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A MEMS Capacitive Microphone Modelling for Integrated Circuits

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ABSTRACT

In this paper, a model for MEMS capacitive microphone is presented for integrated circuits. The microphone has a diaphragm thickness of 1 µm,0.5 × 0.5 mm^2 dimension, and an air gap of 1.0 µm. Using the analytical and simulation results, the important features of MEMS capacitive microphone such as pull-in voltage and sensitivity are obtained as 3.8V and 6.916 mV/Pa, respectively, while there is no pressure on the diaphragm. The microphone has a capacitance of 2.3 pF. Using the relation between the capacitance and pressure signal, a 3 ports model for the MEMS microphone is proposed. To bias the microphone, a 2.3 V DC and a 1 GΩ resistor is used. The voltage and current signal of the microphone is proportional to the applied pressure of the acoustic wave. An RC filter is added to the circuit to eliminate the low band frequency (≤ 20 Hz) noises. The microphone shows good response to amplitude and frequency changes versus applied pressure signal.

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1. INTRODUCTION

A microphone is an acoustic-to-electric transducer or sensor that converts an acoustic signal to an electric one. Microphones are used in many applications such as telephones, hearing aids, cell phones and personal audio systems [1]. The most commonly used microphones are based on the capacitive principle for their low-power and tolerance to high temperature [2]. In recent years, Micro Electromechanical Systems (MEMS) technology is widely applied to design capacitive microphones [3]. The capacitive microphone is in the majority, because of its high achievable sensitivity, miniature size, batch fabrication, integration feasibility, and long stability performance [4-6]. A capacitive microphone consists of a variable gap capacitor between two plates. In order to operate, such microphones must be biased with a DC voltage to form a surface charge [7, 8].

The deflection of the moveable electrode, due to the incoming sound pressure, changes the inter-electrode gap, and as a result changes the capacitance, which is detected as a voltage or current frequency-signal by the readout interface (RI). For an optimal design of the acoustic system, the readout interface must be tailored and the designing approaches must be customized according to MEMS capacitive microphone. This puts forward a multifaceted design task for the readout interface due to the following reasons: (1) the weak capacitive variations of the MEMS capacitive microphone necessitates a low-noise readout with an adequate integration with the electronics to minimize the parasitic interconnect loading, and (2) since most of the applications of MEMS capacitive microphone are in battery - operated devices [9, 10], low-power consumption is an implicit requirement for the readout electronics. Consequently, this study is going to introduce a model for MEMS capacitive microphone, in order to use it to evaluate the capacitive microphone behavior alongside intermediate circuits like buffer circuits and signal amplifiers.

In the first section of this article, the structure of the capacitive microphone and its parameters which are necessary for modeling are explained briefly. In the second section, the way of creating the model of this microphone is investigated and other characteristics

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related to the proposed model are also evaluated in ADS simulator. In the third section, the behavior of proposed model in integrated circuits is evaluated.

2. ANALYSIS OF MEMS CAPACITIVE MICROPHONE

The MEMS capacitive microphone used in this study is shown in Figure 1.Dimension of the diaphragm, including its thickness, and the residual stress of used material are some of the most important factors in the design of the MEMS capacitive microphone.

To minimize microphone size, a small diaphragm is desired. Low sensitivity of the microphone, which is caused by the small size of the diaphragm, is compensated by making slots around the diaphragm, as shown in Figure 1.Since reducing the circumferential suspension can further reduce the effect of initial stress and increase the mechanical sensitivity of diaphragm, consequently, minimum size and high sensitivity can be achieved [9].Microphone's diaphragm is positioned over the back-plate (electrode) and there are 16 holes in it to allow the air in the gap between the electrode and the diaphragm to escape. Therefore, air damping of the microphone is reduced. However, by makingtoo many holes in diaphragm, the air that comes out of them would be a major obstacle to sound waves and, as a result, reduces sensitivity of the microphone. The sensitivity of diaphragm is increased, by reducing its thickness. Therefore, due to the low thickness of diaphragm, Polysilicon with a Young's modulus of 160 GPa and Poisson ratio of 0.23 is used as the material of diaphragm. Silicon is used as the material of back-plate for the proposed microphone.

