特集

High Power Laser with Eye-Safe Wavelength for Laser Radar*

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It is effective to make the light power of a laser diode higher in order to improve the detection performance of a laser radar and to extend the laser radar application. At the same time, the laser must be safe for eyes. A 1.4 μm or longer wavelength laser is safer for eyes than shorter ones, therefore such a wavelength is suitable for laser radar. However, it is difficult to make the light power of lasers higher within the range of this wavelength. We propose a bipolar cascade laser (BCL) structure which has two or more emitting layers in order to increase the laser power. The steep tunnel junction is realized through a combination of dopants to decrease the junction resistance. Consequently, a high emission power of 90W at 120A is achieved by an edge emitting AlGaInAs-InP based BCL with two active layers. A laser radar sensor with this BCL can detect objects with just 5% reflectivity at 30m from the sensor.

Key words：sensor, laser radar, lidar, eye safety, laser diode

1. Introduction

Recently safety and comfort for automobiles are in high demand. In order to meet these needs, sensing applications such as adaptive cruise control (ACC), collision warning and pedestrian detection systems have been developed and some of them are being put to practical use. The ACC system is an important such development. There are 2 types of ACC system; a radio-wave-based system, and a laser-based system. ACC allows a vehicle to slow down when approaching another vehicle and to accelerate again to a preset speed when sufficiently separated from the other vehicle.

The radio-wave-based system is now the most popular sensor for ACC. It emits a millimeter wave which is highly reflected from metals and thus well suited to detect the metallic bodies of vehicles. However, the system is not good at detecting objects of small size or those with low reflectivity to a millimeter wave, since it is difficult to focus the millimeter wave.

Meanwhile the laser-based system, which is called a laser radar, has a sensor with a laser diode. The laser radar sensor has a high spatial resolution because the size of the laser beam can be made small. Therefore the laser radar sensor is useful for spatial sensing applications such as intelligent parking assistance and pedestrian detection systems which need to detect small objects and pedestrians. However, in general, objects around vehicles or on the road, including pedestrians' clothes, have low light reflectivity. In order to realize laser radar sensors suitable for these systems, it is necessary to increase the emission power of the laser diode. However, eye-safety must be considered in light of the increased power. In other words, to improve the performance of laser radar sensors, laser diodes must become safer for eyes.

In this paper, an eye-safe laser diode with high emission power that is realized by an AlGaInAs-InP based bipolar cascade laser structure is demonstrated, and the performance of a prototype laser radar sensor using this laser is demonstrated.

2. Material and structure of the laser diode

2.1. Laser wavelength that is safer for eyes

To realize an eye-safe laser diode, we have focused on the wavelength of light. Safety standards for eyes are determined as the Maximum Permissible Exposure (MPE) in Japanese Industrial Standards (JIS). MPE is the highest energy density of a light source that is considered safe and depends on the light wavelength. As shown in **Fig. 1**, a 1.4 μm or longer wavelength is safer for eyes than shorter ones. In **Fig. 1** 'single pulse' means one pulse with a 30ns pulse width and 'repeated pulses' means pulses with a 30ns pulse width and 13.5kHz frequency. Because light of this

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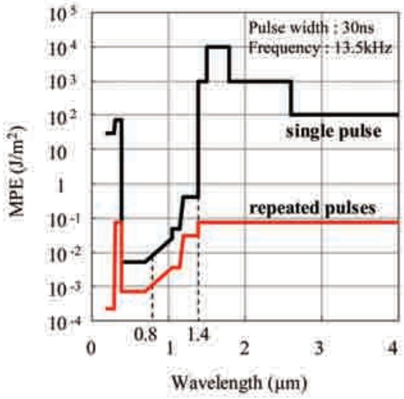


Fig. 1　MPE versus wavelength

wavelength range is easily absorbed by water, most of the light power is absorbed by the crystalline lens of the eye, which is filled with water, before being focused on the retina.

For laser diodes, the efficiency of the conversion of injected current into light decreases as the wavelength becomes longer. The sensitivity of photodiodes also decreases with wavelength ranges of 1.6 μm or longer.

Therefore eye-safe lasers with a wavelength of 1.4-1.6 μm is more effective for laser radars.

2.2. Laser material suitable for sensors on vehicles

In general, laser diodes used for small laser radar sensors consist of GaAs-based semiconductors which have an infrared wavelength of 0.8-0.9 μm. However, it is difficult to realize laser diodes with a wavelength of more than 1.4 μm when made of GaAs-based material. As shown in **Fig. 2**, to realize laser diodes with a wavelength of 1.4 μm or longer, either InGaAsP (indium gallium arsenide phosphide) or AlGaInAs (aluminum gallium indium arsenide) on InP substrate is needed.

