INTERNATIONAL JOURNAL OF ELECTRICAL ENGINEERING & TECHNOLOGY (IJEET)

ISSN 0976 – 6545(Print)
ISSN 0976 – 6553(Online)
Volume 5, Issue 1, January (2014), pp. 66-79
© IAEME: www.iaeme.com/ijeet.asp
Journal Impact Factor (2013): 5.5028 (Calculated by GISI)
www.jifactor.com

IJEET
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STUDY AND CALCULATIONS OF THE MUTUAL IMPEDANCE BETWEEN NEIGHBOR CELLS IN CMUTs

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ABSTRACT

In this study we will talk about Capacitive Micromachined Ultrasound Transducers (CMUTs) technical and explain the fabrication and design of elements, CMUTs have been investigated for a wide range of applications, including medical imaging, therapeutics and sensor applications.

In ultrasound applications, one of the key merits of CMUTs over piezo-based transducers is a larger bandwidth in immersion, even at higher operational frequencies .The fundamental mechanism of the transduction is the vibration of a thin plate under electrostatic forces. Many macro scale devices use this mechanism for generating and sensing sonic waves.

Also, focusing on cross-coupling between neighbor cells in CMUT array each cell is affected by the acoustic loading from neighboring cells. Thus, for an accurate model of a multi cell, CMUT element it is better to consider the mutual acoustic impedance instead of the acoustic impedance of a single cell only, and its effect on performance on CMUT. The multi-cell immersed in a liquid medium (water) is highly affected by mutual acoustic impedance (Z_{ij}). We calculate (Z_{ij}) for multiple cells in array, the value of (Z_{ij}) depends on the dimensions of cell, the separation between the cells normalized with the wavelength in the immersion medium. We performed a simulation by MATLAB to calculate mutual impedance between two neighbor cells and discussed the results.

1. INTRODUCTION

Ultrasound is defined as a sound pressure wave with a frequency greater than the upper limit of human hearing (20 kHz). Frequency (wavelength in air) range of the ultrasound is defined in Figure 1.

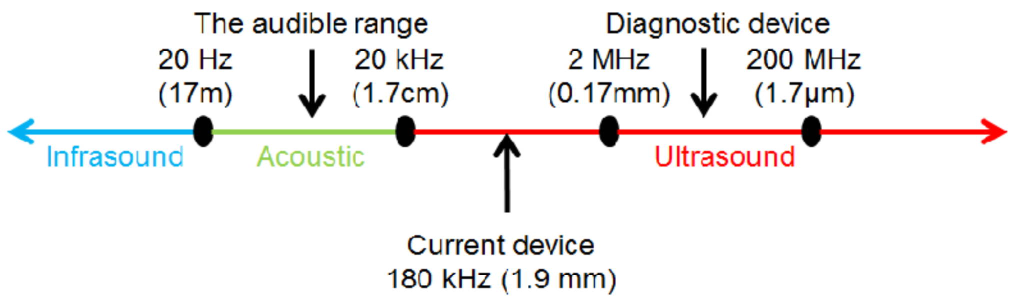


Fig.(1): Frequency (wavelength in air) range of ultrasound

Capacitive micromachined ultrasonic transducers CMUTs with high performance and well characterization were reported as a novel type of ultrasonic transducers developed in Ginzton Laboratory in 1996. This new type of ultrasonic transducer was designed to operate in air at very high frequencies (11 MHz) which is compatible with alternative piezoelectric transducers. This design had circular silicon nitride membranes and evaporated gold electrode on top of the membranes in order to be excited by driven voltages. It was potentially shown that this design could emit and detect 11 MHz ultrasonic signals. CMUTs began to appear in immersion applications, first in underwater imaging and later in medical imaging. Consequently, research interest has increased for both technology development and modeling. Early on, the Office of Naval Research (ONR) approached CMUT technology aggressively to build underwater ultrasound imaging cameras. Recently, the medical imaging community has taken the lead in commercialization of CMUT technology[1]. Creation of 3-dimensional structures using integrated circuits fabrication technologies and special micromachining processes– typically done on silicon or glass (SiO2) wafers.

Recently, (CMUTs) were developed as an alternative technology for ultrasonic measurement. A CMUT sensor is an ultrasonic probe using the vibration of numerous film membranes, typically micromachined on a silicon wafer[2]. (CMUTs) consist of a thin vibrating membrane with an embedded electrode that is separated from the substrate with a small sacrificial gap that vibrates in order to transmit or receive ultrasonic waves[3]. One of the key merits of CMUTs over piezo-based transducers is a larger bandwidth in immersion, even at higher operational frequencies. This wide bandwidth is the inherent result of the CMUT cell structure. CMUT have been subject to research by several research groups during the last two decades[4], the active acoustic part and top electrode of the CMUT is a membrane which is partially or fully covered with a conductive material. The membrane is suspended over a vacuum gap in a heavily doped silicon substrate, which constitutes the bottom electrode, as shown in fig (2).