The dimensions and other physical characteristics of the MEMS capacitive microphone are summarized in Table 1. In this paper, the MEMS mechanical structure is simulated using Intellisuite, which is a multiphysics simulator that uses the finite element method.The amplitude of generated voltage signal is proportional to amplitude of exerted pressure of sound waves on the diaphragm. A large output signal is obtained, if the open loop sensitivity of the microphone (S_{open}) is high. The open circuit sensitivity of microphone can be considered to be the outcome of an electrical sensitivity (S_e) and a mechanical sensitivity (S_m) [10]:

$$S_{open} = S_m \times S_e \tag{1}$$

The mechanical sensitivity of diaphragm is defined as [11]:

$$S_m = dX / dP \tag{2}$$

where, P is the exerted pressure on the diaphragm and $X$the deflection of the diaphragm.

TABLE 1. Physical Characteristics Of The Microphone

Parameter	Length (μm)	Parameter	Length (μm)
W_D	500	L_B	140
W_B	500	L_C	100
t_D	1	L_A	20
t_B	5	d	1

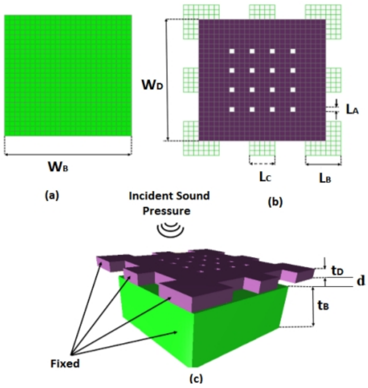

Figure 1. (a) Top view of back-plate, (b) top view of slotted diaphragm, (c) microphone schematic

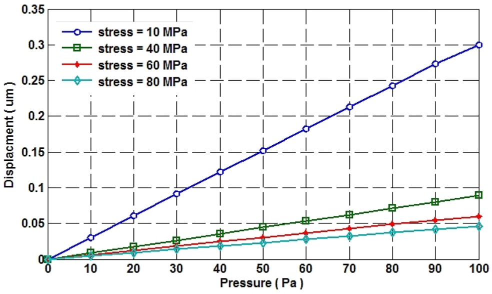

Figure 2. Displacement of the diaphragm vs. exerted pressure with different stress

In Figure 2, displacement of the diaphragm with different stresses versus exerted pressure is shown. It can be seen that the mechanical sensitivity of the diaphragm is increased by reducing its stress. The mechanical sensitivity of the proposed structure with 10 MPa stress is calculated as S_m = 3.01 nm/Pa. The electrical sensitivity of the microphone can be expressed as:

$$S_e = V_b / d \tag{3}$$

where V_b is the DC bias voltage and $d$the initial gap height. In fact, the electrical sensitivity increases with the bias voltage. However, the bias voltage cannot be increased more than pull-in voltage. At pull-in voltage, the diaphragm collapses to the back-plate. Since the microphone is biased 60% of pull-in voltage, thus for the proposed microphone the bias voltage is 2.3 Volts and the electrical sensitivity is 2.3 V/μm.

TABLE 2. Comparison of Open Loop Sensitivity

Paper	Sensitivity (mV/Pa)
This Work	6.916
[9]	0.2
[12]	4
[13]	0.03

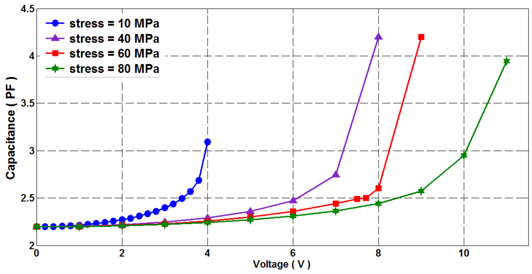

Figure 3. Capacitance of the MEMS microphone vs. voltage with different stress

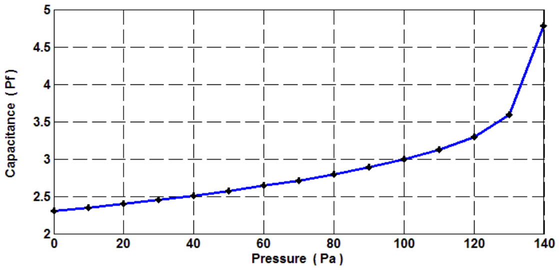

Figure 4. Microphone's capacitance vs. pressure

The open loop sensitivity of microphone (S_{open}) can be obtained as:

