Optical characterization of exciton coupled with surface plasmon resonance (SPR) on InGaN/GaN heterostructures with perforated circle hole arrays have been investigated. We demonstrate an analysis of optical characterization of exciton coupled with SPR on InGaN/GaN heterostructures with perforated circle hole arrays by the measurements of photoluminescence (PL) spectra over a broad range of temperature between 20 and 300 K. From the temperature-dependent PL spectra, it has been observed the better SPR coupling effect, resulting in less carrier confine ability of InGaN energy band. The redshift magnitude of the emission peak for sample with coated aluminum (Al) pattern is larger than no metal film, due to the more exciton coupling surface plasmon within Al/InGaN interface. The enhancement of PL
intensity for sample with deposited Al pattern film can be attributed to stronger coupling interaction with SPR and exciton. These experimental results indicate that a perforated Al circle hole array can significantly affect carrier confinement and enhance the quantum efficiency of Al/In-rich InGaN heterostructures due to the interaction of SPR coupling effect between InGaN QDs-like region and Al film.

KEYWORDS: gallium nitride (GaN), circle hole array, photoluminescence (PL), surface plasmon resonance (SPR)

* E-mail address: neete@mail.cgu.edu.tw
1. Introduction

Optical surface metal film with two-dimensional subwavelength periodic hole arrays reveals exceptional optical transmission.\(^1\) As the holes become smaller than the thickness of the metal film, flat dispersions and a little transmission intensities cause a transition from surface plasmon resonance (SPR) behavior to wavefunction.\(^2\) The SPR is formed by the interaction of light with grating dominate the transmission spectra even when the surface plasmons contributed is presented. If the period of the pattern is appropriate, then the SPR can Bragg reflect and energy opens up in the SPR dispersion relation.\(^3\) Recent work on the conservation of surface plasmons and light through period perforated hole arrays has elucidated the propagation of surface plasmons. In this paper we design SPR dispersion relations with variously sized circle holes are measured to discuss the various surface charge displacements on periodic perforated aluminum (Al) circle hole array. The light is incident in the z direction, allowing the dispersion relation in kx direction to be studied. The conservation of momentum for surface Plasmon is given by

\[
k_{sp} = k_x + iG_x + jG_y
\]  

(1)

where \(k_{sp}\) is the surface plasmon wave vector given by

\[
|k_{sp}| = \frac{\omega}{c} \left( \frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2} \right)^{1/2}
\]  

(2)

For normal incident light k_x=0, Eq. (2) reduce to
As the Eq. 2 comes into existence, the photonic were coupling with SPR on the metal interface. The enhancement of PL intensity for sample with deposited Al pattern film can be attributed to stronger coupling interaction with SPR and exciton. These experimental results indicate that a perforated Al circle hole array can significantly affect carrier confinement and enhance the quantum efficiency of Al/In-rich InGaN heterostructures due to the interaction of SPR coupling effect between InGaN QDs-like region and Al circle hole array. Both the carrier transport mechanism and the abnormal luminescence intensity evolution as a function of temperature were found to be in good agreement with the theoretical analysis model.

2. Experimental Methods

The In-rich InGaN samples investigated in this study were grown by metal organic vapor phase epitaxy (MOVPE) on c-plane sapphire substrates, Ammonia (NH$_3$), trimethylgallium (TMGa), trimethylindium (TMIn), and silane (SiH$_4$) were used either as precursors or as dopants. The carrier gas was H$_2$ and N$_2$, respectively, for the growth of GaN and InGaN. The layer structure of the sample consisted of a 20-nm-thick GaN buffer layer. The wafer was consisting of a 3-µm-thick n-type InGaN layer. The photoresist spun on InGaN/GaN/sapphire surface, and the circle
hole array put on top of the InGaN surface by using E-gun evaporator, and then lifted off. The lattice constant of the hole arrays was \( a = 35, 30, \) and 25 \( \mu \text{m} \), and radius was \( r = 7.5 \mu \text{m} \). The photoluminescence (PL) signals were detected by a Si detector with a 0.5-meter monochromator, using a standard lock-in technique; the samples were examined in a closed cycle He cryostat, whose temperature range was from 20 K to 300 K.

