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Research Article

Investigating the Effect of Piezoelectric Polarization on GaN-Based LEDs with Different Prestrain Layer by Temperature-Dependent Electroluminescence

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The effect of piezoelectric polarization on GaN-based light emitting diodes (LEDs) with different kinds of prestrain layers between the multiple quantum wells (MQWs) and n-GaN layer is studied and demonstrated. Compared with the conventional LED, more than 10% enhancement in the output power of the LED with prestrain layer can be attributed to the reduction of polarization field within MQWs region. In this study, we reported a simple method to provide useful comparison of polarization fields within active region in GaN-based LEDs by using temperature-dependent electroluminescence (EL) measurement. The results pointed out that the polarization field of conventional LED was stronger than that of the others due to larger variation of the wavelength transition position (i.e., blue-shift change to red-shift) from 300 to 350 K, and thus the larger polarization field must be effectively screened by injecting more carriers into the MQWs region.

1. Introduction

GaN-based materials generally exist in a wurtzite crystal structure which has a strong polarization field along the *c*-plane direction. Therefore, the space charges induced by spontaneous and piezoelectric polarization fields were at the interfaces of heterostructure for GaN-based materials, for example, in the *c*-plane InGaN/GaN multiple quantum wells (MQWs) structure. This inherent effect, which was called quantum-confined stark effect (QCSE), has resulted in the reduction of quantum efficiency for the GaN-based LEDs. This is because the QCSE within MQWs region lead to the significant spatial separation of the electron and hole wave functions and the reduction of the electron-hole recombination probability [1–5]. Furthermore, investigating the spontaneous and piezoelectric polarization-induced electrostatic field on InGaN/GaN MQWs heterostructure is a very important key issue currently. Thus, many novel and useful growth techniques and structures have been developed to release the strain and reduce the separation of the wave function in the InGaN QWs to improve the optical properties of nitride-based LEDs [6–14].

Besides, some research groups also calculate both the internal electric-field strengths and the carrier density screening of the potential by the measured spectral shifts using photoluminescence (PL) system [15–18]. In our previous work [19], we also successively reported a simple method by temperature-dependent EL measurement to provide useful comparison of electrostatic fields within the QWs of GaN-based LEDs, specifically for structures consisting of identical active regions with different barrier thicknesses. On the other hand, several studies have revealed that the optical properties of LEDs with the structures of InGaN/GaN short-period superlattices (SPS) or low-temperature (LT) GaN layer between the n-GaN and MQWs can be improved due to the release of the residual strain in MQWs, reduction of the QCSE, enhancement of electron-hole recombination rate, reduction of the V-defect density, and improvement of the crystal quality in MQWs [17, 18, 20, 21]. However, it is very necessary to investigate the more detailed relationship between prestrain layer and QCSE. Moreover, in this study, the strengths of the polarization field and the effect of QCSE in the active region of GaN-based LEDs with different