$$S_o = S_m \times S_e = 6.916 \ mV/Pa \tag{4}$$

The open loop sensitivity of proposed MEMS capacitive microphone is compared with previous works in Table 2 This comparison shows good performance of proposed microphone in detecting weak acoustic waves. Generally, as mentioned before, this can be achieved by reducing the diaphragm thickness and residual stress.

Pull-in voltage of MEMS capacitive structures is the DC voltage that is necessary to pull-in the diaphragm on the back-plate. At this voltage, displacement of diaphragm is almost 1/3 of the air gap. Since, according to Table 1, the air gap height is 1 µm, pull-in happens when displacement of diaphragm is 0.33 µm. The pull-in voltage, V_P, of the microphone is a function of the residual stress (σ), and can be calculated using the equation below [14]:

$$V_p = \sqrt{\frac{6}{5}\frac{d^2}{\varepsilon_0}\left(C_1 \frac{t\sigma}{\hat{a}^2}\left(\frac{d}{3}\right) + C_2(\upsilon)\frac{tE}{\hat{a}^4}\left(\frac{d}{3}\right)^3 \right)} \tag{5}$$

where υ is Poisson ratio, *E*young's modulus, *d* air gap height, *â* half of the diaphragm side length, *t*the thickness of diaphragm, σ the stress of the diaphragm material, and C_1 and C_2 are numerical parameters. As shown in Figure 3, the pull-in voltage of the MEMS capacitive microphone increases by increasing the initial residual stress. Hence, 10 MPa is chosen for the residual stress of the diaphragm to achieve the pull-in voltage of 3.8 volt.

As mentioned before, The MEMS capacitive microphone is biased 60% of pull-in voltage. Both DC voltage and exerted pressure of acoustic wave cause deflection on the diaphragm. So, the total deflection of diaphragm should not reach 1/3 of the air gap height.

Capacitance changes in MEMS microphone are proportional to exerted pressure of acoustic waves on diaphragm. To model a MEMS capacitive microphone for integrated circuits, one needs to find the relationship between the variable capacitance of structure and pressure of acoustic waves. The relation between the capacitance of microphone and sound wave's pressure in 60% of pull-in voltage (2.3V) is shown in Figure 4. It can be seen that the electrostatic capacitance varies linearly within the pressure range (0–100 Pascal). The capacitance shows a drastic change after 120 Pascal, where pull-in happens. The capacitance of MEMS microphone is equal to 2.3 pF when there is no pressure on the diaphragm. According to Figure 4, the relation between the capacitance of MEMS microphone and exerted pressure of acoustic wave is as follows:

$$C(P) = \alpha . P^9 + \beta . P^8 + \gamma . P^7 + ... + 2.3 \ pF \tag{6}$$

where *P* is the exerted pressure of acoustic signal, α, β, and γ are coefficients of the poly nominal, and *C*(*P*) is the capacitance of MEMS microphone. Constant part of this multinomial equation represents microphone capacitance while it is biased and there is no pressure signal. The second part indicates capacitance variations under pressure signal. Higher orders of this formula have very small coefficients and can be neglected.

3. THE PROPOSED MODEL FOR MEMS CAPACITIVE MICROPHONE

The MEMS capacitive microphone is a micromechanical structure that has non-linear response to the applied actuation. To make a realistic model for the MEMS capacitive microphone, we need to find a relation between the electrostatic and mechanical forces. The mechanical forces can be roughly considered as pull-up forces while electrostatic forces are considered as pull-down forces. The incident acoustic force makes the membrane oscillate around its equilibrium point, causing a change in the distance between the membrane and back-plate that is proportional to the acoustic signal [15].