3. Results and Discussion

The different lattice constant between circle holes applied to the SPR effect of the optical properties for lighting device\(^1\) the distance of circle holes (a), radius (r) and the film thicknesses of the Al (w) are listed in Table 1. Fig. 1 represent the temperature dependence of the photoluminescence spectra with various Al lattice constant of the circle hole array (\( a = 35, 30, \) and 25 \( \mu \text{m} \)) at temperature of 20 K. PL intensity gradually increase along with the enhanced Al-coated sample, which also can attribute to have a stronger interaction with SPR. It was found that the enhancement ratio of the PL intensity increase for Al-coated sample at emission peak energy at 2.1 eV, and another clearly shows that an extraordinary peak at nearly 2.71 eV. The enhancement of PL intensity for sample with deposited Al pattern film can be attributed to strong coupling interaction with SPR and exciton. Electron-hole pairs
excited within In-rich InGaN film couple to surface plasmon at the metal/semiconductor interface when the energies of excitons in InGaN and the ones of the metal surface plasmon energy are resemble. It has found that a unique emission peak on PL spectra due to the SPR effect within InGaN/Al interface.

There are different Al pattern lattice constant results in dissimilar PL intensity. The variations of PL intensity have been observed form different Al pattern lattice on the surface of In-rich InGaN film. The intensity curve about hole circle constant $a = 35 \, \mu m$ higher than $a = 30 \, \mu m$ and $a = 25 \, \mu m$, which have the close intensity, because the size of holes, circle hole exceeds a half lattice constant $a/2$, resulting in the appearance of the forbidden photonic band gap. The transmission intensity was resisted by cut-off wavelength from penetration of the electric into the metal, the propagation constant of the TE mode is given by $^4$

$$\beta = \pi \sqrt{\left(\frac{2}{a}\right)^2 - \left(\frac{1}{a}\right)^2}$$

the cut-off wavelength occurs when the TE mode is zero.

Fig. 2 shows the PL intensity of the sample with no metal film been higher than others with coated Al pattern at temperature of 120 K. The carriers receive more energy to deal with recombination and apparent optical absorbed by metal under higher temperature, and far away Al coupling energy in the above discussion. For this reason, we obtain amazed SPR coupling with Al pattern and extraordinary PL
intensity. The temperature-dependent red-shift of the emission peak energy can verify
above discussion as shown in Fig. 3. The shift magnitude of the emission peak for
sample with coated Al pattern is larger than no metal film due to the more exciton
coupling surface plasmon within Al/InGaN interface. In addition, at low temperature,
it is attributed to the enhancement of the confine energy not only in the InGaN
quantum dots-like (QDs-like) region but also in Al pattern, and the area of the circle
within a half lattice constant $a/2$ have superior SPR coupling mode appears.

In order to inspect the dependence of the dynamical carrier transport between
In-rich InGaN film and Al pattern, it is of interest to examine the radiative
recombination of the confined electrons and holes at low temperature. The quenching
of the PL luminescence with temperature is attributed to the thermal emission of the
carriers that escaped from the local potential minima caused by potential fluctuations,
such as alloy disorder and interface fluctuations. The analyzed PL intensity is
responsible for thermal quench can be calculated activation energy by Arrhenius
equation which is valid in the temperature range where thermal effect has been
established. The activation energy is given by

$$I(T) = \frac{I_0}{1 + A \exp\left(-\frac{E_a}{k_B T}\right) + B \exp\left(-\frac{E_b}{k_B T}\right)}$$

where $I(T)$ is the temperature-dependent integrated PL intensity, $I_0$ is the integrated
PL intensity at 0 K, $k_B$ is Boltzmann’s constant. The value of $E_a$ is the thermal
activation energy of the nonradiative recombination center, the value of $E_b$ is the thermal activation energy of the second nonradiative recombination channel, and the coefficients A and B are the efficiency of each one of the quenching mechanisms.\textsuperscript{6-8)} That is, if the value is larger, the delocalization effect is stronger. The fitting curves made by Eq. (5) with the parameters listed in Table 2 are also shown in Fig. 4.

It has found that the confine energy by the temperature-dependent carrier dynamics in the studied sample using the experimental results. Arrhenius equation plotting the PL intensity is also shown in Fig. 4. The activation energies of sample with no metal pattern were $E_a = 137$ meV and $E_b = 7.6$ meV, which denotes the carriers to escape from InGaN QDs-like region to barrier and the light hole to overcome the barrier, respectively. The obtaining energy carriers occur thermal quenching at higher temperature, so carriers transfer from InGaN QDs-like region to nonradiative recombination.\textsuperscript{9-11)} The activation energies are often referred to as the energies for most carriers enough to escape from the localized states. The higher activation energy leads to the energetic carriers being circumscribed in the active region. The sample $a = 35 \mu\text{m}$ which with $E_a = 88$ meV and $E_b = 16$ meV exhibits better coupling effect than sample $a = 30 \mu\text{m}$ and $a = 25 \mu\text{m}$ which have $E_a = 91$ and $92.5$ meV, and $E_b = 25.5$ and 16 meV, respectively, so that carriers transit easily from InGaN QDs-like region to coupling with SPR in Al pattern array. However, the
exciton wavefunction can be successfully tailored by the nanostructure, which facilitates the localization of the injected carriers, as well as promotes radiative recombination in the active region and inhibits the rapid degradation of luminescence. Consequently, the experimental findings imply that Al circle hole array upon InGaN/GaN/sapphire structures with stronger SPR coupling effect may provide alternative paths for radiationless transitions.

