이학석사 학위논문

Morphology controlled growth of GaN microstructures on graphene for flexible light emitting diodes

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이 논문을 이학석사 학위논문으로 제출함

2017년 6월

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유동하의 석사 학위논문을 인준함

2017년 6월

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Abstract

Recently semiconductor materials have great attention for the achievement of technologies such as graphene and GaN. The graphene got a Nobel Prize at 2010. The graphene is suitable for optoelectronic devices such as optically transparency, flexibility, and mechanically strong. Above all things, the graphene can be easily lift off from substrate because bonding between layers is very week. The GaN materials also got a Nobel Prize at 2014. The GaN materials improve the efficiency of light emitting diodes (LEDs). The GaN has many properties such as high carrier mobility, high recombination rate, and long term stability. Therefore, the growth of GaN LEDs on graphene layers have both advantages of graphene and GaN materials. The combination of GaN materials and graphene will lead to wearable display.

The goal of this research is mainly morphology control of GaN microstructures such as pyramid shape, disk shape, and rod shape on graphene layers. However, it is hard to grow GaN microstructures on graphene layers directly. The buffer layer should grow between the graphene and GaN microstructures. Conventionally the GaN LEDs coated

on ZnO nanotube or nanowires, but in this research the GaN micro-rods minimize dependency of the buffer layer. Finally, the high aspect ratio GaN micro-rods are grown on thin ZnO nanowall. To fabricate high quality of LEDs, it is important to control quantum wells. The $GaN/In_xGa_{1-x}N$ is coated on GaN micro-rods, which has a large area of p-n junctions. Optical characteristics show the spectrum of blue light.

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Introduction

1

Recently semiconductor materials have great attention to achievement technologies such as graphene and GaN. The graphene got a Nobel Prize at 2010. The graphene is suitable for optoelectric devices such as optically transparency, flexibility, and mechanically strong. Above all things, the graphene can be easily lift off from substrate because bonding between layers is very week. The GaN materials also got a Nobel Prize at 2014. The GaN materials improve the efficiency of light emitting diodes (LEDs). The GaN has many properties such as high carrier mobility, high recombination rate, and long term stability.[1] The growth of GaN LEDs on graphene layers have both advantages of graphene and GaN materials. The combination of GaN materials and graphene lead to flexible LEDs, large scale LEDs, and transferable LEDs.

In chapter 3, the GaN is deposited on graphene layers using the metal-organic chemical vapor deposition (MOCVD). The condition of *n*-type GaN, *p*-type GaN and $In_xGa_{1-x}N$ is optimized with many times studies.

The conditions are summarized in chapter 3. Furthermore, the methods of LED fabrications and characterizations are described in detail.

The morphology of GaN microstructures can be controlled by growth techniques. The key parameters are growth temperature and V/III ratio, which is summarized in table 3.4. The structural analysis is shown in chapter 4.

Literature survey

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2.1. Inorganic semiconductor

Inorganic semiconductor such as Gallium nitride (GaN) has a high recombination rate and long term stability.[1-2] For the high quality of blue LEDs, inorganic semiconductor materials have a high carrier mobility property. [3-4] Furthermore, GaN microstructures with GaN/$In_xGa_{1-x}N$ multiple quantum wells (MQWs) can be controlled through growth technique. The GaN microstructures with MQWs affect quantum confinement.[5] In particular, coaxial structures GaN LEDs with MQWs have low dislocation density rather than that of GaN thin-film. [6-7]

Regarding fabrication, the top-down method is conventionally used for LEDs although there is an issue of dislocation density. The method of bottom-up is recently used for LEDs such as GaN nanowire. [8] The one dimensional (1D) GaN microstructures have attracted attention as optoelectronic devices.

2.2. GaN on graphene layers

The graphene got a Nobel Prize in physics at 2010, because it has interesting properties such as flexibility and week bonding. Furthermore, the graphene achieves a breakthrough of size as large as 30 inches, as shown in Figure 2.1.[9] It shows that large scale LEDs can be fabricated on graphene layers.

The CVD graphene is synthesized on Cu foil, and multi-layer graphene layers are transferred onto SiO_2/Si substrate. The graphene layers are used as flexible substrates and a buffer layer for epitaxy. Also, the graphene expands for large size substrates.

To control the position of GaN microstructures, the SiO_2 growth mask is deposited on graphene layers, and thickness mask is around 50 nm. Using electron beam lithography (EBL), the hole pattern is designed as fine diameter. After EBL, the SiO_2 is etched by the method of dry etching and wet etching such as CF4 plasma and buffered oxide etchant (BOE).

Experimental methods

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In this chapter, a detail growth condition is described for flexible light emitting diodes. To control the shape of GaN structures, the temperature and V/III ratio is optimized.

3.1. Metal-organic chemical vapor deposition system

3.1.1. Gas delivery system

Metal organic chemical vapor deposition (MOCVD) is well known to the growth of materials, especially metal organic compounds.[10] MOCVD is powerful growth technique for deposition of a high quality semiconductor such as light emitting diodes (LEDs). Also, it is easy to control the thickness of semiconductor using growth time.

