Influence of the Position of Electrodes on Capacitance of Interdigitated Capacitor Fabricated on Flexible Foil

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Abstract—**Printed electronics on flexible substrates is new approach to electronics in last few years. This paper studies performance of interdigitated capacitors printed with ink-jet printing technology on flexible substrate. Focus point of research presented in this paper is influences of different factors (number of capacitors connected in parallel, number of “fingers” of single capacitor, accurate position of electrodes of one capacitor, etc.) on the capacitance of the structure. Main results are in the demonstration of capacitance change due to the influence of position between electrodes. Test platform, using this principle, has been made to demonstrate that it can be used as an effective solution for out-of-shelf problem.**

Keywords-flexible substrate; ink-jet printing; intelligent packaging; interdigitated capacitor (IDC); silver ink.

I. INTRODUCTION

Polymer or printed electronic is expected to be a promising technology for low-cost and large-area electronic components, circuits and systems [1]. Printed electronics industry has developed a number of processes and substrates materials to print devices at low cost [2]. This area of electronics enables easy processing possibilities with the opportunity to print inks on flexible substrates such as foils, papers, textile, etc. Interdigitated electrode (IDE) capacitors are one of the most used electronic components especially in sensors, transducers, filters, etc. Compared with parallel plates structures, the planar design of IDE is particularly suitable for manufacturing on plastic flexible substrate. Printed and polymer electronics can encourage new opportunities in the field of sensing and electronics. Humidity sensor, inkjet printed on flexible foil, based on interdigitated capacitors to allow ultra-low power consumption has already been reported [3]. Additionally, the same group was developed a differential capacitive sensors with integrated temperature sensor made on polyimide [4] or poly ethylene teraphthalate (PET) [5]. Furthermore, a humidity sensor that employs interdigitated capacitors printed with silver nanoparticle based ink on a flexible PET substrate was fabricated using gravure printing process [6]. Realization of flexible strain sensor that have micro scale thick interdigitated capacitors with no residual layer by a simple direct stamping with silver nanoparticles have been demonstrated in [7]. In the article [8] has been investigated dependence of the capacitance of the interdigitated capacitor as a function of the electrode geometry and the bulk electrical properties of the substrate.

However, in all of these papers both sets of electrodes (fingers) of interdigitated capacitors are fabricated on the same substrate. In addition to this, analysis of influence of different position of fingers on total capacitance has not been performed, up to now.

This paper presents comprehensive analysis of influence of various positions of electrodes of interdigitated capacitor (IDC) on its capacitance. IDCs have been fabricated using silver ink on flexible Kapton substrate, using inkjet technology. One set of electrodes was fabricated on one substrate and another set on the other substrate. In this way, it is possible to change position when one set is incorporated in fixed set of electrodes, as a basis. Consequently, different capacitance values can be achieved. Finally, application of this approach in realization of counter of number of products on the shelf has been performed.

II. DESIGN OF INTERDIGITATED CAPACITOR

Guideline for selection of dimensions of IDC were dimension of a standard pharmacologist box of children syrup, which is around 5.0 cm x 5.5 cm. Structures are designed in Microsoft Visio® program and exported in .bmp picture format with resolution 1016 dpi x 1016 dpi. Exact dimensions are visible in Figure 1 and they are given in millimetres.

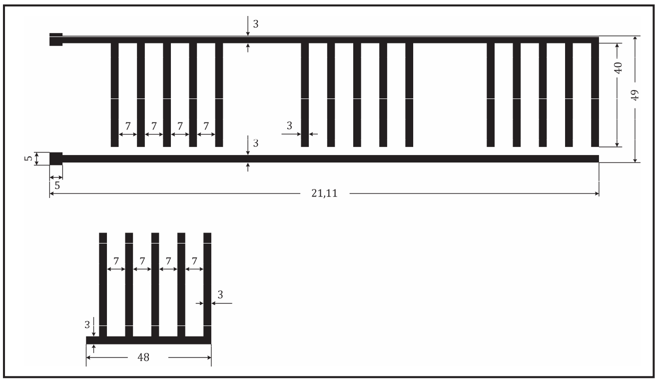

Figure 1. Design of IDC.

Width of all lines is 3 mm. Distance between vertical 5 lines in set is 7 mm. When both parts of interdigitated capacitor are in ideal place distance in vertical 10 line set is now 2 mm and gap distance is 3 mm as shown in Figure 2.

