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An Efficient MEMS Sensor Modelling by Geometrical Parameter Optimization

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***Abstract*—Numerous technological applications use MEMS capacitive sensing technique as a major component, because of their ease of fabrication process, inexpensive and high sensitivity. The paper aims at modeling interdigitated capacitive (IDC) sensing. Virtually observe the contribution of variations in geometrical parameters to sensor efficiency and optimization factor. The sensor design is verified through ANSYS simulations. Results indicate "an efficient but poorly optimized sensor is better than a well-optimized sensor". It is difficult to detect capacitance in the range of few pF generated using capacitive sensing. How it can be maximized with dimension optimization is focused in this paper.**

***Keywords*—virtual IDE modelling; MEMS; sensor optimization; ANSYS modeling and applications**

I. Introduction

THE acronym MEMS stands for Micro Electromechanical Systems. It is most often fabricated with IC processing on silicon wafers. In Europe, it is known as Microsystems. In Japan named Micromachines [1]. It is commonly applied in various fields like automobiles, aerospace engineering, biomedical applications, inkjet printers, wireless and optical communications, much more to enlist. Their size ranges from a millionth of a meter to a thousandth of a meter. MEMS has commonly applicable to fabricate microdevices. It includes manufacturing devices such as microsensors, microband pass filters micro actuators, microwave switches, and so on. This technology is preferred in designing microsensors. It is due to their small size, low power consumption, and minimally invasive implantation.[1] MEMS interdigital structure is a finger-like (Interlock similar to the fingers of 2 clasped hands) or digitlike periodic pattern. This pattern is of parallel-in-plane electrodes. It is used to build the capacitance associated with the electric field. This field penetrates the sensitive coating [2]. Planar capacitive sensors can be build using interdigitated electrodes (IDEs). This can be integrated with electronics to have a smart integrated sensor. As interdigital capacitive sensors are used as they do not consume static power. [3]-[5] Capacitive transducers are used in various field of applications. These field incorporates biomedical applications, automobile automation, robotics and exhaust gas sensing. Material to test and sense can be probed with the help of capacitive sensing structure. A digital converter can be used to extract digital output from capacitive sensing [6]-[8]. Interdigital electrodes are covered with material sensitive to gas (Sensing Layer). This gas sensing layer changes permittivity on gas absorption. Interdigital planal capacitors are mostly preferred for high-frequency applications. Capacitor efficiency is varied for variation in the geometrical parameters of the interdigital planar capacitor. Every application essentially needs a wise selection of sensor design and estimation of the associated parameters. This paper describes the effect of electrode thickness, length, and number of electrodes on optimization of interdigital capacitance and efficiency.

Application started using interdigital electrodes and forms of coplanar electrodes for sensing in the 1960s [9]. Harvey Nathanson fabricated a MEMS device first in 1964. He was an electrical engineer and invented the MEMS device. It is nowadays found in many products from iPhone, aerospace to automobiles and started commercialized in 1980. Work has been done on planar capacitive sensor design and evaluation in 1991-1996. In 2004 Igreja and Dias studied inter-digital sensor design issues with the application of an analytical method. Li et al., in 2006 described the geometry of electrodes includes the shape, spacing, and separation of electrodes. These are the most vital parameters to determine sensor performance. Planar capacitor various sensing mechanism and sensor design issue performance evaluation and applications are discussed by Xiaohui Hu and Wuqiang Yang [10]. Prakriti Kapoor, Vishal Mehta et.al. 2015 proposed the use of an interdigital electrode capacitor over a grid electrode for capacitance detection for moisture measurement. Shown less solution time compared to grid electrodes [11]. Beeresha R S, A M Khan, Manjunath Reddy H V in 2016 proposed biomedical sensing applications of a planar interdigital capacitor. These structure sizes are of the order of 7mm×13mm (4-fingers) to 13mm×30mm (16-fingers) with a high-quality factor. This helps to understand the design and optimization of capacitor parameters.[12]. Siavash Zargari, Saba Falaki, Hadi Veladi in 2016 presented a design for MEMS capacitive pressure sensor. It gives a new electrode in the capacitive sensing. The electrode overlapping area is affected than the electrode spacing because of membrane deformation. A pressure sensor (2.5 mm × 2.5 mm) square membrane can provide a capacitance change of 0.365 pF for pressure in the range of 0-100 KPa.[13]. Huang, Yunzhi and Zhan, Zheng and Bowler, Nicola in 2017 presented optimization of the coplanar interdigitated capacitive sensor. It aims at 3-dimensional finite element modeling for designing parameter analysis. It focuses on the width-to-gap ratio and number of electrodes for analysis purposes. Results show that a trade-off needs to be considered for the desired sensitivity and the designing parameters [14]. Rosane Moura Dos Santos, Jean-Michel Sallese et.al. in 2019 designed a capacitive moisture sensor. It presents the design considerations, shows the relationship between the sensor's performance and the sensor's

