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Design, fabrication, and evaluation of waveguide structure for Si/CaF_2 quantum-well intersubband transition lasers

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Abstract

We have demonstrated the propagation of light at a wavelength of 1.55 μm through a single-mode waveguide using a Si/CaF_2 heterostructure formed on a silicon-on-insulator (SOI) substrate, which is a key component for Si/CaF_2 quantum cascade lasers. In this study, a new design for Si/CaF_2 (core) and SiO_2 (cladding) waveguide has been proposed and a fabrication process utilizing reactive ion etching has been developed. The propagation of near infrared light has been confirmed and the waveguide losses have been evaluated.

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. 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, and 2) similar crystal structure and small misfit (+0.6%@RT) of CaF_2 to Si[1], which enables multilayered epitaxial growth using MBE based crystal growth technique[2] on silicon substrate. 3) CaF_2 is known to be a low optical loss material from near infrared to ultra-violet wavelength region therefore it is suitable for low optical loss waveguide. 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. Moreover, we have demonstrated electroluminescence at near infrared wavelength region using Si/CaF_2 QWs. However, single-mode waveguide applicable to QCL has not been exhibited mainly due to the lack of precise etching technique of CaF_2. In this study, 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.

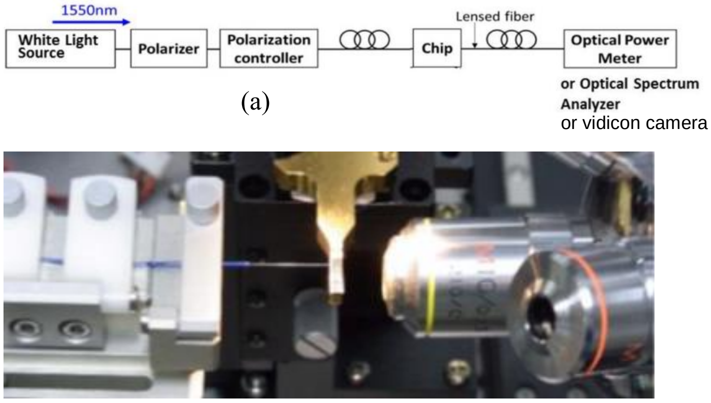
2. Design and fabrication

The materials and schematic structure of the waveguide are shown in Figure 1(a). A Si/CaF_2 multilayered structure was formed on silicon-on-insulator (SOI) substrate, which indicates the core of active layer. The n-Si layers placed above and below the Si/CaF_2 region act as conductive layers and as part of the core of the waveguide. The buried oxide (BOX) layer acts as cladding layer. For the propagation mode analysis, FIMMWAVE was used. Figure 1(b) shows an example of intensity mode profile of the fundamental TM mode with wavelength of 1.55 μm. The equivalent refractive index of the Si/CaF_2 region was determined from the average layer thickness distribution of the Si/CaF_2 QW structure assumed in a QCL structure. In the result of the mode analysis, the final sizes is decided as d=0.6μm (-0.3μm +0.2μm), 2a=0.6μm (-0.3μm +0.7μm), OCL (Optical Confinement Layer)=0.07μm (-0.06μm +0.08μm), where the values in parentheses indicate the tolerance for maintaining the single mode, which are within experimental fabrication tolerances in this study.

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 0.94 μm thick was coated on the chip surface and cured in N_2 ambient. After that, electron beam lithography and RIE (CF_4) are used for formation of the waveguide pattern. The field size of EB lithography is 1000μm/200,000 dots, and the area dot is set as 1120[$\mu C/cm^2$]. Then, molecular beam epitaxy (MBE) is used in the process of crystal growth[3]. Finally, the chip is cut to different lengths of waveguide for characterization. The measurement set up of absorption loss of waveguide is shown in Figure 2. The light with wavelengths from 1530 nm to 1560 nm is emitted from a white light source, and then it is polarized by the polarizer and adjusted by polarization controller to TM mode against a sample waveguide. The input light emitted from fiber tip enters the waveguide on the sample tip and then exit from it, the output light will be measured by an optical power meter, vidicon camera or optical spectrum analyzer.