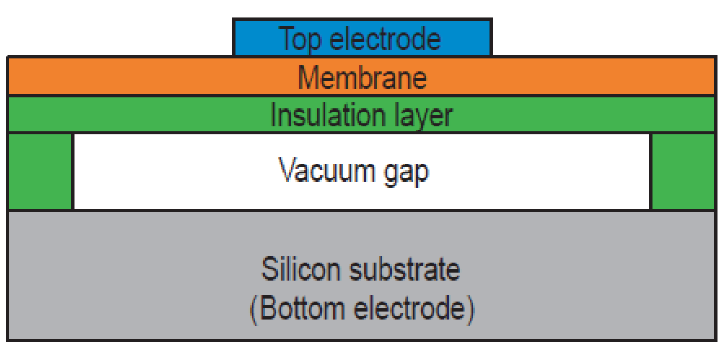
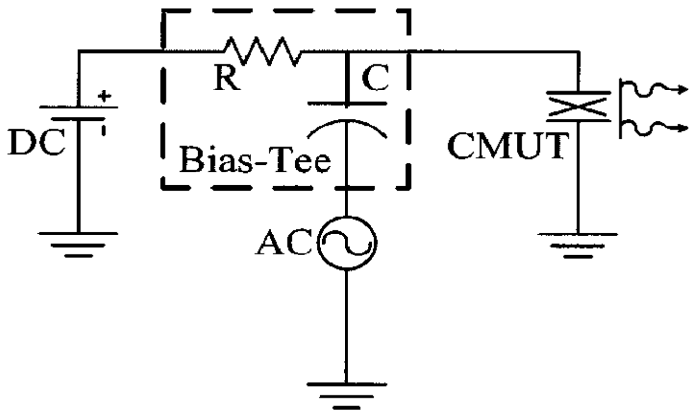


Fig. (2) Typical membrane structure

1.1-Principle of operation

A DC-bias voltage applied between the top and bottom electrode pulls the membrane towards the substrate due to electrostatic attraction. If an AC-voltage is applied to the biased membrane, harmonic membrane motion is obtained. In this mode of operation it acts as a transmitter, as shown in fig (3-a).



Fig(3-a) shows transmitter part of CMUT

If a biased CMUT membrane is subject to an impinging ultrasonic pressure field, the membrane motion leads to harmonic changes in the capacitance of the device, fig(3-b) generating an AC-detection current, in this mode it work as a receiver, [5,6].