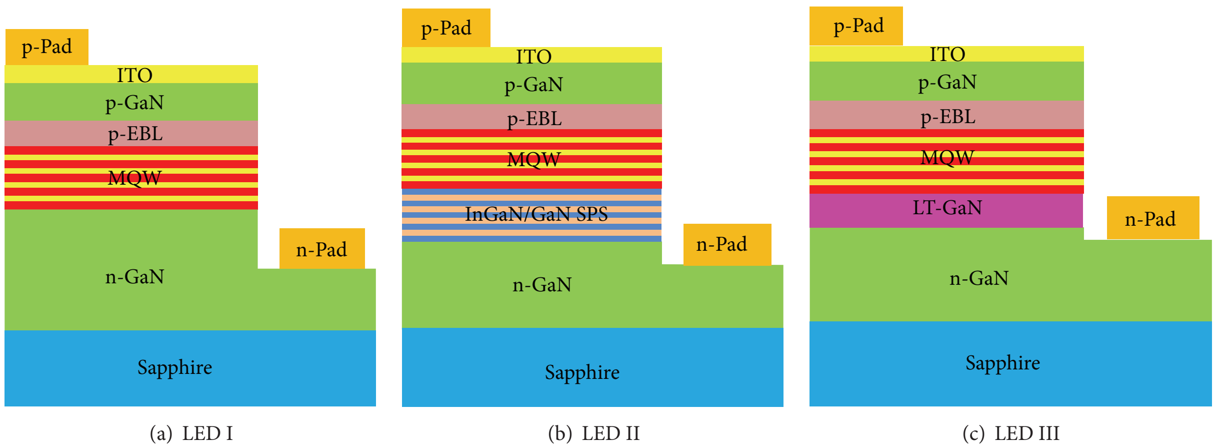


Figure 1: The schematic structures of the three fabricated LEDs. (a) LED I without any specific prestrain interlayer. (b) LED II with InGaN/GaN SPS interlayer. (c) LED III with LT-GaN interlayer.

prestrain layer were compared by using our previous method of temperature-dependent EL measurement.

2. Experimental

All samples used in this study were grown on *c*-plane (0001) sapphire (Al_2O_3) substrate by metal-organic chemical vapor deposition (MOCVD). During the growth, trimethylgallium (TMGa), trimethylindium (TMIn), and ammonia (NH_3) were used as gallium, indium, and nitrogen sources, respectively, while biscyclopentadienyl magnesium (CP_2Mg) and disilane (Si_2H_6) were used as the p-type and n-type doping sources, respectively. The conventional LED structure, called LED I, consists of a 30 nm thick buffer layer grown at low temperature, a 1.5 μm thick undoped GaN layer grown at 1040°C, a 2 μm thick Si-doped n-GaN layer grown at 1040°C, and an MQW active region grown at 750°C. The MQW active region consists of 10 periods of 3 nm thick InGaN well layers (with nominal indium content ~17%) and 10 nm thick GaN barrier layers. Subsequently, the temperature was elevated to 1000°C to grow a 30 nm thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer (EBL) and a 0.3 μm thick p-GaN layer. In order to reduce the strain and polarization effect in the active region, the LEDs with prestrain interlayer structure are also prepared. As shown in Figure 1, the LEDs with lower-indium content (~5%) 10-pair InGaN (2 nm)/GaN (3 nm) SPS interlayer grown at 800°C were labeled as LED II. And the LEDs with LT-GaN (50 nm) interlayer grown at 750°C were labeled as LED III. The as-grown samples were subsequently annealed at 750°C in N_2 ambient to active Mg in the p-type layers.

After the growth, the surface of the samples was partially etched until the 2 μm thick Si-doped n-GaN layer was exposed. Subsequently, a 70 nm thick indium-tin oxide (ITO) layer was deposited by sputter system onto the p-GaN layer to serve as a current spreading layer. A Ni/Au (30 nm/500 nm) metal contact was deposited on the ITO layer to form the p-electrode. A Ti/Al/Ti/Au (15 nm/450 nm/50 nm/500 nm) metal contact was then deposited on the exposed n-GaN layer to form the n-electrode. The LEDs fabricated in this study had a chip size of 250 × 580 μm^2. The light output powers were measured by the integrating sphere detector. The optical characteristics of these samples were measured by EL system.

