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Capacitance Simulation of Interdigitated Metallic Towers for Humidity Sensing Applications

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Abstract

This paper presents simulation works done by CoventorWare™ on interdigitated vertical microelectrodes, the metallic towers. Capacitance study on various structures with different geometries, such as types of interdigitated electrodes, sizes of and gaps between the towers were carried out. Two types of 5x5 tower arrays were arranged so that the neighboring towers form two and four pairs of capacitors. For each type, the towers are 10x10 μm or 20x20 μm wide, 10 μm or 50 μm or 100 μm high, and 5 μm, 10 μm or 20 μm apart from each other. The results show that capacitance of tower array increases with the wider and taller towers but decreases with wider gaps. The capacitance of tower arrays ranges of 0.85-32.6 nF per mm^2 and 1.44-55.92 nF per mm^2 for the two-capacitor and four-capacitor types, respectively. We found that the four-capacitor tower array has average capacitances of 1.57 times that of two-capacitor type demonstrating an advantage of the four-capacitor over the two-capacitor towers.

Keywords: MEMS simulation, capacitance sensing, humidity sensor, metallic tower

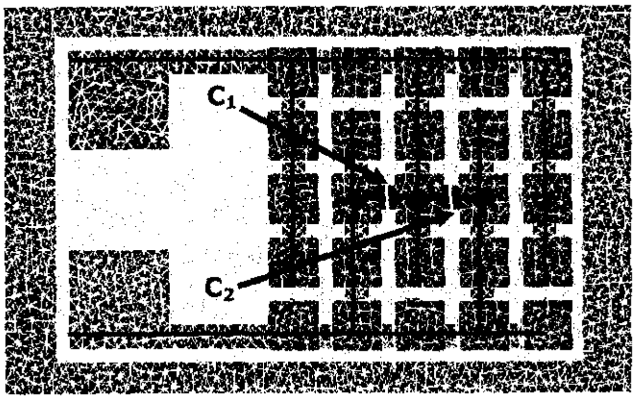
1. Introduction

Recently, integrated humidity sensors have become important part in modern electronic appliances, automotive and consumer applications [1], industrial process controllers [2], as well as scientific and medical equipments [3-5]. These sensors have principles of operation mainly based on humidity sensitive characteristics of materials including resistance and capacitance [6]. Capacitive humidity sensors has been conventionally fabricated in horizontal structures of thin interdigitated metallic electrodes, deposited onto a surface of humidity sensitive polymers film such as polyimide, or of an electrode-polymer-electrode sandwich [7-12]. Since permittivity of polyimide film changes with moisture absorbed, the capacitance between interdigitated electrodes varies with ambient humidity.

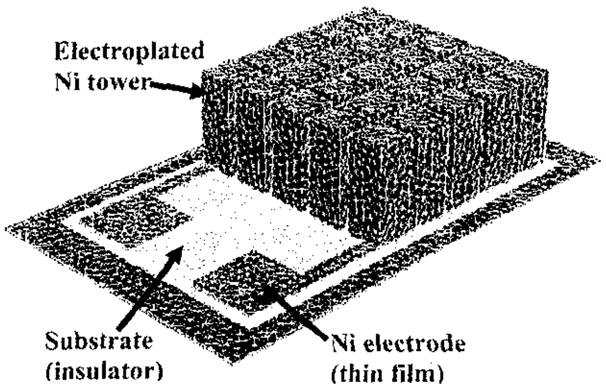
In this paper, we study another form of capacitive humidity sensors with vertical interdigitated electrodes, so called metallic towers, using finite-element simulation to primarily determine their capacitances. We report the simulation work done by CoventorWare™, commercial MEMS simulation software, for such structures.

2. Structural model

Preliminary simulation work were carried out using CoventorWare™ on various geometries of microstructures. The first form of structures is metallic towers made of electroplated nickel. The 10x10 μm or 20x20 μm wide, and 10 μm or 50 μm or 100 μm high nickel towers are arranged into a 5x5 array with 5 μm, 10 μm or 20 μm gap. The towers are interconnected by a nickel thin film to form a pair of interdigitated electrodes as shown in Figure 1. It can be seen from Figure 1(a) that each tower (except ones at the edge of the array) is connected to one electrode and facing two neighboring towers that are connected to another electrode. These three neighboring towers form



(a) Top view of a two-capacitor type tower array.



(b) 3D view of a two-capacitor type tower array.

Fig. 1. Structural model of a 5x5 two-capacitor type tower array. The size, height, and gap of towers in this figure is 20x20 μm, 50 μm, and 5 μm, respectively. (a) Top view (b) 3D view.

