GaSb/AlSb Quantum Cascade Laser for Terahertz Signal Source

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***Abstract*-A phonon depopulation GaSb/AlSb quantum cascade laser was fabricated for the first time. The low longitudinal-optical phonon energy and small effective electron mass of GaSb enables a low electric field at the lasing threshold and a wide design range. The frequency of oscillation was designed to be 2.6 THz. With an increase of injection current, an abrupt increase of luminescence was observed.**

I. INTRODUCTION

Sub-millimeter or terahertz wave regions (1-10 THz) have remained undeveloped because of huge atmospheric absorption, limited source output power, and lack of compact solid-state sources which equal those of semiconductor electronics devices in the millimeter-wave region or semiconductor laser in optics. Figure 1 shows typical output power of optical or electronics sources and atmospheric absorption in microwave, terahertz, and optical regions.

In recent years, the capabilities of terahertz waves (1-10 THz) for applications such as communications, security, imaging, sensing, and chemical and biological identification have attracted much attention. With a number of applications proposed, the need for compact, high-power, and solid-state terahertz sources is increasing. Quantum cascade lasers (QCLs) are one of the most promising candidates for this. The quantum cascade laser is based on intersubband transitions of electrons in the conduction band of a sequence of semiconductor quantum wells. By changing the structure of the quantum wells the desired transition frequency can be designed. The first demonstration of a QCL operation was performed in the infrared region in 1994. The first THz operation of a QCL was reported in 2002 at 4.4 THz [1]. Since then, many ideas such as chirped superlattice structures [1], bound-to-continuum transitions, an interlaced photon-phonon cascade, and a phonon depopulation technique [2] have been used to extend the operating frequency to the lower terahertz region, to raise the operating temperature of the lasers, and to achieve continuous wave operation. The phonon depopulation technique uses longitudinal-optical (LO) phonon scatterings for fast depopulation of the lower state of radiative subbands. This technique is promising because it allows higher temperature operation of lasers at longer wavelengths [2]. However, its electric field corresponding to the lasing threshold is relatively strong. For example, the field strength was 12 kV/cm for a GaAs/AlGaAs QCL [2]. Another subband, whose energy is E_{LO} (longitudinal-optical phonon energy) lower than that of the lower state of radiative subbands at the lasing bias voltage, is necessary for the depopulation. This is the main cause of the high electric field. Furthermore, monolayer control of barrier thickness is required to lower the laser frequency [3]. To avoid these problems, we propose using a GaSb/AlSb (or AlGaSb) material system instead of a GaAs/AlGaAs material system. GaSb has a lower LO phonon energy and smaller electron effective mass (E_{LO} = 28.9 meV, m_e* = 0.041) than GaAs (E_{LO} = 36 meV, m_e* = 0.067). Therefore, the quantum well for the LO phonon scattering can be thicker, and the control over the thickness can be eased.

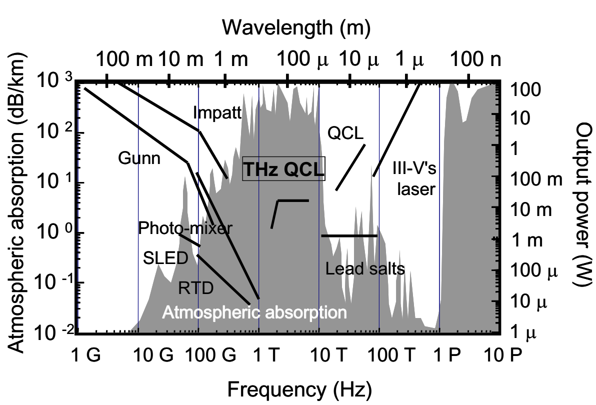

Figure 1. Typical output power of optical or electronics sources and atmospheric absorption in microwave, terahertz, and optical regions.

II. DESIGN

One period of our multi-quantum well (MQW) structure sequence is 4.3 /14.4 /2.4 /11.4 /3.8 /24.6 /3.0 /16.2 nm. Underlined layers represent AlSb layers, and the others are GaSb layers. The 24.6-nm-thick quantum well is n-doped at a level of 1.9 x 10^{16} cm^{-3}.

