Design of interdigital spiral and concentric capacitive sensors for materials evaluation

Tianming Chen
Skyworks Solutions

Nicola Bowler
Iowa State University, nbowler@iastate.edu

Follow this and additional works at: http://lib.dr.iastate.edu/cnde_conf
Part of the Electrical and Computer Engineering Commons, and the Materials Science and Engineering Commons

The complete bibliographic information for this item can be found at http://lib.dr.iastate.edu/cnde_conf/15. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
Design of interdigital spiral and concentric capacitive sensors for materials evaluation

Abstract
This paper describes the design of two circular coplanar interdigital sensors with i) a spiral interdigital configuration and ii) a concentric interdigital configuration for the nondestructive evaluation of multilayered dielectric structures. A numerical model accounting for sensor geometry, test-piece geometry and real permittivity, and metal electrode thickness has been developed to calculate the capacitance of the sensors when in contact with a planar test-piece comprising up to four layers. Compared with a disk-and-ring coplanar capacitive sensor developed previously, the interdigital configurations are predicted to have higher signal-to-noise ratio and better accuracy in materials characterization. The disk-and-ring configuration, on the other hand, possesses advantages such as deeper penetration depth and better immunity to lift-off variations.

Keywords
capacitive sensors, dielectric materials, electrodes, geometry, interdigital transducers, nondestructive testing, numerical analysis, nondestructive evaluation, QNDE, Materials Science and Engineering, Electrical and Computer Engineering

Disciplines
Electrical and Computer Engineering | Materials Science and Engineering

Comments
Copyright 2013 American Institute of Physics. This article may be downloaded for personal use only. Any other use requires prior permission of the author and the American Institute of Physics.

This article appeared in AIP Conference Proceedings 1511 (2012): 1593–1600 and may be found at http://dx.doi.org/10.1063/1.4789232.
Design of interdigital spiral and concentric capacitive sensors for materials evaluation

Tianming Chen and Nicola Bowler

Citation: AIP Conf. Proc. 1511, 1593 (2013); doi: 10.1063/1.4789232
View online: http://dx.doi.org/10.1063/1.4789232
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1511&Issue=1
Published by the American Institute of Physics.

Related Articles
Curved noncommutative torus and Gauss–Bonnet

Shortcomings of the bond orientational order parameters for the analysis of disordered particulate matter

Noncommutative residue and sub-Dirac operators for foliations

Formation of surface nano-structures by plasma expansion induced by highly charged ions

Applied Koopmanism
Chaos 22, 047510 (2012)

Additional information on AIP Conf. Proc.
Journal Homepage: http://proceedings.aip.org/
Journal Information: http://proceedings.aip.org/about/about_the_proceedings
Top downloads: http://proceedings.aip.org/dbt/most_downloaded.jsp?KEY=APCPCS
Information for Authors: http://proceedings.aip.org/authors/information_for_authors

Advertisement

Explore AIP’s new open-access journal
- Article-level metrics now available
- Join the conversation! Rate & comment on articles

Submit Now
DESIGN OF INTERDIGITAL SPIRAL AND CONCENTRIC CAPACITIVE SENSORS FOR MATERIALS EVALUATION

Tianming Chen\(^1\) and Nicola Bowler\(^2,3,4\)

\(^1\)Skyworks Solutions, Cedar Rapids, IA 52411
\(^2\)Department of Materials Science and Engineering, Iowa State University, Ames, IA 50011
\(^3\)Department of Electrical and Computer Engineering, Iowa State University, Ames, IA 50011
\(^4\)Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011

ABSTRACT. This paper describes the design of two circular coplanar interdigital sensors with i) a spiral interdigital configuration and ii) a concentric interdigital configuration for the nondestructive evaluation of multilayered dielectric structures. A numerical model accounting for sensor geometry, test-piece geometry and real permittivity, and metal electrode thickness has been developed to calculate the capacitance of the sensors when in contact with a planar test-piece comprising up to four layers. Compared with a disk-and-ring coplanar capacitive sensor developed previously, the interdigital configurations are predicted to have higher signal-to-noise ratio and better accuracy in materials characterization. The disk-and-ring configuration, on the other hand, possesses advantages such as deeper penetration depth and better immunity to lift-off variations.