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geometrical parameters. For electrode number width and spacing 24, 5mm,5.236mm respectively capacitance obtained 119.50PF. Performance can be improved with the thermal treatment of dielectric in the fabrication process.[15] Wang, Pan & Lu, Qibing & Fan, Zhun. In 2019, Analysed MEMS design optimization methods. Proposed evolutionary computation for MEMS optimization with 3 design issues in EC optimization. [16]. Pelumi W. Oluwasanya et.al. in 2020 presented finite element modeling for analysis of capacitance of MEMS-based capacitor. It shows finite element modeling is the best method for the estimation of the coplanar capacitance. Used conformal mapping approach for the detection of particulate matter. It states that the electrode gap must be at least bigger than the size of the largest particle size which is in nm size.[17]. D. Back, D. Theisen, W. Seo, C. S. J. Tsai, and D. B. Janes in 2020 designed a high resolution interdigital capacitive sensor to detect nanoscale particulate matter for mining and another environment like dust. This paper illustrated the sensor response in terms of airborne particle concentration. [18]. Hence sensor geometry needs optimization. Sensor geometrical parameters need optimization to achieve measurable capacitance. Efficiency needs improvement with the trade-off on sensor size and ease of manufacturing.

The purpose of the study is to explore and simulate the effect of variations in dimensions of Interdigital electrodes. This paper proposes a design and optimization of the interdigital capacitor. It uses silicon carbide as substrate material. It is suitable for high-temperature applications. A relationship of output capacitance to the variations in geometrical dimensions will be verified using finite element analysis. ANSYS simulation tool is used for optimization. Efficiency and optimization of the sensor are addressed for effective sensor optimization and maximum possible efficiency.

The organization of the paper is as follows; Section II explains parameters affecting the sensor performance. It provides input for deciding sensor design parameters. Section III details the efficiency and optimization significance. Illustrated design and optimization of an interdigital capacitor with different space between the electrodes, electrode width, electrode length and number. How efficiency can be improved. Section IV includes efficiency with optimization analysis with simulation results. Section V explains how the optimization factor affects efficiency and summarized the obtained results relating it.

II. Interdigitated Electrode Capacitor (IDC) Sensor Design Parameters

Figure 1 shows the basic structure of Interdigital structure. It is the top view of the sensor structure. Fig. 2 shows the exploded sensor Interdigital electrodes. The major parameters to inspect for IDE sensor design are

1. Geometrical arrangement of electrodes.
2. Geometrical shape of electrodes (Rectangular, Circular).
3. Number of electrodes also known as cells.
4. Shielding of electrodes.

An application area and domain support to decide arrangement and geometrical shape of sensor electrodes. System variables is the base to determine the electrode count. Hence it is necessary to understand capacitance measurement and detection in association with system variables. System space provided in an application for sensing cells also plays acritical role in finalizing electrode structure. It also decides the electrode count which eventually decides and affects sensor performance [19]. Sensor parameters influenced due to geometrical dimensions includes responsivity, signal strength. penetration depth, efficiency, and optimization factor. Stray capacitance can be excluded by shielding and guarding [19]. Mechanical stability to sensor system is provided by substrate. A segregating layer covering sensor electrode is used to avoid direct contact to material to be tested. It provides a scope for choice of material for insulation layer, substrate, and electrodes. A material for electrodes can be selected from conductor category(Cu-Copper, Al-Aluminum, Pt-Platinum, Au-Gold, etc.). The isolation layer ,substrate uses dielectric materials. Testing material and substrate should hold nearly the same permittivity. It is needed for an even electric field in the sensing system. The insulation layer and substrate width have impact on responsivity and signal strength .Hence both needs optimization. Based on the dimension and costings, several fabrication techniques can be selected. These include PCB, MEMS (Microelectromechanical systems), and manual construction.