Figure 5 shows the relation between different factors such as force, pressure, displacement, and capacitance of MEMS microphone. F_t implies total exerted forces on diaphragm that includes electrostatic, mechanical, and acoustic wave. d is the diaphragm deflection which is a function of all imposed forces on diaphragm. C is the capacitance between two plates which changes according to the diaphragm deflection. It can be seen that the microphone's current depends to its capacitance. The pressure signal is defined as:

$$P = A\,Sin\left(wt\right) \tag{7}$$

where A is amplitude of pressure signal and W its frequency. To model MEMS capacitive microphone, it is necessary to extract the voltage and current of microphone as a function of exerted pressure signal.

According to Figure 5, both capacitance and voltage change. Microphone's current and the presented model is expressed as follows:

$$Ic = C(t)\frac{dVc}{dt} + \frac{dC}{dt}Vc(t) \tag{8}$$

where $C(t)$ and $V_C(t)$ are capacitance and voltage of MEMS microphone, respectively. The relation between charge and current is defined as follows [16]:

$$Q(t) = C_{\text{mic}} V_{bias} + C(t)V_c(t) \tag{9}$$

$$\text{I}(t) = \frac{dQ(t)}{\text{dt}} = \frac{dC(t)}{dt}V_c(t) + C(t)\frac{dV_c(t)}{dt} \tag{10}$$

where C_{mic} is microphone's capacitance under DC bias voltage without exerted pressure signal. $C(t)$ is its capacitance under exerted pressure signal which is a time variable signal. $Vc(t)$ is the generated electrical signal of microphone. When a MEMS capacitive microphone is biased by a DC bias voltage, the charge distributed on diaphragm surface, according to Equation (9), is dependent on the capacitance and voltage changes.

Figure 6 shows the proposed model for the MEMS capacitive microphone. As illustrated in Figure 6, the model has 3 ports that represent MEMS microphone structure. Ports 1 and 2 indicate diaphragm and back-plate, and the pressure signal of acoustic wave is connected to the port 3. In this model, Equation (10) is used as the relation between the capacitance of the microphone and inputs.

Figure 7 shows the internal topology of proposed model which consists of 4 ports. Each of them is used for representing the relations between microphone's capacitance and its variable factors. To model the inner behavior of the microphone, the current formula (Equation (8)) is used. There are 3 ports which express diaphragm, back-plate, and pressure. Consequently, there would be 3 ports which are connected to the ground. In the current formula of microphone, there is a derivative of voltage and capacitance. To model them two more ports are used.To define the inner formulas, each two ports which are related to each other are defined as one variable and named 1 through 4. According to Equation (6), relation for each variable is defined as follows:

$$\begin{aligned} &V = \tilde{V}_1 \;, \quad \frac{dV}{dt} = \tilde{V}_2 \\ &P = \tilde{V}_3 \;, \quad \frac{dC}{dt} = \tilde{V}_4 \end{aligned} \tag{11}$$

where $\tilde{V}_1, \ldots, \tilde{V}_4$ are representing the variable values, V indicates microphone voltage, and P is the exerted pressure signal. Using Equation (11) the parameters were defined in model.

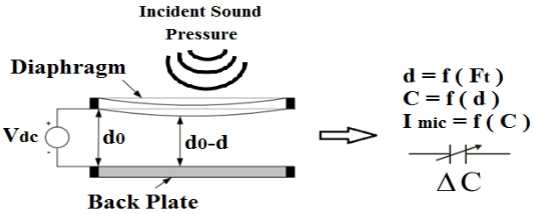

Figure 5. The relation between different parameters in a MEMS capacitive microphone

