3-1-2 GaSb Quantum Cascade Laser

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A terahertz quantum cascade laser (THz-QCL) using a resonant longitudinal optical (LO) phonon depopulation scheme was successfully demonstrated from a GaSb/AlSb material system. A smaller threshold electric field was expected for the GaSb/AlSb QCL because GaSb has a lower LO phonon energy and smaller electron effective mass than GaAs. Experimental results indicated that the threshold electric field of the GaSb/AlSb QCL was 3.2 kV/cm. These results mean that the GaSb/AlSb QCL is suitable for low input power operation. Furthermore, the GaSb/AlSb QCL on a GaAs substrate using single surface plasmon waveguide provides high confinement of terahertz waves in the QCL active region without a complicated fabrication process.

Keywords
Terahertz wave generation, Quantum cascade laser, Plasmon waveguide, Gallium Antimonide

1 Introduction

The terahertz quantum cascade laser (THz-QCL) generates laser oscillation using the intersubband transition of electrons in a multiple quantum well semiconductor structure. This laser has generated high expectations for application as a small, high-power terahertz wave source. Since the initial report on the first oscillation at 4.4 THz in 2002[1], researchers and engineers have been conducting active research aiming at continuous-wave oscillation, improved laser output power, improved operation temperature, and low frequency oscillation. In terms of materials, all previous known terahertz quantum cascade lasers used GaAs/AlGaAs structures, with no alternative material system reported to date. Changing the material system may widen the possible design range of quantum cascade lasers, or may lead to new knowledge regarding the operating principles of such lasers. This article briefly describes our recently fabricated GaSb/AlSb-based terahertz quantum cascade laser[2].

2 GaSb-based quantum cascade laser

2.1 QCL active layer

For a laser to oscillate, a population inversion must be produced in the active layer of the laser. Several techniques have been proposed for producing population inversion in a terahertz quantum cascade laser, including the chirped superlattice method and the bound-to-continuum method. The resonant longitudinal optical (LO) phonon method[3] is another of these proposed techniques. This method produces population inversion using a multiple quantum well structure designed such that the LO phonons scatter the electrons at high speed in the lower of the two subband states with the energy difference between these states corresponding to a terahertz frequency. This method is considered to offer operations at the highest temperature relative to the range of population inversion methods. However, this method poses a problem in that it requires a large electric field to start oscillation.

Figure 1 shows various bulk material constants of GaAs and GaSb. Compared to GaAs, the effective mass of electrons in GaSb is smaller, and the longitudinal optical phonon energy is also smaller. As the effective mass of electrons is smaller, the GaSb quantum cascade laser structure can incorporate wider quantum wells. As a result, film thickness control may be relatively less strict in terms of crystal growth using molecular beam epitaxy (MBE) or other methods. In addition, as the longitudinal optical phonon energy of GaSb is small, using the resonant LO phonon method can lead to a reduction in the oscillation electric field.

We solved the Schrödinger equation and the Poisson equation self-consistently and designed a QCL active layer structure composed of units each of which consists of four wells made of GaSb and four barriers made of AlSb, as shown in Fig. 2. Te is an n-type dopant. The design value of the oscillation frequency is 2.6 THz. The design value of the threshold oscillation electric field is 5.4 kV/cm, lower than the 12 kV/cm (oscillation frequency of 3.4 THz) obtained with the GaAs/AlGaAs quantum cascade laser with a similar structure[3].

Here, the self-consistent calculation of the above Schrödinger and Poisson equations can return only the energies of the subband states. To simulate more detailed conditions of the QCL active layer — i.e., the electron distribution, current-voltage characteristics, and laser gain — we need to consider the multi-body effects, including phonon scattering and electron-electron scattering. Accordingly, we developed a program based on the non-equilibrium Green's function method[4].

2.2 Waveguide

Terahertz quantum cascade lasers present characteristic problems in the waveguide structure. To make the thickness of the QCL active layer approximately equivalent to the wavelength, we need to grow 25 μm of compound semiconductor layers (with a frequency of 3 THz and a semiconductor refractive index of 4). However, it is difficult to grow high-quality semiconductor layers at this thickness using a conventional growth method such as MBE. Accordingly, the thickness of the QCL active layer needs to be reduced to less than the wavelength. In this case, the electromagnetic mode of the laser and the impurity doped layer spatially overlap. As free electrons strongly absorb terahertz waves, this spatial overlap must be minimized. This problem may be resolved, for example, by localizing the modes in a region near the interface using surface plasmons induced in the interface of two substances with dielectric constants of opposite signs, such as a metal and a dielectric sub-

Bulk Material Constants	Unit	GaAs	GaSb
Electron Effective Mass	m^*/m_e	0.063	0.041
Optical Phonon Energy	meV	36	28.9
Refractive Index @3THz	-	3.65	3.99
Thermal Conductivity	W/cmK	0.55	0.32
Energy Gap	eV	1.424	0.726
Conduction Band Offset	eV	0.12	0.4

Fig.1 Bulk material constants of GaAs and GaSb

Material	Thickness (nm)	Doped Te (cm^{-3})
AlSb	4.3	-
GaSb	14.4	-
AlSb	2.4	-
GaSb	11.4	-
AlSb	3.8	-
GaSb	24.6	1.9×10^{16}
AlSb	3	-
GaSb	16.2	-

Fig.2 GaSb/AlSb quantum cascade laser (QCL) active layer structure

stance. Today, two types of waveguides are mainly used for terahertz quantum cascade lasers: the double metal waveguide and the single plasmon waveguide.