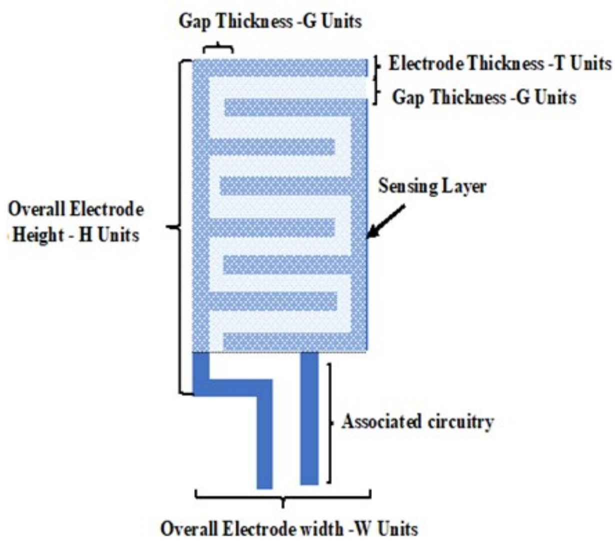

Fig. 1. Electrode pattern and important dimensions of IDE sensor (w=6 mm and H=10 mm)

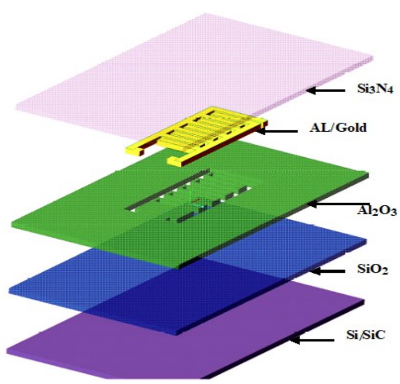

Fig. 2. Exploded view of Interdigital Electrode (IDE) structure with all layers

III. Sensor Efficiency and Optimization.

The electrode pattern shown in Fig.1 works as a template for efficiency analysis and dimension optimization. Important dimensions are overall width as W, height as H, Electrode thickness as T, Electrode gap thickness G also known as a serpentine gap. A serpentine gap represents sensing area of the sensor element. The sensing layer is deposited and covers exterior top of the sensor. The sensing material in the serpentine gap works as a sensing element reacting to an analyte. For capacitive sensor sensing layer part laying between the interdigitated electrode (serpentine gap) is in the dielectric zone. The efficiency of the sensor can be defined as equation (1).

$$\eta = \frac{Sensing\ Area}{Total\ Sensing\ Area} \tag{1}$$

$$\text{Efficiency-}\ \eta = \frac{\frac{GT}{G+T}\left(w-\left(2-\frac{\pi}{2}\right)G-T\right)+G^2+GT}{WH} \tag{2}$$

$$Maximum\ Possible\ Efficiency\ \eta = \frac{G(n-1)}{G(n-1)+nT} \tag{3}$$

$$Optimization\ Measure = \frac{Efficiency}{Maximum\ Possible\ Efficiency} \tag{4}$$

Theoretically, efficiency should be less than 1($\eta < 1$). Sensor efficiency close to maximum possible efficiency, then it is well optimized. The optimization factor defines how well a sensor is optimized. It will be a number between 1 and 0. It can result in optimization nearly equal to 1. It is an estimation of how well a sensor design is optimized. Efficiency is a comparative measurement between sensors. [19]. Optimization gives valuable inputs for improving the quality of the sensor. It also provides inputs for what will contribute to sensor quality performance. Once a sensor is optimized, it can have maximum possible efficiency and optimization allowed for the photolithographic process. Sensor quality improvement tools are efficiency and dimension optimization with 2 understandings

1. The X-scaling should be longer than the dimension defining length of electrode (unit cell). An increase in the X direction affects positively for efficiency than an increase in the Y direction (No. of electrodes).
2. Maximum possible efficiency depends upon the electrode thickness T and gap between electrodes G. It does not bank on the thorough dimensions of X and Y direction. It is needed to keep the gap G larger as compared to the electrode thickness T. This is to have maximum possible efficiency approaching unity. To have the highest maximum possible efficiency electrode thickness should be extremely thin. It causes several issues for the limitations of photolithographic and other fabrication techniques. So, this concept of efficiency and dimension optimization works as a tool for designing interdigitated electrode sensors with improved designs

