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Vibration Characteristics of MEMS Membrane

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***Abstract*—Micro-Electro-Mechanical Systems (MEMS) promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making possible the realization of complete systems-on-a-chip. The process of making these micron length mechanical parts poses a challenge to understand and control the physical systems behavior on these scales. In this work, the vibrations of a 'micro-membrane' have been simulated for obtaining the natural frequency of the membrane. The vibrations are governed by an equation which is the solution of the partial differential wave equation. The membrane is considered to be fixed on all four sides. Simulations for different dimensions of the membrane are carried out and various plots are presented. Results for three different materials have been presented in this report.**

I. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) is an enabling technology allowing the development of smart products, augmenting the computational ability of microelectronics with the perception and control capabilities of micro-sensors and micro-actuators and expanding the space of possible designs and applications. It deals with the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micro-machining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

Currently, there has been a boost in work being carried out in the RF-MEMS field. The versatility of applications that MEMS can provide is certainly driving considerable research into this domain. Modeling of a piezo-electrically actuated planar capacitor actuator membrane was considered in [1], which discusses the results from modeling a planar capacitor piezo-electrically actuated membrane for a MEMS micro-fluidic device. Analytical models, which included linear, elastic, homogenous and isotropic single material and multi-material membranes, were developed to describe the general deflection behavior of a clamped circular plate. The level of deflection obtained in this work ranged from 71 to 150 nm based on the thickness of the piezoelectric layer in the membrane.

An analytical model of fixed-fixed beam RF MEMS Resonator [2] whose basic principle depends on conversion of electrical energy into a form of mechanical energy such as vibration of the beam was designed and simulation results were presented. The above work uses simplified analysis, making use of several assumptions. External damping of vibrations by air resistance, effects of external gravity and magnetic forces are accounted for. The fixed-fixed, or clamped-clamped, beam [9] is stiffer than the cantilever due to anchors at both ends and becomes a candidate for resonator structure to obtain higher resonant frequency without making features too small to be fabricated. Another study [3] in the same direction presents the analytical model for determining the shift in designed resonant frequency of the cantilever beam due to its curling during fabrication. The results of this work give the voltage the beam will have to be tuned to get the resonant frequency back to its designed value.

The modeling of a thin homogeneous wafer for obtaining the natural frequencies of vibrations is carried out in this work. The analysis has been carried out for 3 different materials. Different dimensions of length and breadth of the membrane are considered along with changing thickness of the membrane. The frequency curves plotted indicate the strong influence of mass on the natural frequencies at very small dimensions. The data generated from these observations can be used for synthesis of MEMS membranes. The approach used is based on the closed loop solution obtained by solving a partial differential equation.

II. GOVERNING EQUATIONS

Consider an element ABCD of the membrane, the projection of which on the XOY plane is the rectangle PQRS, as shown in Fig 3.The vertical components of force acting on the membrane are responsible for the transverse motion of the membrane. the equation of the motion of the membrane element under consideration, using Newton's second law of motion can be written as,

$$\frac{\partial^2 y}{\partial t^2} = c^2\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right), c^2 = T/\rho \qquad (1)$$

The general solution of this equation can be written as [8]

$$u(x,y,t) = (C_1 \cos(kx) + C_2 \sin(kx))(C_3 \cos(ly) + C_4 \sin(ly))$$
$$\ldots(C_5 \cos(\sqrt{(k^2+l^2)}ct) + C_6 \sin(\sqrt{(k^2+l^2)}ct)) \qquad (2)$$

III. BOUNDARY CONDITIONS

We assume a rectangular membrane fixed along its boundary: $0 \le x \le a$, $0 \le x \le b$, where a is length and b is the breadth of the membrane. The membrane is assumed to be initially in some random position given by $f(x,y) = xy(a-x)(b-y)$ and is set vibrating in that position with initial velocity zero.

