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The high capacitance for electrode structure of interdigital capacitor thin film models

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Abstract

This paper presents the outcomes of a study to determine the capacitance and electrical properties of interdigital capacitors (IDCs) thin film in 3 models. Three models of IDCs thin film were designed and fabricated on standard FR-4 PCB board using dc magnetron sputtering. The three IDCs thin film models have the same electrode material, the number of electrodes, the length, and the width of electrode but differ in electrode structure. The electrode material is silver (Ag). The capacitance, resistance, impedance, and conductance of IDCs thin films were measured and analyzed by LCR-6100 at room temperature. The electrode structure has a significant effect on the electrical properties of IDCs thin films. The new models of IDCs thin film, model 2 and model 3, show high capacitance in the range frequency of 1 – 100 kHz compare with general IDCs.

Keywords: Electrode thin film; DC magnetron sputtering; Electrical properties; Interdigital capacitors

1. Introduction

Interdigital capacitors (IDCs) have been investigated by many researchers because they have a simple design, inexpensive manufacturing, and can be easily combined with other electronic components. The characteristics of IDCs have been studied extensively [1, 2] and have demonstrated high performance when used as sensor applications in biology, physics, chemistry and other scientific fields. Among other sensor technologies [2, 3], interdigital capacitors have been used in many other applications, strain gauges investigations and permittivity measurements [4, 5], humidity sensing application [6], the application of detection dangerous marine biotoxins in seafood [7], studied in the dielectric properties of polymer films [8], microwave applications [9], and many more.

Many descriptions have been given to the interdigital capacitors according to the application, and overall it can be concluded that the interdigital capacitors are the configuration of the periodic electrode [4]. Although new model has been developed, the working principle of IDCs remains based on parallel plate capacitors. By applying various potentials for each electrode, the electric field is produced between the positive electrode and the negative electrode. The electric field moves from the positive electrode to the negative electrode which passes through the material under test (MUT) and the substrate.

The conventional model of IDCs uses PCB and the material layer of PCB is copper [3, 10]. The conventional model pattern of IDCs consists of two electrode lattice-like comp in the xy plane, each electrode lattice composed of N fingers. Each finger has a width (w) and the gap between two adjacent fingers (g). The periodic spacing between the center lines of the two electrodes of the same type is called unit cell. The unit cell for the new and the conventional models of IDCs depend on the number of electrodes between two similar types of electrode [11, 12].

Three models of interdigital capacitors have been fabricated using dc magnetron sputtering. The Ag thin film electrodes are deposited on the surface of the FR-4 substrate. The substrate of each IDCs thin film has the same area of 20×50 mm^2 and gap of 0.50 mm. All models have the same length of electrodes of 15.00 m, the gap between two adjacent electrodes of 0.50 mm, and the electrodes width of 0.50 mm. Three IDCs thin film models are compiled in the same numbers of electrodes but differ in positive and negative electrodes structure.

This study aims to evaluate the capacitance and electrical properties of IDCs thin film to determine the impact of electrodes structure of IDCs thin film and to determine the best model for sensors. Measurements are conducted for serial equivalent capacitance (C_s), serial equivalent resistance (R_s), impedance (Z) and conductance (G) parameters for each IDCs thin film model.

2. Materials and Methods

Interdigital capacitors design

Fig. 1 shows 3 models of IDCs thin film structure. IDCs thin film configuration 1 or model 1 is a conventional model of interdigital capacitors. It has one negative electrode on each unit cell between two positive electrodes, as shown in Fig. 1 (a). IDCs thin film model 2 and model 3 are designed with different electrode structures to investigate the impact of the number of negative electrodes between two positive electrodes. There are three negative electrodes between two positive electrodes in model 2. Different from model 2, model 3 has five negative electrodes between two positive electrodes. Fig. 1 (b) and (c) show the representation of interdigital capacitors model 2 and model 3, respectively.

