Heteroepitaxial growth of III–V compound semiconductors for optoelectronic devices

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Abstract. An AlGaAs/GaAs multi-quantum well vertical-cavity surface-emitting laser diode (VCSEL) has been grown on a Si substrate using metalorganic chemical vapour deposition (MOCVD). The VCSEL with a 23-pair of AlAs/Al_{0.1}Ga_{0.9}As distributed Bragg reflector on a Si substrate exhibited a threshold current of 223 mA under continuous-wave condition at 220 K. Electroluminescence observation showed that an optical degradation was caused by generation and growth of dark-line defects. An MOCVD-grown InGaN/AlGaN double-heterostructure light-emitting diode on a sapphire substrate exhibited an optical output power of 0.17 mW, an external quantum efficiency of 0.2%, a peak emission wavelength at 440 nm with a full width at half-maximum of 63 nm and a stable operation up to 3000 h under 30 mA DC operation at 30°C. A high current level of 281 mA/mm and a large transconductance (g_m) of 33 mS/mm have been achieved for a GaN metal semiconductor field-effect transistor (MESFET) with a gate length of 2 μ m and a width of 200 μ m at 25°C. The GaN MESFET at 400°C showed degraded characteristics: a low g_m of 13.4 mS/mm, a gate leakage and a poor pinch-off.

Keywords. GaAs/Si; GaN; MOCVD; MESFET; LED; vertical-cavity surface-emitting laser diode.

1. Introduction

Considerable scientific and engineering resources have been devoted to heteroepitaxial growth, such as GaAs on Si and GaN on sapphire. Vertical-cavity surface-emitting laser diodes (VCSELs) on Si are very attractive because of significant advantages over edge-emitting lateral-cavity laser diodes, such as the potential for wafer scale testing, high-density two-dimensional array fabrication, ultrafast parallel optical information processing and possibility of monolithic integration with other optical or electronic devices (Hayashi 1993). In particular, GaAs-based VCSELs on Si are anticipated to be used in future optoelectronic integrated circuits (OEICs). However, previous investigations of laser diodes on Si substrates have focused on the conventional edge-emitting lateral-cavity structures. There have been only a few demonstrations of VCSEL on Si under the pulsed operation at 300 K by Deppe *et al* (1990) and Egawa *et al* (1994).

GaN-based materials are candidates for high-density optical data storage, full-colour displays and electronic devices operating under high-power and high-temperature conditions due to large direct band gap, large saturation velocity, large breakdown electric field and chemical inertness. In the past few years, high-efficiency blue and

green light-emitting diodes (LEDs) (Nakamura *et al* 1994) and laser diodes operating under continuous-wave (CW) condition (Nakamura 1997) have been developed using GaN-based materials on sapphire substrates. There have been many researches on GaN-based metal semiconductor field-effect transistors (MESFETs) (Khan *et al* 1993b; Binari *et al* 1994; Egawa *et al* 1998) and high electron mobility transistors (HEMTs) (Khan *et al* 1993a; Wu 1998).

One of the main problems encountered in the heteroepitaxial growth is that there are mismatches in the lattice constant and the thermal expansion coefficient between the epitaxial layer and the substrate. Two-step growth technique (Akiyama *et al* 1984) has been applied to the heteroepitaxial growth of GaAs on Si and GaN on sapphire. In these systems, however, the epitaxial layers contain high density of the threading dislocations and large strain due to the differences of lattice constants and thermal expansion coefficients between the epitaxial layers and the substrates (Egawa *et al* 1995a; Lester *et al* 1995). Dislocations acting as nonradiative recombination centres cause limitation of stable operation for optical devices under high injected current density and ambient temperature. For example, Egawa *et al* (1995a) have reported that rapid degradations in electrical and optical characteristics of AlGaAs/GaAs single quantum well laser diodes on Si substrates were caused by formation of dark-line defects (DLDs) during high injected

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current density. In this study, we report the characteristics of the AlGaAs/GaAs VCSEL on Si substrate with 23-pair of AlAs/Al_{0.1}Ga_{0.9}As distributed Bragg reflector (DBR), the InGaN/AlGaN LEDs on sapphire substrate and the GaN MESFET at high temperatures.