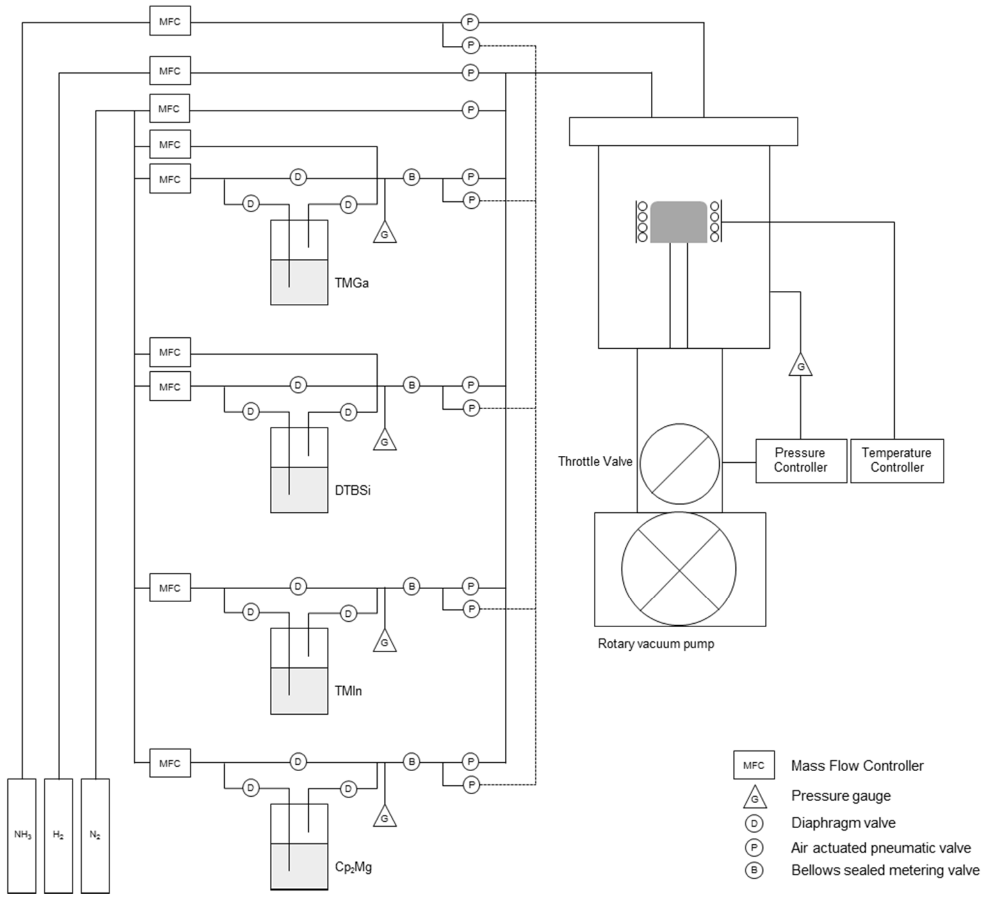

Figure 3.1. Gas delivery schematic of GaN MOCVD. The *n*-GaN, *p*-GaN and InGaN are deposited by MOCVD.

The gas delivery system of MOCVD is shown in Figure 3.1. The mass flow meter (MFC) and pneumatic air actuator valve are connected with 1/2" and 1/4" 316-stainless steel lines. To maintain vacuum well, all connections are VCR fitting using stainless steel gasket. To get high-quality semiconductor, leakage should be forbidden. The portable He detector is mainly used for checking the leakage.

The line pressure affects MO source flow, which is one of the key parameters. The line pressure is controlled by a metering valve (Swagelok Inc. SS4BMG), and the line pressure is measured by Setra gauge (Setra GCT-225). The chamber pressure is controlled by Baratron gauge (MKS co. 870B).

3.1.2. Growth chamber, reactants, and dopants

The GaN is mainly deposited using this chamber such as *n*-type GaN, *p*-type GaN, and $In_xGa_{1-x}N$. The detail information of dopants, reactants, and gas is shown in Table 3.1. The N_2 (99.9999%) is employed as a carrier gas. The purity of carrier gas is a critical factor to affect the quality of GaN epitaxy. High purity gas H_2 (99.9999%) and NH3 (99.9995%) are employed into the chamber for growing III-nitride.

To precisely control the growth of GaN, the MO sources should be kept the same condition. As the temperature of MO source affects vapor pressure, a constant temperature water bath is used. The trimethylgallium (TMGa), trimethylindium (TMIn), Ditertiarybutylsilane (DTBSi), bis-cyclopentadienyl magnesium (Cp_2Mg) maintain at -15 °C, 21.5 °C, -20 °C, 20 °C respectively.

The GaN MOCVD chamber is shown in Figure 3.2. Due to vertical type, the reactants and dopants are injected from the showerhead. The susceptor (TCK co.) is suitable for a 2" substrate. The temperature of the susceptor is controlled by induction heater (Eltek Inc. 80kHz, 15 kW) and a thermal couple (Omega, k-type).

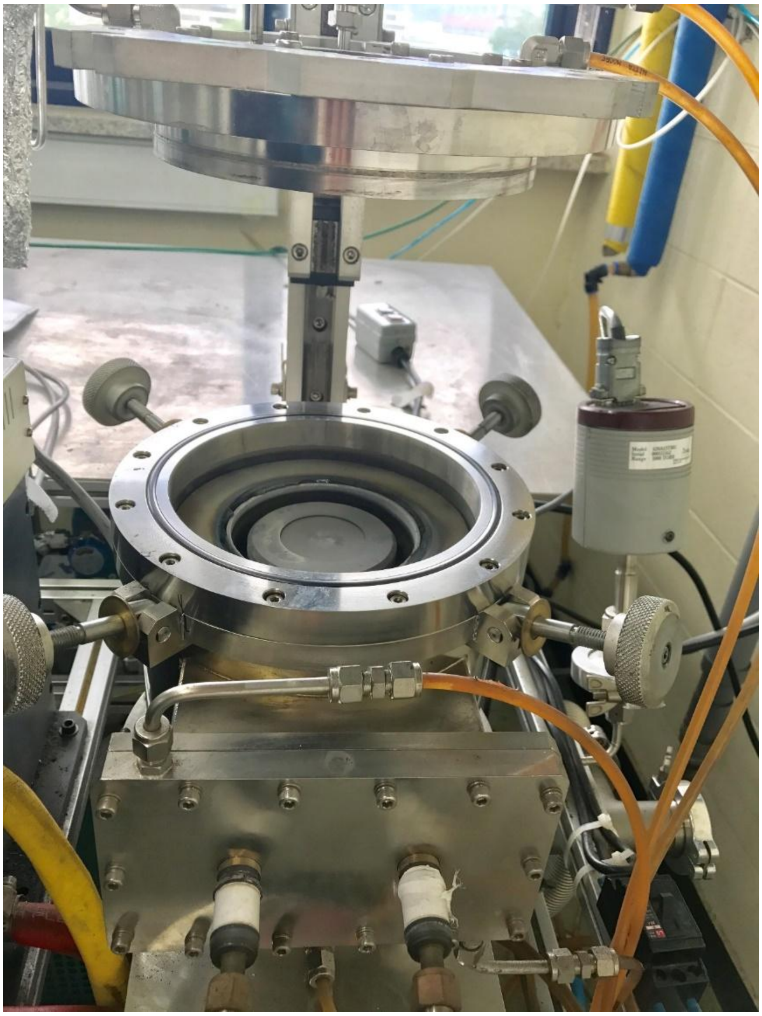

Figure 3.2. Photos of MOCVD chamber. (a) Vertical type MOCVD. (b) The showerhead of MOCVD.

Reactant, dopant, gas	Temperature of source (ºC)	Purity (%)	Company
TMGa	-15	Electronic grade	Epichem
TMIn	-21.5	Electronic grade	Epichem
DTBSi	-20	Epigrade	SAFC hightech
Cp_2Mg	-20	Electronic grade	Epichem
NH_3		99.9995	
H_2		99.9999	
N_2		99.999	

Table 3.1. Detail information of reactants, dopants, and gas.

