Mid-infrared Quantum Cascade Laser Operable in High Temperature (200°C)

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A quantum cascade laser (QCL) is the most promising semiconductor laser for trace gas sensing in the mid-infrared region due to its excellent features such as a small chip size, high speed modulation, and a narrow linewidth. In practical gas-sensing, QCLs are required to achieve single-mode operation and wide-wavelength tuning without mode-hopping for high-sensitive and multiple gas detection. To obtain the wide tuning range of QCLs, increasing the operation temperature is effective. Therefore, we have developed a distributed feedback (DFB)-QCL that can operate at high temperature by introducing our original strain-compensated core structure and buried-hetero waveguide structure. As a result, we have successfully achieved single-mode operation without mode-hopping between -40°C and 200°C under a pulse condition, leading to a wide tuning range of 123 nm with only a single-waveguide QCL. As a future challenge, we will develop a gas-sensing method using the above-mentioned DFB-QCLs as the light source.

Keywords: semiconductor laser, QCL, mid-infrared, gas-sensing, high temperature operation

1. Introduction

The mid-infrared (MIR) region (e.g., 3 to 20 µm) has many optical absorption lines attributed to fundamental vibrational resonances of the molecules of major industrial and environmental gases (e.g., CO_x, NO_x, SO_x), and therefore it is called "the molecular fingerprint region."

The optical absorption attributed to fundamental vibrational resonances is several orders of magnitude higher than that attributed to harmonics and combination tones in the near-infrared (NIR) region. This helps achieve highly sensitive (ppb - ppt) optical gas sensors for gas analysis.(1)

Recently, quantum cascade lasers (QCLs)(2) have been drawing attention as new light sources in the MIR region. QCLs are new semiconductor lasers developed in 1994 that can oscillate in the MIR region. There has been a growing effort to develop QCLs as compact, high-speed, and narrow linewidth MIR light sources.

Gas sensors using QCLs as the light source have many advantages such as compactness, high speed, and high sensitivity due to the features of QCLs noted above. Such sensors are expected to play a key role as measuring instruments in various fields such as monitoring of process gases and measurement of exhaust gases at plants, monitoring of environmental gases, medical diagnosis (e.g., breath analysis), and detection of hazardous materials. The market is expected to expand rapidly.

As shown in Fig. 1, the core region (light emitting region) of QCLs consists of superlattices.*1 This structure effectively utilizes the functions of the quantum well structure: optical transition of carriers (electrons) between the subbands of the conduction band formed in the active region, and subsequent carrier transport in the injector regions by the tunneling effect. This achieved the laser oscillation in the MIR region, which was difficult to achieve in the conventional semiconductor lasers.

The QCL characteristics have been improved since the first successful oscillation using a practical structure in 1994,(2) leading to continuous wave operation at room temperature(3)–(6) and single-mode operation(7)–(9) by introducing the distributed-feedback (DFB) structure, which is required for gas detection, among other developments. QCLs have already been commercialized.

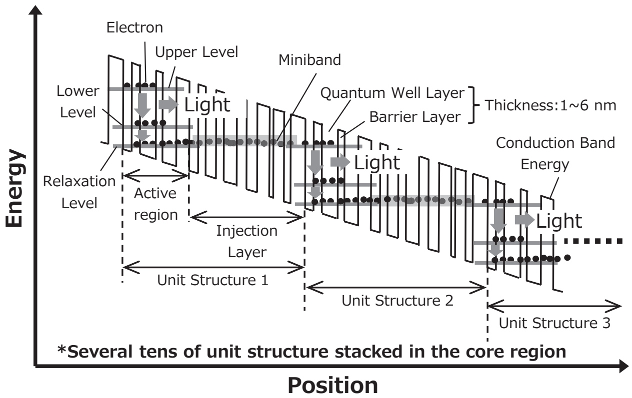

Fig. 1. Schematic diagram of a QCL band structure

Meanwhile, light sources for gas sensors are required to be compact, low power consumption, and single-mode characteristics. Light sources with a wide wavelength sweeping range are also required to collectively detect multiple gas components.

