Optical resonance modes in GaN pyramid microcavities

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(Received 21 April 1999; accepted for publication 16 June 1999)

An array of GaN hexagonal pyramids with a side length of 8.0 μm was fabricated by selective epitaxial overgrowth. These microsized pyramids are highly efficient microcavities. Three types of optical resonance modes with mode spacings of 10, 5.0, and 6.0 Å were observed when a single pyramid was pumped optically by an intense ultraviolet laser beam. An optical ray tracing method has been developed for calculating the optical resonance modes inside the pyramid microcavities. It was shown that a single pyramidal cavity can support several different types of optical resonance modes. The calculated mode spacing agrees very well with the observations. The uniqueness and advantages of this class of hexagonal pyramidal microcavities over the other microcavities are discussed. The implications of our finding on the future GaN microcavity light emitters including micro-light-emitting diodes, microcavity lasers, and vertical-cavity-surface emitting lasers are also discussed. [S0003-6951(99)03632-3]

Recently, great successes in the development and demonstration of room temperature continuous wave III-nitride edge-emitting blue/ultraviolet (UV) laser diodes (LDs) have been achieved,[1] which is encouraging for the research and development of blue/UV LDs in other geometries and configurations. In particular, microcavity lasers including microdisk and microring lasers as well as vertical-cavity-surface emitting lasers offer several benefits resulting from optical confinement to a microcavity, including enhanced quantum efficiency and a greatly reduced lasing threshold. Additionally, the compatibility to a two-dimensional (2D) array fabrication is an inherent attribute of these microcavity lasers, which are of interest for optical display, imaging, scanning, optical parallel interconnects, and ultraparallel optoelectronics applications. Standard photolithography and dry etching techniques have been employed previously to fabricate the III-nitride microdisk and microring cavities.[2–5] A large enhancement of the intrinsic transition quantum efficiency and optical modes corresponding to the whispering-gallery (WG) and radial modes have been observed in AlGaN/GaN and InGaN/GaN multiple quantum well microdisk cavities.[2,3] III-nitrides microcavities can be fabricated either by lithography and dry etching patterning as well as by selective epitaxial overgrowth. III-nitride microcavities prepared by selective epitaxial overgrowth form either hexagonal prisms or pyramids due to the nature of symmetry of the III-nitride crystal structures.[6–10] Optical properties of these hexagonal microsized prisms and pyramids have not been well studied and understood.

In this work, we have studied the optical modes behaviors of a self-organized GaN hexagonal pyramidal microcavity fabricated by metalorganic chemical vapor deposition (MOCVD) selective epitaxial overgrowth. These microsized pyramids are highly efficient microcavities due to the extremely smooth facet surfaces formed by self-organization without any process damage. Optical resonance modes in the GaN pyramidal microcavities can be observed at a pumping intensity which is several orders of magnitude lower than that in the III-nitride MQWs microdisk cavities. Optically pumped lasing actions in these selective epitaxially overgrown GaN pyramids have been observed recently.[9] However, the formation of the optical cavities inside a microsized pyramid and the properties of optical resonance modes are unknown. As will be shown here, a microsized pyramid is a true three-dimensional (3D) cavity, which can support several different types of optical resonance modes. These novel and unique pyramidal microcavities open new avenues for optoelectronic device applications.

An array of GaN pyramids was prepared by selective epitaxial overgrowth using low-pressure MOCVD. Prior to the pyramidal growth, a 1.0 μm GaN epilayer was grown on a (0001) sapphire substrate using a thin AlN buffer layer. A 0.2 μm SiO_2 mask layer was deposited on the top of the GaN epilayer. Patterning of the mask with a circular opening of about 4 μm in diam was achieved by using standard photolithograhic technique together with dry etching, followed by the GaN pyramidal overgrowth. Figure 1(a) shows the scanning electron microscope (SEM) image of an array of the GaN hexagonal pyramids. As can be seen from Fig. 1(a), the six facets of each pyramid formed by self-organization are extremely smooth since their formation does not require any patterning processes such as etching. Figure 1(b) shows the schematic diagram of a GaN pyramid microcavity and provides the dimensions of the pyramids ($a = 8.0$ μm and $h = 1.63\ a$) used in this work. The angle between the facets and the SiO_2 basal plane is $a = 62°$. To study the optical resonance modes behaviors, an UV transmitting objective was used in a confocal geometry to optically pump a single pyramid normal to the sample surface and to collect the light emission in the direction of the surface normal.