The conduction band diagram for two periods of the MQW structure under an applied electric field of 5.4 kV/cm is shown

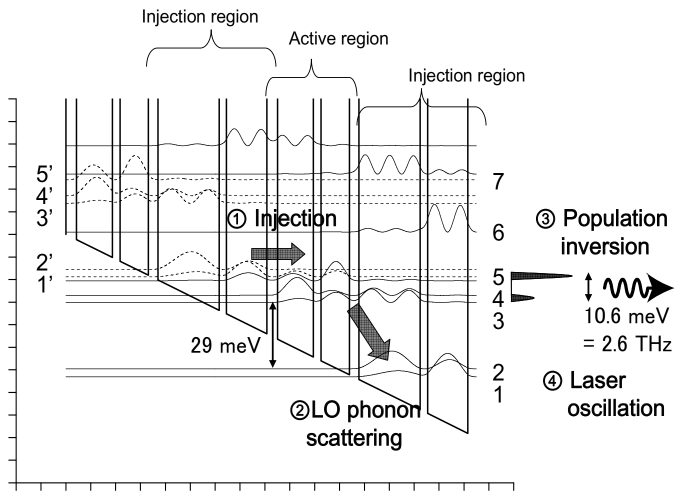

Figure 2. Calculated conduction band diagram of two periods of GaSb/AlSb QCL structure at 5.4 kV/cm.
One division of x-axis and y-axis is 10 nm and 10 meV.

in Figure 2. The subband diagram of a QCL is calculated by self-consistently solving Schrödinger's and Poisson's equations.

The lasing mechanism of the phonon depopulation QCL is as follows. One period of the structure is divided into an injection and an active region. First, electrons are injected from states n = 2' or 1' in the injection region to the excited state n = 5 in the active region. The energy difference, E32, between state n = 3 and state n = 2 is designed to be 28.6 meV, which is almost the same as the LO phonon energy (E_{LO} = 28.9 meV in GaSb). Therefore, the electrons in states n = 4 or 3 are depopulated by the LO phonon scattering into state n = 2, and a population inversion is realized between state n = 5 and states n = 4 or 3. Then, laser oscillation originates. The energy differences of the radiative subbands are designed to be 2.6 THz (E53 =10.6 meV) and 1.9 THz (E54 = 7.7 meV).

III. Fablication

Our quantum cascade laser was grown using molecular beam epitaxy (MBE). Table 1 shows the MBE-grown structure. Buffer layers were grown on the semi-insulating GaAs substrate. The bottom GaSb contact layer is 800 nm thick and n-doped at a level of 3.0 x 10^{18} cm^{-3}. The n-type dopant was tellurium. The QCL structure described above is repeated 230 times. The total QCL structure is 18.4 μm thick. The top GaSb contact layer is 60 nm thick and n doped at a level of 5.0 x 10^{18} cm^{-3}. The growth rate was 1 μm/hour.

Though we did not take special care for the growth of thick layers, the interfaces of the GaSb/AlSb QCL structures are relatively smooth. Figure 3 shows cross-sectional TEM images of GaSb/AlSb QCL structures after about 10 μm of QCL structure growth. This is explained by the high sublimation energy of Sb_4, which leads to a long surface lifetime, and its low atomization energy, which enhances the reaction with Ga surface atoms [4].

The fabrication process was simple. Figure 4 shows the fabrication process. First, layers of Pd/Au were deposited and selectively removed using the lift-off technique. Reactive ion etching with $SiCl_4$ gas was used to selectively remove the QCL structures with the metal layers used as a mask. Layers of Pd/AuGeNi/Au were then deposited on the bottom GaSb

TABLE I
QCL Structure Using Molecular Beam Epitaxy

	Materials	Thickness (nm)	Te doping density (cm^{-3})
Contact layer	n-GaSb	60	5.0 x 10^{18}
QCL structure x 230	AlSb	4.3	
	GaSb	14.4	
	AlSb	2.4	
	GaSb	11.4	
	AlSb	3.8	
	n-GaSb	24.6	1.9 x 10^{16}
	AlSb	3	
	GaSb	16.2	
Contact layer	n-GaSb	800	3.0 x 10^{18}
Buffer layers x 20	GaSb	2.5	
	AlSb	2.5	
Buffer layers	GaSb	1000	
	AlSb	100	
	AlAs	10	
	GaAs	100	
Substrate	S. I. -GaAs	650000	

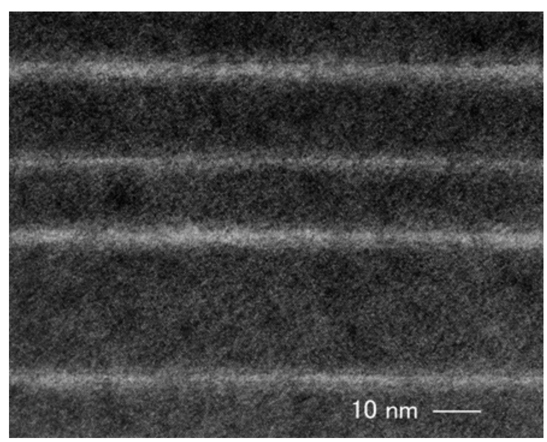

Figure 3. Cross-sectional TEM images of GaSb/AlSb QCL structures after about 10 μm of growth.

