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GaN-based Blue Laser Diodes Grown on SiC Substrate as Light Source of High-density Optical Data Storage

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This paper describes GaN-based blue laser diodes grown on SiC substrate as a new light source of optical disks such as magneto-optical disks and DVD. Laser diodes having better characteristics are expected to be obtained when using SiC substrate than when using the conventional Al_2O_3 substrate. We discuss why we selected the SiC substrate and show the properties of GaN-based materials grown on SiC substrate. We also describe the characteristics of our most recently fabricated laser diodes, and suggest that SiC is a very promising substrate for GaN-based blue laser diodes.

1. Introduction

The capacity of optical data storage media such as magneto-optical disks and DVD increases as the wavelength of laser diodes used for reading and writing information becomes shorter because the minimum spot size of focused light is theoretically limited by the wavelength of the light. Infra-red and red lasers with a wavelength between 780 nm and 650 nm are currently used for optical data storage. To increase the capacity of optical disks, laser diodes with a much shorter wavelength are needed.

GaN-based laser diodes are very promising candidates for such applications. The band-gap energy of InGaN used as the active layer of a laser diode can be changed between 1.9 eV and 3.4 eV, corresponding to the wavelength range between 650 nm and 360 nm, by changing the indium content of the InGaN alloy. The first room-temperature pulsed oscillation of GaN-based laser diodes was achieved at the end of 1995.[1] Since then, many research groups have reported pulsed[2)-9)] and continuous wave[10),11)] (CW) operation. The device lifetime at room temperature has been improved to more than 3,000 hours,[12)] which suggests that this material has high potential for practical use. Because the wavelengths of GaN-based laser diodes reported to date have ranged between 380 nm and 440 nm, corresponding to the ultra-violet and blue regions, we call them blue laser diodes. Replacing red laser diodes with blue laser diodes allows us to increase the capacity of optical disks to about three times the present capacity.

In spite of successful rapid advances made in GaN-based laser diodes, some problems remain to be solved. The most important problem is substrate selection. GaN-based materials are usually hetero-epitaxially grown on substrates other than GaN because it is very difficult to make bulk GaN crystals due to the high equilibrium nitrogen pressure at the melting point of GaN. Al_2O_3 is the substrate most widely used for GaN growth and fabrication of GaN-based laser diodes. However, Al_2O_3 has some drawbacks as a substrate for laser diodes, especially the difficulty in making cleaved facets of GaN, electrically insulating properties, and small thermal conductivity. These drawbacks complicate the fabrication process and degrade the laser characteristics. Therefore, better substrate materials than Al_2O_3 are needed to improve the characteristics of blue laser diodes.

One potential substrate that is better than Al_2O_3 is SiC. Pulsed[8),9)] and CW[11)] operation of GaN-based laser diodes grown on SiC substrate were reported in 1997.

This paper describes the advantages of SiC substrates for the fabrication of laser diodes and discusses some issues concerning the properties of GaN-based materials grown on SiC. We also show the characteristics of our laser diodes grown on SiC.

2. Growth method

We grew crystals using a low-pressure metal-organic vapor phase epitaxy (LP-MOVPE) at a pressure of 100 torr. We used a home-made chimney type reactor, in which the substrate was set face down. Ramp heating was employed. Group III and Group V sources were injected into the reactor through separate holes in the gas injector to prevent pre-reaction from occurring between them. Trimethylaluminum (TMA), trimethylgallium (TMG), triethylgallium (TEG), trimethylindium (TMI), and ammonia (NH_3) were used as the source gases. Monosilane (SiH_4) and bis-cycropentagieneil-magnesium (Cp_2Mg) were used as the dopant source. (0001)Si oriented 6H-SiC made by using the Lely method and modified Lely method were mainly used as the substrate. (111) oriented Si, (001) oriented $MgAl_2O_4$, and (0001) oriented Al_2O_3 were also used as substrates for comparison. We used an AlN buffer layer for Si and SiC, and a GaN buffer layer for $MgAl_2O_4$ and Al_2O_3. We also used an $Al_{0.09}Ga_{0.91}N$ buffer layer for the SiC substrate. The growth temperature of GaN and AlGaN was between 1,050°C and 1,190°C, and that of InGaN was between 780°C and 880°C. We measured the temperature on the back of the susceptor using a thermocouple and defined it as the growth temperature. The growth rate of GaN and AlGaN was between 1 µm/hr and 2 µm/hr, and that of InGaN was between 0.15 µm/hr and 0.27 µm/hr. The p-doped layers were annealed at 800°C in nitrogen ambient for 10 minutes after the growth to depassivate the hydrogen.

Table 1
Properties of GaN.

Lattice constant (A)	a = 3.198, c = 5.185
Thermal expansion coefficient ($\times 10^{-6}$)	5.59
Band-gap energy (eV)	3.39x

3. Substrate materials

In this section, we first discuss the properties of various substrates to show that Si, $MgAl_2O_4$, SiC and Al_2O_3 have appropriate properties for the growth of GaN. Then, we compare Si, $MgAl_2O_4$, SiC, and Al_2O_3 regarding their application to laser diodes[13)] and conclude that SiC is the best hetero-epitaxial substrate for laser diodes.

