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Demonstration of electron beam excitation laser using a GaInN-based multiquantum well active layer

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In this study, an electron beam excitation laser using a GaInN-based multiquantum well (MQW) active layer was investigated, and laser emission was observed for the first time from a GaInN-based MQW excited by an electron beam. This technology has the potential to provide access to an expanded wavelength region for the laser action of nitride-semiconductor-based lasers from deep UV to infrared.

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As a result of several breakthroughs, such as the growth of high-quality GaN on sapphire using a low-temperature (LT)-deposited buffer layer11 and the realization of conductivity control for nitrides,2,3 group III nitride-semiconductor-based bright blue, green, and white light-emitting diodes (LEDs) and high-power violet laser diodes have been achieved.1–5 In addition, these technologies are used in high-power violet laser diodes.6,7

The expansion of the laser emission wavelength is a major concern for the research on nitride-semiconductor-based laser diodes. In the long-wavelength region, nitride-semiconductor-based laser diodes have been achieved not only in the blue region8) but also in the green region.9,10 via the optimization of crystal growth conditions, device structures, and so forth. In contrast, in the short-wavelength region, nitride-semiconductor-based laser diodes have only reached the UV-A region.11–15 The shortest wavelength reported for current-injection-type laser diodes is 326 nm.16) UV semiconductor-based laser sources are important for a variety of fields, including medicine, mechanical processing, chemical processing, biology, and photonics. For wavelengths less than 326 nm, the development of UV laser diodes is strongly hampered because of the difficulties with current injection technology such as the realization of both a high hole concentration and low-resistivity p-type AlGaN with a high AlN molar fraction.17) Because laser oscillation from AlGaN, with a high AlN molar fraction, can be obtained under optical pumping,18,19) UV lasers with controllable wavelengths should be realized if this problem is solved.

One promising technique for avoiding this problems is the use of electron beam excitation. To date, nitride-semiconductor-based lasers have been designed to achieve carrier population inversion and to oscillate using current injection. However, as previously discussed, it is difficult to achieve wavelengths shorter than 326 nm by this method. Therefore, we considered carrier injection from a different perspective. The conductivity control of nitride semiconductors is unnecessary using electron beam excitation. Therefore, it would be possible to expand the wavelength region for the laser action of nitride-semiconductor-based lasers from deep UV to infrared if a nitride-semiconductor-based laser could be oscillated via electron beam excitation. Several studies report the excitation of nitride-semiconductor-based UV light sources using an electron beam.20,21) However, laser oscillation excited via an electron beam using nitride semiconductors has not yet been reported.

Therefore, in this study, an electron beam excitation laser using a nitride semiconductor was investigated. Because the confirmation of laser oscillation from the nitride semiconductor excited using an electron beam was critical, a device structure with a GaInN multiquantum well (MQW) active layer was utilized for laser oscillation at approximately 383 nm, which is in the lowest wavelength threshold region realized by nitride-semiconductor-based lasers. Notably, laser oscillation from the GaInN-based MQWs excited using an electron beam was confirmed.

The sample used in the study was grown via metalorganic vapor-phase epitaxy. Figure 1 shows a schematic of the laser structure, which consisted of a separate confinement heterostructure with a GaInN MQW active layer grown on a c-plane freestanding GaN substrate. Trimethylindium, trimethylaluminum, trimethylgallium, triethylgallium, and ammonia were used as source gases. A 500-nm-thick homoepitaxial GaN layer, a 500-nm-thick A10.08Ga0.92N cladding layer, a 100-nm-thick GaN optical guide layer, 10 pairs of Ga0.95In0.05N (3 nm)/GaN (12 nm) MQW, GaN (100 nm), A10.08Ga0.92N (500 nm), GaN (~500 nm), and GaN substrate were stacked in that order. The laser cavity was formed by a combination of Cl2 inductively coupled plasma etching and wet etching by using tetramethyldiammonium hydroxide aqueous (~25 at. %) solutions.22) The
The portion of the sample irradiated with the electron beam, as determined by Monte Carlo simulation, is expected to result in a high excitation efficiency source, and the luminescence from the sample was determined by fixing the acceleration voltage of the electron beam at 15 kV. In addition, the electron beam current was determined by a Faraday cup and was observed to be 5.5 mA. Note that the structure of the GaInN active layer in this study is expected to result in a high excitation efficiency of the electron beam, as determined by Monte Carlo simulation. The portion of the sample irradiated with the electron beam was evaluated using a micro-CCD image sensor. The excitation spot size of the electron beam was controlled by adjusting the acceleration voltage (15–20 kV). The electron beam current was measured using a Faraday cup and was observed to be 5.5 mA. Note that the structure of the GaInN active layer in this study is expected to result in a high excitation efficiency of the electron beam, as determined by Monte Carlo simulation. The portion of the sample irradiated with the electron beam was evaluated using a micro-CCD image sensor. The excitation spot size of the electron beam was controlled by adjusting the acceleration voltage (15–20 kV).

