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Photon correlation study of background suppressed single InGaN nanocolumns

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Abstract

We report on photon correlation measurements in a single InGaN/GaN nanocolumn, which is the site-controlled nanostructure allowing for pixel-like large-scale integration. We have developed a shadow mask technique to reduce background emissions from the surroundings of single nanocolumns. The technique improves the signal to background ratio from 0.5:1 to 10:1. A nanocolumn with the shadow mask provides the second order coherence function at time zero $g^{(2)}(0) = 0.52$ at 20 K. The value is explained in terms of statistical mixture of single-photon emission with weak background emissions, as well as efficient carrier injection from other localized states.

1. Introduction

Nanocolumns are selectively formed one-dimensional columnar nitride nanocrystals, and have intensively been studied for light emitting diode (LED) applications because of their highly tunable emission energy in the range of 400–1800 nm, and high luminous efficiency, especially in the green-to-red emission region. Regularly arranged nanocolumns in a triangular lattice with a 300 nm were reported in 2014 [1], and a monolithic integration of LEDs with an area of 150 ×150 μm^2 was realized [2]. As shown in Figs. 1(a), a uniform nanocolumn array with a high density of ~$2\times10^9/cm^2$ has been successfully fabricated. The nanocolumns are promising not only for LED applications but also for quantum information devices. Each of the densely integrated nanocolumns show intense and narrow quantum dot (QD) -like photoluminescence (PL) lines upto 90K, suggesting deep confinement potentials suitable for quantum information devices [3].

High temperature operation of single-photon emitters, based on the deep confinement potentials, has been reported in several III-nitride systems. Triggered single photon emission at room temperature was demonstrated in site-controlled GaN/AlGaN nanowire QD [4]. Electrically driven single photon emission at room temperature was reported in InGaN self-assembled QDs [5]. Single photon emissions have been also reported in an GaN/AlGaN self-assembled QDs [6] and InGaN self-assembled QDs formed on site-controlled GaN pyramid [7,8].

In this paper, we show that another site-controlled III-nitride nanostructure called nanocolumns is a promising platform suitable for large-scale integration of single photon emitters. Integration is important for future practical quantum information technology based on quantum error correction [9,10]. The major obstacle to apply the nanocolumn system for single photon emitters is the existence of background emissions from the surroundings of the nanocolumns. Micro-PL and photon-correlation measurements show that the technique solves the obstacle problem.

2. Results and Discussion

Both uniform arrays of InGaN/GaN nanocolumns and single nanocolumns were fabricated on a GaN template on a (0001) sapphire substrate by rf-plasma-assisted molecular beam epitaxy (rf-MBE) with the Ti-mask selective-area growth technique [1,2]. Figure 1(b) shows the schematic and the SEM image of an as-grown single nanocolumn. During the nanocolumn growth, some nitrides were formed around the nanocolumns on the Ti-mask, which resulted in a broad background PL as shown in Fig. 2(a). We removed the nitride deposits by lifting-off the SiO_2 layer inserted below the Ti-mask [Fig.1(c)].The lift-off process produced flat surface around the nanocolumns. After the lift-off process, the sample was cover by a Ti/Ag/Au shadow mask depicted in Fig. 1(d) to suppress the emission from lower parts of the nanocolumns and from the GaN template.

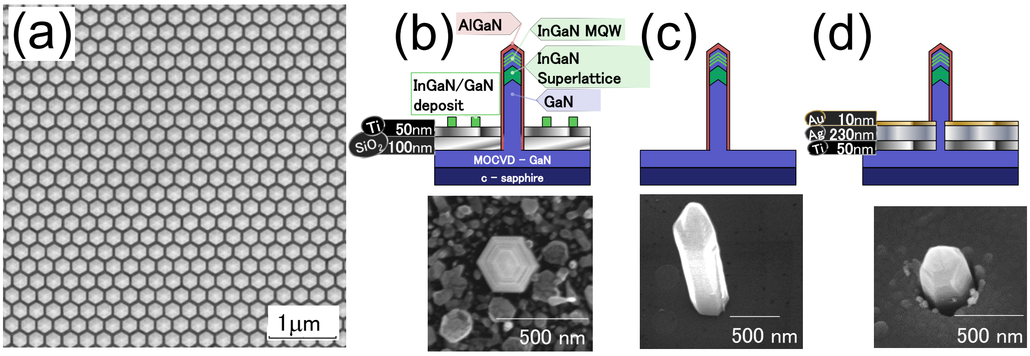

Fig. 1 (a) SEM image of integrated nanocolumns. Schematics and SEM images of (a) an as-grown single nanocolumn, (c) a single nanocolumn after removal of InGaN deposits, and (d) a single nanocolumn after covered by a metal shadow-mask.