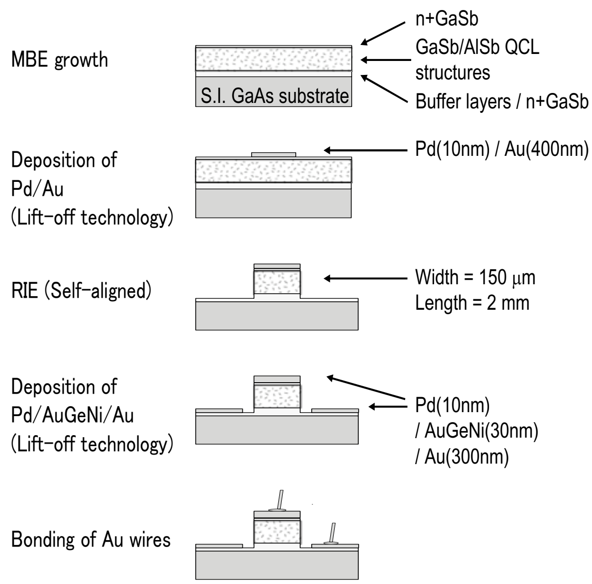

Figure 4. Fabrication process of our quantum cascade laser.

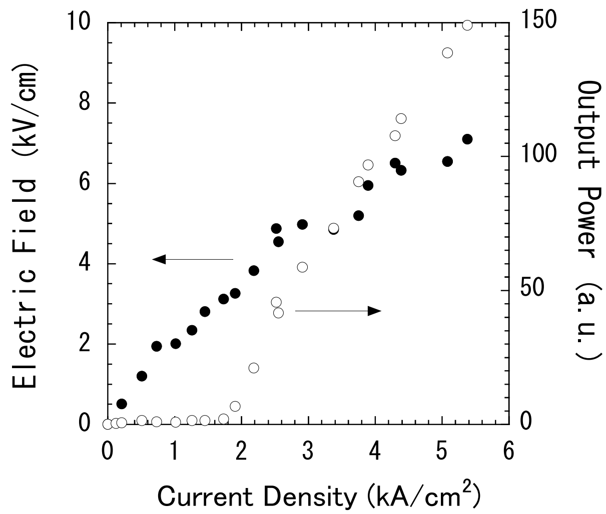

Figure 5. Electric field and output power of GaSb/AlSb QCL as functions of current density.

contact layer. The resulting laser ridge cavity is 150 μm wide and 2 mm long. We bonded Au wires to the top and the bottom Au contact layers to supply voltage to the device.

This cavity also serves as a waveguide based on the surface plasmon propagation along a metal-semiconductor interface [1]. This waveguide is thought to effectively confine terahertz waves to the active part of the QCL and enable high laser output.

IV. Experimental Results

We examined the laser operation of our fabricated QCL. The QCL and a Ga-doped Ge detector were inserted into a cryostat and cooled to the liquid helium temperature (4.2K). The detector range is between 50 μm (6 THz) and 120 μm (2.5 THz). The detector was placed 30 mm away from the QCL. The laser was driven in pulsed mode. The duration of the input voltage pulses was 1 μs, and the repetition rate was 12 Hz.

The electric field-current density characteristics and light output power (L)-current density (J) characteristics are displayed in Figure 5. The L-J curve in Figure 5 clearly shows rapidly increasing emissions. The threshold current density of the L-J curve was 1.8 kA/cm^2, and the electric field corresponding to the threshold current density was 2.8 kV/cm.

We also tried to measure the spectrum of the laser output, but failed because of insufficient output power, power loss in the spectroscope, and worse detector sensitivity than the detector mentioned above.

V. Conclusions

We fabricated a terahertz GaSb/AlSb quantum cascade laser for the first time and studied its operating characteristics. Rapidly increasing emissions were observed in pulsed mode at 4.2 K. Using GaSb LO phonon scattering lowered the threshold electric field and thickened one period of the QCL structure compared to phonon depopulation type GaAs/AlGaAs QCLs. Further improvements in the fabrication process and waveguide design are necessary to obtain a higher output power and a higher operating temperature.

References

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