IV. Interdigitated Electrode Design and Capacitance Analysis

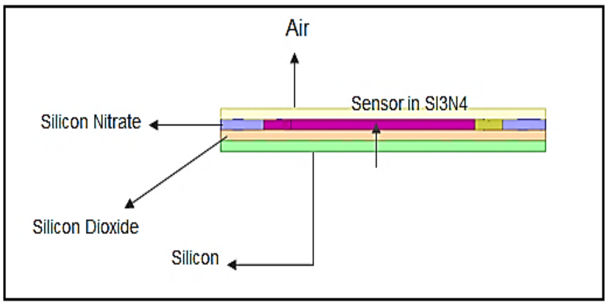

Fig.3 Sensor Modelling in ANSYS (Q3D) Silicon can be replaced with SiC/Si

Capacitive sensing can be applied in the form of interdigitated electrodes. MEMS technology makes it feasible to build and fabricate smart gaseous sensors with interfacing electronics circuits. Fig. 3 and 4 shows the sensor ANSYS modeling. With the aid of finite element analysis (FEA), sensitivity alterations with deviation in metal and film thickness can be studied. It consists of 2 serrated interdigital electrodes on a ceramic substrate in one plane. The IDEs spatial wavelength defined in [21] as double the addition of width (T) and spacing (G). FEA helps highly to analyze effect of film thickness and the metal thickness on sensitivity

$$Sensitivity = Se = \frac{\left(\frac{\Delta C}{C}\right)}{\Delta\varepsilon r} \tag{5}$$

The objective of this analysis is to maximize the IDC. To get capacitance in a detectable range so that it can be amplified for further processing. Table I and II shows the variations of dimensions. Increased number of electrodes, the width of electrodes with constant spacing.

TABLE I
SUMMARY OF COMBINATIONS FOR IDC WITH THE INCREASED NUMBER OF ELECTRODES-N

Set. No.	Width (mm)	Spacing (mm)	Length (µm)	N*	Capacitance (pF)
1.	0.25	0.2	200	5	2.65
2.	0.25	0.2	200	14	7.24
3.	0.25	0.2	200	19	10.08
4.	0.25	0.2	200	24	12.72
5.	0.25	0.2	200	29	15.78
6.	0.25	0.2	200	32	17.12

*(N - Number of electrodes)

Figure 4. shows this structure. Such 6 six sets are validated. It results in increased capacitance. It shows the variation in N, the number of electrodes changes the capacitance in a visible range. It is stated in Table II. It increases charge storages hence IDC.

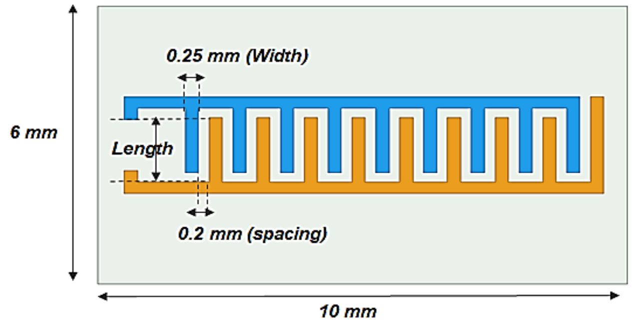

Fig. 4. Sensor geometry with dimensions used for optimization

TABLE II
MAXIMUM EFFICIENCY, OPTIMIZATION FACTOR AND OPTIMUM CAPACITANCE OBTAINED WITH VARYING DESIGN PARAMETERS

N*	Substrate measure (W*X H*) mm	IDC obtained in pF for Electrode Length L (mm) Variation			
		1.4	3.8	4.3	6
5	10x6	2.63	5.39	6.27	8.31
14	16.3x6	7.24	17.21	20.12	26.44
19	19.8x6	10.08	23.74	27.81	36.7
24	23.3x6	12.72	30.41	35.47	46.59
29	26.8x6	15.78	37.28	43.31	57.53
32	29x6	17.12	40.83	47.79	62.56
Efficiency = 50 %, Optimization factor = 0.98					

*(N- Number of electrodes, W- Total width, H - Total Height)