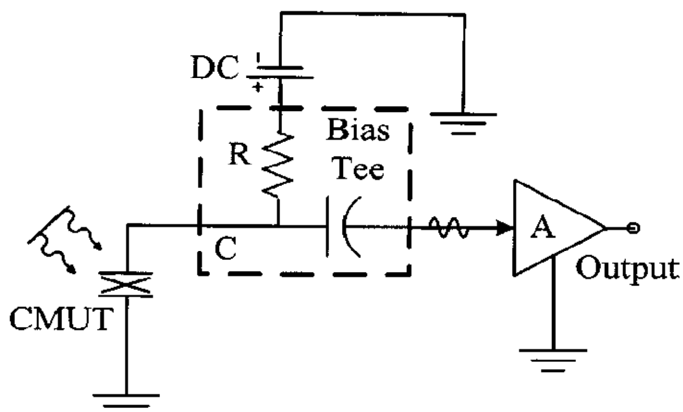
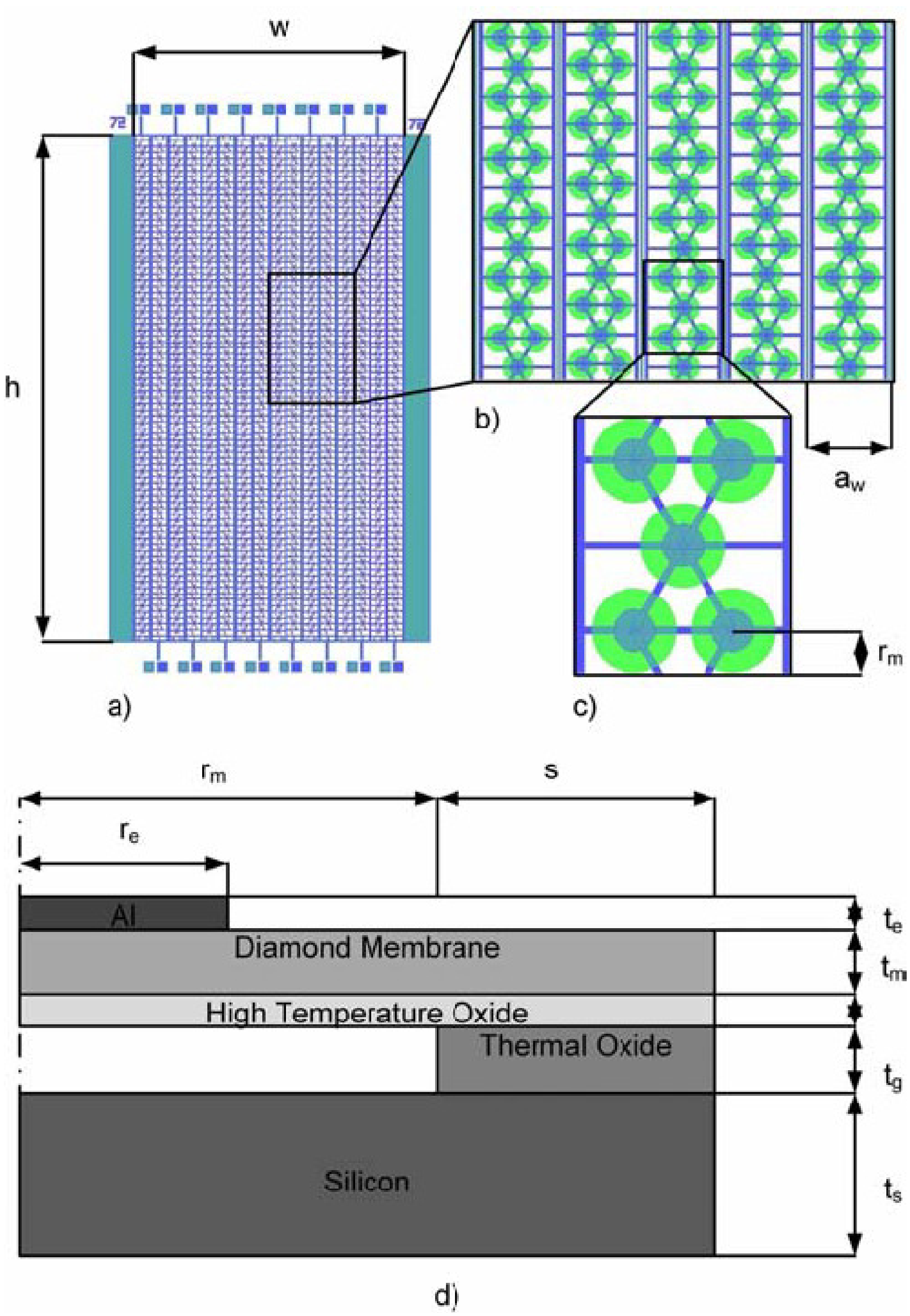


Fig.(3-b) shows receiver part of CMUT

1.2- CMUT elements

As we know the CMUT composed of a large arrays of closely packed cells, the mutual radiation impedance is defined between two couple cells, hence all cells in array are coupled through a radiation impedance matrix at their acoustic terminal [7]. There is electric coupling between the CMUT cells because of the fact that several cells are connected to form larger transducer element [8] fig(4). Pritchard 7 has derived formulas for the mutual radiation impedance between circular pistons. This coupling degrades the performance of transducers in applications such as medical imaging and therapeutic [9], the acoustic crosstalk that occurs between the closely packed cells of CMUT arrays is considered important, because it impairs both beam forming and powerful radiation [10,11,12], this cross talk caused by acoustic interactions that occur when the sound pressure fields of the transducers exert force on each other through the immersion medium. This phenomenon has been recognized in sonar transducer arrays for many decades, and its significant effects on array performance have been studied by means of the mutual radiation impedance between the transducers [13, 14, 15].



Fig(3) Physical dimensions of 72 µm 1-D CMUT array

CMUT membranes have low mechanical impedance, which makes them inherently suitable for immersion applications. With this major advantage, CMUTs are capable of transmitting and receiving wideband acoustic signals. On the other hand, a low mechanical impedance means low quality factor (Q) of mechanical resonance.

It brings with it severe effects resulting from mutual acoustic interactions, which are manifested in the operational bandwidth of the transducer. [16, 17, 18]

Design and analysis of CMUTs using Mason element equivalent circuit requires the knowledge of radiation impedance as shown in fig(5) including the electrical part (left side) and the mechanical part (right side). In this work, we consider the mechanical part of the equivalent circuit, which can be simplified into a three component model. In the simplified model, a voltage represents an applied force on a cell (plate) and a current represents an average velocity of the cell (plate). Both *Cx* and *Lx* represent the mechanical properties of the plate, which can be analytically calculated [19]. In the equivalent circuit model, $Z_{acoustic}$ is the acoustic impedance and can be defined as

$$Z_{acoustic} = \frac{F_{acoustic}}{v}$$

where, $F_{acoustic}$ is the acoustic force applied by a pressure in the surrounding medium.