3. Results and discussion

In order to evaluate side wall roughness of waveguide, scanning electron microscopy (SEM) was used. It was found that the average width of the fabricated waveguide is 974 nm and the line width roughness, σ_{LER}, is 4.9 nm, from which the waveguide loss by line width roughness is estimated to be 7.9 cm^{-1}.[4] The cross-sectional view of waveguide by SEM is also observed. The SEM image is shown in Fig. 3. Although the cross-sectional shape is found to be different from the designed shape, it was found that fundamental TM mode is able to be maintained by using the analysis of mode simulation. The near field image of output light is shown in Fig. 4. The bright spot indicates the output light therefore we can conclude the incident light can be propagated through the waveguide. From the relationship between transmissivity and the waveguide length shown in Fig. 5, absorption loss was estimated to be 51.4 cm^{-1}. The main reason of the loss is probably due to the flatness and verticality of end face of the waveguide. The detail of the cause of the optical loss will be discussed.



(a)

(b)

Fig. 2: (a) A schematic diagram of measurement system of this study. (b) A photograph around the sample stage of the tip.

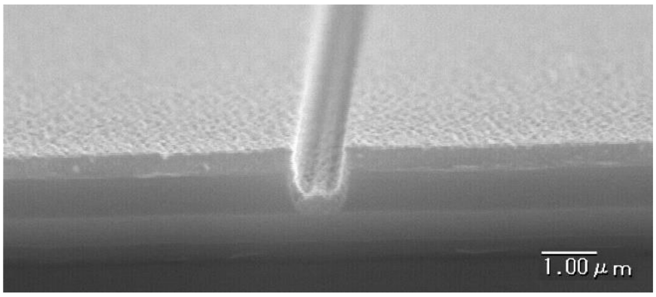


Fig. 3: A cross-sectional view of the waveguide after the growth of Si/CaF_2 region and the top n-Si layer.

Fig. 4: The near field image of output light passing through the waveguide.

4. Conclusion

In this study, the waveguide for 1.55 μm comprised of Si/CaF_2 heterostructure has been proposed and the light propagation has been successfully demonstrated for the first time. A novel fabrication technique with reactive ion etching and EB lithography was developed. The important result of this study is that the waveguide using Si/CaF_2 heterostructure can propagate light in near-infrared wavelength of 1.55 μm. This result is vital for the next stage of the research toward application of electron-photon interaction in Si-QW with electron injection. The measured waveguide loss was around 50 cm^{-1} at the moment however, we believe it can be decreased by optimization of the fabrication process and insertion loss in measurement.

References

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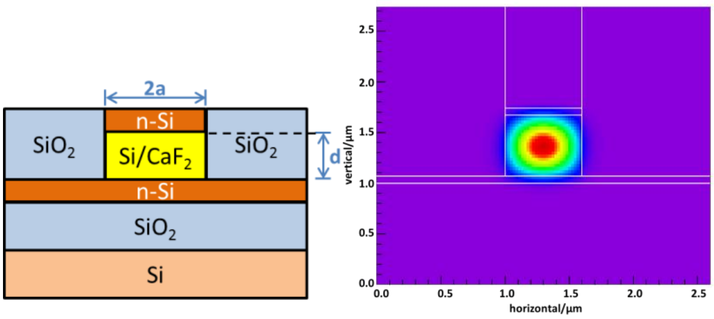

(a) (b)

Fig. 1: (a) The materials and schematic structure of the Si/CaF_2 heterostructure and SiO_2 waveguide. (b) Intensity mode profile of the fundamental TM mode with wavelength of 1.55 μm.

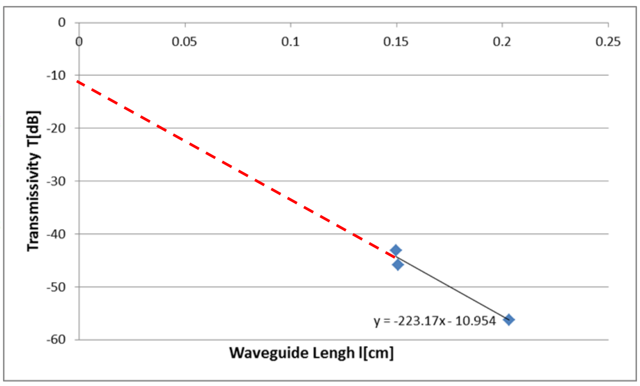

Fig. 5: Relation between the output intensity and the waveguide length.