V. Sensor Model Optimization Analysis with Efficiency

The number of studies to characterize dimension optimization affecting the efficiency of the sensor has been reviewed. Results of keeping one dimension constant while varying another are summarized in Table III. It shows the ratio of width to spacing[20] .With the increase in H dimension that is in the number of electrodes the sensing space also raises by the same approximate powers. It increases linearly in the sensing area. Hence efficiency remains unchanged and it is fundamentally unimproved. For another set of data keeping the number of electrodes, electrode gap, and width constant but varying electrode length. It is observed that the sensing area increases faster than expected powers often. So, the increase in electrode length increases the sensing area and efficiency from 0.72 to 0.90. This analysis is used as a reference to apply optimization rules to get maximum efficiency with optimum throughput (capacitance). These results are listed in Table IV. It explores low efficiency and high optimization but obtained maximum capacitance. Three sets are analyzed for validating efficient but poorly optimized sensor works well than a better-optimized sensor. With equations 1-4 extracted and validated efficiency and optimization factor . SET- I show electrode thickness is less than spacing width gives maximum efficiency and optimization factor but IDC extracted is less to detect . SET-II and SET-III are shown in Table VI and Table VII respectively.

TABLE III.
SENSOR DIMENSIONS RATIO, OPTIMIZATION, AND EFFICIENCY, SERPENTINE GAP – 1 UNIT

W*	H*	T	Sensor Area	Total Area	η*	G/(Gap +T)
10	10^1	10^{-1}	72.919	10^2	0.7292	0.909
10	10^2	10^{-1}	719.3	10^3	0.7193	0.9091
10	10^3	10^{-1}	7183	10^4	0.7183	0.9091
10	10^4	10^{-1}	71820	10^5	0.7182	0.9091
10	10^5	10^{-1}	718200	10^6	0.7182	0.9091
10	10	10^{-1}	72.92	10^2	0.7292	0.9091
10^2	10	10^{-1}	891.1	10^3	0.8911	0.9091
10^3	10	10^{-1}	9073	10^4	0.9073	0.9091
10^4	10	10^{-1}	90890	10^5	0.9089	0.9091
10^5	10	10^{-1}	909100	10^6	0.9091	0.9091

*(N- Number of electrodes, W- Total width, H - Total Height, η - Efficiency)

TABLE IV
OPTIMIZED SENSOR DESIGN DIMENSIONS WITH MAXIMUM POSSIBLE IDC EXTRACTED

Parameter	Size
Electrode Spacing-G	5 µm
Electrode Thickness-T	0.1 mm
Electrode Length-L	4.3 mm
Electrode number-N	38
IDC Value	885.372 pF
Efficiency	4.76 %
Optimization factor	0.9847

*(Interdigitated Capacitance)

It is observed that though it's a good optimization with more sensing area with electrode thickness to electrode spacing ratio [G =5 µm, T =0.5 µm, 0,25 µm,0.1 µm]. But with the decrease in electrode thickness, the efficiency is highest shown in Table V. For the highest optimization factor, the IDC value obtained is 0 PF. It is an indication of poor sensor performance though the number of electrodes increased from 15 to 50.

TABLE V
SENSOR OPTIMIZATION WITH T:G RATIO 1:10 FIXED LENGTH AND NUMBER OF ELECTRODES N [SET-1]

Electrode Length L-4.3mm, No. of Electrodes -15, Spacing Width G= 5µm			
Electrode Thickness T (µm)	IDC *obtained	Efficiency %	Optimization Factor
0.5	323.825 pF	90.32	0.9936
0.25	327.028 pF	94.91	0.9964
0.1	0 pF	97.90	0.9985

*(Interdigitated Capacitance)

Results in Table IV,(Electrode thickness is more than spacing thickness T) gives the optimization factor is 0.9847 with an efficiency of 4.76 % but performing better with a maximum IDC of 885.372 pF. Here T is 0.1 mm and electrode spacing G- 5 µm. It is an efficient but poorly optimized sensor performing better than the other two sets mentioned in Table V and VI .

TABLE VI

SENSOR DESIGN OPTIMIZATION WITH T: G RATIO 1:10 [SET-II] WITH VARYING LENGTH AND NUMBER OF ELECTRODES

IDC * variation with change in Electrode Thickness T, Spacing Width G =5 µm									
Electrode Length	4.3mm			6.3mm			8.3mm		
Electrode width T(µm)	0.5	0.25	0.1	0.5	0.25	0.1	0.5	0.25	0.1
No. of electrodes N	3	8	8	3	8	8	3	8	8
IDC (pF) *	64.78	180.85	0	90.86	267.26	0.0286	118.03	356.43	0.0083

*(IDC- Interdigitated Capacitance)

TABLE VII
OPTIMIZATION FACTOR AND EFFICIENCY WITH THE STANDARD DESIGN NORMS SHOWING LOW IDC [SET-III]

