INTREDEGITATED ELECTRODE AS MATERIAL SENSOR

Fecha de aceptación: 01/07/2024

Maryam Liaqat
Department of Physics, University of Okara (UO), Okara, Pakistan

Sumble Yousaf
Department of Physics, University of Okara (UO), Okara, Pakistan

Muhammad Yasir
Department of Physics, University of Okara (UO), Okara, Pakistan

Hina Maryam
Department of Physics, University of Okara (UO), Okara, Pakistan

Ghulam Nabi
Department of Physics, University of Okara (UO), Okara, Pakistan

Zunaira Fatima
Department of Physics, University of Okara (UO), Okara, Pakistan

Farkhanda Shabbir
Department of Physics, University of Okara (UO), Okara, Pakistan

Ali Raza
Department of Electrical and Computer Engineering, São Carlos School of Engineering, University of São Paulo, Brazil

Muhammad Azeem Aslam
Department of Physics, University of Okara (UO), Okara, Pakistan

Zunaira Javeed
Department of Physics, University of Okara (UO), Okara, Pakistan

Kamran Arshad
Department of Physics, University of Okara (UO), Okara, Pakistan

Hafza Laraib
Department of physics Government College Women University, (GCWU), Sialkot, Pakistan

ABSTRACT: This work is to focus on the modeling and simulation of interdigitated electrodes (IDEs) that describes a single-step and quick production method based on inkjet printing. The IDEs on a substrate were created using a commercially available inkjet-printer on circuit board (PCB) printer. The inkjet printer was used specifically for printing IDEs which are designed on a computer. The size of IDEs 25×75mm^2 1.6mm thickness the design have 20 fingers 0.31mm width fingers of copper materials. For chemical sensing applications, a

frequency range of 1 Hz to 10 GHz was used an electrochemical workstation. The IDE sensors performed well in terms of water quantification on material sensor. Different parameters like S-characteristics, impedance with and without sample material was measured. Characteristics of water particles, Zn nano particles and water detected through simulation. Whereas Zn nano particles and water content were detected in laboratory. Inkjet printing, on the other hand, delivers IDE sensors at a fraction of the cost and time. The inkjet printing-based IDE sensor, which can be made in less time and less cost can be adopted as a suitable IDE sensor with quick fabrication process competencies. Which shows very good resonance frequency peaks that shows good results.

INTRODUCTION

What are Sensors?

A sensor is a device that receives and responds to environmental stimuli. The world is separated into natural and manmade objects. Natural sensors initiate in living organisms like eyes, skin, tongue, nose and ear etc. receive external stimulus and respond in an electrochemical nature. Human body sensors are presented in Fig. 1(a–e).

(a) (b) (c) (d) (e)

Fig. 1 Natural sensors: **(a)** Eye (Detects light), **(b)** Nose (Detects smell of chemicals), **(c)** Ear (Detects sound), **(d)** tongue (Detects Taste), **(e)** Skin (Detects Pressure and Temperature)

Sensors change or transform energy, in complex systems transducers may transform multiple forms of energy before generating output electrical signals. The block diagram, is shown in Fig. 2 presents a chemical sensor, in which transducer 1 convert's energy from reaction of chemical into heat and transducer 2 converts' heat into electrical signal. From Fig. 2, S1 is the stimulus from chemical reaction S2 is the thermal energy incentive to transducer 2, and S3 is the complex sensor's electrical yield.

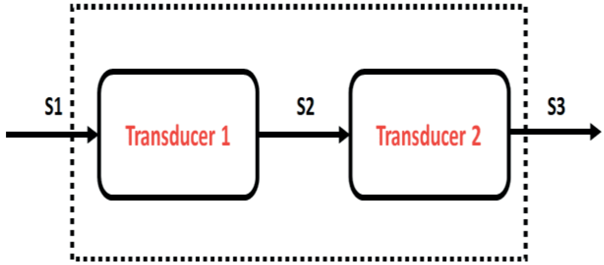

Fig. 2 Complex sensor system.

Sensors are employed in wide variety of applications, with progression in technology and development in human living standards new areas of applications are identified broadening scope of sensors. Sensors are employed in various and automated sectors like manufacturing industry, aeronautics, biomedical, military, security and robotics [1]. Under environmental finding, sensors are engaged for detection of movement of animals and birds [2] shown in Fig 3, monitoring pollution and environmental conditions which may affect irrigation and livestock [3], and flood detection [4]. In health applications, sensors are used for patient monitoring [5-7] presented in Fig. 4, drug delivery and diagnostics [8]. Commercial applications of sensors include product quality monitoring, control and automation of manufacturing factories [9, 10], and vehicle tracking and theft detection [11, 12] etc.

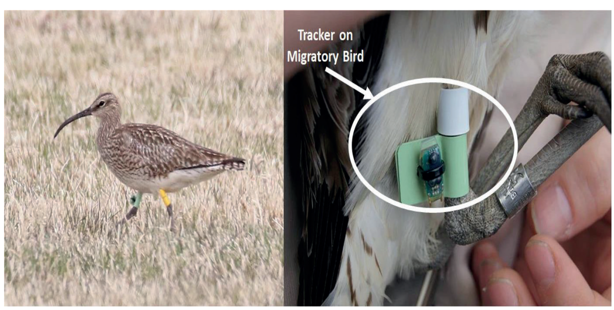

Fig. 3 Migratory bird tracking [13].