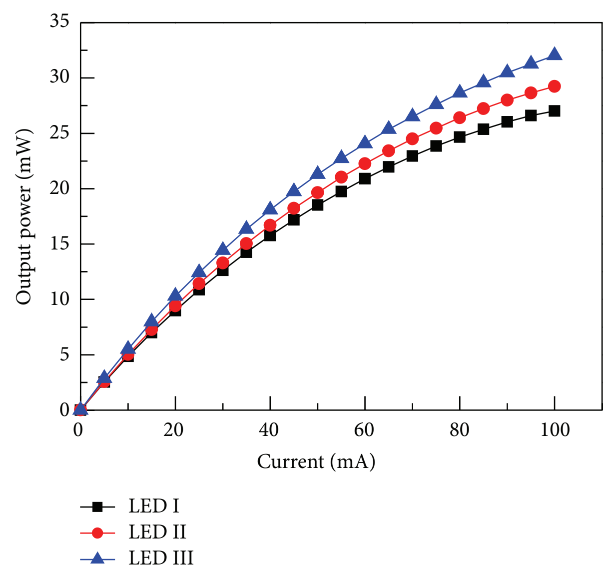


Figure 2: Light output powers measured from LEDs I, II, and III as functions of injection currents.

3. Results and Discussion

Figure 2 shows the measured light output power as a function of the injection current for these three fabricated LED structures. In order to avoid the effects of self-heating, we applied pulse-width-modulated injection currents on each of the measured LEDs [22]. By increasing the injection current, the light output powers of these three fabricated LED

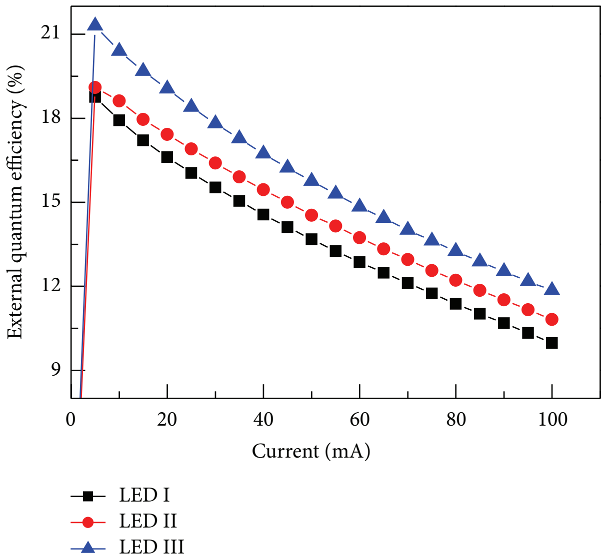


FIGURE 3: EQE as functions of injection currents for LEDs I, II, and III.

structures are increased. At an injection current of 20 mA, the light output powers of LEDs I, II, and III are 8.99, 9.42, and 10.30 mW, respectively. The output powers of LEDs II and III with prestrain structures were 4.8 and 14.6% higher than those of LED I, respectively. It was also found that the difference of output power between these three LEDs was remarkably enlarged especially at higher injection current. Compared with LED I, the light output powers of LEDs II and III were improved by approximately 8.2% and 18.6% under an injection current of 100 mA, respectively. These results show that the light output power can be improved obviously with inserting the prestrain interlayers between the n-GaN and MQWs. This means that the improvement of output power can be attributed to the release of the residual strain, the reduction of the polarization field and QCSE, the enhancement of electron-hole recombination rate, the reduction the V-defect density, and the improvement of the crystal quality in MQWs for LEDs II and III [20, 21]. Figure 3 shows the measured external quantum efficiency (EQE) as a function of injection current. The EQE is defined as

$$\mathrm{EQE} = \frac{P/(h\nu)}{I/e}, \tag{1}$$

where P is the light output power, $h\nu$ is the energy of photon emitted from a semiconductor, I is the injection current, and e is the electron charge. When the LED is operated with injection current, the light power and emission wavelength are measured by integrating sphere detector at the same time. Thus, the values of EQE can be calculated by using (1). The peak efficiency of LEDs I, II, and III is 18.8%, 19.1%, and 23.3%, respectively. The improvement of EQE for LEDs II and III is mainly due to the partial strain relaxation within the active region, which resulted in a less tilt of band-edge and a better overlap of the electron and hole wave functions in each quantum well. It implies that the polarization field within the active region in this study could be reduced effectively by inserting prestrain interlayer structure.