The following boundary deduced from the above specifications:

$u(0,y,t) = 0$ where $0 \le y \le b, t \ge 0$ (3a)

$u(a,y,t) = 0$ where $0 \le y \le b, t \ge 0$ (3b)

$u(x,0,t) = 0$ where $0 \le x \le a, t \ge 0$ (3b)

$u(x,b,t) = 0$ where $0 \le x \le a, t \ge 0$ (3c)

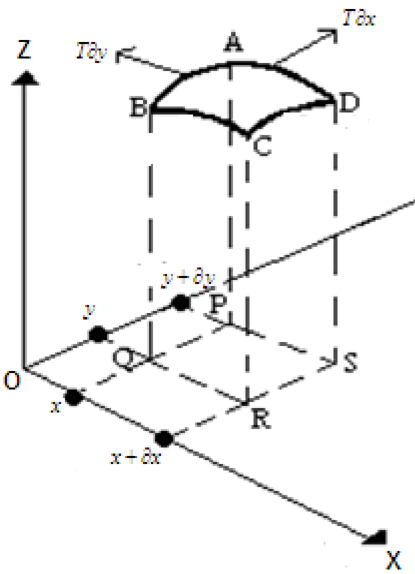

Figure 1. Elemental area of membrane

The initial conditions:

$u(x,y,t) = f(x,y) = xy(a-x)(b-y) \qquad 0 \le x \le a, 0 \le y \le b$ (3e)

$(\partial u/\partial x)_{t=0} = 0$, $0 \le x \le a, 0 \le y \le b$ (3f)

The analytical solution considering the boundary and the initial conditions is given by

$$u(x,y,t) = \frac{64a^2b^2}{\pi^6} \sum_{\substack{m=1 \\ m,n\ odd}}^{\infty} \sum_{n=1}^{\infty} \frac{1}{m^3 n^3} \sin(m\pi x/a)$$
$$\ldots\sin(n\pi y/b)\cos(p_{mn}t)$$

where $p_{mn} = \pi c\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$

$0 \le x \le a, 0 \le y \le b, t \ge 0$ (4)

IV. RESULTS AND DISCUSSION

The analysis to find the natural modes of vibration was carried out for three different elements commonly used in the VLSI industry; namely; Silicon Nitride, Gallium Arsenide and Silicon. The values of density of these elements are:

- Silicon Nitride: $2.8e^{-12}$gms/um^3
- Gallium Arsenide: $5.3174e^{-12}$gms/um^3
- Silicon: $2.328e^{-12}$gms/um^3

The behavior of a membrane with the density of silicon nitride $(2.8 gms/\mu m^3)$ was simulated for $5\mu m \times 7\mu m$ membrane for $8\mu s$.

In the above mentioned time, 16 time instants were observed starting at time 0 corresponding to t_1 and ending at time $8\mu s$ corresponding to t_{16}. 12 of the observed patterns are presented in Fig 4 with the relevant time slots. Fig 5 presents the frequency of vibration for each of the three elements for different dimensions of the membrane. All the dimensions of the membrane are in μs scale. The mass of the membrane significantly influences the frequency of vibration. It is observed that reducing the thickness of the membrane from $0.1\mu s$ to $0.01\mu s$ causes the frequency of vibrations to increase approximately by 3 fold under the given assumptions and approximations. It is also observed that the frequency of vibration is largest for the smallest dimension and has a relatively sharp fall for a comparatively marginal ($1\mu s$) increase in dimension. When the membrane dimensions approach approximately $20\mu s$, the frequency of vibration almost remains constant for any higher dimensions of the membrane.

V. CONCLUSION

The solution of the partial differential equation governing the vibrations of a membrane has been simulated using MATLAB. The plots of frequencies of vibration for different dimensions of the membrane were presented. Three elements, namely, Silicon Nitride, Gallium Arsenide and Silicon were compared for their frequency responses. Several graphs showing the effect on the natural frequency of vibrations by changing area/thickness/density (material) of the membrane are presented pertaining to each of the above mentioned elements.