3.2. Growth techniques

The shape of GaN microstructures depends on growth conditions such as temperature and V/III ratio. The optimized conditions of *n*-type GaN, *p*-type GaN, GaN/InGaN quantum wells (QWs) are described in this section.

3.2.1. Growth of GaN on c-sapphire substrate

To get high quality of LEDs, the condition of GaN films is described in Table 3.1. Before the growth of GaN films, the c-sapphire is cleaned by acetone and IPA. First, the substrate is heated at high temperature, 1050 °C, with H_2 gas to remove residues on the surface of the substrate, and the NH_3 is also employed for nitridation on the surface.

The un-doped and n-type GaN films are grown on c-Al_2O_3 using two step growth. First, low-temperature GaN (LT GaN) is grown at 470 °C as a role of a buffer layer between high-quality GaN and c-Al_2O_3. And high-temperature GaN (HT GaN) is grown at 1060 °C. The others conditions are summarized in Table 3.2.

	GaN buffer	GaN thin-film	*n*-type GaN
Temperature of substrate (ºC)	450 - 470	1020 – 1060	1060
Growth time (min)	1	60	5
Reactor pressure (Torr)	200	100	100
TMGa flow rate (sccm)	9	21	21
TMGa line pressure (Torr)	430	430	430
DTBSi flow rate (sccm)		1	1
DTBSi line pressure (Torr)		1050	1050
NH_3 flow rate (sccm)	2000	2000	2000
H_2 flow rate (sccm)	2000	2000	2000

Table 3.2. Growth condition of *n*-type GaN thin-film on c-sapphire.

The QWs are deposited to improve light efficiency between the *n*-type GaN and *p*-type GaN. Usually, three-period GaN/$In_xGa_{1-x}N$ multiple quantum wells (MQWs) are grown as an active layer. The temperature of quantum barrier (QB) and quantum well (QW) are optimized at 850 °C and 780 °C respectively.

For the *p*-type GaN, the growth temperature is optimized at 1000 °C, and flow rate of Cp_2Mg is 500 sccm. To improve hole carrier concentration, the process of activation is at 800 °C for 5 min using rapid thermal annealing (RTA). The Ni/Au is deposited on the p-type electrode, and metal annealing is at 300 °C for 5 min for ohmic contact.

The Figure 3.3. is a SEM of GaN thin-film on c-sapphire. The detail process follows the Table 3.2. and Table 3.3.

	GaN quantum barriers	GaN quantum well	*p*-type GaN
Substrate of temperature (ºC)	850	780	1000
Growth time (min)	3	1	60
Reactor pressure (Torr)	300	300	100
TMGa flow rate (sccm)	4.2	1.1	13
TMGa line pressure (Torr)	430	430	430
TMIn flow rate (sccm)		15	
TMIn line pressure (Torr)		430	
Cp_2Mg flow rate (sccm)			500
Cp_2Mg line pressure (Torr)			430
NH_3 flow rate (sccm)	2000	2000	2000
H_2 flow rate (sccm)			2000
N_2 flow rate (sccm)	2000	2000	

Table 3.3. Growth condition of *p*-type GaN.

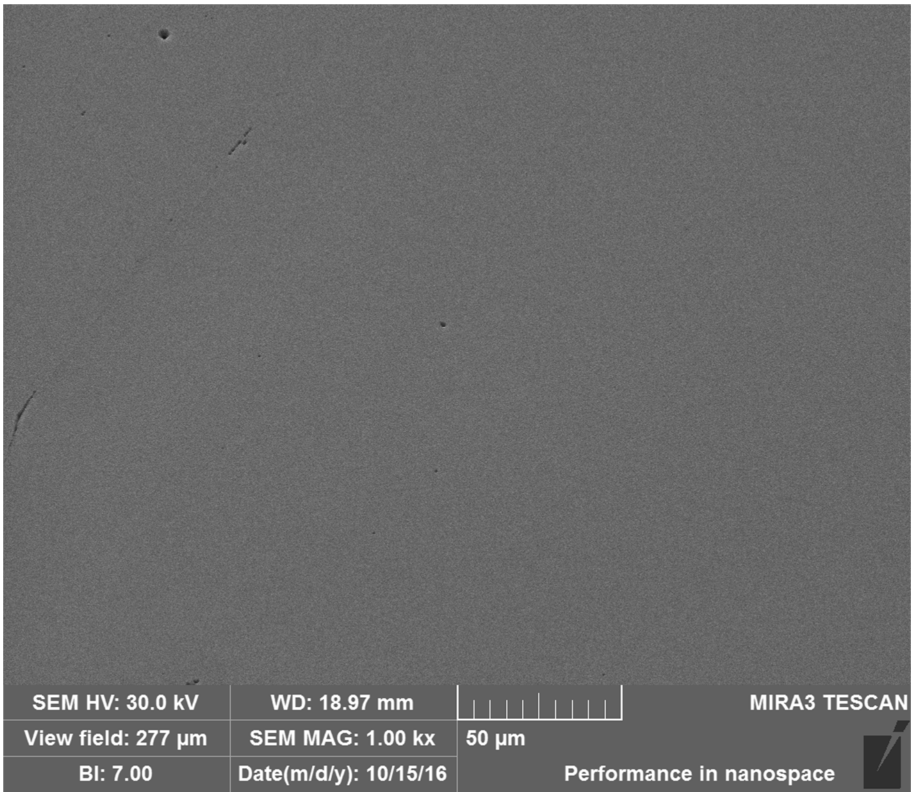

Figure 3.3. The SEM image of GaN thin-film. The *n*-type, quantum well and *p*-type GaN are grown on the c-sapphire substrate.

3.2.2. Growth of GaN on graphene layer

The GaN microstructures are selectively grown on graphene layers for flexible LEDs. There are three preparation steps before the growth of GaN such as graphene transfer, growth mask, ZnO seed layer.

The CVD graphene is synthesized on Cu foil, and multi-layer graphene layers are transferred onto SiO_2/Si substrate. The graphene layers are used as flexible substrates and a buffer layer for epitaxy. Also, the graphene expands for large size substrates.

To control the position of GaN microstructures, the SiO_2 growth mask is deposited on graphene layers, and thickness mask is around 50 nm. Using electron beam lithography (EBL), the hole pattern is designed as fine diameter. After EBL, the SiO_2 is etched by the method of dry etching and wet etching such as CF4 plasma and buffered oxide etchant (BOE).

It is hard to directly grow GaN on graphene layers, so the ZnO seed layers are deposited for buffer layers. The ZnO nanowalls are selectively grown on graphene layers. In other words, the role of ZnO is used for buffer layer between graphene and GaN microstructures.