3.1 Properties of various substrates

GaN has the wurtzite type crystal structure belonging to the hexagonal system category. **Table 1** shows the lattice constant, thermal expansion coefficient, and band-gap energy of GaN. In considering the appropriateness of a certain substrate for the crystal growth of GaN, we must consider (i) thermal and chemical stability under ambient conditions for GaN growth, (ii) the effective lattice mismatch, which is defined as the difference in the bond length between GaN and the substrate material normalized by the bond length of GaN, and (iii) difference in thermal expansion coefficient between GaN and the substrate material. **Table 2** lists these properties for various commercially-available single crystal substrates.

Among these properties, the requirement for stability is the most difficult to satisfy because the crystal growth of GaN is usually conducted under extreme ambient conditions such as at high temperature in reactive gases. When the substrate is unstable, it is impossible to grow GaN on it. We experimentally investigated the stability

Table 2
Properties of various single crystal substrates.

Material	Crystal structure	Effective lattice mismatch (%)	Difference in thermal expansion coefficient ($\times 10^{-6}$)	Cleavage	Stability
Si	Diamond	20.1	−2.0	(111)	Good
GaAs	Zinc blende	25.3	0.4	(110)	Fair
GaP	Zinc blende	20.7	−0.9	(110)	Fair
MgO	Rock salt	−6.5	4.9	(100)	Fair
MnO	Rock salt	−1.4		(100)	Bad
CoO	Rock salt	−5.4		(100)	Bad
NiO	Rock salt	−7.6		(100)	Bad
$MgAl_2O_4$	Spinel	−10.3	1.9	(100)	Good
$NdGaO_3$	Perovskite	−1.2	1.9		Fair
ZnO	Wurtzite	2.0	−2.7	(1-100) (11-20) (0001)	Fair
6H-SiC	ZnS 6H	−3.4	−1.4	(1-100) (11-20) (0001)	Good
$LiAlO_2$	ß-$NaFeO_2$	1.7	1.7	(001)	Fair
$LiGaO_2$	ß-$NaFeO_2$	−0.1	1.9	(010)	Fair
Al_2O_3	Corundum	−13.8	1.9	(1-102)	Good
$LiNbO_3$	Ilmenite	−6.7	9.9	(1-102)	Bad
$LiTaO_3$	Ilmenite	−6.8	10.6	(1-102)	Fair

of the substrates. We kept the substrates at 900°C in hydrogen ambient for 30 minutes and observed the appearance of the substrate after treatment by using the naked eye and an interference microscope. When no difference was observed between before and after the treatment, we judged the stability as good. When only the surface was deteriorated without any change in the bulk crystal shape, we judged the stability as fair. When the bulk crystal shape changed, we judged the stability as bad. As shown in Table 2 , we found only four materials (Si, $MgAl_2O_4$, SiC, and Al_2O_3) that have good stability and can be used as the substrate for GaN growth.

The effective lattice mismatch and difference in thermal expansion coefficient affect the density of such defects as dislocation and cracks formed in the GaN epitaxial layer. To reduce the defect density, it is better to select a material with smaller effective lattice mismatch and difference in thermal expansion coefficient, though there is no clear standard for judgment. SiC has the smallest effective lattice mismatch and difference in thermal expansion coefficient among the four materials noted above.

3.2 Comparison of substrates for laser application

Here, we investigated the suitability of the properties of each material as the substrate of laser diodes for Si, $MgAl_2O_4$, SiC, and Al_2O_3 which have sufficient stability for GaN growth. The items compared were the cleavage plane relationships between the substrate and GaN epitaxial layer, the electrical properties, and thermal conductivity.

The reason why we investigated the cleavage plane relationships was to judge the ease of fabricating the cavity mirror for each substrate. In a laser diode made of a conventional III-V compound such as GaAs and InP, a (110) cleaved facet is usually used as the cavity mirror because (i) the cleaved facet is smooth on an atomic scale, (ii) the cleaved facet is perpendicular to the (001) surface of the substrate, and (iii) the cleavage process is easy. We do not have to consider the relationships of cleavage plane between the substrate and epitaxial layer because both have the same Zincblende type crystal structure and cleavage plane. Meanwhile, GaN is hetero-epitaxially grown on a substrate that has a different crystal structure and cleavage plane from those of GaN, so we had to investigate the relationships of cleavage plane between the substrate and GaN epitaxial layer to determine whether it is possible to make a cavity mirror by using a cleavage. The cleavage plane of GaN is (1-100), which is perpendicular to the (0001) plane that most likely becomes the surface during GaN growth. The cleavage planes of Si, $MgAl_2O_4$, SiC and Al_2O_3 are (111), (100), (1-100) and (1-102), respectively. Since the relationships of the cleavage plane can be deduced from the epitaxial relationships, we grew a GaN epitaxial layer on each substrate and measured asymmetric X-ray diffraction to determine the epitaxial relationships. The following are the epitaxial relationships between each substrate and GaN epitaxial layer determined by the results of X-ray diffraction measurements:

(i) Si (111) // GaN (0001), Si (11-2) // GaN (1-100),
(ii) $MgAl_2O_4$ (111) // GaN (0001), $MgAl_2O_4$ (11-2) // GaN (1-100),
(iii) SiC (0001) // GaN (0001), SiC (1-100) // GaN (1-100), and
(iv) Al_2O_3 (0001) // GaN (0001), Al_2O_3 (11-20) // GaN (1-100).