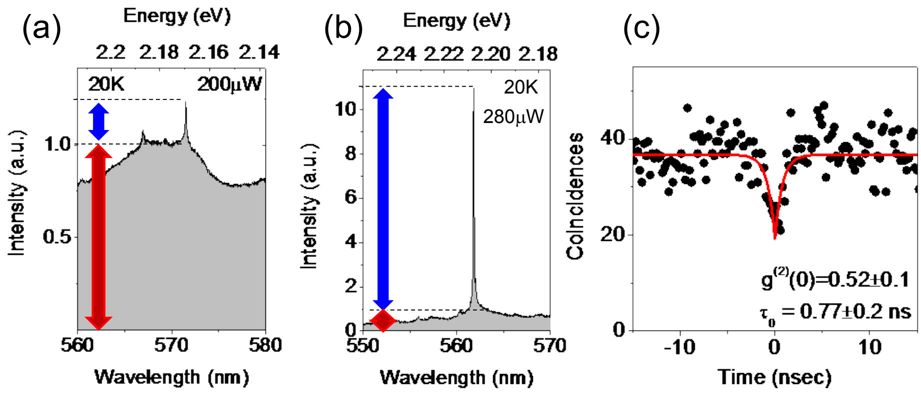

Fig. 2 Micro-PL spectra at 20 K from (a) a typical as-grown single nanocolumn and (b) a single nanocolumn covered by a metal shadow-mask. The excitation laser wavelength was 390 nm. The spectra are normalized to the background intensity at the wavelength of the representative PL peak. (c) Number of measured coincidence for the PL peak at 561.8 nm in (b), plotted as a function of relative delay between two detectors. The solid line is fit to the data by the equation described in the text.

The sharp peaks with the linewidth of 0.4 meV, shown in Fig. 2(a) and (b), are attributed to localized states of the InGaN quantum well (QW) in the nanocolumn. The shadow mask processing improves the intensity ratio of a sharp peak to the broad background for the peak from 0.5:1 to 10:1. The residual background emission which remains even after the shadow mask process is attributed to the emissions other than the localized state, such as emissions from the superlattice below the InGaN QW and/or the emissions from defect states in GaN. Continuum states of InGaN QW can also superimpose on the localized emission states when large potential fluctuation exists.

Second-order coherence function is measured using the Hanbury Brown-Twiss setup under cw-excitation with the bin width set to 108 ps. Autocorrelation histogram corresponding to the peak in Fig. 2(b) is shown in Fig. 2(c). The photon correlation data is fitted with the function $A\left(1-\left(1-g^{(2)}(0)\right)\exp\left(-|\tau|/\tau_0\right)\right)$, where τ is relative delay between photons detected at two detectors. The obtained $g^{(2)}(0)$ of 0.52 is close to the 0.5 threshold for single photon emission. The value slightly higher than 0.5 is attributed to the residual background emissions other than the InGaN localized state, as well as efficient carrier injection processes from other relatively shallow localized states.

The $g^{(2)}(0)$ for a statistical mixture of a single-photon source and a background of emissions with poissonian statistics is given by $2\mu/\langle n\rangle-(\mu/\langle n\rangle)^2$, where $\langle n\rangle$ is the mean total photon number for the mixture, and μ describes the mean photon number of the background [6]. The ratio $\mu/\langle n\rangle$ estimated from the integrated PL intensity to be 0.23, which gives $g^{(2)}(0)$ = 0.4. Further degrade of $g^{(2)}(0)$ can be caused by efficient carrier injection from localized states in the InGaN QW [3]. The efficient injection degrades $g^{(2)}(0)$ due to the enhanced probability of the exciton repumping after emitting a photon [11] or the spectral diffusion effects [12]. We note that in the nanocolumn system, both of the two degradation factors of the background and other localized states can be reduced by decreasing the diameter of the nanocolumns because it increases the volume ratio of localized state to other states. Recently, nanocolumns with less than 30 nm in diameter have been reported [13].

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