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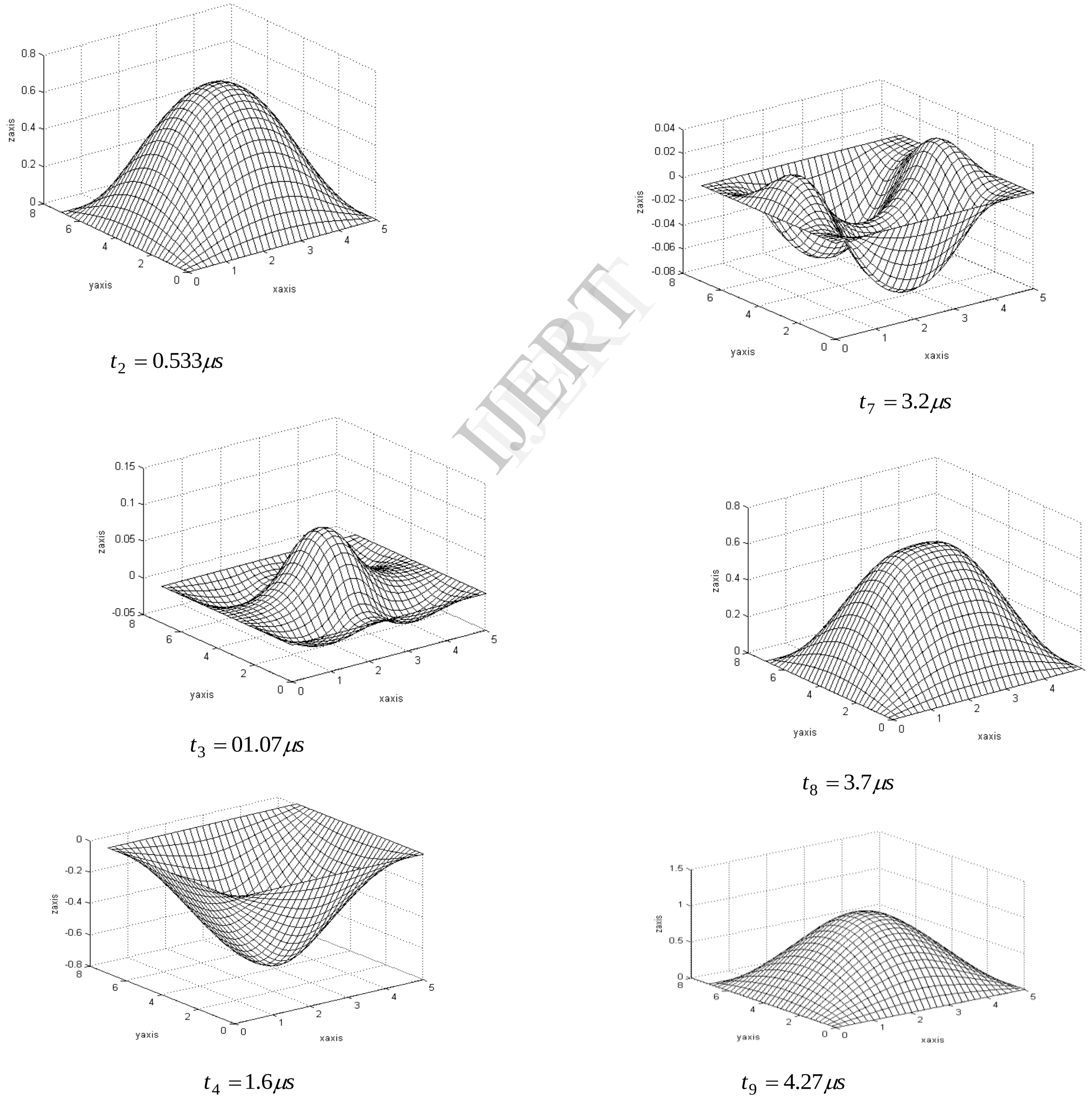


