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On-Chip Electrical Field Sensing For Lab-On-A-Chip Applications

Yehya H. Ghallab, and Wael Badawy

Department of Electrical and Computer Engineering, University of Calgary, 2500 University Drive, N.W, Alberta, T2N 1N4, Canada.

This paper presents a novel CMOS electric field sensor, termed as a Differential Electric Field Sensitive Field Effect Transistor (DeFET). It's based on a standard 0.18µm CMOS technology. The DeFET shows a sensitivity of 76 µA/V/µm. Also, the DefET's theory of operation is presented and discussed. Both the experimental and simulation results confirm the DeFET's theory of operation is presented..

1. Introduction

Recently, an explosion of interest in microsystems for biological and chemical analysis, with particular emphasis directed towards the development of a Lab-on-a chip. Lab-on-a chip technology is exciting the interest of scientists in many areas [1,2]. This technology can be used not only to synthesize chemicals, biological, cancer cells, and DNA efficiently and economically but also to carry out biological and clinical analyses, to perform combinatorial chemistry, and to carry out full-scale analyses from sample introduction to cell separation, manipulation and detection, on a single, miniaturized device. Hence, the underpinning concept of Lab-on-a-chip is the integration of several functional units such as actuation, sensing, separation, concentration, and detection systems onto one chip.

The electric field suitable to actuate and manipulate the biocells is a nonuniform electric field (i.e. Dielectrophoresis). Dielectrophoresis (DEP) [3-5] has been a fairly well known phenomenon in which a spatially nonuniform electric field exerts a net force on the field-induced dipole of a particle. There are many techniques that have been used for sensing, analyzing and monitoring the behavior of the biocells. They are optical technique [6-8], fluorescent labeling (e.g., microfabricated fluorescence-activated cells sorter (µFACS)) technique [9,10], and impedance sensing technique [11-15]. Most recently, the sensing parts in the currently used labs-on-a-chip are based on impedance sensing technique [16,17], and optical technique (i.e., using photo detectors) [18,19]. These labs-on-a-chips, which are based on a nonuniform electric field to manipulate the biocells, have been using indirect measurement for sensing, i.e. there is no real time sensing of the variation of the electric field due to the existence of biocells.

In this paper, we present a novel electric field sensor, i.e. Differential Electric field sensitive Field Effect Transistor (DeFET). Using DeFET, we can directly get real time information about the electric field and consequently we can extract useful information about the biocells. Also, it can be simply integrated with the CMOS based lab-on-a-chip. The remainder of this paper is organized as follows:

Section 2 introduces the theory of operation of the DeFET and represents a mathematical model of it. The simulation and experimental results are presented in section 3. Section 4 concludes the paper and discusses the merits of the proposed DeFET based on the experimental findings.

2. The Differential Electric Field Sensitive MOSFET (DeFET)

In DEP process, the manipulating electric field is a nonuniform 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 MOSFET [eFET], as a novel electric field sensor. Fig.1 shows the physical structure of the eFET [20]. It consists of two adjacent drains, two adjacent floating gates with distance "d" between them, and one source. For the eFET, it is equivalent to two identical enhancement MOSFET devices, as shown in Fig.2. Thus, under the influence of the nonuniform electric field, the current imbalances of the two drain currents occur. Due to the drain current dependence on the gate voltage, the eFET device that has two adjacent gates, and two adjacent drains, but isolated from each other, can sense the difference between the two gates voltage, which reflects the intensity of the applied nonuniform electric field. To increase the range of measurement of the eFET, we are using the CMOS concept to implement the Differential Electric Field Sensitive MOSFET (DeFET) sensor. 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.3. From Fig.3, 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. The output current I_O is equal to the difference between the two drain currents I_p-I_n (i.e. $I_O = I_p-I_n$, see Fig.3). On the other hand, I_p and I_n are functions of the two applied gate voltages V_{in1} and V_{in2}, respectively, and we have designed the DeFET to obtain I_O directly related to the difference between the two applied gate voltages (V_{in1}-V_{in2}). As, V_{in1}-V_{in2} is equal to the applied electric field above the two gates multiplied by the distance between them (V_{in1}-V_{in2}/d = E), where d is the distance between the two-split gates, which is constant. So, I_O is related directly to the intensity of the applied nonuniform electric field. Thus by measuring I_O we can detect the intensity of the nonuniform electric field.

2.1 DeFET's Theory of operation

From Fig. 3, a simple analysis shows that the output current (I_{out}) is:

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

where I_p and I_n are the two currents pass in the P transistor (M_2) and the N transistor (M_3), respectively. The sensitivity is given by

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

Also, the electric field intensity above the sensor (E), which produces ΔV, is related to this voltage as follows:

$$\Delta V = -E.d \quad (3)$$

where: ΔV is the difference between the two gate input voltages (i.e. $\Delta V = V_{in1} - V_{in2}$).
From (2), I_{out} can be expressed as:

$$I_{out} = \int \mathrm{S}d(E) \quad (4)$$

$$I_{out} = SE + Constant \quad (5)$$

Constant in (5) is equal I_{out}, when E equals zero, i.e. Constant=I_{out} when E=0.
We can notice that in our case, E=0 means that ΔV=0, so we have the same voltage drop at the two input gates (i.e. $\Delta V = V_{in1} - V_{in2} = 0$), so $V_{in1} = V_{in2}$. On the other hand, $V_{in1} = V_{in2}$ means that we apply a uniform electric field. So, we can rewrite (5) as:

$$I_{out} = I_{Non} + I_{Uni} \quad (6)$$

where: I_{Non}=SE is the output current when we apply a nonuniform electric field, and I_{Uni} is the output current when we apply a uniform electric field.
From (2) into (1):

$$S = \frac{d(I_p - I_n)}{dE} \tag{7}$$

$$S = \frac{d(I_p - I_n)}{d(\Delta V)} \cdot \frac{d(\Delta V)}{dE} \tag{8}$$

For simplicity, we can assume that:

$$\Delta V = -(I_p - I_n)(r_p // r_n) \tag{9}$$

where r_p and r_n are the output resistance of the M_2 and M_3 transistors, respectively.
From (9)

$$\frac{d(I_p - I_n)}{d(\Delta V)} = -\frac{1}{(r_p // r_n)} \tag{10}$$

From (3)

$$\frac{d(\Delta V)}{dE} = -d \tag{11}$$

From (10) and (11) into (8), the sensitivity can be given as:

$$S = \frac{d}{(r_p // r_n)} \tag{12}$$

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

$$I_{out} = SE + I_{Uni} \tag{13}$$

From (12) into (13)

$$I_{out} = \frac{d}{(r_p // r_n)} E + I_{Uni} \tag{14}$$

Equation (14) shows a liner relationship between the DeFET's output current and the intensity of the applied electric field. Thus, if we have an array of DeFET, then we can obtain an electric field intensity image at different locations.