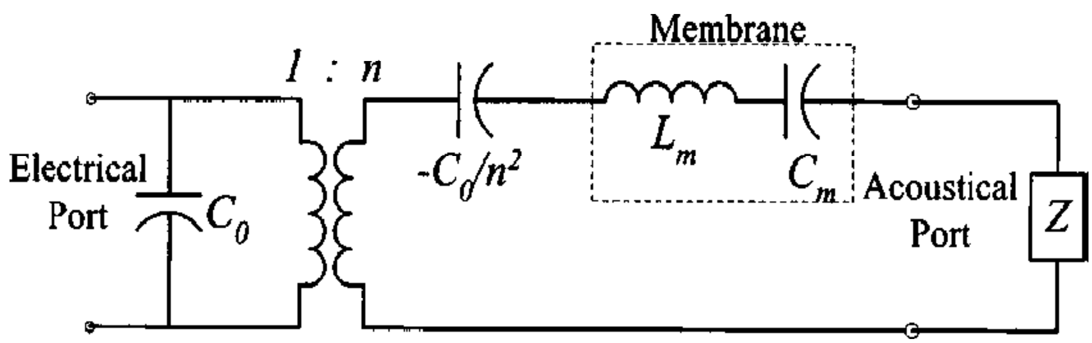


Fig.(5) Equivalent circuit(electrical and mechanical parts)

The equivalent circuits of single CMUT cells can then be used to model arrays by appropriately terminating each cell with respective impedance. Recently, there has been a significant improvement on this topic for both single cells and arrays [20,21].

So, we could find the total radiation impedance (Z_i) between neighbor cells in CMUT cells because of the array is consist of multiple cells which are usually closely packed and electrically driven in parallel, as shown in fig (6) illustrated the generic CMUT array.[22,23]

$$Z_i = Z_{ii} + \sum_{\substack{j=1 \\ i \neq j}}^{N} \frac{v_j}{v_i} Z_{ij}$$

Where N = mn is the number of cells, Ziiis the self radiation impedance of the ith cell when it is located on an infinite rigid plane baffle, vi and vj are the references velocities for the ith and jth cells, and Zij is the mutual radiation impedance between them.

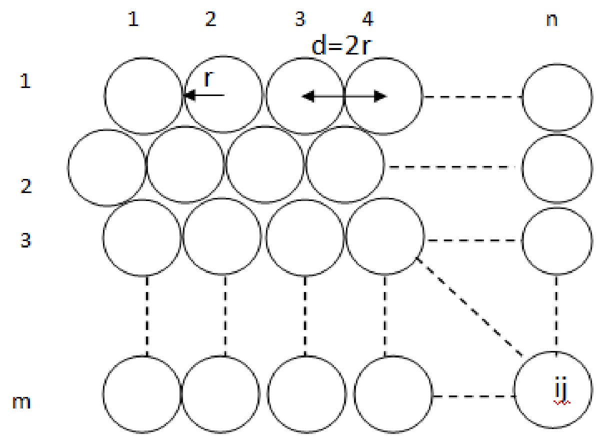


Fig .(6) Configuration of a rectangular array of CMUT cells, where the d=2r displacement between the *i*th and *j*th cell is denoted

Typical CMUTs consist of multiple cells, closely packed, and, thus, require a model that considers this multi-cell configuration accurately. The acoustic impedance is affected by the neighboring cells; consider two cells separated by a center-to-center distance of d where ($d=2r$). Then, the acoustic impedance of cell number 1 can be defined as follows,

$$Z_1 = Z_{11} + Z_{12}\frac{v_2}{v_1}$$

where Z_{12} is a mutual acoustic impedance term due to the neighboring cell.

The acoustic force at the radiation interface of each cell can be interpreted in matrix form with where F_i and v_i represent the rms force and the rms velocity of the individual cells, respectively. The square matrix, $\mathbf{Z} = [Z_{ij}]$, is the impedance matrix. If all the transducers in the array are identical, the self-radiation impedance is the same for all of them. According to the acoustical reciprocity theorem, $Z_{ji} = Z_{ij}$, so that $\mathbf{Z}$ is a complex symmetric matrix [24].

$$\begin{bmatrix} F_1 \\ F_2 \\ F_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{1N} \\ Z_{21} & Z_{22} & Z_{2N} \\ Z_{N1} & Z_{N2} & Z_{NN} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_N \end{bmatrix}$$

