{2.2 * 20k}\,; C = 864\ \rho F$$

Equation 28: Capacitance

$$C = 864\rho F - 277\rho F\,; C = 587\ \rho F$$

Equation 29: Capacitance of the material.

Using the capacitance to obtain the permittivity a value of 18.8 pF/m was obtained (Eq.30), once the permittivity was calculated, the dielectric constant of the material was calculated, obtaining a value of 2.13 (Eq.31)

$$\varepsilon = \frac{587\rho * 1m}{0.24 * 0.13}\,;\; \varepsilon = 18.8\ \rho$$

Equation 30: Permittivity

$$\frac{18{,}8p}{8.854p} = \varepsilon_R \; ; \; K = \varepsilon_R = 2.13$$

Equation 31: Dielectric constant of the material

CAPACITANCE IN SMARTPHONES

SMD Capacitors

The use of Surface-Mount Devices (*SMD*) is very popular in electronic devices, such as laptops, mobile phones and many other devices, where the available space in the Printed Circuit Board (*PCB*) is limited, there are different types of SMD capacitors, and they are used depending on their properties, for example, the specifications of the project, the voltage, capacitance or temperature, based on this, one component will be more suitable than others.

SMD can have some advantages over through-hole capacitors, but a few disadvantages must be considered when designing a circuit (*Table 1*)

Advantages	Disadvantages
Small size	Difficult to repair or change
High performance	Low heat capacity
No leads or holes in the PCB	Difficult manual operation

Table 1: Shows some advantages and disadvantages.

SMD capacitors size and values.

Some of the advantages of these capacitors are the elimination of holes in the PCB, and the reduction of the size of the capacitors, these components have a smaller size compared with the standard through-hole capacitors (*Figure.1*).

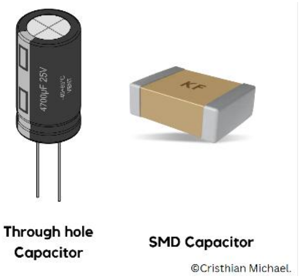

Figure 1: Shows different capacitors

There are a large variety of sizes and values for these components, the size of these components is expressed by using the EIA size code (*Table 2*), this code shows the size of the component in metric code (mm) or Imperial code (in).

CASE CODE	SIZE (mm)	SIZE (inch)
0201	0.6 x 0.3	0.02 x 0.01
0603	1.6 x 0.8	0.063 x 0.031
1206	3.20 x 1.60	0.126 x 0.063
1812	4.5 x 3.2	0.18 x 0.13
1825	4.5 x 6.4	0.18 x 0.25
2512	6.3 x 3.2	0.25 x 0.13

Table 2: SMD capacitor examples

The voltage values of these capacitors can be printed on one of the faces of the component, and the most common voltage range used for these devices can be from 6.3V to around 100V, and to specify the value that a particular capacitor has, it is used the EIA code, this code in SMD capacitor is represented by a letter, this letter represents the maximum voltage that the capacitor can support without exploited or being damaged (*Table 3*).

Code	j	A	C	E	V	H	J	2A
Voltage	6.3	10	16	25	35	50	63	100

Table 3: Shows some examples of the voltage code.

Applications

Capacitors can be used in a huge range of projects, including in the design of devices that use Radio Frequencies (RF), for example, capacitors are used in RF circuits to filter unwanted frequencies, and they can be used with inductors to create different filters that allow only a specific range of frequency to pass through, another use of capacitors in RF circuits is to block the flow of DC current while allowing the AC current to pass, this application is called DC blocking and it is useful for preventing DC offsets from affecting the operation of the circuit.

Capacitors are usually used in power supplies to store electrical charge and smooth out voltage fluctuations, they can be used to regulate the output voltage of a power supply by drawing current from the capacitor to smooth any dips in the input voltage, this produces a more stable power supply to sensitive devices such as smartphones.

They can help in the conversion of AC voltage to DC voltage, in an AC rectification, the input AC voltage is converted to DC voltage using a bridge rectifier which is made up of diodes, however, the output of the bridge rectifier is not a smooth DC voltage, because its output is a wave signal rather than a straight line, because it contains a significant amount of ripples, to smooth out the voltage and remove the ripple, a capacitor is placed across the output of the bridge rectifier, the capacitor will work as a reservoir of electrical charge storing excess charge when the output voltage is high and realising the charge when the output voltage falls below the desired level, this will produce a more stable DC voltage.