3. Experimental and Simulation Results

The proposed DeFET is implemented in a standard CMOS 0.18µm technology. Fig. 4 shows a microscopic picture of two DeFETs and the electrodes used to apply the required electric field pattern.

3.1 DC Response

The DC response of the DeFET is experimentally tested, and the result is shown in Fig. 5. From this figure, we can observe a good agreement between the experimental and the simulation results. Also, we can observe that the sensitivity of the DeFET is 76 µA/V/µm, which is high.

3.2 AC Response

The frequency response of the DeFET in Air is experimentally tested and shown in Fig. 6. From this figure, we can notice that the DeFET works as a band path filter with bandwidth 11 MHz, and the quality factor Q is 2.182 (Q= f_o/BW). Also the response of the DeFET with different electric field profiles and in different media, i.e. Air and Silicon Rubber, has been tested and the results are shown in Figs. 7 and 8. From these figures we can verify that the DeFET is working properly.

3.3 Noise Analysis

The noise floor of the DeFET is measured using the network analyzer (HP 4395A Network/ Spectrum/ Impedance Analyzer). The experimental results are plotted in Fig. 9. From this figure, we can observe that the noise level is low, thus, the signal to noise ratio, and consequently the dynamic range will be high. We can observe also, that although we are using floating gates we still get a low noise floor, the reason is that we are using cross coupling between the P eFET and N eFET, see Fig. 3, at the output. So any common noise will be rejected.

3.4 Other Features

Other dynamic and static characteristics of the DeFET have been measured. The input offset voltage is 25 μV. The sensitivity of the DeFET is 71.6 μA/V/μm. The rise and fall times have been measured using a square signal, and they are 17 ns, and 15ns, respectively. The selectivity [21], which is defined as the ability of the sensor to select a specific measurand among different input measurands, is also tested, by using the DeFET in different temperature environments (i.e. at room temperature and 10 degree above it). The results shown in Fig.10 verify that it has a very high selectivity. The dynamic range of the DeFET is high, as we mentioned before, because we have a low noise floor. A summary of these results is shown in Table1.

4. Conclusion

A novel electric field sensor named Electric Field Sensitive Field Effect Transistor (DeFET) is presented. It is based on CMOS TSMC 0.18um technology. Its properties and characteristics is presented and discussed. It has a sensitivity 76.2 μA/V/μm. The proposed DeFET sensor has many applications in the biomedical field.

References

[1] Yehya Ghallab, and Wael Badawy Sensing methods of Dielectrophorieses from Bulky instruments to Lab-on-a-chip", IEEE Circuit and Systems Magazine, Quarter 3 issue, vol. 4, pp.5-15, 2004.

[2] Available: Internet web site, www.lab-on-a-chip.com.

[3] H.A. Pohl, Dielectrophoresis, Cambridge University Press, Cambridge, 1978.

[4] T.B. Jones, Electromechanics of Particles, Cambridge Univ. Press, Cambridge, 1995.

[5] H. Morgan, and N. G. Green, AC ElectroKinetics: Colloids and nanoparticles, Research Studies press LTD, England, 2003.

[6] M. S. Talary and R. Pethig, "Optical technique for measuring the positive and negative dielectrophoretic behavior of cells and colloidal suspensions," Proc. Inst. Elect. Eng., IEE—Sci. Meas. Technol., vol. 14, no. 5, pp. 395399, Sept. 1994.

[7] J.P.H Burt, T.A.K Al-Ameen, R. Pethig, and X. Wang," An optical dielectrophoresis spectrometer for low frequency measurements on colloidal suspensions," J. Physics E: Sci. Instr. Vol.22, pp. 952-957, 1989.

[8] J.A.R. Price, J.P.H Burt and R. Pethig," Applications of a new optical technique for measuring the dielectrophoretic behavior of microorganism," Biochim. Biophy. Acta, vol. 964, pp. 221-230, 1988.

[9] Shulamit Eyal, and Stephen R. Quake," Velocity-independent microfluidic flow cytometry," Electrophoresis, vol.23, pp. 2653-2657, 2002.

[10] Available: http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/F/FACS.html, internet website

[11] S. Gawad, L. Schild, and Ph. Renaud, "Micromachined impedance spectroscopy flow cytometer for cell analysis and particle sizing," Lab on a Chip, vol. 1, pp. 76–82, 2001.

[12] K. C. Fuller, J. Hamilton, H. Ackler, P. Krulevitch, B. Boser, A. Eldredge, F. Becker, J. Yang, and P. Gascoyne, "Microfabricated multi-frequency particle impedance characterization systems," in Micro Total Analysis Systems. Enschede, The Netherlands: Kluwer, 2000.

[13] L. L. Sohn, O. A. Saleh, G. R. Facer, A. J. Beavis, R. S. Allan, and D. A. Notterman, "Capacitance cytometry: measuring biological cells one by one," in Proc. Nat. Acad. Sci. USA, vol. 97, pp. 10 687–10690, 2002.
[14] H. E. Ayliffe, A. B. Frazier and R. D. Rabbitt, IEEE J. Microelectromech. Syst., 8(1), 50-57, 1999.
[15] S. Gawad, L. Schildb and Ph. Renauda, "Micromachined impedance spectroscopy flow cytometer for cell analysis and particle sizing," Lab on a Chip, vol. 1, pp. 76–82, 2001.
[16] G. Medoro, N. Manaresi, A. Leonardi, L. Altomare, M. Tartagni, and R. Guerrieri," A lab-on-a-chip for cell detection and manipulation", Proceedings of IEEE SENSORS 2002, vol. 1, pp.472-475, 2002.
[17] G. Medoro, N. Manaresi, M. Tartagni, and R. Guerrieri," CMOS-only Sensors and Manipulation for microorganisms", Proc. IEDM, pp. 415-418, 2000.
[18] N. Manaresi, A. Romani, G. Medoro, L. Altomare, A. Leonardi, M. Tartagni, and R. Guerrieri," A CMOC Chip for Individual Manipulation and Detection", IEEE International Solid-State Circuits Conference, ISSCC 03, pp. 486-488. 2003.
[19] Gianni Medoro, Nicoló Manaresi, Andrea Leonardi, Luigi Altomare, Marco Tartagni, and Roberto Guerrieri," A Lab-on-a-Chip for Cell Detection and Manipulation," IEEE Sensors Journal, vol. 3, no. 3, pp. 317-325, June 2003.
[20] Yehya H. Ghallab and Wael Badawy" A CMOS lab-on-a-chip for Biomedical Applications", ISCAS 2005, pp. 1346-1349, Kobe, Japan, 2005
1. [21] Arnaldo D' Amico, and C. Di Natale" A contribution on some basic Definitions of Sensors Properties" IEEE Sensors Journal, vol. 1, no.3, 2001.