In a double metal waveguide, metal layers are placed above and below the QCL active layer and surface plasmon modes are induced on both sides of the active layer. The degree of overlap between the modes and the active layer can be expressed in terms of the confinement factor. The value of this factor is approximately 1 for the double metal waveguide, which indicates complete confinement. In addition, as we can reduce the thickness of the contact layer doped with impurities, the loss of the waveguide mostly occurs in the metal layer. On the other hand, the fabrication of a double metal waveguide involves complicated processing, requiring sophisticated techniques such as wafer bonding and selective etching.

The single plasmon waveguide places a metal layer above the QCL active layer and a semi-insulating semiconductor substrate through a semiconductor layer (featuring a thickness of 0.5 μm to 1.0 μm) doped with a high concentration of impurities below the active layer. The dielectric constant of the semiconductor layer, doped with high concentration of impurities, is expressed by the Drude equation and takes a negative value in the terahertz range. Thus, plasmon modes are also induced above and below the doped semiconductor layer, as well as in the metal-semiconductor interface above the active layer. This causes the modes to extend into the semiconductor substrate and leads to a low confinement factor, at approximately 0.1 to 0.5. On the other hand, a single plasmon waveguide has the advantage of easier fabrication relative to a double metal waveguide.

Figure 3 shows the electric field distribution of a GaSb-based quantum cascade laser fabricated on a GaSb substrate based on a single plasmon waveguide. We calculate the eigen modes using the finite element method[5]. The thickness of the active layer of the GaSb/AlSb laser is 15 μm, the width of the laser ridge structure is 150 μm, the thickness of the impurity doped semiconductor layer below the active layer is 1.0 μm, and the electron concentration in the doped layer is 4×10^{18} cm^{-3}. The confinement factor is 0.5. Here the calculation requires the values of the complex refractive index of the compound semiconductors and the metal in the terahertz range. However, the complex refractive indices of many materials are unknown. We measured the complex refractive index of the metal in the terahertz range using terahertz time domain spectroscopy (THz-TDS)[6].

Notably, a GaSb-based quantum cascade laser can be grown on a GaAs substrate with a buffer, instead of on a GaSb substrate. As shown in Fig. 1, the refractive index of GaSb is larger than that of GaAs. Electromagnetic waves tend to propagate through regions featuring a high refractive index, such that replacing the substrate of the GaSb-based quantum cascade laser with GaAs can lead to higher confinement, using a single plasmon waveguide. Figure 4 shows the electric field distribution of a GaSb-based quantum cascade laser fabricated on a GaAs substrate based on a single plasmon waveguide. The structure is the same as the sample indicated in Fig. 3, except that the GaSb substrate is replaced with

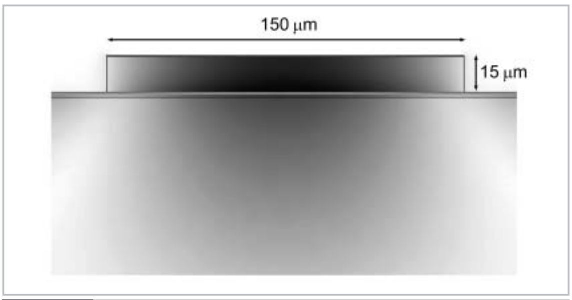

Fig.3 Electric field distribution of GaSb-based quantum cascade laser fabricated on GaSb substrate based on single plasmon waveguide

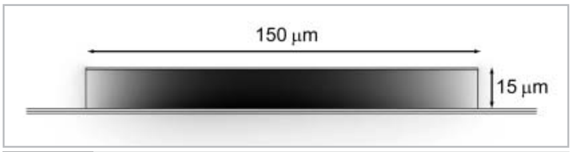

Fig.4 Electric field distribution of GaSb-based quantum cascade laser fabricated on GaAs substrate based on single plasmon waveguide

a GaAs substrate/a buffer layer. The confinement factor is thereby increased, to a value of 0.9 or greater.

As such, a GaSb-based quantum cascade laser fabricated on a GaAs substrate with a single plasmon waveguide can offer a confinement factor comparable to the double metal wave guide quantum cascade laser, with no complicated fabrication process required. As the thermal conductivity of GaAs is relatively large, as shown in Fig. 1, use of a GaAs substrate also offers the advantage of improving the cooling the quantum cascade laser. Further, antimony is a rare metal. Although molecular beam epitaxy growth of GaSb/AlSb itself is costly, using inexpensive GaAs as the substrate can limit such costs. Here, even if a buffer layer is introduced, we cannot avoid dislocations in the GaSb layer due to the differing GaAs and GaSb lattice constants. Nevertheless, as the quantum cascade laser oscillates with only electrons and there are few holes, it is unlikely that the dislocations will act as electron-hole recombination centers, thus damaging the laser and hindering operation.