	Pyramid shape	Disk shape	Rod shape
Substrate of temperature (ºC)	950 - 970	1020 – 1060	1100 - 1180
Growth time (min)	10	15	30
Reactor pressure (Torr)	100	100	100
TMGa flow rate (sccm)	21	21	21
TMGa line pressure (Torr)	430	430	430
DTBSi flow rate (sccm)	1	1	1
DTBSi line pressure (Torr)	1050	1050	1050
NH_3 flow rate (sccm)	2000 (continuous)	100 (pulse, 3s during 10s)	500 (pulse, 3s during 10s)
H_2 flow rate (sccm)	2000	2000	2000

Table 3.4. Growth condition of various shape GaN on graphene layers.

The shape of GaN microstructures can be controlled through the growth temperature and V/III ratio. There are three types of microstructures as shown in Table 3.4. such as a pyramid, disk, and rod. Regarding V/III ratio, the pyramid shape of GaN is grown when a large amount of NH_3 is injected. On the other words, the disk and rod shape of GaN is grown when a small amount of NH_3 is injected. Regarding the growth temperature, the disk shape of GaN is grown at low temperature. While rod shape of GaN is grown at high temperature. Figure 3.4. shows that various morphology of GaN can be controlled on graphene layers.

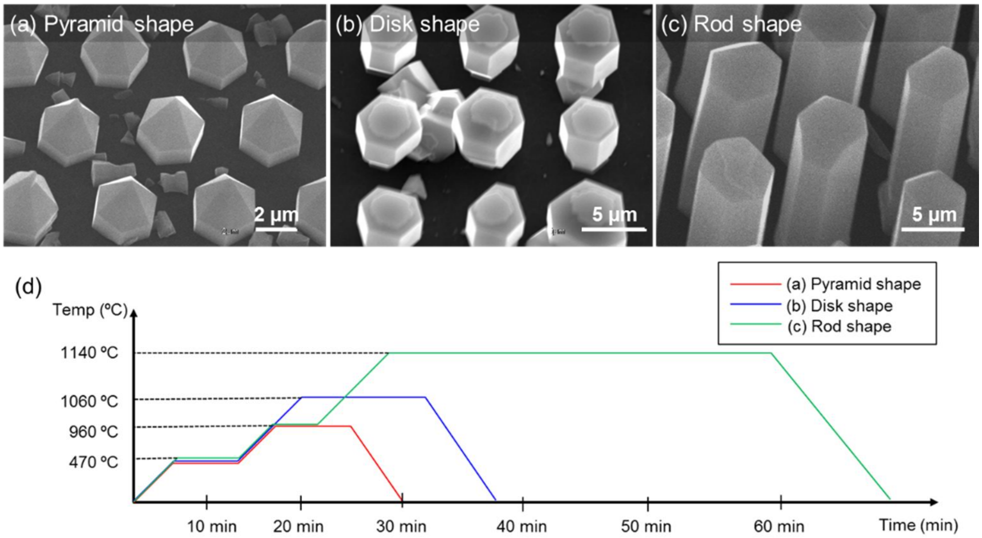

Figure 3.4. Morphology controlled GaN microstructures on graphene layers. (a) The pyramid shape of GaN. (b) Disk shape of GaN. (c) Rod shape of GaN. (d) Graph of various GaN growth type.

3.3. Characterization system

3.3.1. Structural characterization

The morphology of GaN microstructures is analyzed using JEOL scanning electron microscopy (SEM) or TESCAN field-emission SEM (FE-SEM). Because the size of GaN structures is around micro-size, it is enough to see a surface of GaN using JEOL SEM. To see the surface of three dimensional (3D) GaN, the samples are detected with 30 °C tilt view. The working distance is always fixed at 18 mm, and accelerating voltage is 30 kV.

3.3.2. Optical characterization

The photoluminescence (PL) measurement and the electroluminescence (EL) measurement are representative characterizations of LED devices. A He-Cd laser (325 nm) and a pulsed ND: YAG laser (355 nm) share a monochromator (Dongwoo Optron co. DM320i) and a charge coupled device (CCD, Andor Inc. DUO401A). The schematic of detail PL measurement is shown in Figure 3.5.

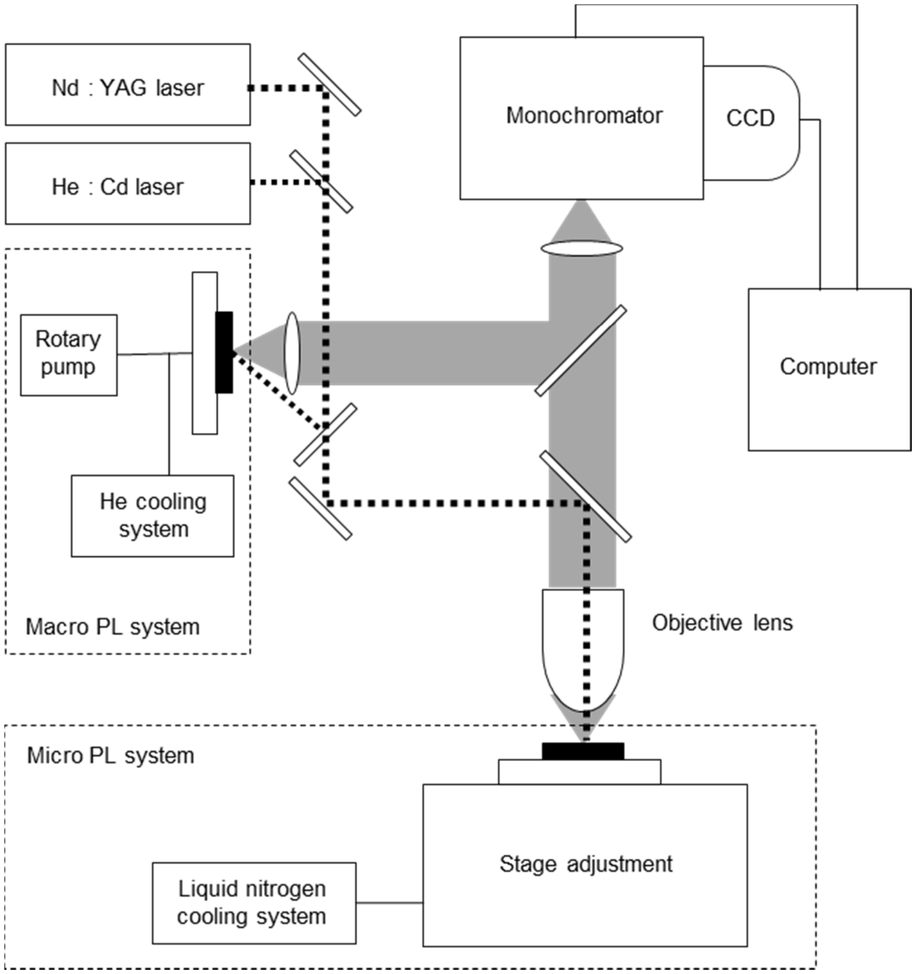

Figure. 3.5. Schematic of the PL measurement system.

