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Silicon Photonic Biosensors with MEMS Flow Control

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Abstract

We have investigated the performance of MEMS wavelength selection filter and MEMS flow control micro-valves. From the estimation of operation voltage, device size and wavelength range, 8 × 8 arrayed biosensor chip is possible at an area of 1 × 1 mm^2 and an operation voltage of 30 V. For MEMS wavelength filter, we have succeeded in the fabrication and the operation confirmation.

1. Introduction

Biosensor chips which enable simple and easy detection for many kinds of diseases are desired especially for the aging society. Recently, silicon photonic devices have been reported as immunoassay biosensors [1,2]. Figure 1 shows a schematic image of multiple bio-sensing system where the ring-resonator biosensors are arrayed. Different bio-materials are set on each biosensors by flow control of solutions using micro-electro-mechanical systems (MEMS) micro-valves in fluid channel. Selections of optical signal from each biosensors are carried out by ring-resonator wavelength selection filters. Resonance wavelengths of each biosensors are different from each other and one of them is selected after the operation of the wavelength filter as shown in Fig. 2.

For large operation range of wavelength, MEMS optical device is investigated. By an electrostatic force, waveguides are deformed and the slot width is changed (Fig. 3). Large wavelength change is expected because of large refractive-index difference between 3.48 for silicon and 1.00 for air. For the micro-valves, vertical and lateral types are considered as shown in Figs. 4 and 5. For easy fabrication and low voltage operation, valves consist of SU-8 resist. In the lateral type, the outlets are 2-way and controlled by voltages of V_1 and V_2. To reduce the operation voltage, the fixed finger are arranged at not only lateral direction but also vertical direction. Al electrodes in the fluid channel are covered by SU-8 resist because solutions for bio-sensing are generally conductive.

2. Simulation and Experimental

The resonance wavelength change $\Delta\lambda_{res}$ is calculated to evaluate the performance of the proposed slot ring resonator, which is given by $\Delta\lambda_{res} = \lambda_{res}\cdot\Delta n_{eff}/n_g$. Here, effective refractive index n_{eff} and group index n_g of slot waveguide is simulated using the finite element method. The n_{eff} has dependence of applied voltage due to the deflection of slot waveguide Δd by the applied voltage. The proposed slot ring resonators were formed by electron-beam lithography and reactive ion etching and the beam structure was formed by selective HF etching of bottom SiO_2 layer. Optical measurements were carried out using an infrared tunable semiconductor laser (1480-1540 nm) and an InGaAs photodetector.

To evaluate the proposed micro-valves, voltage dependences of the maximum displacement of movable parts are calculated. For the vertical type, the deflection of circular plate by the capacitance is calculated. The maximum displacement Δt is given by $\Delta t = R^4p/(64D)$ where R, p and D are radius of circular plate, pressure by the capacitance and flexural rigidity, respectively. For the lateral type, $\Delta t = (\partial C/\partial t)\cdot(V^2/2k)$ where C, V and k are capacitance, applied voltage and spring constant of the folded spring, respectively [3].

3. Results and Discussion

Wavelength Selection Filter

The simulated resonance wavelength change of the proposed slot ring resonator is shown in Fig. 6 as a parameter of the slot width d, where the beam length between the clamped points L, slot waveguide height h_{wg} and slot waveguide width W are 10 μm, 300 nm and 250 nm, respectively. More than 0.8 nm change is obtained at low voltage of 1.0 V when the slot width is 50 nm. When the full width at half maximum (FWHM) is 10^{-2} nm, 8 channels (8 × 8 array) are realized at the crosstalk less than −20 dB.

The resonance characteristics of the fabricated device is shown in Fig. 7 where the waveguide width W is 250 nm and the slot width d is ~ 50 nm. The measurement result of the resonance wavelength change is 0.05 nm, which is small compared with the simulation result. The considerable reasons are a carrier-trap in the waveguide, ununiformity of etching process and so on. For further high performance, the fabrication process is necessary to be optimized.

Micro-valves

The voltage dependence of displacement of vertical valve is shown in Fig. 8 as a parameter of the height of SU-8 h_{SU}, where the radius of circular plate R and the height of Al layer h_{Al} are 50 μm and 0.1 μm, respectively. When h_{SU} is 0.5 μm, more than 3 μm is obtained at the applied voltage of 30 V. When the height of fluid channel h_{ch} is < 3 μm, the valve can be closed. The voltage dependence of displacement of lateral valve is shown in Fig. 9 as a parameter of the number of fingers m, where the width of Al layer w_{Al}, the height of Al layer h_{Al}, the width of SU-8 w_{SU}, the height of SU-8 h_{SU} and the gap between fingers w_{gap} are 2.0 μm, 0.1 μm, 0.5 μm, 0.5 μm and 2.0 μm, respectively. When m is 100 which implies large device length of ~ 500 μm (the length of the other direction can be fixed), more than 3 μm is obtained at 15 V of applied voltage. It is better that vertical type valves (50 × 50 μm^2) are used for flow control of each biosensors and lateral type valves are used for brunches at upper stream as shown in Fig. 1 because the size of biosensors is a few tens μm. Then, 8 × 8 array is possible at an area of 1 × 1 mm^2.

4. Conclusions

We have investigated the performance of MEMS wavelength selection filter and MEMS flow control micro-valves. From the simulation, more than 0.8 nm resonance wavelength change is estimated at 1.0 V. We have succeeded in the fabrication of proposed device structure and measurement of the resonance wavelength change of 0.05 nm at 10 V. For further high performance, the fabrication process is necessary to be improved. The operation voltage of vertical valve is estimated as ~ 30 V and that of lateral valve is 15 V. After taking device size and wavelength range into consideration, 8 × 8 arrayed biosensor chip is possible at an area of 1 × 1 mm^2. For the practical use of multiple silicon photonic biosensor chip, not only sensors but also flow control system is necessary to be integrated on a chip. In this paper, we have, for the first time, whole system including sensors and fluid channel with flow control micro-valves are designed.