4. Conclusions

In this article, we demonstrate an analysis of optical characterization of excition coupled with SPR on InGaN/GaN heterostructures with perforated circle hole arrays by the measurements of PL spectra over a broad range of temperature between 20 and 300 K. With increasing temperatures to 120 K, the SPR couplings effect less and weaker may be due to a lack of willingness to thermal effects. The enhancement of PL intensity for sample with deposited Al pattern film can be attributed to stronger coupling interaction with SPR and exciton. The SPR coupling on circle array of Al holes generate extraordinary strong intensity as area of circle hole smaller than half of lattice constant, and also cause the photonic band gap opens up as holes area bigger. The redshift magnitude of the emission peak for sample with coated Al is larger than no metal film, due to the more exciton coupling surface plasmon within Al/InGaN
interface. These experimental results indicate that a perforated Al circle hole array can significantly affect carrier confinement and enhance the quantum efficiency of Al/In-rich InGaN heterostructures due to the interaction of SPR coupling effect between InGaN QDs-like region and Al film.

Acknowledgments

This study was supported by the National Science Council of the Republic of China under Contract No. NSC 97-2112-M-182-002-MY3.
References


Table Captions

Table 1 The dimension parameters of the Al circle hole array on the surface of GaN/InGaN/sapphire structure.

Table 2 Fitting parameters used in the Arrhenius equation for calculating the activation energy in the In-rich InGaN film with perforated aluminum circle hole arrays at various the different lattice constant between circle holes
Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Star</th>
<th>Triangle</th>
<th>Square</th>
<th>Pentagon</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (µm)</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>No metal pattern</td>
</tr>
<tr>
<td>r (µm)</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>No metal pattern</td>
</tr>
<tr>
<td>w (nm)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>No metal pattern</td>
</tr>
<tr>
<td>Symbol</td>
<td>Star</td>
<td>Triangle</td>
<td>Square</td>
<td>Pentagon</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>----------</td>
<td>--------</td>
<td>----------------</td>
</tr>
<tr>
<td>a (µm)</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>No metal pattern</td>
</tr>
<tr>
<td>r (µm)</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>No metal pattern</td>
</tr>
<tr>
<td>Ea (meV)</td>
<td>88.0</td>
<td>91.0</td>
<td>91.5</td>
<td>137</td>
</tr>
<tr>
<td>Eb (meV)</td>
<td>16</td>
<td>25.5</td>
<td>16.0</td>
<td>7.6</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1 Photoluminescence spectra of InGaN film with Al pattern in the different lattice constant between circle holes range from 25 to 35 µm. The ambient temperature is 20 K.

Figure 2 Photoluminescence spectra of InGaN film with Al pattern in the different lattice constant between circle holes range from 25 to 35µm. The ambient temperature is 120 K.

Figure 3 Normalized temperature-dependent peak energies of the InGaN film with Al pattern as a function of temperature in the different lattice constant between circle holes range from 25 to 35 µm.

Figure 4 Temperature-dependent photoluminescence intensity of the InGaN film with Al pattern in the different lattice constant between circle holes range from 25 to 35 µm.
Figure 1

T = 20 K
GaN/InGaN/Al(10 nm)
Circle a, r (µm)
- a = 35, r = 7.5
- a = 30, r = 7.5
- a = 25, r = 7.5
- No metal pattern

PL intensity (a.u.)

Energy (eV)
Figure 2
Figure 3
GaN/InGaN/Al(10 nm)
Circle a, r (µm)
   a = 35, r = 7.5   Ea = 88.0 meV, Eb = 16.0 meV
   a = 30, r = 7.5   Ea = 91.0 meV, Eb = 25.5 meV
   a = 25, r = 7.5   Ea = 92.5 meV, Eb = 16.0 meV
No metal           Ea = 137 meV, Eb = 7.6 meV

Figure 4