2. Experimental

2.1 AlGaAs/GaAs VCSEL on Si

An AlGaAs/GaAs VCSEL structure was grown on an *n*⁺-Si substrate oriented 2° off (100) toward [110] using metalorganic chemical vapour deposition (MOCVD) at atmospheric pressure (Egawa *et al* 1994). The VCSEL structure was grown on Si substrate at 750°C by the conventional two-step growth technique. The laser structure consists of a 2.1 μm thick thermal-cycle annealed *n*⁺-GaAs buffer layer, a 23-pair of *n*⁺-AlAs/*n*⁺-Al_{0.1}Ga_{0.9}As (71 nm/60 nm) quarter-wave multi-layer DBR, a 290 nm thick *n*-Al_{0.7}Ga_{0.3}As lower cladding layer, a 51 nm thick undoped Al_{0.3}Ga_{0.7}As lower confining layer, ten undoped 9 nm thick GaAs multi-quantum well (MQW) active layers separated by 5.5 nm thick undoped Al_{0.3}Ga_{0.7}As barrier layers, a 51 nm thick undoped Al_{0.3}Ga_{0.7}As upper confining layer, a 220 nm thick *p*-Al_{0.7}Ga_{0.3}As upper cladding layer, and a 34 nm thick *p*⁺-GaAs contact layer. After the growth, the laser device was fabricated as follows: a SiO₂ insulating layer was deposited on the *p*⁺-GaAs contact layer and 50 μm diameter contact windows were opened by wet chemical etching of SiO₂. Next, Ti/Au were evaporated on the *p*⁺-GaAs layer as a *p*-side electrode except for the 20 μm diameter area at the centre of the 50 μm diameter contact window. A semi-transparent Au was then evaporated on the *p*-side surface. AuSb/Au was used for the *n*-side electrode on the *n*⁺-Si substrate. The devices were mounted (junction up) on sample holders and tested. In the VCSEL on Si, the light output was measured by detecting the emitted light through the 20 μm diameter semi-transparent Au. The lifetime tests were examined under automatic power control (APC) condition. Growth of DLDs was studied using an electroluminescence (EL) observation system.

2.2 InGaN/AlGaN LED and GaN MESFET on sapphire

An InGaN/AlGaN LED was grown on the sapphire substrates with (0001) orientation (*c* face) by MOCVD at atmospheric pressure using the two-step growth technique (Egawa *et al* 1996). The structure consists of the following growth sequence: a 30 nm thick GaN nucleation layer, a 4 μm thick *n*-GaN layer, a 150 nm thick *n*-Al_{0.15}Ga_{0.85}N layer, a 50 nm thick In_{0.06}Ga_{0.94}N layer, a 150 nm thick *p*-Al_{0.15}Ga_{0.85}N layer, and a 350 nm thick *p*-type GaN cap layer. Thermal annealing in N₂ ambient

was performed to obtain *p*-type GaN and AlGaN layers at 750°C for 30 min. After the growth, the sample was partially etched by reactive ion etching in a BCl₃ plasma until the *n*-GaN layer was exposed. The ohmic electrodes of Ni/Au and Ti/Al were formed by vacuum evaporation on the *p*- and *n*-GaN layers, respectively.

The GaN MESFET was grown on the sapphire substrate by MOCVD (Egawa *et al* 1998). The epitaxial layers consisted of a 30 nm thick GaN nucleation layer, a 2.4 μm thick undoped GaN layer and a 0.2 μm thick *n*-GaN layer with Si doped to $\sim 2 \times 10^{17} \text{ cm}^{-3}$. After depositing SiO₂ film on the *n*-type GaN, the 22 × 215 μm mesas were defined on the *n*-GaN layer by use of standard photolithographic technique. These mesas were electrically isolated by reactive ion etching in a BCl₃ plasma. The drain-source ohmic contacts were obtained with Ti/Al annealed at 900°C for 60 sec in N₂ ambient. The gate metallization was done by vacuum evaporation of Pt/Ti/Au. The gate length and width of the GaN MESFET were 2 and 200 μm, respectively, and the channel opening (source to drain distance) was 10 μm. The Hall effect measurements by van der Pauw method were performed for the *n*-GaN layer at various temperatures.

