Integrated Silicon Microspectrometers

Seong-Ho Kong, José Higino Correia, Ger de Graaf, Marian Bartek, and Reinoud F. Wolffenbuttel

Microspectrometers, which read color and the results from analytical chemistry, are used for quality inspection in industry and agiculture. They read the chromatography results by measuring the infrared (IR) absorption of the chemical constituent between the IR source and the grating. Micromachining can implement the dispersion and detection elements in a silicon microspectrometer so that it can analyze the spectrum of incident light. The microspectrometer may either operate an array of detectors, each with a uniform spectral response, or scan the dispersion element using a single calibrated detector. Compared to bulky macroscopic devices, this microspectrometer has inferior spectral resolution but its small size and low cost more than compensates for this limitation in many applications.

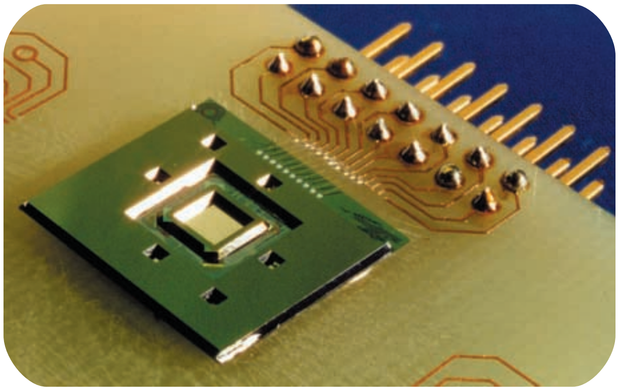
Spectrometers

Spectrometers are basically composed of three components:

- A dispersion element,
- A detector or array of detectors,
- An optical path with lens systems to collimate and focus the incident and refracted light beam.

Scaling limitations of each of these components affect the dimensions of a spectrometer at the microsystem level.

Gratings and Fabry-Perot resonance cavities have been successful as dispersion elements in a microspectrometer. The fabrication of arrays has been demonstrated for integrated silicon photon detectors for the visible spectral range and thermoelectric detectors in IR applications. A sufficiently long optical path and the implementation of lenses have impeded fully integrated silicon, optical microspectrometers. Usually, a simple lens-less configuration is used. Such a device yields sufficient spectral resolution, typically 10 to 20 bands within a selected spectral operating range, for use in moderately demanding applications.



Grating-Based Microspectrometers for the Visible Spectrum

A grating is commonly used to disperse the spectrum of incident optical radiation. It yields an interference pattern with an angular distribution determined by the spectral components. The incident light is analyzed through measurements of the distributed spectra. Techniques using silicon bulk micromachining can fabricate an integrated grating and detector array in a microspectrometer for the visible and near-infrared spectrum [8].

The microspectrometer comprises two silicon p-type wafers with an n-epilayer on which electrochemically controlled etching (ECE) is applied to construct channels. After wafer bonding, the channels form an optical path between a grating and an array of photodiodes; see Fig. 1(a). Deep boron diffusions form an electrically isolated region of epilayer to define the locations of the grating and backside-illuminated photodiodes. A 32-element, 4-μm pitch, symmetrical (2-μm line with a 2-μm space) grating is used, and 2-μm wide photodiodes with 4- μm pitch are formed by implantation into

1094-6969/01/$10.00©2001IEEE

the epilayer. Aluminum, which forms conventional interconnects, is also used in fabricating the grating and for shielding the array of photodiodes to prevent frontside illumination by the incident light. Even though the reflectance of aluminum is lower than silver or gold for most of the visible and near infrared spectrum, it is more suitable for fabrication.

The light, which is dispersed by the grating, projects onto a bevel that results from bulk micromachining on a d-wafer. The d is used most often; it is the crystallographic direction of the wafer surface and it identifies the wafer type. The slope of the bevel has a well-defined angle of 54.7° that originates from the intersection between the d-wafer plane and the {111} etch bordering planes after anisotropic etching in potassium hydroxide (KOH). The {111} designates the wafer plane which is used as the etch stopping plane. The etch rate of alkaline etchants is different for the different planes, which is the very reason why these etchants can be used to sculpture microstructures. After reflection from the epilayer of the lower wafer and a second bevel, the light projects onto the array of photodiodes.

The major problem in this device is the roughness of the bulk micromachined surfaces which scatters the reflected light. Since the dispersed light reflects three times before falling on the photodiode array, the device needs a surface roughness comparable to that of the polished frontside of a wafer. Both the bevels and ECE etch stopping surface shows considerable roughness. Avoiding the high temperature steps that are used for epilayer growth and the deep boron diffusion, and applying a borophosphosilicate glass (BPSG) reflow step, solves this problem. Only the lower wafer requires these measures because the lower wafer defines the optical path. The upper wafer can undergo the standard bipolar processes used for the fabrication of the photodiodes and the readout circuits. This functional separation of the device into an active wafer with photodiodes and circuits and a passive wafer for reflection, with low-temperature wafer bonding at the very last processing step, circumvents problems during fabrication and is an advantage of this two-wafer solution.

Fig. 1(b) shows the fabricated device. An interesting issue is the backside illumination of the photodiodes in the array. The surface roughness, any leftover substrate, and surface charges left at the original epilayer-substrate junction after bulk micromachining seriously limit the short-wavelength response [10]. The use of aluminum interconnect for fabrication of the grating is convenient but it imposes constraints. Designing a grating with a line width equal to the space between lines is essential for eliminating the second-order diffraction. A problem in the standard process is the general practice to over-etch the metal.

