

Analysis of 1.27 μm Near-Infrared Quantum Cascade Lasers using Si/CaF₂ Heterostructures on SOI Substrate

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Introduction

Silicon lasers for optical integrated device applications on silicon substrates have long been a challenge to realize due to the indirect band gap. Quantum Cascade Laser (QCL) scheme based on intersubband transition is a promising candidate for light amplification device principle even using indirect band gap material such as Si. In this study, we have proposed QCL using Si/CaF₂ heterostructures targeting near infrared light emitting devices with potential possibility of integration of Si-LSI technology. Si was used as quantum-wells (QWs) and calcium fluoride (CaF₂) as barriers in active layers. CaF₂ is known to be a low optical loss material for wide range from mid-infrared to extreme ultraviolet wavelength region, it has been widely used for low optical loss components, and its lattice has low mismatch with Si (+0.6%), therefore, it can be well integrated in Si based heterostructure devices.

In our previous work, we have demonstrated electroluminescence of 1.7 μm [1], 1.2 μm [2] and light propagation in waveguides [3] using Si/CaF₂ QWs. In this work we have proposed and analyzed a near-infrared QCL structure with $\lambda = 1.27 \mu\text{m}$ using Si/CaF₂ QWs with injection layers composed of the sequence of the ground states of Si-QWs.

Analysis and results

Conduction band profile and probability density of wavefunction of quasi-states are shown in Fig.1. The active layer consists of an emitter layer, injection layer, transition layer, extraction layer, blocking layer and relaxation layer. The layer thickness sequence is designed to be **10/2/3/2/2/2/6/2/5/3/4/3/2/3/20** (Si/CaF₂ unit: ML), here 1 ML = 0.31 nm for Si and CaF₂ with (111) orientation. The active layer has 4 barriers of 2-ML-thick CaF₂ and Si QWs with different width at injection layer to supply sufficient electrons for laser oscillation, and transition layer is designed to be 4ML narrow Si QW. In transition layer, electrons transit from level 2 to level 1, which corresponds to $\lambda = 1.27 \mu\text{m}$, and scatter to level 1* by tunneling at extraction layer for population inversion. The waveguide structure is designed as Fig.2, the n-Si conduction layers besides active layer are designed to be 150 nm and 570 nm-thick SiO₂ layer acts as a cladding for waveguide, which is BOX layer of SOI substrate.

The waveguide mode analysis was implemented using FIMMWAVE[®]. According to the simulation result, the width of waveguide is designed to be 0.9 μm for single

mode propagation in TM mode. The relation between threshold current density and period number is indicated as Fig.3, and the mode profile is indicated as insert figure. It realizes oscillation when the period number is only 2, where the threshold current density was 5.5 kA/cm².

References

- [1] Gensai Tei et al., Jpn. J. Appl Phys., 60, SBBE03 (2021)
- [2] Gensai Tei et al., Jpn. J. Appl Phys., 62, 072004 (2023)
- [3] Long Liu et al., IEICE TRANS. ELECTRON., E106-C, 1 (2023)

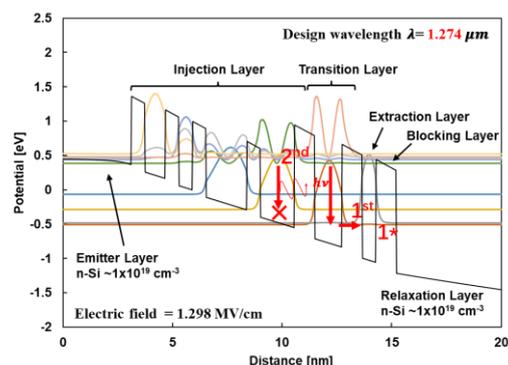


Fig.1 Conduction band profile and quasi-states of Si/CaF₂ active layer quantum-wells.

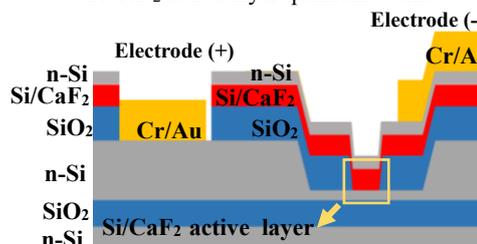


Fig.2 Structure of Si/CaF₂ QCL

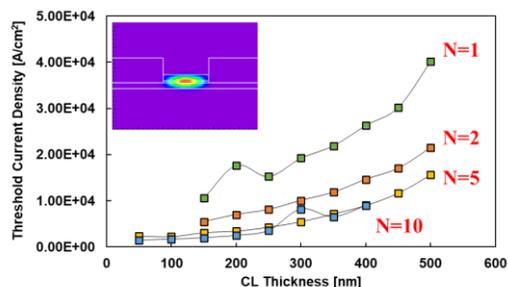


Fig.3 Threshold current density versus CL thickness. Insert figure: TM mode profile with 0.9 μm width and 2-period waveguide.