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Enhancement of the Optical Output Power of InGaN/GaN Multiple Quantum Well Light-Emitting Diodes by a CoFe Ferromagnetic Layer

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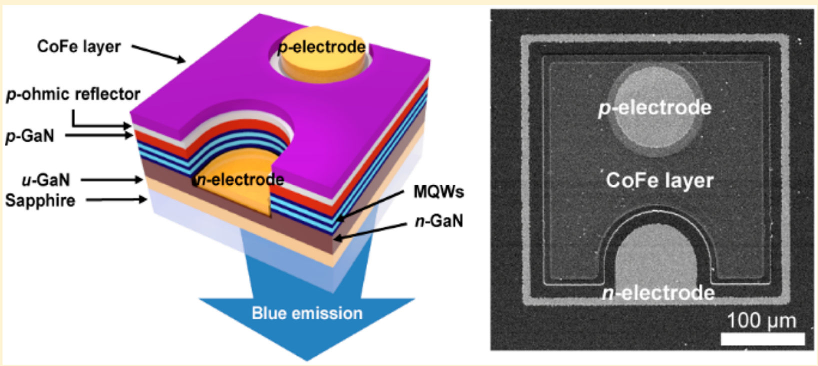

ABSTRACT: We report the increase of the optical output power of InGaN/GaN multiple quantum well (MQW) flip-chip blue light-emitting diodes (LEDs) using cobalt−iron (CoFe) ferromagnetic layers. The CoFe alloy layer is deposited on a p-ohmic reflector of the flip-chip LEDs to apply a magnetic field in the MQWs. The optical output power of LEDs with a CoFe layer after magnetization is increased by 23% at an injection current of 20 mA compared with LEDs that have a CoFe layer before magnetization. The time-resolved photoluminescence spectra and magnetic field simulations indicated that the improvement of the optical output power of the LEDs is attributed to an enhanced radiative recombination rate in the MQWs by the additional drift of carriers in the MQWs due to the gradients of the magnetic field of the CoFe ferromagnetic layer.

KEYWORDS: *magnetic field, ferromagnetic layer, InGaN/GaN light-emitting diodes, carrier localization, radiative recombination*

Recently, much attention has been given to high-efficiency GaN-based light-emitting diodes (LEDs) for various applications, including general illumination, displays, and automobiles, due to their intrinsic advantages, such as low energy consumption and environmental benefits.[1] For high-efficiency GaN-based LEDs, many studies have been carried out to improve the external quantum efficiency of LEDs, which is a product of the internal quantum efficiency (IQE) and the light extraction efficiency (LEE). The LEE of top-emitting, flip-chip,[2] and vertical LEDs[3] has been enhanced using surface roughening,[4] patterned sapphire substrates,[5] antireflection subwavelength gratings,[6] photonic crystals,[7] and triangular-shaped LEDs.[8] The IQE has also been improved by increasing the radiative recombination rate in the active region of LEDs, which often employs an electron blocking layer,[9] modified multiple quantum wells (MQWs),[10] polarization matching,[11] and surface plasmons.[12] Recently, thin-film flip-chip LEDs and vertical LEDs have been widely used to improve light extraction efficiency, current spreading, drive current density, and heat dissipation.[13]

It has also been reported that the electrical and optical properties of various optoelectronic devices could be significantly changed when a magnetic field was applied to the active region. In organic semiconductor devices, an external magnetic field caused changes in the electroluminescence (EL), photoluminescence (PL), photocurrent, and electrical-injection current due to the modified ratio of singlet to triplet.[14] An external magnetic field increased the EL output, EL quantum efficiency, and the current in tris(8-hydroxyquinolinato)-aluminum(III) (Alq_3)-based organic LEDs due to the modulation of the ratio between singlet and triplet spin states.[15] In inorganic semiconductors, the low-temperature PL of GaAs/AlGaAs heterostructures[16] and the Hall measurements of InGaN/GaN MQWs[17] showed that the localization of carriers was increased in the active region by an external magnetic field. A gradient of the magnetic field of ferromagnetic stripes caused a drift motion of electrons in GaAs/AlGaAs heterojunctions due to external magnetic fields.[18] However, most of these results have been demonstrated for MQWs under strong external magnetic fields of over 1 T that were produced from separate magnets. It is desirable to examine the effect of

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the magnetic field from a thin magnetic layer in GaN LEDs on the electrical and optical properties of GaN LEDs. In this study, we first demonstrate that the optical output power of InGaN/GaN MQWs LEDs can be significantly enhanced by the gradient of the magnetic field from a CoFe ferromagnetic layer deposited on a p-ohmic reflector in flip-chip LEDs. The results of this study indicate that the gradient of the magnetic fields from the CoFe layer deposited on the p-ohmic reflector layer of LEDs increases the carrier drift in the MQWs and enhances the radiative recombination rate of electrons and holes in the MQWs.