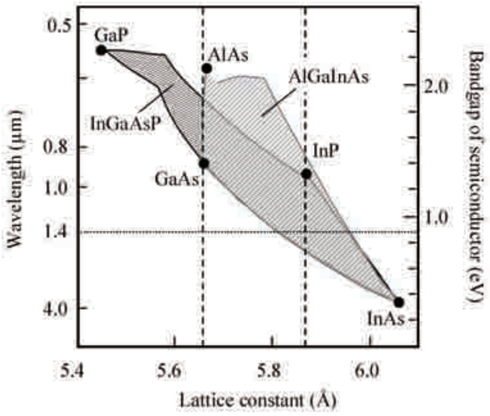


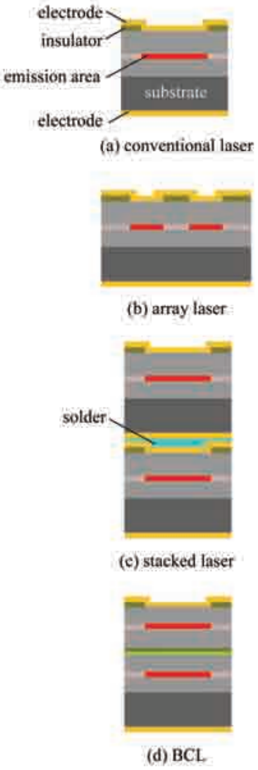
Fig. 2　wavelength versus lattice constant

InGaAsP-InP based lasers are mainly used as a light source in telecommunication applications. However, in InGaAsP-InP based lasers, the injected current isn't effectively converted into light at high temperature. Consequently, high emission power is not realized at high temperature. In AlGaInAs-InP based lasers, the decrease in emission power at high temperature is smaller 1) 2). We have developed an AlGaInAs-based laser which is more suitable for sensors loaded on vehicles.

2.3 Structure of laser diode

To increase the emission power of laser diodes, three types of structure, an array laser, a stacked laser, and a bipolar cascade laser (BCL), are proposed as shown in **Fig. 3 (b)**, **Fig. 3(c)**, and **Fig. 3(d)**, respectively.

An array laser structure has several emission areas arranged in a row, compared with a conventional laser shown in **Fig. 3 (a)**. In this structure, high emission power is realized by simultaneously injecting current into each emission area. However, in this structure emission areas are arranged in parallel and consequently significant drive current is needed to realize high emission power. In addition, it is difficult to collect light from each emission area because they are separated horizontally.



(a) conventional laser

(b) array laser

(c) stacked laser

(d) BCL

Fig. 3　Structure of laser diode

A stacked laser has a structure in which several laser diode chips are stacked using solder. In this structure, emission areas are arranged in series so that high emission power is realized by lower injected current. However, the light from a stacked laser splits into two after passing through a collimator lens because the laser diode chip is about 100 μm thick and each emission area is separated vertically. Therefore such an array is not suitable for a laser radar.

A BCL array is a laser chip structure with several emission areas. In this structure, emission areas are arranged in series on the chip so that high emission power is realized by lower injected current similar to a stacked laser 3) 4) 5). In addition, light from a BCL array is hardly split after passing through a collimator lens because some emission areas are within approximately 10 μm thick. Therefore a BCL array is the most suitable light source for a small laser radar sensor.

2.4 BCL

In a BCL structure, one laser unit which includes an n-type layer, emitting layer and p-type layer is stacked two or more times. Therefore current must be injected from the n-type layer to the p-type layer at the boundary between each laser unit to inject current into every emission area. However, it is usually difficult to pass current through an n-type layer to a p-type layer, and therefore a tunnel junction must be added between each laser unit.

2.4.1 Tunnel junction

A tunnel junction usually consists of n-type and p-type layers which are tens of nanometers thick, respectively. To reduce electrical resistance in the tunnel junction, there are two effective approaches; one is to use a narrow bandgap material for the tunnel junction, and the other is to make the dopants concentration in the tunnel junction layers higher. Narrow bandgap material, InGaAs is the most suitable for AlGaInAs-InP based BCL, as it is not easy to increase the dopants concentration because semiconductor crystals are usually grown at high temperature so the dopants easily diffuse to other layers. In addition, the higher the dopants concentration in semiconductor layers, the more the dopants diffuse. Therefore p-type dopants in the p-type layer and n-type dopants in the n-type layer mutually diffuse in the tunnel junction layers and electrical resistance in the tunnel junction is higher. That is to say, it is very important to prevent the dopants from diffusing to other layers. We proposed a unique combination of dopants with Selenium (Se) in the n-type layer and Zinc (Zn) in the p-type layer to solve the diffusion of dopants.

