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Performance Comparison between Sapphire and SiC as Substrate for GaN 2D Photonic Crystal

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ABSTRACT

In this work, we present a structure design L3 cavities of 2D photonic crystal on a triangular photonic crystal lattice on Gallium Nitride (GaN) with two different substrate sapphire and SiC. The designed was simulated with LUMERICAL finite different time domain (FDTD). The resonant wavelength and quality factor (Q-factor) of design PhC structure were studied. The forbidden region or stop band observed are between 420 to 520 nm. The performance of the Q-factor has been enhanced with sapphire and SiC substrate, where the highest Q-factor that obtained are 22 500 and 28 400 respectively.

Keywords: Photonic Crystal, GaN, Sapphire, Silicon Carbide, Q-Factor.

1. INTRODUCTION

Photonic crystals (PhCs) [1] are dielectric interruption on nanoscale which used to control the mode of light scattered in the medium. They are artificial materials consisting of periodic arrangement in which the dielectric constant (refractive index) periodically exists in one, two and three dimensions and provide propagating light in the direction and scale of a particular wave [2]. Due to its advantages, photonic crystals have been the preferred material for optical devices. PhCs can be fabricated using several types of organic and inorganic materials. Nitride semiconductors have also been considered as suitable materials for short wavelength and UV nano photonics due to their wide bandgap and higher operating temperature [3,4]. Recently, GaN PhC has gain a lot of attention as they have great potential for the development of optical devices. Additionally, GaN devices emit at visible wavelength thus making it an ideal competitor for nano fluorescents and micro-opto-electro mechanical systems. The PhC structure can be optimized and designed by varying the diameter and position of the holes to get high Q value [5]. Nanocavities with high quality factor (Q) and awfully small mode volume (V) have been successfully with the confinement and localization of light in a PhC nanocavities [6-9]. In two dimension (2D) PhCs, there are two types of structural lattice that work to modify the flow of light in different ways. 2D PhCs has a good ability to integrate [10] with other materials and devices. Lattice geometry of 2D PhCs include square [11] and triangles (for hexagons) [8] structure. PhC has also been used in the field of biomedical optical sensors has been reported because of its features such as flexibility, small size, remote capability and passive electrical power that will be used for moisture, pH sensors, molecules and DNA [12-16]. A large amount of attention, laser diodes fabricated using GaN-based structures grown on sapphire and silicon carbide (SiC) substrates cover nearly the entire visible spectrum. SiC also attracted much attention because they are considered to be promising candidate for electronic devices [17]. However, sapphire substrate a good crystalline quality and excellent high temperature stability [18]. The lattice mismatch for sapphire is 14% with the epitaxial nitride layer.

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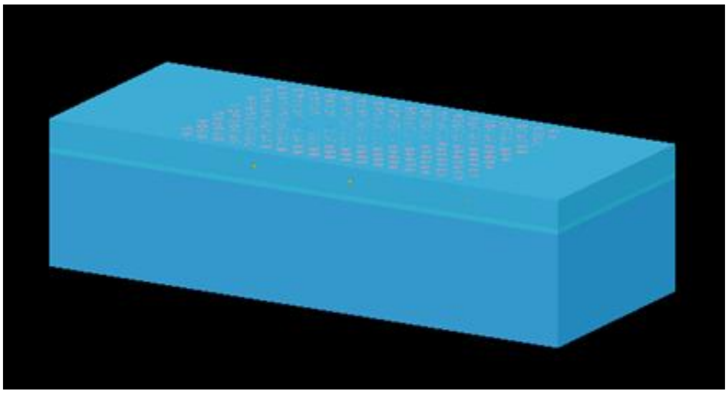
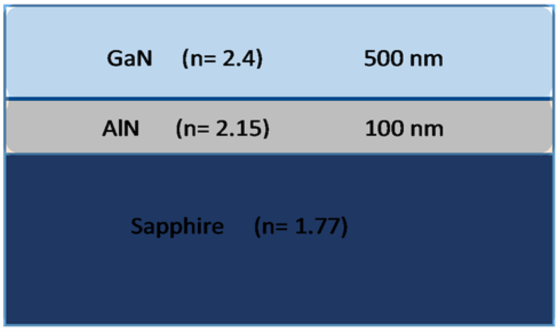
2. MATERIAL AND METHODS

