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An experimental study about the influence of well thickness on the electroluminescence of InGaN/GaN multiple quantum wells

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ABSTRACT

The influence of well thickness on the electroluminescence (EL) of InGaN/GaN multiple quantum wells (MQWs) grown by metalorganic chemical vapor deposition is investigated. It is found that the peak wavelength of EL increases with the increase of well thickness when the latter is located in the range of 3.0–5.1 nm. The redshift is mainly attributed to the quantum confined Stark effect (QCSE). As a contrast, it is found that the EL intensity of InGaN/GaN MQWs increases with the increase of well thickness in spite of QCSE. The result of X-ray diffraction demonstrates that the interface become smoother with the increase of well thickness and suggests that the reduced interface roughness can be an important factor leading to the increase of EL intensity of InGaN/GaN MQWs.

1. Introduction

The investigations on GaN and related III-nitrides have been focused for many years due to their extensive applications. Great successes have been obtained so far. For example, not only high brightness blue light emitting diodes (LEDs) have been commercialized, but also GaN-based laser diodes (LDs) with long lifetime have been realized ten years ago [1]. The quality of InGaN multiple quantum wells (MQWs) is very important for the high performance of GaN-based LEDs and LDs. There is a lot of papers about the growth and properties of InGaN MQWs (e.g. see Refs. [2–5]). However, due to the complexity and difficulty of growing high quality InGaN MQWs, it is necessary to study the optimization of the growth parameters of InGaN MQWs. Especially it is an interesting topic to investigate the influence of well thickness on the electroluminescence (EL) of InGaN MQWs by metalorganic chemical vapor deposition (MOCVD). In this paper it is found that both EL intensity and peak wavelength of InGaN/GaN MQWs increase with the increase of well thickness. The X-ray diffraction experiments indicate that the interface roughness of InGaN/GaN MQWs decreases with the increase of well thickness, and the interface roughness is suggested to play an important role in determining the EL intensity of InGaN MQWs.

2. Experimental procedure

All investigated InGaN/GaN MQWs are grown on c-plane sapphire substrate by MOCVD. The growth process is as follows: firstly a low temperature GaN buffer layer is deposited on the substrate, then an about 2.5-μm thick GaN epilayer with high Si doping is grown at 1040 °C, followed by InGaN/GaN MQWs grown on the GaN epilayer, finally about 200-nm thick p-GaN layer is grown. After the material growth, the samples are annealed to activate the Mg. For these InGaN/GaN MQWs, the barrier layers are GaN, but the wells are InGaN. The triple-axis X-ray diffraction (TAXRD) experiments are performed at the Beijing Synchrotron Radiation Facility. In this work, all the measurements are carried out at room temperature.

3. Results and discussion

Six InGaN/GaN MQWs samples A–F are studied in this experiment. For these samples, except the growth time of well layers other growth conditions are held constant. The GaN barrier thickness is about 25 nm and the In content in InGaN wells is around 10% for all these samples. All samples have five periods of QWs. The well thickness of samples A, B, C, D, E, and F is about 3.0, 3.3,

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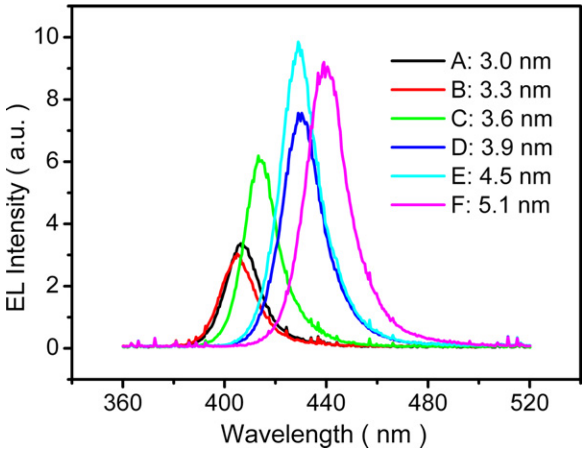

Fig. 1. The EL spectra of InGaN/GaN MQWs samples, the well thickness is 3.0, 3.3, 3.6, 3.9, 4.5 and 5.1 nm for samples A–F, respectively.