■ METHODS

We first grew a flip-chip InGaN/GaN MQW LED (Figure 1) on a double-sided polished sapphire substrate using metal−organic chemical vapor deposition. The LED structure on the sapphire substrate consisted of an undoped GaN layer (2.5 μm), a Si-doped n-GaN layer (2 μm), five periods of InGaN/GaN (3 nm/7 nm) MQWs with an emission wavelength of 460 nm, and a Mg-doped p-GaN layer (200 nm). After etching the n-GaN layer using inductively coupled plasma to provide an n-contact area, Ni/Ag/Ni (5 nm/120 nm/2 nm) layers were sequentially deposited on p-GaN as a p-ohmic reflector using electron beam (e-beam) evaporation to fabricate the flip-chip LEDs. Then, the Ni/Ag/Ni layers were annealed at 500 °C for 1 min in air to achieve a good ohmic contact with the p-GaN layer. Moreover, Cr/Au (50 nm/150 nm) layers were deposited on the n-GaN as n-pad electrodes and on the Ni/Ag/Ni layer as p-pad electrodes using e-beam evaporation. A 300 nm thick CoFe (90:10 wt %) layer was then deposited on the p-ohmic reflector using direct current magnetron sputtering at room temperature, and a 3 nm thick Ta layer was deposited on CoFe as a capping layer to prevent oxidation of the CoFe layer. A p-electrode with a smaller diameter than the hole was formed on the p-ohmic reflector through the hole in the CoFe layer as shown in Figure 1b, and the current was directly injected into the p-ohmic reflector to prevent a possible spin-polarized current injection into the LEDs through the ferromagnetic CoFe layer.[19] Finally, the sample was magnetized by an external magnetic field of 0.5 T in the in-plane direction of the LED wafer at 180 °C for 1 h.

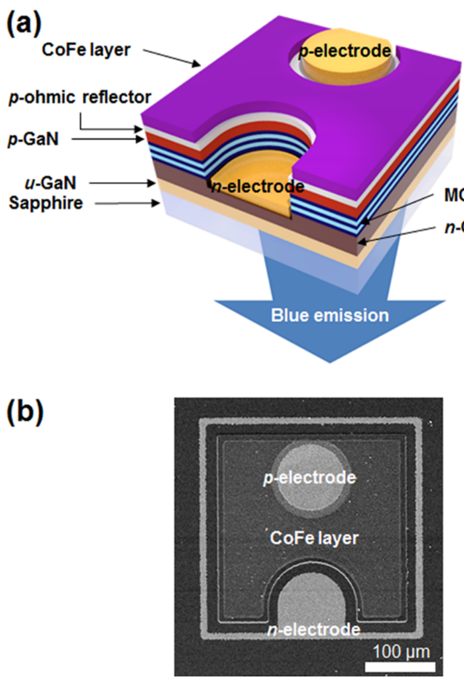

Figure 1. (a) Structure of the flip-chip LEDs with the CoFe ferromagnetic layer. (b) Scanning electron microscope image of flip-chip LEDs with a CoFe ferromagnetic layer.

The electrical and optical output power of the flip-chip LEDs with a CoFe layer were measured using a semiconductor parameter analyzer (HP-4155A) and a calibrated Si photodiode connected to an optical power meter. The time-resolved photoluminescence (TR-PL) spectra were measured at 290 K to further understand the emission mechanism. The light source was a wavelength-tunable mode-locked Ti:sapphire laser with a 140 fs pulse width and 80 MHz repetition rate (Chameleon Ultra II, Coherent Inc.). To measure the TR-PL spectra, the laser beam was frequency-doubled to 400 nm using a β-BaB_2O_4 crystal, and the InGaN/GaN MQWs were selectively excited using a laser beam introduced from the bottom side of the sapphire substrate in the flip-chip LEDs with the CoFe layer. The repetition rate was reduced to 976 kHz using a pulse picker to obtain a temporal window as long as 1 μs. The collected PL was dispersed by a 30 cm monochromator and detected by a streak scope (C10627, Hamamatsu Photonics K.K.) to measure the PL decay curves.