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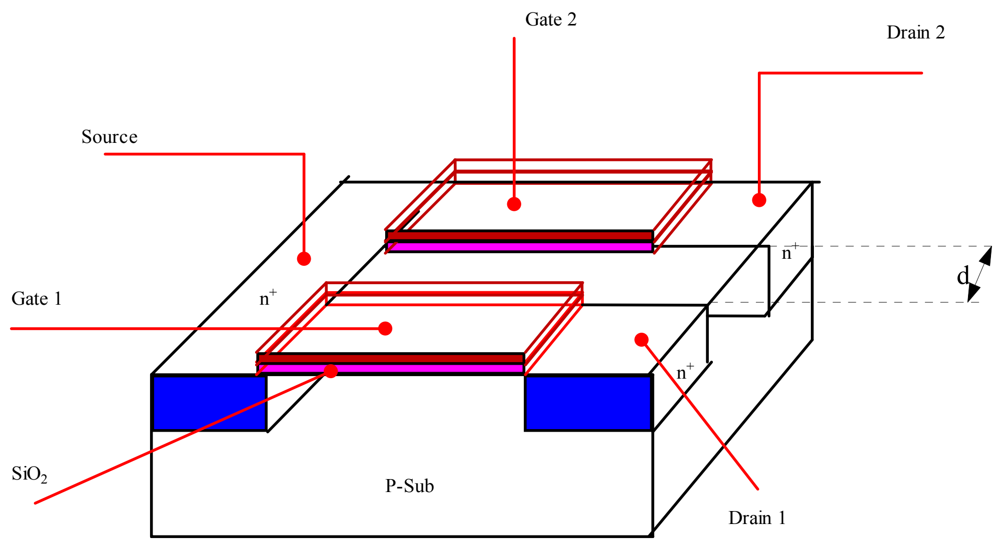


Fig.1 Physical structure of an eFET [20]