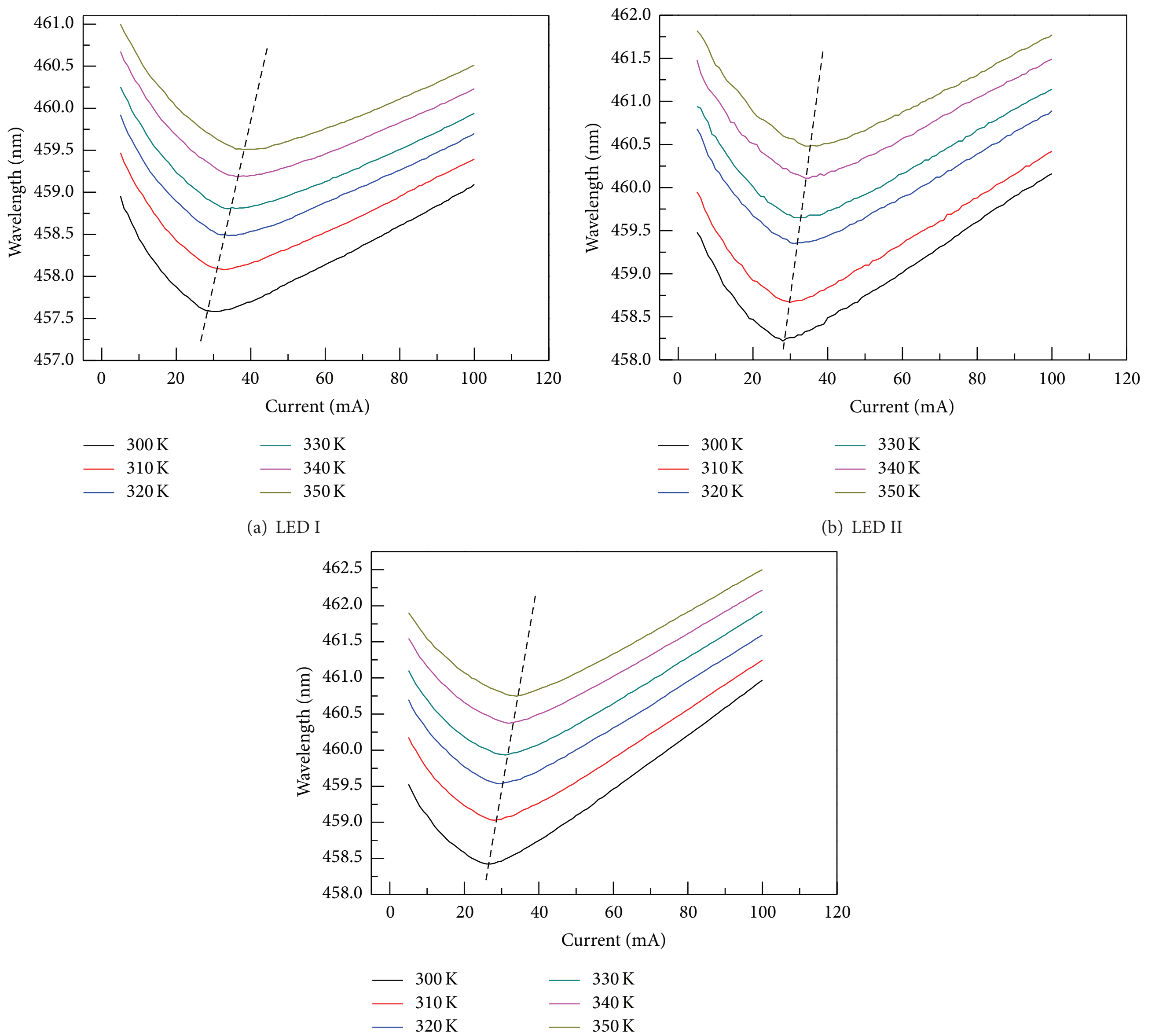
In order to further differentiate the piezoelectric polarization field for these three fabricated LED structures, the emission spectrum characteristics of the LEDs by temperature-dependent EL were measured and achieved. The temperature of the LEDs was varied by using a heat controller. The temperature was ramped from 300 K up to 350 K with a step of 10 K. Figures 4(a)–4(c) show the peak emission wavelength of these three fabricated LEDs at various ambient temperatures as a function of injection current. First, it was obviously found that the overall emission wavelength in these three LEDs shifted to longer wavelength as the ambient temperature increased. The temperature dependence of the energy band-gap for a semiconductor can be expressed by the *Varshni formula*:

$$E_g = E_g\big|_{T=0\,\mathrm{K}} - \frac{\alpha T^2}{T+\beta}, \tag{2}$$

where α and β are fitting parameters, frequently called the Varshni parameters [23]. It indicates that the energy band-gap of semiconductor generally decreases as the temperature increases, and thus the overall emission wavelength of the LEDs shifted to longer wavelength. The reason is that energy band-gap of quantum well became narrow which is caused by the increase in ambient temperature according to the Varshni effect [23, 24].

Then, it was also found that the wavelength of these three LEDs initially shifted toward shorter wavelength and then shifted toward longer wavelength as the injection current was increased. It is well known that the phenomenon of the wavelength shifting toward shorter wavelength was called blue-shift, which can be attributed to the screening effect and band-filling effect [25]. On the contrary, the wavelength shifted toward longer wavelength was called red-shift, which was induced by the thermal effect created by the parasitic resistances of contacts and semiconductor layers due to the I^2R dependence of Joule heating [24]. Regarding the blue-shift values of emission wavelength which was related with polarization field within the active region, it was found that these values for LEDs I, II, and III at room temperature were 1.37, 1.22, and 1.11 nm, respectively. Such a result showed that the conventional LEDs possess a larger blue-shift value than that of LEDs II and III with prestrain interlayer. This is because the stronger QCSE for LED I induced by the spontaneous and piezoelectric fields in the MQW layers would show an obvious screening effect and band-filling effect. These results once more explained that the polarization field within the active region in this study could be reduced effectively by inserting prestrain interlayer structure. Therefore, the output powers of LEDs II and III were improved due to a better overlap of the electron and hole wave functions in each quantum well.

On the other hand, it is very worthy to note that the value of injection current, at which the wavelength of blue-shift changed to red-shift, shifted to larger injection current



(a) LED I

(b) LED II

(c) LED III

Figure 4: The emission wavelengths as functions of injection currents under different ambient temperatures measured from 300 to 350 K for (a) LED I, (b) LED II, and (c) LED III.

when the temperature increased, as shown in the dashed line of Figure 4. It can be seen clearly that LED I as shown in Figure 4(a) has a more obvious change than those of LEDs II and III as shown in Figures 4(b) and 4(c). This is because the carriers injected into the MQWs would be excited by the higher ambient temperature. Thus, these excited carriers would escape from the MQWs, and the energy bandgap of MQWs caused by QCSE cannot be screened and filled effectively. In other words, it needs higher injection current to provide more carriers which can complete the screening effect of LEDs. Therefore, LED I without prestrain structure with more serious QCSE resulting from larger polarization field within the active region must inject more currents into QWs to compensate the screening effect.

Figure 5 also shows the blue-shift value as a function of ambient temperature on these three fabricated LED structures. It was found that the blue-shift values of these three LEDs kept almost the same with increasing ambient temperature. Such a result indicated that the value of blue-shift induced by screening and band-filling effect for these three LEDs was independent of the ambient temperature. In other words, this pointed out that QCSE caused by polarization field in this study did not change with the ambient temperature increase. Figure 6 shows the variation of the injection current of wavelength transition position from blue-shift to red-shift, which was extracted from the dashed line of Figure 4, as a function of the ambient temperature. It can be seen clearly that the slope of conventional LED is