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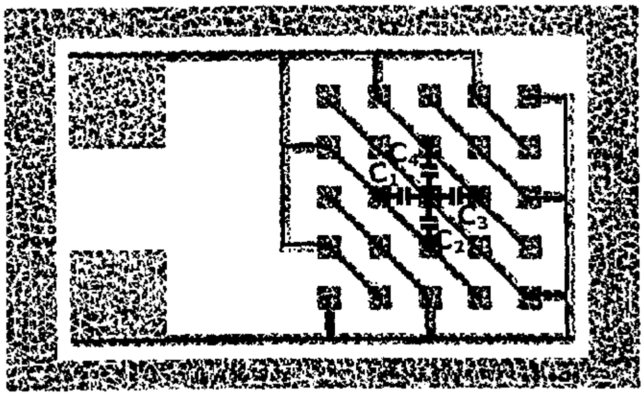
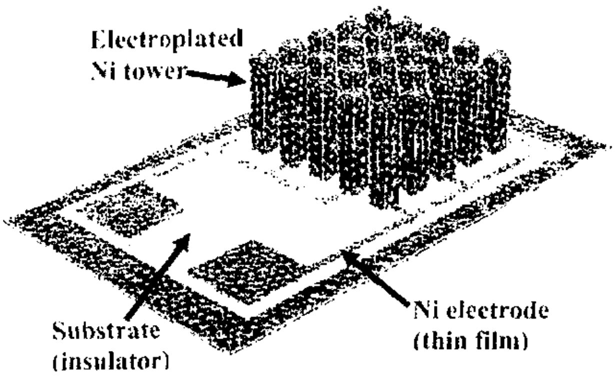


(a) Top view of a four-capacitor type tower array.



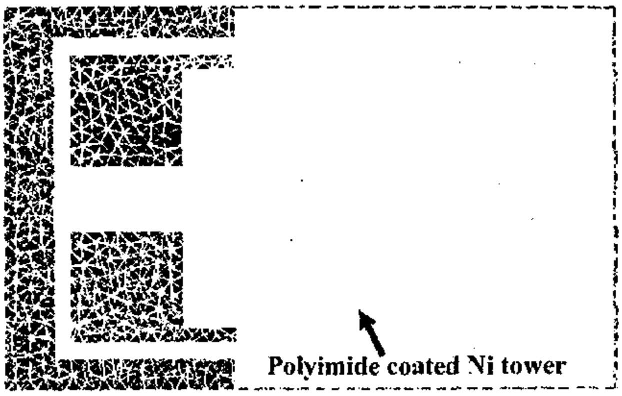
(b) 3D view of a four-capacitor type tower array.

Fig. 2. Structural model of a 5x5 four-capacitor type tower array. The size, height, and gap of towers in this figure is 10x10 μm, 50 μm, and 10 μm, respectively. (a) Top view (b) 3D view.

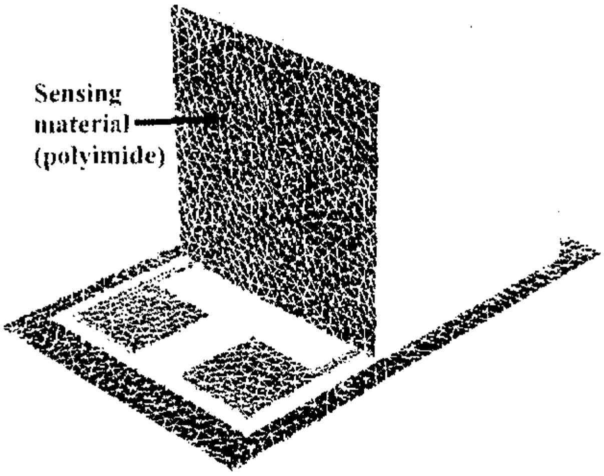
two pairs of capacitors. Therefore, this tower array is of a two-capacitor type. Another form of metallic towers, with the same sizes and gaps arrangement as those in two-capacitor type, is called the four-capacitor type. Since the tower interconnection allow each tower (except ones at the edge of the array) to face four neighboring towers that are connected to the opposite electrode as shown in Figure 2. These five neighboring towers form four pairs of capacitors. In both types of tower array, the medium between nickel towers is assumed to be air or polyimide. The relative permittivity ε_r of an air medium is unity, while that of polyimide varies with ambient humidity from approximately 3.0 in dry air to 4.2 at 100% RH [11]. Figure 3 shows a structural model of metallic tower array with polyimide as a dielectric medium. The solid models of two-capacitor and four-capacitor types of tower arrays, each of which with different sizes, gaps and dielectric materials, are constructed, meshed, and then simulated to determine their capacitances.

3. Simulation results

We observed the influence of polyimide on capacitances of the tower arrays by comparing simulation results of two-capacitor arrays with and without polyimide coating. Figure 4 shows that polyimide coating increases array capacitances, since polyimide has higher permittivity



(a) Top view of a tower array with polyimide.