Printed Electronics for Sensor Fabrication

Sensors can be broadly classified as flexible and non-flexible sensors. Flexible sensors are manufactured on materials that are malleable, whereas, the later are fabricated on brittle and rigid substrates. Conventional electronics employs inorganic materials such as Silicon, Gallium Arsenide etc. to fabricate on brittle and rigid substrates through photolithographic techniques. Electronic equipment developed by photolithography finds severe limitations in utilization of material variability, mechanical flexibility, optical transparency, and bio-compatibility. Other disadvantages include requirement of clean room facilities, and high cost of development. These disadvantages have limited the conventional electronics usage to certain areas of applications.

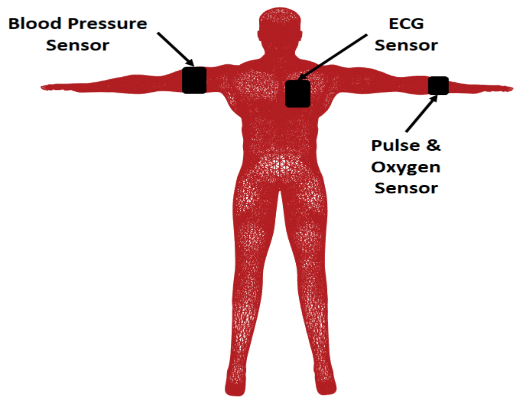

Fig. 4 Patient Monitoring (modified from [14]).

Classification of Sensors

- Electrochemical biosensing
- Amperometric biosensors
- Potentiometric biosensors
- Impedimetric biosensors
- Biorecognition agents
- Interdigitated electrodes

Interdigitated electrodes

To measure impedance, macro-sized metal rods or wires were immersed in the media as electrodes. Microelectrodes in combination with typical detection systems are currently being considered as possible possibilities for sensor miniaturization and enhanced sensitivity. This is due to the fact that microelectrodes provide faster reactant supply rates than macro electrodes and require lower electroactive ion concentrations to create a bilayer. Microelectrodes, for example, can detect impedance in low-conductivity fluids, whereas big electrodes may not be sensitive [15].

Interdigitated electrodes (IDEs) are microelectrodes with prospective advantages such as low-ohmic trickle flow, faster steady-state formation, fast reaction kinetics, and enhanced signal-to-noise ratio. [15], [16]. They are made up of a series of microstrip electrodes that are linked together to form a set of intermediate electrode fingers. Because the anode and cathode electrodes are so near together, trace amounts of ionic species can move between them efficiently (>0.98) [17]. Thus, IDE eliminates the need for a reference electrode and provides a simple method for obtaining a steady-state current response, which is particularly compatible with three- and four-electrode configurations [18].

Printing Technologies

Printing techniques can be divided into two basic categories of contact and non-contact processes [19, 20]:

- Direct contact techniques use a printing plate or master template for printing, these techniques include screen printing, gravure printing, flexography and soft lithography. Master template comes in direct contact with the substrate during the process of printing.
- Non-contact or additive printing doesn't require a master template. Functional materials are directly deposited on top of substrates in layer formation. Some commonly used additive printing processes are aerosol printing, laser direct writing and inkjet printing.

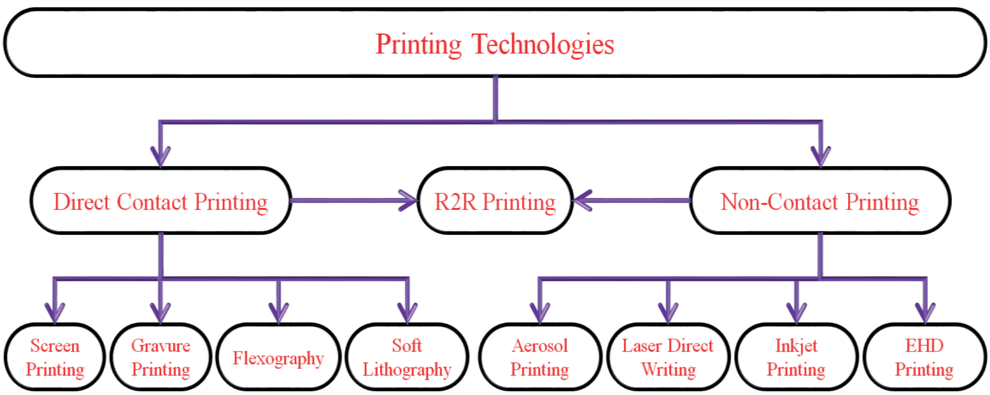

Fig. 5 Printed techniques classifications.

- Direct Contact Printing
- Screen Printing
- Flexography
- Gravure Printing
- Soft Lithography
- Non-Contact Printing
- Aerosol Printing
- Electrohydrodynamic Printing
- Laser Direct Writing
- Inkjet Printing

Inkjet Printing

Inkjet printing is a new technology and has widely attracted researchers because of its direct deposition methods of functional materials on top of substrate employing only digital imagery. Ink solutions are deposited by means of droplets from nozzle jets and ink is dried by evaporation of solvents. This technique has advantages of adaptability for patterning on a vast variety of substrate materials such as rigid, flexible, smooth and rough etc. Continuous injection mode caters continuous flow of droplets from nozzles and after departure from nozzle electric field excitation determines the path/trajectory of the droplet. Low viscosity inks are compatible for deposition through this mechanism with smallest droplet size of 20 µm. Fig. 6 (a) shows continuous injection mode of inkjet printing.