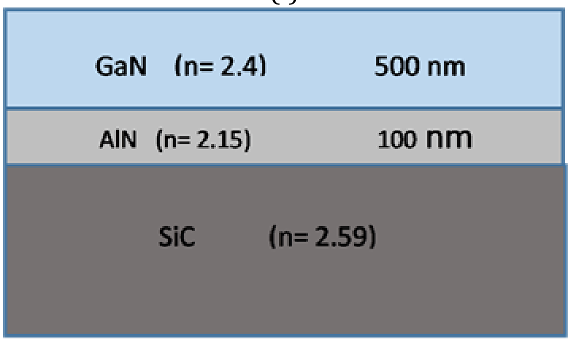
The 2D PhC was designed and with width at 2 μm, length, L, 5μm on GaN (500 nm thickness). The design consists of two types of L3 cavities, sapphire and SiC substrate as shown in figure 1 (b). There are three layer GaN (refractive index of 2.5), AlN as buffer layer (refractive index of 2.15), sapphire and SiC substrate with refractive index 1.7 and 2.59 respectively [19]. The lattice constant, a, is 157 nm and the diameter of hole is 106 nm while shift the hole position at 152 nm for design figure 2. The Finite Difference Time Domain (FDTD) is a common technique used as it provides the structural and physical properties of the structure. The design structures were simulated using 2D of FDTD where it provides the structural and physical properties of the structure as a common technique.



(a)



(i)



(ii)

Figure 1. (a) Layer structure simulated in 2D FDTD for sapphire or SiC (b) Side view (i) GaN-sapphire (ii) GaN-SiC.

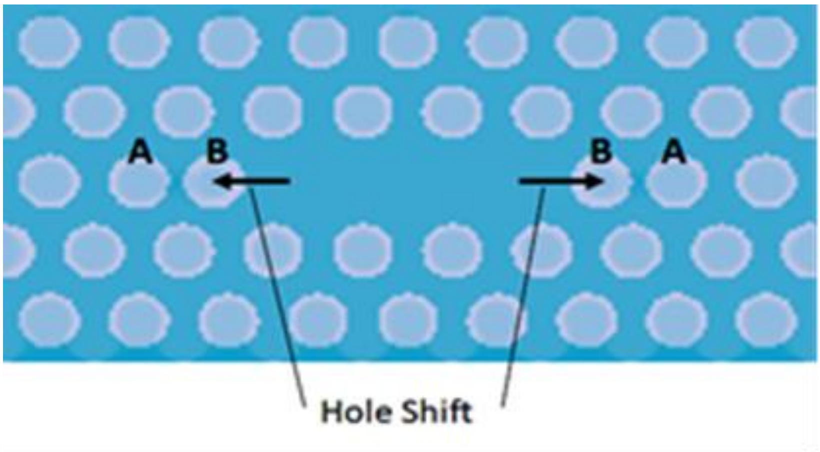


Figure 2. Schematic of the designed cavity structure by turning the positions of two holes near both edges to obtain higher Q factor for both sapphire and SiC substrate.

Figure 2 show the design cavity structure where the turning position two hole near the both edge. The actual lattice constant is 157 nm then we shifted the hole with distance of lattice for B to A is 152 nm. In previous study [19], the transmission is very low and higher Q factor without turning the hole. However, when the hole were shift the result of transmission increased and the Q factor decreased but still high Q factor.

3. RESULTS AND DISCUSSION

Figure 3 shows the stop-band PBG is the forbidden region at blue to green region where wavelength between 400 to 520 nm. We observed three sharp resonance peak in the middle of stop-band with the removal of three holes (L3) with turning position of holes between layered sapphire and SiC substrate.

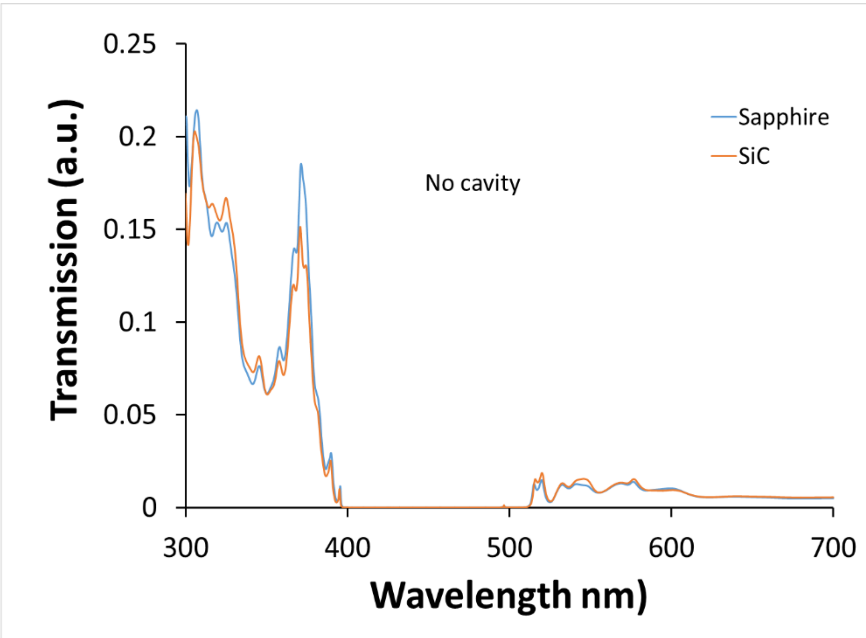


Figure 3. 2D FDTD simulation result 2D FDTD for stop-band without of cavities for GaN-sapphire and GaN-SiC.