Keywords: Interdigital Sensors, Dielectric Materials, Modeling

PACS: 41.20.Cv, 02.70.-c, 77.22.Ch.

INTRODUCTION

A simple disk-and-ring coplanar capacitor, shown in Fig. 1 a), has been developed previously for obtaining quantitative information in materials characterization [1]. It is useful for detecting anomalies and determining permittivity of particular layers in multilayered dielectric structures such as aircraft radomes. Due to its simplicity, this sensor has the advantage that it can be modeled very accurately, but suffers from the fact that the resulting capacitance is relatively low, typically \( \sim 2 \) pF. This is because the sensitive region of the sensor, between neighboring oppositely charged electrodes, covers only a small fraction of the total sensor surface area. To increase the sensor capacitance and the signal-to-noise ratio, the electrode design of capacitive sensors having \textit{interdigital} spiral and concentric configurations is described here. These interdigital spiral and concentric capacitive sensors, Fig. 2, possess a much bigger sensitive area than the disk-and-ring sensor, covering more of the total sensor surface area. Consequently, the sensor capacitance of the interdigital sensors is substantially larger than that of the simple disk-and-ring configuration, for given sensor diameter, also improving the signal-to-noise ratio.
A thorough literature review on interdigital capacitive sensors can be found in [2]. Their applications range from moisture content measurement [3] to food inspection [4, 5]. Compared to traditional interdigital sensors with rectangular electrodes, the spiral and concentric sensors described in this paper have rotational symmetry and, therefore, the resulting capacitance is less sensitive to the relative orientation of the sensor and the material under test.

This paper is organized as follows. First, a numerical model that characterizes the interdigital spiral and concentric sensors is outlined. Next, numerical comparisons of the performance of the interdigital and the disk-and-ring sensors are made, in terms of sensor sensitivity for materials characterization, and in terms of penetration depth and susceptibility to lift-off variations.

SENSOR CONFIGURATION

Figure 2 shows configurations of the interdigital spiral sensor and concentric sensor. The two sensor electrodes are permitted to have different numbers of turns, $N_1$ and $N_2$, where $|N_1 - N_2| \leq 1$, and the inter-electrode spacing is fixed. Each electrode finger of the spiral and concentric sensors interacts with its neighboring, oppositely charged, fingers. Compared to the disk-and-ring configuration shown in Fig. 1 a), the interaction area to sensor surface area ratio of the circular interdigital sensors is substantially larger.
MODELING

Numerical modeling of the spiral and concentric sensors follows two steps: i) a first approximation using the concentric ring model shown in Fig. 1 b) is the same for both sensors, and ii) a correction to account for the ways in which the spiral and the concentric configurations differ from concentric rings is then applied.

The first approximation utilizes the concentric annular ring model depicted in Fig. 1 b). Both of the circular interdigital sensors are modeled as a number of concentric annular rings: \( N_1 \) annular rings are charged to the same potential to form one electrode, while the other \( N_2 \) rings form the other oppositely charged electrode. This concentric annular ring configuration is a reasonable first approximation of the concentric and the spiral interdigital sensors because of the following facts. For the concentric configuration, capacitance resulting from the discontinuity of the circular fingers and the existence of the two straight leads is relatively small compared to the capacitance resulting from the rest of the sensor, which means that each interdigital loop can be modeled by one full circular loop. For the spiral configuration, the sensor is actually formed by two groups of concentric semi-annular rings of different \( s \) (\( R_1 \) and \( R_2 \)) but identical \( w \) and \( g \) (see Figs. 2 and 1 b)). It has been demonstrated in [1] that the capacitance \( C_{\text{con}} \) of concentric sensors is a linear function of \( s \) for fixed \( g \) and \( w \), i.e., \( C_{\text{con}} = ks \) where \( k \) is the slope determined solely by the test-piece material property. Therefore, the capacitance of the spiral sensor can be expressed as

\[
C_{\text{spiral}} = \frac{1}{2} C_{\text{con}1} + \frac{1}{2} C_{\text{con}2} = \frac{1}{2} k s_1 + \frac{1}{2} k s_2 = k \frac{s_1 + s_2}{2}.
\]  

In other words, one spiral loop formed from two consecutive half circles can be modeled equivalently as \( s = (s_i + s_{i+1})/2 \).