3.3.3. Electrical characterization

The LED devices are investigated by EL measurement. The EL system is a similar set up with PL system. The current is injected by DC supplier (Keithley 2400), and the voltage is sweeping from 0V to a specific value. When light emitted from LEDs, CCD can measure the spectra of light. As shown in Figure 3.7. the GaN LEDs are emitted blue light at 8V to 30V. the more current is injected to LEDs, the more bright light is coming from LEDs.

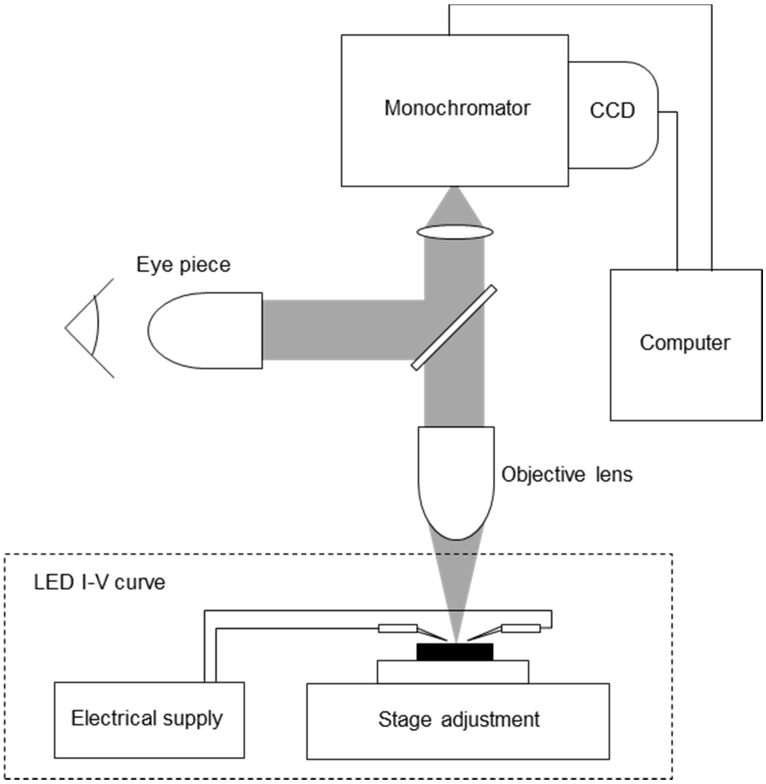

Figure 3.6. Schematic of the EL measurement system.

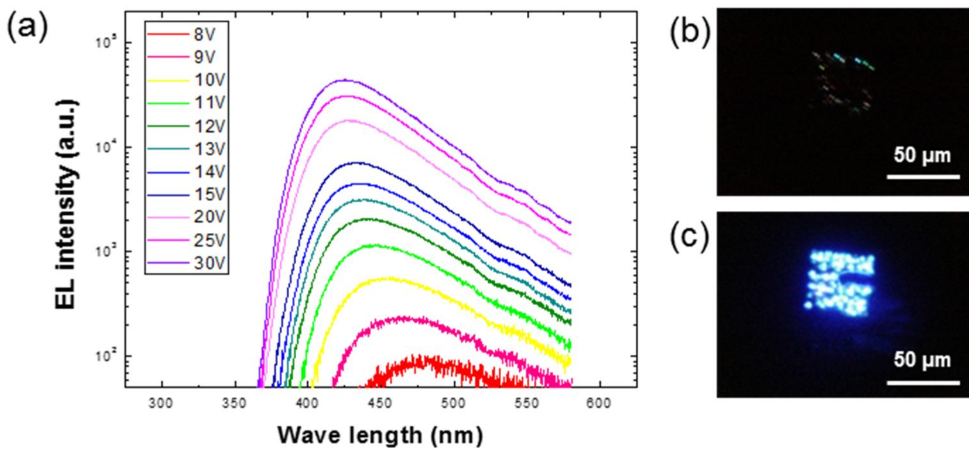

Figure 3.7. The EL Characterization of LEDs grown on graphene layers. (a) The EL spectrum with various voltage. (b) Image of LEDs at 17V. (c) Image of LEDs at 23 V.

Morphology controlled GaN microstructures on graphene layers

4

4.1. Introduction

Recently optoelectronics devices using GaN nanostructures receive a lot of attention because it has been improved great performance for several decades.[11-12] To control dimension and position of nanomaterials, the top-down approach is well-developed using lithography and etching process. However, there is a defect issue between GaN thin-film and substrates.[13] To solve this problem of mismatches, GaN microstructures are directly grown on localized spots on graphene layers. This bottom up approach allows single-crystalline growth for high-quality LEDs.

The microstructures of GaN such as micro-rods and micro-wires have great attention as potential advantages over thin-films.[14-15] One dimensional (1D) materials can have coaxial quantum structures such as GaN/InGaN for enhanced optoelectronic devices. Sophisticated position controls of micro-rods would achieve a breakthrough.

In this chapter, the GaN microstructures are grown on graphene layers. The two dimensional (2D) materials such as graphene has an excellent mechanical flexibility.[16-17] The GaN LEDs grown on graphene layers have a flexible property and reliable operation.

4.2. Morphology controlled GaN microstructures

4.2.1. Pyramid shape condition study

The shape of GaN microstructures can be controlled by growth temperature and V/III ratio. To grow GaN on graphene, ZnO seed layers are employed as a nucleation layer.[18] The ZnO nanowalls are selectively grown on graphene layers. Due to a similar lattice constant, GaN can be easily epitaxy on ZnO.

Using a nanoscale growth mask, the ZnO seed layers are grown on graphene layers. The diameter is around 300 nm and height is around 3 μm in Figure 4.1. (a). And GaN is coated on ZnO nanotube for 10 min and 30 min in Figure 4.1. (b) and (c) respectively. When the growth time increased, the shape of GaN structures become a pyramid.

