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Room Temperature Near Infrared Electroluminescence of Si/CaF_2 Quantum Cascade Laser Structures grown on SOI Substrate

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Abstract

Room temperature near infrared electroluminescence (EL) from Si/CaF_2 quantum cascade laser structures has been demonstrated. The structure was equipped with 25 periods of active region comprised of Si/CaF_2 multi quantum-wells and single mode waveguide grown by molecular beam epitaxy based technique on the silicon-on-insulator (SOI) substrate. EL spectra with multiple peaks around near infrared region were obtained at room temperature and the EL intensity response with injection current clearly confirmed the EL emission was originated from current injection. Moreover it was found that EL peak shift by changing applied bias was reasonably explained by energy shift due to electric field applied to the Si quantum-well of active region.

1. Introduction

Quantum Cascade Laser (QCL) scheme based on intersubband transition is a promising candidate for light emitting device principle even using indirect band gap material such as Si. Recently, we have proposed QCL using Si/CaF_2 heterostructures targeting near infrared light emitting devices with potential possibility of integration of Si-LSI technology. Up to now, we have proposed and fabricated a QCL structure using CaF_2 that can be directly grown on a Si substrate[1]. The Si/CaF_2 heterostructures as the components of quantum-well (QW) have attractive features as follows: 1) the large conduction band discontinuity ΔEc (2.3 eV) at the heterointerface, which enables the near infrared light emission by intersubband transition of electrons in Si QW sandwiched by CaF_2 barrier layers, 2) similar crystal structure and small misfit (+0.6%@RT) of CaF_2 to Si[2], which enables multilayered epitaxial growth using MBE based crystal growth technique on silicon substrate. 3) CaF_2 is known to be a low optical loss material from mid infrared to ultra-violet wavelength region therefore it is suitable for low optical loss waveguide for QCL. Taking advantage of these features, we have proposed QCL structure using Si/CaF_2 heterostructures targeting near infrared light emitter with potential possibility of integration of Si-LSI technology. However, single-mode waveguide applicable to QCL has not been exhibited mainly due to the lack of precise etching technique of CaF_2. Recently, we have developed a novel fabrication process of Si/CaF_2 heterostructure single-mode waveguide and demonstrated propagation of light with 1.55 μm wavelength[3]. In this study, Si/CaF_2 QCL structures for the near-infrared region (λ = 1 - 3 μm) with single mode waveguide were proposed and fabricated. The characteristics of current injection and electroluminescence (EL) will be discussed.

2. Design

The materials and schematic structure of the QCL are shown in Figure 1. A Si/CaF_2 multilayered structure was formed on silicon-on-insulator (SOI) substrate, The n-Si layers placed above and below the Si/CaF_2 active region act as conduction layers and as parts of the core of the waveguide. The buried oxide (SiO_2) layer acts as cladding layer. An electrode made of Cr / Au is formed outside the waveguide. Current is injected by applying a voltage from the electrode through the n-Si conduction layer in the vertical direction of the active layer. Figure 2 shows the Si / CaF_2 active layer band profile per period and the probability density distribution of the wave functions. For the band profile analysis, the self-consistent method, which combines Schrodinger equation and Poisson equation, is used. The layer composition per period excluding the relaxation layer is **0.63** / 1.26 / **0.63** / 2.51 / **0.63** / 1.88 / **0.94** / 1.57 / **0.94** / 0.94 / **0.94** (**CaF_2**, Si) [nm] from the barrier at the left end. The applied voltage is 937 kV / cm, and the design wavelength is estimated to be 1.70 μm at the transition layer. In addition, the current density that can be supplied to the transition layer was estimated to be 81.1 kA / cm^2 from the theoretical estimation of the resonant tunneling current. The threshold current density was designed to be less than this value. Propagation mode analysis of the waveguide and calculation of the threshold current density was carried out taking into account optical gain, free carrier absorption of n-Si, and propagation loss, etc. J_{th} was estimated to be 1.31 kA /cm^2 with 25 periods of active region.

3.Fabrication

After organic cleaning and SPM washing of SOI substrate, trenches are formed on SOI by photolithography and reactive ion etching (RIE) using Cl_2 gas. Then, rapid thermal annealing (RTA) at 900ºC, 30 minutes in H_2 ambient was carried out for preparing atomically flat Si surface. Next, Spin on Glass (SOG) of 1 μm thick was coated and cured in N_2 ambient. After that, electron beam lithography and RIE (CF_4) were used for formation of the waveguide pattern of 1 μm-width and 2 mm-length. According to the active layer thickness design (Fig.2), molecular beam epitaxy (MBE) was used in the process of crystal growth[4]. After that, a hole for electrode contact was formed by RIE, a Cr/Au electrode was deposited, lifted off, and finally cleaved to complete a Fabry-Perot QCL. Fig.3 shows a cross-sectional SEM image of the fabricated device.