Acknowledgement

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References

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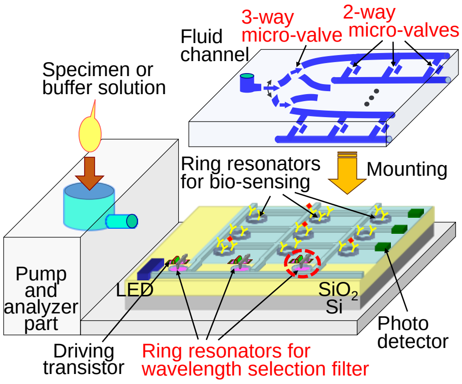

Fig. 1 Basic concept of multiple bio-sensing system.

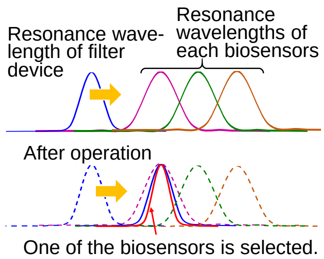

Fig. 2 Method of wavelength division for multiple biosensors.

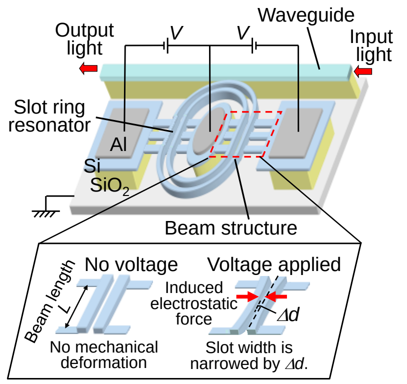

Fig. 3 Schematic image of the proposed wavelength selection filter.

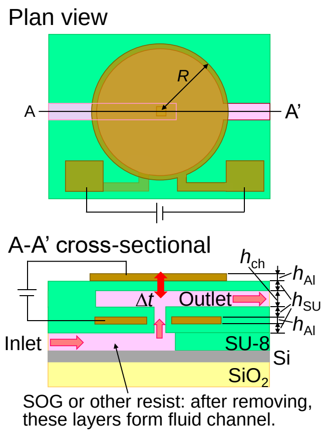

Fig. 4 Schematic image of vertical type valve.

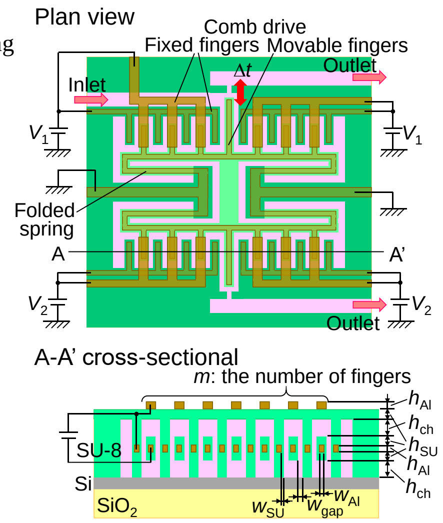

Fig. 5 Schematic image of lateral type 3-way valve.

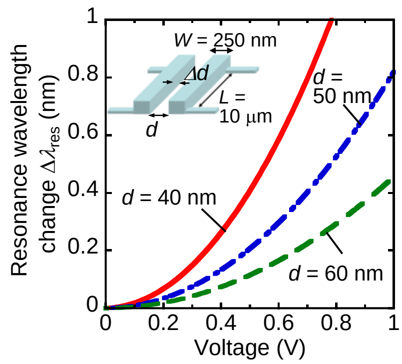

Fig. 6 Simulated voltage dependence of resonance wavelength change.

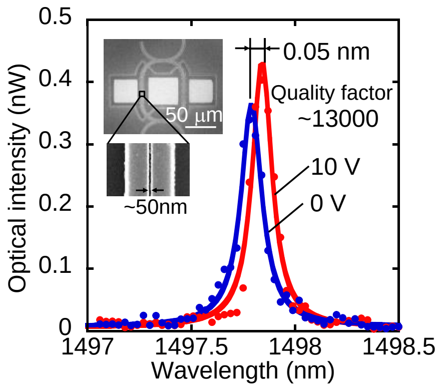

Fig. 7 Measured resonance characteristics of the fabricated device.

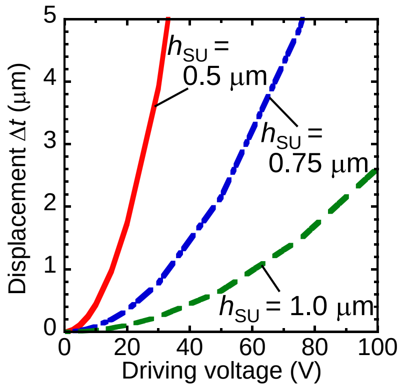

Fig. 8 Calculated voltage dependence of displacement for vertical type valve.

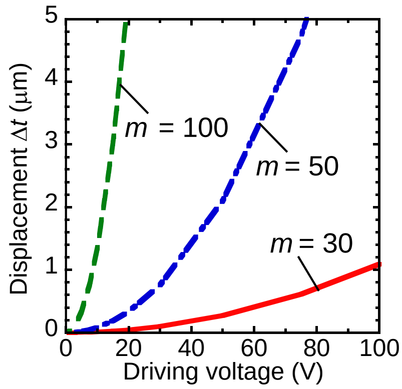

Fig. 9 Calculated voltage dependence of displacement for lateral type valve.