Using these epitaxial relationships, we estimated the relationships of the cleavage plane as shown in **Figure 1**. The minimum condition that the relationships must satisfy so that we can make a cavity mirror using a cleavage is that the cleavage direction of the substrate coincides with that of GaN. Si, $MgAl_2O_4$ and SiC satisfy this condition, but Al_2O_3 does not. For a substrate that satisfies this condition, it is preferable that the substrate has its cleavage plane perpendicular to the surface because cleavage becomes more reproducible with a perpendicular cleavage than with an inclined one. Only SiC falls into this category. It was therefore inferred that cavity mirrors could be made reproducibly with SiC substrate.

Some researchers have tried to make cavity mirrors using the dry etching process.[1),4)] However, they failed to produce the far field pattern with a simple oval shape necessary for optical disk applications. This was because the light was reflected from the substrate surface remaining in front of the etched facet and the reflected light interfered with the direct light. It thus seems that the cavity mirror must be made by cleavage for optical disk applications.

Electrical properties are related to the ease of the electrode process of laser diodes. Si and SiC are semiconductors that can be made highly conductive by increasing the amount of impurity doping, while $MgAl_2O_4$ and Al_2O_3 are insulators. **Figures 2 (a) and (b)** show the laser structures taken in the case of using a conductive and an insulating substrate, respectively. The structure shown in Figure 2 (a) is the same as that of conventional semiconductor laser diodes, and its fabrication process is simple. A more complicated process is required for the structure shown in Figure 2 (b), so it is preferable to use a conductive

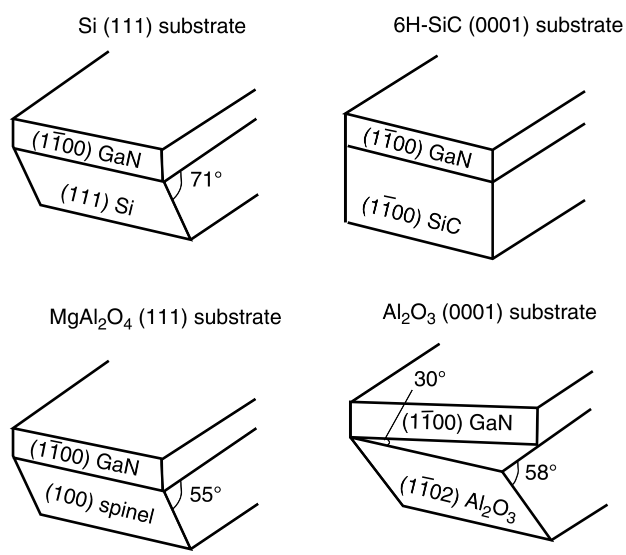


Figure 1
Relationships of cleavage plane between GaN epitaxial layer and substrate.

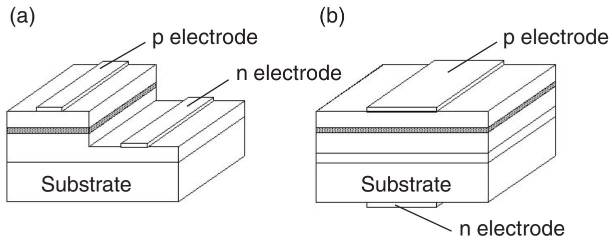


Figure 2
Structure of laser diodes when using (a) insulating substrate and (b) conductive substrate.

Table 3
Thermal conductivity of substrates.

Material	Thermal conductivity (W/cmK)
Si	1.5
$MgAl_2O_4$	-
SiC	4.9
Al_2O_3	0.46

substrate such as Si or SiC.

When we use a substrate with high thermal conductivity, the amount of heat dissipating from the laser diodes increases, which improves the characteristics of laser diodes. **Table 3** shows the thermal conductivity of Si, $MgAl_2O_4$, SiC, and Al_2O_3. The thermal conductivity of SiC is the highest among them. An external heat sink made of diamond or SiC is usually used in conventional semiconductor laser diodes to enhance the heat diffusion from the device to the outside. It might be unnecessary to use such an external heat sink for laser diodes made on an SiC substrate.

From the discussion in this section, we conclude that SiC is the best hetero-epitaxial substrate for laser diodes.

4. GaN-based materials grown on SiC

In this section, we show the structural, electrical, and optical properties of GaN-based materials grown on SiC to assess their potential for laser fabrication. We also discuss the conductive buffer layer necessary for realizing the back contact type laser structure shown in Figure 2 (a).

4.1 Method of evaluating epitaxial layers

The structural defects in the GaN epitaxial layer were investigated by using a transmission electron microscope (TEM). The acceleration voltage of electrons in TEM observation was between 200 and 300 kV. The electrical properties were measured by Hall measurement using the Van der Pauw method at room temperature. Optical properties of InGaN MQW structures were investigated by photoluminescence (PL) measurement at room temperature. As a pumping laser, we used a He-Cd laser with a wavelength of 325 nm and a wavelength-doubled, pulsed optical parametric oscillator with a wavelength of 380 nm. The alloy contents of InGaN and AlGaN were determined using X-ray diffraction, and by assuming Vegard's law and complete relaxation of the lattice.