Figure 2(a) shows a low temperature (10 K) photoluminescence (PL) emission spectrum of a GaN pyramid pumped under a low excitation intensity. The mechanism of these optical transition lines has been discussed previously.[10] We concentrate here on the optical resonance modes behavior,

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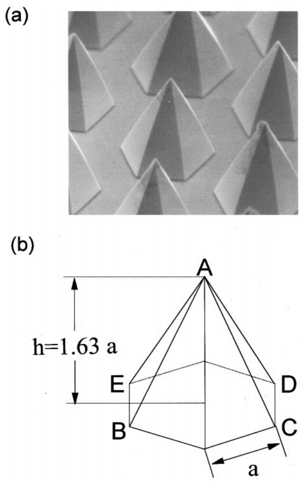

FIG. 1. (a) SEM image of an array of self-organized hexagonal GaN pyramids. (b) A schematic diagram of a single GaN pyramidal microcavity, $a=8.0\mu$m and $h=1.63\ a$.

which is shown in Fig. 2(b). The observed optical modes patterns shown in Fig. 2(b) are quite complicated, but can be classified into three different groups with different mode spacings. The first group includes the emissions peaks at 3555, 3565, and 3576 Å giving a mode spacing of $\Delta\lambda_1^{obs}=10$ Å. The second group includes the emission peaks at 3698.5, 3703.5, and 3708.5 Å as well as at 3681 and 3686 Å giving a mode spacing of $\Delta\lambda_2^{obs}=5$Å. The third group includes emission peaks at 3590, 3596, and 3602 Å as well as those at 3649.5 and 3655.5 Å giving a mode spacing of $\Delta\lambda_3^{obs}=6.0$ Å. Notice that $\Delta\lambda_1^{obs}/\Delta\lambda_2^{obs}=2$ and $\Delta\lambda_1^{obs}/\Delta\lambda_3^{obs}=1.7$.

The observed mode spacing can be understood from the following calculation, which also provides a clear picture for the formation of the optical cavities inside a microsized pyramid. The first type can be identified quite easily from Fig. 3(a). Two opposite facets together with the SiO_2 basal plane form one cavity, i.e., between planes AEB, ADC, and EBDC [Fig. 1(b)]. The side view of such a cavity or its projection on a plane normal to these two facets (AEB and ADC) is presented on the top half of Fig. 3(a). The six facets of the pyramids together with the SiO_2 basal plane [see Fig. 1(b)] form three pairs of cavities of this type. A light beam (line P) propagating in a direction normal to one of the facets (facet AC) will be reflected by the basal plane BC. The reflected light beam is also normal to the opposite facet (facet AB) since $\angle ABC=\angle ACB=\alpha$. A cavity is thus formed with a cavity length of about $L_c^{\mathrm{I}}=(3/2)a$, where a is the side length of the pyramids. This cavity, which is similar to the Fabry–Pérot cavity formed by two parallel facets, is formed by three facets in a pyramidal microcavity. This cavity gives a standing wave of light inside a pyramid with a total optical path of about $2L_c^{\mathrm{I}}(=3\ an)$ with n being the index of refraction of GaN.