IDC variation with change in Electrode Thickness T, Spacing Width G =5 µm			
Electrode width T(µm)	0.5	0.25	0.1
No. of electrodes N	3	8	8
IDC (pF)	64.78	180.85	0
Efficiency	74.074	94.59	99.99
Optimization	0.8148	0.9931	1

Table VII showing the efficiency and optimization factor for a perfectly optimized sensor (Electrode thickness $(1/10)^{th}$ of spacing width or less than it) but extracts low IDC values. These optimizations are as per electrode width to electrode spacing ratio defined in Table III. If electrode spacing width is 5 µm then width of electrode is kept at 0.5 µm , which enables to extract capacitance of 64.78pF with efficiency of 74.074% .But with this standard ratio of electrode width to spacing able to extract 0pF (Very negligible to measure) though increase in number of electrodes and with high efficiency 99.99% and optimization factor 1 which is ideal. Figure 5 shows optimized sensor dimensions and Fig. 6 shows stored charges. The sensor structure simulated shows the dimensions referred in Table IV .

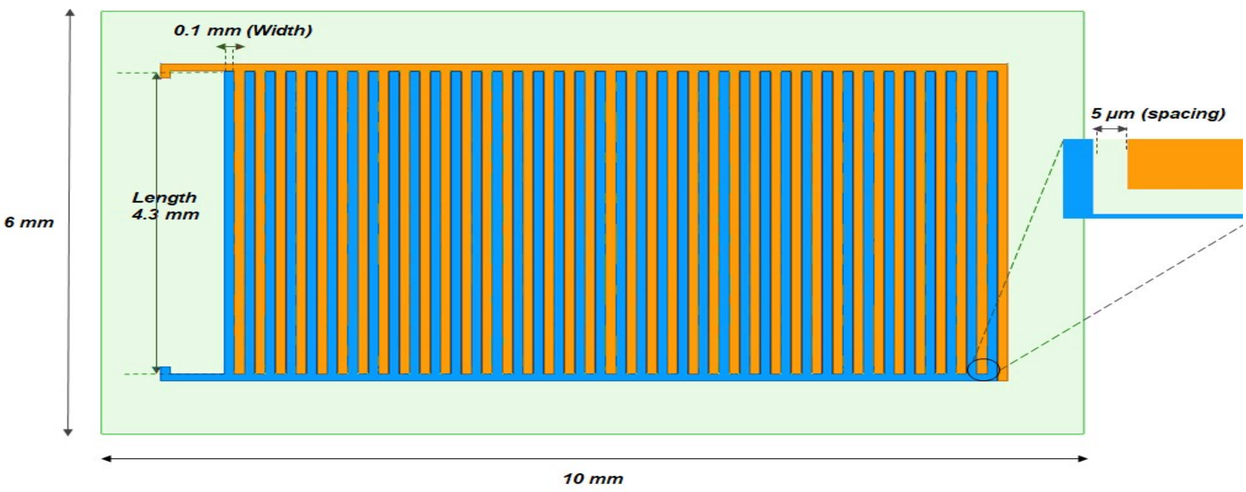

Fig.5. Sensor optimized design with all dimensions(Table IV)

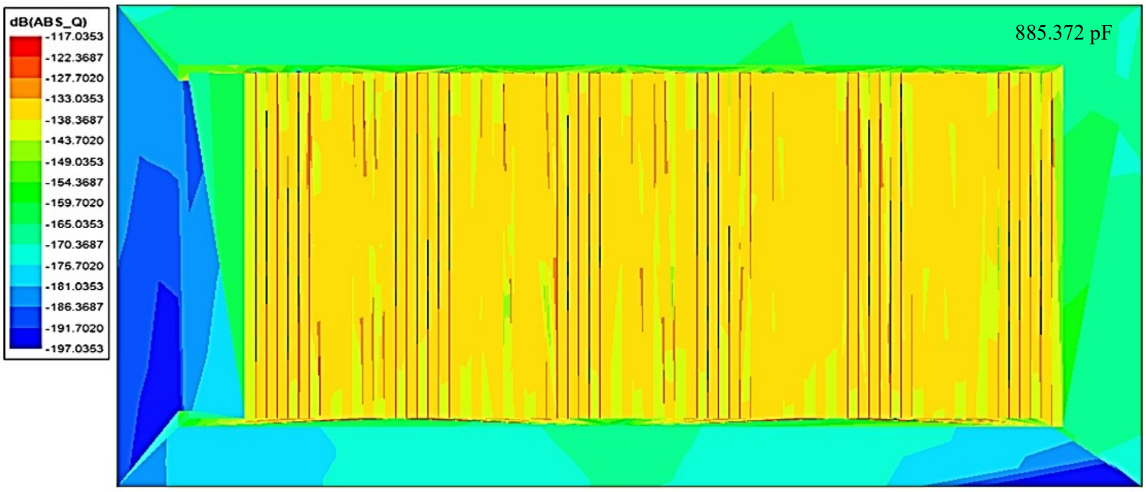

Fig. 6. The charge stored and extracted IDC from it for sensor design (Table IV)