$t_2 = 0.533\mu s$

$t_3 = 01.07\mu s$

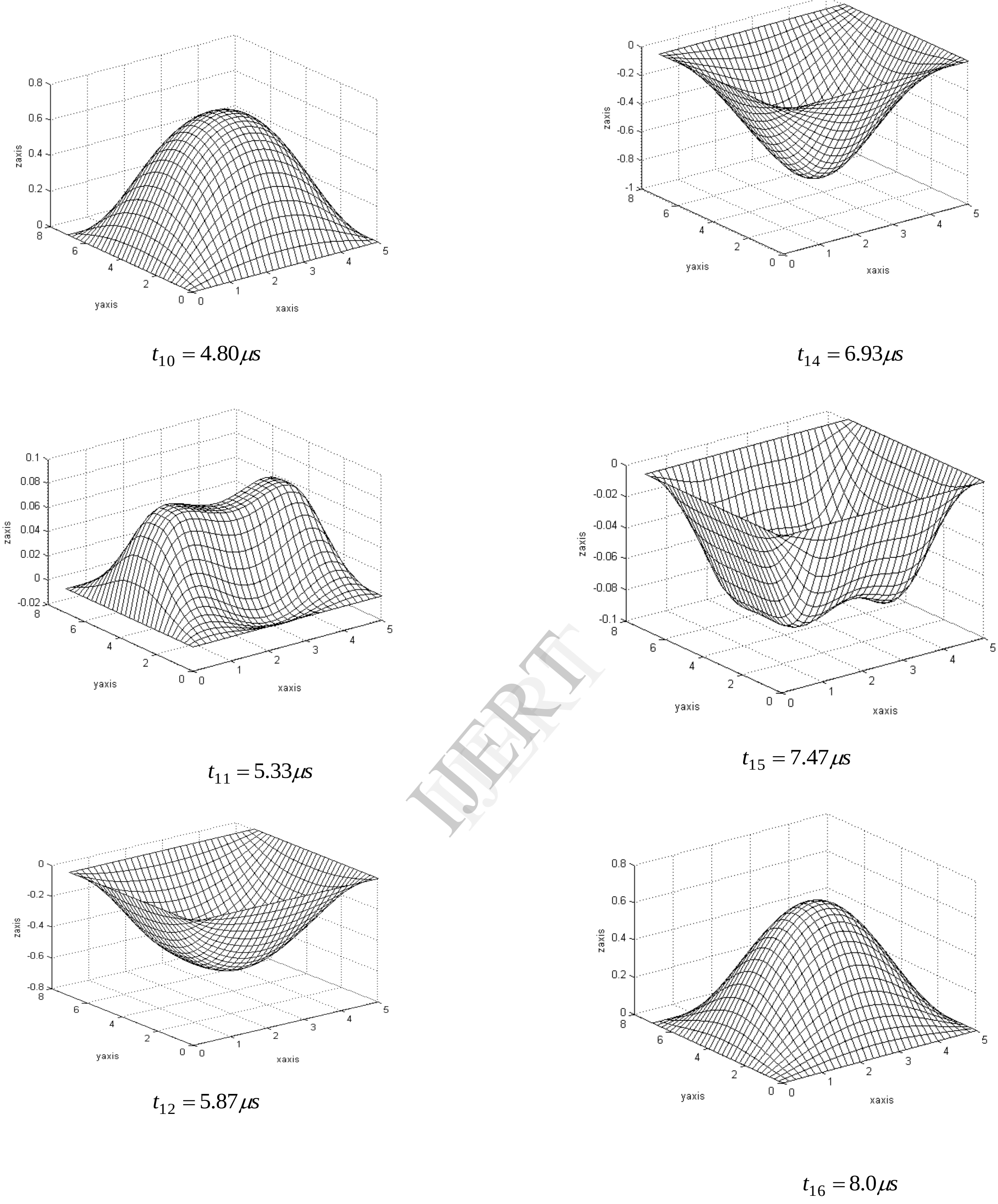
$t_4 = 1.6\mu s$

$t_7 = 3.2\mu s$

$t_8 = 3.7\mu s$

$t_9 = 4.27\mu s$

Figure 2. Snapshots of patterns observed during vibration



$t_{10} = 4.80\mu s$

$t_{11} = 5.33\mu s$