A more intriguing way to visualize this cavity in the pyramids can be achieved by the following method. Instead of reflecting the light beam (line P) at point O on the basal plane, we allow the light beam to propagate continuously on a straight line and the pyramid to reflect about the basal plane BC [see the lower half of Fig. 3(a)]. By doing so, the total active area involved in this particular type of optical

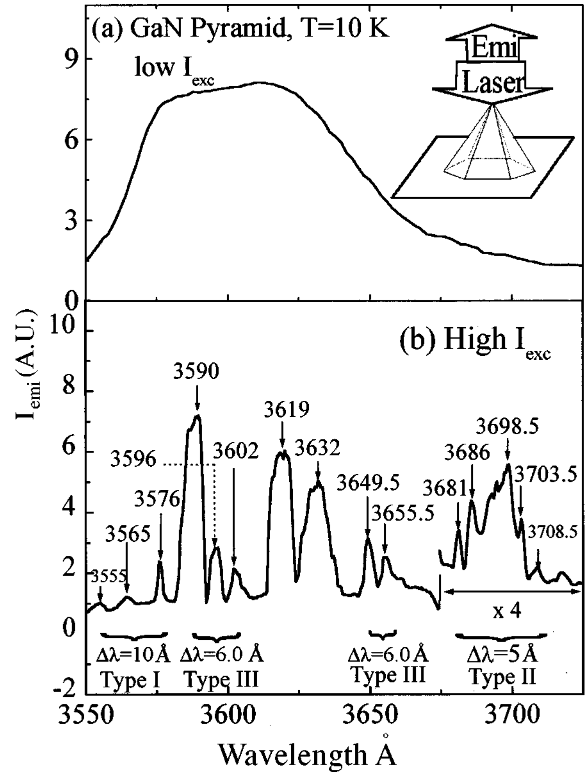

FIG. 2. (a) PL emission spectrum of GaN pyramids under a low pump intensity and (b) optical resonance modes behavior of an individually pumped pyramid under a high pump intensity.

resonance modes can be easily determined, which is the lower half area of the facets, between planes HC and GB (the thicker lines). This is a relatively large area and thus gives a strong signature of this type of optical modes in the emission spectrum as shown in Fig. 2(b).

By employing the same method described above, the second type of cavity can be readily identified and is schematically illustrated in Fig. 3(b). It is easy to prove [following all the angles in Fig. 3(b)] that the light beam, which is normal to the plane of AC, is also normal to the plane A′B′. It thus forms a cavity with a cavity length of about $L_c^{\mathrm{II}}=3\ a$, twice the cavity length of the first optical mode type. The mode spacing of the second type resonance modes is thus one-half of that of the first type, which is observed experimentally in Fig. 2(b), $\Delta\lambda_2^{obs}=5$ Å and $\Delta\lambda_1^{obs}=10$ Å. Again, the thicker lines on the top portion of the pyramid represent the size of this type of cavity. Resonance modes in Fig. 3(b) are also a standing wave.

One can also visualize the existence of the third type optical modes inside the pyramids. The dotted line between x and x″″ in Fig. 4 represents a straight light beam reflecting six consecutive times from ABC to A″B″C′. It is clear that the point x″″ on the plane A″B″ is the same point as x on the plane AB. With light beam P parallel to the plane BC, it is easy to prove that the plane AB is parallel to the plane A″B″ by following all the angles indicated along the light beam xx″″ by using the relation $2a+\beta=180°$. The optical path thus take a complete cycle, which has a great similarity as the WG modes in the microdisk and microring cavities. One of the actual optical paths is indicated in Fig. 4 by the solid line inside the pyramid ABC. The total optical path for this type of mode is about $3\sqrt{3}\ an$.