3. Results and discussion

3.1 AlGaAs/GaAs VCSEL on Si

Figure 1 shows the calculated and measured reflectivities of the 23-pair of AlAs/Al_{0.1}Ga_{0.9}As DBR on Si.

Figure 1. Calculated and measured reflectivities of the 23-pair of AlAs/Al_{0.1}Ga_{0.9}As DBR on Si.

The measured peak reflectivity of the 23-pair of $\text{AlAs}/\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ DBR on Si was 98.6% at 860 nm. Comparing with the calculated reflectivity, the reflectivity of 98.6% still remains to be low probably due to the zigzag interfacial roughness and the Al-Ga interdiffusion in the DBR on Si (Egawa *et al* 1995b). The top mirror had the reflectivity of 93.6% and transparency of 0.6% for the semi-transparent Au. Figure 2 shows CW light-current (L - I) characteristic and emission spectrum of the VCSEL on Si at 100 K. The VCSEL on Si exhibited the threshold current (I_{th}) of 73 mA, the threshold current density (J_{th}) of 3.7 kA/cm^2 , and the external differential quantum efficiency (η_d) of 0.8%. The VCSEL on Si showed the peak wavelength of 834.4 nm with the full width at half maximum (FWHM) of 39.5 nm at $0.96 \times I_{\text{th}}$, and 844 nm with the FWHM of 2.2 nm at $1.2 \times I_{\text{th}}$. The relatively broad FWHM of 2.2 nm may be due to the generation of multi transverse-modes near the single fundamental mode. We have achieved CW operation with the I_{th} of 223 mA up to 220 K for the VCSEL on Si. The CW operation was thought to be achieved by the uses of the $\text{AlAs}/\text{AlGaAs}$ DBR and MQW structure. Figure 3 shows the results from the aging tests for the VCSEL on Si operating at a constant output power under 300 K pulsed and 100 K CW conditions. Under 300 K pulsed operation, the current increased gradually at a rate of $\sim 30 \text{ mA/h}$ in the first 170 min and then increased rapidly at $\sim 114 \text{ mA/h}$ in the next 90 min. The VCSEL on Si degraded rapidly in $\sim 1 \text{ min}$ under the CW operation at 100 K. The formation

of DLDs was investigated for the VCSEL on Si using the EL observation to study the progressive optical degradation. The EL observations showed that the dark regions enlarged and resulted in the DLDs with the aging. Egawa *et al* (1995a) have reported that the growth of dark regions strongly depended on the injected current density. Therefore, the stable CW lasing operation was prevented by the rapid formation and propagation of the dark regions because the dark regions acted as the nonradiative recombination centres.

3.2 InGaN/AlGaN LED and GaN MESFET on sapphire

The InGaN/AlGaN LED exhibited a forward turn-on voltage of 3 V at the forward current of 1 mA, and a reverse voltage of 10 V at a reverse current of 0.1 mA. Figure 4 shows the L - I characteristic of the InGaN/AlGaN LED on the sapphire substrate under DC operation at 30°C. The InGaN/AlGaN LED exhibited the optical output power of 0.17 mW, η_d of 0.2%, and a peak emission spectrum at about 440 nm with FWHM of 63 nm at the injected current density of 60 A/cm^2 (30 mA). The light output power increased linearly with increasing current, and saturated at a high injected current level probably due to heating. The inset of figure 4 shows an aging result of the LED under a constant current density of 60 A/cm^2 (30 mA) at 30°C. We confirmed the stable operation up to 3000 h under this aging condition.

Figure 2. L - I characteristic and emission spectrum under CW condition at 100 K for the $\text{AlGaAs}/\text{GaAs}$ VCSEL on Si.

Figure 3. Results from the aging tests for the $\text{AlGaAs}/\text{GaAs}$ VCSEL on Si operating at a constant output power under 300 K pulsed and 100 K CW conditions.