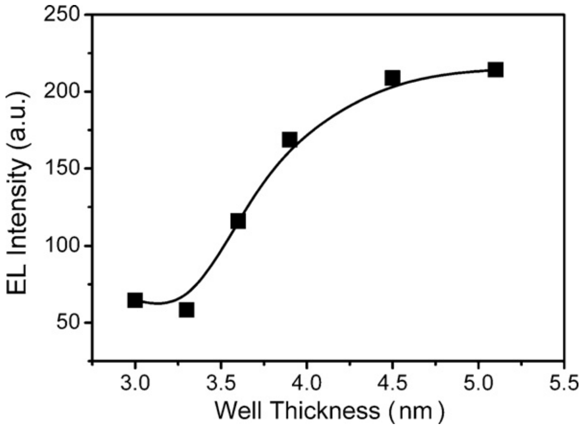

Fig. 3. The integrated EL intensity of InGaN/GaN MQWs vs. the well thickness. The line is a guide to the eye.

3.6, 3.9, 4.5 and 5.1 nm, respectively. The EL spectra of these samples are shown in Fig. 1. It is noted that the EL spectra of these samples are different. Not only the peak wavelength, but also the EL intensity change obviously with the variation of well thickness. The EL peak wavelength of samples A–F is 406, 404, 413, 430, 430, and 439 nm, respectively. It suggests that there is certain relationship between EL peak wavelength and well thickness of MQWs. Fig. 2 shows the dependence of the EL peak wavelength on the well thickness for these samples. There is a statistical trend that the EL peak wavelength increases with the increase of well thickness. Two mechanisms may be responsible for the redshift of EL peak wavelength: quantum confinement effect and quantum confinement Stark effect (QCSE). It is reported that due to the large effective electron mass of the nitrides, the quantum confinement effect is observed only when the well thickness of violet InGaN/GaN QW is less than 3.0 nm [6]. We attribute the redshift mainly to the QCSE caused by the spontaneous and piezoelectric effects in InGaN/GaN MQWs, which is a more important mechanism to induce remarkable redshift when the well width is large. It is known that a strong electric field results from the spontaneous and piezoelectric polarizations in GaN-based heterostructures [7–9], which will lead to the tilt of potential profile of QWs. With the increase of InGaN well thickness, as well known, the strain-induced polarization field increases, and the incline of energy band also increases, consequently the optical transition energy decreases due to the QCSE [10–13]. In fact, it has been demonstrated that the emission wavelength is strongly influenced by the QCSE for the InGaN/GaN quantum well structures with relatively wide well layers grown on sapphire [10]. Therefore, the increase of EL peak wavelength with the increase of well thickness is mainly due to the QCSE because of the existence of spontaneous and piezoelectric polarization field.

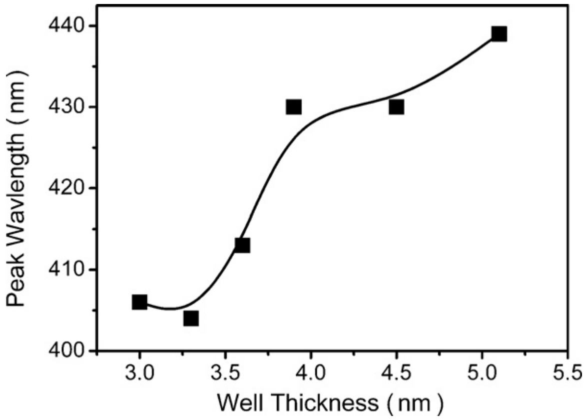

Fig. 2. The EL peak wavelength of InGaN/GaN MQWs vs. the well thickness. The line is a guide to the eye.

It is noted from Fig. 1 that the EL intensity of InGaN MQWs samples changes also very much with the well thickness. We have calculated integrated EL intensity of the six InGaN MQWs samples and studied the relationship between the EL intensity and well thickness. The integrated EL intensity values of these six InGaN MQWs samples are 64, 58, 116, 168, 208 and 214 for samples A, B, C, D, E, and F, respectively. It seems that statistically there is a strong dependence of the integrated EL intensity on well thickness, as shown in Fig. 3. The integrated EL intensity increases with the increase of well thickness. Especially when the well thickness changes from 3.3 to 4.5 nm, the EL intensity increases nearly as large as 3 times. It is a little surprising since there is strong QCSE due to the existence of spontaneous and piezoelectric polarizations. The electron and hole wave functions in the well will be separated in space and the transition matrix element will be reduced with the increase of well thickness [10]. As a result, the corresponding radiative transition probability and the EL intensity should be reduced. But the obtained experimental result contradicts this expectation. Therefore, it is speculated that there are other important factors playing an important role in determining the luminescence intensity of InGaN/GaN MQWs, leading to the increase of EL intensity even in the presence of QCSE.