The resonant modes of wavelength λ in the pyramidal

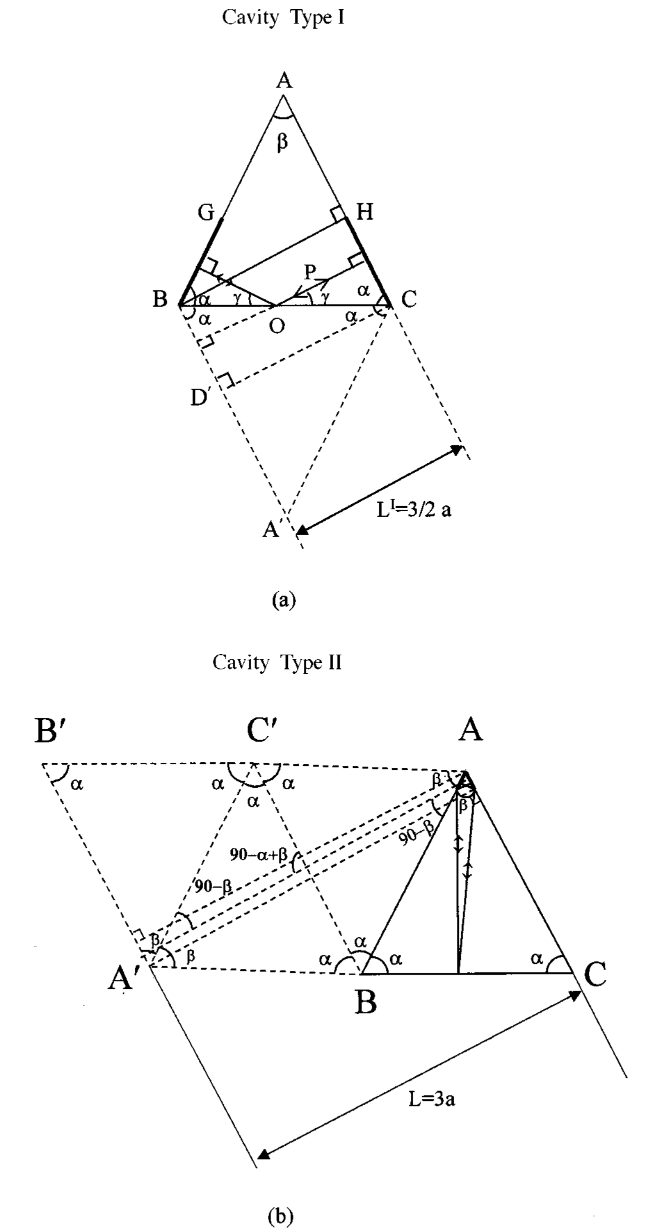

FIG. 3. Optical paths of Fabry–Perot-like cavities formed in a GaN hexagonal pyramidal microcavity determined by an optical ray tracing method. The effective optical path of (a) the first type optical resonance odes is about 3 *an* and (b) the second type optical resonance modes is about 6 *an*, where *n* is the refractive index of GaN.

microcavities can be calculated by

$$Ln' = m\lambda, \quad (m \text{ is an integer}) \tag{1}$$

with mode spacing

$$\Delta\lambda = \lambda^2/Ln', \tag{2}$$

where Ln' is the total optical path of different resonance modes and n' is the GaN effective index of refraction which was taken as $n'=2.65$. From Figs. 3 and 4, the total optical paths of the first, the second, and the third optical mode types are about $3\,an'$, $6\,an'$, and $3\sqrt{3}\,an'$ with mode spacings of $\Delta\lambda_1^{\mathrm{cal}}=20.4$ Å$\approx 2\Delta\lambda_1^{\mathrm{obs}}$, $\Delta\lambda_2^{\mathrm{cal}}=10.2$ Å$\approx 2\Delta\lambda_2^{\mathrm{obs}}$ and $\Delta\lambda_3^{\mathrm{cal}}=11.8$ Å$\approx 2\Delta\lambda_3^{\mathrm{obs}}$, respectively. The ratios are expected to be $\Delta\lambda_1^{\mathrm{cal}}/\Delta\lambda_2^{\mathrm{call}}=2$ and $\Delta\lambda_1^{\mathrm{cal}}/\Delta\lambda_3^{\mathrm{cal}}=1.7$. We see that the calculated mode spacings ratios agree very well with the observation of $\Delta\lambda_1^{\mathrm{obs}}=10$ Å, $\Delta\lambda_2^{\mathrm{obs}}=5$ Å, and $\Delta\lambda_3^{\mathrm{obs}}=6.0$ Å and the ratios of $\Delta\lambda_1^{\mathrm{obs}}/\Delta\lambda_2^{\mathrm{obs}}=2$ and $\Delta\lambda_1^{\mathrm{obs}}/\Delta\lambda_3^{\mathrm{obs}}=1.7$. A