- Drop on demand, the print nozzle ejects the droplets only when desired, reducing the wastage of ink. The image is constructed by successive pulsed droplet formations. Some common methods to generate pulses are acoustic, piezoelectric, and electrostatic type systems. This mode is presented in Fig. 6 (b) [21].

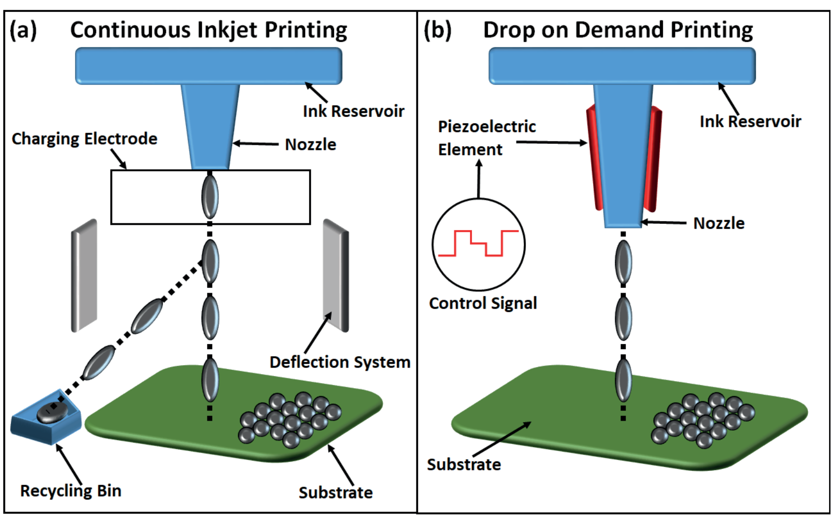

Fig. 6 Inkjet Printing **(a)** continuous **(b)** drop on demand.

Principles of Inkjet Printing

Inkjet printing is a technique used to create two-dimensional shapes on additive substrates. It can accurately deposit ink droplets in specific spots without the need for substrate pre-modeling, making it simple to use while minimizing waste. It has been widely utilised in industry as a fast manufacturing technology and may be used to a range of substrates for applications ranging from advertising to printed circuit boards. Continuous inkjet (CIJ) and drop-on-demand (DOD) printing are the two methods of inkjet printing. Liquid ink is pumped via nozzles, where vibrating piezoelectric crystals generate a continuous jet of droplets in CIJ printing. An electric field, the strength of which can be varied, charges the droplets. After then, the droplets are subjected to another electric field, with the higher charged droplets bouncing more than the less charged droplets. A picture is formed using this approach, and the waste ink is dumped down the toilet and recycled. DOD printers, on the other hand, eject substantial only when necessary. This is accomplished by compelling ink through a number of nozzles positioned on a print head. DOD printers are the conventional choice for printing functional materials since they do not reprocess ink, which may cause degradation when exposed to air. Furthermore, because DOD printing wastes less material, it is a better process for printing expensive materials.

The three basic phases of inkjet printing are depicted in Figure 7: drop ejection, drop spreading, and drop solidification. The dew is ejected from the nozzles and spreads across the substrate when the print head is positioned to the proper position. They spread across the surface and interact with other droplets to form a film of liquid ink when they collide. Finally, the solvent evaporates, leaving only the ink's solid components on the substrate.

DOD printers use two types of inkjet printing elements to achieve drop ejection: thermal inkjet printing elements and piezoelectric inkjet printing elements. A resistor in the ink chamber of thermal printheads superheats the ink above the bubble nucleation temperature when a voltage is supplied. Air bubbles expand, forcing ink through the nozzle and out of the chamber. As the ink is evacuated, the chamber rapidly cools, allowing more ink to enter. This whole procedure occurs in a few microseconds [22]. An inkjet printhead with piezoelectric components, on the other hand, pulses under electrical excitation, creating pressure waves that push ink out of the chamber. The vibration of the piezoelectric material can be accurately adjusted to control the ejection of droplets from the nozzle. Inkjet printheads generally include hundreds of ink chambers and nozzles to achieve high throughput. A greater number of nozzles allows for higher resolution patterns to be printed in less time, which is a crucial factor in mass production.