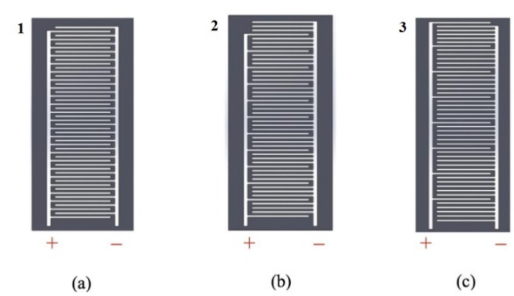

Fig. 1 Three models structure of IDCs thin film

Derivation of IDCs Capacitance

Capacitance is a measure of the amount of charge that must be held to produce a potential difference between the positive and negative terminals, the greater the capacitance the more charge is required. In another definition, the capacitance is a pure geometric quantity determined by the size, shape, and separation of the two conductors. The evaluation of the capacitance of a conventional IDCs or model 1 for 48 electrodes configurations is shown in Fig. 2.

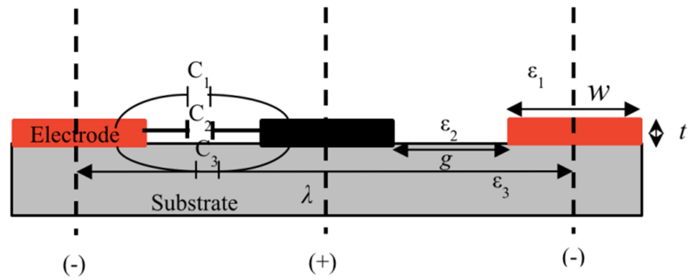

Fig. 2 Cross section view of IDCs thin film model 1

The capacitance of IDCs thin film model 1 is obtained by the number of unit cell capacitance (C_{uc}) and multiplied by the length of the electrode. The total capacitance of IDCs thin film model 1 is as follows,

$$C_{uc} = C_2 + 2(C_1 + C_3) \tag{1}$$

where, C_1 is the capacitance between two adjacent electrode (positive and negative electrode) that the electric field lines pass through the medium above the electrode film. C_2 is the capacitance between two adjacent electrode that the electric field lines pass through the medium between the electrode film. C_3 is the capacitance between two adjacent electrode that the electric field lines pass through the substrate of IDCs.

The electric field lines in C_2 are straight horizontal lines from the positive electrode to the adjacent negative electrode as shown in Fig. 2. The equation for C_2 is

$$C_2 = \varepsilon_0 \varepsilon_r \frac{t}{g} \tag{2}$$

The electric fields lines in C_1 and C_3 are in the form of curved lines from the positive electrode to the adjacent negative electrode as shown in Fig. 2. The equation for C_1 and C_3 is using complete elliptic integral of the first kind (K).

$$C_1 + C_3 = \frac{\varepsilon_0(\varepsilon_r + \varepsilon_s)}{2} \frac{K\sqrt{1-k^2}}{K(k)} \tag{3}$$

So the unit cell capacitance for model 1 is,

$$C_{uc} = \varepsilon_0(\varepsilon_r + \varepsilon_s) \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} + 2\varepsilon_0 \varepsilon_r \frac{t}{g} \tag{4}$$

where, ε_0 is vacuum permittivity (8.854×10^{-12} F m^{-1}), ε_r is relative permittivity or dielectric constant of MUT, ε_s is dielectric constant of the substrate, g is distance between the electrodes (m), λ is length of the unit cell (m), λ is obtained from w + g, w is width of electrode, $k = \frac{g}{2\lambda}$, t is thickness of the electrode (m) and *K* is complete elliptic integral of the first kind.

The total capacitance of IDCs thin film model 1is calculated by the equation:

$$C_{TOTAL} = C_{uc}(N-1)L \tag{5}$$

where N is the number of unit cell and L is the length of electrodes (m). The capacitance equation of IDCs thin film model 1 was studied by many researchers [1, 3].