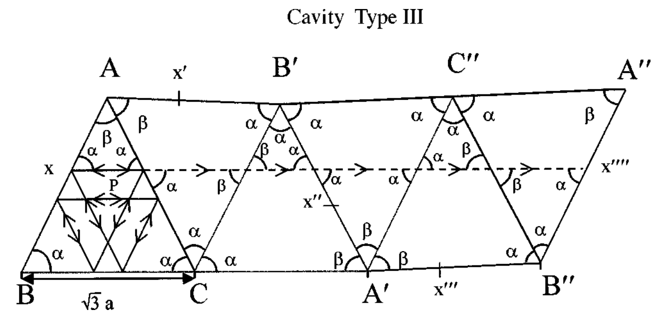

FIG. 4. WG-like cavity formed in a GaN pyramidal microcavity with a total optical path of about $3\sqrt{3}$ *an*, where *n* is the refractive index of GaN.

factor of two difference between the observed and calculated mode spacing is due to symmetric conditions imposed on the Maxwell equations in hexagonal pyramids, which are unable to be included in the simplified ray tracing method described above.

The advantages and uniqueness of the pyramidal microcavities include (i) six facets per each pixel, (ii) extremely smooth facet, and (iii) larger total surface area. Since GaN pyramids are a completely new kind of microcavity, novel properties related with microcavity effects[11] should be investigated before we can take the full advantage of this new class of cavities.

In summary, properties of optical modes in GaN pyramidal microcavities fabricated by MOCVD selective epitaxial overgrowth have been studied in detail. An optical ray tracing method has been developed and used to calculate different resonance modes in the GaN pyramidal microcavities. It was shown that each pyramidal microcavity is a 3D cavity and can support more than three different groups of optical resonance modes. The calculated mode spacings follow the unique relationships $\Delta\lambda_1/\Delta\lambda_2=2$ and $\Delta\lambda_1/\Delta\lambda_3=1.7$, which agree well with the observation.

The research at Kansas State University is supported by ARO, DOE (Grant No. 96ER45604/A000), NSF (Grant Nos. DMR-9902431 and INT-9729582), ONR, and BMDO. The research at the Honeywell Technology Center was supported by Air Force Wright Laboratory (Contract No. F33615-C-1618).

[1] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umenoto, M. Sano, and K. Chocho, Appl. Phys. Lett. **72**, 1939 (1998).
[2] R. A. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zhang, L. Dai, H. Tang, A. Botchkarev, W. Kim, H. Morkoc, and M. A. Khan, Appl. Phys. Lett. **71**, 2898 (1997).
[3] R. A. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zhang, L. Dai, A. Botchkarev, W. Kim, H. Morkoc, and M. A. Khan, Appl. Phys. Lett. **72**, 1530 (1998).
[4] K. C. Zeng, L. Dai, J. Y. Lin, and H. X. Jiang (unpublished).
[5] K. Saotome, A. Matsutani, T. Shirasawa, M. Mori, T. Honda, T. Sakaguchi, F. Koyama, and K. Iga, Mater. Res. Soc. Symp. Proc. **449**, 1029 (1997).
[6] R. Underwood, D. Kapolnek, B. Keller, S. DenBaars, and U. Mishra, Topical Workshop on Nitrides, Nagoya, Japan, September 1995.
[7] T. Akasaka, Y. Kobayashi, A. Ando, and N. Kobayashi, Appl. Phys. Lett. **71**, 2196 (1997).
[8] B. Beaumont, S. Haffouz, and P. Gibart, Appl. Phys. Lett. **72**, 921 (1998).
[9] S. Bidnyk, B. D. Little, Y. H. Cho, J. Karasinski, J. J. Song, W. Yang, and S. A. McPherson, Appl. Phys. Lett. **73**, 2242 (1998).
[10] K. C. Zeng, J. Y. Lin, H. X. Jiang, and W. Yang, Appl. Phys. Lett. **74**, 1227 (1999).
[11] R. K. Chang and A. J. Campillo, *Optical Processes in Microcavities* (World Scientific, Singapore, 1996).