Wavelength-Tunable Resonant Cavity-Enhanced Photodetector Array Using Quantum Confined Stark Effect

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***Abstract*—In this study, we present a wavelength-tunable resonant cavity-enhanced photodetector (RCE-PD) with InGaAs/InAlAs multiple quantum wells using the Quantum Confined Stark Effect (QCSE). The tuning of the resonant wavelength is performed using the refractive index change associated with the absorption change when the QCSE occurs. Calculations of tunable RCE-PD's quantum efficiency, measurements of spectral response characteristics of its fabricated device, and its temperature dependence will be discussed.**

Keywords—Resonant Cavity-Enhanced Photodetector, tunable photodetector, WDM, QCSE

I. Introduction

While optical fiber communications, which excel in high-speed, large-capacity, long-distance transmission, have been used, it is predicted that the transmission capacity will reach its limit in years to come[1-2]. To overcome this limitation, Wavelength Division Multiplexing (WDM) is essential technology, in addition to the advanced multi-level modulation format[3-4]. WDM communication systems can be significantly expanded by transmitting and receiving optical signals with multiple wavelengths over a fiber. However, one PD is required for each wavelength at the receiver side, resulting in increased footprint and power consumption in optical transceivers. In this study, we present a Resonant Cavity-Enhanced Photodetector (RCE-PD) array device using the Quantum Confined Stark Effect (QCSE) active layer that can receive optical signals of multiple wavelengths simultaneously with a wavelength-tuning function. It is necessary to obtain high sensitivity at a specific wavelength to receive light irradiation on the RCE-PD, which has high sensitivity and wavelength selectivity. A resonant wavelength may shift owing to manufacturing errors or temperature characteristics, therefore, tuning the resonant wavelength is necessary to compensate for this issue.

II. Wavelength tuning in RCE-PD using QCSE

The QCSE is observed when an external electric field in the perpendicular direction is applied to multiple quantum wells (MQWs), which are formed by repeatedly stacking two materials with different bandgaps. The QCSE was first reported for a GaAs/AlGaAs combination by Miller et al.[5]. When an external electric field is applied, the electron states of a quantum well shift to lower energies, and the hole states shift to higher energies. Thus, the optical absorption spectrum shows a peak shift to lower energies. This effect is also used in electro absorption optical modulators. When the QCSE occurs, this absorption change is accompanied by a change in the refractive index. Refractive index change is given by Eq.(1) [5], where $\Delta\alpha$ is the absorption change of the MQWs, ω is the angular frequency, and c is the speed of light. We used this refractive index change to tune the resonant wavelength.

$$\Delta n(\omega) = \frac{c}{\pi}\int_0^\infty \frac{\Delta\alpha(\omega')}{\omega'^2 - \omega^2} d\omega' \tag{1}$$

Fig. 1 shows calculated absorption characteristics of 14 InGaAs/InAlAs MQWs as the absorption region sandwiched by two InP cladding layers, where the wavelength range was 1400–1600 nm, with a maximum absorption coefficient of 1200 cm^{-1}, and a large absorption change in the wavelength range of 1520–1560 nm. The change in the refractive index was calculated using the absorption characteristics in Fig. 1, and Eq. (1) leads to the results shown in Fig. 2. A large refractive index change occurs in the wavelength range where the absorption change is steep. The refractive index change obtained from this MQW was approximately -0.009 at the maximum, and the wavelength tuning range of 1.25 nm could be calculated (Fig. 3).

