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科学研究費助成事業　　研究成果報告書

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研究課題名（和文）	High brightness yellow and red LEDs with p-side down structure by using polarization-induced tunneling junction
研究課題名（英文）	High brightness yellow and red LEDs with p-side down structure by using polarization-induced tunneling junction

研究代表者

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研究成果の概要（和文）：The theory of polarization engineering was applied into the design of device structure of InGaN/GaN LED. At the end of the project, new device processing and epitaxial structure for long wavelength LED was developed.

研究成果の学術的意義や社会的意義
This research propose a novel device structure with advanced device theory toward the issue of developing high efficiency red and yellow InGaN/GaN LED.
The research has great potential in overcome the basic problem of InGaN/GaN LED to mitigate "the green gap".

研究成果の概要（英文）：The theory of polarization engineering was applied into the design of device structure of InGaN/GaN LED. At the end of the project, new device processing and epitaxial structure for long wavelength LED was developed.

研究分野： semiconductor and microelectronics

キーワード： GaN　LED　Polarization Engineering　Tunneling Junction

１．研究開始当初の背景

GaN-based long-wavelength light-emitting diodes (LEDs), such as green, yellow and red LEDs, are of importance in full color displays, and solid state lighting. However, the long-wavelength LEDs, especially in yellow and red emission range, still exhibit low efficiencies as compared with those of InAlGaP-based LEDs. Although the physical origin of low efficiency in long-wavelength LEDs is still under debate, the high In-composition InGaN in the multiple quantum wells (MQWs) is believed increasingly to be the key factor. The first point is the quality degradation of In-rich InGaN resulting from the low temperature growth of InGaN QWs, large lattice mismatch between InGaN and GaN, and high temperature destruction during the epitaxial process after the growth of MQWs. The other important point is reduced overlap between electron and hole wave functions in MQWs due to the quantum confined Stark effect (QCSE), mainly caused by the spontaneous and piezoelectric polarization field. These two issues become even worse for the high In-composition and thick InGaN QWs, two necessities for the long-wavelength LEDs. In order to weaken the QCSE in MQWs and improve the efficiency of long-wavelength LEDs. Recently, the concept of reversed polarization LEDs (RPLEDs) has been proposed based on reversing the direction of polarization field in MQWs. Conventional LEDs are grown along the [0 0 0 1] orientation on top of the Ga-polar n-type underlying layer with p-type cladding layer grown on top of the MQWs, which are called normal polarization LEDs (NPLEDs) structures. The RPLEDs can be achieved using a p-side-down structure (PDLEDs, p-type cladding layer is grown before MQWs) with Ga-polar III-nitrides or n-side-down structure (n-type cladding layer is grown before MQWs) with N-polar III-nitrides. Usually, the realization of high-quality N-polar III-nitrides by metal-organic chemical vapor deposition (MOCVD) is a challenging task, which limit the development of RPLEDs using N-polar III-nitrides. PDLEDs present several advantages for the development of long-wavelength emission emitters. For PDLEDs, the growth temperature of the p-GaN could be higher for the better electrical and crystalline quality without damaging the high In-composition MQWs, which may otherwise be subjected to the potentially damage by the high temperature required for the growth and annealing of Mg-doped AlGaN and GaN epilayers in conventional n-side down LED (NDLEDs). In addition, since it is much easier to grow n-type GaN with good crystalline quality and low sheet resistance even at much lower temperature, more In incorporation and better surface current spreading can be realized in PDLEDs, which are favorable for long-wavelength emission and electrode fabrication of LEDs. Moreover, PDLEDs allow a more stable emission wavelength with little blueshift even at the high current densities, enabling improved efficiency for long-wavelength devices. Some numerical simulations and experimental results also demonstrate several merits of PDLEDs in decreasing electron overflow, improving hole injection efficiency and reducing turn on voltage. Considering that the Ga-polar LEDs on sapphire substrates grown by MOCVD have been commercialized with smooth surface morphology and excellent electrical and optical properties, the growth of RPLEDs with p-side-down structures using Ga-polar III-nitrides can be compatible with the currently large-scale and commercial LEDs techniques.

Since the first report of PDLEDs more than a decade ago, many achievements have been realized. However, the recent performance of PDLEDs are still low as compared with that of conventional NPLEDs, which are mainly due to the high resistance buried p-GaN and the limited lateral current spreading of buried p-GaN. To solve these issues, the high brightness yellow and red LEDs with p-side down structure by using polarization-induced tunneling junction will be investigated in this research.

