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Room Temperature Electroluminescence of CdF_2/CaF_2 Inter-subband Transition Laser Structures grown on Si Substrate

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1. Introduction

Light emitting devices on Si substrate have been studied widely to realize the optoelectronic integrated circuits (OEIC) [1] on Si wafers. We have studied fluoride based quantum effect devices [2-5] which can be expected to be utilized for Si based OEIC. The CdF_2/CaF_2 and Si/CaF_2 heterostructures are very attractive materials for these application because of 1) its large conduction band discontinuity ΔEc (~2.9 eV and ~2.3 eV) at the heterointerface which enables the near infrared light emission by inter-subband transition of electrons in quantum well, and 2) their similar lattice constant to Si which enables the epitaxially growth on Si substrate.

On the other hand, III-V materials based Quantum Cascade Lasers (QCLs) [6] have shown high performance and lasing operation has been reported from mid-infrared to THz region [7-9]. Up to now, however, QCLs operating at near infrared region haven't been reported.

In this work, we propose the near infrared inter-subband QCLs using CdF_2/CaF_2 and Si/CaF_2 heterostructures with SOI slab waveguide and calculate the threshold current density theoretically. Moreover, electroluminescence (EL) of (CdF_2/CaF_2) single cascade structures grown on Si substrates by molecular beam epitaxy (MBE) has been observed for the first time.

2. Theoretical Analysis

Design of Active Region and Waveguide

The (CdF_2/CaF_2) and (Si/CaF_2) active regions of QCLs are designed for operating at near infrared region. The typical conduction band diagram of (CdF_2/CaF_2) active region is shown in Fig.1, where the optical inter-subband transitions of electrons occur in CdF_2 active well and wavelength is estimated to be 1.37 μm. The waveguides of both QCLs are formed into SOI slab structure: active regions are sandwiched by Si optical confinement layers (OCLs) and SiO_2 cladding layers in order to realize the higher optical confinement to active regions (Fig. 2(a)). In these waveguides, electric fields are confined enough to active regions as shown in Fig. 2(b).

Theory

Threshold current density ($\mathbf{J_{th}}$) of inter-subband QCL is expressed by the following equation.

$$J_{th} = \frac{\alpha_{Loss}}{N_p \cdot \xi \cdot \left(\omega \sqrt{\frac{\mu}{\varepsilon}} \left| z_{12} \right|^2 \frac{\tau_{in} \cdot \tau_{2-1}}{e \cdot \hbar \cdot W} \right)} \qquad (1)$$

where $\mathbf{N_p}$ is the number of active region, ξ is the optical confinement factor, $\boldsymbol{\omega}$ is the angular frequency, $\mathbf{z_{12}}$ is the dipole moment, $\boldsymbol{\tau_{in}}$ and $\boldsymbol{\tau_{2\text{-}1}}$ are the intra-subband and inter-subband relaxation time respectively, $\mathbf{W}$ is the effective width of wavefunction and $\boldsymbol{\alpha_{loss}}$ is the sum of waveguide loss $\boldsymbol{\alpha_w}$ and mirror loss $\boldsymbol{\alpha_{mirror}}$. In the numerical calculation, mirror loss is assumed to be 20 cm^{-1} and the other parameters in eq.(1) are calculated theoretically.

Calculation Result and Discussion

Fig. 2(c) shows the calculation results of threshold current density ($\mathbf{J_{th}}$), optical confinement factor (ξ) and waveguide loss coefficient ($\boldsymbol{\alpha}$) as a function of the number of active region ($\mathbf{N_p}$), where these results are compared with those of (Si/CaF_2) QCL designed for operating at 1.47 μm. As can be seen, $\mathbf{J_{th}}$ is decreasing with the increase of the number of active region. These results indicate that the laser oscillation below the $\mathbf{J_{th}}$ of 1 kA/cm^2 is possible with several periods of active region. In the comparison with the calculation results of (Si/CaF_2) QCL, any results of (CdF_2/CaF_2) QCL exceed those of (Si/CaF_2) QCL in aiming to realize the QCLs operating at lower $\mathbf{J_{th}}$.

3. Experiment

The layer sequence and schematic illustration of the device structure fabricated in this work are shown in Fig. 3. The p-type Si(111) substrate with a 0.1° miscut angle was chemically cleaned and protective oxide layer was removed in an ultrahigh-vacuum chamber by thermal heating with Si flux at 750°C. After the protective oxide layer removal, a 1.24-nm-thick CaF_2 layer was grown at 650°C through CaF_2 ionization by electron bombardment with the electron current for ionization, I_e = 490 mA; the acceleration bias voltage of the CaF_2 ions towards the substrate (V_a) was 0 V. Subsequently, (CdF_2/CaF_2) superlattice was grown on CaF_2 bottom layer at 80°C by MBE, where CaF_2 layer was grown under the condition, I_e = 490mA and V_a = 0.5 kV. An Au/Al electrode was evaporated on the CaF_2 top layer. Finally, the wafer was polished to less than 100μm in thickness and cleaved to be 500 μm-square.