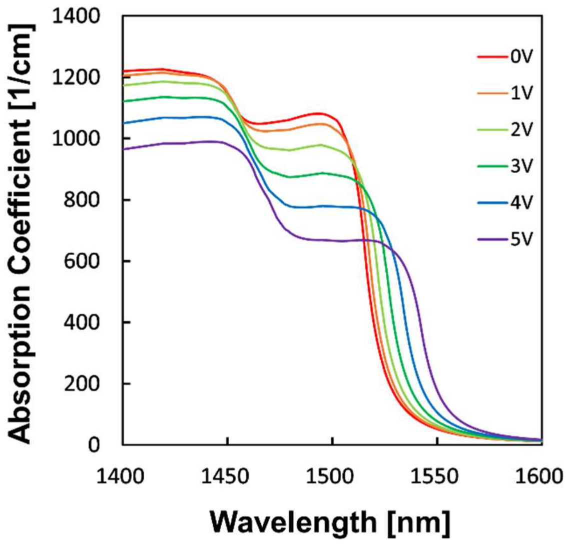

Fig. 1 Simulated absorption characteristics of InGaAs/InAlAs MQWs

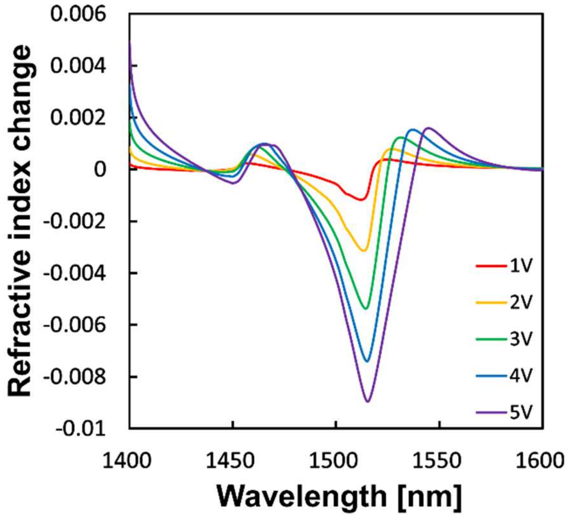

Fig. 2 Simulated reflactive index change obtained from InGaAs/InAlAs MQWs

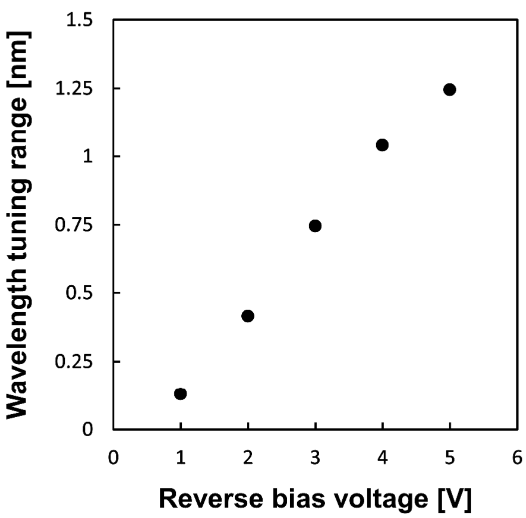

Fig. 3 Bias voltage dependence of a wavelength tuning range

III. Design of RCE-PD array

With RCE-PDs, the active device structure of a p-i-n photodiode is placed inside a Fabry-Perot interferometer. The light incident on the PD is frequently reflected between the two mirrors, and the only light with a specific wavelength that satisfies the resonance condition is absorbed more strongly (Fig. 4). Therefore, compared to a conventional photodiode, the RCE-PD can provide large quantum efficiency as well as large wavelength selectivity. The quantum efficiency of the RCE-PD is given by the following Eq.(2) [6], where R_1 is reflectivity of the front mirror, R_2 is reflectivity of the end mirror, α is the absorption coefficient of the absorption region, d is its thickness, β is the propagation constant ($= 2\pi/\lambda$), L is the distance between the two mirrors, and ψ_1, ψ_2 are respectively the phase shifts due to light penetration into the mirrors. The quantum efficiency of 2-WDM tunable RCE-PD whose peaks are 10 nm apart can be calculated as shown in green-line (PD-1) and red-line (PD-2) in Fig. 5, and the device parameters are listed in Table 1. The peak quantum efficiency of 48–56% was calculated with full width half measure (FWHM) of 11.7–12.7 nm. When applying the reverse bias voltage of 5 V to the QCSE active layer, the resonant wavelength of PD-1 was shifted to be 1.25 nm in calculation (see PD-1': blue-line).