1.3-Advantages of CMUT

The most important advantages of the CMUT compared to its piezoelectric counterpart are high frequency bandwidth, smaller size, higher sensitivity and a better electromechanical coupling coefficient (k_t). The fact that the CMUT has a large bandwidth, especially immersed in liquids, High temp. Capable (ca. 800 ºC) [25]. The table below shows the properties of CMUT compared with piezoelectric:

	Piezoelectric transducer	CMUT
Fabrication method	Ceramic technology	MEMS technology
Array fabrication	Difficult and high cost, very difficult for 2D array, ring array	Easy and low cost, arrays with through-wafer interconnects
Frequency range	Relatively narrow	Broad
Bandwidth	Moderate, matching layers required	Wide
Array uniformity	Moderate	High
Thermal stability	Low	High
IC integration	No	Yes
Output pressure	High	Relatively low but improving

1.4-Transducer design and fabrication process

Several fabrication processes and membrane geometry alternatives have been carried out with membrane diameters ranging from 50 to 70µm. A schematic representation of a single membrane is shown in Fig.(7). The device has two silicon nitride layers. The first one isolates the sacrificial material from the bulk of the wafer and it is used as an etching barrier to protect the wafer from the sacrificial etchant. The second one constitutes the structural layer, i.e. the moving membrane. The substrates for the CMUTs are one-side polished 4" n-type <100> silicon wafers. The main steps of the process are described in Fig. (8). An n+-region is created with phosphorus diffusion, thus generating the bottom electrode; followed by the deposition of 0.5 lm of LPCVD silicon nitride and a 0.5 lm PECVD silicon oxide to create an insulator layer. The thickness of the sacrificial material, 0.5 µm LPCVD polysilicon and 0.5 µm of PECVD silicon oxide, determines the 1 µm air gap of the device. The structural layer, made of 0.5 µm LPCVD silicon-rich nitride, is annealed in O2 in order to reduce the residual stress. The proportion of dichlorosilane and ammonia used in this deposition has been changed to (3:1) from the stoichiometric ratio (1:3) to change the stiffness of the silicon nitride layer, finally yielding a refractive index of 2.19. Nevertheless, instead of using greater ratios of Dichlorosilane in the LPCVD deposition—thus compromising the thickness uniformity—an O2 annealing is carried out to further reduce the residual stress. The polysilicon sacrificial layer is doped with phosphorous in order to achieve higher etching velocity. The second photolithography and RIE process create the apertures on the nitride layer which are used in the sacrificial etching of the oxide and polysilicon with a standard solution for silicon isotropic etching (HNO3:HF: CH3COOH). Such holes are placed in the corner area between four neighboring cells so as to keep uniformity in the moving membrane. Special care has been taken during the membrane liberation process to avoid stiction. Final steps of the process are evaporation and patterning of aluminum over the free standing membranes (top electrode). The wafer is then diced, and the CMUTs are bonded to standard circuit board (PCB). [26]