To expand the wavelength band, DFB-QCL array modules, which integrate multiple waveguides of different oscillation wavelengths, and external cavity (EC)-QCL modules, which have micro electro mechanical system (MEMS) gratings as external cavities, are on the market.

Regarding the DFB-QCL array modules, the packaging form and the chip operation become complicated as the number of waveguides increases. Regarding the

EC-QCL modules, a mechanism to control external cavities is also required, resulting in a relatively large package size.

Thus, we decided to expand the oscillation wavelength band by enabling operation of a DFB-QCL chip with a single waveguide (which is the simplest chip form) at high temperature.

2. Core Design for High Temperature Operation

To achieve high temperature operation of QCLs, the quantum well design of the light-emitting core is extremely important in the first place. As discussed in the previous chapter, the MIR light is generated by transporting electrons from the injector region to the light-emitting region and then transitioning from the laser upper level to the laser lower level in the light-emitting region.

When the energy height of the AlInAs barrier, which reduces the leakage current from the laser upper level, is inadequate, the influence of the thermal leakage current (which does not contribute to light emission) increases as the temperature rises, resulting in poorer temperature characteristics. In the core design, it is important to ensure high efficiency in light emission while securing adequate height for the AlInAs barrier.

Figure 2 shows the structural comparison between the conventional core[10] and a newly designed core with improved temperature characteristics.

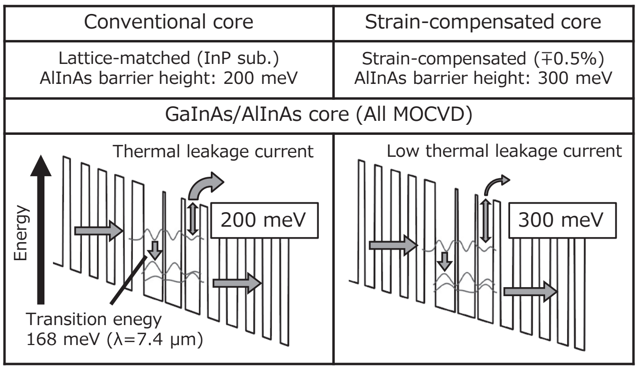

Fig. 2. Comparison of the core structure

The conventional core is lattice-matched to the InP substrate. The height of the AlInAs barrier is 200 meV. Given that the transition energy equivalent to the wavelength of 7.4 μm is 168 meV, thermal leakage current may be generated at high temperature even if the lasing characteristics show good performance at room temperature.

Meanwhile, the newly designed core is a strain-compensated core with tensile strain of +0.5% in the AlInAs layer and compressive strain of 0.5% in the GaInAs layer. The introduced strain compensation increased the height of the AlInAs barrier from 200 meV (conventional core) to 300 meV, making it possible to reduce the thermal leakage current.

The design film thickness of the core structure was optimized to obtain good crystal quality even if the core layer was strained, by taking into account the crystal growth using organometallic vapor phase epitaxy (OMVPE). The strain-compensated core was designed to ensure adequate barrier height and crystal quality.

3. Fabrication Process

OMVPE was used for epitaxial growth of a strain-compensated core layer (35 stages) and an n-GaInAs grating layer, in that order, on the n-InP substrate. Gratings were then formed by photolithography and dry etching.

A waveguide stripe pattern of approximately 5 μm width was fabricated by photolithography, and this was used as a mask to dry-etch an epitaxial layer, including the core, and fabricate the mesa waveguide.

In the third epitaxial growth, Fe-doped semi-insulating InP was buried for current blocking on both sides of the mesa waveguide to form the buried heterostructure (BH).

After forming the BH structure, an insulating film was deposited on the entire wafer. Then, the insulating film only on the n-GaInAs contact layer was selectively removed, and an ohmic electrode was formed by vacuum deposition.

A thick Au plating layer was then added onto the electrode to form a top electrode. Subsequently, the back side of the wafer was thinned by grinding to form a back electrode. Laser bars were made by cleaving, and high reflectivity (HR) facet coatings using Au film were applied to the rear facet in order to reduce the threshold current.