(b) 3D view of a tower array with polyimide.

Fig. 3. Structural model of a 5x5 tower array, coated by polyimide as a humidity sensitive dielectric material. The size, height, and gap of towers in this figure is 10x10 μm, 100 μm, and 5 μm, respectively. (a) Top view (b) 3D view.

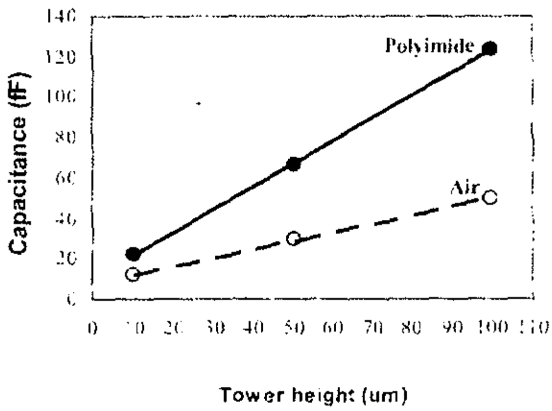


Fig. 4. Capacitances of nickel tower arrays at various heights, with and without polyimide coating ($\varepsilon_r = 2.8$). The two-capacitor arrays with towers of 10x10 μm width and 5 μm gap were used.

conventional two-capacitor counterparts. When a metallic tower array is coated with polyimide, its capacitance will be increased. Furthermore, the array capacitance depends on the size of the towers and gaps distance between them. Increasing tower size and reducing the gap help increase total capacitance. Besides the fact that four-capacitor type tower electrodes give out more capacitance than the conventional ones, the novel tower structure proposed here also has other advantages. The metallic tower structures require small substrate area which is a desirable factor of integrated sensors. The vertical tower array allow both vertical and lateral pathway for moisture diffusion during humidity uptake and discharge periods of the sensing material. This advantage is expected to improve response time of the sensors.

Since the simulation work reported here is only an early survey of this novel interdigitated vertical electrodes, extensive further work in both simulation and fabrication must be carried on in order to identify its advantages and disadvantages as well as its utilization in more details. The future work to realize the metallic towers as sensing electrodes include improvement of high aspect ratio electroplating for tall tower formation, development of polyimide coating onto the tower array as well as design optimization of the structures for fastest response time.

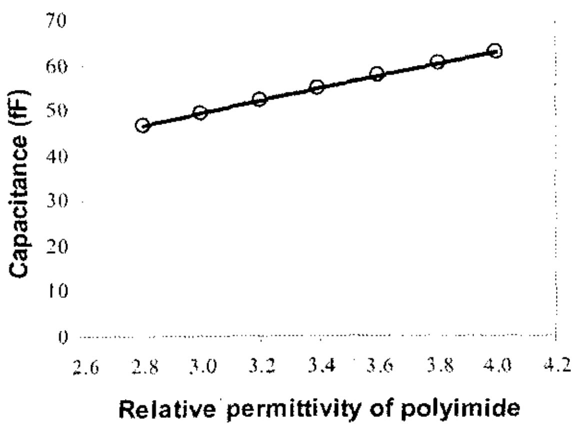


Fig. 7. Capacitances of a four-capacitor type tower array with 5 μm gaps, 10x10 μm widths, and 10 μm heights. It is assumed that the relative permittivity of the polyimide coating varies from 2.8 to 4.0 in accordance with the changing ambient humidity.

5. Conclusions

The concept of metallic tower array as a vertical interdigitated capacitive sensing electrode was proposed. We also proposed method of arranging the tower array so that it gives out high capacitance. Dependencies of array capacitance on structural geometries and humidity changing dielectric properties of the array were surveyed via simulation work using commercially available MEMS-simulation software. Preliminary results show that the capacitance is proportional to the size of the towers and the permittivity of the sensing polymer, but inversely proportional to the gap distance between them.

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than the air. Furthermore, we simulated polyimide-coated tower arrays of different types and geometries and obtained capacitances of each nickel tower arrays as shown in Table 1. In this table, the capacitance values of tower arrays are expressed in terms of array capacitance as well as capacitance per square millimeter. If the capacitance per square millimeter is known, one can estimate capacitance of a given substrate area. We found from the table that capacitances of tower arrays are in a range of 0.85-33.6 nF per mm^2 and 1.44-55.92 nF per mm^2 for the two-capacitor and four-capacitor types, respectively.

Table 1. Capacitances of nickel tower arrays.