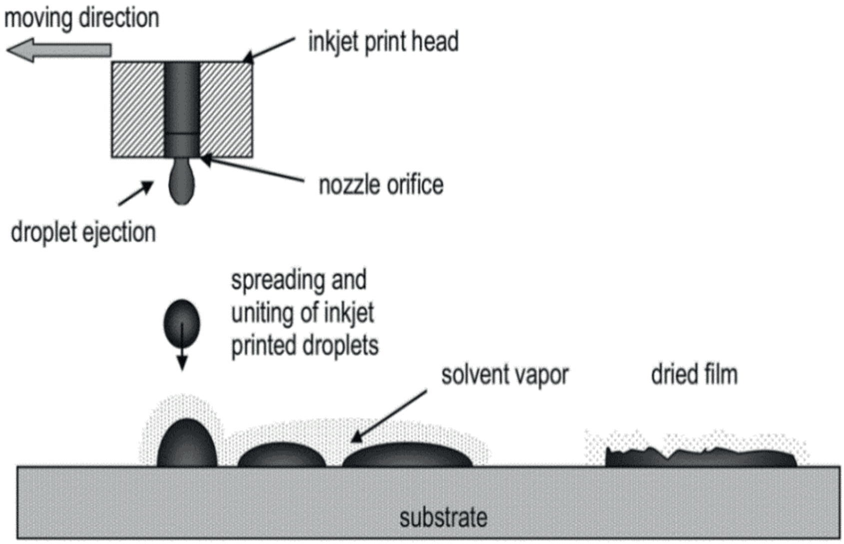

Fig 7. Schematic design of the inkjet printing procedure [23].

Because there are no moving parts in thermal print bonces, they are less expensive and require less maintenance than piezoelectric print heads. If the nozzles get clogged or broken, the user can simply change the holder on which the print heads are installed for a modest cost. On the other hand, if the piezo crystals of a piezo printhead are crushed, this often requires a more costly maintenance operation by a technician. On the other hand, piezoelectric printheads are ideal for printing various functional materials because they do not require ink heating, which can lead to ink contamination. Furthermore, a broader range of solvents, including water, oils, and organic solvents, can be employed with piezoelectric systems; thermal print bonces are often limited to aqueous inks due to the nucleation temperature required for droplet ejection. When using thermal printheads, ink viscosity, surface tension, and density must all be properly regulated. Ink viscosity should typically be around 10 cP [24, 25]. Because of their adaptability to ink composition and physical property connections, piezoelectric print heads are more commonly used in inkjet printing of nanomaterials.

Droplet spreading is the second stage of inkjet printing and is determined by the ink-to-substrate relationship. Once the droplet makes contact with the substrate surface, inertial and capillary forces influence dispersion behaviour, whereas gravity has no effect [26]. As illustrated in Figure 7, these forces are linked by Re, We, and Oh. These factors determine the surface energy and contact angle of a droplet on a substrate, which can be changed by varying the viscosity, surface tension, and density of the ink, as well as the shape, composition, and temperature of the substrate. Surface treatment is frequently the simplest technique to ensure good print persistence and optimal dispersion behavior.

Inkjet prints of useful materials typically consist of nanoparticles dispersed in a solvent, often with surfactants added. As a general rule, the solids range in the ink should be less than one-fiftieth the size of the printhead nozzle. Because inkjet printer nozzles are typically tens of micrometres wide, nanomaterials should be no more than a few hundred nanometers in size to avoid nozzle clogging [27]. Solid clumping can also create obstruction; consequently, solvent selection is crucial for achieving uniform dispersion. When the printer is turned off, the solvent around the nozzle evaporates, increasing the viscosity locally and interfering with droplet production. The time necessary for this gelation to occur is known as ink latency, and it is one of the most important difficulties in the creation of inkjet printing inks [28]. When compared to other processes as screen printing and 3D printing, inkjet printer inks must have a low viscosity.

The solvent evaporates during spreading and afterward, leaving a solid layer. Curing is affected by the solvent employed and the temperature of the substrate. The volume normally reduces significantly when the solvent disappears, especially when the solid is present loading absorption is low, as is usually the case when printing nanomaterials. If the ink is not dispersed evenly, a solid matter buildup may occur, resulting in the formation of isolated islands. Another common issue is the coffee ring effect, which develops after drying when particle concentration increases at the periphery of the droplet relative to the center [29]. This can cause variances in conductivity within the printed pattern as well as issues with device processing. Several ways for reducing the coffee ring effect have been demonstrated [30-34].

This study aims to development of low-cost, and standard/flexible sensors realizable through inkjet printing techniques. As a proof of concept, multiple practical applications for humidity detectors/sensors are available in market. Micro spectroscopy is a noval technique for the detection of nano particle of humidity detection in remote areas. Some specific objectives of this study are:

a. Designing and fabrication of Interdigitated Electrodes
b. Testing of IDEs by using:
    I. S11
    II. Impedance (real and Imaginary)
    III. LCR using VNA
c. Sensing of water content and nanoparticles

Materials

For designing interdigitated electrode in this research work we used material:

- Two way copper Clad FR-4
- Polyimide

Design and Simulation of the IDEs

This effort defines a single-step, quick IDE sensor production procedure based on inkjet printing. The IDEs on a polyimide substrate were created using a profitable inkjet PCB printer. Carbon ink, viscosity adjusted to Post-printing was enabled and considered. The ratio of distance between consecutive fingers and the ratio of the spacing between consecutive fingers to the electrode width is an important aspect in establishing the sensitivity of IDE-based sensing applications. Metallization value enhanced analytically, a = 0.66. The distance between each finger is predicted to be 205 m based on the thickness of the specified electrodes. Another important factor to consider is the amount of fingers to be used.

The cell constant is the battery constant. A smaller cell constant is desired, which can be accomplished by increasing the number (n) of fingers. The investigation discovered no statistically significant change in the cell constant after 20 fingers. Furthermore, because 20 fingers can be easily mounted on a glass substrate, n = 20 was chosen for the IDE's development and fabrication. The interdigitated electrodes are produced after the parameters are chosen. Using the layout editor, an array of 205 m finger spacing and electrode width was generated for the CAD model, with 310 m for a total of 20 fingers. The design also has a 5 mm ×7 mm contact pad.