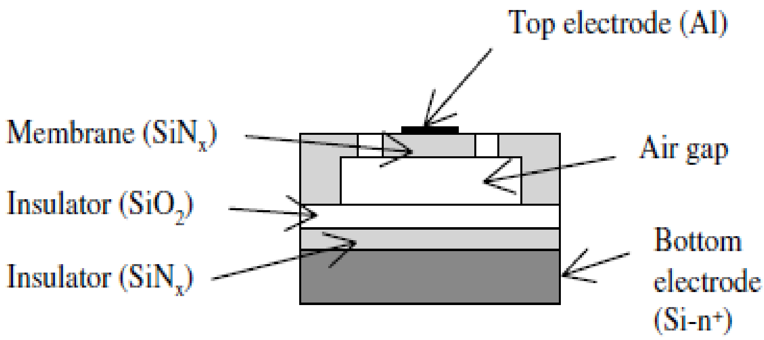


Fig. (7) Cross-section of typical CMUT device design

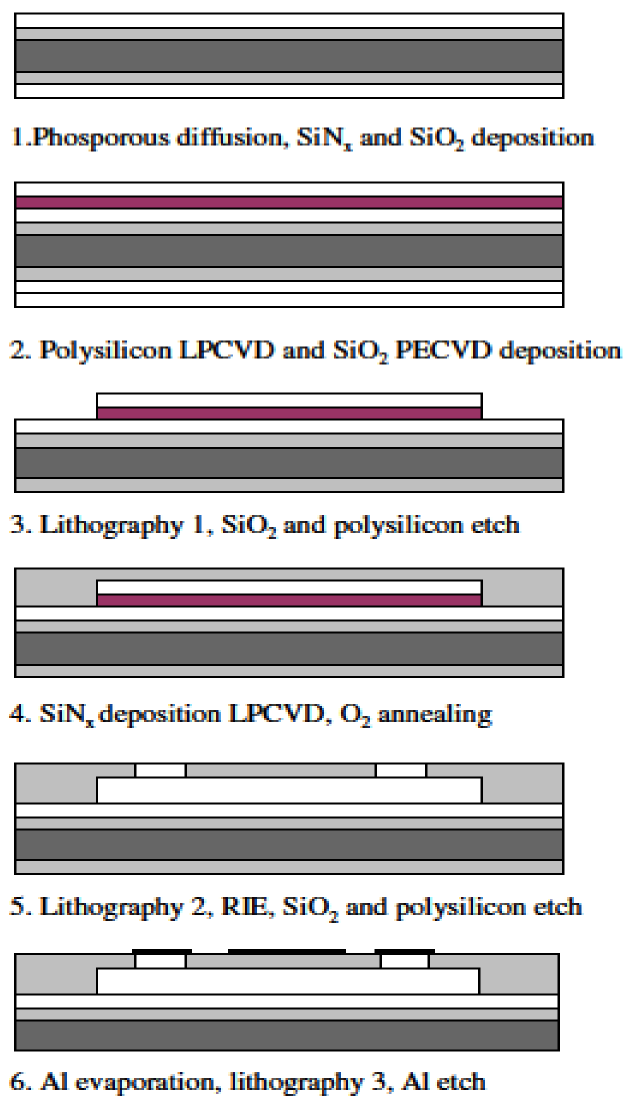


Fig .(8) process flow used to fabricate the CMUTs

1.5-Applications

In ultrasound applications CMUT have been investigated for a wide range of applications, including medical imaging, therapeutics and sensor applications. (CMUTs) bring the fabrication technology of standard integrated circuit into the field of intracardiac medical imaging, rangefinder.

Today's ultrasound technology covers a wide range of measurements, diagnostic, and other applications, e.g. from non-destructive testing to medical ultrasonic imaging or from surveillance in process plants to distance measurement. Capacitive micro machined ultrasonic transducers (CMUT) receive increasing acceptance as an alternative to piezoelectric transducers for certain fields of applications due to a number of distinctive features. The development of high-frequency ultrasonic imaging benefits many fields of medicine. These fields include dermatology, ophthalmology, cardiovascular medicine, and small animal research. The use of high-frequency ultrasound makes it possible to resolve the details of fine features that are close to the transducer. Recent developments have facilitated the fabrication of high-frequency arrays for ultrasonic imaging. The ability to make high-frequency arrays in various configurations also enables new applications for ultrasonic imaging.[27,28] Hitachi Medical is an integrated medical systems manufacturer involved in every aspect of the medical equipment and medical information systems.

GlobalSpec for engineers and industrial **developed CMUT sensor** for applications as a wide-band acoustic receiver in the MHz range; these devices can easily operate in the high frequency range due to the silicon micromachining technology used. In order to calibrate large bandwidth high frequency CMUT array probes, they designed and fabricated a single element transducer on the same wafer used for the CMUT array. Since the sensor is fabricated on the same wafer, it has the same characteristics of the probe and, hence, the measurements are possible in the same operative range (3-20 MHz).

3. ANALYTIC WORK

In this work, we perform MATLAB simulation as analytic work and we will discuss the results.

By Bessel function we can find the acoustic impedance for cell number 1(Z_{11}:[17]

$$\frac{Z_{11}}{Z_0} = 1 - \left(\frac{192}{(2kr)^5}\right)(F_1(2kr) + i.F_2(2kr)$$

Where:

$$F_1(y) = (20 - y^2)J_1(y) - 7yj_0(y) - 3y$$

$$F_2(y) = (y^2 - 20)H_1(y) + 7yH_0(y) - \frac{2y^2}{3\pi}$$

$$k = \frac{2\pi}{\lambda} = 2\pi\frac{f}{c}$$

$$Z_0 = \rho c A$$

Where:

k:the wave number in the immersion medium (m^{-1})

ρ: the density of water =1000kg\m^2

c: the velocity of sound in the medium =1500m\sec

A: area of cell (μm^2).