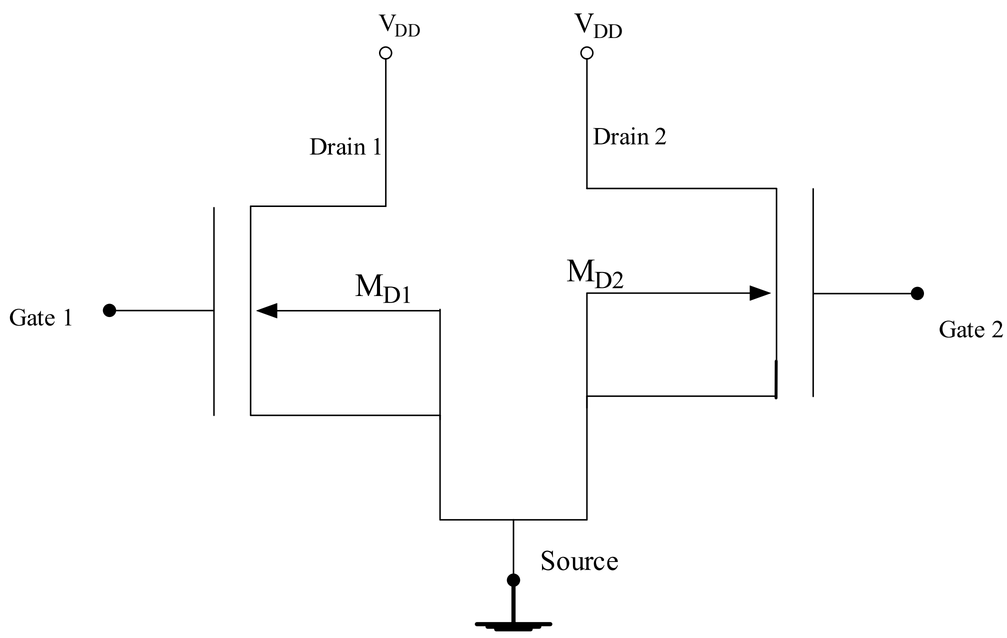


Fig.2 Equivalent circuit of an eFET

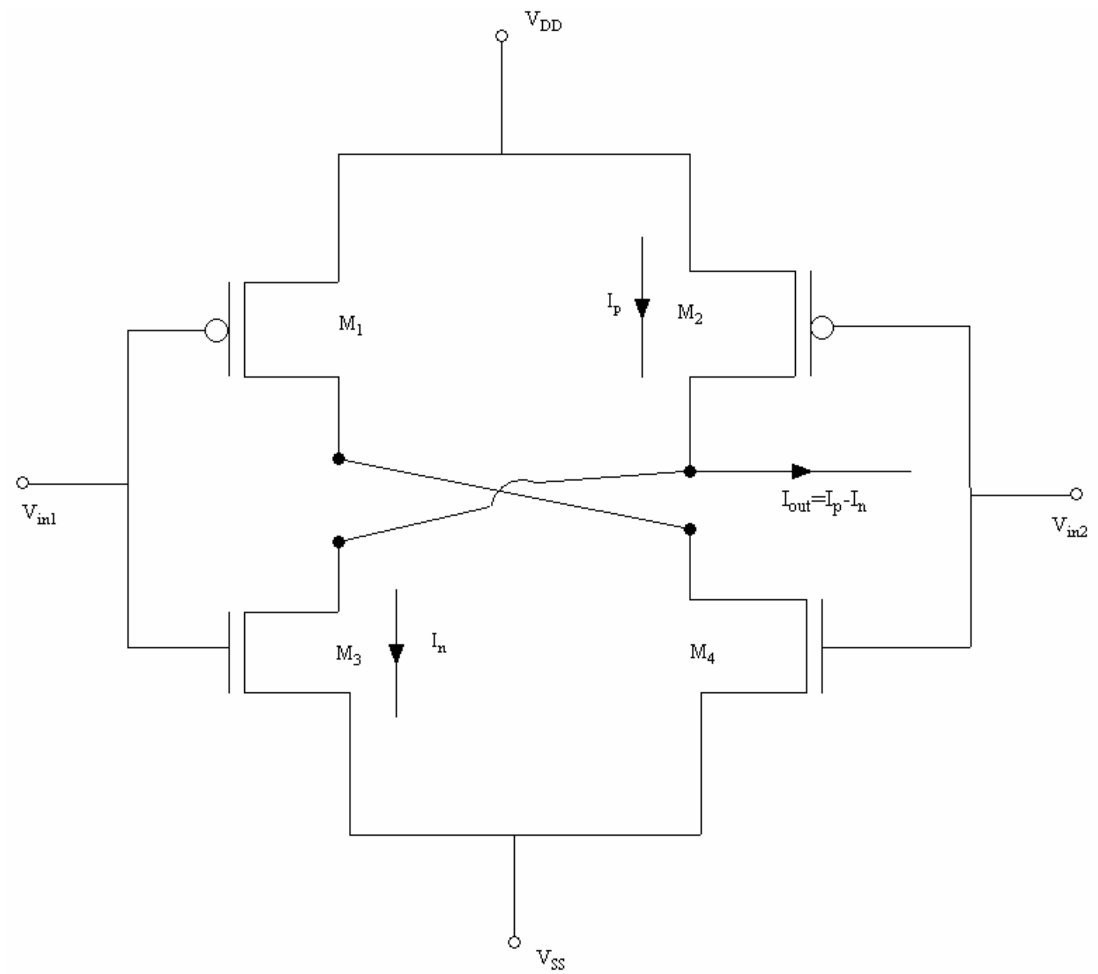


Fig.3 An equivalent circuit of a DeFET [20]

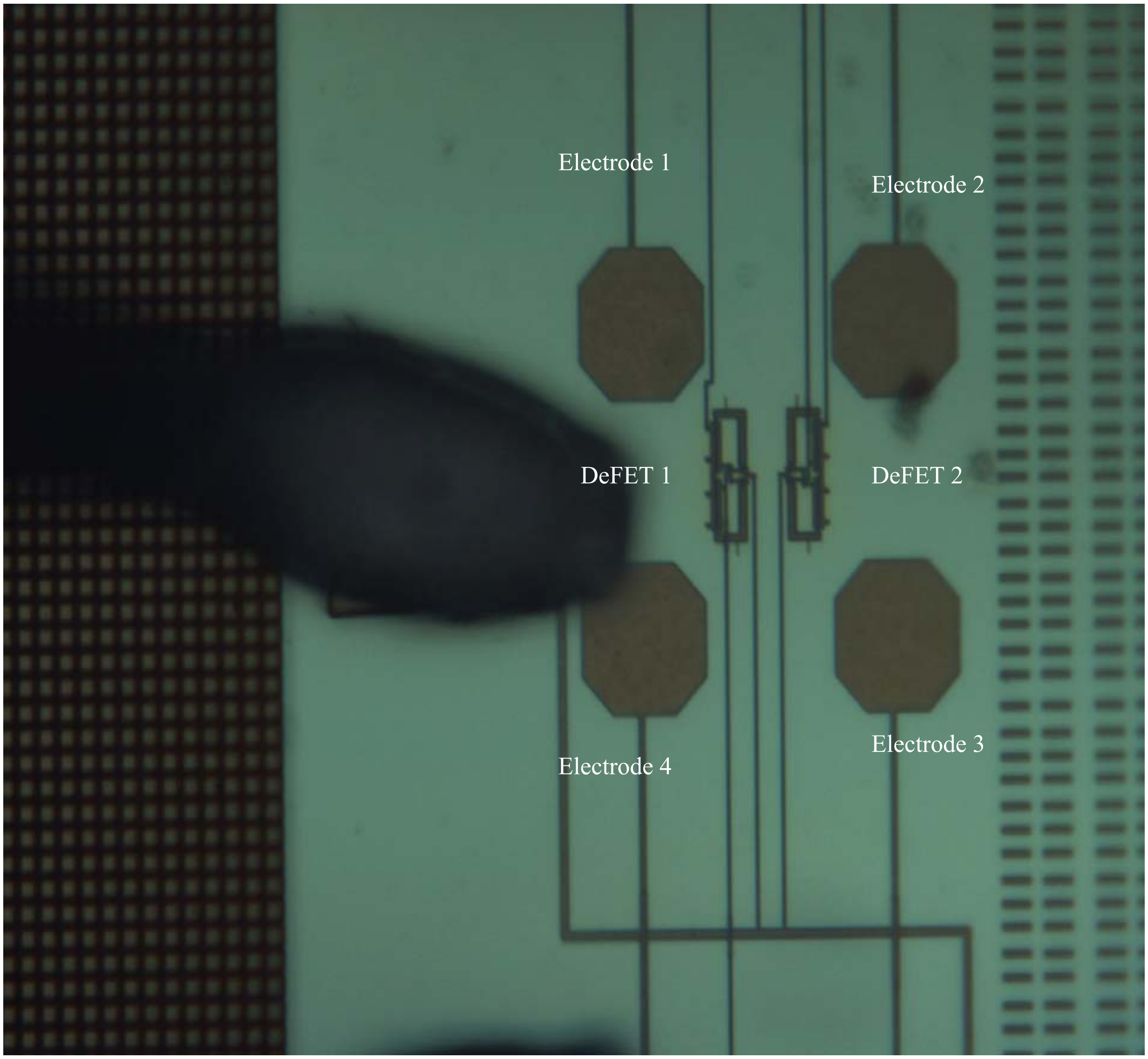


Fig. 4 A microscopic picture shows two DeFET sensors and the electrodes used to apply the electric field