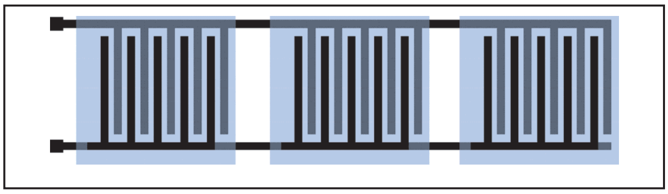

Figure 2. Ideal position of electrodes shown for tree IDCs.

The conductive electrodes of the proposed structure of interdigitated capacitor were manufactured using Dimatix DMP-3000 [9] cartridge based piezo ink jet printing system. Silver nanoparticle (with 20 % concentration) commercial ink [10] was used as a conductive material to be printed on Kapton film substrate [11] with the thickness of 50 µm. DMP-3000 printing frequency was set to be 4 kHz with nozzle voltage amplitude of 28 V, and drop spacing resolution of 25 µm. After printing, the structure was sintered in oven up to 200 ºC for 45 minutes. The Kapton film was selected as a substrate due to its mechanical flexibility, chemical resistant properties and thermal stability. For easier handling one part of the IDC structure is stick to the plexiglass board (further called fixed part) as shown in Figure 3. Figure 4 shows other electrode of IDC (further called mobile part) printed in same technology and on the same substrate as the fixed part of IDC. Wires for terminals were glued on the platform with conductive epoxy silver paste and the whole structure was connected to an instrument HP4194A Impedance/Gain Phase Analyzer to conduct measurements. Figure 3 and Figure 4 have identical dimensions like dimensions in Figure 1.

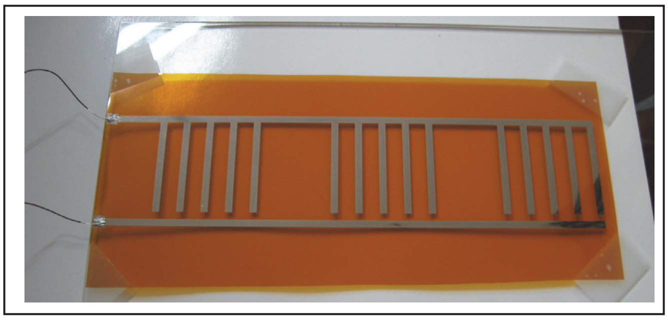

Figure 3. IDC fabricated on the Kapton film using silver as a conductive material – set of tree half's connected in parallel (fixed part).

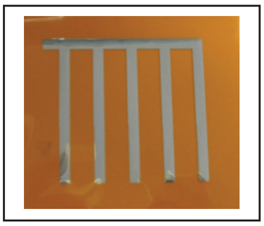

Figure 4. IDC fabricated on the Kapton film using silver as a conductive material – second half of one IDC (mobile part).

III. Results and Discussion

Four types of influences on the capacitance of this IDC structure are analysed in this paper:

- Influence of number of capacitors in parallel on the total capacitance,
- Influence of number of "fingers" of IDC,
- Influence of paper placed between electrodes and changed position,
- Influence of accurate position of mobile part of IDC.

A. Influence of number of capacitors in parallel on the total capacitance

To demonstrate parallel connection of this type of capacitors and to determine their behaviour, three capacitors were designed. Capacitance of fixed structure exists because both contacts (square parts on the left side of Figure 5) are on this part of IDC structure. Realisation of complete capacitors occurs when mobile part makes the physical connection with thin line of fixed part (visible in Figure 6). This is the way we achieved free movement of mobile part.

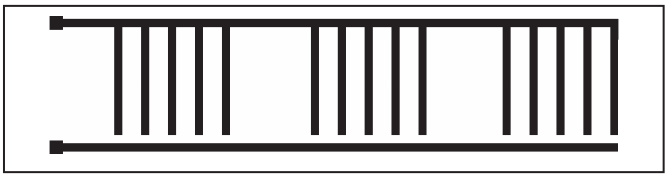

Figure 5. Fixed part of IDC.

Table I demonstrates that capacitance rises almost linearly in steps in average of 5.7 pF per addition of one capacitor. Capacitance of fixed part shown in Figure 5 is equal to 4.45 pF. Therefore, by adding mobile parts of capacitors overall capacitance rises in discrete values.