4.2 Properties of epitaxial layers

To evaluate the structural properties of GaN grown of SiC, we performed cross sectional TEM observations. **Figure 3** shows the TEM image of a 1.3-μm thick GaN layer and 0.02-μm thick AlN buffer layer grown on SiC substrate. Dark lines seen in the TEM image are dislocations. Almost all dislocations are generated at the hetero-interface between the SiC substrate and AlN buffer layer. The number of dislocations is large in the AlN buffer layer and lower part of the GaN layer, but decreases as the thickness of GaN layer increases. The dislocation density near the surface was estimated to be about 10^9 cm^{-2}. In comparison with GaN grown on Al_2O_3, the dislocation density of GaN on SiC is slightly lower than that of GaN on Al_2O_3 (10^9 - 10^{11} cm^{-2}), presumably due to the small lattice mismatch between SiC and GaN. The dislocation density of 10^9 cm^{-2} is, however, far higher than that of conventional III-V semiconductors. For GaN-based materials, CW operation of laser diodes has been reported using highly dislocated materials grown on Al_2O_3, indicating that the dislocations do not greatly affect the initial

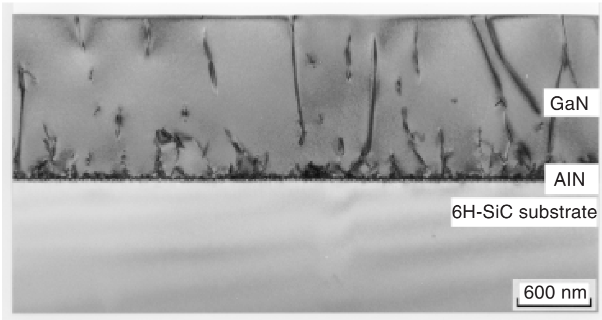


Figure 3
Cross-sectional TEM image of GaN grown on SiC substrate.

characteristics of laser diodes.[10] Considering only the dislocation density, it is probably possible to achieve the CW operation of laser diodes using materials grown on SiC substrate. On the other hand, it has been also reported that the dislocations may affect the lifetime of laser diodes.[12] Therefore, the reduction of dislocations is an important subject that needs to be addressed.

Despite the very poor structural properties, we can obtain good electrical and optical properties using GaN-based materials. Electrical properties were investigated with GaN and AlGaN layers, which are used as the conductive layers in laser diodes. The undoped layer showed high resistivity. We could, however, control both n-type and p-type conductivity using Si and Mg as the dopant. **Table 4** shows the carrier concentration, mobility, and resistivity of the materials with the highest carrier concentration that we have obtained for n-GaN, n-$Al_{0.1}Ga_{0.9}N$, p-GaN and p-$Al_{0.1}Ga_{0.9}N$. The electrical properties of n-GaN, n-$Al_{0.1}Ga_{0.9}N$, and p-GaN are sufficient for fabricating laser diodes, while those of p-$Al_{0.1}Ga_{0.9}N$ look somewhat problematic. The present carrier concentration of p-$Al_{0.1}Ga_{0.9}N$ does not prevent the laser diodes from lasing, but we have to improve the electrical properties of this material further to reduce the resistivity of laser diodes.

Since InGaN multiple quantum wells (MQWs) are used as an active layer of laser diodes, we investigated the optical properties of InGaN MQWs. **Figure 4** shows the PL spectrum of a sample consisting of 12 periods of $In_{0.12}Ga_{0.88}N$/$In_{0.03}Ga_{0.97}N$ MQWs (2.5 nm/2.5 nm) capped by 0.1-µm thick GaN. The spectrum was governed by the band-edge emission of InGaN MQWs with very weak deep level emission, indicating the high optical quality of InGaN MQWs. We also evaluated the luminescence efficiency by investigating the dependence of luminescence intensity on pumping power. The results are shown in **Figure 5**. In Figure 5, we see that the slope on a log-log plot is unity, which means that the recombination of carriers is governed by the radiative recombination and that the radiative efficiency is very high.

Here, we showed the properties of GaN-based materials grown on SiC substrate. Although some problems remain, the materials grown on SiC seem to have adequate quality for fabricating laser diodes.

4.3 Conductive buffer layer

To make best use of the conductivity of the SiC substrate, it was necessary to develop a conductive buffer layer. When we grow GaN on SiC, it is usually difficult to obtain a smooth surface as with direct growth. A buffer layer containing aluminum (e.g., AlN and AlGaN) is indispensable for obtaining a smooth surface. In considering application to lasers, AlN is not effective because

Table 4
Electrical properties of doped GaN and AlGaN.