２．研究の目的

①. Weakening the QCSE in InGaN/GaN MQWs for a better overlap of between electron and hole wave functions in MQWs and higher efficiency of LED.

②. Improving the crystalline quality of high-In composition InGaN in MQWs for a longer wavelength emission.

③. Improving the current spreading of buried p-GaN and increasing the hole injection ability into MQWs.

④. Developing suitable device processing.

３．研究の方法

①. Developing high quality InGaN/GaN MQWs with high In-composition: InGaN/GaN MQWs will be deposited by MOCVD. Important growth parameter should be optimized for better crystalline quality of high In-composition InGaN.

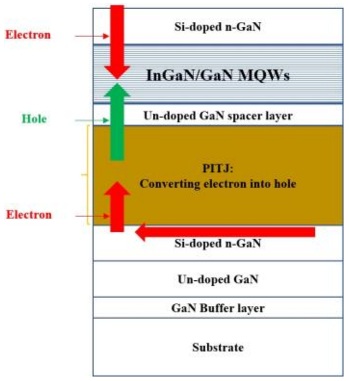


Fig.1. Schematic of p-side down LEDs structure with polarization-induced tunneling junction.

②. Developing polarization-induced tunneling junction (PITJ): Polarization-induced two- dimensional hole gas (2DHG) and two-dimensional electron gas (2DEG) will be integrated to form tunneling junction. The epitaxy of tunneling junction will be optimized in epilayer thickness, doping concentration, and alloy composition.

③. Integrating InGaN/GaN MQWs above the PITJ: High In-composition InGaN/GaN MQWs will be integrated above the PITJ to form a p-side-down structure LED, as shown in Fig.1.

④. Device processing: Then, device processing will be developed and optimized in such as lithography, metal deposition, mesa isolation and dielectric passivation.

4．研究成果

①. <u>The investigation of polarization-induced 2DHG for PITJ.</u>

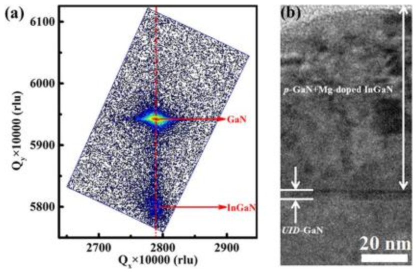


Fig.2. (a) The (10-14)-plane HRXRD reciprocal space mapping and (b) Bright-field cross-sectional TEM image with *g* vector of 0002 along the zone axis of [1-100] of the InGaN/GaN heterostructure.

The concept of p-channel InGaN/GaN heterostructure field effect transistor (FET) using a 2DHG induced by polarization effect is demonstrated. The existence of 2DHG near the lower interface of InGaN/GaN heterostructure is verified by theoretical simulation and capacitance-voltage profiling. The high-resolution X-ray diffraction (HRXRD) reciprocal space mapping (RSM) around (10-14)-plane reveals that the InGaN layer is totally strained on the GaN template, ensuring a good quality with large piezoelectric polarization field (as shown in Fig. 2(a)). Figure 2(b) shows the cross-sectional bright field transmission electron microscopy (TEM) image of the InGaN/GaN heterojunction. An abrupt interface can be clearly seen at the view in a high magnification.

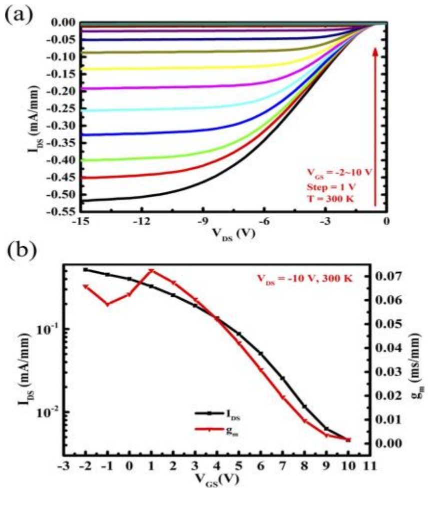
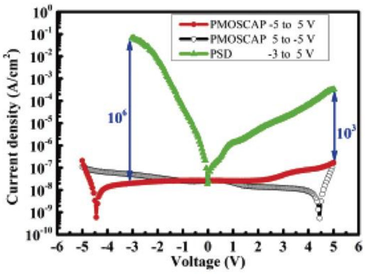


Fig.3. (a) DC output and (b) Semi-log plot of transfer characteristics and transconductance of the InGaN/GaN heterostructure MOSFET at 300 K.