$$\eta = \frac{(1 + R_2 e^{-\alpha d})(1 - R_1)(1 - e^{-\alpha d})}{1 - 2\sqrt{R_1 R_2} e^{-\alpha d} \cos(2\beta L + \psi_1 + \psi_2) + R_1 R_2 e^{-2\alpha d}} \quad (2)$$

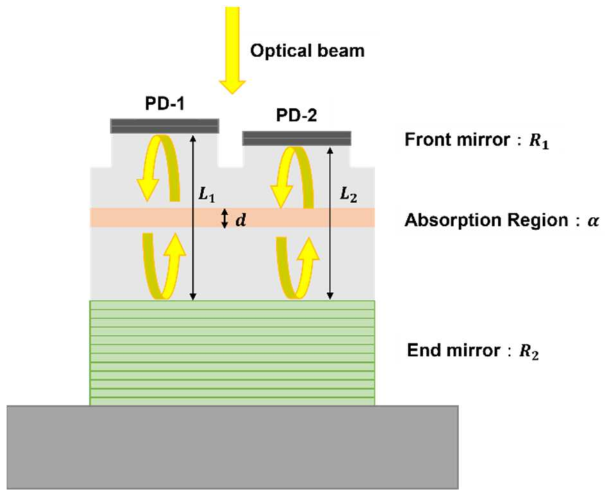

Fig. 4 Analysis model of a RCE photodetector

TABLE 1. Device parameters for 2-WDM tunable RCE-PD's quantum efficiency calculations

Device Parameter	R_1 **[%]**	R_2 **[%]**	α **[1/cm]**	d **[nm]**	L **[nm]**
PD-1	80	95	Fig. 1	456	1533
PD-2					1543

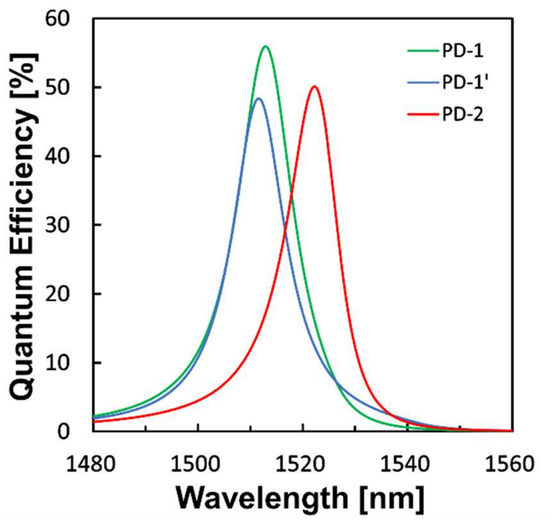

Fig. 5 Calculated quantum efficiency of 2-WDM tunable RCE-PD (PD-1: green-line and PD-2:red-line), resonant characteristics of PD-1':blue-line when the resonant wavelength is tuned by the QCSE

IV. Device Structure and Fabrication

We fabricated a wavelength-tunable RCE-PD using MQW, which consists of an InGaAs/InAlAs×14 periodic multilayer, showing a large absorption change at 1520–1560 nm, in the absorption region. DBR is an InGaAlAs/InP multilayer end mirror with 95% reflectivity over a wide wavelength range.