Material	Carrier concentration (cm^{-3})	Mobility (cm^2/Vs)	Resistivity (Ωcm)
n-GaN	8.3×10^{18}	91	0.0082
n-$AL_{0.1}Ga_{0.9}N$	6.3×10^{18}	115	0.0086
p-GaN	1.3×10^{18}	5	1
p-$AL_{0.1}Ga_{0.9}N$	4.6×10^{17}	3	5.1

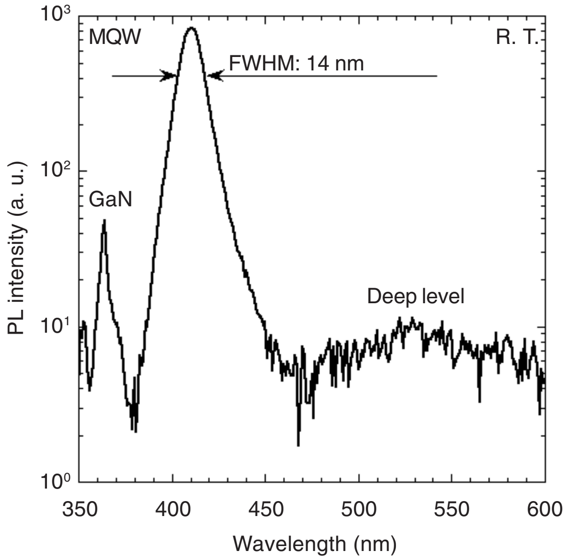


Figure 4
Room temperature photoluminescence of InGaN MQW.

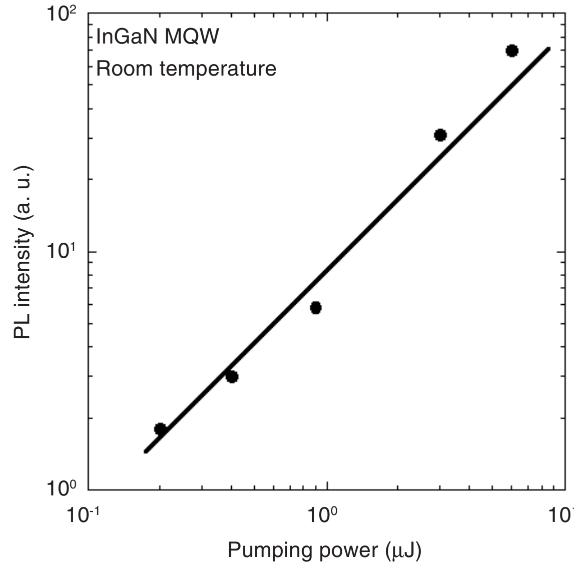


Figure 5
Pumping power dependence of room-temperature PL intensity of InGaN MQW.

it is insulating. Meanwhile, we can obtain n-type conductivity for AlGaN up to an aluminum content of 40%. Therefore, we selected AlGaN as the conductive buffer layer of laser diodes.

To determine the appropriate Al content of the AlGaN buffer layer, we investigated the dependence of surface morphology on Al content.[14] **Figure 6** shows the surface morphology of AlGaN with various Al contents grown directly on SiC substrate. Figure 6 shows that the surface was rough when the aluminum content was less than 8 %, and that an aluminum content exceeding 9% was necessary for obtaining a smooth surface. Therefore, we selected an aluminum content of 9% for the buffer layer because it has the smallest lattice mismatch to GaN among the contents with smooth surfaces.

Since there was a possibility that a considerable potential barrier might exist at the AlGaN/SiC hetero-interface, we then investigated how the AlGaN/SiC heterointerface influenced the current injection. **Figure 7(a)** shows the sample structure used for the measurement. The sample consisted of a 0.2-μm thick n-GaN and a 1.0-μm thick n-AlGaN grown on a 250-μm thick n-SiC substrate. We formed a Ti/Al electrode on the n-GaN surface and defined it as the anode. We also formed an Ni electrode on the back of the n-SiC substrate and defined it as the cathode. **Figure 7 (b)** shows the current versus voltage (I-V) char-

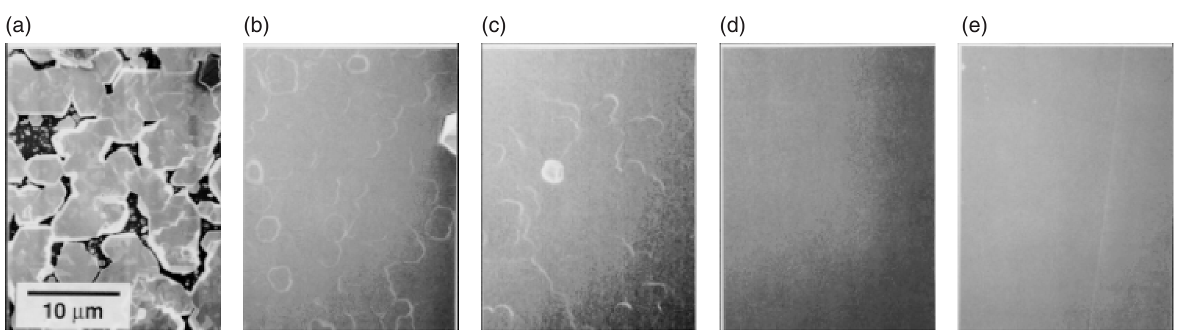


Figure 6
Surface morphology of AlGaN with various Al contents. Al contents are (a) 0%, (b) 6%, (c) 7%, (d) 9%, and (e) 13%.