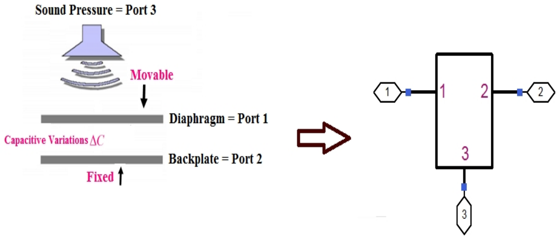

Figure 6. The proposed model for MEMS capacitive microphone

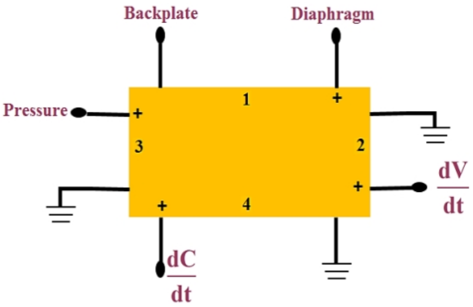

Figure 7. Internal structure of proposed model for MEMS capacitive microphone

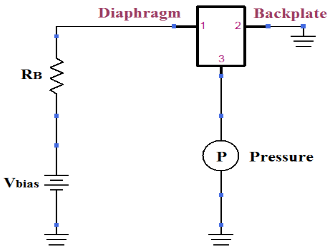

Figure 8. The proposed model for MEMS microphone with the bias circuit

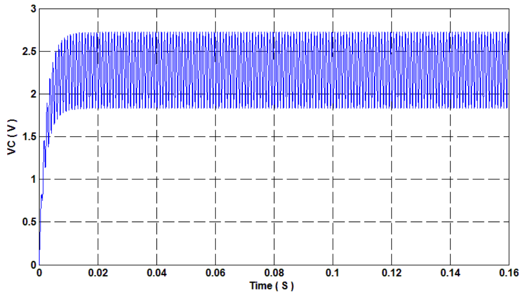

Figure 9. Voltage signal of the microphone vs. time

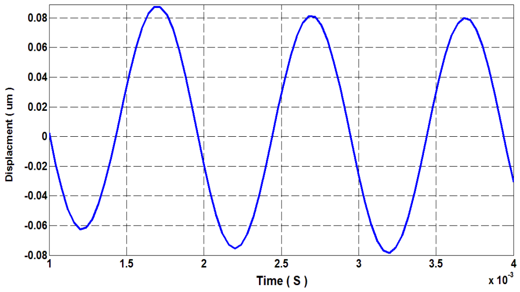

Figure10. Central deflection of diaphragm under sinusoidal pressure

Since a capacitive microphone needs a driver circuit to work properly, it is biased by a DC circuit as shown in Figure 8. The bias circuit includes a resistance (R_B = $1G\Omega$) and DC voltage source (V_{bias} = 2.3 V) which is 60% of pull-in voltage. Applied pressure signal is modeled by a simple sinusoidal source. Several simulations have been done using Advanced Design System (ADS) simulator to verify the circuit operation and characteristics.

Since the auditory frequency range of human is from 20 HZ to 20 KHZ, and capacitance value is around pF, thus the microphone impedance increases, therefore the R_B value should be so large. Another factor that should be considered is the large RC time constant that can guarantee the microphone's behavior under constant charge condition. The resistor is used to keep constant charge stored in microphone.

4. RESULTS AND DISCUSSION

When an acoustic wave hits the diaphragm, the distance between two plates change and cause the microphone's capacitance to change. With the hypothesis of constant charge, due to the resistor R_B, a voltage is generated at the output of the microphone as a function of the displacement of the moving diaphragm. Figure 9 shows the voltage of MEMS capacitive microphone versus time. In practical cases, the acoustic wave that hits the surface of the diaphragm makes it to vibrate, and as a result, the capacitance between back plate and diaphragm changes. Therefore, according to Equation (8), current and voltage of the MEMS microphone changes as well. It should be noted that the voltage signal of MEMS microphone oscillates with a frequency equal to the frequency of acoustic signal around bias point of microphone (V_{bias}).