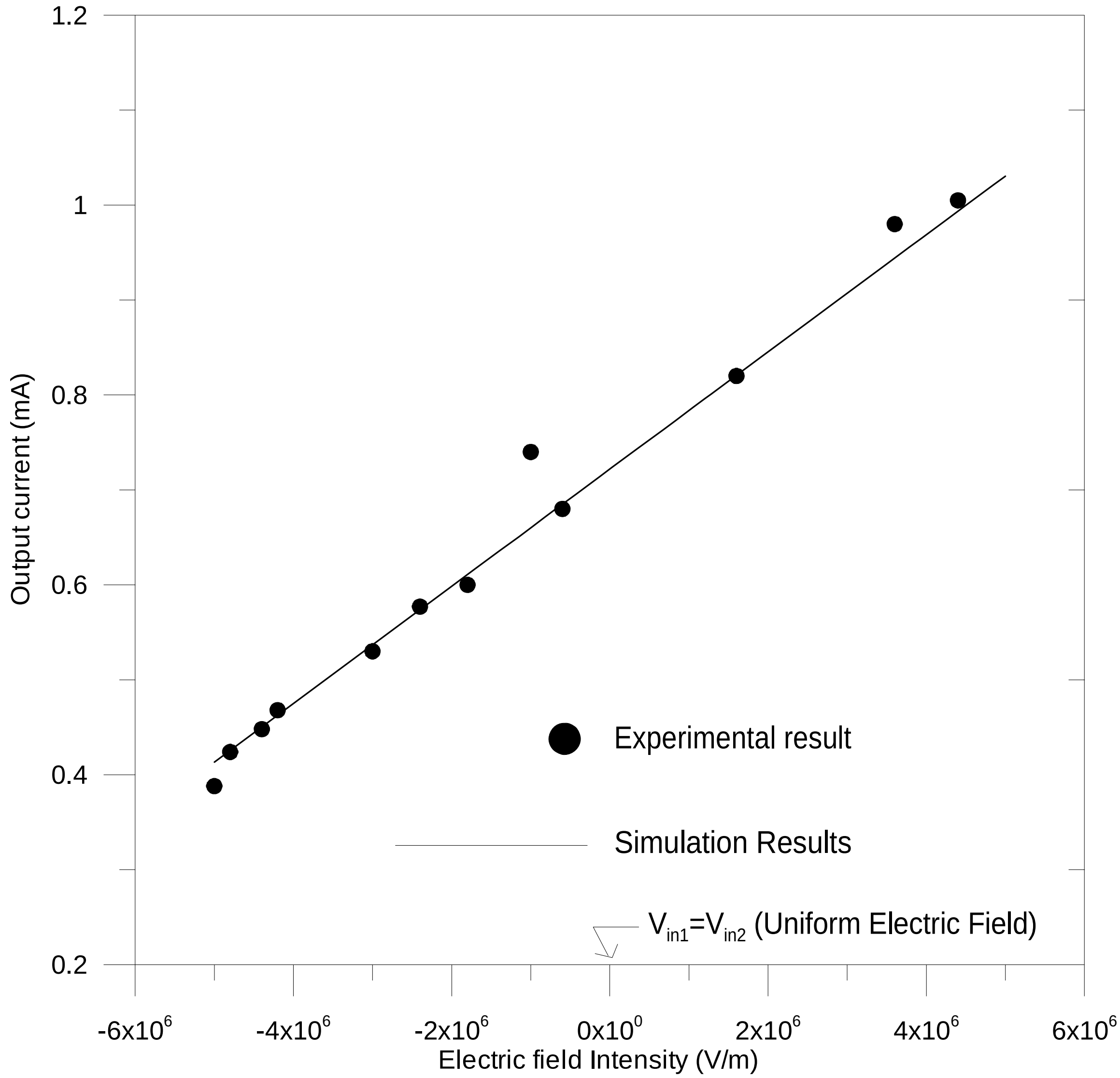


Fig. 5 The DC response of the DeFET [20]

