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A novel electrode structure compared with interdigitated electrodes as capacitive sensor

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ABSTRACT

Serpentine structure is a novel electrode structure presented in this work. It consists of a combination of meandering and interdigitated electrodes in a single structure with the aim of improving the transduction sensitivity. Capacitors based on this structure, known as serpentine, have been numerically simulated, comparing their capacitance with the interdigitated electrode structure. Simulation results show a bigger capacitance in the serpentine structures than in the interdigitated ones, enhanced for increasing number of fingers. Theoretical calculations agree with results obtained from the experimental characterization of inkjet-printed serpentine and interdigitated structures used as humidity capacitive sensors. We have measured an increase of 28% in humidity sensitivity with capacitors of the same area. Other sensor characteristics such as dynamic response, hysteresis and time drift remained unchanged for both capacitive structures. As this novel serpentine electrode structure presents a bigger geometrical capacitance factor compared to the interdigitated capacitor, in our opinion, it will be a promising base structure for multiple applications in the field of signal transduction.

1. Introduction

Capacitive structures have been broadly used in electronics covering different applications from energy storage to signal processing and sensing [1,2]. The most common structures are the planar parallel plate and the interdigitated electrode (IDE). The former is characterized by the simplicity of its geometry and the ease of modelling and calculation. However, IDE structure present very different and interesting features such as one-side access (the other side can be open to the ambient), control of signal strength by easily changing its dimensions, multiple physical effects in the same structure (electric, magnetic, acoustic), simplified modelling in 2D when the aspect ratio of the electrode finger length to the spatial wavelength is large, and a wide frequency spectrum of use. Moreover, it has been fabricated with multiple materials and following different manufacturing processes, from integration in semiconductor dices to printing on flexible substrates [3].

Many efforts have been devoted to the characterization of the IDE. Igreja et al. [4] developed a theoretical model of the capacitance of this structure. These capacitors have also been simulated using different simulations tools [5–7]. This structure has been typically adopted as sensor because of the low energy consumption of the capacitive transduction mechanism and its compactness, high contact area and relative ease of manufacturing. Some authors have analysed other constructions such as spiral electrodes and concentric rings in order to improve the performance of this design [8,9]. Furthermore, apart from different geometries, various strategies have been applied to broaden and improve its sensing capabilities, for instance the deposition of a more sensitive layer on top of the electrodes [10,11].

The flourishing demand for inexpensive and biodegradable systems has also focused the attention on printed electronics that use low-cost and environment-friendly materials. Different physical and chemical sensors based on IDE have already been developed through different printing techniques, such as gravure, screen printing and inkjet printing. One of the most demanding

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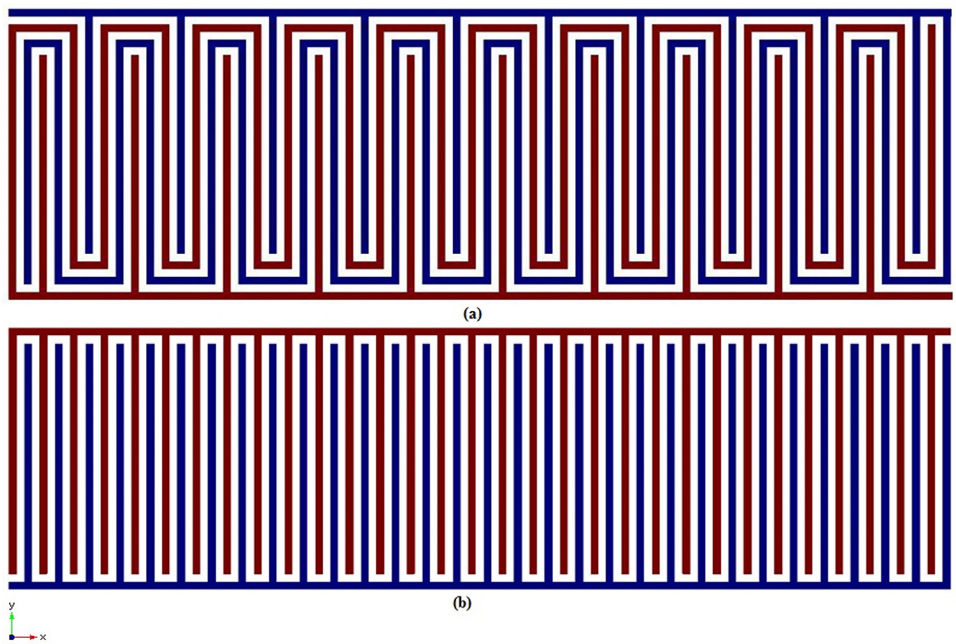