There are several physical possibilities to make the EL intensity change with increasing well thickness. For example, the In compositional aggregation-induced disorders in InGaN layers may change with layer thickness. However, the In composition and the layer thickness of the investigated samples are small (approximately 10% and 3–5 nm, respectively), the clustering effect in different samples will not have any essential change under the same growth conditions. In addition, a reduced penetration of carrier wave functions into the barrier for wider well QWs may increase the radiative transition probability of the QWs. However, the enhancement of EL intensity with increasing well thickness is strong. The EL intensity of sample F ($d = 5.1$ nm) is nearly 3 times higher than sample A ($d = 3.0$ nm). Such an enhancement cannot be explained by the reduced wave function penetration of electrons and holes alone. To gain a deep insight into the mechanism of well thickness influence on the EL properties, the TAXRD measurements were carried out for four typical InGaN/GaN MQWs samples B, C, D, and E since the EL intensity changes most rapidly for these four samples. Fig. 4 shows the (0 0 0 2) ω–2θ scan XRD curves where a clear difference of interface roughness between these four samples is found. For example,

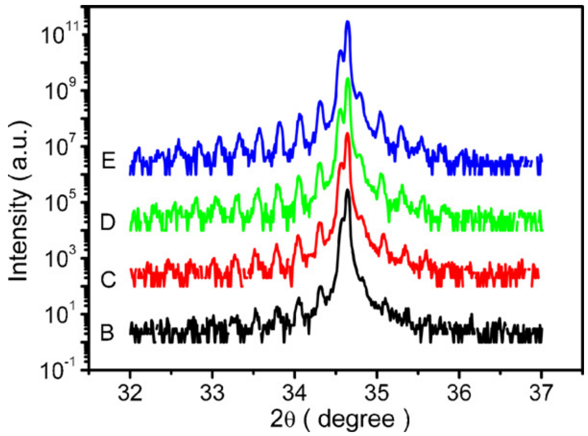

Fig. 4. The TAXRD (0 0 0 2) ω–2θ curves of samples B, C, D, and E. The corresponding well thickness is 3.3, 3.6, 3.9 and 4.5 nm, respectively.

only about four satellite peaks of superlattice (SL) structure can be observed in sample B. However, about eight satellite peaks can be distinctly observed in sample E. It is known that the full width at half maximum (FWHM) of satellite peaks will be broadened if the interface roughness of the SL structure exists, and for the MQWs samples the number of observed satellite peaks will be reduced by the rougher interfaces. Actually, the FWHM value for different order of satellite peak is not constant. It will increase with increase of the order [14]. Therefore, the interface roughness can be obtained according to the change of satellite peak's FWHM with the satellite peak's order. If the interface roughness is described by a Gaussian distribution function with standard deviation, the FWHM of the nth satellite peak will be expressed as [14]:

$$W_n = W_0 + (\ln 2)^{1/2} \cdot n \cdot \Delta\theta_{\mathrm{M}} \cdot (\sigma/\Lambda)$$

