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Feasibility Study of GaN-based MEMS capacitive microphone using Finite Element Method

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ABSTRACT

Gallium nitride (GaN) is an excellent choice of semiconductor material due to its optoelectronic, mechanical and wide bandgap properties which are highly demanded by high-power and radio-frequency (RF) electronics but also widely employed for the fabrication of Light Emitting Diode (LED). In this paper, we explored the advantage of GaN as an electromechanical material to be used in microelectromechanical systems (MEMS) microphone as a thin film membrane through a theoretical study performed using the finite element method. We consider also the anisotropy and symmetry structural of GaN to be employed as microphone membrane. In addition, we compared also its performance in terms of sensitivity, C-V measurement and pull-in voltage with several conventional membrane materials such as silicon, nickel, and silicon nitride. The result shows that GaN-based MEMS capacitive microphone has sensitivity -57 dBV/Pa which is 4% higher than silicon nitride-based microphone and resonance frequency of 19 kHz which is higher 11.3% than nickel-based microphone. Hence, this theoretical study could pave a way for GaN to be developed especially for MEMS microphone applications and boasted also by the recent advancement of GaN related fabrication. The advantages of GaN compared to other conventional semiconductor material could be useful for the development of ultrasonic MEMS microphone for utilize detection of sound beyond audible frequency range.

Keywords: Gallium nitride; MEMS capacitive microphone; sensitivity; ultrasonic

ABSTRAK

Gallium nitrida ialah sebuah pilihan cemerlang untuk bahan semikonduktor disebabkan sifat optoelektronik, mekanikal, sifat jurang jalur yang lebar sehingga sangat diperlukan bagi elektronik frekuensi radio (RF) tetapi juga digunakan secara meluas untuk fabrikasi diod pancaran cahaya (LED). Dalam kajian ini, kami meneroka kelebihan GaN sebagai bahan elektromekanikal yang digunakan pada sistem mikrofon kapasitif mikroelektromekanikal (MEMS) iaitu sebagai membran filem nipis dengan cara sebuah kajian keteorian menggunakan kaedah unsur terhingga. Kami juga memilih GaN dengan struktur anisotropi dan simetri untuk diletakkan sebagai membran mikrofon. Seterusnya, kami membandingkan prestasi-prestasi MEMS mikrofon berdasar-GaN seperti kepekaan, pengukuran C-V, voltan tarik-dalam dengan beberapa bahan membran konvensional lainnya seperti silikon, nikel, dan silikon nitrida. Akhirnya, hasil kajian menunjukkan bahawa mikrofon kapasitif MEMS berdasar-GaN mempunyai kepekaan sebesar -57 dBV/Pa iaitu 4% lebih tinggi daripada mikrofon berdasar-silicon nitrida, dan resonans frekuensi 19 kHz iaitu 11.3% lebih tinggi daripada mikrofon berdasar-nikel. Oleh itu, pada kajian keteorian diharapkan dapat membuka sebuah jalan untuk GaN agar dikembangkan terutama untuk penerapan mikrofon MEMS serta didukung oleh perkembangan terbaharu daripada fabrikasi berkait GaN. Dengan ini diharapkan, kelebihan daripada bahan GaN ini apabila dibandingkan dengan bahan semikonduktor konvensional lainnya dapat digunakan untuk pengembangan mikrofon MEMS ultrasonik iaitu untuk mengesan suara di atas julat frekuensi boleh dengar.

Kata kunci: Gallium nitrida; mikrofon kapasitif MEMS; kepekaan; ultrasonik

INTRODUCTION

Gallium nitride (GaN) is second cheapest semiconductor material after silicon that has been widely employed in optoelectronic, radio-frequency (RF) electronics and light emitting diode (LED) (Hanser and Evans, 2010). It shows good performance due to its excellent properties, such as wide band gap, high electron mobility, high Young modulus as compared to the conventional semiconductor material. Despite of remarkable achievement of GaN for those applications, a small numbers of research has been conducted to apply GaN in MEMS applications (Rais-Zadeh et al. 2014). It offers a few advantages as an electromechanical material such as high elasticity, piezoelectricity and stability towards chemical and thermal perturbation as compared with other common MEMS materials. In the literature, GaN has been applied in the surface acoustic wave (SAW) platform due to its high electromechanical coupling (Muller et al. 2010; Wong et al. 2007) with the possibility to increase its resonance frequency by using a layered structure in order to excite Sezawa mode. Furthermore, the fabrication of suspended microstructure using GaN such as cantilever (Stonas et al. 2001) and resonator (Ansari and Rais-Zadeh, 2014) has also been demonstrated driven by the recent progress of high quality GaN growth process in particular on the low cost substrate such as Silicon. Since GaN has excellent thermochemical stability, it is quite difficult to perform etching process especially using CMOS fabrication process. Therefore, the advantage to conduct growth of GaN on Si could facilitate the fabrication of the suspended microstructure in term of release and removal of sacrificial layer. Besides, the maturity of Si etching process either isotropic or anisotropic through wet or dry etching could enhance the success of the fabrication process by ensuring the selective removal of the substrate below the GaN layer.

