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# An integrated spectrophotometer chip fabricated in silicon

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**Abstract :** An integrated spectrophotometer chip fabricated in silicon substrate is presented. The chip consists of an incident light slit, a diffraction grating, a photodiode array and a light-wave-guide surrounding them. The chip size is twenty millimeters square. The chip is based on a usual photodiode-process and additional post-processing has been done to fabricate the optical system. The incident light slit, the diffraction grating, the photodiode array are all located on the "Rowland's circle". Two types of photodiodes are fabricated ($pn^-n$ type and $pn^-n^+n$ type). The $pn^-n^+n$ type photodiode demonstrates better characteristics for spectral resolution than that of $pn^-n$ type.

## 1. Introduction

Recently, many chemical analysis sensors have been developed which can detect small amounts of chemical substances. On-chip fabrication of transducer, which converts physical parameters to electrical parameters is an important technical issue in integration of analysis system. For example, F. Van. Steenkiste *et al.* reported a CMOS integrated biochemical microsensor[1]. The sensor integrates ISFET's, amperometric sensors and reference electrodes by the use of CMOS process. With this sensor, they detected pH, $pO_2$ and $pCO_2$ in blood gases.

The spectoroscopic method has good performance of sensitivity, response time and linearity. C. Müller *et al.* have reported a microspectrometer fabricated by the LIGA process [2]. With a grating fabricated on PMMA and a photodiode array they achieved spectral resolution of 0.23 nm/$\mu$m and the intensity was more than 20%. Gaylin M. Yee *et al.* have reported a spectrometer which has a transmisson grating on an image sensor device [3]. They proved a dispersion of 1.7 nm/pixel and the resolution of 0.0747 nm/$\mu$m. Before these reports, A. Kwa and R. F. Wolffenbuttle fabricated an integrated silicon spectrometer composed of two silicon wafers[4]. A transmission grating and a photodiode array is formed on one wafer and a light path is formed on the other wafer; they achieved the spectral range of 380～720nm and the dispersion of 1.7nm/pixel with this spectrometer.

This paper proposed the spectrophotometer chip for a device which integrates an optical system composing of a spectrometer and a photodiode.

## 2. Design

The layout of an incident light slit, a diffraction grating, a photodiode array and a fiber mount region are shown in Fig. 1. Light guide region from the slit to the photodiode array is etched $20\,\mu m$ in depth, and aluminum membrane is deposited on the region. Light path is formed as aluminum-air-aluminum light-wave-guide by bonding another aluminum coated plate to the integrated substrate. Chip size is 20 mm×20 mm, slit width is $50\,\mu m$, and line numbers of the grating is 333 lines/mm (spectral resolution : 0.2 nm/$\mu$ m). Two types of photodiodes are fabricated. One is $pn^-n$ type (without buried layer), and the other is $pn^-n^+n$ type (with buried layer). The photodiode array has eight element diodes corresponding to 340-800nm dispersed light. Width of detective region of the element photodiode is $50\,\mu m$. The incident light slit, the diffraction grating and the element photodiodes are located on the "Rowland's circle". The optical fiber is a bundled type made of quartz. Diameter of the fiber is 0.275 mm, NA is 0.35 and the numbers of element fibers is 3000.

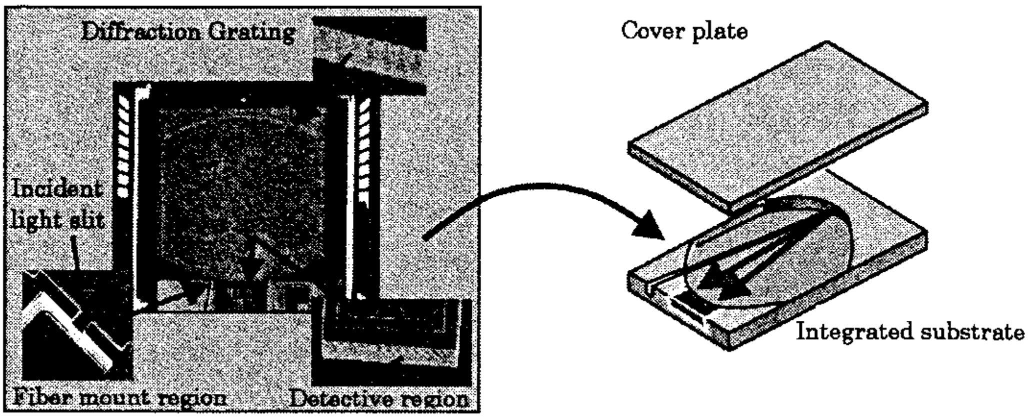


Fig. 1. Layout of the integrated spectrophotometer chip. Left figure shows layout of integrated substrate. Right figure shows operation of the spectrophotometer chip.