The size of the capacitor and the frequency of the AC voltage can have a significant impact on the effectiveness of the smoothing process, usually, large capacitors and lower frequency input voltages result in a smoother output voltage.

Touchscreen Display

Resistive Touchscreen.

One of the simplest touchscreens used in the market incorporates two resistive layers opposing each other with a conducting material, separated by an insulator (Figure 2).

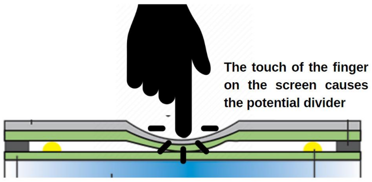

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Figure 2: Resistive Touchscreen

In order to send data to the smartphone or other devices, the screen has to be pressed, the reason for this, is that the resistive layers incorporate a conductive material, however, this material is separated by an insulator, and when the first resistive layer that is made of flexible material is pressed, the conductive material of the resistive layer touches the conductive material of the other resistive layer, this causes a voltage divider in the circuit (*Figure 3*), this is used by the smartphones to identify the location of the finger in the screen panel.

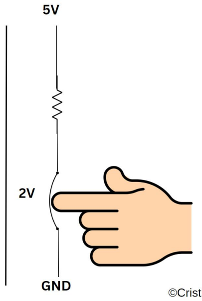

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Figure 3: Voltage divider

Capacitive Touchscreen.

A capacitive touch sensor is a user-friendly technology that allows using capacitors in touchscreen devices such as smartphones, the user can use his finger to control the smartphone, this technology follows a basic concept, to create a capacitor, two components are required, the first one is an insulator or dielectric material, and the second one is the use of two plates of a conductive material separated by the dielectric material, these components form a capacitor, for capacitive touchscreen the same procedure is followed, however, instead of using two conductive plates and only one dielectric material, another dielectric will be added, the reason of this is because, when the user touches the screen which is the second dielectric material it will produce a second capacitor that will be connected in parallel with the capacitor formed with the two conductive plates and the first dielectric material (*Figure 4*), once the user touches a specific area of the screen, a change in the capacitance is produced, this change is detected by the smartphones [4].

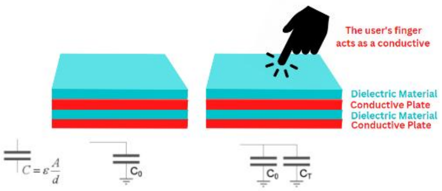

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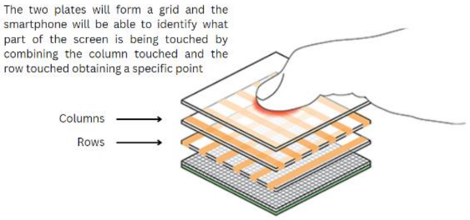
Figure 4: Capacitive Touchscreen.

Even though smartphones can detect the change in capacitance, they cannot detect the specific location that has been touched, to provide a precise approximation of the location that is been touched by the user, the two conductive plates have a specific structure, one of the plates is formed by rows of the conductive material, and the other plate is formed by columns of the conductive material, this will form a matrix arrangement that will be able to detect the specific location touched in the screen panel (*Figure 5*).



The two plates will form a grid and the smartphone will be able to identify what part of the screen is being touched by combining the column touched and the row touched obtaining a specific point

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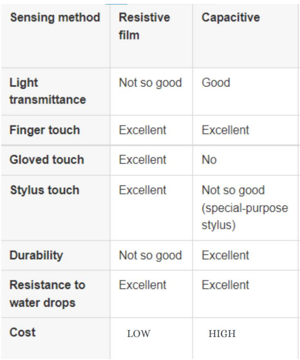
Figure 5: Matrix arrangement

These columns and rows form a grid, and the smartphone will be able to identify the location that is being touched, by checking the column touched and the row touched, the result will be a specific point on the screen panel.

Comparison.

