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Photonic Crystal Structures Based on GaN Ultrathin Membranes

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We report on maskless fabrication of ultrathin ($d \sim 15$ nm) nanoperforated GaN membranes exhibiting a triangular lattice arrangement of holes with a diameter of 150 nm, and show that these membranes represent an intermediate case between two-dimensional (2D) and three-dimensional (3D) photonic crystals (PhC). A calculation of the dispersion law in the approximation of scalar waves is indicative of the occurrence of surface and bulk modes, further, there is a range of frequencies where only surface modes can exist. Advantages of the occurrence of two types of modes in ultrathin nanoperforated GaN membranes from the point of view of their incorporation in photonic and optoelectronic integrated circuits are discussed.

Keywords: Photonic Crystals, GaN Ultrathin Membranes, Nanostructure Fabrication, Theory and Design.

RESEARCH ARTICLE

1. INTRODUCTION

Photonic crystal structures based on GaN, as an emergent field of applications, widen the traditional applications of GaN and related materials restricted mainly to short-wavelength light-emitting devices and heterostructure field-effect transistors for high-frequency/high-power applications.[1] In particular, one-dimensional photonic crystal (1D-PhC) GaN/AlGaN microcavities have been designed for nonlinear optical applications in integrated photonics.[2] Two-dimensional photonic crystals (2D-PhC) are widely used to address the issue of light extraction for achieving large external quantum efficiency in GaN-based LEDs. The goal in this case is to overcome the total internal reflection at the interface between a LED device and air, which originates from the large difference in the refractive indices between GaN and air.[3–5] Besides that, recent works on photonic crystal resonators have demonstrated the potential of these structures to achieve optical modes with high quality factor (Q) values within small modal volumes, allowing for the occurrence of interesting phenomena such as the Purcell effect, strong coupling, and low-threshold lasing.[6,7]

Nitride-based high-quality photonic crystal membranes, however, are not easy to fabricate since the chemical inertness of III-N materials makes their processing difficult. Moreover, photonic crystal structures optically active at short wavelengths require a rather small lattice constant, typically between 100 and 200 nm, and transverse sizes of holes between 50 and 150 nm.[6] The realization of reliable ultrathin GaN membranes with designable nanoarchitecture still remains a major technological challenge. Due to the high chemical stability of GaN, its nanostructuring is usually based on inductively coupled plasma reactive ion etching (ICP-RIE) through lithographically opened windows.[8,9] Electron beam lithography and dry etching techniques including focused-ion beam milling employed to pattern the GaN layer and to fabricate suspended thin membranes through wet etching of sacrificial films are rather expensive, and are generally not suitable for achieving veritable ultrathin membranes.

An original method, not based on etching of III-N materials, has been recently proposed for the fabrication of III-nitride photonic crystal membranes.[6] A photonic crystal pattern was first realized in a silicon substrate. GaN quantum dots embedded in a thin AlN layer were then grown on top of the patterned silicon substrate, and a free-standing membrane was achieved by selective etching of the silicon substrate through the holes of the photonic crystal.

In this paper, we demonstrate the fabrication of GaN PhC ultrathin membranes using a cost-effective technology

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