Fig. 3 shows a cross section view of the IDCs thin film model 2. The two positive electrodes separated by three negative electrodes. Based on the equations (1) – (4), we can obtain the equations the IDCs thin film model 2. The unit cell capacitance is as follows,

$$C_{uc} = 2C_2 + 2(C_1 + C_3) + 2(C_4 + C_5) + 2(C_6 + C_7) \tag{6}$$

where, for C_1, C_2 and C_3, the explanations are the same as model 1, C_4 is the capacitance between positive electrode to the second negative electrode that the electric field lines pass through the medium above the electrode film, C_5 and C_7 are the capacitance between positive electrode to the second and third negative electrode, respectively, that the electric field lines pass through the substrate of IDCs and C_6 is the capacitance between positive electrode to the third negative electrode that the electric field lines pass through the medium above the electrode film.

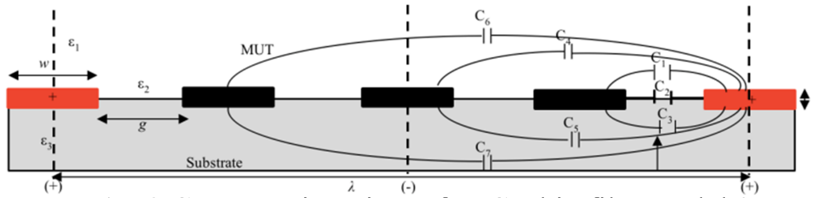

Fig. 3 Cross section view of IDCs thin film model 2

The equation C_2 for model 2 is similar with model 1, equation (2). The electric fields lines in C_1, C_3, C_4, C_5, C_6 and C_7 are in the form of curved lines from the positive electrode to the negative electrode as shown in Fig. 3. The equations of C_1, C_3, C_4, C_5, C_6 and C_7 are using complete elliptic integral of the first kind (K).

$$C_1+C_3=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_1^2}}{K(k_1)} \tag{7}$$

where, $k_1=\frac{g_1}{\lambda}=\frac{g}{4(w+g)}$

$$C_4+C_5=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_2^2}}{K(k_2)} \tag{8}$$

where, $k_2=\frac{g_2}{\lambda}=\frac{3g}{4(w+g)}$

$$C_6+C_7=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_3^2}}{K(k_3)} \tag{9}$$

where, $k_3=\frac{g_3}{\lambda}=\frac{5g}{4(w+g)}$

The unit cell capacitance for model 2 is,

$$C_{uc}=\varepsilon_0(\varepsilon_r+\varepsilon_s)\left(\frac{K\sqrt{1-k_1^2}}{K(k_1)}+\frac{K\sqrt{1-k_2^2}}{K(k_2)}+\frac{K\sqrt{1-k_3^2}}{K(k_3)}\right)+2\varepsilon_0\varepsilon_r\frac{t}{g} \tag{10}$$

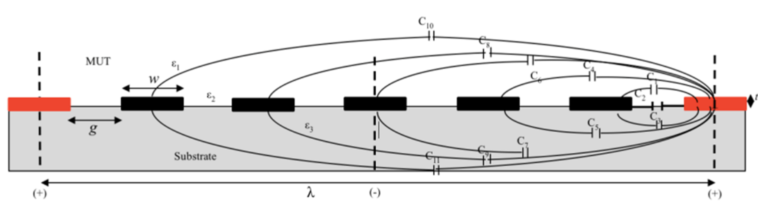

Fig. 4 Cross section view of IDCs thin film model 3

Fig. 4 shows a cross section view of the IDCs thin film model 3. The two positive electrodes separated by five negative electrodes. Similar to the derivation of model 2, we can know the equation of IDCs thin film model 3 as follows,

$$C_{uc}=2C_2+2(C_1+C_3)+2(C_4+C_5)+2(C_6+C_7)+2(C_8+C_9)+2(C_{10}+C_{11}) \tag{11}$$

where, C_1, C_2, C_3, C_4, C_5 and C_6, the explanations are the same as model 2. C_8 and C_{10} are the capacitance between positive electrode to the fourth and fifth negative electrode, respectively, that the electric field lines pass through the medium above the electrode film. C_9 and C_{11} are the capacitance between positive electrode to the fourth and fifth negative electrode, respectively, that the electric field lines pass through the substrate of IDCs.