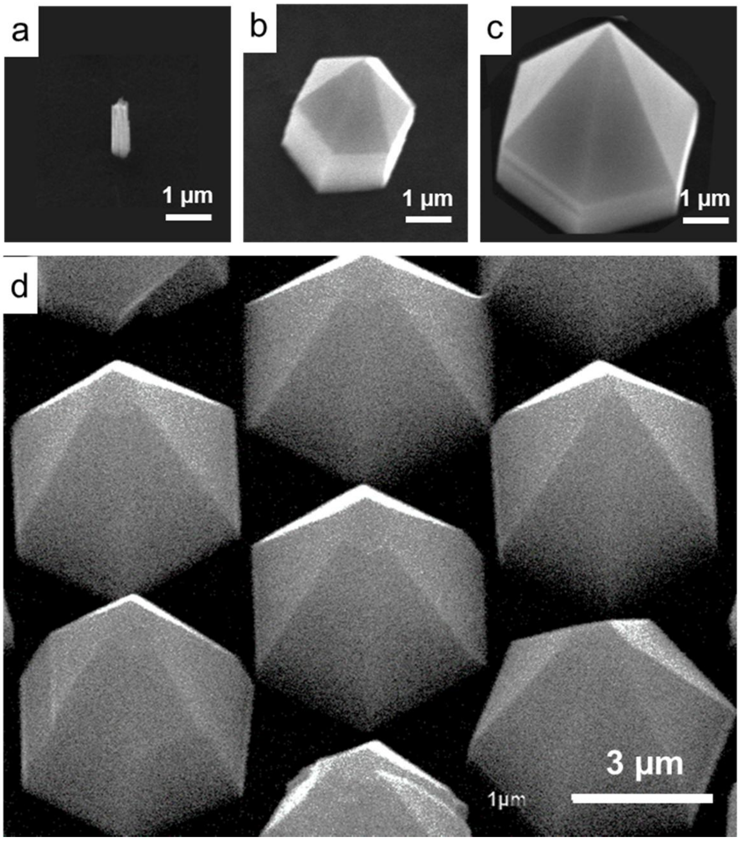

Figure 4.1. SEM images of pyramid shape GaN microstructure grown on graphene layers. (a) ZnO nanotube on graphene. (b) *n*-type GaN coated on ZnO nanotube for 10 min. (c) *n*-type GaN coated on ZnO nanotube for 30 min. (d) The 30° tilt view SEM image of pyramid GaN on graphene layers.

4.2.2. Disk shape condition study

The key point of GaN is epitaxial lateral overgrowth (ELOG). For the preparation of the substrate, graphene layers are transferred on a SiO_2/Si substrate. For dot graphene, a photoresist (PR) is patterned by Mask aligner, and O_2 plasma is treated for 30 sec to remove graphene.

ZnO seed layers are selectively grown on dot graphene, and then the low-temperature GaNs are deposited at 470 °C. to optimize a growth condition, the high temperature is changed from 1020 °C to 1100 °C. The SEM images are shown in Figure 4.2. The morphology of GaN is hexagonal shape at 1020 °C and 1060 °C as shown in Figure 4.2 (a-d). When the temperature increase, the morphology of GaN become rough as shown Figure 4.2. (e-f).

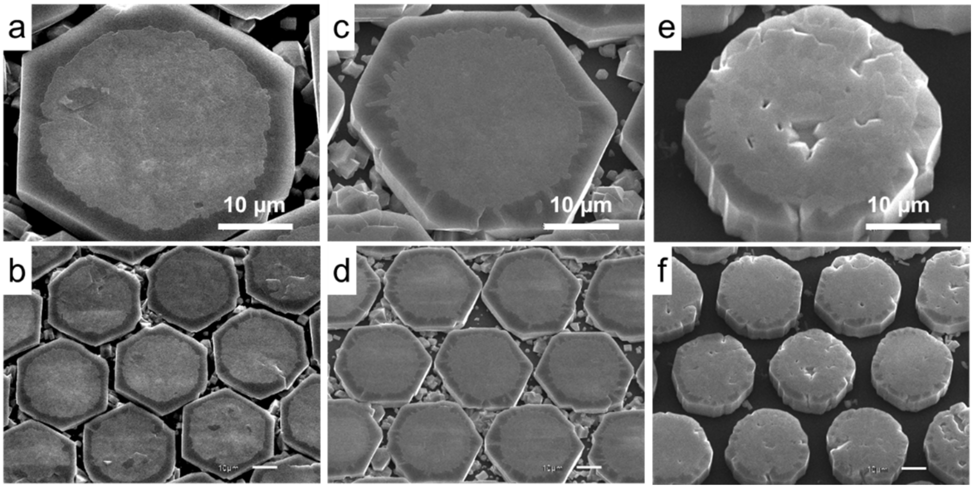

Figure 4.2. SEM images of disk shape GaN on dot graphene. (a), (b) GaN is grown at 1020 °C. (c), (d) GaN is grown at 1060 °C. (e), (f) GaN is grown at 1100 °C.

4.2.3. Rod shape condition study

The key point of GaN micro-rods is two step growth temperatures. For the preparation of the substrate, graphene layers are transferred to a SiO2/Si substrate, and the SiO_2 growth mask is deposited on graphene layers. The hole pattern is etching with CF4 plasma and BOE.

The role of ZnO seed layer is only for buffer layer between graphene layers and GaN microstructures as shown in figure 4.3. (a). The LT GaN is coated on ZnO seed for protecting from H_2 at high temperature. The first step of GaN micro-rods is at 1060 °C, and the second step is at 1140 °C.

NH_3 is repeatedly injected with pulsed for 3 sec during 10 sec. The tendency of relation NH_3 flow rate and yield of GaN micro-rods. If the NH_3 flow rate is not enough, the yield becomes bad. So, the optimized value is 100 sccm and 500 sccm at first step and second step respectively.

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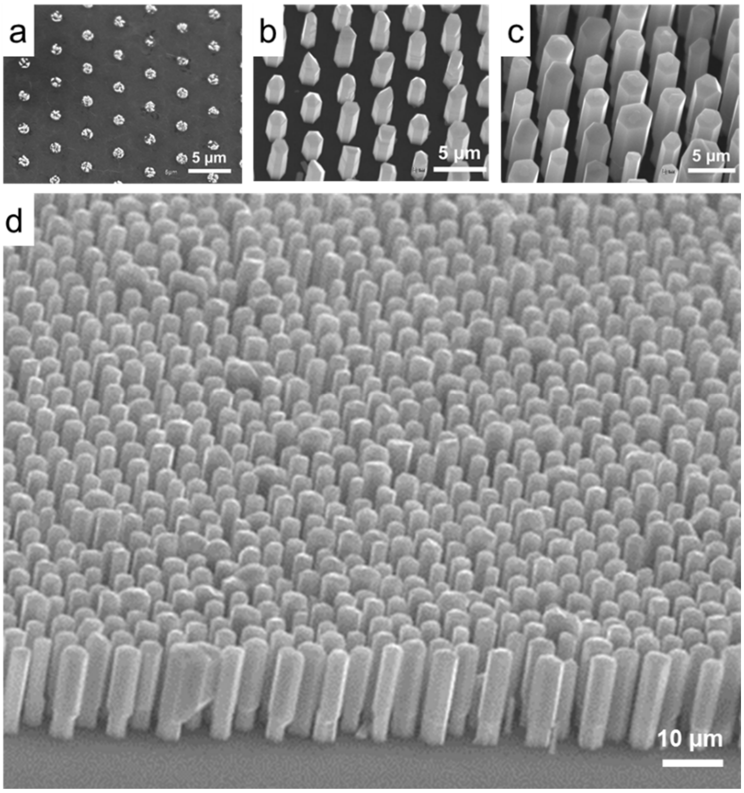