Nowadays, amongst the commercialized MEMS device, MEMS capacitive microphone has been produced in the industrial quantity by several companies like Infineon and ST to be integrated in various electronic device such as mobile phone (Peña-García et al. 2018), computer, artificial ears (Latif et al. 2010), hearing aid (Woo et al. 2017) and handheld device (Dehé et al. 2013). Basically, microphone is a sensor that converts acoustic pressure into electrical signal by using membrane. Capacitive microphone has an advantage of higher sensitivity and lower noise compared to another detection-type of microphone such as piezoelectric, electrostatic, and transistor microphone (Scheeper et al. 1994). MEMS capacitive microphone is equipped by two parallel electrodes that form a capacitive value. First electrode sticks to elastic membrane, while the second electrode sticks to rigid backplate. Theoretically, membrane vibrates as sound hit the surface and spontaneously changes the capacitance value as membrane move toward the fixed backplate. Since performance of MEMS capacitive microphone highly depends on the properties of membrane, the geometrical parameter and its material properties should be design with optimum consideration (Woo et al. 2017). Furthermore, a few approaches have also been considered related to the geometrical shape of the membrane in order to reduce membrane tension such as making spring-supported membrane and corrugated membrane (Mohamad et al. 2010; Soin and Majlis, 2006). Even though the adjustment of certain dimension such as widening the diameter of membrane and electrode or narrowing the airgap could certainly increase its mechanical sensitivity, it is unfortunately insufficient in the case of MEMS microphone since many limitations in terms of device miniaturization process with a final product in range of a few millimeters. However, by fixing the dimension of the design, the performance of microphone could also be tuned via modification of its material properties especially Young modulus and density of membrane.

Currently, most of the MEMS microphones were fabricated using CMOS process with a Silicon-based membrane. Several materials such as PMMA (Woo et al. 2017) and graphene (Todorović et al. 2015) have also been proposed to act as the membrane in the microphone. An excellent membrane material should has high modulus young and low density in order to extend frequency range beyond human audible range 20 kHz and achieve ultrasonic frequency regime. However, high modulus young of material could also decrease microphone sensitivity due to difficulty to produce a large displacement triggered by the input sound. In the literature, Dehe et al. has successfully fabricated polysilicon-based membrane with sensitivity -38 dB up to 22 kHz of frequency (Dehé et al. 2013). Meanwhile, Scheeper et al. developed silicon nitride-based membrane with a sensitivity of -33 dB and a frequency response to 20 kHz (Scheeper et al. 2003). Ganji et al proposed a perforated aluminum diaphragm with dimension of 500 µm x 500 µm x 3 µm (Ganji and Majlis 2009a, b). The performance of this aluminum membrane can stand up to 20 kHz of bandwidth with a bias voltage of 105 V. For mass production of miniaturized microphone, B&K employed a nickel based membrane in their product such as 4134 (Brüel 1996). Also, polymeric membrane have also been used such as polyimide (Pederson, Olthuis, and Bergveld, 1998) which could only yields low resonance frequency 1 kHz due to low Young modulus. Nevertheless, it has not been reported the usage of GaN as membrane for capacitive microphone despite its excellent electromechanical properties.

In this paper, we study theoretically the feasibility of GaN-based membrane as MEMS capacitive microphone by comparing its performance with other conventional material. We use theoretical approach by using finite element method to get an overview on the performance of GaN based membrane MEMS microphone prior to the prototype fabrication and experimental measurement.

SIMULATION MODEL

We used a simulation model based on the principle of condenser microphone using COMSOL Multiphysics software enabling the coupling of several physics interface including thermoviscous acoustics, electrostatic and structural mechanic. These complex physics could have a full understanding of its physical working principles and should evaluate the effect of each parameter towards the global performance of a microphone. Based from previous studies employing these combined physics to simulate the properties of a real microphone, the obtained results showed a good agreement with the experimental data (Peña-García et al. 2018, Woo et al. 2017; Herring Jensen and Olsen, 2013).