$t_{12} = 5.87\mu s$

$t_{14} = 6.93\mu s$

$t_{15} = 7.47\mu s$

$t_{16} = 8.0\mu s$

Figure 2 (continued). Snapshots of patterns observed during vibration

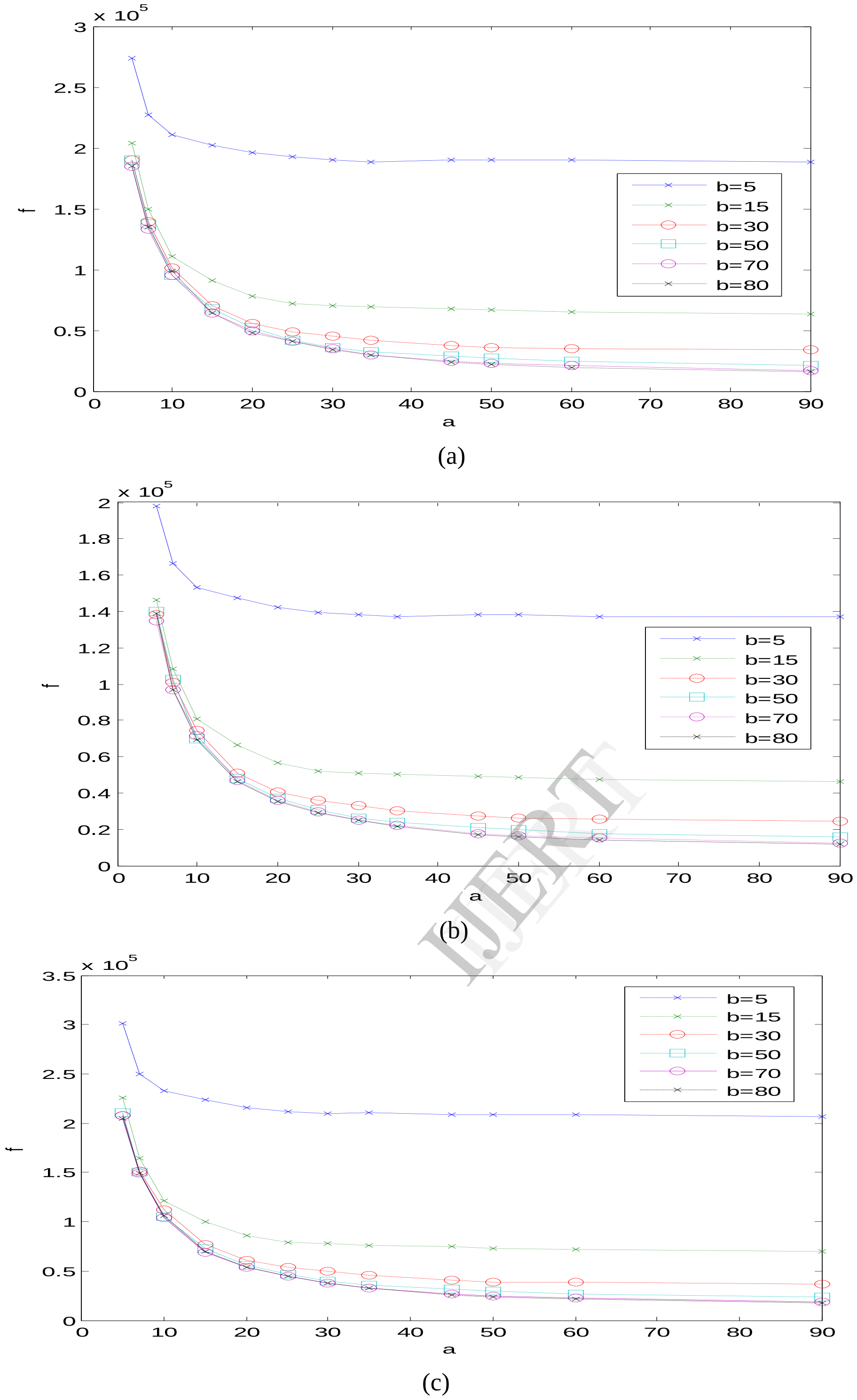
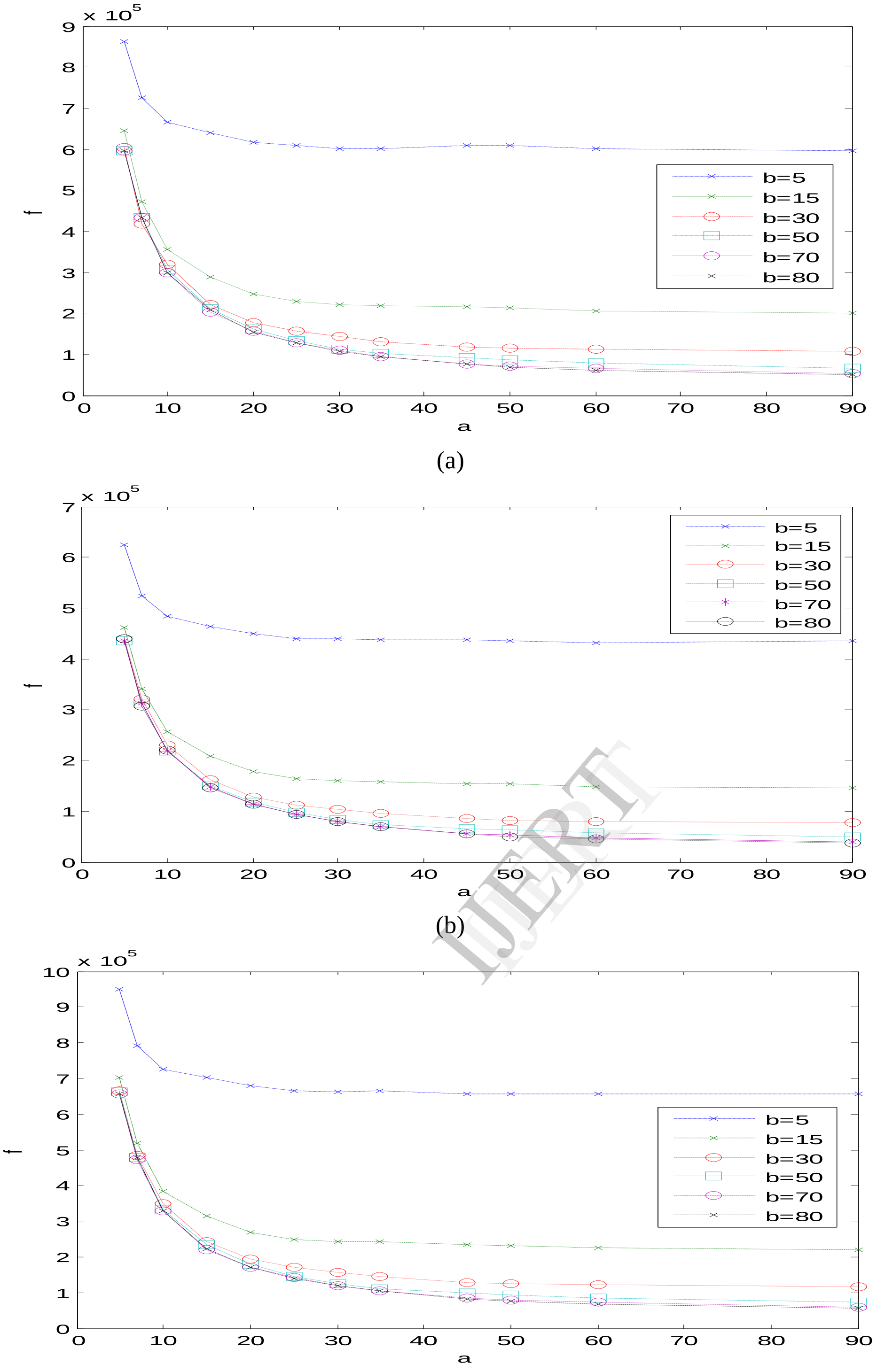


Figure 3. The frequency of vibration for thickness of the membrane 0.1 micrometers for (a) Silicon Nitride (b) Gallium Arsenide (c) Silicon



(a)

(b)

(c)

Figure 4. The frequency of vibration for thickness of the membrane 0.01 micrometers for (a) Silicon Nitride (b) Gallium Arsenide (c) Silicon.