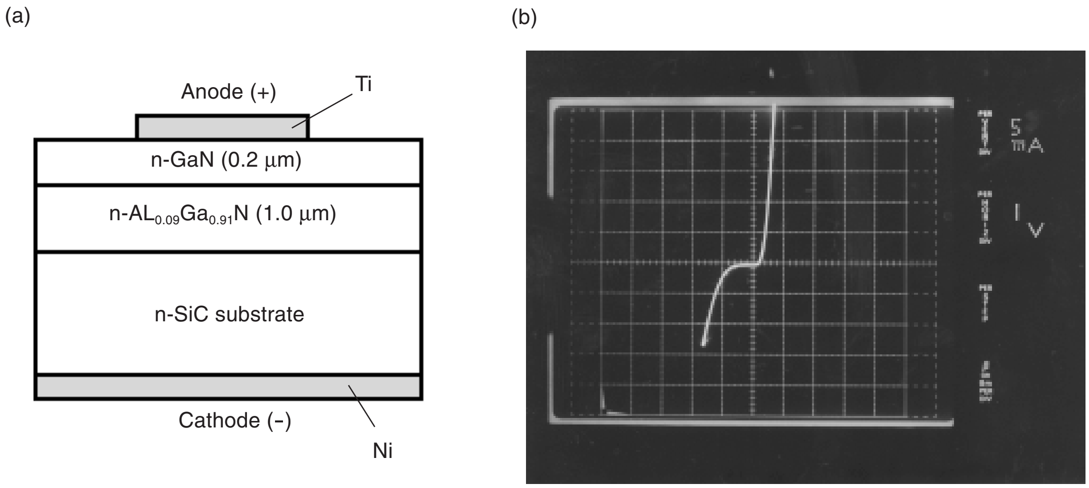


Figure 7
(a) Schematic drawing of sample used in I-V measurement. (b) I-V characteristics of AlGaN/SiC interface.

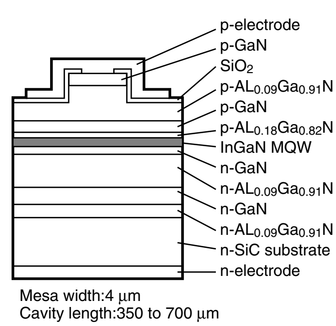
acteristics of the sample. The I-V characteristics showed Schottky-like behavior, suggesting that there is some potential barrier at the AlGaN/SiC hetero-interface. The origin of this potential barrier is not clear at present. This potential barrier prevents us from injecting electrons from n-AlGaN to n-SiC, but hardly affects electron injection from n-SiC to n-AlGaN. Fortunately, the direction in which it is easy to inject electrons corresponds to the direction of the forward current injection of laser diodes. Therefore, we judged that the AlGaN functions as the conductive buffer layer of laser diodes.

5. Laser diodes

In this section, we show the characteristics of InGaN MQW laser diodes fabricated on an SiC substrate, and discuss how to effectively improve the characteristics of the devices. We also consider the present status of our laser diodes.

5.1 Fabrication method of laser diodes

Figure 8 is a schematic diagram of the laser diodes. We used the InGaN MQWs as an active layer. We compared two types of MQW structures (named type A and B). Type A consisted of five pairs of 2.5-nm thick wells and 5-nm thick barriers. Type B consisted of three pairs of 4-nm thick wells and 5-nm thick barriers. A 0.15-μm thick n-$Al_{0.09}Ga_{0.91}N$ buffer layer was first grown on an SiC substrate, followed by a 0.2-μm thick n-GaN buffer layer, 0.5-μm thick n-$Al_{0.09}Ga_{0.91}N$ cladding layer, 0.1-μm thick n-GaN optical guiding layer, undoped InGaN / InGaN MQWs active layers, 20-nm thick p-$Al_{0.18}Ga_{0.82}N$ electron blocking layer, 0.1-μm thick p-GaN optical guiding layer, 0.5-μm thick p-$Al_{0.09}Ga_{0.91}N$ cladding layer, and a 0.2-μm thick p-GaN contact layer. After the growth, the rear of the SiC substrate was lapped until wafer thickness was reduced to approximately 100 μm. Then we etched part of the p-GaN contact layer using dry-etching to form 4-μm wide and 0.4-μm deep



$In_{0.15}Ga_{0.85}N/In_{0.03}Ga_{0.97}N$ MQW

Type	Period	Well	Barrier
A	5	2.5 nm	5 nm
B	3	4 nm	5 nm

Figure 8
Schematic drawing of laser diode.

mesa structures. An n-type electrode consisting of Ni/Ti/Au was formed on the rear of the SiC substrate. A p-type electrode consisting of Ni/Ti/Au was formed on the p-GaN contact layer through the 2-µm wide window of the SiO_2 coating. Then we cleaved the wafer by using the conventional cleavage technique and formed 700-µm and 350-µm long cavities. The direction of the stripe was [1-100], and the cleaved facet was (1-100).

The characteristics of the laser diodes were measured under pulsed current injection at room temperature. The pulse duration was between 100 ns and 1.0 µs, and the repetition frequency was between 1 kHz and 10 kHz, resulting in a duty ratio between 0.01% and 1.0%. Light output was measured using an Si detector. The spectrum was measured through a monochromator by using a photomultiplier.

5.2 Characteristics of laser diodes

Since we used an SiC substrate, we could fabricate the cavity mirror using cleavage. **Figure 9** shows a cross-sectional scanning electron microscope (SEM) image of the laser diodes. We see a smooth cleaved facet. The cleavage of SiC substrate was quite reproducible.

