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Exciton Wavefunction Coupled Surface Plasmon Resonance on In-rich InGaN Film with Perforated Aluminum Circle Hole Arrays

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1. Introduction

Optically surface metal film with two-dimensional subwavelength periodic hole arrays reveal 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 formed by the interaction of light with grating dominate the transmission spectra even when the surface plasmons contributed is present. 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 Al film. The light is incident in the z direction, allowing the dispersion relation in $\mathbf{k}_x$ direction to be studied.

The conservation of momentum for surface plasmon is given by

$$k_{sp} = k_x + iG_x + jG_y \qquad (1)$$

Where $\mathbf{k}_{sp}$ is the surface plasmon wave vector given by

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

For normal incident light $\mathbf{k}_x$=0, Eq. (2) reduce to

$$(i^2 + j^2)^{1/2}\lambda = a\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \qquad (3)$$

$|G_x| = |G_y| = 2\pi/a$, i and j are integers.

As the Eq.2 comes into existence, the photonic were coupling with SPR on the metal interface.

2. Experiment

The In-rich InGaN samples were both grown by metal organic vapor phase epitaxy (MOVPE) on c-plane sapphire substrates with a 20-nm-thick GaN buffer layer. The wafer consisted of a 3-μm-thick n-type InGaN layer. The photoresist was spun on InGaN/GaN/Sapphire surface and the circle hole array was defined. The 10 nm aluminum (Al) film was deposited 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, 25 μm, radius was r = 7.5 μm. The photoluminescence (PL) signals were detected by a Si detector with a 0.5-meter monochromator, employing a standard lock-in technique; the samples were examined in a closed cycle He cryostat, the temperature range was from 20 K to 300 K.

3. Result and discussions

The temperature dependence of the photoluminescence spectra with various Al lattice constant of the circle hole array (a = 35, 30, 25 μm) is shown as Fig. 1 at 20 K. It is find that the PL intensity enhance ratio increase for Al-coated sample at emission peak energy 2.1 eV, and another clearly shows that a 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.

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 circle constant a = 35 μm higher than a = 30, 25 μm, due to the size of holes circle hole exceeds a half lattice constant a/2, the forbidden photonic band gap exists. The transmission intensity resist by cut-off wavelength from penetration of the electric into the metal, the propagation constant of the TE mode is given by

$$\beta = \pi\sqrt{\left(\frac{2}{\lambda}\right)^2 - \left(\frac{1}{a}\right)^2} \qquad (4)$$

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

The PL intensity of the sample with no metal film was been higher than others with coated Al pattern, at temperature of 120 K, as shown in Fig. 2. The carriers receive more energy to 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 array pattern and extraordinary PL intensity. The energy red-shift temperature dependent can verify above discussion as shown in Fig. 3. 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 InGaN/Al interface. At low temperature, there are strong peak energy at coated Al samples, it is attributed to the enhancement of the confine energy not only in the InGaN QDs-like region but Al film, 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 array, 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. Arrhenius equation plot the PL intensity are shown in Fig. 4 .The activation energy of no metal pattern sample were E_a = 137, and E_b = 7.6 meV, which denoted the carriers to escape from InGaN QDs-like region to barrier and the light hole to overcome the barrier, respectively, the carriers obtain energy occur thermal quench at higher temperature, thus carriers transit from InGaN QDs-like region to non-radiation recombination. The sample with a = 35 μm (E_a = 88 meV, E_b = 16 meV) it indicates to more coupling than sample with a = 30, 25 μm (E_a = 91 and 92.5 meV, E_b = 25.5 and 16 meV), respectively, so that carriers transport effectively from InGaN QDs-like region to coupling with SPR in InGaN/Al interface.

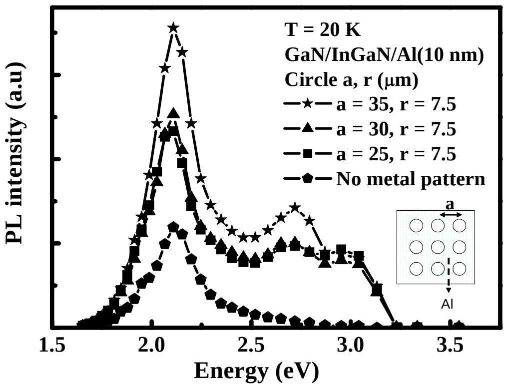

Fig. 1 PL spectra of the InGaN film with Al pattern at 20 K.

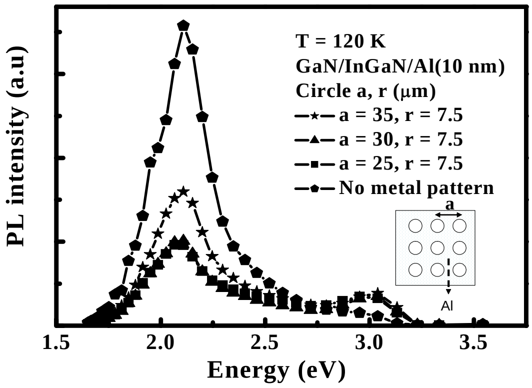

Fig. 2 PL spectra of the InGaN film with Al pattern at 120 K.

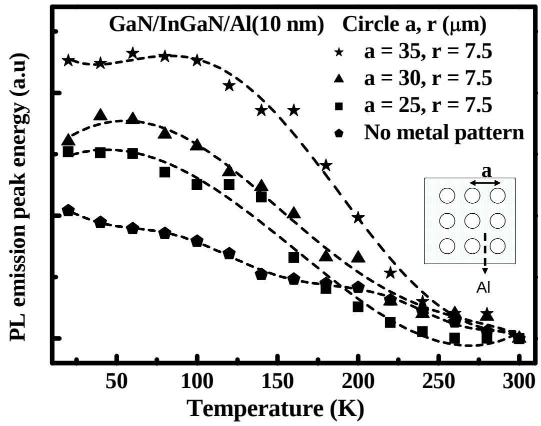

Fig. 3 Normalized temperature-dependent peak energies of the InGaN film with Al pattern.

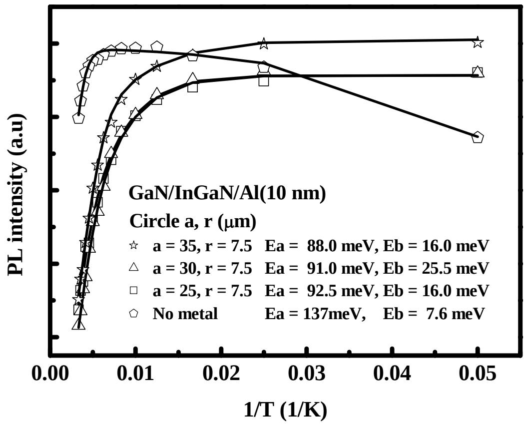

Fig. 4 Temperature-dependent photoluminescence intensity of the InGaN film with Al pattern.

4. Conclusions

The enhancement of PL intensity for sample with deposited Al pattern film can be attributed to strong 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 generate 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 InGaN/Al interface. These experimental results indicate that a perforated Al circle hole array can significantly affect carrier confinement and enhance the quantum efficiency of In-rich InGaN/Al heterostructures due to the interaction of SPR coupling between InGaN QDs-like region and Al film.

Acknowledgements

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