First, we deposited and lifted off the p-electrode (Ti/Pt/Au) on the wafer surface. Then, to form the n-electrode, we covered the SiO_2 mask to prevent etching in the photodetection area and performed a dry-etching process with chlorine-based gases down to the middle of the n-InP layer. Next, we deposited and lifted off the n-electrode (AuGeNi/Au) on the surface of the n-InP layer. Finally, high reflection films (SiO2/Si) were formed on the entire surface, and RCE-PD was completed after etching Si and part of the SiO_2 films with fluorine-based gas to prevent damaging the electrode surface, and wet etching of SiO2 remained in the electrode. Fig. 6 shows a top-view photograph of the fabricated device, and a schematic cross-sectional view of A-A' in Fig. 6 is shown in Fig. 7.

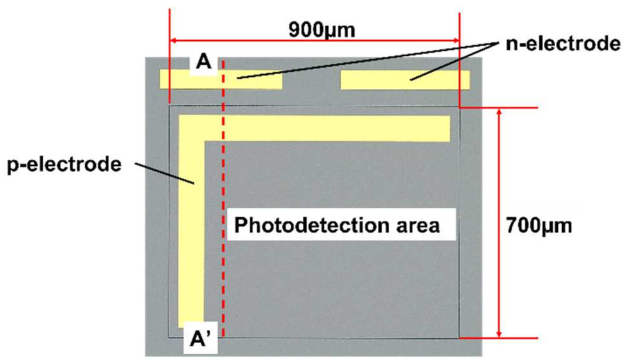

Fig. 6 RCE-PD's appearance after all the processes

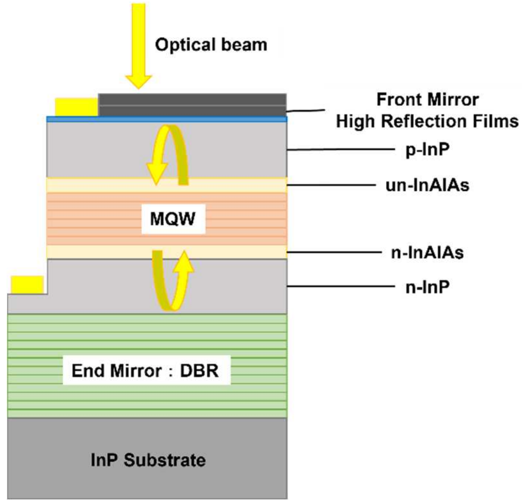

Fig. 7 A-A' cross-sectional view of tunable RCE-PD

V. Experimental Result

We measured the photocurrent and estimated its quantum efficiency using Eq. (3), where I_{ph} is photocurrent and P_{in} is the power of the input laser beam. In this experiment, reverse bias voltages of 1, 3, 6, 9 and 12 V were applied to the RCE-PD with a DC power supply, a 1mW wavelength-tunable semiconductor laser beam was irradiated onto the fabricated RCE-PD surface, and the photocurrent was measured using a digital multimeter. The measured spectral response characteristics under various applied reverse bias voltages are shown in Fig. 8. As the reverse bias voltage was tuned, the quantum efficiency also changed and was 38.8% at the maximum, the FWHM was 5.6 nm at 12 V. As the reverse bias voltage was increased, the resonant peak shifted to a shorter wavelength, and comparing at 1 V and at 6 V, the wavelength tuning range was 0.5 nm.

$$\eta_{cal} = \frac{\frac{I_{ph}(\lambda)}{e}}{\frac{P_{in}}{h\nu}} \tag{3}$$

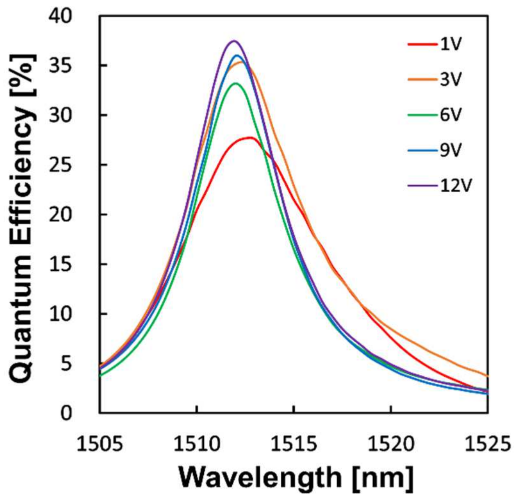

Fig. 8 Experimental quantum efficiency of tunable RCE-PD under different applied reverse bias voltages