A schematic description along with the geometrical parameter is given in Figure 1 and Table 1. In this 3D model, a circular membrane with diameter, *a* and thickness, *b* is clamped at the edge, while the center of membrane is freely vibrating. At the bottom, we include also six holes with diameter 60 um and four small vents for pressure equalization. The working principle of the condenser microphone can be described by the transformation of the mechanical movement of the membrane, which generated by the external acoustic pressure, p_{in}, into electric signal, V_{out}. We applied also a fixed charge at the backplate, generating an electrostatic attraction that will vary the airgap,$\boldsymbol{c}$ along with the bias voltage, V_b=39 V. Hence, the sensitivity level can be defined as the relation between the input pressure and the output voltage:

$$Sensitivity\ (dB\ rel. 1\ V/Pa) = 20 \text{ x} \left[log_{10} \frac{V_{out}}{p_{in}}\right] \qquad (1)$$

The material of the membrane consist of Silicon (Si) with Young modulus, E = 160 GPa, density, ρ = 2,320 kg/m^{3}and Poisson ratio, η = 0.22, Nickel (Ni) with Young modulus, E = 219 GPa, density, ρ = 8900 kg/m^{3}and Poisson ratio, η = 0.31, and Silicon Nitride (Si_3N_4) with Young modulus, E = 250 GPa, density, ρ = 3,100 kg/m^3 and Poisson ratio, η = 0.23. We considered the anisotropy and the symmetry properties of GaN membrane by using elastic constant c_{11} = 285 GPa, c_{12} = 149 GPa, and c_{44} = 157.7 GPa, while its density, ρ = 6,150 kg/m^3 (Moss et al. 2009, Riobóo et al. 2016)

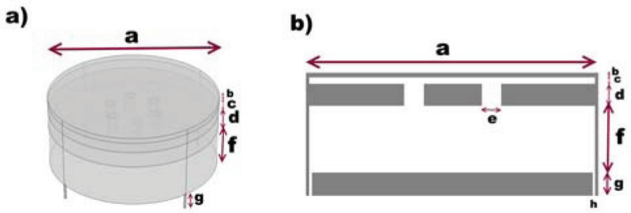

FIGURE 1. Design of MEMS capacitive microphone design with six holes, backchamber and four vents in a) three-dimension configuration and b) its cross-section

TABLE 1. Geometry of MEMS microphone used in simulation

Indicator	Geometry of microphone	Length (μm)
a	Diameter of microphone	2,000
b	Thickness of membrane	7
c	Air gap	18
d	Thickness of backplate	190
e	Diameter of hole	60
f	Height of backchamber	500
g	Height of vent	190
h	Width of vent	60

RESULTS AND DISCUSSION

Figure 2 displays normalized displacement of the membrane using various materials: GaN, Si, Ni, and Si_3N_4 for applied frequency of 10 kHz. The figure shows the center region of the membrane gets the highest displacement due to lowest amount of stress with almost a similar displacement field between them corresponding to monomode resonance of a circular membrane. The frequency of 10 kHz is chosen since it is the upper limit of operating frequency as shown in figure 3 before the peak of resonance frequency. The gradients of displacement indicate Si yields the highest deflection indicated by the highest concentration of displacement in the middle of membrane indicated by red color area, while on the contrary Si_3N_4 gets the smallest deflection depending mainly by the highest value of Young modulus. In the case of GaN, the displacement field did not show any significant difference except its gradient caused by anisotropy characteristic of Young modulus.

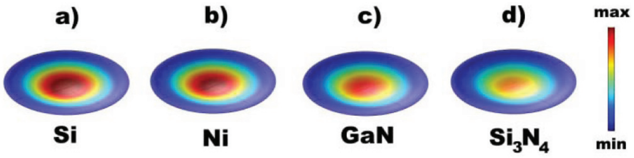

FIGURE 2. The normalized displacement of membrane in harmonic perturbation of material GaN, Si, Ni, and Si_3N_4 with applied frequency of 10 kHz.

Based from the simulation model described in Figure 1, we calculate the sensitivity curve versus frequency from 100 – 100 kHz for various material of the membrane as shown in Figure 3. The peak for all curves indicates the first resonance frequency of the membrane around 20 kHz, which means that the proposed microphone could operate perfectly in the audible range. In term of sensitivity, our proposed GaN membrane demonstrated a similar sensitivity as compared to Ni around -57 dBV/Pa and surpasses Si_3N_4 membrane sensitivity, which is 4% higher. Next, the resonance frequency for GaN membrane is around 19 kHz, which is 11.3% higher than Ni membrane. A slight increase of a few dB can be observed for Si membrane above other materials. In order to improve the sensitivity and the resonant characteristics of the membrane, the material properties of the membrane like Young modulus and density could play a determinant role along with the geometrical parameter of microphone. In the case of GaN, previous studies related to its mechanical properties were mainly influenced by the growth condition and the substrate enabling to tune the performance of the microphone. For example, the elastic constant of GaN could be dramatically increased with the highest reported 390 GPa (Rais-Zadeh et al. 2014) which could improve the operating frequency range towards ultrasonic regime.