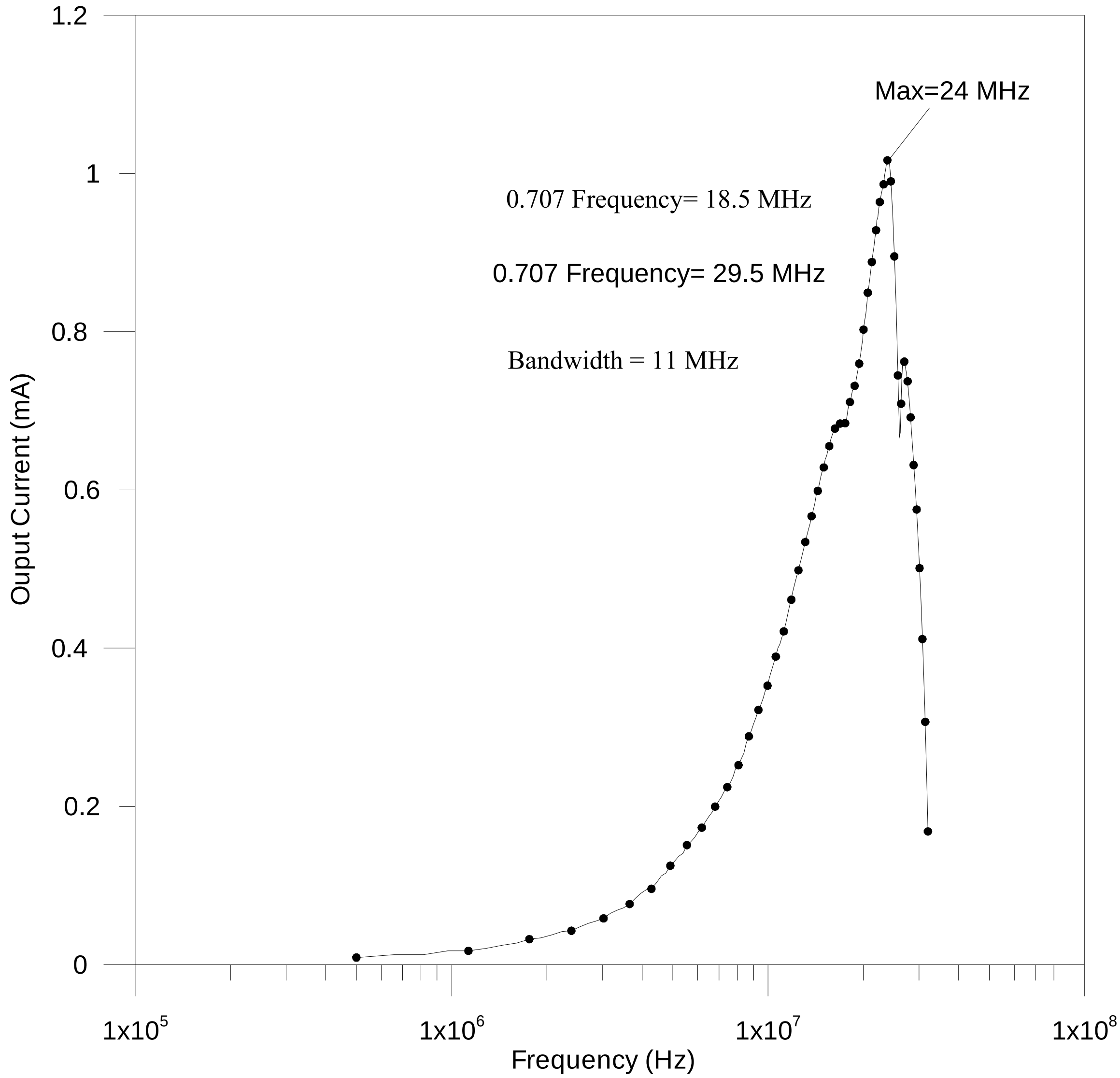


Fig. 6 The measured frequency response of the DeFET

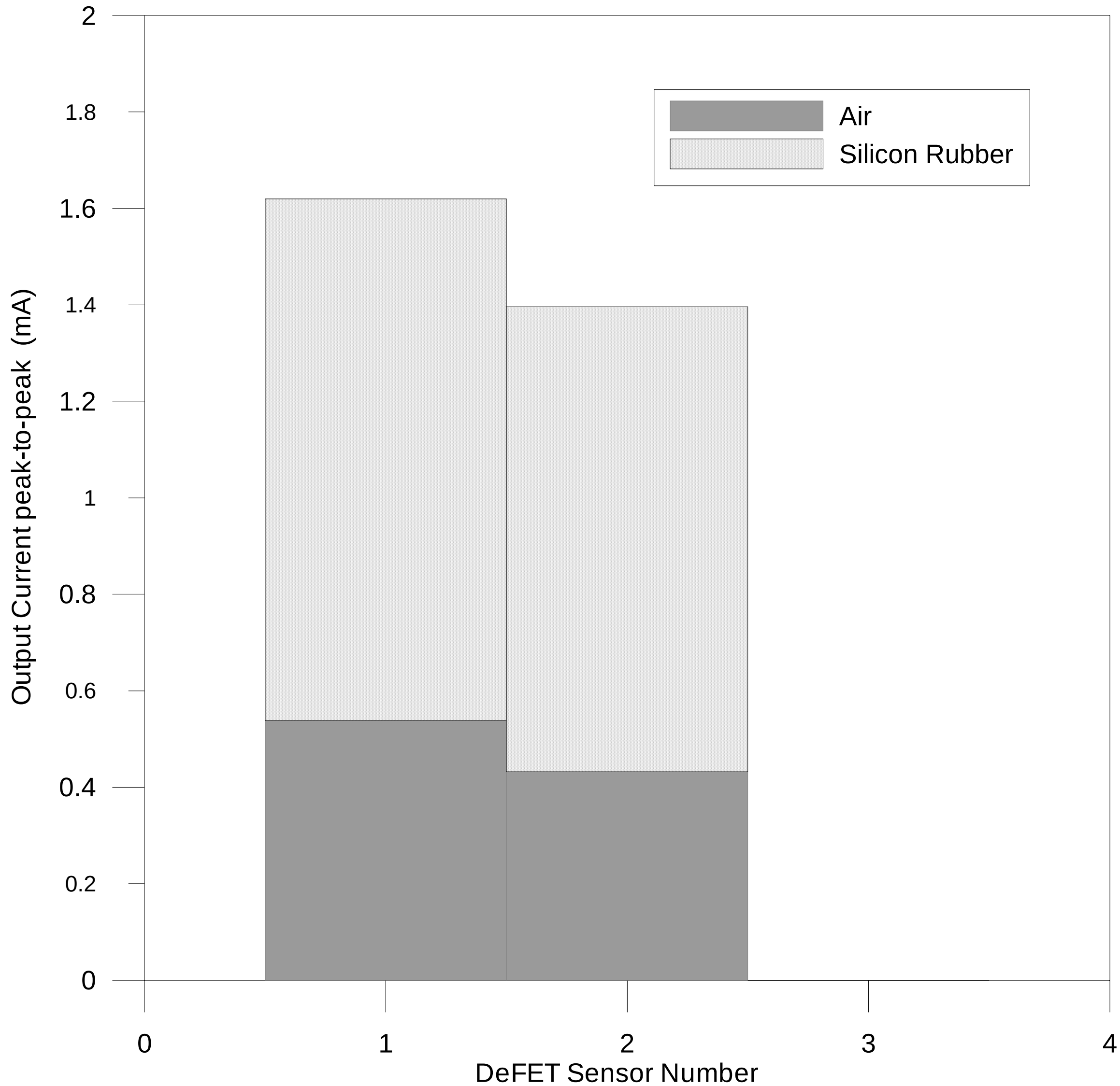


Fig. 7 The measured output current for different DeFET sensor with the configuration Electrode 1 and 2= +5V p-p, Electrode 4= +5V p-p, and Electrode 3 is not connected and the frequency is 10 MHz