Figure 4.3. SEM images of pyramid shape GaN microstructure grown on graphene layers. (a) ZnO nanowall on graphene layers. (b) *n*-type GaN micro-rods are grown for 10 min. (c) *n*-type GaN micro-rods are grown for 30 min. (d) The 60° tilt view SEM image of GaN micro-rods on graphene layers.

4.3. Material characterization

4.3.1. Structural characterization

The GaN micro-rods are selectively arrayed on the graphene layers for flexible light emitting diodes as shown in figure 4.4. (a). Using the methods which are mentioned in chapter 2, the positions and shapes GaN microstructures are controlled.

The GaN LEDs grown on the graphene make it possible to transfer the GaN LEDs to other substrates.[19] As shown in figure 4.4. (b) GaN LEDs are transferred to the copper foil. Because the graphene layers have a property of flexibility, it can be transferred to any foreign substrates such as metals, glass, plastics.

The figure 4.4 (c) shows that the GaN microstructures can be extremely bent. The diameter of GaN micro-rods are around 5 μm, and height is around 20 μm. The quantum wells (QWs), $In_xGa_{1-x}N$, are coated on the surface of GaN micro-rods. The GaN micro-rods are suspended with a polyimide (PI) between rods, so it allows durability during the bending test.

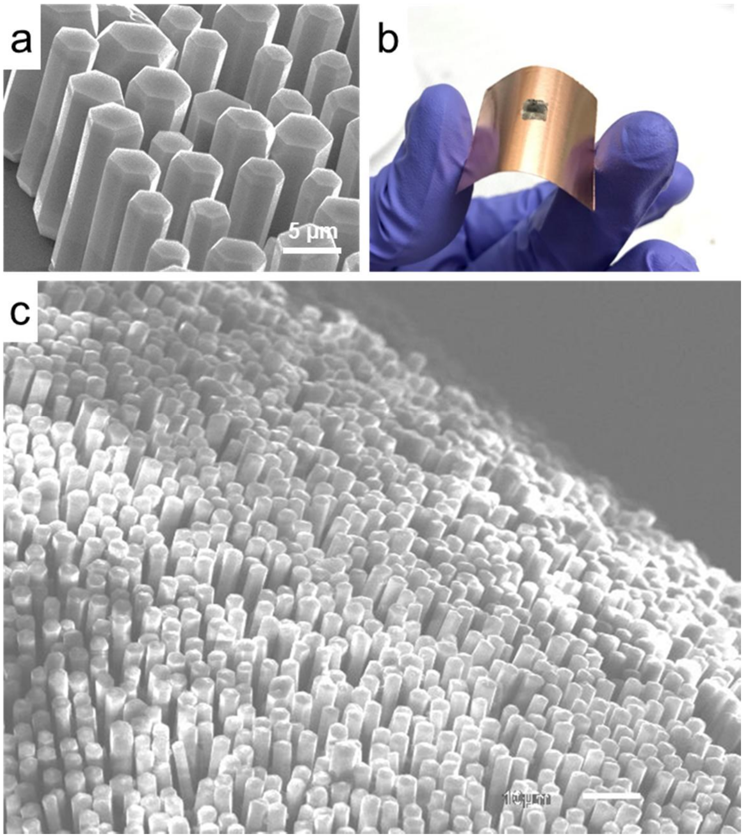

Figure 4.4. Flexible GaN micro-rods on graphene layers. (a) The SEM image of GaN micro-rods on graphene layers. (b) Flexible LEDs on Cu foil. (c) The flexible SEM image of GaN micro-rods on graphene layers.

4.3.2. Optical characterization

The optical properties of GaN micro-rods are measured by electroluminescence (EL). The spectrum demonstrates the successful fabrication of high-quality GaN/InGaN coaxial microstructures. The blue light is emitted from coaxial structures LEDs as shown in figure 4.5. (a). The blue light becomes bright when the current is injected from 0.5 mA to 2.0 mA. The figure 4.5. (b) displays the *I-V* characteristic curve which is nonlinear behavior. The coaxial LEDs exhibit dominant peaks at 421 nm as shown in figure 4.5. (c). The EL intensity displays bright light output as a function of input power.

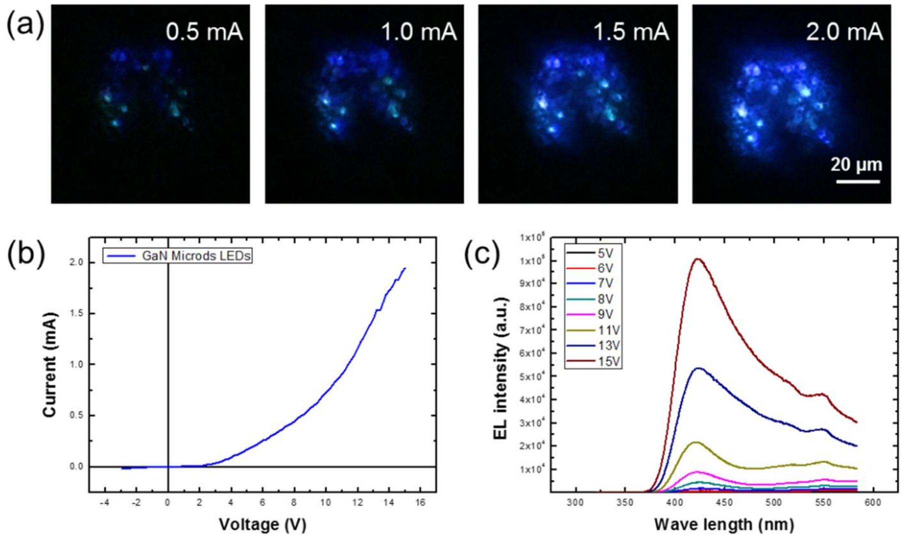

Figure 4.5. Electrical characterization of GaN micro-rods LEDs. (a) Images of blue light at different applied current from 0.5 mA to 2.0 mA. (b) I-V characteristic curve. (c) Power dependent EL spectra as a function of voltage from at 5V to 15V.