Conclusion

The paper aims at designing aspects of MEMS sensors. Initially considering electrode length as 200 µm, electrode width as 0.25mm, spacing 0.1 mm and increasing number of electrodes from 5 to 32. With this extracted capacitance is 17.12 pF. Optimization factor 0.96 and 28.5 % efficiency Taking 0.2 mm as electrode width and spacing between electrode ,increasing number of electrodes ranging from 5 to 32 and electrode length maximum to 6mm , able to extract capacitance of 62.56pF.It gives 50% efficiency and 0.98 as optimization factor. But with electrode width 5 µm spacing width 0,1 mm length as 4.5mm and maximum number of electrodes 38 able to extract 885.372pF capacitance which is maximized value. It gives less efficiency as 4.76% and optimization factor as 0.984. Results also proves that perfectly optimized sensor with 99.99% efficiency and 1 as optimization factor able to extract very less value of capacitance varying from 0 to 180.85 pF which is very difficult to detect . Efficiency and optimization are at most important while working on designing a sensor. The effectiveness of these parameters on optimization is illustrated with virtual iterations. It is observed that the capacitor value increases with an increase in the length of the electrode and the number of electrodes. It also increases with an increase in the width of electrodes but decreases with the increase in spacing between electrodes. As the increasing sensing area increases the capacitor value. So, it affects an optimization factor and efficiency. This approach helps to work with well efficient sensor though it may or may not be well optimized. It also covers a wide range of dimensions in all directions. Extracted the maximum possible outcome of a designed sensor. It can also extend in the future with changing substrate dimensions to occupy more than one sensor on the same substrate. In the future there is scope to address the robustness of the MEMS. These results help to work for the design and optimization of interdigital capacitors for a specified application in various fields.

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References

[1] Bryzek Janusz,”162:Principles of MEMS”, Handbook of Measuring System Design., John Wiley & Sons, 2005,pp. 1–6.

[2] A.V. Mamishev, K. Sundara-Rajan, F. ang, Y. Du and M. Zahn, “Interdigital Sensors and Transducers,*” Proceedings of the IEEE* ,vol 92, pp. 808-45,May 2004. https://doi.org/10.1109/JPROC.2004.826603

[3] C. Sapsanis, H. Omran , V. Chernikova ,O. Shekhah , Y. Belmabkhout, U .Buttner., et.al., “Insights on Capacitive Interdigitated Electrodes Coated with MOF Thin Films: Humidity and VOCs Sensing as a Case Study,” *Sensors*,vol.15,pp.18153-18166,Aug.2015. https://doi.org/10.3390/s150818153

[4] C. Sapsanis , Sivashankar ., H. Omran, U. Buttner and K.N. Salama, "Capacitive immunosensor for C-reactive protein quantification," *2015 IEEE 58th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Fort Collins, CO, USA, Aug.2-5, 2015. https://doi:org/10.1109/MWSCAS.2015.7282094.

[5] M. Omran, Arsalan, and K. N. Salama, “A Robust Parasitic-Insensitive Successive Approximation Capacitance-to-Digital Converter,” in *Proc. IEEE Custom Integrated Circuits Conference (CICC 14)*, 2014, pp 515-518. https://doi.org/ 10.1109/CICC.2014.6946080.

[6] H . Omran , M . Arsalan , and K.N. Salama., “7.9 PJ/Step Energy Efficient Multi-Slope13-Bit Capacitance-to-Digital Converter,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 61, pp. 589–593, Aug 2014. https://doi.org/10.1109/TCSII.2014.2327312.