Polyimide (PI)

Polyimides (PI) are polymer imide monomers with two acyl groups allocated to nitrogen. Thermoset and thermoplastic materials can coexist. It replaced materials such as glass, aluminium, and even steel in some demonstrations. It has excellent dielectric characteristics, a low thermal growth coefficient, and extremely high thermal stability (>500°C). Polyimide is a commonly utilised dielectric material in electronics, aerospace, and transportation to address the increased demand for materials that operate well in harsh situations such as high temperatures. Because of their outstanding chemical resistance, high temperature stability, and mechanical qualities, polyimides are an essential family of step-growth polymers.

Mechanical qualities

Since polyimides have great mechanical qualities, they are used in applications that call for tough organic materials, like construction.

- Very hot fuel cells
- Panel display, flat
- Applications in aerospace
- Environmental and chemical industries
- Additionally a number of military uses

They can be used as high temperature structural adhesives, plastics, films, laminating resins, and insulating coatings.

1.8.1 LCR meter: An LCR meter, also known as an impedance meter, is a specialized electrical instrument used to measure a component's or circuit's impedance (resistance, capacitance, and inductance). It is widely used in the electronics, physics, engineering, and manufacturing industries for a variety of tasks, including testing and characterizing passive electronic components such as resistors, capacitors, and inductors.

1.8.2 Impedance Measurement: The basic function of an LCR meter is to measure impedance. It measures a component's impedance, which includes both resistance and reactance (inductive or capacitive), and is commonly shown as a complex number in polar or rectangular shape.

$$Z = R + jX$$

Where Z = Impedance, R stands, for resistance, X is the, reactance, where X = X_L - X_C, with X_L representing, the inductive reactance, and X_C representing the capacitive reactance.

1.8.3 Inductive Reactance (X_L): Inductive reactance is the resistance to the flow of alternating current (AC) caused by the qualities of the inductor.

$$X_L = 2\pi f l$$

Where, *L* denotes, the inductive reactance, π (pi) is, about 3.14159*, f* = frequency, of the alternating current signal, *l* is the, inductor's inductance.

1.8.4 Capacitive Reactance (X_c): Capacitive reactance is the resistance to the passage of alternating current caused by the capacitor's characteristics.

$$X = \frac{1}{2\pi f c}$$

Where, X_C denotes capacitive reactance, π (pi) is about, 3.14159, and f is the frequency, of the alternating, current signal, C is the capacitor's capacitance.

1.8.5 Phase Angle (θ): In an alternating current circuit, the phase angle represents the phase difference between the voltage and current.

$$\theta = tan^{-1}(\frac{X}{R})$$

Where: θ denotes the phase angle, arctangent function is represented by tan^{-1}, reactance is denoted by X, R stands for resistance.

1.8.6 Quality Factor (Q): The quality factor in an LCR circuit is a measure of the sharpness of the resonance.

$$Q = \frac{\omega L}{R}$$

Where, Q is the quality, factor, ω is the angular, frequency, L denotes the, inductance, R stands for resistance.

1.8.7 Capacitance Measurement: LCR meters can determine a component's capacitance, which indicates its ability to retain electrical charge.

$$C = \frac{1}{2\pi f X_c}$$

1.8.9 Measurement of Inductance: LCR meters can measure a component's inductance, which indicates its ability to generate an electromotive force in response to a change in current.

$$L = \frac{X_L}{2\pi f}$$

1.8.10 Resistance Measurement: LCR metres may also measure a component's pure resistance without taking into account its reactance.

RESULTS

An interdigitated electrode was fabricated by using inkjet printing technique. A simple, quick, and one-step interdigitated electrode production procedure is addressed here and its chemical sensing capabilities are disclosed. The IDE sensor fabricated using inkjet printing and was created in less time. This portray the IDE sensor's reaction to several taste imitating chemicals via inkjet printing. According to the model resistivity (real Z) increases with frequency. The charts show how impedance values change at different frequencies. The resistance to solution and the double layer Capacitance is essential in describing EIS behaviors. The resistance to the solution. As a result, resistance increases at higher frequencies. Reaction (fictitious Z). Among other things, behavior is affected by double-layer capacitance. Testing shows the microwave spectroscopy range by changing frequency with respect to the materials.

Graphs for 5 pair IDE

Here we will discuss the graphs for the IDE with 5 pairs of fingers Sensors with the IDE structure operating at microwave frequencies were chosen for their versatile design that combines ease of manufacturing with the desired functionality. The sensor pattern layouts was tested, which differ as a result of the number of IDE pair. Copper was used as the conductive metal material for the both bottom layer, which acted as a ground plane, and the IDE pattern on the top layer to maintain chemical neutrality when the device is placed in contact with water.

