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Fabrication and Characterization of Interdigital Capacitors Thin Film by DC Magnetron Sputtering for Measuring the Permittivity of Crude Oil

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Abstract

The Interdigital Capacitors (IDCs) are integrated circuits within metal fingers electrode for measurement of specific properties. A new model has been carried out for fabrication and characterization of silver and copper thin film electrode of IDCs for the measurement of crude oil permittivity. Thin film electrode was fabricated by Direct Current (DC) Magnetron Sputtering method using silver and copper target on Flame Resistant (FR)-4 Printed Circuit Board (PCB). The electrode configuration was composed in seven designs.The experimental results show that, IDCs thin film has a great potential to determine the permittivity of crude oil.

Keywords: thin film; interdigital capacitors; DC magnetron sputtering; permittivity; crude oil

1. Introduction

Crude oil exhibits wide variations in composition and properties, and these variations not only occur in from different fields but also manifested in petroleum taken from different production depths in the same well. Generally, crude oil consists of a complex mixture of various hydrocarbons and some non-hydrocarbon components [1]. One of the important steps in the processing of crude oil is the heating of crude oil [2]. This process aims to eliminate vapors and reduce viscosity crude oil. One of the physical properties that affect the heating process of crude oil is permittivity. The permittivity value is determined by the material's ability of the polarized medium to provide or allow an electric field, which ultimately reduces the electric field in the material. The permittivity of a material is closely related to the capacitance of the capacitor on a dielectric material.

The parallel plate capacitor technology has been developed in the form of a periodic electrode configuration printed on Flame Resistant (FR)-4 Printed Circuit Board (PCB) called an interdigital capacitors (IDCs). IDCs have been widely researched and developed due to their low cost and easy to combine with other electronics signal processing and processing components. IDCs have been used since 1970 in many applications, such as dielectric constant measurement of the complex material [3], [4], measurement of relative permittivity and sugar concentration in sugar solution [5] and measurement of fluid dielectric properties by measuring the change in capacitance [6]. The sensor application depends on both the characteristics of the particular sensor and the characteristics of material under test (MUT).

The purpose of this paper is to development thin film electrode of interdigital capacitors by DC magnetron sputtering method, using silver and copper target on FR-4 PCB substrate. The application of interdigital capacitors thin film is to measure permittivity of crude oil. The crude oil sample is taken from well of petroleum resource A in PT Pertamina Cepu (TBR 1).

2. Interdigital Capacitors

Interdigital capacitors (IDCs) is a sensor shaped like a comb, has periodically electrode patterns and printed on the board, usually uses a printed circuit board (PCB). Interdigital capacitors consists of two electrodes pattern, positive and negative electrodes in the *xy* plane. The distance spatially periodic of interdigital cell, called a unit cell, can be defined as the distance between the centre line of the electrode to the same nearest electrode [7]. The design of interdigital capacitor is shown in Fig. 1 .

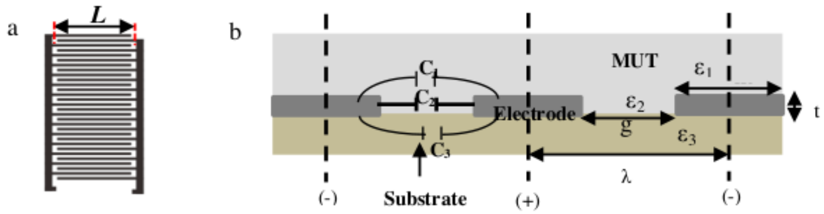

Fig. 1. (a) Top view and (b) cross section view of interdigital capacitors [8].

The capacitance was determined by summing the unit cell capacitance (C_{uc}) and the unit cell capacitance is obtained by summing C_1, C_2 and C_3 for a parallel circuit as shown in Fig.1.

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

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

where ε_r is the dielectric constant of MUT, ε_s is the dielectric constant of the substrate, g is the distance between the electrodes (m), λ is the length of the unit cell (m), λ is obtained from $w + g$, w is width of electrode, $k = \frac{g}{2\lambda}$, t is the thickness of the electrode (m) and K is complete elliptic integral of the first kind. The total capacitance of IDCs is calculated by the equation:

$$C_{TOTAL} = C_{uc}(N-1)L \tag{3}$$

where N is the number of unit cell and L is the length of electrodes (m) [7]-[9].

3. Fabrication of Interdigital Capacitors

The IDCs silver (Ag) and copper (Cu) thin films were fabricated by using DC magnetron sputtering in Thin Film Research Laboratory (TFR-L), Sakon Nakhon Rajabhat University (SNRU), Thailand. This sputtering system consists of: DC power supply, gas controls, vacuum pump unit, vacuum chamber and cooling system [9]-[11].