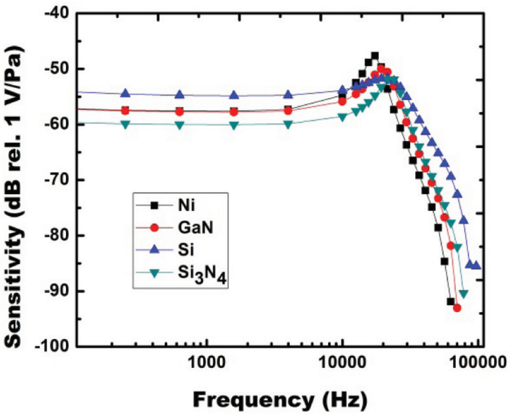

FIGURE 3. Sensitivity curve of MEMS microphone using GaN, Si, Ni, and Si_3N_4

In Figure 4, we calculated the capacitance against bias voltage for all materials of the membrane. A similar trend with Figure 3 was obtained where Si shows the most sensitive curve compared to others with the highest capacitance value along bias voltage 0-200 V. In terms of capacitance gradient to bias voltage, Si gets the highest gradient which is 0.026 pF/V, while another membrane material displayed a gradient around 0.017 pF/V. In order to further improve the capacitance characteristics of microphone, a decrease of air-gap could be proposed with a compromise related to the viscous damping which could affect its frequency response. Moreover, a higher membrane radius could also increase the capacitance but the latest trend and design would require for a smaller size for many consumer applications. Hence, a proper optimization on air-gap length should be a key to microphone performance.

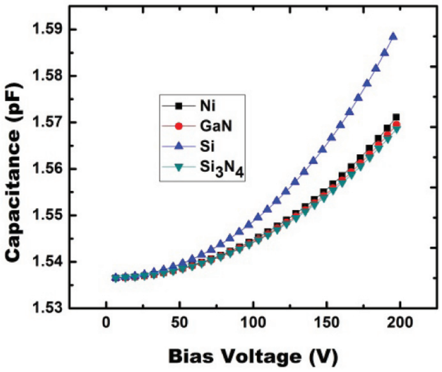

FIGURE 4. Simulated Capacitance against voltage for materials GaN, Si, Ni, and Si_3N_4

In the case of MEMS capacitive microphone, bias-voltage induces attractive force between the membrane and backplate and with higher bias-voltage will improve electrical sensitivity of microphone. However, the presence of pull-in voltage threshold will limit the highest bias voltage that could be applied as the membrane will touch the backplate when bias voltage exceeds pull-in voltage. Again, in order to accommodate high pull-in voltage of microphone, the airgap between two electrodes should be increased but simultaneously induce the reduction of capacitance of microphone. Therefore, an alternative optimization of pull-in voltage should concern on mechanical and geometrical properties of membrane. Improved design and geometrical of the membrane will support its spring restoring force as well as the present of holes in the backplate to reduce air damping. In order to show bias voltage limitation, we plotted in Figure 5 the effect of bias voltage to membrane displacement in z-direction for GaN, Si, Ni, and Si_3N_4 materials by using the design in Figure 1. It shows that all materials can stand up until voltage 400 V which is sufficient for MEMS capacitive microphone requirement. From the graph, GaN produces a pull-in voltage 524 V which is 21.6% higher than pull-in voltage of Si enabling GaN to operate in higher bias voltage and facilitate its integration for high power electronics device. Moreover, Ni and Si_3N_4 membrane material has the value of pull-in voltage almost similar with GaN. From the graph, membrane displacement when the pull-in voltage occurred is around 2/3 of airgap, which agrees with the theory (Senturia 2007).

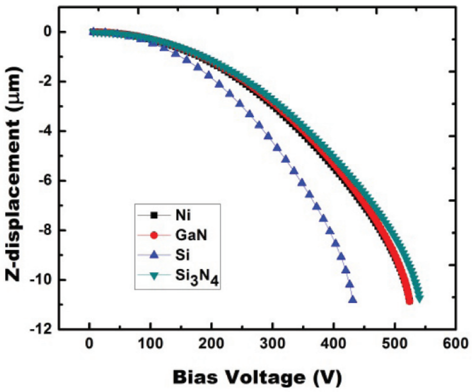

FIGURE 5. Z-displacement against voltage for materials GaN, Si, Ni, and Si_3N_4

CONCLUSION

In this paper, we studied the performance of GaN-based membrane in MEMS capacitive microphone using Finite Element Method. GaN-based membrane demonstrated a promising performance compared to conventional materials in terms of its sensitivity, capacitance and pull-in voltage. The sensitivity of GaN microphone is 4% higher than Si_3N_4 microphone and resonance frequency of GaN microphone is 11.3% higher than Ni microphone, while pull-in voltage of GaN membrane is 21.6% higher than Si membrane. Furthermore, the advantage of GaN related to the microfabrication and high quality epitaxial growth technique could be further explored for the development of GaN-based microphone especially for the detection of ultrasonic sound frequency.

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