The solution of this equation, Z_{11} as a function of a normalized radius of the cell (kr). The acoustic impedance between two neighbor cells Z_{12} can be found from:

$$z_{12(kd)} = R_{12(kd)} + i.X_{12(kd)}$$

From the calculations of (kr) and (kd) for d=2r as a function of kd, we have kr<< 1 for frequency range (0.2-2)MHz and kr<<kd, so R_{12} and X_{12} may be approximated form two equations below:[24]

$$R_{12} = \rho c A \frac{(kr)^2}{2}\frac{\sin kd}{kd}$$

$$X_{12} = \rho c A \frac{(kr)^2}{2}\frac{coskd}{kd}$$

Neighbor coupling between CMUT elements at the CMUT water interface is a problem that many research groups have addressed. The fig (9) shows the real and imaginary parts of the kd-dependent curves where kd depending on frequency because all cells are identical in terms of their materiel properties and dimensions. Since, the mutual impedance Z_{ij} is only depended on kd, many elements of Z_{ij} have the same value between two neighbor cells for example the distance between cell 1 and 2 and between 3,4 are identical so, $Z_{12}=Z_{21}=Z_{34}=Z_{43}$.

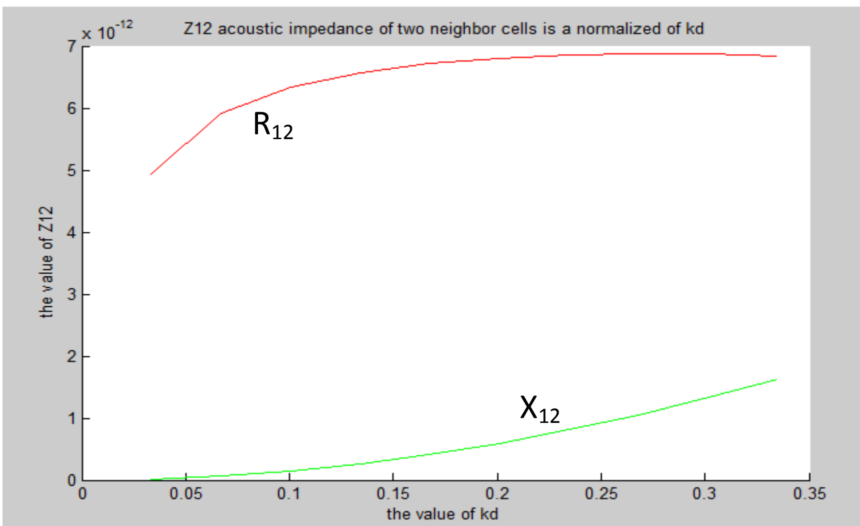


Fig .(9) mutual impedance normalize of kd (real and imaginary part)

In general case, we find Z_{ij}^{nm} is the mutual radiation impedance between the transducers having the velocity profiles $\upsilon_n(r)$ and $\upsilon_m(r)$; it can be written as a double infinite summation with μ and υ being the summation indices [29].

$$z_{ij}^{nm} = z_0 \frac{2^{n+m} n!\, m! \sqrt{2n+1}\sqrt{2m+1}}{\sqrt{2kd_{ij}}(kr)^{m+n}} \times \sum_{\mu=0}^{\infty}\sum_{\upsilon=0}^{\infty}\left\{\frac{\Gamma(\mu+\upsilon+0.5)}{\mu!\,\upsilon!}\left(\frac{r}{d_{ij}}\right)^{\mu+\upsilon} \times J_{\mu+n+1}(kr)J_{\upsilon+m+1}(kr) \times \left[J_{\mu+\upsilon+0.5}(kd_{ij}) + i(-1)^{\mu+\upsilon}J_{-\mu-\upsilon-0.5}(kd_{ij})\right]\right\}$$

Where d_{ij} is the distance between ith and jth transducers. This convinces us to obtain an accurate approximation ofthe following form:

$$\frac{Z_{12}}{Z_0} = A(kr)\,\frac{\sin(kd)+j\cos(kd)}{kd} \qquad \text{For kr >5.5}$$

where $A(kr)$ is found by curve fitting and it is a complex function as depicted in Fig. (10). To obtain the real and imaginary parts of $A(kr)$, tenth-order polynomials are
used, the coefficients of which are given in fig(9), When $ka \ll 1$ and $kr \ll kd$, $A(kr) = (5/9)(kr)2/2$ [25]. To calculate Zij must be replaced with the corresponding dij, the dependence of $Z12$ on $ka$and $kd$is now separated. For kr> 5.5, this approximation is not correct, because in the vicinity of kr= 2π the decay of $Z12$ is not simply proportional to kd. However, beyond this limit the values of $Z12$ are very small compared with the self radiation resistance and can be ignored.