Numerical modeling of the interdigital sensors is performed in the electroquasistatic regime, i.e., the wavelength is much greater than the dimension of the problem of interest. Figure 3 a) shows the sensor and test-piece configuration used in the modeling. The infinitesimally thin electrodes are sandwiched by two layered-half-space dielectrics. The dielectric materials are assumed to be homogeneous and infinite in the horizontal directions (perpendicular to \( \hat{z} \)). Media 1 and 4 in Fig. 3 a) are infinitely thick while the thicknesses of media 2 and 3 are \( T_2 \) and \( T_3 \), respectively.

![FIGURE 3.](image)

**FIGURE 3.**  a) Numerical modeling of the circular interdigital sensors. The sensor is sandwiched by two layered half-space dielectrics. b) A point charge sandwiched by the same layered half-space dielectrics. In one practical example, medium 1 represents free space, medium 2 represents the sensor substrate, and the sensor electrodes lie in the interface between media 2 and 3. Media 3 and 4 may represent the test-piece, unless probe lift-off is present, in which case medium 3 represents the lift-off and medium 4 represents the test-piece.
Procedures of modeling the circular interdigital sensors are the same as those adopted in [1] and are summarized only briefly here: i) a potential Green's function for the multi-layered dielectric in Fig. 3 b) is derived; ii) this Green's function is utilized to set up an integral equation that relates the prescribed potentials on the interdigital electrodes to the unknown surface charge distribution on the electrodes; iii) the integral equation in ii) is discretized into a matrix equation, from which the unknown surface charge distribution is determined; iv) after finding the surface charge distribution, the total charge $Q$ on each electrode is obtained and v) capacitance of the interdigital sensor is computed from $C = Q/V$, where $V$ is the potential difference between the two electrodes.

As mentioned above, a correction is applied to the first approximation that takes into account the difference between the actual sensor configurations and the concentric annular ring model. End corrections are applied to models of both the spiral and the concentric sensors. The end correction for the spiral configuration is straightforward: the total capacitance $C_0$ is obtained by adding the capacitance due to the two square contacts $C_{\text{contacts}}$ to $C_a$ as

$$C_0 = C_a + C_{\text{contacts}},$$

where $C_{\text{contacts}}$ is computed using the method of moments in the same manner as described in [1].

As shown in Fig. 4, the capacitance for the concentric sensor, shown in Fig. 2 b), denoted $C_0$, is computed as

$$C_0 = C_a - C_b + C_c,$$

where $C_a$ is calculated from the configuration shown in Fig. 1 b), $C_b$ and $C_c$ are the capacitance due to parts b) and c) in Fig. 4, respectively. $C_b$ is the capacitance 'lost' when parts of the rings are removed to insert the parallel tracks, whereas $C_c$ adds the capacitance of those tracks and the surrounding structure. The parallel rectangular electrode structure b) is used to approximate the structure within the dashed box in a), a reasonable approximation considering the length $l$ is small compared to the circumference of the circles. $C_b$ is calculated using the analytical model described in [6], whereas $C_c$ is computed the same way as $C_{\text{contacts}}$.

FIGURE 4. End corrections made to the concentric sensor configuration shown in Fig. 2 b). Tracks of similar color are charged to the same potential.
In cases for which the thickness of the electrodes is not negligible compared with their width, stray capacitance resulting from fringing fields contributes to the total sensor capacitance. To account for the existence of this stray capacitance, compensation for finite electrode thickness is made in the model: instead of using the actual electrode width $w$ for the circular interdigital sensors (Fig. 1 b)), an effective electrode width $w + 2\Delta$ is adopted [7], with

$$
\Delta = \frac{t}{2\pi \epsilon_r} \left[ 1 + \ln \left( \frac{8\pi w}{t} \right) \right],
$$

where $t$ is the thickness of the rings and $\epsilon_r$ the average permittivity of the two layers in contact with the rings (media 2 and 3 in Fig. 3 a)). The effective gap between neighboring rings now becomes $g - 2\Delta$, while the total dimension of the interdigital sensors is unchanged. This approximation was proven to work well in many cases and has been adopted in modeling coplanar capacitive sensors composed of parallel microstrips [7].