It should be noted that Au coating directly on a rear facet causes electrical short circuits, resulting in insulation breakdown. Thus, an alumina film was inserted between the Au film and the rear facet. Finally, the QCL laser bar was divided into chips, and QCL chips were mounted on the C-mount with the epitaxial side up.

4. Experiment Results

4-1 Temperature characteristics evaluation of QCL core

First, electro-luminescence (EL) measurement, which is used to measure spontaneous emission light from the core, was conducted to check whether the strain-compensated core could emit adequate light in the high temperature range.

A Fabry-Perot (FP) type QCL was fabricated, with the mesa width (W) and cavity length (L) optimized for EL measurement. To detect weak spontaneous emission light power before laser oscillation, Fourier-transform infrared spectroscopy (FT-IR) with a lock-in amplifier added was used. EL measurement was conducted with pulse operation (pulse width: 125 ns, pulse period: 80 kHz). The QCL chip temperature was controlled to 200°C. The measurement results are shown in Fig. 3.

As evident from Fig. 3, the EL intensity of the strain-compensated core is about six times that of the conventional core in the 7 μm wavelength band. The EL intensity improved significantly at high temperature (200°C). The results show that the laser temperature characteristics are also likely to be improved.

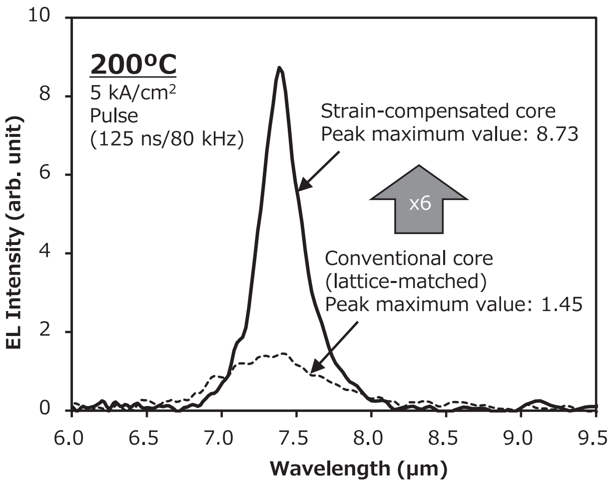

Fig. 3. EL measurement result (200°C)

Next, an FP-QCL with a strain-compensated core was fabricated, and its laser temperature characteristics were compared with those of the conventional core. The each FP-QCL was the same size (mesa width: 7 μm, cavity length: 2 mm) for both core structures, and the temperature dependence of threshold current density (J_{th}) in pulse operation was compared as shown in Fig. 4.

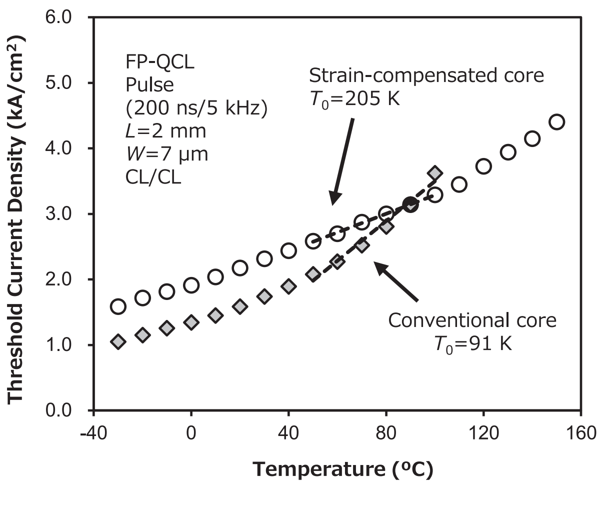

Fig. 4. Comparison of temperature dependence of threshold current density in the conventional core and strain-compensated core

For the conventional core, J_{th} is smaller than that of the strain-compensated core at room temperature (20°C). This is attributable to two factors. First, the number of core stages (52 stages) is greater than that of the strain-compensated core (35 stages). Second, the influence of thermal leakage current is small at around room temperature.