■ RESULTS AND DISCUSSION

Figure 2a shows the vibrating sample magnetometer characteristics of a 300 nm thick CoFe layer on a p-ohmic reflector of Ni/Ag/Ni (5 nm/120 nm/2 nm) deposited on a Si substrate. The CoFe layer had a square hysteresis loop (Figure 2a), with a saturation magnetization of 1078 emu/cm^3 at room temperature. To show the distribution of the magnetic flux density in LEDs, we performed a simulation using the finite-element method magnetics.[20] In the simulation, the distance between the CoFe layer and the MQW layer of the LED was 350 nm, and the thickness and area of the CoFe layer were 0.30 μm and 300 × 300 μm^2, respectively. Figure 2b shows the distribution of the magnetic field in the MQWs of the LEDs. The magnetic field is strong at both edges of the MQWs and decreases with increasing distance from the edge to the center region of the MQWs. The result shows that magnetic field gradients are produced in the MQWs by the CoFe layer and that the carriers can drift in a direction (in-plane of the MQW layer) parallel to the magnetic field gradient.[21]

Figure 3a shows the current−voltage (I−V) characteristics of the flip-chip LEDs with the CoFe layer before and after magnetization of the CoFe layer. The external magnetic field for magnetization of the CoFe layer was removed to measure the electrical and optical output power of the LEDs. The forward voltages of 3.9 V of both LEDs were nearly the same at 20 mA, but the series resistance of the LED with the CoFe layer after magnetization was slightly increased compared with that of the LED with the CoFe layer before magnetization. The slight increase in series resistance is presumably due to the magnetic-field-induced drift of carriers in the lateral direction of the LEDs.[17] Figure 3b shows the optical output power of the LEDs with the CoFe layer before and after magnetization as a function of injection current. The optical output power was measured from the bottom side of the flip-chip LEDs using a Si photodiode. The optical output power of the LEDs with the CoFe layer after magnetization was increased by 23% at an injection current of 20 mA compared with that of the LEDs

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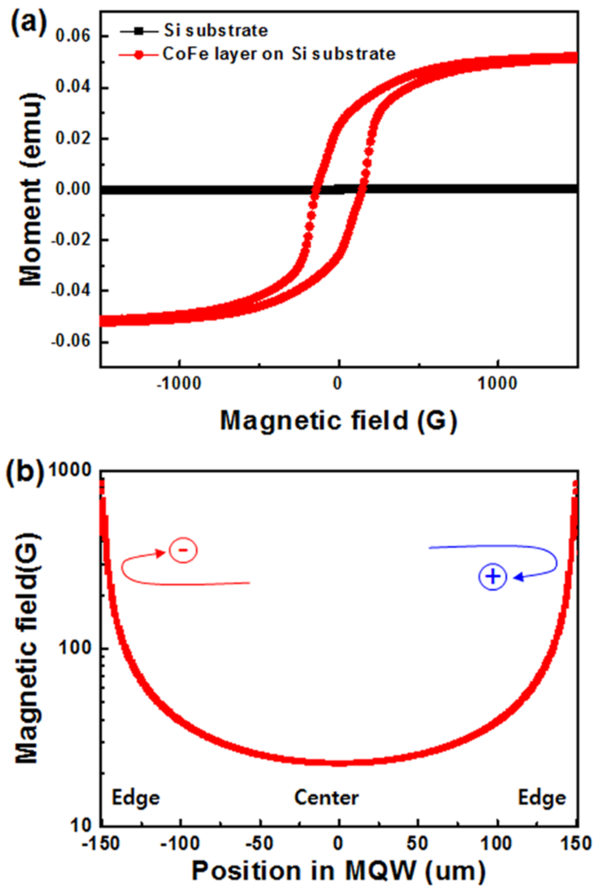

Figure 2. (a) Vibrating sample magnetometer characteristics of the CoFe layer. (b) Simulation result of magnetic field distribution between the edge and the center of the MQWs in the LEDs.