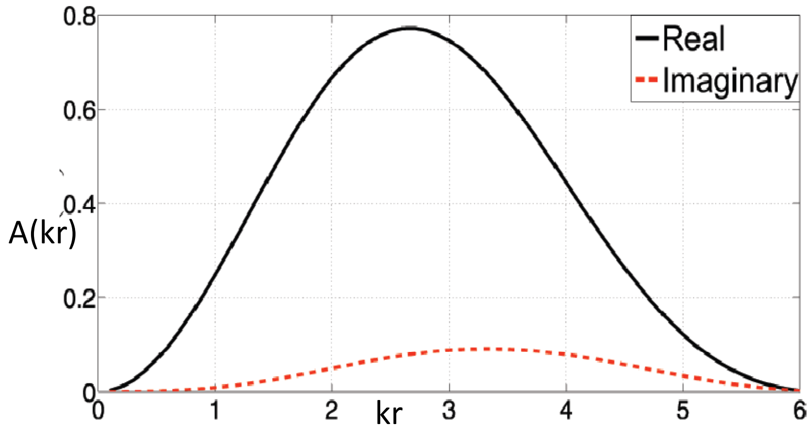


Fig.(10) . The real and imaginary parts of the *kr*-dependent term, *A*(*kr*), of the approximate mutual radiation impedance expression given in for *ka*< 5.5

From fig (11) we find a correct evaluation accuracy frequency range and normalized response(db) to show the Z_{ij}. model.

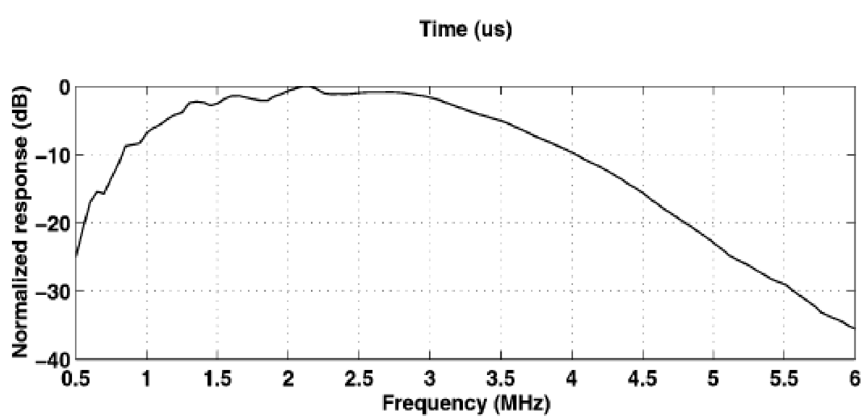


Fig (11) shows impulse and frequency range of cells in CMUT when change values of kr

```
Clc
%y=2*k*r;
%k=(2*pi*f)/c;
%Zo=pcA;        %p is density of water, A= r^2 * pi
% p=1000kg/m^3  , c=1500m/sec     ,r=10*10^(-6)m
%Z11/Zo=1-(192/(2kr^5) * f1(2kr) + i * f2(2kr),  f=2* 10^6
Zo= 4.7124*10^(-4);
f1y=(20-(.167)^2)*besselj(1,.167)-((7*0.167)*besselj(0,0.167))-(3*0.167);
f2y=(0.167^2-20)*besselh(1,2,.167)+(7*0.167*besselh(0,2,0.167))
Z11=Zo*(1-(192/(0.167^5))*f1y+i*f2y);
%Z11=  3.6417e+02 - 2.3888e+00i

clc ;
%y=2*k*r;
%kr=(2*pi*f)/c*r;
%kd=2*kr
%Zo=pcA;        %p is density of water, A= r^2 * pi
% p=1000kg/m^3  , c=1500m/sec     ,r=10*10^(-6)m
%R12=(p*c*A)*((kr)^2*sin(kd))/2*(kd);
%f= frequecy kilo hertiz
c=1500;
r=10*10^(-6);
p=1000;
A=r^2*pi;
Zo=p*c*A;
for f= 200:200:2000
kr(f)=(2*pi*f*r)/c;
kd=2*kr*(f);
   R12(f)=Zo*((kr(f))^2*sin(kd))/(2*(kd));
   X12(f)=Zo*((kr(f))^2*cos(kd))/(2*(kd));
   Z12(f)=(R12(f)+i*X12(f));

end
hold on;
plot(kd(200:200:2000),X12(200:200:2000),'r');
plot(kd(200:200:2000),R12(200:200:2000),'g');
xlabel ('the value of kd');
ylabel ('the value of Z12');
title 'Z12 acoustic impedance of two neighbor cells is a normalized of kd';
```

4. CONCLUSION

The points below summarize the conclusions:-

1- The effects of the mutual acoustic impedance interactions can be analyzed very rapidly with an high accuracy by using to Matlab.
2- We focusing on the general equations to find Z_{ij} to give maximum no of cell in arrays and depend on mode and shaping of the cell c/cs.

3- Cross coupling between elements is one of the most important factors affecting the performance of an array transducer also we find the solution to reduce crosstalk.
4- Z_{ij} for neighboring cells are depends on the dimensions of cell, the separation between the cells normalized with the wavelength in the immersion medium.

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