	Gap (μm)	Size (μm)	Height (μm)	C (fF)	C (nF/mm²)
Two-capacitor type	5	10×10	10	28	5.77
	5	10×10	50	86	17.59
	5	10×10	100	160	32.60
	5	20×20	10	49	3.41
	5	20×20	50	159	11.06
	5	20×20	100	288	19.98
	10	10×10	10	22	2.67
	10	10×10	50	58	7.12
	10	10×10	100	106	13.10
	10	20×20	10	36	1.83
	10	20×20	50	93	4.74
	10	20×20	100	165	8.44
	20	10×10	10	18	1.07
	20	10×10	50	43	2.54
	20	10×10	100	77	4.56
	20	20×20	10	28	0.85
	20	20×20	50	67	2.07
	20	20×20	100	112	3.47
Four-capacitor type	5	10×10	10	50	10.30
	5	10×10	50	149	30.46
	5	10×10	100	274	55.92
	5	20×20	10	88	6.10
	5	20×20	50	284	19.70
	5	20×20	100	520	36.08
	10	10×10	10	35	4.29
	10	10×10	50	93	11.48
	10	10×10	100	168	20.74
	10	20×20	10	61	3.11
	10	20×20	50	161	8.24
	10	20×20	100	287	14.62
	20	10×10	10	28	1.68
	20	10×10	50	65	3.84
	20	10×10	100	116	6.84
	20	20×20	10	47	1.44
	20	20×20	50	110	3.38
	20	20×20	100	180	5.54

To better understand the effects of tower width, height, and gap, the results in Table 1 are presented graphically. Figure 5 and Figure 6 show that increasing tower height will increase the capacitance in all cases. In addition, increasing tower width or decreasing tower gap will increase array capacitance.

Another set of simulations was carried out to observe changes in capacitance when relative permittivity of polyimide is modified by up-taken moisture. The graph in Figure 7 clearly shows that the array capacitance increase linearly with increment of relative dielectric constant of the sensing polymer.

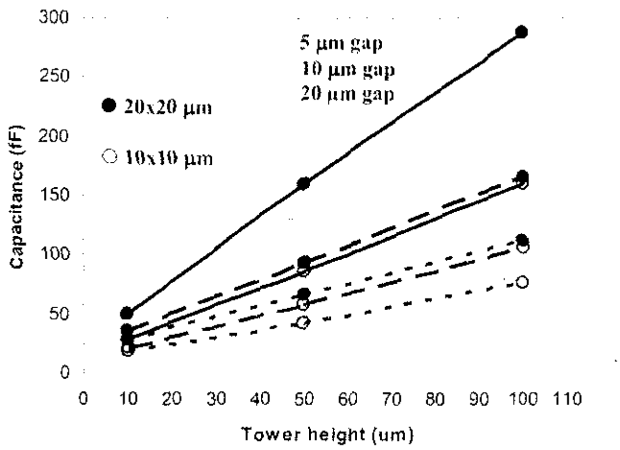

Fig. 5. Capacitances of two-capacitor type tower arrays with polyimide coating (ε_r = 2.8). The arrays have 5 μm, 10 μm or 20 μm gaps, 10x10 μm or 20x20 μm widths, and 10 μm or 50 μm or 100 μm heights.

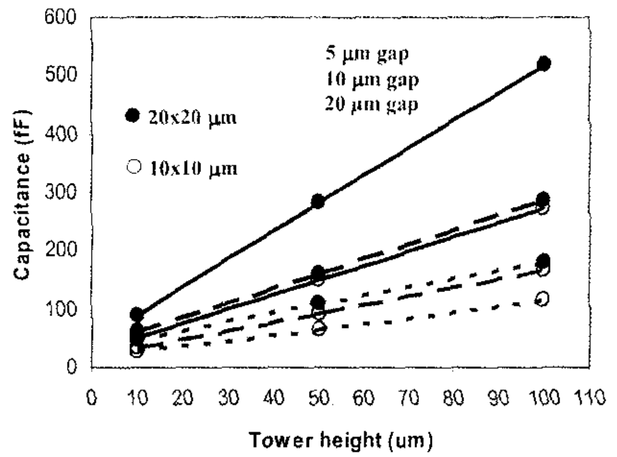

Fig. 6. Capacitances of four-capacitor type tower arrays with polyimide coating (ε_r = 2.8). The arrays have 5 μm, 10 μm or 20 μm gaps, 10x10 μm or 20x20 μm widths, and 10 μm or 50 μm or 100 μm heights.

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4. Discussion

Comparing the two array-types, it has been found from Table 1 that the four-capacitor type arrays have capacitance approximately 1.57 times that of two-capacitor type. This capacitance ratio is slightly less than our expected ratio of 2 since the two-capacitor arrays contain a larger number of stray capacitance between the next nearest neighbors than the four-capacitor arrays. This infers that designing the arrays with four-capacitor type will results in higher capacitance per unit area than the