New Type of High Sensitive Detection of Particles Based on DeFET

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ABSTRACT

This research work presents a new implementation of the CMOS electric-field sensor, titled as Differential Electric Field Sensitive Field Effect Transistor (DeFET). The DeFET is successfully used in detection of small partials and it is a suitable candidate to be used in biochemical and environmental applications. The developed implementation of the DeFET provides an improved sensitivity, thus it can be used to detect tiny particles in the range of nano meter scale. The direct application of the proposed sensor is the air pollution and environmental detection. The chip is implemented using 180 nm CMOS technology; it contains both the actuation and sensing parts. The sensors are distributed in two different arrays (uniform and nonuniform arrays).

Keywords: DeFET, electrode, micro, nano, sensing, environmental.

1. INTRODUCTION

Movement of particles caused by polarization effects in a nonuniform electric field is called Dielectrophoresis (DEP) phenomenon. In 1951, Pohl was the leader of describing this Dielectrophoresis (DEP) phenomenon [1, 2, 7]. Either direct (DC) or alternating (AC) electric fields can cause DEP [3]. A finite separation between equal amounts of positive and negative charges is found in any dipole (induced or permanent). The electric field will align with the dipole, but one side of the dipole will be in a region with lower field intensity than the other, if the electric field is nonuniform. This will produce an uneven charge density in the particle; i.e., uneven charge alignment in the particle; and it will be forced to move toward the regions of greater field strength. If the effective polarizability of the medium is lower than that of the particle then the particle will exhibit positive dielectrophoretic behavior since it will be attracted to regions of greater field intensity [4, 5]. Negative dielectrophoretic behavior or repulsion from regions of greater electric field intensity, is observed in medium with greater polarizability than that of the particles [4, 5].

In the early studies utilizing DEP to manipulate cells, electrodes of different shapes were employed in order to produce nonuniform electric fields. Pin-plate and pin-pin electrodes were used to separate live and dead yeast cells and achieved collection of yeast cells on the electrodes [4, 6]. Recently, arrays of microelectrodes and AC electric fields are used to carry out the DEP applications, due to the availability of micro-fabrication techniques. The DEP forces and heating effects are improved due to the scaling down of microelectrodes' dimensions which generate higher electric field intensity due to the decreasing of space between electrodes [5, 6]. A lot of cell manipulate devices (based on programmable DEP-force cages by using 3D structures of electrodes) were used for cells trapping, levitating and dragging for many applications [6].

Recently, one of the hottest areas of research is Lab-on-a-chip based on DEP phenomenon. It has many applications in the pollution, medical, pharmaceutical, and biological fields. To increase the effectiveness of Lab-on-a-chip it needs to integrate functions such as actuation, sensing, and processing. Lab-on-a-chip is faster, better and cheaper biological analysis. There are two different Lab-on-a-chip approaches are proposed [9, 10, 12]. The first one [9] is the 1st lab-on-a-chip approach for detection of microorganism and electronic manipulation. It combines impedance measurement with Dielectrophoresis to trap and move particles, while monitoring their location and quantity into the device. The prototype has been realized using standard printed circuit board (PCB) technology. The sensing part in this approach can be performed for any electrode by switching it from the electrical stimulus to a transimpedance amplifier, while all the other electrodes are connected to ground. In 2003, the second Lab-on-a-chip was proposed [10]. It is a microsystem for cell manipulation and detection based on standard 0.35μm CMOS technology. This lab-on-a-chip consists of two main units, the actuation unit, and the sensing unit. The chip surface implements a 2D array of micro sites, each consisting of a superficial electrodes and embedded photodiode sensor and logic. The actuation part is based on the DEP technique. While the sensing part depends on that particles in the sample can be detected by the changes in optical radiation impinging on the photodiode associated with each micro-site. During the sensing, the actuation voltages are halted, to avoid coupling with the pixel readout. However, due to inertia, the cells keep their position in the liquid.

There are three main disadvantages of the recent Lab-on-a-chips. First: there is no real time detection of the cell response under the effect of the non-uniform electric field, as we halted the actuation part and activate the sensing part. Second: the sensing part in these two lab-on-a-chips depends on the inertia of the levitated cells. Thus, only cells with higher inertia can be sensed and detected by using these two lab-on-a-chips. Third: Although the detection of the position of the levitated cells can be done, based on these two systems, the actual intensity of the non-uniform electric field that produces the DEP force can’t be detected.