TABLE I. Influence of number of capacitors in parallel on the total capacitance

No. of capacitors	Related Figure	Measured capacitance (pF)
0	Figure 5	4.45
1	Figure 6(a)	10.19
2	Figure 6(b)	15.94
3	Figure 6(c)	21.52

Figure 6 gives an overview of increasing number of IDCs connected in parallel. Blue square marks correspond to Kapton film of mobile electrodes. Black coloured parts resemble to visible electrodes (looking from the top), blue shadowed parts represents electrodes below Kapton film.

Further measurement demonstrates that there is no connection between positions of capacitor and capacitance or order of setting and capacitance. Therefore, it is no mater of importance was the left, right or middle capacitor put first on the fixed part, result on full amount of capacitance is the same.

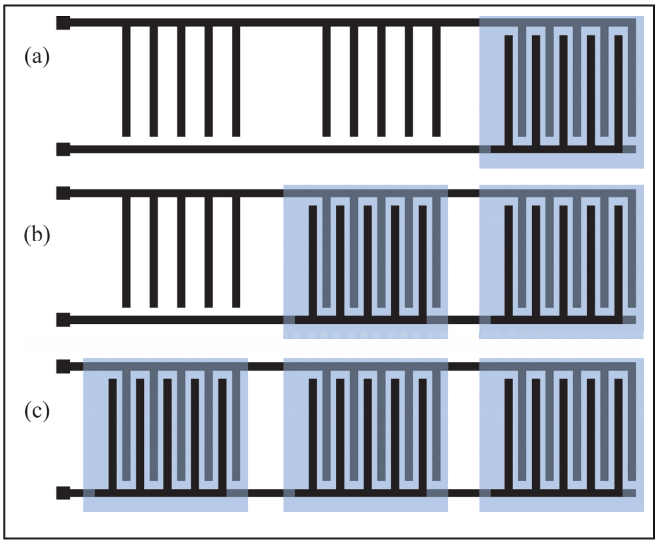

Figure 6. Changing the number of IDCs connected in parallel.

B. Influence of number of "fingers" of IDC

This part of research was important because of future modifications and adjustments of capacitor size.

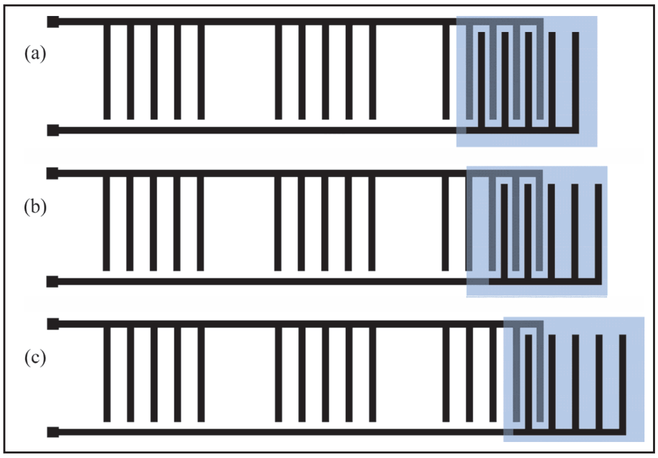

Figure 7. Changing the number of "fingers" of IDC.

TABLE II. CHANGING POSITION OF ONE CAPACITOR

No. of capacitors	Related Figure	Measured capacitance (pF)
0	Figure 5	4.45
1	Figure 6(a)	10.19
1	Figure 7(a)	8.89
1	Figure 7(b)	7.52
1	Figure 7(c)	6.42

Figure 5, Figure 6(a) and Figure 7 together with Table II demonstrate the influence of number of IDE's "fingers" on the capacitance. Calculations driven from Table II data illustrates that the average capacitance reduction in case of reduction of two "fingers" per measurement is 1.26 pF. Value of one capacitor is approximately 5.7 pF (capacitance of 10 fingers minus capacitance of fixed part or base structure). Therefore, by reducing number of "fingers" from 10 to 8 the capacitance of IDC is equal to 4.4 pF. Reduction of number of "fingers" from 8 to 6 causes a decrease of capacitance to 3.1 pF and reduction from 6 to 4 causes lowering of capacitance value to 2.0 pF. The consequence of disposition of electrodes capacitance can be increased for 2.19 pF, as it will be shown in the section D. Reduction of number of "fingers" from 6 to 4 can cause unreliable operation of the whole structure.