2.3 Processes

Compared to the processing techniques for GaAs-based compound semiconductors, those of the GaSb-based compound semiconductors are in the early stage of development and often require improvements.

AuGe/Ni/Au is generally used as the contact electrode for the n-doped GaAs layer. We fabricated an AuGe/Ni/Au electrode for the GaSb layer but it easily peeled off in wire bonding and presented high contact resistance. In response, we processed the GaSb surface with ammonium sulfide, evaporated palladium on the surface, and then fabricated the AuGe/Ni/Au electrode. This treatment increased adhesion and reduced contact resistance.

In the case of a GaSb-based quantum cascade laser fabricated on a GaAs substrate, dislocations exist, as described above. Wet etching of the QCL active layer with liquids such as tartaric acid caused rapid etching in areas near the dislocations, resulting in uneven etching. To counter this effect, we decided to use an etching method based on plasma gases, such as the reactive ion etching (RIE) method. Here, as it was necessary to etch the surface over 10 μm deep, and given that the RIE method leads to unevenness of approximately 10% in planar etching, countermeasures were required, such as increasing the contact layer, which acts as an etching stop layer.

2.4 Experimental results

We fabricated a single plasmon waveguide GaSb/AlSb-based quantum cascade laser on a GaAs surface. First, we grew a 1.3-μm thick buffer layer composed of GaSb and AlSb on a semi-insulating GaAs substrate, then grew a 0.8-μm thick GaSb bottom contact layer n-doped at a concentration of 4×10^{18} cm^{-3}, an 18.4-μm QCL active layer consisting of 230 periods of the structure indicated in Fig. 2, and finally an n-type GaSb top contact layer. We fabricated a laser ridge structure with a width of 150-μm using the RIE method to expose the bottom contact layer. We formed Pd/AuGe/Ni/Au electrodes on the top and bottom contact layers and created a 2-mm cavity structure by cleavage.

Figure 5 shows the relationship between the electric field and the current density and the relationship between the terahertz wave output power and the current density for this quantum cascade laser. Measurement was performed by cooling the quantum cascade laser and Ga-doped Ge detector to the temperature of liquid helium. The laser was oscillated in the pulse mode (with an input voltage pulse width of 1 μs). We observed a rapid increase in terahertz wave output power near a current density of 1.8 kA/cm^2. The electric field corresponding to this rise is 3.2 kV/cm, a value significantly smaller than that of the GaAs-based QCL, as expected.

3 Conclusions

We fabricated a terahertz quantum cascade

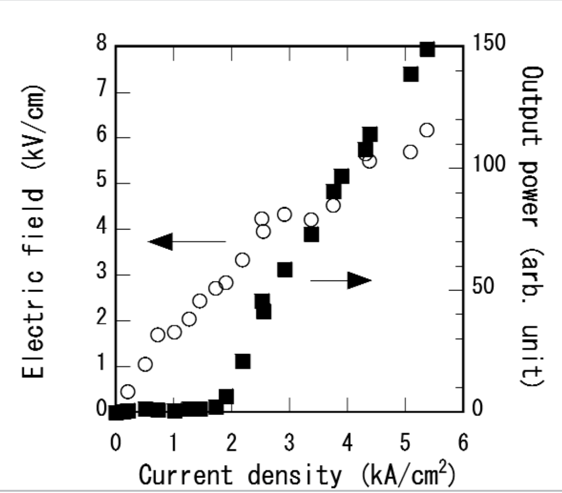

Fig.5 Electric field vs. current density characteristics and terahertz wave output power vs. current density characteristics for GaSb/AlSb-based quantum cascade laser

laser (QCL) using a GaSb-based semiconductor material. To allow oscillation at a higher temperature, we used the resonant longitudinal optical (LO) phonon method for the QCL active layer in designing the GaSb/AlSb-based multiple quantum well structure. As the longitudinal optical phonon energy and electron effective mass of GaSb are smaller than those of GaAs, we were able to reduce the threshold electric field for oscillation of the GaSb/AlSb-based terahertz quantum cascade laser relative to the electric field of a GaAs/AlGaAs-based quantum cascade laser. Further, we adopted the single plasmon waveguide, which can be fabricated through a relatively uncomplicated process. By fabricating the GaSb-based quantum cascade laser on a GaAs substrate, we arrived at a high degree of confinement for the terahertz wave in the QCL active layer — comparable to that of a double metal waveguide. In view of practical applications of the terahertz quantum cascade laser, a diverse range of problems remain to be solved, including the challenge of room-temperature operation. We believe that quantum cascade lasers using other than GaAs-based materials will represent one solution to some of these problems, or at the very least, will provide clues leading to a solution.

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