The microphone diaphragm deflects when the acoustic wave hits it, and this deflection is proportional to the exerted pressure of acoustic signal. The relation between the diaphragm deflection and acoustic pressure signal is as follows [17]:

$$P = 4.2\,E\frac{d^4}{\left(1-\upsilon^2\right)\hat{a}^4}\left(\frac{w}{d}\right) + \pi\frac{d^2}{\hat{a}^2}\left(\frac{w}{d}\right)\sigma \tag{12}$$

where w is the central displacement of diaphragm. Using Equation (12), the central displacement of diaphragm in terms of the exerted pressure is expressed as follows:

$$w = \left(1 \Big/ \left(4.2\,E\frac{d^3}{\left(1-\upsilon^2\right)\hat{a}^4} + \pi\frac{d}{\hat{a}^2}\sigma\right)\right)P \tag{13}$$

According to Equation (13), if the acoustic wave is sinusoidal, diaphragm's deflection is expected to be sinusoidal as well. Figure 10 shows the central displacement of diaphragm under acoustic wave. The applied pressure signal (f=1 KHz) on the diaphragm is $p = p_1 \cos(wt) = 90\cos(2\pi f \times t)$. It can be seen that the diaphragm's deflection is sinusoidal. Using Equation (13), the displacement should have amplitude of 0.081μm which is very close to the simulation result (0.084 μm).

According to Equation (10), the voltage and the current signal generated by microphone would be sinusoidal. Figures 11 and 12 respectively show the exerted pressure on the diaphragm and voltage of microphone versus time. By increasing the pressure, the diaphragm pulls down and the capacitance increases. It is expected that by increasing the capacitance, the voltage of microphone to decrease, as shown in Figure 12. Figure 13 shows the current signal of MEMS capacitive microphone. The current of a capacitor is proportional to its capacitance. Therefore, by increasing the capacitance, it can be seen that the current signal is increased. Moreover, current and voltage signals have the same frequency as exerted pressure on port 3.

As mentioned before, the limitation of frequency for acoustic signal is between20 HZ and20 KHZ. However, in a bias circuit, there is a probable increase of noise in low frequencies (lower than 20 Hz). Hence, to eliminate the noise of microphone, an RC filter is used. The cutoff frequency of the RC filter, which is the frequency that the filter will attenuate to half its original power, is obtained as follows:

$$f_C = \frac{1}{2\pi R_f C_f} = 20\ Hz \tag{14}$$

where the value of capacitor and resistor are C_f= 10 pF and R_f= 5 GΩ, respectively. So, cutoff frequency of the filter would be 20 Hz. Figure. 14 shows the final circuit containing MEMS capacitive microphone, bias circuit, and RC filter.