C. Influence of paper placed between electrodes and changed position of IDC's electrodes

One of ideas was to investigate behaviour of this IDC structure as regular non interdigitated capacitor with paper as dielectric between the electrodes as it is illustrated in Figure 8. The same fixed and mobile parts are used like in the case of interdigitated capacitor. Measurement reveals that capacitance of this unusual capacitor is equal to 7.04 pF (the measured value of 11.49 pF minus the capacitance of fixed part of 4.45 pF). This is completely according to expectation, because now ideal overleaping among "fingers" is achieved and this results in higher capacitance value comparing with IDC structure (where we have some shift among electrodes). The difference in capacitance between IDC used up to now and this type of capacitor (with paper as a dielectric) is approximately 1.35 pF.

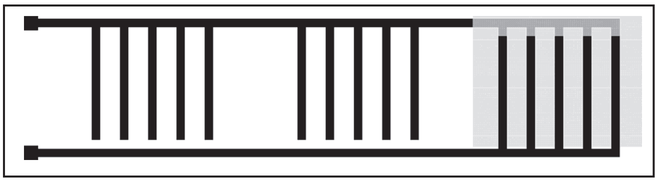

Figure 8. Behaviour of designed IDC in the case of positioning with complete match of electrodes, with paper as a dielectric.

D. Influence of accurate position of mobile electrode.

Capacitance of IDC depends of the geometry of electrodes, material of electrodes, substrate and dielectric. In this section, deviation of results of measured capacitance in the case of non-ideal positioning will be discussed. The main reason for examination of these cases is a need for determination of differences in capacitance caused by relocation from an ideal position.

Figure 9 gives a list of extreme cases of relocations in four directions: up, down, left and right. This is maximum deviation in movement with which IDC is still working properly (that means that no short circuit is created).

TABLE III. CHANGING POSITION OF ONE CAPACITOR

No. of capacitors	Related Figure	Measured capacitance (pF)
1	Figure 9(a)	11.94
1	Figure 9(b)	12.35
1	Figure 9(c)	12.38
1	Figure 9(d)	10.68

Measurement results of this deviation are presented in Table III. In consideration that one capacitor has the measured value of 10.19 pF in an ideal position, calculation evaluates that worst case scenario is when deviation is in up-right direction or in down-left direction. Hence, that capacitance of the capacitor is 12.35 or 12.38 pF. Thus, capacitance is increased for 2.19 pF maximum. From the information in Table III we can see that capacitance value is higher in any case of deviation in movement in comparison with the capacitance of one IDC in an ideal position. This is a consequence of closer position of IDC fingers which has effect in higher capacitance.

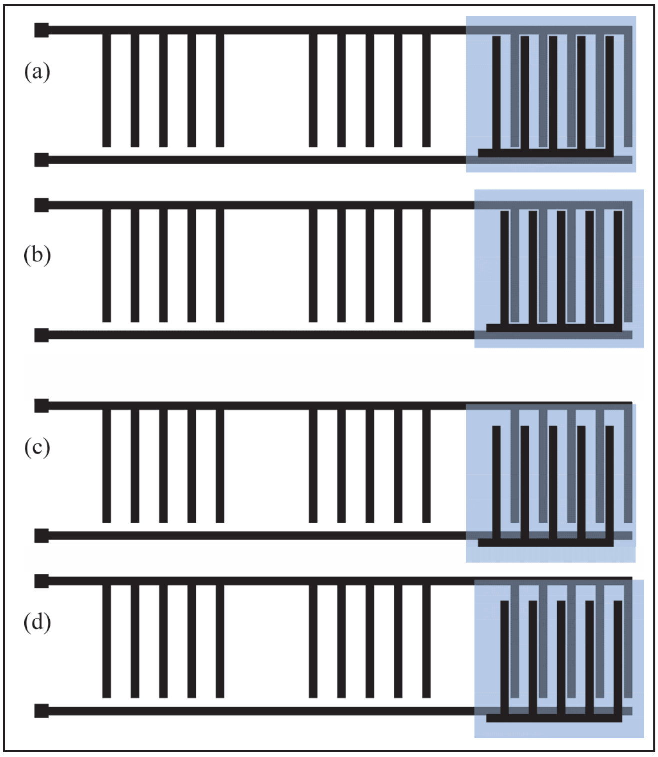

Figure 9. Preview of maximum deviations in movement in four directions (up-down and left-right). Displacement to the up-left corner (a); displacement to the up-right corner (b); displacement to the low-left corner (c) and displacement to the low-right corner (d).