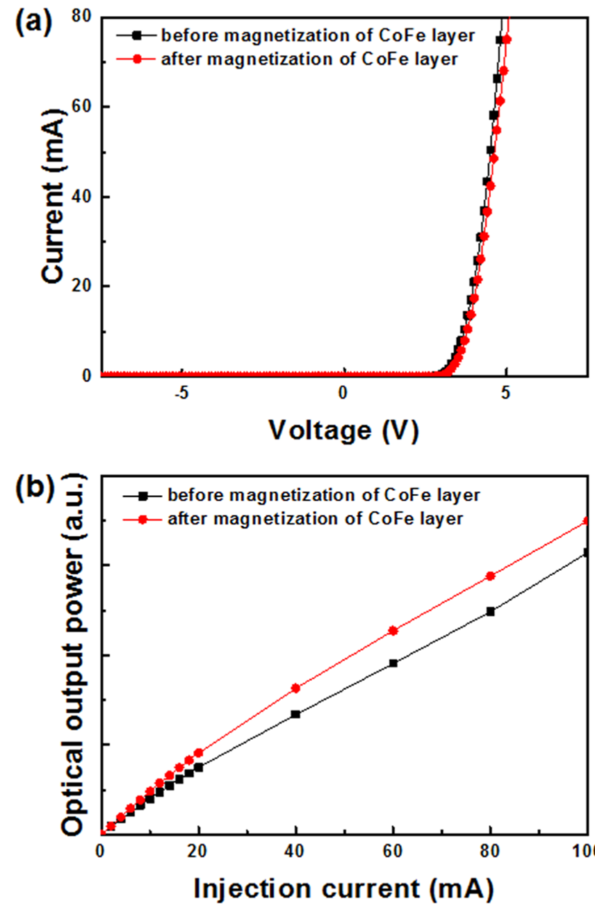

Figure 3. (a) $I-V$ characteristics and (b) optical output power of the LEDs before and after magnetization of the CoFe layer.

with the CoFe layer before magnetization. We attribute the increase of the optical output power of the LEDs with ferromagnetic CoFe layers after magnetization to the lateral drift and localization of carriers in the potential minima of the In-rich region in MQWs[16,17,21] and the subsequent increase in the radiative recombination rate. When the carriers diffuse in MQWs and are trapped in the radiative recombination centers, they will radiatively recombine. To estimate the increase of optical output power due to the magnetic field gradient, we assume that the localized states (In fluctuation) are uniformly distributed in InGaN MQWs and that the carriers are radiatively recombined in the localized states contained in the area defined by the diffusion length of the carrier. To estimate the diffusion length of the carrier increased by the magnetic field gradient, we estimated the resistivity changes according to the procedure in ref 18. First, the lateral resistivity was estimated to be decreased to 0.62 by a magnetic field gradient of CoFe, assuming that CoFe has a saturation magnetization of 1.43 T.[22] Then, the lateral diffusion coefficient of the carrier was expected to increase by a factor of 1.62 because of the relation $\rho = (h/4\pi m^* e^2)D^{-1}$, where ρ is the resistivity, h is the Planck constant, m^* is the effective mass in GaN, and D is the diffusion coefficient. Thus, the increased diffusion length l_D was estimated to be 27% based on the relation $l_D = (D\tau_r)^{1/2}$, where τ_r is radiative lifetime. Then, the number of localized states in the area corresponding to the diffusion length under a magnetic field gradient was increased by 61%, compared to that in LEDs without a magnetic field gradient. However, this value should be divided by a factor of 2 because the diffusion process is enhanced in one direction under the magnetic field gradient and the increased optical output power will be 30.5%. This result indicates that the enhanced optical output power of 23% is mostly attributed to the increased diffusion length of carriers in MQWs resulting from the magnetic field gradient from the CoFe layer.

To examine the effect of uniform magnetic fields on LEDs, we also measured the electrical and optical properties of the same LEDs without magnetic films. The LEDs were exposed to a uniform magnetic field of 0.35 T, produced by permanent magnets. The direction of the external magnetic field was aligned either parallel or perpendicular to the MQW planes in the LEDs. In these configurations of LEDs and the magnetic field, the forward voltage, series resistance, and optical output power of the LEDs did not change. These results indicate that carrier motion in the MQWs was not affected by the weak uniform magnetic field of 0.35 T at room temperature in this study, while a few studies have reported that the localization of the carrier in an active region can be increased at low temperatures under strong and uniform magnetic fields.[16,17] However, it was reported that the carriers can drift in a GaAs/AlGaAS heterojunction under a magnetic field gradient produced from a magnetic layer even though the magnetic field is very weak, i.e., below 0.05 T.[18] In this study, the strength of the magnetic field from the CoFe magnetic layer on the p-ohmic reflector was 0.1 T in the MQWs. Although the strength of the magnetic field in our sample was weaker than those