The equation C_2 for model 2 is similar with model 1 and model 2, Eqs. (2). The electric fields lines in C_1, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10} and $C_{11}$are in the form of curved lines from the positive electrode to the negative electrode as shown in Fig. 4. The equations of C_1, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10} and C_{11} are using complete elliptic integral of the first kind (K).

$$C_1+C_3=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_1^2}}{K(k_1)} \tag{12}$$

where, $k_1=\frac{g_1}{\lambda}=\frac{g}{6(w+g)}$

$$C_4+C_5=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_2^2}}{K(k_2)} \tag{13}$$

where, $k_2=\frac{g_2}{\lambda}=\frac{3g}{6(w+g)}$

$$C_6+C_7=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_3^2}}{K(k_3)} \tag{14}$$

where, $k_3=\frac{g_3}{\lambda}=\frac{5g}{6(w+g)}$

$$C_8+C_9=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_4^2}}{K(k_4)} \tag{15}$$

where, $k_4=\frac{g_4}{\lambda}=\frac{7g}{6(w+g)}$

$$C_{10}+C_{11}=\frac{\varepsilon_0(\varepsilon_r+\varepsilon_s)}{2}\frac{K\sqrt{1-k_5^2}}{K(k_5)} \tag{16}$$

where, $k_5=\frac{g_5}{\lambda}=\frac{9g}{6(w+g)}$

The unit cell capacitance for model 3 is,

$$C_{uc}=\varepsilon_0(\varepsilon_r+\varepsilon_s)\left(\frac{K\sqrt{1-k_1^2}}{K(k_1)}+\frac{K\sqrt{1-k_2^2}}{K(k_2)}+\frac{K\sqrt{1-k_3^2}}{K(k_3)}+\frac{K\sqrt{1-k_4^2}}{K(k_4)}+\frac{K\sqrt{1-k_5^2}}{K(k_5)}\right)+2\varepsilon_0\varepsilon_r\frac{t}{g} \tag{17}$$

The total capacitance of IDCs thin film model 2 and 3 use the equation (5) by substituting the unit cell capacitance equation (11) and (18), respectively.

Interdigital capacitors fabrication and measurement

The thin film electrode material is pure Ag target (99.99%, ULVAC, Thailand) at 60 mm diameters and 3 mm thickness. The substrate material is FR-4 PCB board with a thickness of 2 mm, the length and width of which is adjusted to the mask design. The thin film electrode of interdigital capacitors is deposited on the substrate by using dc magnetron sputtering system [13]. The deposition conditions are the base pressure of 7.90×10^{-5} Pa, operating pressure of 1.50×10^{-2} Pa, Ar flow rate of 2.50 sccm, current flow of 0.15 A, and deposition time of 5 minutes, respectively. Before deposition process of thin film in vacuum chamber, first, the substrate must be cleaned by water and soap then put into a glass box containing acetone in an ultrasonic cleaner for 15 minutes, then dried with air compressor. The mask fixed to the surface of substrate that has been cleaned. Then, it fixed to the aluminium plate as anode by using polyamide. The anode is placed in a vacuum chamber 6 cm under the target [14].

The measurement of electrical parameters performed by LCR-6100 REV C7.05 Basic Accuracy 0.05% measuring device in room temperature, 27 °C. Each electrode is connected to the measuring device. After the measurement system has been setup, the measurements are conducted serial equivalent capacitance (C_s), serial equivalent resistance (R_s), impedance (Z) and conductance (G) parameters at the constant voltage 2.00 V and in the range of frequency 1 – 100 kHz, in 20 replicates for each model of IDCs thin film.