where n is the order of satellite peak, Λ is the period length, $\Delta\theta_{\mathrm{M}}$ is the angle distance between adjacent satellite peaks, and σ/Λ is the interface roughness. W_0 and W_n are the FWHMs of zeroth- and nth order peaks, respectively. Fig. 5 shows the relationship between the satellite peaks's FWHM and the peak's order for the InGaN MQWs samples B, C, D, and E. These data show a linear relationship, and according to the above-mentioned formula the interface roughness can be calculated from the slope of linear fitting of the data. It is found that the slope value for sample B is the largest, while the one of sample E is the smallest. In other words, the FWHM of sample B changes most rapidly with increasing diffraction order in the four samples, while the FWHM of sample E changes most weakly in the four samples. The interface roughness obtained according to the slope values is about 8.8%, 3.8%, 2.3%, and 1.0% for samples B, C, D, and E, respectively. We thus can judge that sample B has the roughest interface, while sample E has the flattest interface. Taking the dependence of EL intensity on the well thickness into account, it is deduced that the interface roughness may play a dominant role in determining the EL intensity of InGaN MQWs samples. A flatter interface will correspond to a stronger EL intensity in InGaN MQWs. It is also implied that the smoother interface of InGaN MQWs samples can be obtained by increasing the well thickness from 3.3 to 5.1 nm in the MOCVD process.

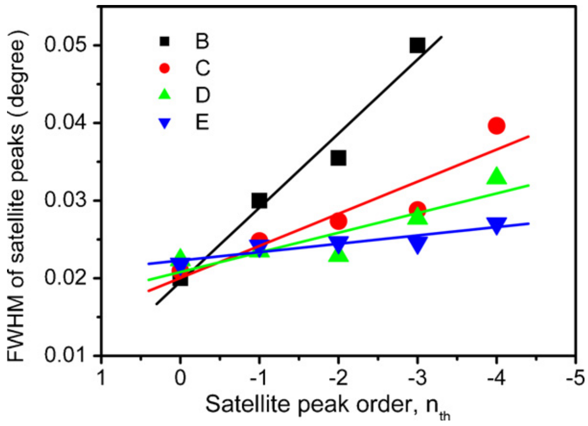

Fig. 5. The dependence of FWHM of satellite peaks on the satellite orders of InGaN/GaN MQWs samples B, C, D, and E. Symbols and lines are experimental data and linear fit curves, respectively.

Some research works have reported about the photoluminescence or EL dependences on the well thickness of InGaN/GaN quantum wells [10,15]. However, such influences of well thickness parameter depend on both physical mechanism and real growth conditions of strained InGaN QWs. The latter may be different for different groups. It is noted that few works have investigated the influence of well thickness on interface roughness and the corresponding luminescence intensity of InGaN QWs. In our experiment it is found that the interface becomes rougher when the well is narrower, and the interface becomes smoother when the well becomes wider. In fact, a part of wave functions of electrons and holes of QWs will more easily penetrate into the barrier when the well is thin, and will cause an increase of non-radiative recombination through non-radiative interface defects, especially in the case of rough interface [6,16,17]. As a result, it is observed that the EL intensity decreases when the well thickness is small. When the well thickness increases, the interface becomes smoother, the wave functions of electrons and holes are better confined in the wider wells, so the luminescence transitions will not be influenced as much by the interface-related defects. Consequently, the EL intensity increases with increasing well width remarkably. In fact, the high interface quality is very important for the efficient emission of GaAs/AlGaAs MQWs [18,19]. Our experimental result confirms that the smooth interface is necessary for the high performances of InGaN MQWs. In view of the rather low In composition in the investigated samples, normally the QCSE is rather low and other effects can play a more important role in determining the luminescence of InGaN MQWs samples. However, we are aware that when the well layer is too wide, due to the stronger spontaneous and piezoelectric polarization effect, the QCSE will play a more important role. In addition, the quality of strained InGaN layers will seriously deteriorate and the EL intensity will be reduced [17]. It is worth to note that the reported InGaN well thickness along the polar c-plane is typically ~2.5–4.0 nm [20]. We think that the value may be the optimized result related to physical and structural factors up to now, including the important influences of QCSE and interface roughness.

4. Summary

In summary, the influences of well thickness on the EL of InGaN/GaN MQWs are investigated. It is found that the EL peak wavelength has a redshift with the increase of well thickness, which is mainly attributed to the action of QCSE due to the effect of spontaneous and piezoelectric polarizations. It is also found that the EL intensity of InGaN MQWs increases with the increase of well thickness between the range of 3.3 and 5.1 nm. The X-ray diffraction experiments demonstrate that the interface roughness decreases with the increase of well thickness. It suggests that the interface roughness may play a key role in influencing the EL intensity of InGaN MQWs as it can be improved by suitably increasing the well thickness.

Acknowledgments

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