IV. Application

These examination of IDCs printed on flexible substrate are response of demands for smart packaging. One of the problems in smart packaging is so called out-of-shelf (OOS) problem. This problem of products missing from the shelf is still a frequent phenomenon in the grocery retail sector and can lead to lost sales and decreases consumer loyalty [12]. The term "out-of-shelf" (OOS) is used to describe situation where a consumer does not find the product (or sufficient number of that product) one wishes to buy on the shelf of a supermarket, during a shopping tour. It might be that product exists in the store (back-room), but it is not on shelf. The reasons for the OOS are usually ordering problems and replenishing problems. Performing visual and manual inspection by store personnel is slow, expensive, and susceptible to human error. Because of that it is necessary to develop a precise product availability monitoring device or system. Consequently, we constructed the test platform for imitation of the store shelf (Figure 10) and we monitored the response of IDCs structure described earlier. White boxes are made as a product imitation and mobile part of IDC is glued from the bottom side of these packages.

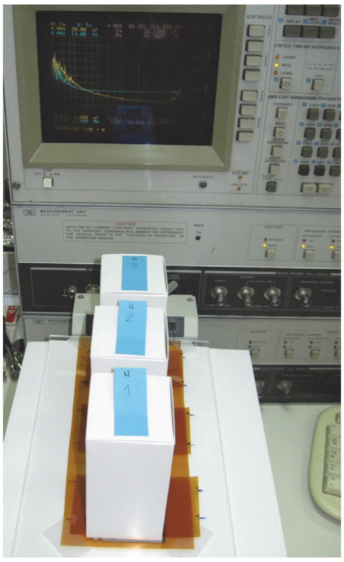

Figure 10. Application of IDC on intelligent packaging.

Closer look on IDC connection between two parts manufactured on flexible substrate (in this case Kapton film) can be seen in Figure 11. Measurements showed almost no difference between capacitance when mobile part is free and when is fixed to the boxes. For this reason we believe that there are no obstacles which consider transition from free mobile part to mobile part fixed to product for further developing of this type of IDCs. For future developing, printing directly on the product will be our next step.

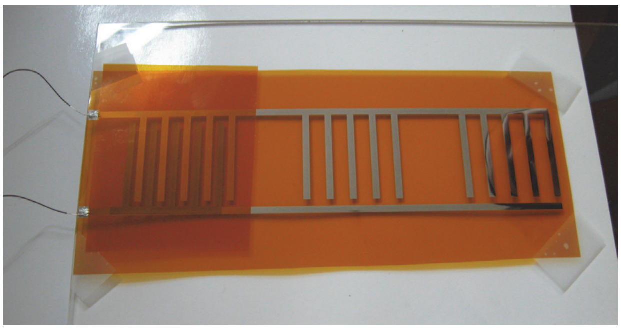

Figure 11. One IDC realized on flexible substrate.

V. Conclusion

This paper has presented a structure of interdigitated capacitor printed using ink-jet technology on flexible substrate. The proposed solution of interdigitated capacitor was printed on different substrates where on set of electrodes is fixed to the Plexiglas platform and another set of fingers free (or glued on the box or packaging). The silver electrodes of IDC have been fabricated on flexible Kapton film by means of ink-jet printer (Dimatix DMP-3000). Mechanical flexibility of Kapton substrate enables that proposed solution can have a wide range of applications. The total capacitance of IDC decreases with decreasing number of products on the shelf. Influences of: number of IDCs connected in parallel, number of fingers of one IDC and position of electrodes were examined in detail. The proposed solution can be used for development of complex system for accurate anticipation of "out-of-shelf" situation and inform the store personnel before an "out-of-shelf" problem occurs.

ACKNOWLEDGMENT

This work is partly supported within the project TR32016 and the equipment provided within the FP7 APOSTILLE project, no. 256615.

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