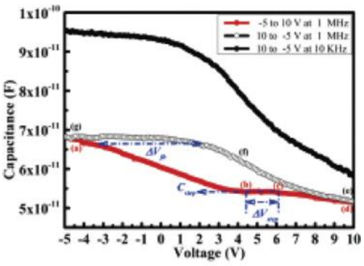
The metal-oxide-semiconductor FET (MOSFET) with Al_2O_3 gate dielectric shows a drain-source current density of 0.51 mA/mm at the gate voltage of -2 V and drain bias of -15 V, an ON/OFF ratio of two orders of magnitude and effective hole mobility of 10 cm^2/Vs at room temperature, as shown in Fig.3. The normal operation of MOSFET without freeze-out at 8 K further proves that the p-channel behavior is originated from the polarization-induced 2DHG. The work proved that the device design theory of GaN polarization effect can be utilized to realize 2DEG and 2DHG, which will beneficial for the further development of PITJ.

②. The investigation of dielectric/p-GaN interface for optimized device processing.



(a)

Fig. 4. I-V curves of the ALD-Al_2O_3/p-GaN PMOSCAP and PSD.



(a)

Fig.5. Bidirectional C-V characteristics of the ALD-Al_2O_3/p-GaN MOSCAP

Dielectric was usually for the device passivation of LED. The quality of dielectric on GaN is related to the leakage current, surface defects, which further influence the LED performance. In this work, the electrical hysteresis in current- voltage(I-V) and capacitance-voltage characteristics was observed in an atomic-layer-deposited Al_2O_3/p-GaN metal- oxide-semiconductor capacitor (PMOSCAP). As shown in Fig.4, the current density of the PMOSCAP was saturated at the positive bias owing to the lack of minority carriers. For the negative bias, the leakage current was totally suppressed with a current density of 2×10^{-7} A/cm^2 at -5 V. The gate leakage current for the PMOSCAP was three to six orders of magnitude lower than that of the p-GaN Schottky diode (PSD), indicating a good insulating property of ALD-Al_2O_3. However, in contrast to the PSD, the I-V characteristic of the PMOSCAP reveals a pronounced hysteresis when the forward and backward scans are compared. The absolute minimums of the current during the forward and backward scans occurred not at the minimum voltage level (0 V) but at -4.5 and +4.5 V, respectively. The shift of the absolute minimum in a direction opposite to that of the bias sweeping indicates that the current and the applied external gate bias were of opposite polarities, as the absolute minimum of a MOSCAP is usually fixed at 0 V, where current and voltage switch their polarities. As shown in Fig.5, A negative flat-band voltage shift of 5.5 V was acquired with a capacitance step from +4.4 to +6.1 V during the forward scan. Figure 6 displays an HRTEM image of the interface between ALD-Al_2O_3 and p-GaN. An interface layer with a thickness of ~2 nm is observed between the surface of p-GaN and ALD-Al_2O_3, as indicated by the yellow arrows. It was revealed that the Mg, Ga, Al, and O atoms were mixed with each other at the Al_2O_3/p-GaN interface. Therefore, an Mg-Ga-Al-O interface oxidized layer was formed with a large amount of a mixture of GaO_x, MgO_x, and AlO_x. Owing to the Mg surface accumulation, a Mg-Ga-O oxidized layer is usually created on the surface of p-GaN. Because this oxidized layer is a mixture of Mg-O and Ga-O, a disordered crystal lattice and inferior crystalline quality arise. This disordered region can serve as an atomic-diffusion channel. Therefore, Mg, Ga, Al, and O atoms at the Al_2O_3/p-GaN interface diffused easily into each other during the ALD process. The high-density trap states are considered to have resulted from the Mg-Ga-Al-O interface layer at the Al_2O_3/p-GaN interface, which also induced a large surface band bending of p-GaN and the electrical hysteretic characteristics of the PMOSCAP. Mg surface accumulation on p-GaN was demonstrated to induce an Mg-Ga-Al-O oxidized layer with a trap density on the order of 10^{13} cm^{-2}. The electrical hysteresis is attributed to the hole trapping and detrapping process in the traps of the Mg-Ga-Al-O layer via the Poole-Frenkel mechanism. The results indicate that effective surface pretreatments or novel oxide-free dielectric are necessary to optimize passivation process.

