Spontaneous emission control of InGaN/GaN pyramidal structure by localized surface plasmonic modes

Su-Hyun Gong, Je-Hyung Kim, Yong-Ho Ko, and Yong-Hoon Cho
Department of Physics and KAIST Institute for the NanoCentury, KAIST, Daejeon, 305-701, Republic of Korea
Author e-mail address: yhc@kaist.ac.kr

Abstract: To improve poor emissions from quantum wires and dots in GaN pyramidal structure, we introduced silver film on pyramid structure. Due to the pyramidal geometry, we could successfully control the spontaneous emission of these structures.

OCIS codes: (250.5590) Quantum-well, -wire and -dot devices; (250.5403) Plasmonics

Recently, InGaN/GaN multi-quantum well on GaN pyramid structures have attracted much attention due to their hybrid characteristic of quantum well, quantum wire, and quantum dot[1]. Since exciton wavefunction would confined at the edge and the apex of pyramid structure, quantum wire and quantum dot structure could be naturally formed, respectively[2]. Figure 1a shows schematic of pyramid structure which has multi-dimensional structure. The existence of this multi-dimensional structure could be confirmed by cathode luminescence image or photoluminescence characteristic depending on the temperatures[1]. This hybrid structure gives us broadband emission which is good at white light emitting diode. Furthermore, site controlled quantum wire and quantum dot could be realized using this GaN pyramid template[3]. However, the absorption and emission cross-section of quantum wire and quantum dot are much smaller than that of quantum well structure, which leads to poor emission properties of one-dimensional and zero-dimensional structure.

Here, to overcome above limitations, we demonstrated spontaneous emission control of multi-dimensional structure in GaN pyramid with coupling on localized surface plasmon modes inside pyramid. We could easily get the localized surface plasmon mode after deposit the metal thin film because GaN pyramid template has the pyramidal geometry. For numerical modeling and experimental studies, we used two different size of pyramid structure, one is micro-size (~2µm) and the other is nano-size (~200 nm) pyramid structure.

To figure out plasmonic modes inside pyramid structure, we conducted numerical modeling by solving Maxwell equations using the three-dimensional finite-difference time-domain (FDTD) method. Figure 1b indicates the magnetic field profiles inside silver-coated nano and micro pyramid structure. Plasmonic modes are highly confined at the edge and apex of the pyramid structure due to the tapered geometry[4, 5]. Therefore, spontaneous emission rate of quantum wire and quantum dot could be highly enhanced due to these intense plasmonic modes. However, scattering efficiencies of plasmonic modes in micro-size pyramid are extremely low. In case of nano-size pyramid, because finite size of nanop pyramid side walls act like antenna structure, scattering (radiation) of plasmonic modes are quite better than micro size pyramid.

Figure 1 (a) schematic image of single pyramid structure having multi-dimensional structure (b) numerically calculated plasmonic modes profile distributed inside nano and micro pyramid structures
To confirm these localized surface plasmon effect experimentally, we deposited Ag thin films on InGaN/GaN pyramid structures using e-beam deposition. After deposited silver film, we found that emission from pyramid structures show red shift compare to reference sample (no silver film). Since longer wavelength part is dominated by quantum wire and quantum dot emission, we assume that quantum wire and quantum dot emission were more enhanced compare to quantum well emission. With cathode-luminescence measurement, spatial resolved spectrum could be obtained. Figure 2 shows CL image of silver coated and reference pyramid structures at different wavelength. With Ag film, contrasts of images at the wavelength of quantum wire and quantum dot emission are enhanced compare to the reference samples. Then, photoluminescence and time-resolved photoluminescence were carried out to measure the improvement of spontaneous emission rate (Purcell effect).

Using micro-photoluminescence measurement, we can distinguish emission of single quantum dot from pyramid structure. Therefore, we could carry out Purcell effect on single quantum dot in detail. Strong spontaneous emission rate enhancements of single quantum dots were observed, which is much higher enhancement compare to the quantum well case. Tapered geometry of pyramid structure gives an advantage of highly confined plasmonic modes at the position of quantum dot. With support of strong Purcell enhancement, we observed single photon generation from our site-controlled InGaN quantum dot.

In summary, we investigated localized surface plasmon polariton effects in GaN pyramid structure which have multi-dimensional structure. Since plasmonic modes are highly localized at the tapered metallic structure, silver-coated pyramid structure shows great enhancement of quantum wire and quantum dot emission. Furthermore, we believe that highly focused localized surface plasmon around site-selective InGaN quantum dot system could be a feasible bright single photon emitter.

![Figure 2 SEM and CL image of Ag coated and reference pyramid structure at the wavelength of quantum well, quantum wire, and quantum dot](image)

References