In this paper, a new configuration of an electric-field sensor with different geometry is presented, thus, a modification of the differential electric-field sensitive field-effect transistor (DeFET) is presented and discussed. Also, this paper presents the DeFET’s theory of operation and presents test results which validate the geometry modifications effect of the proposed DeFET. We are planning to design and prototype a new device that senses and characterizes the response for difference nano and micro size particles. This prototype will have applications in the area of environmental monitoring where fine dust matters can be detected and characterized for pollution and occupancy air quality. It can be used in other applications which deal with small size particles, such as biocells and DNA. The fabricated chip is based on a standard 0.18-µm Taiwan Semiconductor Manufacturing Company (TSMC) CMOS technology, and it includes the sensors which are designed with different dimensions in order to study the effect of changing the dimension on the output voltage which consequently affects the sensitivity of the sensor. In addition, a 16x1 multiplexer is implemented on chip to multiplex 16 sensors; the multiplexer reduces the chip area and provides accurate scanning and monitoring of different sensors.

2. The Proposed CMOS Lab-On-A-Chip

The proposed lab-on-a-chip is implemented in a standard CMOS 0.18µm TSMC technology. Fig. 1 shows the die photo, the total die area is 1.5mm x 1mm. The proposed lab-on-a-chip consists of three main parts. (1) The actuation part, which is a quadrupole electrode configuration to produce the required non-uniform electric field profile, and consequently a DEP force to levitate the cell that we want to characterize, (2) the sensing part, which is two sets of 8-array of the Differential Electric Field Sensitive Field Effect Transistor (DeFET), one set is uniform sensors, i.e. with the same dimension, and the other set is non-uniform sensors with different dimensions. (3) Multiplexing part: a 16x1 multiplexer is implemented on chip to multiplex 16 sensors, hence, to reduce the chip area and provides accurate scanning and monitoring of different sensors.

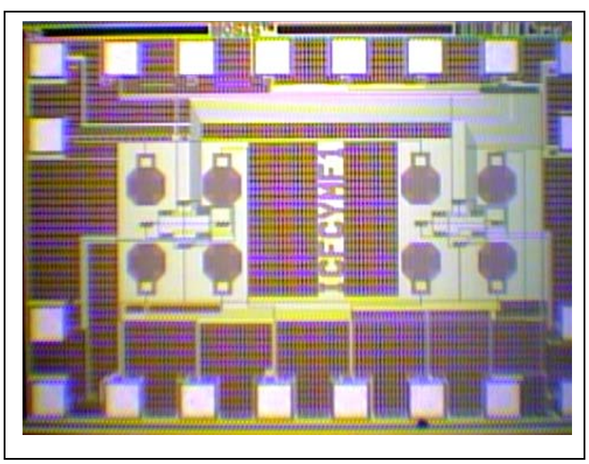

Figure 1. Photo of the layout of the fabricated proposed DeFET circuit.

The Actuation Process: A quadrupole configuration of electrodes are used to perform the actuation process, see Fig.2, using this configuration we can control the profile of the non-uniform electric field by connecting the whole four electrodes or some of them. Also, the quadrupole levitator comprises an azimuthally symmetric electrode arrangement capable of sustaining passive stable particle levitation. For these reasons, we selected the quadrupole electrode configuration as an actuation part in our design [5].

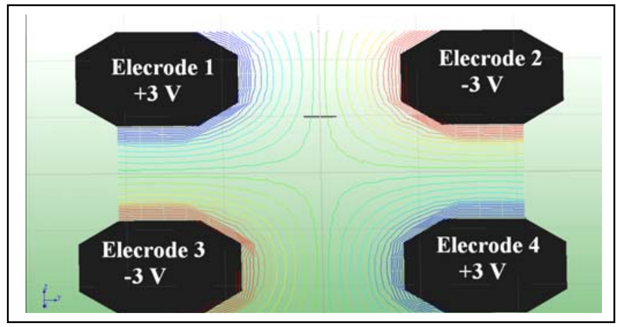

Figure 2. The quadrupole configuration

The Sensing Process: The sensing part is composed of a two sets, each set consists of 8 DeFET sensor array. This array located around the central point, where the cell will be passed (as shown in Figure 1). In sensing process, the manipulating electric field is a non-uniform electric field (i.e. the electric field is a function of the distance). Thus, we can detect the electric field by using the Electric Field Sensitive Field Effect Transistor [eFET], as a new electric field sensor [11, 12]. Fig. 3 shows the physical structure of the eFET. It consists of two adjacent drains, one source, and two adjacent floating gates with distance “d” between them. For the eFET, it is equivalent to two identical enhancement MOSFET devices. The current flow of the two drain currents occur, under the influence of the non-uniform electric field over the gates. As the drain current dependence on the gate voltage, the eFET can sense the difference between the two gates voltage, which reflects the intensity of the applied non-uniform electric field. To increase the measurement range of the eFET, we can use the CMOS concept to implement the Differential Electric Field Sensitive Field Effect Transistor (DeFET) sensor, and this sensor is the basic sensing block in the sensing part of the proposed lab-on-a-chip [11, 12].