## 3. Fabrication Process

The spectorophotometer chip is fabricated with standard semiconductor fabrication process using an ICP etcher. First, the photodiode array is formed on a silicon wafer. After patterning of electrode structures, the light-wave-guide region (inside of the Rowland's circle) is formed by etching of the silicon substrate with ICP etcher. The incident light slit, the diffraction grating and the detective region of photodiodes are formed simultaneously with this etching process. This etching is done with a photoresist pattern mask. An i-line stepper is used for this photolithography processing. Blaze pattern is rounded in proportion as the depth of etching increases. The limit of blaze pattern depth is dependent on blaze pitch. In our experiments, limit of depth versus blaze pitch($\mu$ m/$\mu$ m) for keeping the original pattern was 20/1.5, 40/3.0, 60/6.0. The etching depth of the chip was fixed 20 $\mu$ m for the blaze pitch of 3.0 $\mu$ m(the depth is a half of the limit). The light-wave-guide region and the grating are coated by aluminum film which are deposited by sputtering method. The fiber mount region is formed with the ICP etching. Depth of the etching is 150 $\mu$ m. The cover substrate is also coated by aluminum, and fiber mount region is also formed.

## 4. Results and Discussions

For the purpose of estimating spectral resolution, the relationship between output current of photodiodes and wavelength of incident light was measured using a halogen light source. The light was transmitted to the chip through the optical fiber after being filtered by a monochrometer; Fig. 2 shows the results. Peak wavelength of the output current matches the wavelength of incident light. This is an important advantage of our spectrophotometer chip designed using the Rowland's circle.

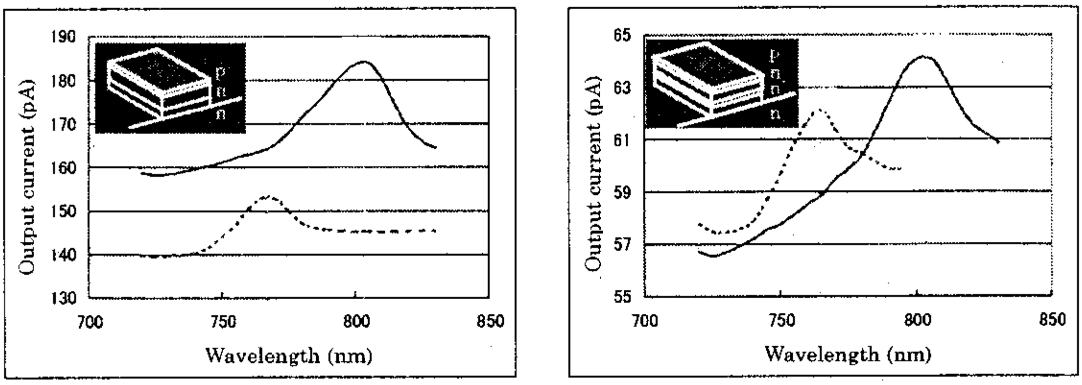


Fig. 2. Output current of photodiodes versus wavelength. Left figure shows the result of $pn^{-}n$ type photodiode, and right figure shows the result of $pn^{-}n^{+}n$ type photodiodes. Revese vias voltage of 2V was added to the photodiodes. Solid lines indicate 800nm light and broken lines indicate 760nm light.

Half width of the peak in the spectrum in Fig. 2 is 18nm ($\lambda$ =760nm) and 27nm ($\lambda$ =800nm) for the $pn^{-}n^{+}n$ type photodiode, while 20nm ($\lambda$ =760nm) and 32nm ($\lambda$ =800nm) for the $pn^{-}n$ type photodiode. Designed value is 10nm ($\lambda$ =760, 800nm). The reason why the half width of $pn^{-}n^{+}n$ type photodiode is smaller than that of $pn^{-}n$ type is that $n^{+}$ layer (buried layer) obstruct inflow of carriers generated in the substrate by stray light.

Table 1 shows output current of four element photodiodes that receive the light of 340, 540, 760, 800nm respectively. The light source used was a halogen lamp, and the light was directed to the chip through the optical fiber. Loss of light in the light-wave-guide depends on reflectivity of the coated aluminum. The reflectivity is more than 90% at the wavelength of 300nm. So, output current for ultra-violet light is relatively high in comparison with other spectral region.

Table. 1. Output current of four element photodiodes. The pn'n type photodiodes was used. Reverce vias voltage of 2V was added to the photodiodes.

| | Wavelength (nm) | | | |
|---|---|---|---|---|
| | 340 | 540 | 760 | 800 |
| Output current (pA) | 68 | 109 | 364 | 844 |

## 5. Future Work

Future work is focused at on-chip fabrication of linear image sensor and CMOS peripheral circuits. If an analog to digital converter is integrated with this chip, useful circumstance will be brought to users. Improvement of characteristics, especially increase of output, is also important. Authors estimate that the output current will increase 100 times larger than present value by improvement of ICP etching process, increase of quantum yield of photodiodes and use of single core/cladding optical fiber. Moreover, technology of an on-chip microlens array, an on-chip white light source and an on-chip sample cell will be developed, and the integration of an analysis system will be advanced.

## 6. Conclusion

The spectrophotometer chip which integrates an optical system and a photodiode array was fabricated on a silicon substrate. The chip is fabricated using general semiconductor fabrication processes and ICP etching. Performance of this spectrophotometer chip was confirmed and the optical characteristics were measured.

## 7. References


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