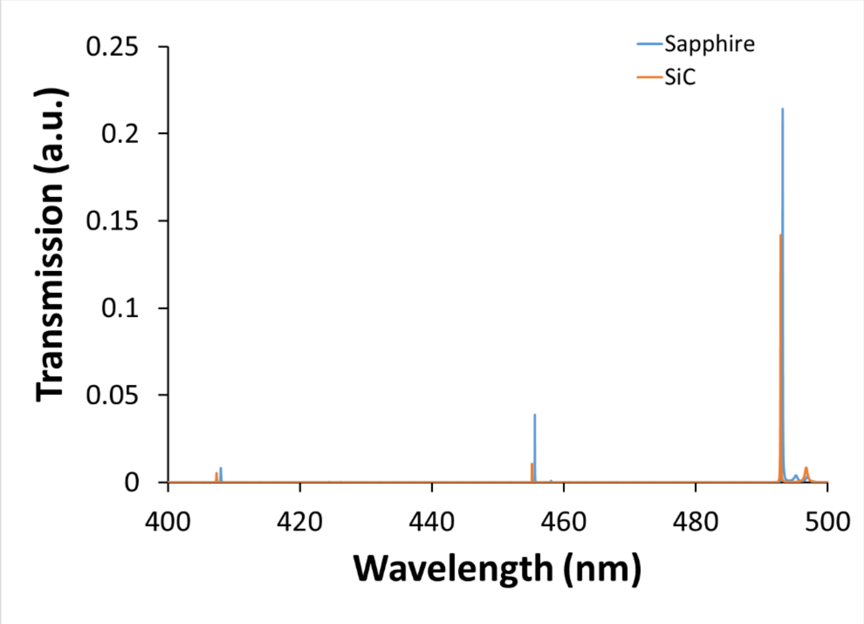


Figure 4. Transmission to resonance peak intensity for shifted hole between GaN-sapphire and GaN-SiC.

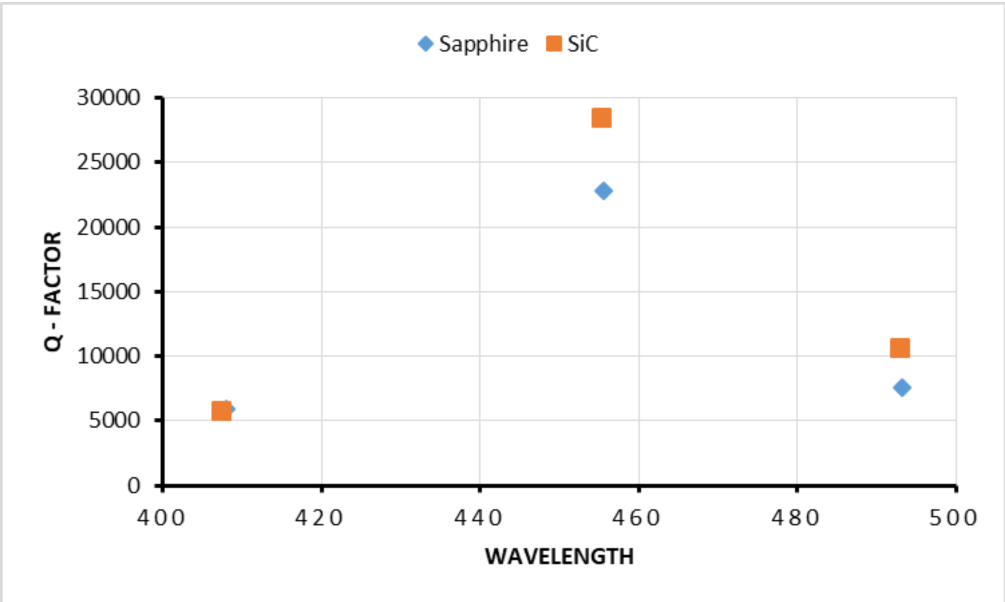


Figure 5. Quality factor (Q) with three peaks resonant wavelength for sapphire and SiC substrate.

Figure 4 shows the graphs of position resonance transmission for a hole displacement between sapphire and SiC substrate where there are three sharp resonances transmission respectively. So, the three peaks from SiC were shifted to the left and the transmission decrease. The Q factor also is determined by the reflection loss at the interface between the internal and external of the cavity. The high Q of sapphire substrate design based on FDTD method resulting in Q is 2.25×10^4 at resonance wavelength of 456 nm. However, the Q factor for SiC substrate design is 2.84×10^4 at resonance wavelength of 455 nm. This result showed at figure 5. This high Q cavity design will be fabricated for experimental characterization in future.