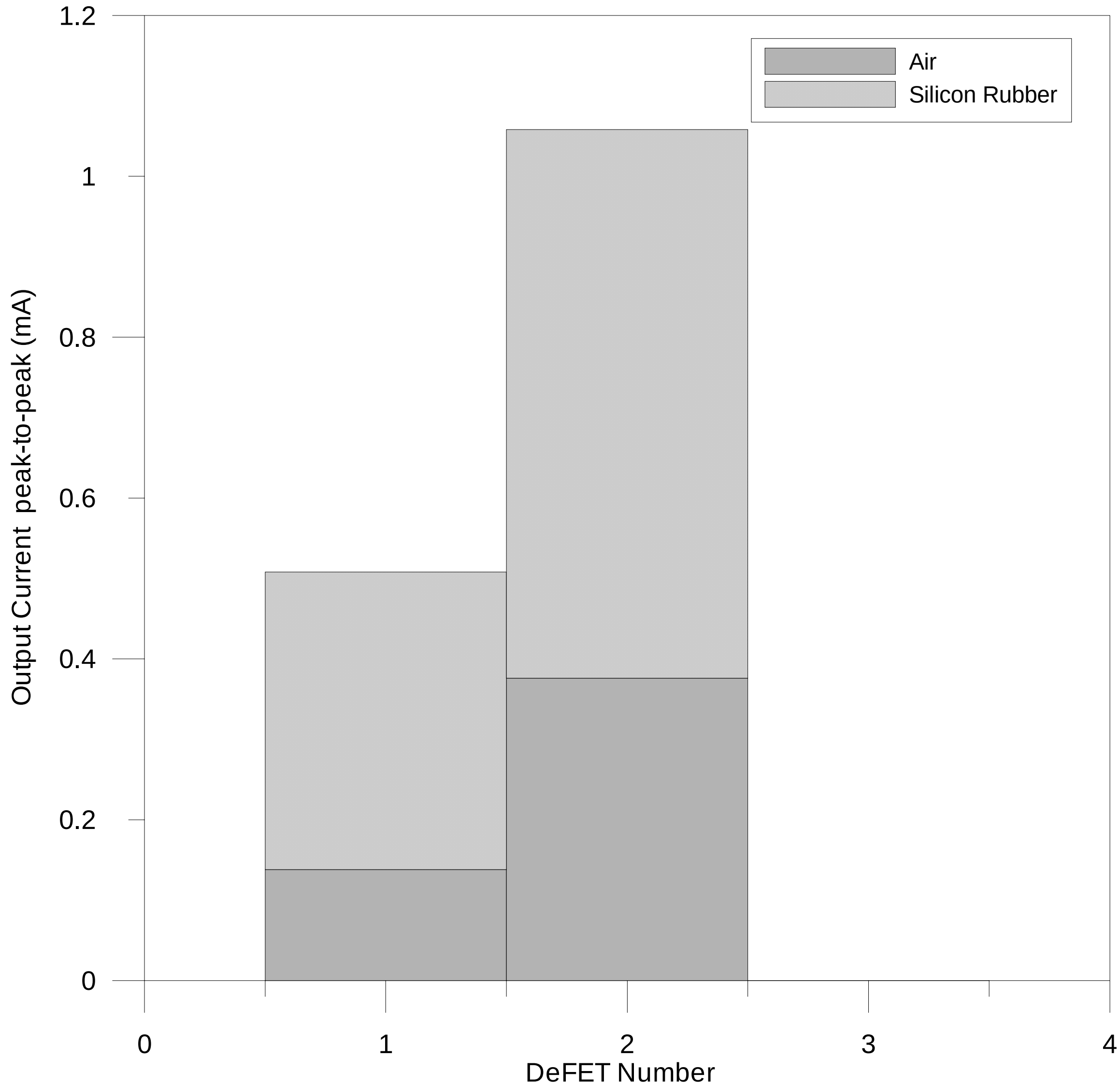


Fig. 8 The measured output current for different DeFET sensor with the configuration Electrode 1 and 2= +5V p-p, Electrode 3= +5V p-p, and Electrode 4 is not connected and the frequency is 10 MHz