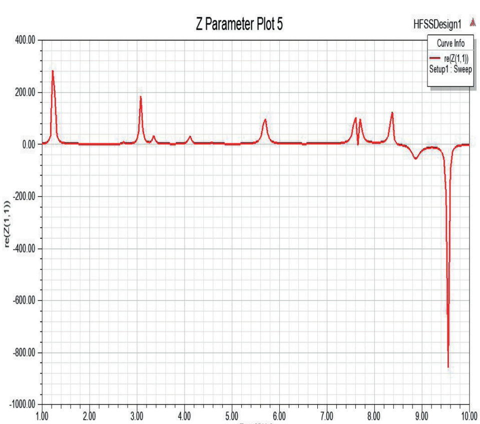

Fig 4.1 Impedance (real Z) vs. Frequency, (GHz)

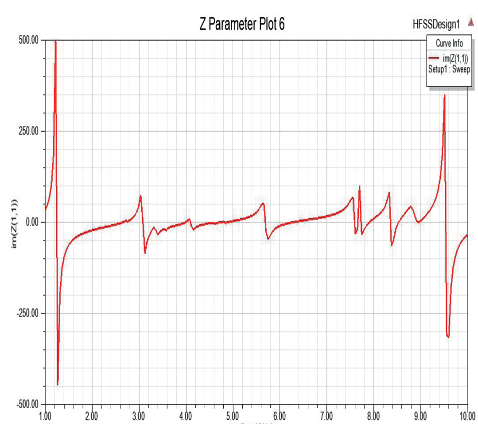

Fig 4.2: Impedance (img Z) vs. Frequency, (GHz)

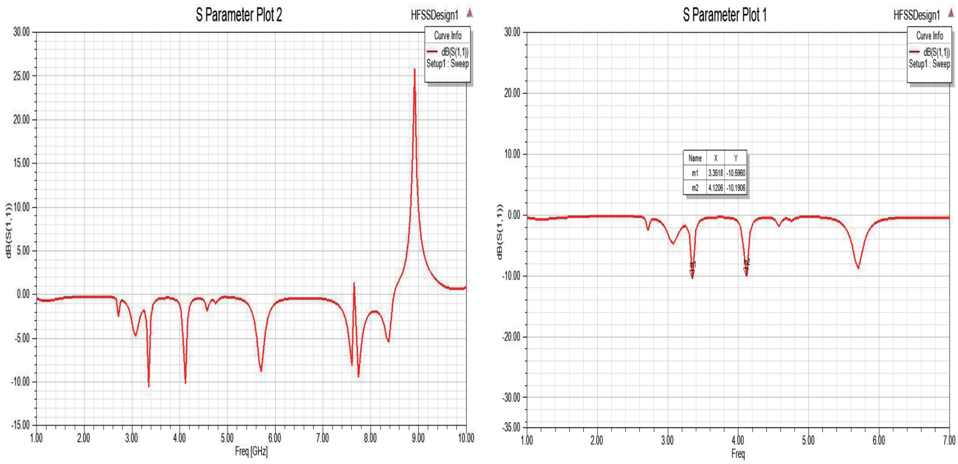

Fig 4.3: S parameter vs. Frequency, (GHz)

The design of any microwave sensor is the key parameter that regulates its performance. In this work, the sensing responses of two printed microwave sensors with different number of IDEs were evaluated to reveal the most appropriate structure for water quality monitoring purposes. Figure 4.3 illustrates S11 signal distribution of five-pair IDE microwave sensors when in contact with air. One may note the significant number of resonant peaks available with the IDE sensor, which indicates that the various sensing elements (or digits) each influence the obtained spectrum. This will give significant advantages in terms of identifying the presence of water contaminants with greater sensitivity, selectivity and high resolution.

Graphs for 10 pairs IDE

Here we will discuss the graphs for the IDE with 10 pairs of fingers Sensors with the IDE structure operating at microwave frequencies were chosen for their versatile design that combines ease of manufacturing with the desired functionality. The sensor pattern layouts was tested, which differ as a result of the number of IDE pair. Copper was used as the conductive metal material for the both bottom layer, which acted as a ground plane, and the IDE pattern on the top layer to maintain chemical neutrality when the device is placed in contact with water.

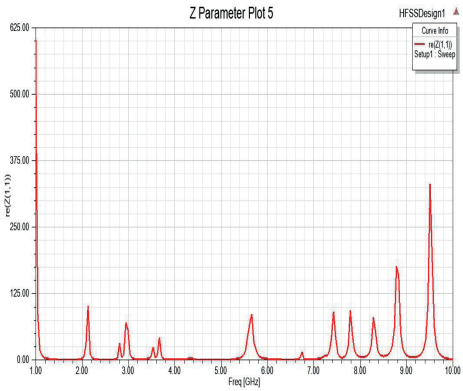

Fig 4.4 Impedance (real Z) vs. Frequency, (GHz)

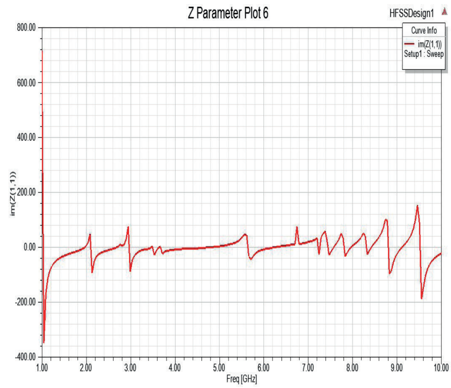

Fig 4.5 Impedance (img Z) vs. Frequency, (GHz)