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observed in refs 16 and 17, the magnetic field gradient from the CoFe layer is strong enough to localize the carriers in the In-fluctuations in the MQWs of LEDs. When the distance between the external permanent magnet and the LED was large, the uniform magnetic field was too weak to localize the carriers in the MQWs at room temperature. However, when the CoFe layer was deposited on the LED, the distance between the CoFe layer and the MQWs was very close and the magnetic field gradients produced from the edges of the CoFe layer were strong enough to localize the carriers in the In-rich regions and increase the radiative recombination rate of carriers in the MQWs and optical output power of the LEDs. We also examined the effect of the annealing temperature of 180 °C used for the magnetization of CoFe on the electrical and optical properties of LEDs with the CoFe layer. After the LEDs without the CoFe layer were annealed at 180 °C for 1 h, the measured $I-V$ curves and optical output powers were not changed at all, indicating that the increase of optical output power was not due to the change of properties of the various layers in the LEDs via the thermal annealing process.

We measured the TR-PL spectra of the LEDs before and after magnetization of the CoFe layer to understand the carrier recombination process in LEDs, as shown in Figure 4. The

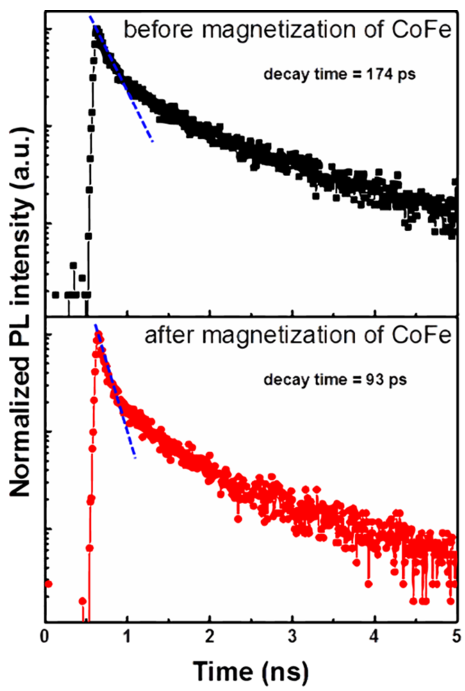

Figure 4. TR-PL spectra of LEDs before (top) and after (bottom) magnetization of the CoFe layer.

decay time of the LEDs with the CoFe layer after magnetization decreased from 174 ps to 93 ps compared with that of the LEDs with the CoFe layer before magnetization. It is known that the decay time is increased by the localization of the carriers from the localized state to the lower-lying localized state.[23] However, the TR-PL decay time can be decreased by increasing the density of the carrier in the localized state due to the band-filling effect of the localized states that occurs because the localized states are fully occupied by the carriers and the radiative recombination rate is increased due to the Coulomb screening of the internal electric field and the band-filling effect of localized states.[24] In this study, the TR-PL decay time was decreased in LEDs with a magnetic layer after magnetization compared with that of LEDs with a magnetic layer before magnetization because the magnetic field gradient increased the carrier density in the localized states and the band-filling effect decreased the TR-PL decay time. Therefore, the TR-PL measurement of decay time strongly indicates that carriers efficiently recombined in the In-rich regions, increasing the optical output power of the LEDs with a ferromagnetic CoFe layer.

In summary, we first report the improvement of the optical output power of InGaN/GaN MQW flip-chip LEDs with a CoFe ferromagnetic layer deposited on a p-ohmic reflector. The optical output power of LEDs with a CoFe layer after magnetization was enhanced by 23% at 20 mA compared with that of the LEDs with a CoFe layer before magnetization. The magnetic field simulation indicated that the gradient of the magnetic fields enhanced the lateral drift of carriers in the MQWs and efficiently confined carriers in the potential minima of InGaN MQWs. The TR-PL spectra of the LEDs also showed that the enhancement in the optical output power could be attributed to the improvement of the radiative recombination rate in the MQWs of LEDs due to the gradient of the magnetic field from the CoFe ferromagnetic layer.

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Author Contributions

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Notes

The authors declare no competing financial interest.

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