2.4.2 BCL structure

A schematic diagram of the BCL structure is shown in **Fig. 4**. The BCL structure is grown by Metal Organic Vapor Phase Epitaxy (MOVPE). The fabricated BCL has two emitting layers and a tunnel junction with a pair of p-type and n-type layers. The structure of two emitting layers with multiple quantum wells (MQW) is the same. The substrate is S-doped n-type InP.

The emitting layer is composed of three quantum wells of AlGaInAs, barrier layers of AlGaInAs and waveguide layers of AlGaInAs. The AlGaInAs composition ratio of the barrier layers is different from that of the quantum wells and the bandgap is larger than that of quantum wells. The wavelength from the emitting layers was 1.5 μm. The undoped waveguide layers of AlGaInAs, which had the same composition ratio as well as the barrier layers, were placed on the downside and upside of each MQW structure.

The tunnel junction layers were composed of Se-doped n-InGaAs and Zn-doped p-InGaAs. The concentrations of Se and Zn in the tunnel junction layer are 2×10^{18} cm^{-3} and 7×10^{18} cm^{-3}, respectively. The thickness of the tunnel junction layer is 25nm for each p-type and n-type layer.

Se-doped n-cladding layers are located between the lower emitting layer and the substrate, and between the upper emitting layer and the tunnel junction layer. Zn-doped p-cladding layers are located between the lower emitting layer and the tunnel junction layer, and on the upside of the upper emitting layer. The concentration of Se and Zn in the cladding layers are 1×10^{18} cm^{-3} and 1×10^{18} cm^{-3}, respectively. Zn-doped p-contact layers are grown on the upper p-cladding layer and the Zn concentration is 7×10^{18} cm^{-3}.

An insulator composed of SiO_2 is deposited on the contact layer, and a current-injection aperture is formed by removing a stripe-shaped portion. The width of the current-injection aperture is 200 μm and the emission width is almost equal to the current-injection-aperture width. An Au/Pt/Cr electrode was deposited on the current-injection aperture, and an Au/Ni/Au-Ge electrode is deposited on the backside of the substrate. The cavity length of the BCL is 600 μ m.

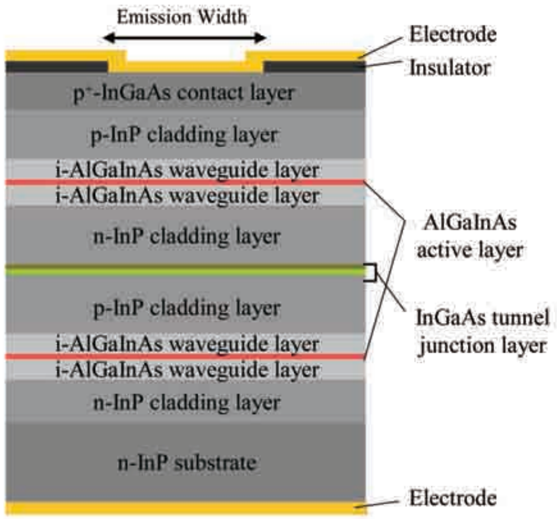
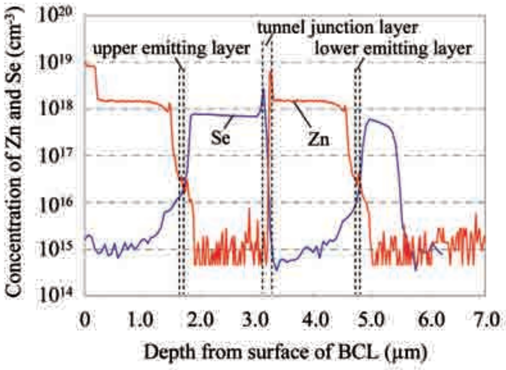
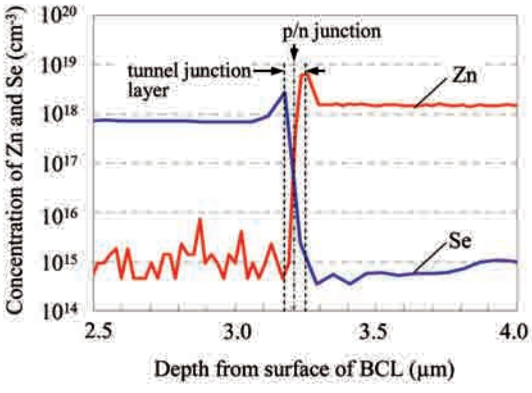