3. Results and Discussion

The serial equivalent capacitance of IDCs thin film is tested to determine the performance of each model of IDCs thin film as a capacitor in the range of frequency 1 – 100 kHz. The capacitance measurement result is the number of the unit cell capacitance of the electric field parallel lines. The electric field lines pass through the substrate and the material under test or medium above and between the electrode film. Equation (4) is for model 1, Eqs. (10) is for model 2 and Eqs. (17) is for model 3. The medium above the electrode film for the measurements is air. The structure and electrical parameters in the frequency range 1 – 100 kHz of each model as shown in Table 1.

Table 1 The structure and electrical parameters in the frequency range 1 – 100 kHz of each model.

Parameter	Model 1	Model 2	Model 3
Number of electrode on each unit cell	1 negative electrode between 2 positive electrodes	3 negative electrodes between 2 positive electrodes	5 negative electrodes between 2 positive electrodes
Capacitance (F)	order of 10^{-11}	order of 10^{-10}	order of 10^{-10}
Resistance	decreased	increased	increased
Conductance	smoothly increased	decreased	decreased
Impedance	decreased	decreased	decreased

The study demonstrated that serial equivalent capacitance (C_s) values of IDCs thin film model 2 and 3 smoothly increased and relatively constant in order of 10^{-10} F with increasing frequency, but smoothly decreased and relatively constant in order of 10^{-11} F for IDCs thin film model 1 as shown in Fig. 5. The graph of IDCs thin film model 2 displays the similar path as the graph of IDCs thin film model 3. They have the same structure but differ in configuration. The capacitance of IDCs thin film model 2 is greater than IDCs thin film model 3 over frequency range of 1 – 100 kHz, since the number of negative electrode of IDCs thin film model 3 is more than IDCs thin film model 2, so the unit cell distance of IDCs model 3 is longer than IDCs model 2 which is affected to the electric field line between the positive and negative electrodes.

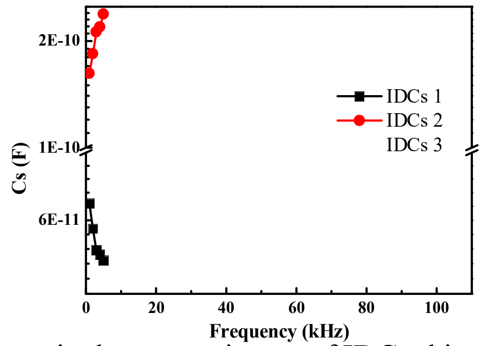

Fig. 5 The serial equivalent capacitance of IDCs thin film dependence on frequency

The capacitance due to the effect of frequency variation has been studied by Li et all which describes the capacitance of Ag on FR-4, similar with IDCs model 1, with typical Ag line dimensions were 25 – 50 µm thick, 300 – 400 µm wide, 8 – 14 mm electrode length, 0.20 – 1 mm gab between electrode and the number of electrodes ranged from 10 to 24, have a nominal capacitance of 4 – 25 pF. But the capacitance of Ag on graphite composite and Ag on alumina gauges are relatively constant in the range of 1 – 100 kHz, with the value capacitance of 13 and 7.50 pF, respectively [15]. Ren et all were investigated the capacitance of BST thin film capacitive sensor in the frequency from 15 – 500 kHz at 20 °C and 200 °C . The capacitance decreased in the frequency range of 15 – 400 kHz while increased gradually above 400 kHz. The relationship between the capacitance at the frequency can be explained by the Debye equation, where the dielectric permittivity decreased with increasing frequency [5].