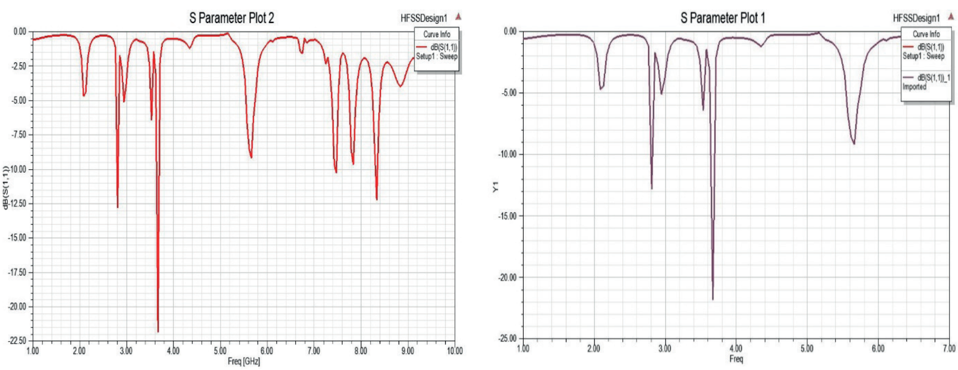

Fig 4.6 S parameter vs. Frequency, (GHz) for 10 pair

The design of any microwave sensor is the key parameter that regulates its performance. In this work, the sensing responses of three printed microwave sensors with different number of IDEs were evaluated to reveal the most appropriate structure for water quality monitoring purposes. Figure 6 illustrates S11 signal distribution of the pair IDE microwave sensors when in contact with air. One may note the significant number of resonant peaks available with the IDE sensor, which indicates that the various sensing elements (or digits) each influence the obtained spectrum. This will give significant advantages in terms of identifying the presence of water contaminants with greater sensitivity, selectivity and high resolution. The response of each sensor was measured for air and then when in contact with DIW and tap water (TW) samples to evaluate if the sensors respond differently. Three spectra are plotted on common graphs to illustrate that each sample has a unique response to the microwave signal resulting in resonant peaks occurring at different frequencies, and this particular feature makes the developed sensors an attractive option for real-time monitoring of water quality.

CONCLUSION

A simple, quick, and one-step interdigitated electrode production procedure is addressed here, and its chemical sensing capabilities are disclosed. The IDE sensor based on inkjet printing was created in less time and low cost which can be used as an appropriate sensor with quick fabrication capabilities. Different parameter S (1,1) impedance with and without sample material was measured characteristics of Zn nano particles and $NdFe_3O$ and water detected through simulation. Here in this research from literature studied that impedance measured. And its frequency range is 1GHz to 10 GHz. It gives prominent peaks produces good results for nano particle analysis. The performance of an IDE sensor based on inkjet printing was compared to that of an IDE sensor based on DLW inkjet printing. The DLW-inkjet-based IDE sensor has greater geometric tolerances and performs better. The controlling values of the sensing, ranges for the inkjet printing, based IDE sensor are being improved, and the sensor is being evaluated for broader application. This work could be expanded further, in the future. Allow for the quick manufacture of IDEs on substrates suited for flexible sensing applications. We made a very effective and good low cost and easily fabricated interdigitated electrode that can be used in industry for sensing the gas or liquid. That perform very good work in this field. By increasing the numbers of fingers its gives better results and better resonance peaks that shows good results.

REFERENCES

1. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” Computer networks, vol. 38, pp. 393-422, 15 March 2002. https://doi.org/10.1016/S1389-1286(01)00302-4

2. Cerpa, J. Elson, D. Estrin, L. Girod, M. Hamilton, and J. Zhao, “Habitat monitoring: Application driver for wireless communications technology,” ACM SIGCOMM Computer Communication Review, vol. 31, pp. 20-41, April 2001. https://doi.org/10.1145/84419. 844196.

3. B. Halweil, “Study finds modern farming is costly,” World Watch, vol. 14, pp. 9-10, 2001.

4. P. Bonnet, J. Gehrke, and P. Seshadri, “Querying the physical world,” IEEE personal Communications, vol. 7, pp. 10-15, October 2000. https://doi.org/10.1109/98.878531

5. B. Celler, T. Hesketh, W. Earnshaw, and E. Ilsar, “An instrumentation system for the remote monitoring of changes in functional health status of the elderly at home,” in Proceedings of 16th annual international conference of the IEEE engineering in medicine and biology society, 1994, pp. 908-909.

6. G. Coyle, L. Boydell, and L. Brown, “Home telecare for the elderly,” Journal of Telemedicine and Telecare, vol. 1, pp. 183-184, 1 September 1995. https://doi.org/10.1177/1357633X9500100309

7. P. Johnson and D. Andrews, “Remote continuous physiological monitoring in the home,” Journal of telemedicine and telecare, vol. 2, pp. 107-113, 1 June 1996. https://doi.org/10.1177/1357633X9600200207

8. B. Sibbald, “Use computerized systems to cut adverse drug events: report,” ed: Can Med Assoc, 2001.

9. J. Agre and L. Clare, “An integrated architecture for cooperative sensing networks,” Computer, vol. 33, pp. 106-108, May 2000. https://doi.org/10.1109/2.841788

10. D. Estrin and R. Govindan, “J. Heidemann,” Embedding the internet,”” Commun. ACM, vol. 43, pp. 39-41, 2000.

11. E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, et al., “Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks,” in Proceedings of the 7th annual international conference on Mobile computing and networking, 2001, pp. 272-287. 122.