Fig. 4　Schematic diagram of the BCL structure

The Secondary Ion Mass Spectrometry (SIMS) profile of the BCL is shown in **Fig. 5(a)** and the SIMS profile at the tunnel junction in the BCL is shown in **Fig. 5(b)**. As shown in **Fig. 5(a)**, the Zn in the p-type layer easily diffused to the emitting layer. (This diffusion never deteriorates the performance of the laser diode.) On the other hand, as shown in **Fig. 5(b)**, the Zn in the tunnel junction layer did not diffuse to the n-type layer in the tunnel junction. Both the concentrations of Zn and Se decrease down to 1×10^{16} cm^{-3} or less at a distance of 20nm from the junction, thus sufficient steepness of the junction was realized. The diffusion length of Zn in InGaAs is generally known to be much longer than 20nm. We assume the complementary diffusion-suppression of Zn and Se as the reason why the steepness of the junction is realized despite the long diffusion-length of Zn.



(a)　SIMS profile of Zn and Se in BCL



(b) SIMS profile of Zn and Se around the tunnel junction

Fig. 5　SIMS profile of Zn and Se in BCL

3.　Results

3.1　Performance of BCL

Fig. 6 shows the current-voltage (I-V) curve of the BCL with and without the tunnel junction. A characteristic of a conventional laser diode with single emitting layer (single emitter laser) is also added in **Fig. 6** as a reference. In **Fig. 6**, the slope of the curve represents the electrical resistance in the laser diode. As shown in **Fig. 6**, while the resistance of the BCL without the tunnel junction is more than ten times larger than that of a conventional laser diode, that of the BCL with the tunnel junction is almost the same as the single emitter laser. This means the tunnel junction prevented the resistance between the two laser units from increasing.

Fig. 7 shows the emission power-injection current (L-I) characteristic of the BCL. The emission power was measured when injecting 11ns pulse current, up to 120A. The duty ratio of the current pulses was 0.002%. The measurement was implemented at room temperature without any cooling device. A characteristic of a single emitter laser is also added in **Fig. 7** as a reference. An emission power of about 90W is achieved as the maximum value of BCL as shown in **Fig. 7**, when the injection current is 120A. This emission power is twice as large as that of the single emitter laser under the same conditions. This means the injected current into the two emitting layers has the same value and the emission power is not influenced by the heat that occurred in the two emitting layers.

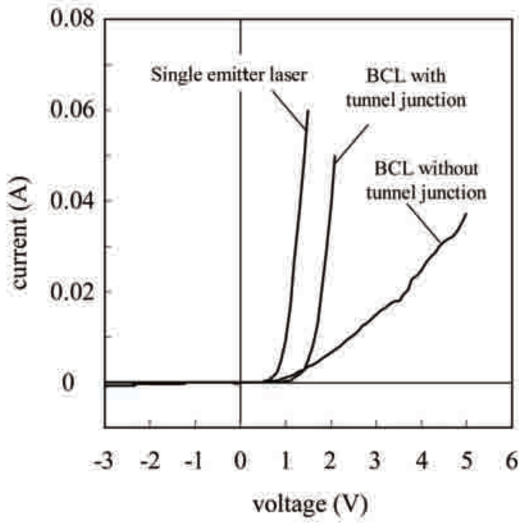


Fig. 6　I-V characteristic of the BCL and a single emitter laser

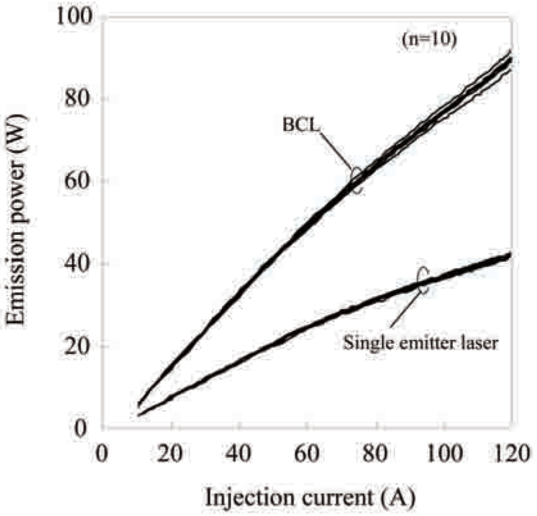


Fig. 7　L-I characteristic of the BCL and a single emitter laser

Fig. 8 shows the micrograph of the emitting layers of the BCL. As shown in **Fig. 8**, the laser is emitted from the two layers and the emitting layers are about 3.5 μ m apart.