Fig. 1. (a) Serpentine electrode (SRE) and (b) interdigitated electrode (IDE) structures.

environmental properties to control is the relative humidity. Different strategies have been applied to include the sensing capability in the capacitor. The most common approach has been to deposit a sensing layer over the IDE capacitor [5,12,13]. Some frequently used polymers are cellulose acetate butyrate (CAB), polymethylmethacrylate (PMMA) and polyvinylchoride (PVC), among others. Another possibility is to use the flexible substrate as sensing element. In this case, the use of polyimide [14] and photographic paper [15] have already been described, saving fabrication steps compared with the former approach. Recently, Rivadeneyra et al. [16] described a humidity IDE sensor where the sensing material was directly the substrate.

In this work, the focus is on the underlying electrode structure instead of novel materials to improve the sensor sensitivity. We have looked into the geometry of the structure to enhance the sensor performance as it was indicated in the review of Mamishev et al. [3]. Here, we present a novel capacitive structure, known as serpentine, and its general behaviour compared with the IDE structure. This novel design consists of meandered electrodes arranged as interdigitated ones. Serpentine-like electrodes have previously been used as electrode guard of IDE structures [17], impedance sensor for conformal skin hydration monitoring [18] and a three phase electrode array for AC electroosmotic flow pumping, where the serpentine electrode creates a compact and symmetric design [19].

Here, this novel serpentine electrode (SRE) structure and the well-known IDE structure have been compared in detail as generic capacitive transducers by numerical simulation, showing the bigger capacitance for the former one with identical areas. From these simulations, the relevant geometrical dimensions which increase the SRE capacitance even more have been found. To verify the theoretical analysis, we have measured the response to relative humidity of printed SRE and IDE capacitive sensors on a flexible substrate. Capacitors have been printed with silver nanoparticles by inkjet printing on a polyimide thin film whose electrical permittivity changes with the moisture in the environment. Our results show the advantages of the SRE as a higher sensitive sensor compared with IDE structures made of the same materials and dimensions. Finally, the main conclusions will be remarked.

2. Materials and methods

2.1. Design and numerical simulation of the novel electrode structure: the serpentine electrode

Dimensionally identical serpentine electrode (SRE) and interdigitated electrode (IDE) structures are represented in Fig. 1a and b, respectively. As we will show throughout this document, this SRE structure will exhibit a bigger capacitance than the IDE one with the same geometrical dimensions. Therefore, SRE will have a higher sensitivity as a capacitive transducer only due to its geometrical structure.

To prove this, we have simulated deposited SRE and IDE capacitors on a substrate, always with the same dimensions, the same bottom substrate and the same top layer, calculating and comparing the DC capacitance of each structure. Given the complicated geometry of the serpentine capacitors, we have skipped the development of an analytical model and we have directly used a multiphysics numerical simulator: COMSOL Multiphysics (Comsol Inc., Stockholm, Sweden). This software, based on partial differential equations with the finite element method, has been previously used to calculate distributions of potential field in similar structures [7,16].

A three dimensional view of the simulated structure including the notation of its geometrical parameters is depicted in Fig. 2. Multiple numerical simulations have been carried out to compare and contrast both structures, as described below. We have looked over which dimensions are relevant to the capacitance differences of SRE with respect to IDE capacitors. The electrical properties of the substrate, top layer and the conductive electrodes have also been included in the simulator. In view of the very different vertical (submicron in some cases) and horizontal dimensions (millimetres), extremely long simulation times could be necessary. To overcome this drawback, we have taken advantage of the negligible influence of the electrode thickness in the calculated capacitance for the analysed range of thicknesses (around and below 1 μm). Here, we have applied an extrapolation method, presented in our previous work [16]. The thickness has been set to 5 μm for all the simulations to drastically reduce the computational time and after that,