12. G. J. Pottie and W. J. Kaiser, “Wireless integrated network sensors,” Communications of the ACM, vol. 43, pp. 51-58, May 2000. https://doi.org/10.1145/332833.332838

13. J. A. Alves, M. P. Dias, V. Méndez, B. Katrínardóttir, and T. G. Gunnarsson, “Very rapid long-distance sea crossing by a migratory bird,” Scientific reports, vol. 6, pp. 1-6, 30 November 2016. https://doi.org/10.1038/srep38154

14. Patient Monitoring. Available: https://i.stack.imgur.com/52wtJ.png

15. M. Varshney and Y. Li, Biosens. Bioelectron, 2009, 24, 2951–2960.

16. S. Ding, C. Mosher, X. Y. Lee, S. R. Das, A. A. Cargill, X. Tang, B. Chen, E. S. Mclamore, C. Gomes, J. M. Hostetter and J. C. Claussen, ACS Sens., 2017, 2, 210–217.

17. T. A. Postlethwaite, J. E. Hutchison, R. Murray, B. Fosset and C. Amatore, Anal. Chem., 1996, 68, 2951–2958.

18. D. Liu, R. K. Perdue, L. Sun and R. M. Crooks, Langmuir, 2004, 20, 5905–5910.

19. S. Khan, S. Ali, and A. Bermak, “Smart Manufacturing Technologies for Printed Electronics,” in Hybrid Nanomaterials-Flexible Electronics Materials, ed: IntechOpen, 2019.

20. S. M. F. Cruz, L. A. Rocha, and J. C. Viana, “Printing Technologies on Flexible Substrates for Printed Electronics,” 2018. 10.5772/intechopen.76161

21. Z. Yin, Y. Huang, Y. Duan, and H. Zhang, “Introduction of Electrohydrodynamic Printing,” in Electrohydrodynamic Direct-Writing for Flexible Electronic Manufacturing, ed: Springer, 2018, pp. 1-29.

22. J. Aden, J. Bohórquez, D. Collins, M. Crook, A. García, and U. Hess, “The Third-Generation HP Thermal InkJet Printhead,” Hewlett-Packard Journal, pp. 41-45, 1994.

23. J. Li, F. Ye, S. Vaziri, M. Muhammed, M. C. Lemme, and M. Östling, “Efficient Inkjet Printing of Graphene,” Advanced Materials, vol. 25, pp. 3985-3992, 2013.

24. X. Wang, W. W. Carr, D. G. Bucknall, and J. F. Morris, “High-shear-rate capillary viscometer for inkjet inks,” Review of Scientific Instruments, vol. 81, p. 065106, 2010.

25. J. Stringer and B. Derby, “Limits to feature size and resolution in ink jet printing,” Journal of the European Ceramic Society, vol. 29, pp. 913-918, 2009.

26. J. A. Lim, J. H. Cho, Y. Jang, J. T. Han, and K. Cho, “Precise control of surface wettability of mixed monolayers using a simple wiping method,” Thin Solid Films, vol. 515, pp. 2079-2084, 2006.

27. Y. Su, J. Du, D. Sun, C. Liu, and H. Cheng, “Reduced graphene oxide with a highly restored π-conjugated structure for inkjet printing and its use in all-carbon transistors,” Nano Research, vol. 6, pp. 842-852, 2013.

28. R. D. Deegan, O. Bakajin, T. F. Dupont, G. Huber, S. R. Nagel, and T. A. Witten, “Capillary flow as the cause of ring stains from dried liquid drops,” Nature, vol. 389, pp. 827-829, 1997.

29. D. Soltman and V. Subramanian, “Inkjet-Printed Line Morphologies and Temperature Control of the Coffee Ring Effect,” Langmuir, vol. 24, pp. 2224-2231, 2008.

30. R. D. Deegan, O. Bakajin, T. F. Dupont, G. Huber, S. R. Nagel, and T. A. Witten, “Contact line deposits in an evaporating drop,” Physical Review E: Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics, vol. 62, pp. 756-765, 2000.

31. D. Kim, S. Jeong, B. K. Park, and J. Moon, “Direct writing of silver conductive patterns: Improvement of film morphology and conductance by controlling solvent compositions,” Applied Physics Letters, vol. 89, p. 264101, 2006.

32. J. Park and J. Moon, “Control of Colloidal Particle Deposit Patterns within Picoliter Droplets Ejected by Ink-Jet Printing,” Langmuir, vol. 22, pp. 3506-3513, 2006.

33. B.-J. de Gans and U. S. Schubert, “Inkjet Printing of Well-Defined Polymer Dots and Arrays,” Langmuir, vol. 20, pp. 7789-7793, 2004.

34. A. Rivadeneyra, J. Fernández-Salmerón, J. Banqueri, J. A. López-Villanueva, L. F.Capitan-Vallvey, & A. J. Palma. “A novel electrode structure compared with interdigitated electrodes as capacitive sensor”. Sensors and Actuators B: Chemical, 204, 552-560, (2014).