These types of screens have different applications and depending on them, designers and engineers will choose the most appropriate for the device they are producing (*Figure 6*).



Sensing method	Resistive film	Capacitive
Light transmittance	Not so good	Good
Finger touch	Excellent	Excellent
Gloved touch	Excellent	No
Stylus touch	Excellent	Not so good (special-purpose stylus)
Durability	Not so good	Excellent
Resistance to water drops	Excellent	Excellent
Cost	LOW	HIGH

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Figure 6: Comparison of the two methods

Some of the most common differences between these two touchscreens are that a capacitive touchscreen cannot be used if the user is wearing gloves or other insulator material because the insulator material will decrease the capacitance created by the user's finger with the conductive plate of the screen, on the other hand, the resistive touchscreen can be used even if the user is wearing gloves or another insulator material because these screens work once the pressure of the finger touches the screen, this can be considered as an advantage of the resistive screens over the capacitive screens, however, the continuous pressure of the finger on the screen causes that the durability of the screen is reduced compared to the capacitive screen, these advantages and disadvantages of these two touchscreens have to be analysed closely at the moment of choosing one for a design.

Accelerometer

Accelerometers are complex devices that measure the acceleration force in three dimensions (X, Y, Z), these devices can be used for many applications due to their properties, two of the most common accelerometers in the market are Piezoelectric accelerometers and Micro-electro-mechanical Systems (MEMS).

One of the most common applications of these devices is as a sensor rotation in smartphones, the ability of these devices to detect different motions like shaking, lifting or rotation, makes this device a good component to work as a sensor in a smartphone, every time that the user rotates the smartphone, the accelerometer detects this change of motion, and it will send this data to another microchip, that will produce an output that in this case will be the change in orientation of the screen [5]

Another common use of these devices is in the automotive industry, accelerometers are used in collision safety systems, for examples when a car has a collision with another car, the accelerometer detects a rapid deceleration, and sends this data to the microchip of the car that will deploy the airbags. [6]

Piezoelectric accelerometer.

The internal structure of this type of accelerometer is composed of two electrode layers separated by a crystal composition of piezoelectric material(*Figure 7*).

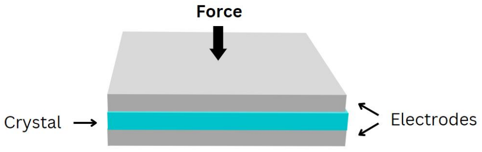

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Figure 7: Piezoelectric accelerometer.

Once a force is applied, the structure of the accelerometer will be disturbed due to the force applied, the electrons inside the crystal material will start moving generating an electric charge, this charge obtained will be proportional to the force that has been applied, once the force has been obtained, it is possible to observe that this device obey Newton's second law (Eq.32).

$$F = m * a$$

Equation 32: Newton's law

Micro-electro-mechanical Systems

This type of accelerometer has a complex design inside of it, it is made of a microscopy mechanism printed directly inside the integrated circuit (IC)(*Figure 8).* It can be used to detect the orientation of the phone and switch between portrait and landscape modes, it can be used in other devices such as tracking steps for a fitness app, or detecting if a phone has been dropped.

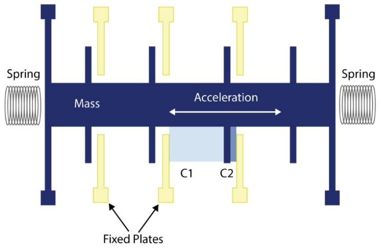

Figure 8: Micro-electro-mechanical Systems

CONCLUSION

Capacitors are important components used in everyday devices, smartphones use the concept of capacitors to create touch screen technology, and the simplicity of its manufacturing makes these devices a good choice for many applications, using two conductive plates and an insulator material it possible to create a capacitor, however, it important to identify some characteristic for the components that are going to be used, for example, the dielectric constant of the material, the distance between the conductive plates, the size of the material, these factors will affect in the capacitance produced by the capacitor, so it's important to track these factors in order to obtain the desired capacitance, finally, many electronic devices produce capacitance, however, this capacitance is unintentionally, but it can cause an incorrect capacitance measurement if it is not taken into account.

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