At temperature over 60°C, J_{th} of the conventional core increased gradually, but the increase in J_{th} of the strain-compensated core was suppressed. The characteristic temperature (T_0) between 50°C and 100°C and maximum oscillation temperature (T_{max}) were also compared: T_0 = 91 K and T_{max} = 100°C for the conventional core and T_0 = 205 K, T_{max} = 150°C for the strain-compensated core. This shows significant improvement in both T_0 and T_{max}.

Based on the results of EL measurement and J_{th} temperature dependence of the FP-QCL, we confirmed that the newly designed strain-compensated core is far superior to the conventional core in terms of temperature characteristics.

4-2 DFB-QCL characteristics

For commercial application to gas sensing, it is necessary to pinpoint the target gas wavelength. This inevitably requires a DFB-QCL with single-mode characteristics. Thus, we fabricated a DFB-QCL with the abovementioned strain-compensated core.

Unlike an FP-QCL, the oscillation wavelength can be designed for a DFB-QCL depending on the grating period in a QCL chip (detuning) separately from the gain band of the core.

Thus, we fabricated a DFB-QCL with the grating period designed to oscillate in the wavelength region between 7.4 μm to 7.5 μm by using the gain band of Fig. 3 as a reference. For the QCL chip structure, a BH structure with the mesa width of 7 μm and cavity length of 1 mm was applied. Only the rear facet was coated with HR film.

The I-L-V temperature characteristics in pulse operation (pulse width: 200 ns, pulse period: 5 kHz) are shown in Fig. 5 (20°C only for I-V). As the figure shows, pulse oscillation is successful up to 200°C. As far as we know, 200°C is the highest pulse oscillation temperature in the world for a DFB-QCL.

The threshold current (I_{th}) and threshold voltage (V_{th}) at 20°C were 131 mA and 7.7 V, respectively. The threshold power consumption (P_{th}) was as low as 1.0 W.

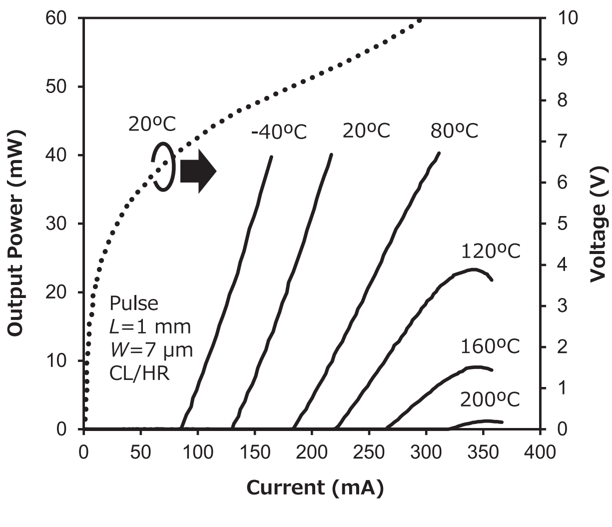

Fig. 5. I-L-V characteristics of the DFB-QCL

We also confirmed that an optical output of mW was attained even at 200°C.

Figure 6 shows the temperature dependence of the oscillation spectra when the abovementioned DFB-QCL was operated under the same pulse conditions. For the FT-IR measurement conditions, the QCL operation current (I_{op}) was I_{th} × 1.1 and the measurement resolution (*Res*) was 0.4 cm^{-1}.

Based on Fig. 6, we verified single mode oscillation (side-mode suppression ratio [SMSR] > 20 dB) without mode hopping in the temperature range between −40°C and 200°C. The wavelength shift against temperature was 0.514 nm/K. The wavelength tuning width of 123 nm in total was attained in the abovementioned temperature range.

Next, in view of application to sensing, we evaluated the far field pattern (FFP) of the abovementioned DFB-QCL to confirm the beam quality. The results are presented in Fig. 7. The measurement current was set to 300 mA at 20°C to ensure adequate optical output.