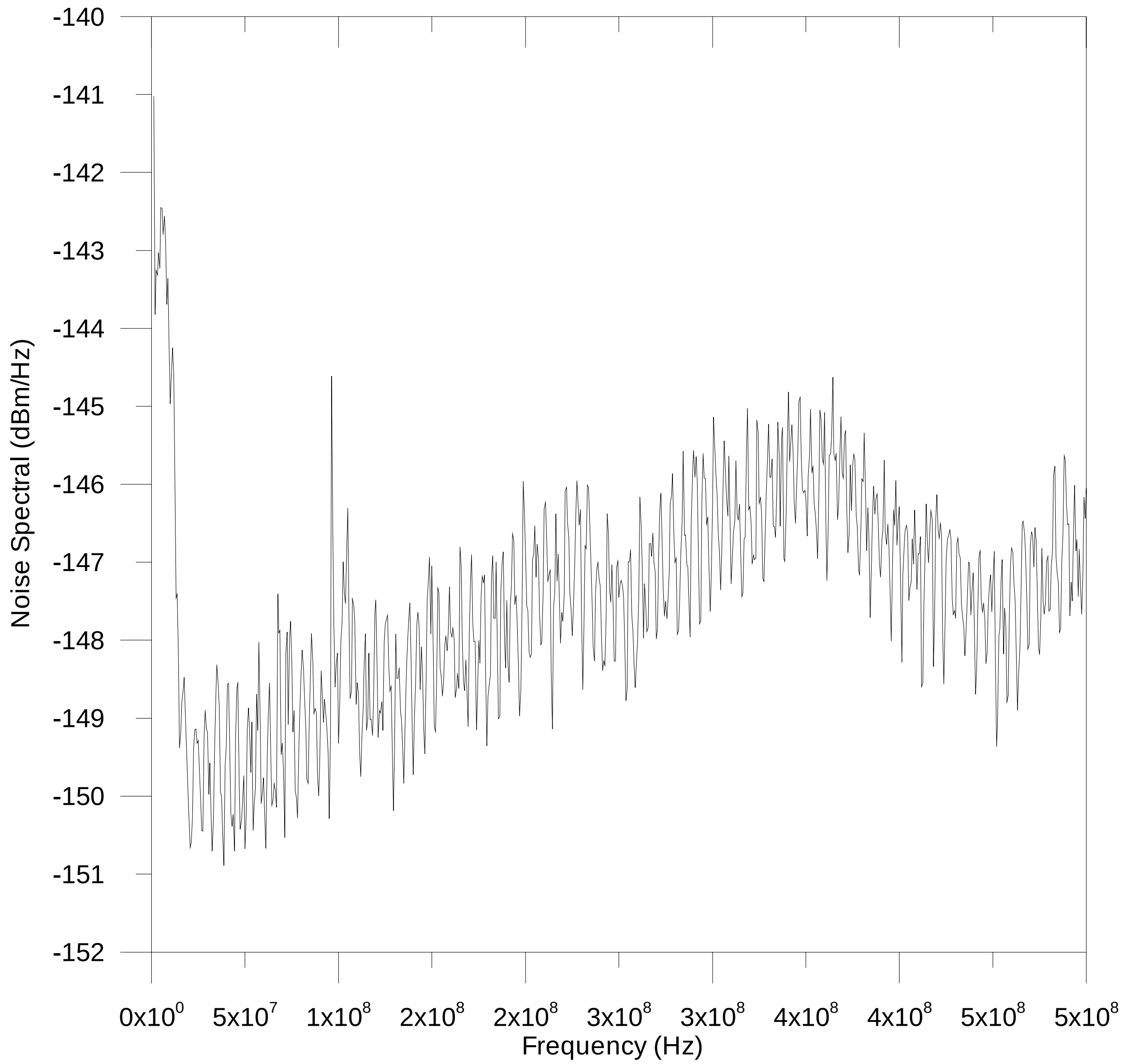
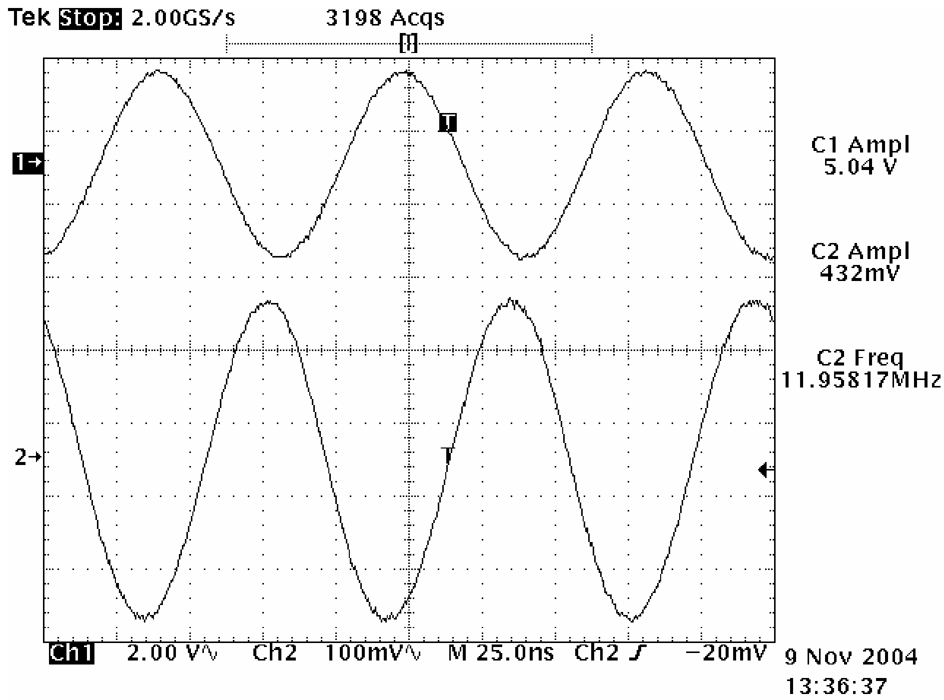
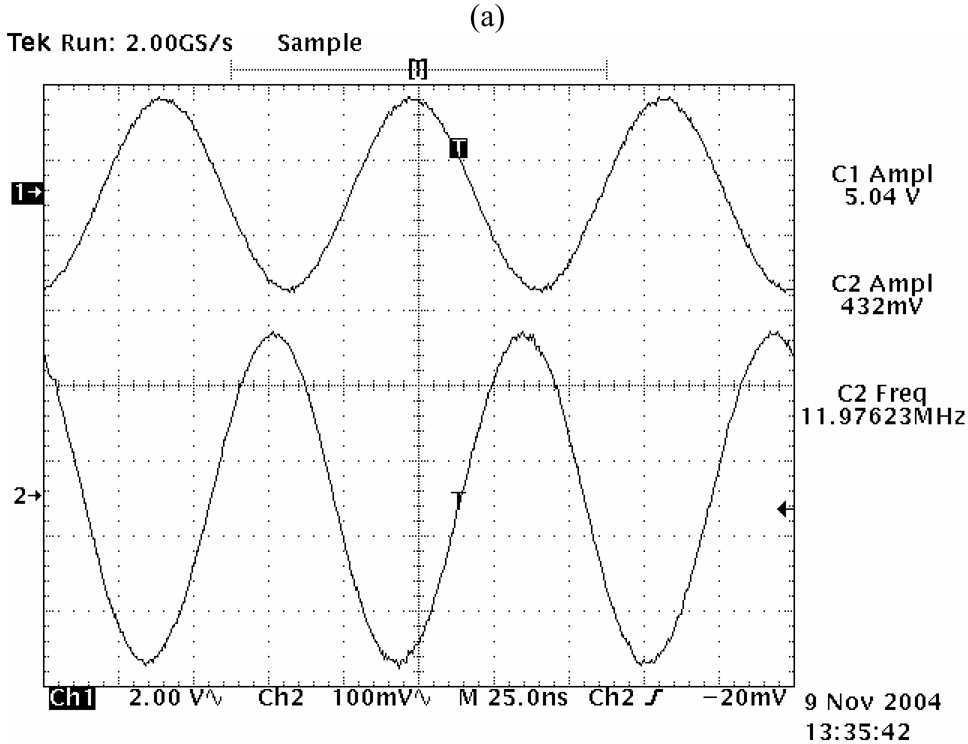


Fig. 9 The measured noise floor of the DeFET using spectrum Analyzer



(a)



(b)

Fig. 10 (a) The response of the DeFET at regular room temperature
(b) The response of the DeFET at temperature 10 degrees above the room temperature

Parameter	Value	Unit
Die Area	0.0005	mm^2
Supply voltage	+/- 3.3	Volt
Sensitivity	71.6	µA/V/µm
Signal/noise ratio	>78.2	dB
Offset voltage	25	µV
Bandwidth	Band pass with BW=11 MHz	Hz
DC power consumption	1.23	mW
Rise Time	17	ns
Fall Time	15	ns
Noise Level	Very low	

Table 1 Summary of the DeFET features