3. Results and discussion

In the FTIR measurement under current injection, EL spectra were clearly observed at room temperature as shown in Fig. 4. The injection current was 200 mA and 280 mA, which corresponds to the current density of 10 and 14 kA/ cm^2, respectively. It should be noted that the value of the current density was approximately 7 times larger than ever achieved value of our previous work [5] mainly because the CaF_2 barrier layers were carefully designed to be as thin as a few monolayer thick and moreover the crystal growth was successfully achieved. It was found that the EL intensity increases with increasing injection current, which confirms the EL emission was originated from current injection. And it was also found that the EL peak shift due to applied electric field was observed and the shift can be reasonably explained by energy shift of quasi-levels of Si-QW, which is strong evidence of intersubband transition. However we have to note that multiple peaks of EL spectra in the wavelength range from 1 to 3 μm was observed although the pre-designed wavelength was 1.70 μm, which strongly indicates that layer thickness fluctuation especially of quantum-well thickness, which determines the intersubband transition wavelength. Effect of energy relaxation and distribution of electrons before injection will be also discussed.

4. Conclusion

We have demonstrated near infrared EL emission from quantum cascade laser structure comprised of Si/CaF_2 multi quantum-wells at room temperature. Reasonable dependence of EL intensity and the peak shift to the applied bias strongly indicates that the EL emission is originated from intersubband transition in Si/ CaF_2 multiple quantum-wells. We believe the results shows the potential feasibility of Si/CaF_2 QWs as a Si-based light sources and other optical applications.

References

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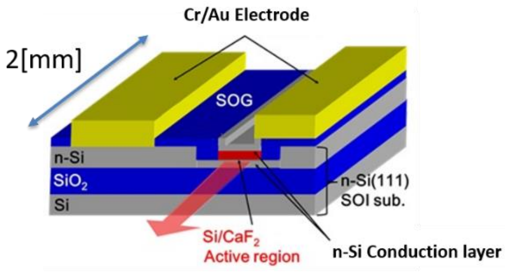

Fig.1 Schematic structure of the Si/CaF_2 QCL

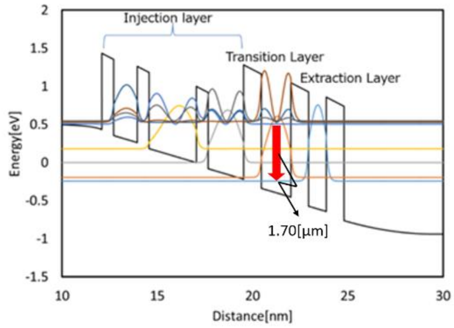

Fig.2 The conduction band profile and electronic states for the Si/CaF_2 QCL calculated for the applied electric field of 937 kV/cm. The wavelength of the intersubband transition is estimated to be 1.70 μm.

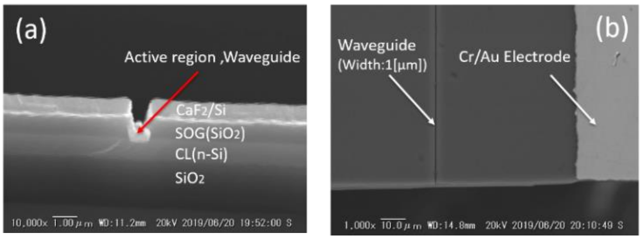

Fig.3 (a) A cross-sectional SEM image around the active layer of a fabricated QCL device (b) A SEM plan view image of a waveguide and a Cr/Au electrode.

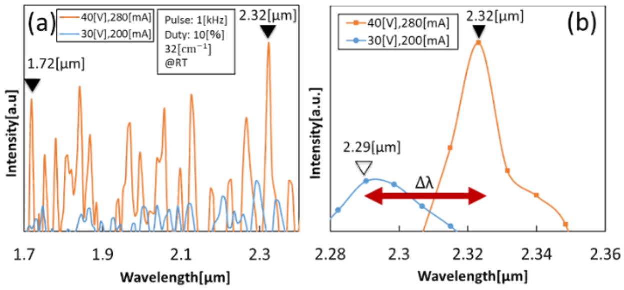

Fig.4 (a) Room temperature EL spectra for the injection current (I) of 200 mA (blue line) and 280 mA (orange line). (b) Magnified EL peaks of (a) at around λ ~2.3 μm for I = 200 mA (blue) and 280 mA (orange), where Δλ indicates the peak shift.