The validity of the numerical model has been verified by benchmark experiments, where very good agreement between numerical predictions and measurement results has been observed (to within 3.4% on average). This correlation result, together with other experimental studies on interdigital spiral and concentric sensors, is in preparation for publication [8].

**NUMERICAL EXAMPLES**

The purpose of numerical calculations presented in this section is to study the effect of sensor geometry on the performance of circular interdigital sensors. Comparisons have also been made between the circular interdigital sensors and the simple disk-and-ring sensors, in terms of sensor sensitivity, penetration depth and susceptibility to lift-off effects. The interdigital sensors studied in this section have equal numbers of oppositely charged annular rings, i.e., $N_1 = N_2 = N$ in Fig. 1 b). In this section, $C_a$ alone is computed.

Figure 5 shows the capacitance of circular interdigital sensors as a function of substrate relative permittivity and the sensor geometry. The sensors are in surface contact with a one-layer dielectric substrate in free space ($\epsilon_1 = \epsilon_2 = \epsilon_3 = \epsilon_0$ in Fig. 3). The capacitance of the interdigital sensors is also compared to that of a simple disk-and-ring sensor. All the sensors whose capacitance is shown in Fig. 5 have a fixed diameter of 25.4 mm except for one whose diameter is 41.66 mm. It is found that the sensor capacitance, $C$, of all configurations is a linear function of the substrate permittivity. The sensor sensitivity $k$, defined as the slope of each line, is also observed to be greater for the interdigital sensors than for the disk-and-ring configuration. On the one hand, for fixed $g$ and $w$, the sensitivity of the interdigital sensors increases as the number of annular rings $N$ increases. On the other hand, for interdigital sensors with fixed sensor diameter, $k$ increases as $w$ and $g$ decrease (smaller $w$ and/or $g$ means larger $N$ for fixed $D$). The influence of $g$ is found to be more significant than that of $w$. This is because smaller $g$ allows for more interaction between the neighboring oppositely charged electrodes, and therefore improves the sensor sensitivity.

The sensor sensitivity illustrated in Fig. 5 plays an important role in inferring test-piece permittivity from measured capacitance. As can be seen from Fig. 5, uncertainty in the measured capacitance $\Delta C$ is related to the uncertainty of inferred test-piece permittivity $\Delta \epsilon$, as: $\Delta C = k \Delta \epsilon_r$. This relationship shows that, for sensors with sensitivity $k$ greater than 1, the uncertainty in the inferred test-piece permittivity will be...
FIGURE 5. Sensor capacitance as a function of substrate permittivity $\varepsilon_3$ (Fig. 3). All the sensor configurations have fixed starting radius $s = 1.02$ mm and diameter $D = 25.4$ mm, except for the one corresponding to the top line, for which $D = 41.66$ mm (see Fig. 1 b)). The dimensions for the disk-and-ring configuration are $s_0 = 10.67$ mm, $g_0 = 0.51$ mm and $t_0 = 1.52$ mm (see Fig. 1 a)).

smaller than the uncertainty in the measured capacitance, and vice versa. For instance, the sensitivity of the uppermost line in Fig. 5 is $k = 2.31$ whereas, $k = 0.47$ for the lowest line (disk-and-ring configuration). If one assumes that $\Delta C = \pm 0.01$ pF in the capacitance measurements, then the uncertainties in the inferred permittivity for the top and bottom lines are $\Delta \varepsilon_r = \pm 0.004$ and $\pm 0.02$, respectively. In this comparison, $\Delta \varepsilon_r$ when using the interdigital sensor is $1/5$ of that when using the disk-and-ring sensor. Figure 5 shows that the interdigital configuration therefore provides larger sensor sensitivity and better accuracy in materials permittivity characterization.