Substrates of FR-4 PCB were cleaned by acetone, methanol and distilled water in ultrasonic cleaner for 20 minute respectively, then dried by air compressor. Finally, the masks were attached on the substrate and laid the substrate holder in vacuum chamber, 6 cm above the target. The Ag and Cu thin films were deposited by using DC magnetron sputtering in high purity argon (99.99%) at vacuum state and the intensity of magnetic field above the erosion track more than 60 mT. The deposition conditions are shown in Table 1.

Table 1. Deposition condition of Ag and Cu thin films by DC magnetron sputtering

Parameter	Ag	Cu
Base Pressure (Pa)	0.03	0.8
Operating Pressure (Pa)	1.2	3
Voltage (Volt)	520-570	600-700
Current flow (A)	0.1	0.12
Vacuum chamber Temperature (°C)	30-50	30-50
Deposition time (minute)	5	10
Substrates	PCB	PCB
Film thickness (μm)	1	1

The sputtering results is shown in Fig. 2, (a) for IDCs silver thin film and (b) for IDCs copper thin film. There are seven designs in each IDCs thin film. The configuration of each design, like length (L), width (w), gab between electrodes (g), electrode thickness (t) and number of electrodes (n), is shown in Table 2. The thin film thickness of all designs are same, about 1 μm. It was measured by using Tolansky method.

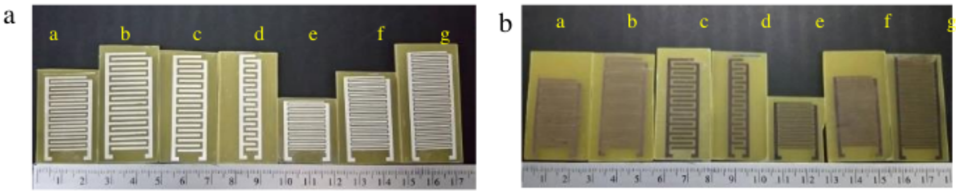

Fig. 2. IDCs thin film (a) Silver (Ag) and (b) Copper (Cu).

4. Characterization of Interdigital Capacitors Thin Film

The thin film of IDCs have been characterized by measure the resistance of IDCs, the crystal structure using X-Ray diffraction (XRD) in TRC Laboratory SNRU, the capacitance of IDCs and the permittivity of crude oil in instrumentation laboratory of ITS. The tools and material of measurement permittivity of crude oil are: PM 6303A RCL meter type Phillip, thermometer TM-903A, thermocouple K and crude oil.

Table 2. Resistance and Capacitance of IDCs thin film

Design	L(mm)	w(mm)	g(mm)	t(μm)	n	R_{Ag}(Ω)		R_{Cu}(Ω)		C_{Ag}(pF)	C_{Cu}(pF)
						1	2	1	2		
a	15	0.75	0.75	1	20	7.8	6.8	21.9	11.6	8.0	8.6
b	15	1	1	1	20	8.1	9.1	25.1	38.1	8.0	8.5
c	10	1	1	1	20	6.9	6.3	41.0	70.8	5.5	6.0
d	5	1	1	1	20	4.6	4.8	40.2	56.0	3.7	4.2
e	15	0.5	0.5	1	20	5.3	5.1	52.5	41.2	7.8	8.4
f	15	0.5	0.5	1	30	6.4	6.8	42.9	37.3	12.3	12.7
g	15	0.5	0.5	1	40	10.7	13.8	42.6	56.1	16.5	16.7

Table 2 shows the resistance value both of electrode fingers. It has almost the same value that is indicate the thin film characteristics by the sputtering process both of electrode fingers have almost the same characteristics. The resistance of each design has different values because it depends on the material resistivity, length and cross-sectional area as in the equation below:

$$R = \rho \frac{L}{A} \quad (6)$$

where *R* is the resistance (Ω), *ρ* is the resistivity of thin film material (Ωm), *L* is the length of electrode fingers (m) and *A* is the cross-sectional area (m^2). The resistivity of silver and copper at 298, respectively are $1.617 x 10^{-8}$ Ω m and $1.712 x 10^{-8}$ Ω m [12]. Copper resistivity is higher than silver resistivity so it is directly proportional to the value of resistance.

The capacitance value both of IDCs Ag and Cu thin film is almost same because the capacitance only depends on the geometric factor. The longer the length of electrode, the smaller the gab of electrode, the more number of electrodes is proportional to the capacitance value that is corresponds to equation (4) and (5).

Characterization of IDCs silver (Ag) thin film indicates the thin film test result in accordance with Ag reference data as shown in Fig 3 (a). The graph shows that there are four peaks in the range of intensity 20° - 80°, i.e., 38.1, 44.46, 64.3 and 77.44 with d_{hkl} values respectively are 111, 200, 220 and 311. The system of silver crystal is cubic with lattice parameters of 4.08562 Å while the lattice parameter value of Ag reference is 4.0862 Å. The average value of the silver crystals size is 309.6025 Å from the four crystals size: 259.78, 193.13, 234.89 and 550.61. The calculation result of lattice strains are 0.0095, 0.0112, 00065 and 0.0024 and the average value is 0.0074.