In the measurement of current-voltage (I-V) characteristic, the negative differential resistance (NDR) was observed at room temperature as shown in Fig. 4(a). Furthermore, EL was measured at room temperature under DC bias operation using a monochromator and photomultiplier. In this measurement, a near infrared EL emission with multi peaks around 1.5 μm was observed under a forward bias of 1.46 V and a current of 100 mA.

4. Conclusions

We have proposed the fluoride based inter-subband QCL operating at near infrared region and calculated the threshold current density theoretically. The results of this analysis indicate that the laser oscillation below the threshold current density of 1 kA/cm^2 is possible at room temperature with several periods of active region. In the experiment, (CdF_2/CaF_2) single cascade structure was grown on Si(111) substrate by MBE. The NDR was observed at room temperature and EL emission around 1.5 μm was observed for the first time.

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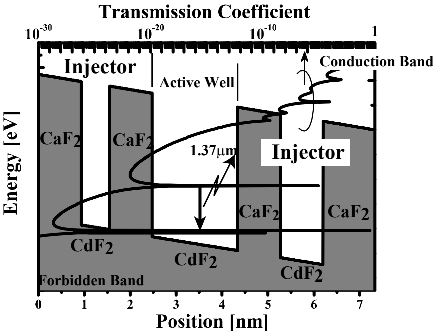

Fig. 1 Calculated conduction band diagram of Injector/Active/Injector Layers in (CdF_2/CaF_2) active region under an electric field of 0.69 V/period. The layer sequence of one period (in nanometers) is, starting from the injection barrier, 0.93/**0.62**/0.93/**1.86**, where CdF_2 quantum well layers are in bold. The electron transmission coefficient is also shown in this figure and the wavelength is estimated to be 1.37 μm.

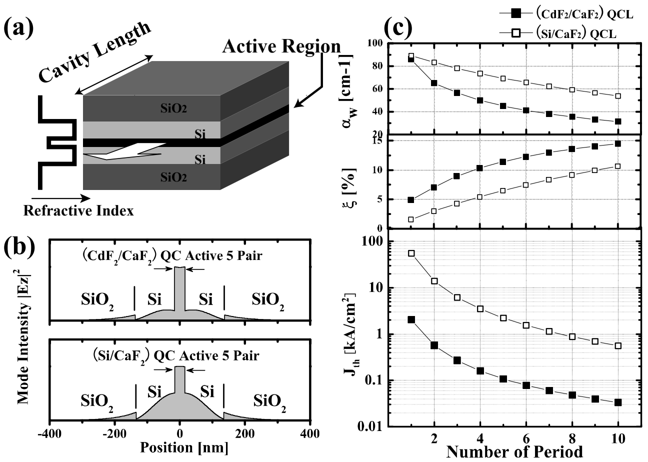

Fig. 2 Schematic illustration of the waveguide and calculation result of (CdF_2/CaF_2) QCL, which is compared with the result of (Si/CaF_2) QCL. The layer sequence of one period (CdF_2/CaF_2) active region is same as in Fig.1 and that of (Si/CaF_2) is 0.93/**0.62**/1.24/**1.55**, where Si quantum well layers are in bold. (a) Schematic illustration of SOI waveguide with active region. The active region is sandwiched by Si OCLs and SiO_2 cladding layers. (b) Calculated Electric field distributions of the waveguide with 5 periods of (CdF_2/CaF_2) and (Si/CaF_2) active region. (c) Calculation results of threshold current density (**J_{th}**), optical confinement factor (ξ) and waveguide loss coefficient (**α_w**) as a function of the number of active region.

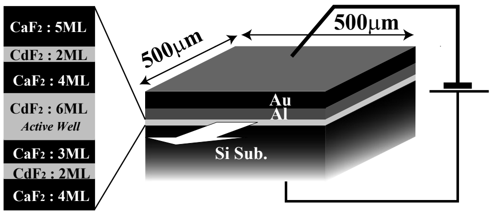

Fig. 3 Schematic illustration of the (CdF_2/CaF_2) single cascade light emitting device fabricated in this work. The layer sequence of the (CdF_2/CaF_2) active region is 1.24/**0.62**/0.93/**1.86**, where CdF_2 quantum well layers are in bold. In this structure, the wavelength of the light generated in CdF_2 active well is estimated to be 1.4 μm.

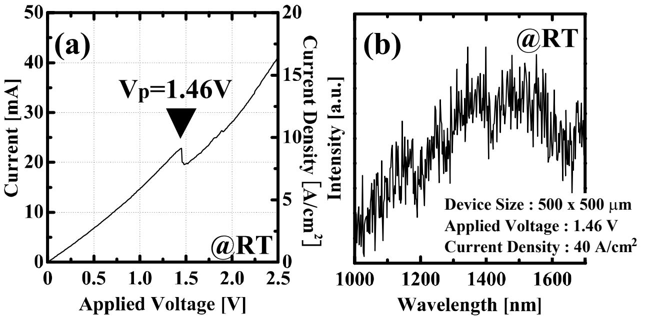

Fig.4 (a) I-V characteristic and (b) EL spectrum of (CdF_2/CaF_2) single cascade structure grown on Si substrate. The negative differential resistance (NDR) was observed at the applied voltage of 1.46 V and EL emission was observed around 1.5μm.