The quality factor values have been calculated by using the Full Width Half Maximum (FWHM) method, based on;

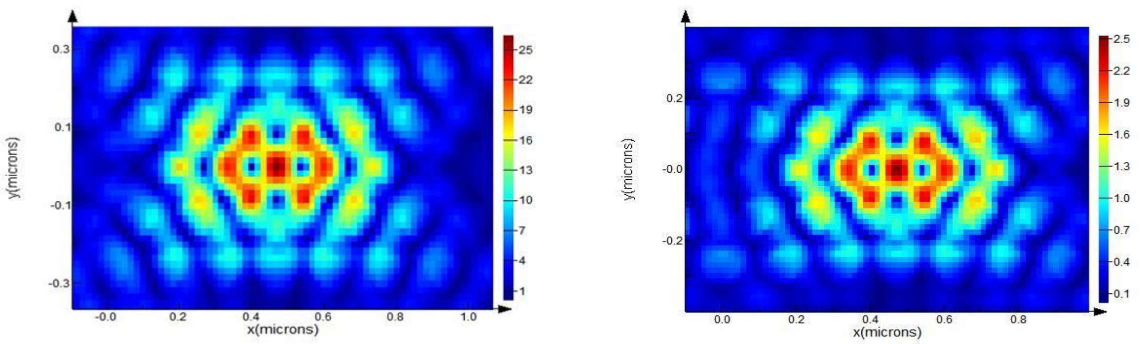
$$Q = \lambda_0 / \Delta\lambda_0 \quad (1)$$

where the λ_0 is the resonant wavelength and $\Delta\lambda_0$ is bandwidth or $\Delta\lambda_0 = \lambda_2 - \lambda_1$, is measured at full width half maximum (FWHM) of the resonance. The Quality Factor (Q) was used to calculate the quality of the resonant cavity and provide a measure of the ratio of energy stored to energy dissipated in the cavity.

Purcell factor is the emission rate enhancement of a strong light matter inside a cavity or resonator for high Q/V with most PhC applications. The high Q factor measured by the Purcell factor, given by

$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V} \quad (2)$$

where λ is the resonant wavelength, n is refractive index and Q and V are the quality factor and mode volume of the cavity. So, this is giving a Purcell factor of ~10^4 which is the Q factor for sapphire substrate of 2.25×10^4 and mode volume of $0.17 (\lambda / n)^3$. For SiC substrate, the Purcell factor of ~10^4 for mode volume of $0.22 (\lambda / n)^3$ with Q factor 2.84×10^4. V as the ratio of the electric field energy were defined the volume of electromagnetic energy of the resonant mode. There have two thing to increase the Purcell factor which are increase the quality factor, Q, and to decrease the effective mode volume, V. In short, our goal is to design a high Q and low Vmode by using finite difference time domain (FDTD) solutions.



(a) (b)

Figure 6. FDTD frequency that shows the light confinement by turning position holes through the centre of cavity in the x-planes (a) sapphire substrate (b) SiC substrate.

Figure 6 shows the |Ex|-field through the centre of the cavity in x-plane. So, the light was confined in the cavity. In 2D photonic crystals there are two polarizations of electric transverse (TE) and electric field (TM). TE is an electric field that has no component along the direction of z = 0 and only has a component in the plane (xy) while TM does not have components along the z direction. The light confined in the center of the cavity is the minimum loss of transmission where the high intensity of light.

4. CONCLUSION

In summary, we have successfully demonstrated high Q-factors resonance with L3 cavities by means of FDTD simulation and we have determined high Q L3 PhC on GaN-Sapphire and GaN-SiC which we demonstrated by simply shifting position two hole away from a line cavity respectively. This proves that by introducing cavity in gallium nitride on sapphire and SiC will give high Q factor. The Q factor as high as 2.25×10^4 and 2.84×10^4 has been observed in 2D shifted hole. The

Purcell factor of ~10^4 which Q of 2.25 × 10^4 and mode volume of 0.17 $(\lambda/ n)^3$ for sapphire substrate and Q of 2.84 × 10^4 and mode volume of 0.22 $(\lambda/ n)^3$ was calculated. This study have also shown that excitation wavelengths are appropriate for future LOC devices for biomedical sensors applications where we can integrate blue LEDs or blue-spectrum lasers in devices and measure the effects of analytical fluorescence. The next challenge is the fabrication of holes to achieve high performance device structure and the characterization based on the fabrication of the device structure will be compared with the simulation results presented in this study.

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