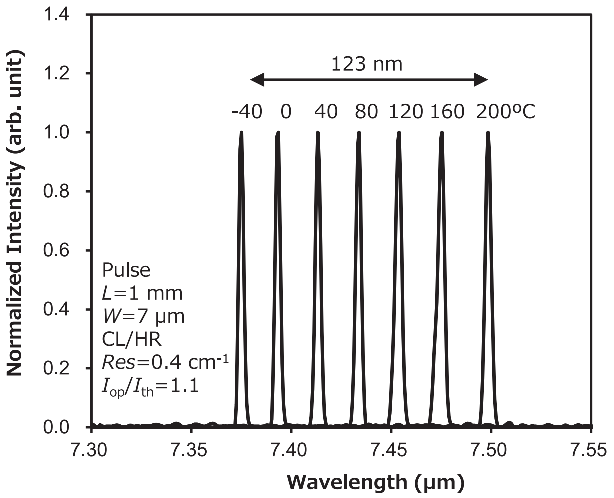

Fig. 6. spectra of the DFB-QCL

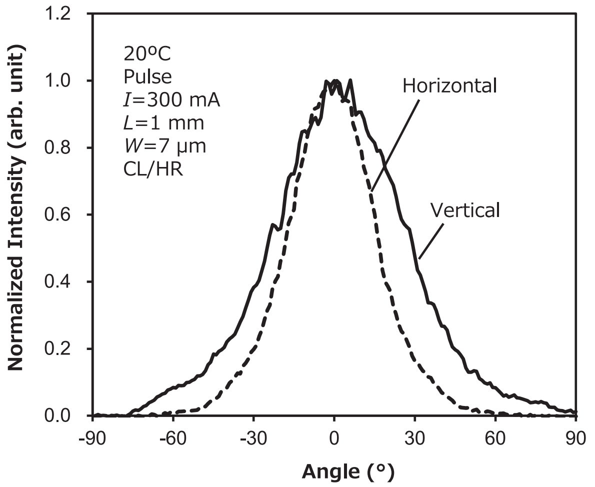

Fig. 7. FFP measurement result of the DFB-QCL

The full width at half maximum (FWHM) in the horizontal direction (dashed line) and vertical direction (solid line) was 36° and 56°, respectively, both of which showed a unimodal peak. It is considered to be easy to focus or collimate the beam using a lens.

Based on the above results, we succeeded in oscillating a single-waveguide DFB-QCL at high temperature (up to 200°C) in the wavelength region of the 7 μm band by introducing the newly designed strain-compensated core and demonstrated that the 123 nm wavelength tuning width can be attained in the temperature range between −40°C and 200°C.

The fabricated DFB-QCL has excellent temperature characteristics and is easy to operate. In terms of beam quality, it is easy to use with a unimodal peak. We will conduct sensing experiments using this DFB-QCL to verify its applicability.

5. Conclusion

We developed a new proprietary strain-compensated core structure that ensures adequate barrier height and crystal quality of the current block layer. Introduction of a buried heterostructure (BH) attained an EL intensity six times that of the conventional core. We confirmed that the characteristic temperature (T_0) of the FP-QCL also improved significantly.

The abovementioned core was introduced to the DFB-QCL with single-mode characteristics, which are required for gas sensing. As a result, single mode oscillation without mode hopping in the range between −40°C and 200°C in pulse operation.

As far as we know, 200°C is the highest pulse oscillation temperature in the world for a DFB-QCL. We also succeeded in achieving a wavelength tuning width of 123 nm with a single waveguide. These research findings are expected to be useful for QCL-based sensing in the future.

Technical Term

*1 Superlattice: A superlattice consists of a structure with two types of ultrathin semiconductor layers (about a few nanometers or less in thickness) laminated alternately in large numbers (several tens to several hundreds). In this structure, many subband levels, in which quantum levels of each semiconductor layer are connected, are formed in the conduction band. A QCL is a semiconductor laser that oscillates by using the light-emitting transition between subbands.

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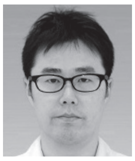

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