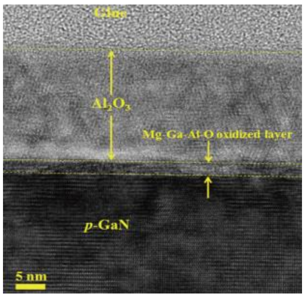


Fig. 6. HRTEM image of the ALD-Al_2O_3/p-GaN interface.

③. The development of LEDs device processing toward longer wavelength emission and higher efficiency.

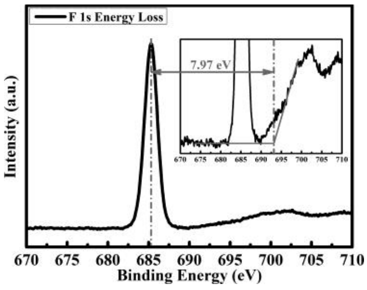


Fig. 7. F 1s CL spectrum with photoelectron energy loss peak for the 30-nm-thick CaF_2 bulk sample on p-GaN.

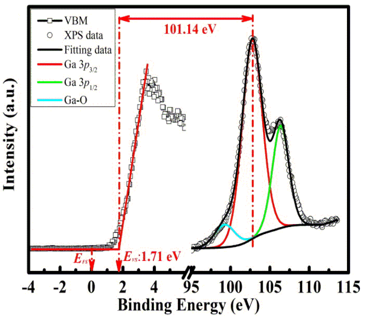


Fig. 8. Ga 3p3/2 core-level and VB spectra for bulk p-GaN.

The fabrication processing of LED device, such as lithography, metal deposition, mesa isolation and dielectric passivation has been improved. Calcium fluoride (CaF_2) was used as new dielectric to passivate the p-GaN. The interfacial chemical state and the band alignment of the sputtering-deposited CaF_2/p-GaN hetero-structure were investigated by angle-resolved X-ray photoelectron spectroscopy. As shown in Fig.7, by extrapolating a linear fit of the leading edge for the photoelectron energy loss peak to the baseline, the threshold energy of the F 1s photoelectron energy loss peak was determined to be 693.22 eV. The difference between the F 1s (685.25 eV) CL binding energy and the threshold energy of the photoelectron energy loss peak gives a band gap energy of about 7.97 eV, which is in good agreement with the reported values. As shown in Fig.8, from linear extrapolation of the leading edge of the spectra, the surface Fermi level E_{FS} of bulk p-GaN is estimated to be at 1.71 eV above the VBM. Assuming that the Fermi level is about 200 meV above the VBM, i.e., the Mg impurity level in the p-GaN bulk, this indicates a downward band bending of about 1.51 eV. As discussed previously, the large downward band bending of p-GaN surface is related to the surface Mg-Ga-O layer. The dependence of Ga 3p core-level positions on the collection angles proves that the downward band bending of p-GaN is reduced from 1.51 to 0.85 eV after the deposition of CaF_2, which may be due to the reduction of Mg-Ga-O-related interface states by the oxygen-free deposition of CaF_2. As shown in Fig.9, by taking into account the p-GaN surface band bending and potential gradient in the CaF_2 layer, the VBO at the CaF_2/p-GaN interface is estimated to be 2.66, with a total error of ±0.20 eV. Using the value of 7.97 eV for the CaF_2 bandgap and 3.39 eV for the p-GaN bandgap, a conduction band offset (CBO) is determined to be 1.92 ± 0.20 eV. These large band offsets indicate that CaF_2 can be a potential dielectric layer for the passivation of p-type GaN. the non-oxide gate dielectric with oxygen-free deposition processing is beneficial for the improvement of the quality of the dielectric/p-GaN interface.

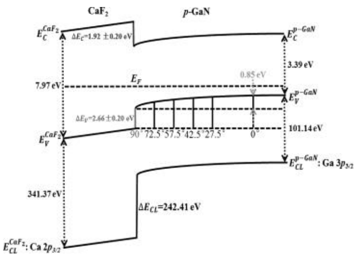


Fig. 9. Schematic band diagram for the CaF_2/p-GaN heterojunction.

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〔図書〕（計 0 件）

〔産業財産権〕

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権利者：
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〔その他〕
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