Figure 6 a) shows the penetration depth of circular interdigital sensors as a function of test-piece permittivity and sensor geometry. The sensors are in surface contact with a one-layer dielectric slab as for cases considered in Fig. 5. The sensor penetration depth $T_{10}$ is defined by identifying the one-layer test-piece thickness $T$ for which the capacitance is $10\%$ smaller than its value when in contact with a similar but infinitely thick test-piece. The vertical axes of Fig. 6 is defined as

$$\text{Difference}\% = \left(\frac{|C - C_\infty|}{C_\infty}\right) \times 100\%,$$

where $C$ is the sensor capacitance for a particular test-piece slab and $C_\infty$ is that as the slab thickness tends to infinity. Hence $T_{10}$ is defined $T_{10} = T$ at Difference $= 10\%$. As can be seen from Fig. 6 a), the sensor penetration depth increases as the test-piece permittivity increases, for given electrode configurations. The penetration depth of interdigital sensors is also found to increase as $g$ increases. This is because larger inter-electrode spacing permits deeper field penetration into the dielectric materials. Changes in the electrode width $w$, however, have less impact on the sensor penetration depth.

A similar relationship between the penetration depth and test-piece permittivity is observed for the disk-and-ring configuration, Fig. 6 b). In addition, the sensor penetration depth increases as $g_0$ increases, but is insensitive to changes in $s_0$ and $t_0$. It can be seen from Fig. 6 that $T_{10}$ of the disk-and-ring configurations are greater than that of the interdigital configurations, for equivalent inter-electrode spacing dimensions $g$. Specifically, $T_{10}$ is greater than $g_0$ for the disk-and-ring configuration, but smaller than $g$ for the interdigital design. Comparisons between Figs. 6 a) and b) demonstrate that, for a given Difference (%) value, the penetration depth of the disk-and-ring configuration is greater, and therefore it is more capable of detecting subsurface flaws.
FIGURE 6. Penetration depth of sensors as a function of test-piece permittivity and sensor geometry. a) interdigital sensors: \( N = 6 \) and \( s = 1.02 \) mm for all the sensors. Dashed lines show the corresponding penetration depth for each sensor. b) simple disk-and-ring configuration: \( s_0 = 10.67 \) mm, \( g_0 = 0.51 \) mm and \( t_0 = 1.52 \) mm except where indicated.

Figure 7 shows the comparison of the sensors' susceptibility to lift-off variations. In the calculations, \( \varepsilon_2 = \varepsilon_4 = 1 \) and \( \varepsilon_3 = 3.34 \). \( T_3 = 0.31 \) mm and \( T_2 \) varies as lift-off. The dimension of the simple disk-and-ring sensor is as for Fig. 6. The vertical axis of Fig. 7 is defined as the relative change in sensor capacitance with respect to \( C_0 \), in which \( C_0 \) is the capacitance when the lift-off is zero. The interdigital configuration with \( w = g = 0.51 \) mm has the same diameter, 25.4 mm, as the disk-and-ring configuration. It is observed that the relative change in \( C \) for the interdigital configurations shown in Fig. 7 is at least twice that of the disk-and-ring configuration for any particular value of lift-off. The number of electrodes/rings \( N \) for the interdigital sensors has a negligible effect on the sensors' susceptibility to lift-off variations. Comparisons in Fig. 7 demonstrate that the simple disk-and-ring configuration has the advantage of being less susceptible to lift-off variations than the interdigital sensors. This is an important feature during practical inspections. Figure 7 also shows how much variation to expect in capacitance when the sensors scan over a rough test-piece surface.

FIGURE 7. Comparison of sensors' susceptibility to lift-off variations. \( C \) is the sensor capacitance at a certain lift-off, and \( C_0 \) is the capacitance when lift-off is zero. The parameters of the simple disk-and-ring sensor are as for Fig. 6. Solid line: disk-and-ring configuration. Others: circular interdigital configuration. \( s = 1.02 \) mm for all interdigital configurations.
CONCLUSION

Spiral and concentric interdigital capacitive sensors have been designed, to improve the output capacitance and signal-to-noise ratio when compared with a previously developed disk-and-ring coplanar concentric capacitive sensor. A numerical model has been developed to describe the behavior of the interdigital sensors. Through numerical comparisons, the disk-and-ring configuration was found to possess advantages such as deeper penetration depth and better immunity to lift-off variations. The interdigital configurations were found to be able to achieve higher output signal strength and better accuracy in materials characterization.

ACKNOWLEDGEMENTS

This work is supported by the Air Force Research Laboratory under contract FA8650-04-C-5228 at Iowa State University’s Center for NDE.

REFERENCES