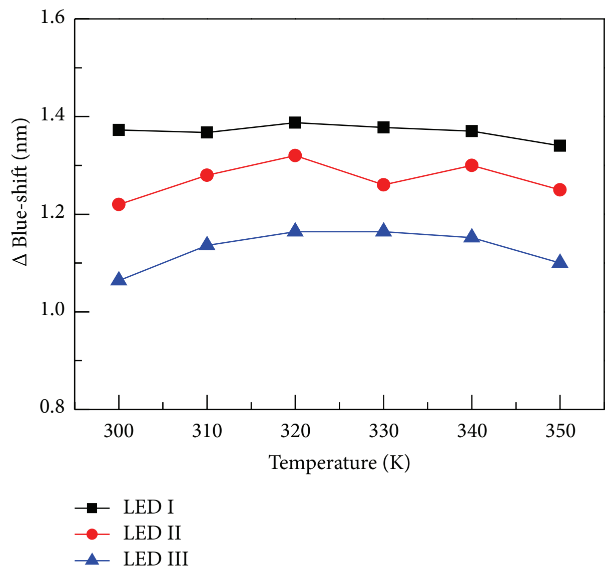


Figure 5: Blue-shift values of emission wavelength as functions of ambient temperatures for the three fabricated LEDs.

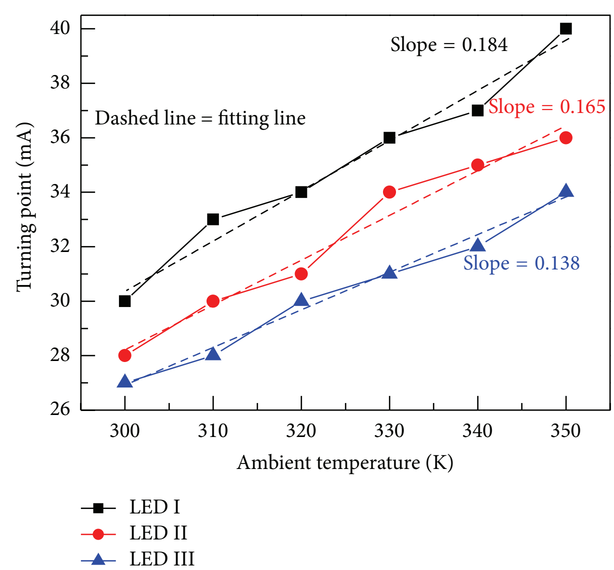


Figure 6: The turning points of injection currents (i.e., wavelength transition position from blue-shift to red-shift as shown by the dashed lines in Figures 4(a)–4(c)) as functions of ambient temperatures for the three fabricated LEDs.

larger than that of the other LEDs with prestrain interlayer. According to Figure 6, it was found that the injection current of wavelength transition position from blue-shift to red-shift of LED I, LED II, and LED III is 30, 28, and 27 mA at room temperature and that those of LED I, LED II, and LED III are 40, 36, and 34 mA at 350 K. The results again imply that the polarization fields within the active region of LED I were stronger than others due to larger variation of the injection current of the wavelength transition position from 300 K to 350 K, and thus it needed more injection carriers (higher injection current) to complete the screening of QCSE within the active region. Thus, we reported a simple method to provide useful comparison of electrostatic fields within the InGaN MQW active region on the GaN-based LEDs, specifically for structures consisting of identical active regions with different prestrain layers.