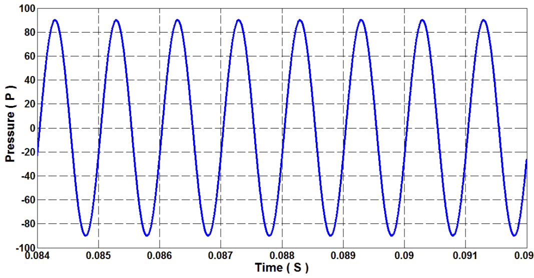

Figure 11. Applied pressure of acoustic wave on microphone diaphragm

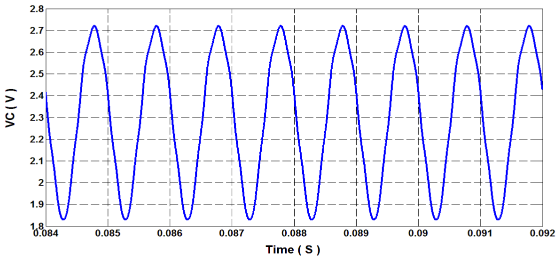

Figure 12. Voltage of MEMS capacitive microphone

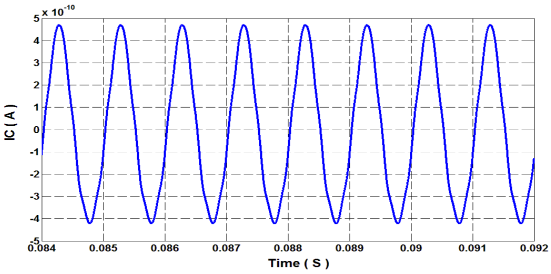

Figure 13. Current of MEMS capacitive microphone vs. time

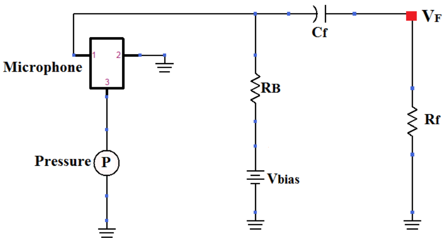

Figure 14. MEMS capacitive microphone model with bias and filter circuit.

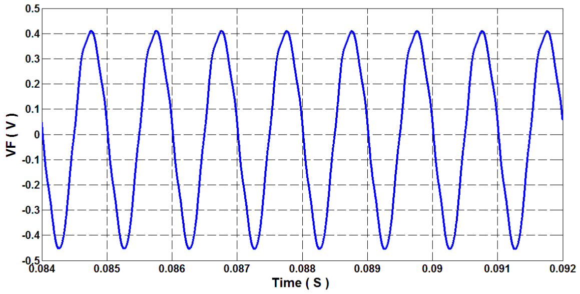

Figure 15. The output voltage of the circuit in pin *F*

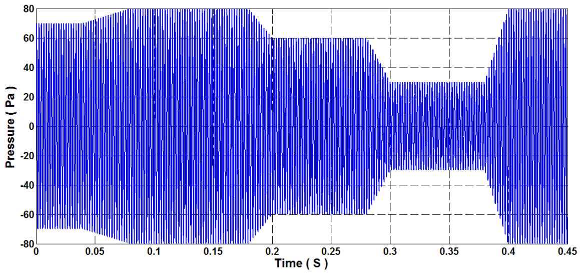

Figure 16. Applied pressures on diaphragm with different amplitudes

Figure 15 shows the output voltage of the pin *F*. This voltage is generated by the current variations in MEMS capacitive microphone. Since, according to Equation (6) the relation between the capacitance of microphone and the exerted pressure on diaphragm is nonlinear, it is expected that the output (Pin F) current and voltage not be completely sinusoidal.

Since acoustic signals have different amplitudes and frequencies in different times, in order to evaluate the effectiveness of the proposed model and circuit, it is necessary to define pressure signal in port 3 that has different amplitude and frequency in different times. Thus, the frequency of microphone current and other signals are equal with the applied pressure frequency on port 3. The pressure signal that is imposed to port 3 is shown in Figure 16. We expect that the voltage and current change according to pressure signal. Figure 17 indicates the voltage, and Figure 18 shows the current signal of the microphone versus time.

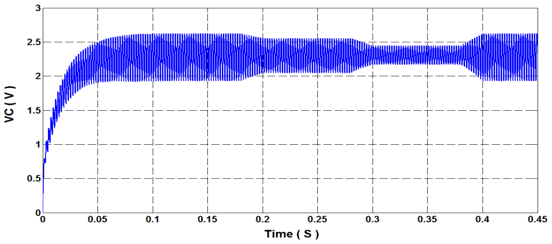

Figure 17. Effect of changes in amplitude of pressure on voltage signal of the microphone

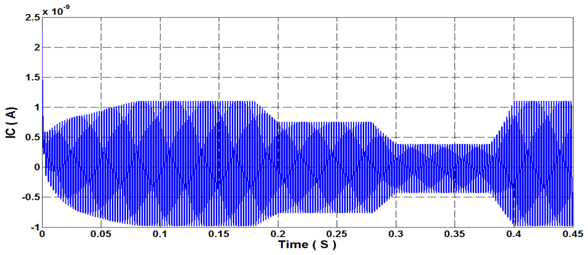

Figure 18. Effect of changes in amplitude of pressure on current signal of the microphone