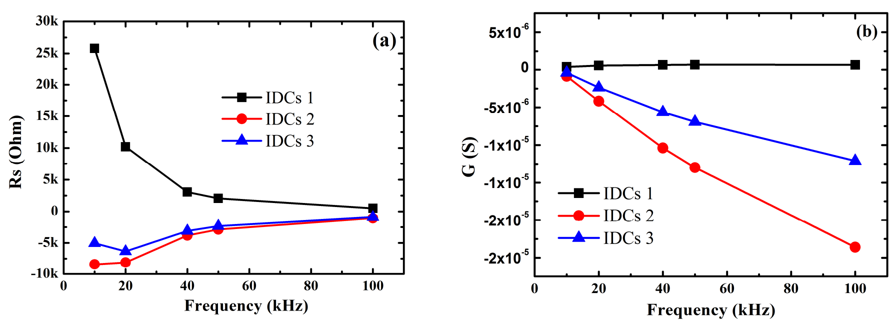

Fig. 6 The relationship between frequency with (a) serial equivalent resistance and (b) conductance of IDCs thin film

Fig. 6 (a) shows the measurement result of serial equivalent resistance of IDCs thin film in the frequency range 1 – 100 kHz. The conventional model of IDCs thin film or model 1 has a different path with other models. The serial equivalent resistance of model 1 has sharply decreased at frequency 10 – 40 kHz and smoothly decreased at frequency 50 – 100 kHz. The resistance value of model 2 and model 3 decrease in the range of frequency 1 – 2 kHz. Model 2 and model 3 have negative results and the same trend line at frequency 10 – 100 kHz. At a frequency of 100 kHz, all models have almost the same serial equivalent resistance value that seems to be the same point. This result is different from the result of conductance measurement as shown in Fig. 6 (b). Model 1 has a positive value of conductance but negative value for model 2 and model 3. The conductance value of model 1 was smoothly increased with increasing frequency, 3.78×10^{-7} S at 10 kHz to 6.58×10^{-7} S at 100 kHz. Model 2 and model 3 have contrary result from model 1, the conductance of models 2 and model 3 have negative value in the range of frequency 10 – 100 kHz and decreased with increasing frequency.

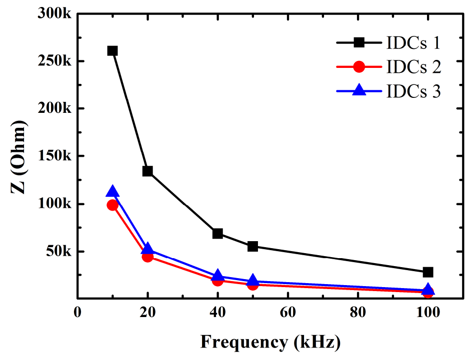

Fig. 7. The impedance of IDCs thin film dependence on frequency

Based on the measurement result, serial equivalent resistance and conductance model 2 and model 3 have positive values at frequency 1 – 2 kHz and have negative values at frequency 10 – 100 kHz. Resistance represents a measure of how difficult electrons go through a component while conductance is the inverse, namely the ease of electrons through a component. Mathematically, the relationship between conductance and resistance of interdigital capacitors is G = (1/R) which corresponds to the conductivity of the same geometrical term (A/g) that connects relative capacitances and permittivity. A is the area of the electrode and g is the gap between two adjacent electrodes [10].

The IDCs thin film impedance measurement results are shown in Fig. 7. All models have the same path, impedance values decrease along with increasing frequency value. The electric field lines generated by the periodic electrode of IDCs thin film pass through into the material under test (air) and substrate, thus causing IDCs thin film impedance changes. In a previous study, the sensor system for detecting dangerous bio toxins in seafood by Syaifudin et al, the impedance of IDCs thin film can be calculated by:

$$Z = \frac{V_e}{I} = \frac{V_e}{V_{sen}/R_s} = \frac{V_e}{V_{sen}} \times R_s \tag{18}$$

where V_e is the voltage through the IDCs thin film; V_{sen} is the voltage through the serial equivalent resistance, R_s; I is the current flowing in the sensor [7].

4. Conclusion

Three different models of interdigital capacitors are designed, fabricated, measured and analyzed. The electrical properties of IDCs thin film differ from one another which show the impact of the electrodes structure of interdigital capacitors. The new models of IDCs thin film (model 2 and model 3) have a greater capacitance more than conventional IDCs thin film, model 1 in the frequency range of 1 – 100 kHz.

5. Suggestions

Further research can be optimized to find out the best design.

6. Acknowledgements

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