The dependence of the Hall mobility for the Si-doped *n*-GaN layer on temperature is shown in figure 5. The Hall mobility first increased by $T^{3/2}$ and then decreased by $T^{-3/2}$ with increasing temperature. The main scattering mechanisms which contributed to the Hall mobility appeared to be the ionized impurity scattering below 130 K and the acoustic phonon scattering above 130 K. The Hall mobilities of the *n*-GaN layer were 585 cm²/V·s with the electron carrier concentration of 1.1×10^{17} cm⁻³ at 300 K, and 1217 cm²/V·s with that of 2.4×10^{16} cm⁻³ at 77 K. The maximum Hall mobility was 1476 cm²/V·s with the electron carrier concentration of 5.4×10^{16} cm⁻³ at 130 K. The Hall mobility obtained in this sample was much higher than the previous results by Khan *et al* (1993b) and Binari *et al* (1994).

Figure 6 shows the drain-source current (I_{DS}) characteristic as a function of the drain-source voltage (V_{DS}) for the gate bias (V_g) ranging from +1 to -11 V at 25°C. The GaN MESFET with the gate length of 2 µm and the gate width of 200 µm showed the maximum transconductance (g_{mmax}) of 33 mS/mm, which was higher than the previously reported MESFETs by Khan *et al* (1993b) and Binari *et al* (1994). The value of I_{DS} was as high as 281 mA/mm at $V_g = 1$ V and $V_{DS} = 40$ V. The GaN MESFET exhibited the modulation characteristic with nearly pinch-off at the V_{th} of approximately -13 V, which resulted from a sharp interface between the *n*-GaN and the undoped GaN layers. The temperature dependence of g_m for the GaN MESFET is shown in figure 7. With increasing temperature, the value of g_m decreased from

29.8 mS/mm at 25°C to 13.4 mS/mm at 400°C. The GaN MESFET at 400°C exhibited the gate leakage, the poor pinch-off and the low g_m in comparison to that of the MESFET measured at 25°C. As expected from figure 5, the decreases in g_m were caused by the reduction of the electron mobility at high temperature. The data shown by open circle in figure 7 indicates the g_m at 25°C

Figure 5. Temperature dependence of electron mobility for the *n*-GaN layer grown on sapphire by MOCVD.

Figure 4. I - P characteristic of the InGaN/AlGaIn LED on sapphire under DC operation at 30°C. The inset shows the aging result under a constant current density of 60 A/cm² (30 mA) at 30°C.

Figure 6. Drain-source current (I_{DS}) characteristic of the GaN MESFET at 25°C as a function of the drain-source voltage (V_{DS}). The gate length and width are 2 and 200 µm, respectively.

Figure 7. Temperature dependence of transconductance (g_m) for the GaN MESFET. Open circle shows the value at 25°C measured again after its measurement at 400°C.

measured again after its measurement at 400°C. Although a little gate leak was observed, the GaN MESFET showed the initial characteristic with the g_m of 30 mS/mm. This gate leak at 25°C was caused by the degradation of Schottky gate metal after the measurements at high temperatures.

4. Conclusions

The CW operation up to 220 K has been demonstrated for the AlGaAs/GaAs MQW VCSEL on Si with the 23-pair of AlAs/Al_{0.1}Ga_{0.9}As DBR. The value of I_{th} under the CW operation was 223 mA at 220 K. However, the VCSEL on Si showed the optical degradation due to the generation and growth of DLDs. The InGaN/AlGaIn LED on sapphire grown by MOCVD exhibited the optical output power of 0.17 mW, the external quantum efficiency of 0.2%, the peak emitting spectrum at 440 nm with FWHM of 63 nm and the stable operation up to 3000 h

under 30 mA DC operation at 30°C. The MOCVD-grown GaN MESFET with the gate length of 2 μ m and the width of 200 μ m showed the high current level of 281 mA/mm and the large g_m of 33 mS/mm at 25°C, which resulted from the electron mobility as high as 585 cm²/V·s at 300 K. Although DC characteristics were degraded at high temperature, the GaN MESFET exhibited the g_m of 13.4 mS/mm at 400°C.

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