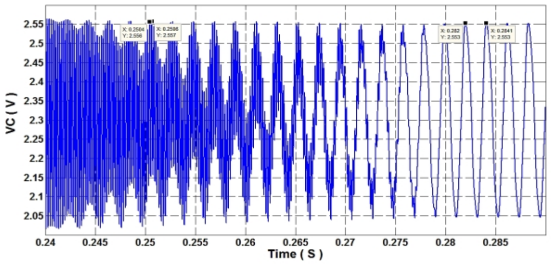

Figure 19. Effect of changes in the frequency of pressure on voltage of microphone

When the amplitude of pressure signal increases, it causes larger diaphragm deflection. In other words, it causes larger changes in microphone capacitance. As a result, the amplitude of voltage and current signal increases, as shown in Figures 17 and 18. Another factor that should be particularly considered is the effect of pressure signal frequency on the output frequency. Figure 19 illustrates the behavior of the voltage of MEMS capacitive microphone versus time, while the frequency of exerted pressure signal is changed at$t$=0.24s. As the frequency of pressure signal is decreased, the frequency of voltage signal of microphone decreases as well.

5. CONCLUSION

In this article, a model has been presented for MEMS capacitive microphone. Using relation between the capacitance and pressure signal, a 3 port model for the MEMS microphone is introduced. The internal topology of the model is explained. In addition, the model is simulated in the DC bias circuit. Simulation results verified the numerical ones. The voltage and current signal of the microphone are proportional to the exerted pressure of the acoustic wave. Moreover, to eliminate the noises in low frequencies (lower than 20 Hz) an RC filter is used. Finally, the effect of amplitude and frequency of the exerted pressure on the voltage and current signal of the microphone is analyzed. Generally, the proposed model for the MEMS capacitive microphone shows a good performance under different pressure signals.There are different parameters in designing a MEMS capacitive microphone. One of the most important factors is the exerted pressure signal on the diaphragm. In previous works on MEMS microphones [15, 18], there is only an electrical model of microphone and the effect of pressure signal, which is the main factoring the value of capacitance of microphone, is not considered. As shown by Equation (6), there is a nonlinear relation between the capacitance of microphone and the exerted pressure signal. The proposed model for MEMS microphone, according to that equation, is illustrated in Figure 7. In this model, the exerted pressure signal is connected to port 3, which helps us to evaluate the behavior of microphone more realistic beside other circuits. The results of simulations shows that the proposed model can be used for evaluation of different MEMS capacitive microphones beside different electrical circuits including matching circuits, and preamplifiers before the fabrication process.

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A MEMS Capacitive Microphone Modelling for Integrated Circuits

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چکیده

در این مقاله یک مدل برای میکروفون خازنی MEMS ، جهت استفاده در مدارهای مجتمع نشان داده شده است. میکروفون دارای یک دیافراگم با ضخامت 1 µm و ابعاد 0.5 × 0.5 mm و فاصله هوایی 1 µm می باشد. با استفاده از نتایج تحلیلی و شبیه سازی، مشخصات اساسی و مهم میکروفون خازنی MEMS، مانند ولتاژ pull-in و حساسیت، هنگامی که هیچ گونه فشاری به دیافراگم وارد نمی شود، به ترتیب برابر با 3.8 V و 6.916 mV/Pa می باشد. همچنین در این حالت ظرفیت میکروفون برابر 2.3 pF می گردد. با استفاده از روابط میان ظرفیت و سیگنال فشار، یک مدل با سه پورت برای میکروفون MEMS نشان داده می‌شود. برای بایاس کردن میکروفون از یک منبع ولتاژ 2.3 V و یک مقاومت 1 GΩ استفاده شده است. سیگنال ولتاژ و جریان میکروفون متناسب با فشار اعمال شده به عنوان امواج آکوستیک می باشد. از یک فیلتر RC برای از بین بردن نویزهایی با فرکانس کمتر از 20 Hz استفاده می‌شود. مدل ارائه شده برای میکروفون پاسخ مناسبی به تغییرات دامنه و فرکانس سیگنال فشار اعمال شده، می‌دهد.

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