Because the cavity length was small, no facet coating was applied. Figure 2 shows a schematic view of the electron beam excitation and measurement systems. The laser sample was mounted on a cooling stage using a cryocooler. After mounting the sample by using Ag paste, the chamber was evacuated to approximately 1 × 10⁻⁵ Pa using a turbomolecular pump. A LaB₆ electron beam gun was used as the excitation source, and the luminescence from the sample was detected by fixing the acceleration voltage of the electron beam at 15 kV. In addition, the electron beam current was measured using a Faraday cup and was observed to be 5.5 mA. Note that the structure of the GaInN active layer in this study is expected to result in a high excitation efficiency of the electron beam, as determined by Monte Carlo simulation. The portion of the sample irradiated with the electron beam was evaluated using a micro-CCD image sensor. The excitation spot size of the electron beam was controlled by adjusting the acceleration voltage (15–20 kV).

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The electron beam was used in pulse irradiation mode (pulse width: 20 ns, cyclic frequency: 3 MHz, and duty 6%). The sample was analyzed after cooling to approximately 107 K using a cryocooler. The luminescence light emission from the sample edge was passed through a viewport and collecting mirrors, and then detected using a spectrometer (OceanOptics HR4000, wavelength resolution: ∼0.05 nm) with an optical fiber. The sample stage temperature was also monitored using a thermocouple.

Figure 3 shows the luminescence spectra from the Ga₀.₉₃In₀.₀₇N (3 nm)/GaN (12 nm) MQW active layer after excitation using electron beams with power levels of 170, 280, and 470 kW/cm², whereas Fig. 4 shows integrated light intensity (integration range: 380–390 nm) as a function of excitation electron power density. We also used integrated light intensity in this graph after the deconvolution of the background level. When the excitation electron beam power was 170 kW/cm², a spontaneous emission peak at 383 nm was observed. Upon increasing the excitation electron beam power to 280 kW/cm², a sharp emission was observed. From the plot of integrated light intensity as a function of excitation electron power density, a clear threshold power density (Pth) at approximately 280 kW/cm² was confirmed. Over this threshold electron beam power density, the integrated light intensity increased linearly. We also confirmed the comparatively large spontaneous emission light before reaching the laser oscillation. The spontaneous emission light from other than the edge surface is detected, because the distance of the laser sample (in the vacuum chamber) and the light-detection portion (in air) is large. In addition, Figs. 5 and 6 show the lasing spectrum passed with a polarizer (THORLABS GL510) and the polarization feature at 1.68 Pth, respectively. From the lasing spectra and polarization feature, the laser is stimulated emission with TE polarization. In addition, the peak wavelength intervals (∼0.5 nm) of the laser spectrum agree well with the longitudinal mode intervals in a laser cavity of 50 µm. Thus, it was concluded that this sample exhibited laser emission. Lasing emission was also observed at a wavelength of approximately 383 nm when the excitation power density was 280 kW/cm². This GaInN MQW active layer led to laser oscillation at approximately 100 kW/cm² excited by a Nd: YAG laser (fourth harmonic, λ = 266 nm). When calculated with this light power density, the carrier concentration in the GaInN active layer required for laser oscillation is equivalent to the range from mid-10¹⁸ to low-10¹⁹ cm⁻³. Since the excitation carrier concentration required for laser oscillation is the same, it is considered that the generation rate of electron–hole pairs by electron beam excitation is approximately 1/3 times that of light excitation.

In conclusion, we investigated an electron beam excitation laser using a GaInN-based MQW active layer and confirmed, for the first time, laser oscillation from GaInN-based MQWs excited by an electron beam. This technology should address...
the problems associated with current injection systems; hence, it can be an extremely useful solution for AlGaN-based UV lasers and greatly contribute to the expansion of nitride semiconductor UV photonics.

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