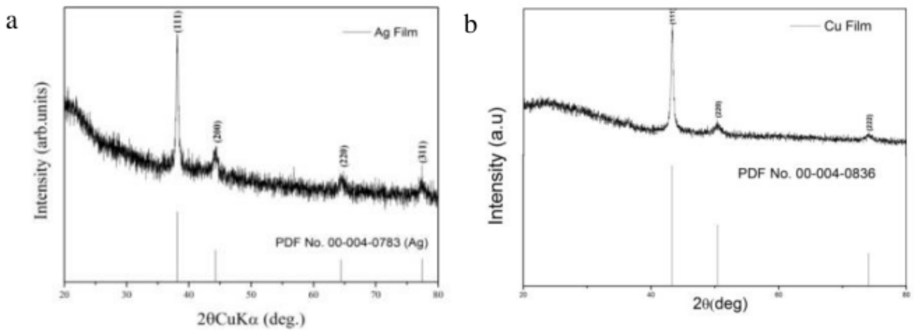

Fig. 3. (a) XRD results of (a) silver thin film (Ag) compared Ag references (PDF No. 00-004-0783) and (b) copper thin film (Cu) compared Cu references (PDF No. 00-004-0836)

Characterization of IDCs Cu thin film shows in Fig. 3 (b). There are three peaks intensities in the range of 20° - 80°, i.e., 43.3054, 50.468 and 73.9202 with d_{hkl} values respectively are: 111, 220 and 222. The system of copper crystal is cubic with lattice parameter values is 3.58721 Å. The average value of copper crystal size is 662.63 Å from three crystal sizes: 286.26, 747.5 and 954.13. The calculation result of lattice strains are 0.0073, 0.0025 and 0.0014 and the average value is 0.0037.

Table 3. Capacitance and relative permittivity of crude oil

Design	**Ag**		**Cu**	
	C (pF)	**ε_r**	**C(pF)**	**ε_r**
a	9.6	4.40	10.5	5.26
b	9.5	4.31	10.3	5.07
c	6.4	4.40	6.8	4.97
d	4.3	7.54	4.9	9.26
e	9.1	3.92	9.7	4.50
f	14.0	3.83	14.2	3.95
g	17.5	3.15	18.5	3.60

Fig. 4. Set up of measurement relative permittivity of crude oil

The relative permittivity of crude oil was measured by – 1 kHz frequency of PM 6303A RCL meter at room temperature 26.6° C as shown in Fig. 4. The measurement results crude oil capacitances are used to calculate the relative permittivity of crude oil by using the equations (4) and (5). The relative permittivity of FR-4 PCB board is 4.75. The calculation result of crude oil relative permittivity is shown in Table 3.

The relative permittivity values of crude oil were measured by using IDCs Ag thin film and Cu thin film as a sensor, relatively are 4.51 and 5.23. The difference of relative permittivity is due to the difference types of thin film materials that is affected the measurement sensitivity. When the frequency increased the relative permittivity will decreased. The effect of the electric field frequency on the dielectric constant value of crude oil can be shown in the equation:

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{(\omega^2 - \tau^2)} \quad (7)$$

ε_∞ is permittivity at high frequencies where the material cannot longer be polarized so the value is close to 0, ε_s is permittivity at low frequencies so the value is close to 1, τ is relaxation time and $\omega = 2\pi f$.

The sensitivity of IDCs Ag thin film is higher than Cu thin film because the average value closed to the reference data [13]. While, based on the electrode configuration, the most sensitive design is g that is influenced by the length, the gab and the number of electrodes so it is proportional to the capacitance value. The measurement result of design d is farthest from the reference values due to the shortest of the electrode length so the sensitivity is low.

5. Conclusion

This paper has reported a new model for the measurement of crude oil permittivity. The Interdigital Capacitors thin film has been fabricated by DC Magnetron Sputtering method and characterized by X-ray diffraction. Thin film electrode was deposited using silver and copper target. The deposition conditions of Ag and Cu thin film are different. The resistances of each electrode fingers have almost the same value that is indicate both of electrode fingers have almost the same characteristics. The characterization of IDCs Ag and Cu thin film by X-ray diffraction indicates that the thin film test result in accordance with reference data. The relative permittivity of crude oil was measured by – 1 kHz frequency of PM 6303A RCL meter at room temperature 26.6 °C. The measurement result of relative permittivity of crude oil by using IDCs Ag thin film g design is 3.15.

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