Next, we measured the temperature dependence of the resonant photocurrent characteristics to confirm wavelength tuning. Fig. 9 shows the measured photocurrent when a 3 V reverse bias voltage was applied, and the temperature was varied to 18, 35, and 50 °C. Approximately the same quantum efficiency in the three conditions could be recognized when the temperature was changed, and there were also few changes in the FWHM. The resonant wavelength increased with increasing temperature and was proportional to the temperature coefficient (0.094 nm/ °C) (Fig. 10). A shift range of 3 nm was obtained when comparing the resonant wavelength at 18 °C with that at 50 °C.

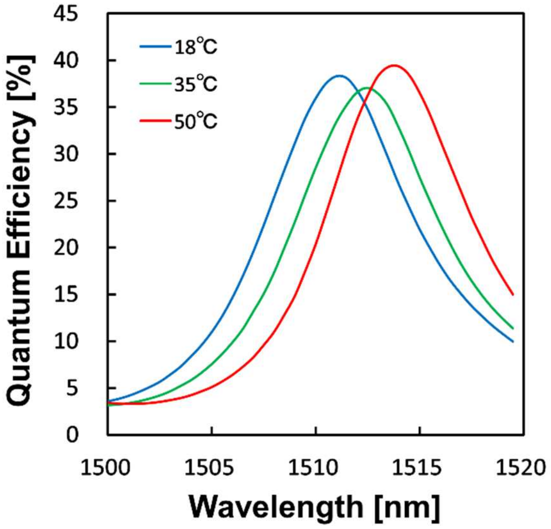

Fig. 9 Temperature characteristics of tunable RCE-PD at 3V reverse bias voltage

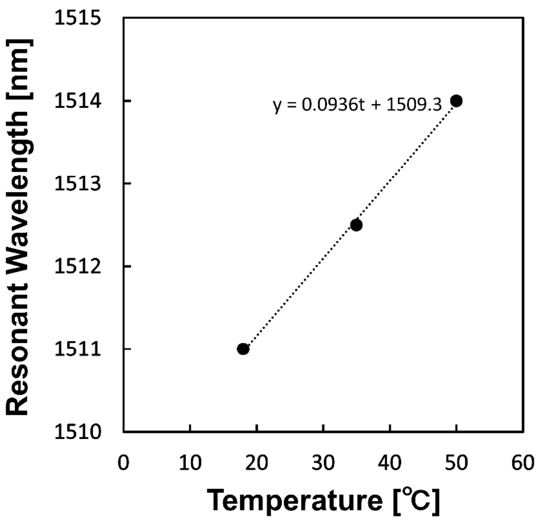

Fig. 10 Temperature dependence of resonant wavelengths

VI. CONCLUSION

We fabricated a resonant cavity-enhanced photodetector by using InGaAs/InAlAs multiple quantum wells in the active layer. Using a SiO_2/Si high reflection mirror with 80% reflectivity for the front mirror and InGaAlAs/InP DBR with 95% reflectivity for the end mirror, a peak quantum efficiency of 38.8% was measured with an FWHM of 5.6 nm at 3 V of reverse bias voltage. It was confirmed that the resonant peak of one PD can be tuned by 0.5 nm (1.25 nm in calculation) by applying reverse bias voltage, and the overall resonant wavelength can be tuned by 0.094 nm/ ℃. Our tunable RCE-PD could obtain a wavelength tuning range of 0.5 nm, whereas it was estimated to have the potential to achieve a tuning range of 1.25 nm. We believe that this is because the MQW layer used in our fabricated tunable RCE-PD was not optimized yet against the design model described in section-II.

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