The structure of the MQW active layer generally influences the characteristics of laser diodes. Therefore, we first tried to improve the characteristics of the laser diodes by changing the MQW structure. We used the samples as cleaved with no facet coating and with a cavity length of 700 µm. **Figure 10** compares the I-L characteristics for two types of MQWs. In our first laser diodes, we used the type A structure. By changing the MQW structure from type A (2.5 nm × 5) to type B (4.0 nm × 3), we could improve both the threshold current and slope efficiency. The threshold current was reduced from 800 mA to 650 mA. The slope efficiency increased from 0.12 W/A to 0.6 W/A.

In conventional III-V laser diodes, we seldom observe such a large change in slope efficiency when we change the structure of the active layer because the slope efficiency is determined by the internal loss and internal quantum efficiency. Since the degree of improvement in slope efficiency shown in Figure 10 was very large, we considered that this improvement was mainly due to the reduction in internal loss. We presumed that the reduction in internal loss originated from the reduction in inhomogeneous hole injection into the MQWs.[15),16)] For GaN-based materials, the inhomogeneous hole injection into MQWs is expected to occur more readily than for other III-V com-

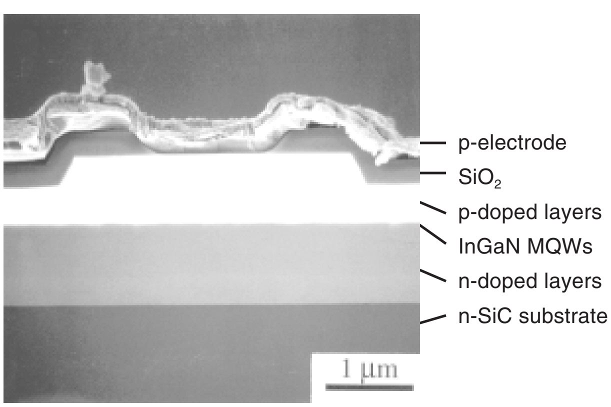


Figure 9
SEM image of mirror facet of laser diode.

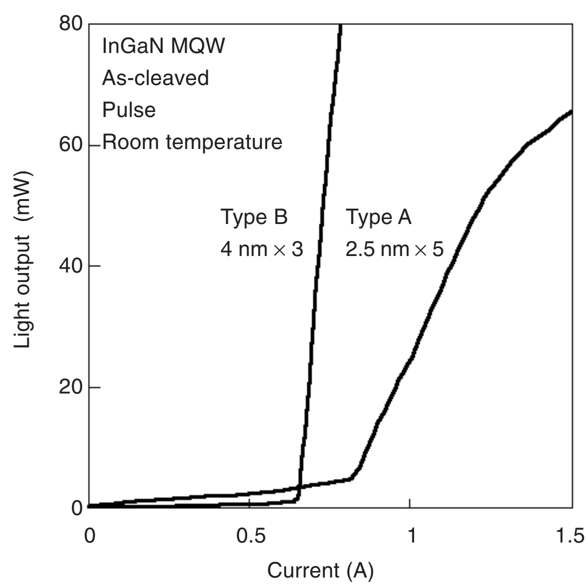


Figure 10
Comparison of I-L characteristics of samples with different MQW structures.

pounds because the hole effective mass is very large and hole mobility is low. When this occurs, wells on the n-doped layer side may cause some absorption and the internal loss becomes larger as the number of well layers increases. Our experimental results seem to correspond to this finding. If our presumption is correct, we would expect more improvement than that expected from the effect of volume reduction when we reduce the number of well layers.

To further reduce the threshold current, we employed high-reflection (HR) facet coating. **Figure 11** compares the I-L characteristics of laser diodes with and without HR coating. We used a quarter-wave HR coating consisting of two pairs of SiO_2 and TiO_2. The HR coating effectively reduced the threshold current from 650 mA to 500 mA. This is the lowest threshold we have ever obtained using a 700-µm long cavity.

We also succeeded in reducing the threshold voltage as well as the threshold current. It is usually very difficult to make good p-type ohmic contact for GaN, so the device resistance of our laser diodes was governed by the p-contact resistance. We found that the following are effective in reducing contact resistance: (i) widening the width of the p-contact metal, (ii) changing the kind of metal, and (iii) changing the growth conditions of the p-contact layer. We applied these techniques to laser diodes and reduced the resistance of the devices. **Figure 12** shows the I-V and the I-L characteristics of the laser diodes which have the lowest threshold voltage we have ever obtained. The threshold voltage was reduced from more than 30 V to 15 V by improving the p-contact resistance.

Figure 13 shows the spectra of laser diodes for various drive currents. Below the threshold, the spontaneous emission peak was blue-shifted as the current increased and the full width at half maximum (FWHM) gradually narrowed. The change in the spectrum below the threshold coincides with the change expected when the spontaneous emission is dominated by the band to band recombination. When the current exceeded the threshold, a sharp lasing emission line appeared. The FWHM of this emission line was 0.1 nm. The longitudinal mode could not be observed due to lack of wavelength resolution.