4. Conclusions

The effect of piezoelectric polarization on GaN-based LEDs with different kinds of prestrain layers between the MQWs layers and n-GaN layer is studied and demonstrated. Compared with the conventional LED, it was found that more than 10% enhancement in the output power of the LED with prestrain layer can be attributed to the reduction of polarization field within MQWs layers. In this study, we reported a simple method to provide useful comparison of polarization fields in the LEDs which were estimated using temperature-dependent EL measurement. The results pointed out that the polarization field of conventional LED was stronger than that of the others due to larger variation of the wavelength transition position (i.e., blue-shift change to red-shift) from 300 to 350 K, and thus the larger polarization field must be effectively screened by injecting more carriers.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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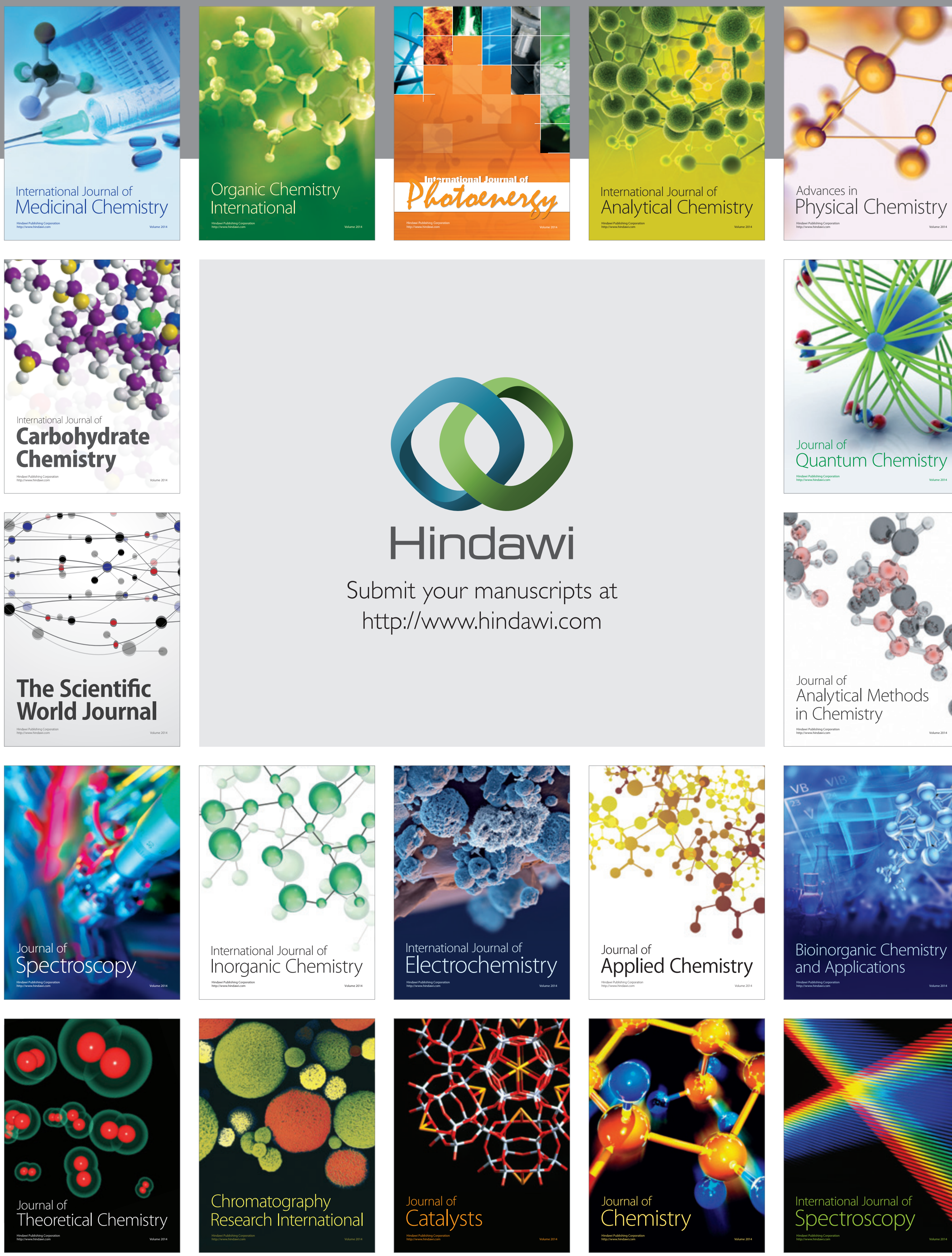

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