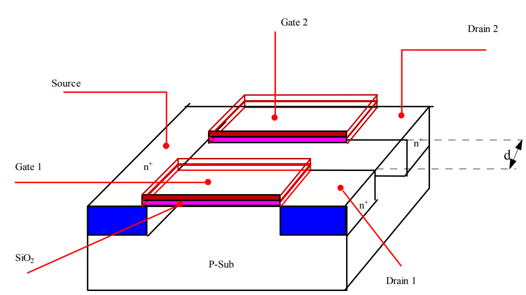

Figure 3. Physical structure of an eFET [12].

3. DeFET’s Theory of Operation

The DeFET consists of two complementary eFETs, one of them is a P eFET type and the second is an N eFET type. The equivalent circuit of the DeFET is shown in Fig. 4. From Fig. 4, the two gates of P eFET and N eFET are connected with each other, and there is a cross coupling between the two drains of the P eFET and the N eFET. I_p and I_n are functions of the two applied gate voltages V_{in1} and V_{in2}, respectively. The output current I_{Out} is equal to the difference between these two drain currents I_p-I_n (i.e. $I_{Out} = I_p - I_n$). The DeFET is designed to achieve that I_{Out} is directly related to the difference between the two applied gate voltages (V_{in1}-V_{in2}), and V_{in1}-V_{in2} is equal to the applied electric field above the two gates (E) multiplied by the distance (d) between them (i.e. $(V_{in1}-V_{in2})/d = E$), where d is the distance between the two split gates. So, I_{Out} is related directly to the intensity of the applied non-uniform electric field if the distance "d" is constant. Thus by measuring I_{Out} we can detect the intensity of the non-uniform electric field [12].

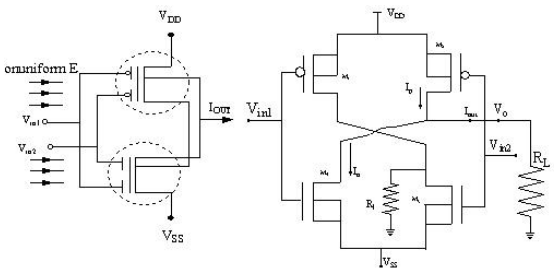

Figure 4. An equivalent circuit of a DeFET [12]

Using simple analysis, the expression relates I_{Out} and E can be driven [11]. From Fig. 4, the output current (I_{out}) is:

$$I_{out} = I_p - I_n \quad (1)$$

The sensitivity S_1 is given by

$$S_1 = \frac{dI_{out}}{dE} \quad (2)$$

As a linear equation, we can express the sensitivity (I_{out}) in terms of the output current and the electric filed as follows:

$$S_1 = \frac{d(I_p - I_n)}{dE}, \quad S_1 = \frac{d(I_p - I_n)}{d(\Delta V)} \cdot \frac{d(\Delta V)}{dE} \quad (3)$$

$$(I_p - I_n) = -g_m \Delta V, \quad \frac{d(I_p - I_n)}{d(\Delta V)} = -g_m,$$

$$\frac{d(\Delta V)}{dE} = -d \quad (4)$$

From (3) and (4), the sensitivity can be given as:

$$S_1 = g_m d \quad (5)$$

$$V_{out} = I_{out} R_L = S_1 R_L E + \text{Constant}, \; S = S_1 R_L \quad (6)$$

From (5) into (6) $\quad S = g_m \cdot d \cdot R_L \quad (7)$

$$V_{out} = g_m \cdot d \cdot R_L \cdot E \quad (8)$$

Where; gm: transconductances of the Transistors, d : the distance between the two split gates, and R_L: load resistance

Equation (7) shows a liner relationship between the DeFET's sensitivity and the distance between the two split gates. Thus, if we have an array of DeFET sensors with different distance (d), then we can obtain higher sensitivity.

4. SIMULATION RESULTS

The proposed CMOS lab-on-a-chip has been tested for both DC and AC response. Electrodes 1 and 3 are connected together with the same voltage and Electrodes 2 and 4 have out of phase voltage with the same amplitude.

For the DC response, the measured results are shown in Table 1 and Figs. 4 and 5. These results clarify the relationship between the output voltages of each sensor with respect to the variation of its geometry (the distance between the two split gates (d)) at different electrodes' voltages (see equation 8). The circuit is tested at (d) equals 0.5, 1, 1.25, 1.5 and 2 um, respectively.