[7] J. Gardner , P. Guha., F. Udrea., and J. Covington, “CMOS Interfacing for Integrated Gas Sensors: A review,” IEEE Sensors Journal, vol. 10, pp. 1833–1848, Jun 2010. https://doi.org/10.1109/JSEN.2010.2046409

[8] R. A Potyrailo, C. Surman, N. Nagraj, and A. Burns, “Materials and Transducers Toward Selective Wireless Gas Sensing,” *Chemical Reviews*, vol.111,pp.7315–7354,Nov 2011 https://doi.org/10.1021/cr2000477

[9] R. S. Jachowicz and S. D. Senturia, “A Thin-Film Capacitance Humidity Sensor,” *Sensors and Actuators*, vol. 2, pp. 171–186, Jan 1981. https://doi.org/10.1016/0250-6874(81)80036-4

[10] X. B . Li .,S.D. Larson., A.S. Zyuzin . and Mamishev, “Design Principles for Multichannel Fringing Electric Field Sensors,” *IEEE Sensors Journal.*, vol.6,pp.434-40,Mar.2006. https://doi.org/10.1109/JSEN.2006.870161

[11] P. Kapoor, V. Mehta, R. Bansal, S. Rana ,J. Singh, A. Singh, “Comparative Analysis Between Multi-Grid MEMS Structure and Interdigital Electrodes for Moisture Measurement,” *International Journal of U- and E-Service, Science and Technology*, vol.8, pp.347-356, Jul 2015. https://dx.doi.org/10.14257/ijunesst.2015.8.7.35

[12] R. S. Beeresha, A. M. Khan, and H. V. Manjunath-Reddy, “Design and Optimization of Interdigital Capacitor,” *International Journal of Research in Engineering and Technology*, vol 5, pp.73-78, Nov 2016

[13] S. Zargari, S. Falaki and H. Veladi, "Design and finite element analysis of a MEMS based capacitive pressure sensor using CNT/PDMS nanocomposite electrodes, “in Proc. *24th Iranian Conference on Electrical Engineering(ICEE 16)*,2016,pp.1619-1623, https://doi.org/10.1109/IranianCEE.2016.7585780.

[14] Y. Huang, Z. Zhan & N. Bowler, “Optimization of the Coplanar Interdigital Capacitive Sensor,” .in Proc. *American Institute of Physics (AIP)*, 2017, pp. 110017. https://doi.org/10.1063/1.4974695

[15] R. Moura Dos Santos, J. Sallese, M. Mattavelli, A. Santos Nunes, C. Dehollain and D. Barrettino, “High Precision Capacitive Moisture Sensor for Polymers: Modeling and Experiments,” *IEEE Sensors Journal*, vol. 20, pp. 3032-3039, Dec 2020 https://doi.org/10.1063/1.4974695

[16] W.Pan , L.Qibing , and F.Zhun., “Evolutionary Design Optimization of MEMS: A Review of Its History and State-of-the-Art,” *Cluster Computing*,vol.22,pp.9105-9111,Jul.2019. : https://doi.org/10.1007/s10586-018-2085-3

[17] P.W. Oluwasanya, G. Rughoobur, and L.G. Occhipinti, “ Comparison of Analytical and Numerical Methods of Obtaining Coplanar Capacitance of Microelectrodes for Particulate Matter Detection,” *IEEE sensors Journal* ,vol,20,pp.8631-8636,Apr.2020. https://doi.org/10.1109/JSEN.2020.2985969

[18] D. Back, D. Theisen, W. Seo, C. S. J. Tsai, and D.B. Janes, “Development of Interdigitated Capacitance Sensor for Real-Time Monitoring of Sub-Micron and Nanoscale Particulate Matters in Personal Sampling Devices for Mining Environment,” *IEEE Sensors Journal*, vol.20, pp.11158-11597, Jul 2020. https://doi.org/10.1109/JSEN.2020.2995960

[19] X.Hu and W.Yang.,“Planar Capacitive Sensors – Designs and Applications,” *Sensor Review*, vol. 30, pp. 24-39, Jan 2010. https://doi.org/10.1108/02602281011010772

[20] Grover William Henri, “Interdigitated Array Electrode Sensors: Their Design, Efficiency, and Applications” Chancellor’s Honors Program Thesis Projects, Department of Chemistry, University of Tennessee , Knoxville ,1999. https://trace.tennessee.edu/utk_chanhonoproj/310

[21] H. Omran and K. N. Salama, “Design and Fabrication of Capacitive Interdigitated Electrodes for Smart Gas Sensors," in Proc. *IEEE 3rd International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA 15)*, 2015, pp. 1-4. https://doi.org/10.1109/ICSIMA.2015.7559021