4.3.3. Electrical characterization

The Morphology of GaN microstructures can be controlled from disk shape to rod shape as different a growth temperature. The GaN disks are grown at 1060 °C, and the GaN rods are grown at 1140 °C. For fabricating LEDs, Ni/Au are coated on p-GaN surfaces to make good ohmic contacts. The pad size is 50 μm by 50 μm, and the thickness of Ni and Au is each 10 nm as shown in figure 4.6. (b).

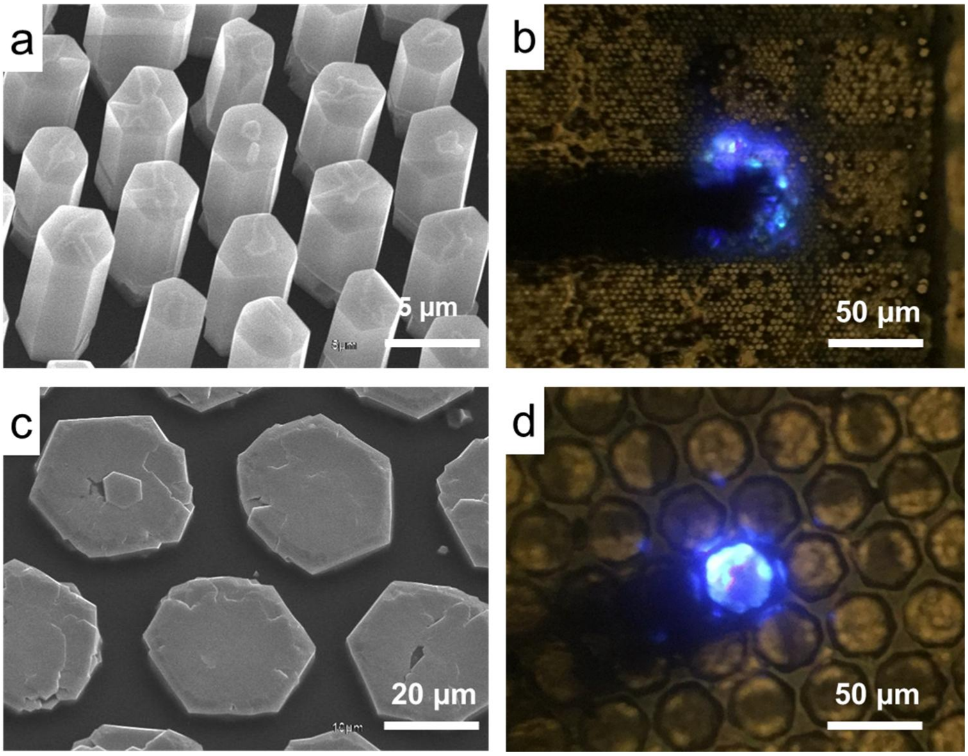

Figure 4.6. Various type of LEDs on graphene layers. (a) The SEM image of GaN micro-rods on graphene layers. (b) Blue light from GaN rod shape of LEDs. (c) The SEM image of GaN micro-disks on graphene layers. (d) Blue light from GaN disk shape of LEDs.

4.4. Summary

The morphology controlled GaN microstructures are demonstrated on graphene layers. Furthermore, the position also can be selectively arrayed for efficient LEDs. The GaN shape is precisely controlled such as a pyramid, disk, and rod as a function of growth temperature.

The two properties are demonstrated such as flexibility and transfer. The GaN microstructures are transferred to any foreign substrates, and the flexible GaN micro-rods are examined by SEM images. It shows that there is a potential application for optoelectronic devices.

Conclusion

5

The goal of this research is mainly growth of GaN on graphene layers and morphology control of GaN microstructures. To fabricate high quality of LEDs, it is important to control quantum wells. The GaN/$In_xGa_{1-x}N$ is coated on GaN micro-rods, which has a large area of p-n junctions.

It is hard to grow GaN micro-rods on graphene without ZnO buffer layer. Conventionally the GaN LEDs depend on ZnO nanotube or nanowires, but in this research the GaN micro-rods minimized dependency of the buffer layer. Finally, the high aspect ratio GaN micro-rods are grown on thin ZnO nanowall.

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국문 초록

최근에 그래핀, 질화갈륨과 같은 반도체 소재들이 주목을 받고 있다. 그래핀과 질화갈륨 소재는 각각 2010년, 2014년에 노벨 물리학상의 주인공들이다. 그래핀은 투명하고 휘어지고 뛰어난 전기적인 특성을 가지고 있기 때문에 전자소자로 응용되는데 적합하다. 무엇보다도 그래핀은 서로 약한 결합을 하고 있기 때문에 쉽게 떼어내고 옮겨 붙일 수 있다. 그리고 질화갈륨 역시 발광소자의 효율을 증가시키는데 큰 역할을 하였다. 특히, 높은 전자 이동속도, 높은 결합률 그리고 안정적인 내구성으로 전자 소자로 사용되기 좋은 소재이다. 그래서, 질화갈륨 발광소자를 그래핀 기판에 성장시키면 두 가지 소재들의 장점을 살릴 수 있다. 질화갈륨과 그래핀의 결합은 착용 가능한 디스플레이로 응용가능성이 전망된다.

이 연구의 목표는 질화갈륨 마이크로 구조물의 형태를 그래핀 기판 위에서 조절하는 것이다. 구체적으로 피라미드 구조, 디스크 구조 그리고 막대기 구조로 성장하는 것이다. 하지만, 질화갈륨 마이크로 구조물을 그래핀 위에 바로 성장시키는 것은 아주 어렵다. 그래서 질화갈륨을 그래핀 위에 성장시킬 때는 산화아연과 같은 완충제 소재를 사용한다. 기존에는 막대 모양의 질화갈륨 구조물을 얻기 위해서는 산화아연을 막대모양으로 성장시킨 후에 질화갈륨을 겉에 성장시키는 방법으로 성장을 시켰다. 그러나, 이번 연구에서는 산화아연의 완충제의 의존도를 낮추어서 질화갈륨 마이크로 막대 구조물을 성장시키는데 성공하였다. 그

리고 효율 좋은 발광소자를 만들기 위해서는 빛이 나오는 접합에 양자우물을 잘 만들어 주는 것이 중요하다. 이렇게 발광소자에서 나오는 빛을 광학적 측정으로 분석하였다.