The ratio between the sensors output voltages and the output of (d=2 um) sensor is shown to clarify the effect of changing the geometry of the sensors on the output voltage. From Table 1, Figs. 4 and Fig.5, we can observe the following:

- The sensitivity changes with (d) (The slope of the curves), see equation 7.
- The change of the output voltage is observed with all geometries; therefore, if we are aiming low power consumption, we can use lower electrode voltages with acceptable sensitivity. However, it depends on the properties of the particle that we are targeting.

Table 1: The effect of changing the distance between gates (dB)

Electrodes 1&3 Voltage	Output Voltage w.r.t. Vout at d= 2um (dB)				
	Sensor with d=0.5um	Sensor with d=1um	Sensor with d=1.25um	Sensor with d=1.5um	Sensor with d=2um
5 V	5.3852	5.3014	5.3014	5.3014	0
4 V	4.7948	4.7948	4.72095	4.6464	0
3 V	4.44365	4.44365	4.4102	4.376632	0

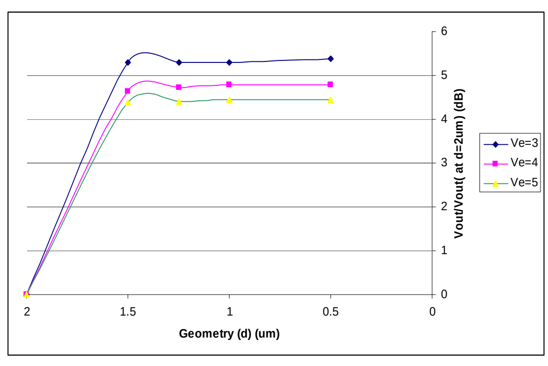

Figure 5. The measured output voltage for different DeFET geometry sensors at different electrodes voltage (Electrode 1 and 3 voltage = - Electrode 2 and 4 voltage).

The electric field and its sensation can be simultaneously actuated in a real time; this is a significant advantage over the proposed in [13, 14, 15, 16].

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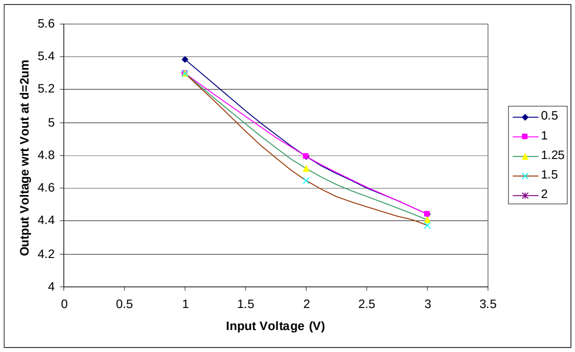

Figure 6. The output voltage vs. the input voltage for different sensor geometries.

5. APPLICATIONS OF THE PROPOSED LAB-ON-A-CHIP

The proposed lab-on-a-chip can be used in many applications, such as; extract properties of the media, to analyze biocells, e.g. the membrane capacitance. It has also application in the DNA analysis, to detect the radius of the DNA molecule. In cancer research area, it detects the distribution of the charges on the surface of the cancer cell and consequently a suitable antibody can be selected to be used in cancer treatment [12]. Moreover, it can be used as an impedance sensor, to measure the impedance of the cell above the sensor using transimpedance amplifier as a read-out circuit, this application is important in cell detection [9]. This sensor is based on CMOS standard technology; thus, we can easily integrate the read-out circuitry in addition to the actuation and sensing parts, which already integrated.

Finally, The DeFET, as it is high sensitive electric field sensor, it can be used within a printed circuit board (PCB) prototype to trap, concentrate, and quantify different types of micro and nano particles. This sensor can also be used in the DNA analysis, to detect the radius of the DNA molecule. In cancer research area, it can be used to detect the distribution of the charges on the surface of the cancer cell and consequently a suitable antibody can be selected to be used in cancer treatment [17].

6. CONCLUSION

A new integrated lab-on-a-chip has been proposed. It's based on CMOS 0.18μm TSMC technology. It consists of two main parts; which are the actuation and the sensing parts. The simulation results verify the theory of its operation. This research work will open a new area of research field which is to use the electric field as a diagnosis tool that can be used in different applications. Also, it can be used as an impedance sensor, to measure the impedance of the cell above the sensor using transimpedance amplifier as a read-out circuit, this application is important in cell detection and characterization. Moreover, this sensor is based on CMOS standard technology; thus, we can easily integrate other read-out and conditioning circuitry in addition to the actuation and sensing parts, which already integrated.

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