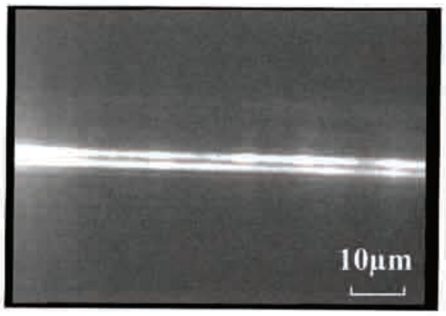


Fig. 8　Micrograph of the BCL emitting layers

3.2　Sensor with eye-safe BCL

We investigated the reflected intensity of a 1.5 μ m wavelength laser from objects which should be detected by a laser radar sensor on vehicles. The following objects were selected for testing; asphalt, concrete, white lines on a road, a metallic car body with dirt and a black cloth with 5% reflectivity. Asphalt, concrete, and the black cloth were assumed to be a road, wall, and pedestrian's clothes, respectively. This experiment employed a simple structure as shown in **Fig. 9**.

Since the sensitivity of an experimental system with a 1.5 μ m wavelength laser is different from that with a 0.88 μ m wavelength laser, the difference of the sensitivity between the two wavelengths was corrected using a standard reflection plate which has the same reflectivity, 50%, for each laser wavelength.

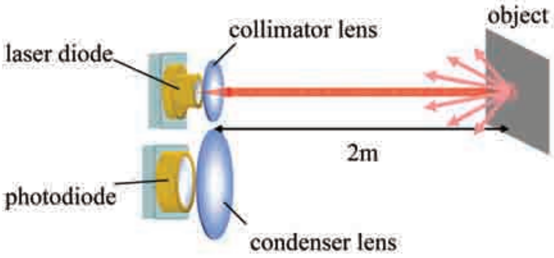


Fig. 9　Structure of the experiment

The **table 1** below shows the reflected intensity of a 1.5 μ m wavelength laser on each object when the reflected intensity of a 0.88 μ m wavelength laser is regarded as 1.0. As shown in the Table, the reflected intensity of a 1.5 μ m wavelength laser is equal to or higher than that of a 0.88 μ m wavelength laser. Consequently the performance of the laser radar sensor with a 1.5 μ m wavelength laser is assumed to be higher than that with a 0.88 μ m wavelength laser. The reflection from asphalt, concrete, a car metallic body and a black cloth can be regarded as almost complete diffuse reflection from the relation between the reflected intensity and the injection angle.

Table 1　Relative reflected intensity of a 1.5 μm laser

object	asphalt	concrete	white line	car body with dirt	black cloth
reflected intensity	3.0	3.5	2.5	0.9	2.7

The prototype of a laser radar sensor with an eye-safe BCL was assembled as shown in **Fig. 10**. This sensor was composed of a BCL, an InGaAs photodiode, drive circuits for each diode, a collimator lens and a condenser lens with a 30mm diameter. The size was about 50 x 50 x 50mm.

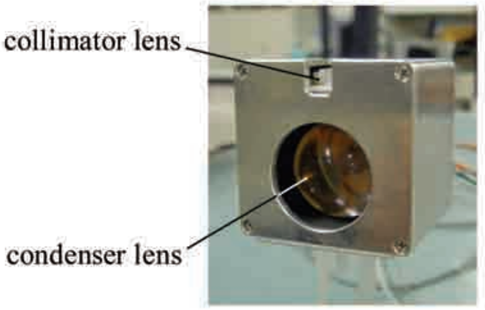


Fig. 10　Prototype of the laser radar sensor

To estimate detection performance, the distance at which a black cloth with 5% reflectivity can be detected was measured. When the emission power of the BCL in this sensor was 20W, the detection distance was about 25m.

4.　Discussion

For laser radars, the detection distance is proportional to the root of the emission power of the laser when the size of the laser beam is bigger than the object. Therefore, when the emission power of the BCL in the prototype of the laser radar was increased to 90W, the detection distance of the black cloth was assumed to be approximately 52m.

To realize a laser radar sensor on vehicles, higher emission power is required. To make emission power higher, it is effective to increase the number of laser units in the BCL. It is important to make the emission power higher in proportion to the number of the laser units when the number of the laser units is increased to three or more.

5.　Conclusion

To realize a high power eye-safe laser, an AlGaInAs-InP based BCL structure was proposed. Dopants in the tunnel junction are prevented from diffusing by using a combination of Zn and Se as dopants. Consequently, low resistivity in the tunnel junction of the BCL and high emission power of 90W at 120A was achieved. The prototype of the laser radar sensor with a BCL with 20W emission power can detect a black cloth with 5% reflectivity at 25m. Detection performance can also be improved by increasing the emission power.

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