The shape of the far field pattern is important for optical disk applications. We set a sheet

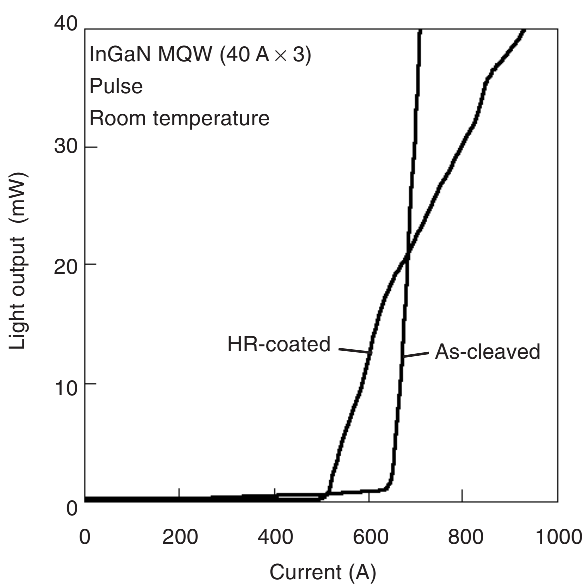


Figure 11
Comparison of I-L characteristics of samples with and without HR coating.

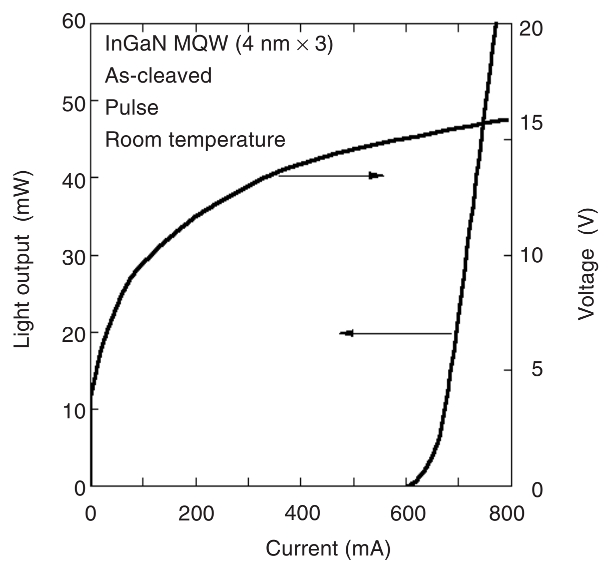


Figure 12
I-L and I-V characteristics of laser diode.

of white paper in front of the laser diode and took pictures of the light projected on the sheet. **Figure 14** shows a far field pattern of our laser diodes. We can see a far field pattern with an oval shape. The side fringes are probably due to insufficient control of the lateral transverse mode. Since the oval-shaped far field pattern is easily obtained when using the cleavage technique, SiC is a suitable substrate for lasers for optical disk applications.

The following describes the best data for laser diodes that we have obtained. The maximum duty ratio was 1%. The minimum threshold current was 400 mA, which was obtained using the 350-μm length cavity. The minimum threshold current density was 12 kA/cm^2. The minimum threshold voltage was 15 V. The maximum light output was 100 mW. Finally, the oscillation wavelength was between 405 and 427 nm. This data cannot match the best data reported by Nichia's group[12] but is comparable to other lasers fabricated on sapphire substrates.[1)-7)] This suggests that the use of SiC poses no serious problems in terms of the characteristics of laser diodes.

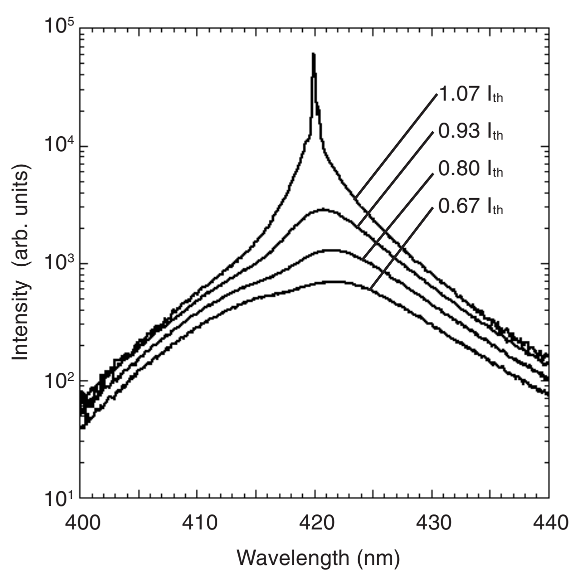


Figure 13
Spectra of laser diode under various amounts of current injection.

6. Conclusion

We compared various substrates regarding the application to GaN growth and fabrication of laser diodes, and concluded that SiC appears to be the best hetero-epitaxial substrate for laser diodes. We investigated the structural, electrical, and optical properties of GaN-based materials grown on SiC. The data obtained suggests that these properties offer sufficient potential for fabricating laser diodes. We also showed that n-$Al_{0.09}Ga_{0.91}N$ can function as the conductive buffer layer of laser diodes. Regarding the characteristics of laser diodes, we found that changing the MQW structure and employing HR coating were effective in reducing the threshold current and that reducing the p-contact resistance was effective in reducing device resistance. We will continue to develop the GaN-based blue laser diodes on SiC substrates in the future for use as the light

Figure 14
Far field pattern of laser diode.

source of optical disks.

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