Grating-Based Microspectrometers for the IR Spectrum

Bulk micromachined spectrometers have been developed for operation in various wavelength ranges in the IR spectrum. Bulk silicon and aluminum are used for both the optical path and the multiple-slit grating. Silicon is transparent for wavelengths exceeding 1 µm, beyond which free-carrier absorption can be disregarded. Therefore, the bulk silicon can define the optical path rather than air, which would require etching a channel. The IR spectrometer, shown in Fig. 2, has two independently processed wafers which are bonded in the final step [7]; this is similar to the spectrometer for the visible spectrum. Thermal detectors, however, replace silicon photodetectors which do not work in the IR spectral range. Another difference from the visible range microspectrometer is that the first wafer

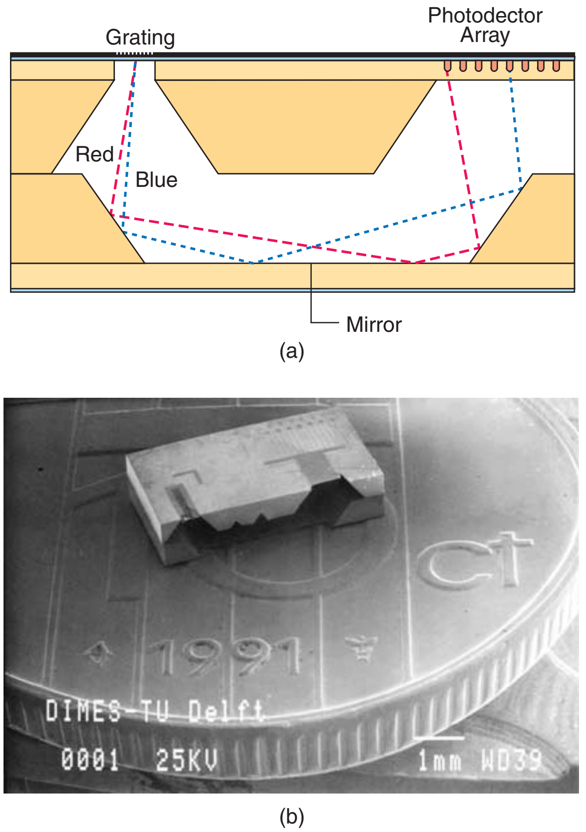


Fig. 1. Grating-based spectrometer for the visible spectrum (a) operation and (b) photograph of realized device.

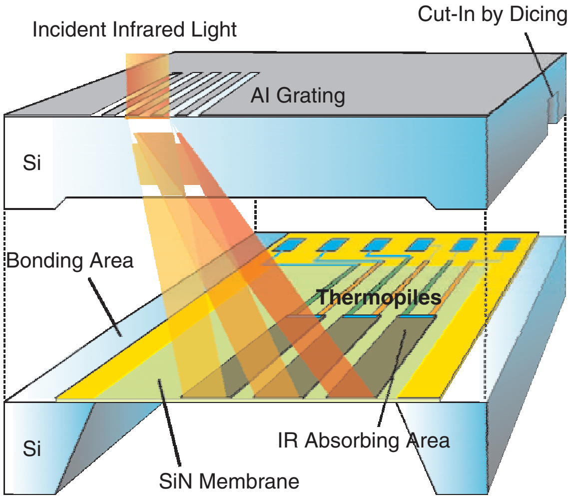


Fig. 2. Cross-sectional view of the IR spectrometer structure.

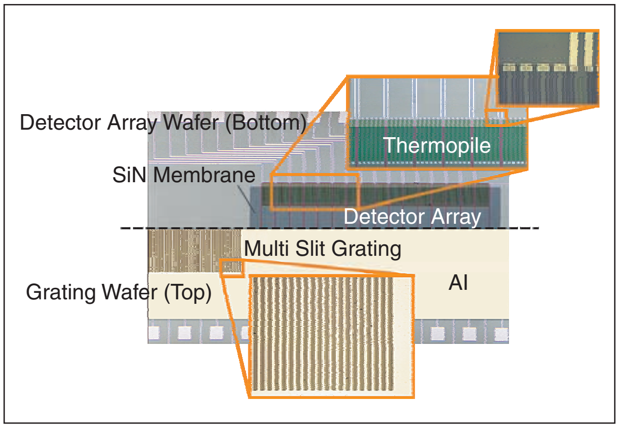


Fig. 3. Top view of a fabricated IR microspectrometer; aluminum grating (top wafer), thermopile based detector array (bottom wafer).

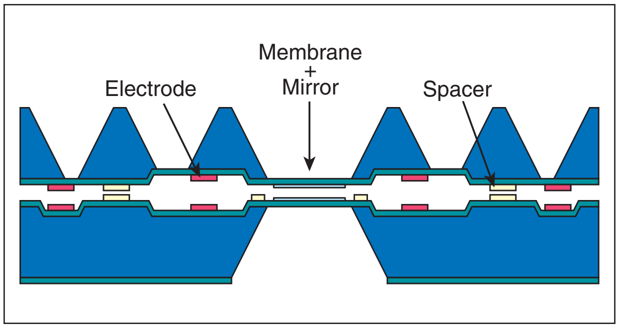


Fig. 4. Schematic structure of the two-wafer bulk micromachined, electrically tunable, Fabry-Perot interferometer.

contains the grating while the second wafer has the thermopile-based detector array.

The grating comprises 30 or 60 slits with a grating constant ranging from 4 to 20 µm. The length of the strips is 400 µm. The width of a single IR detector on the bottom wafer is 100 µm. The number of detectors in one array varies between six and 16; the number depends on the detectable wavelengths which is determined by the grating constant. A wafer polished on both sides provides the grating to avoid the scattering of incident light at the bottom surface and to enhance the adhesion with the wafer containing the detector array during the fusion bonding. The backside of this grating wafer is recessed using 33 weight % KOH solution at 85 °C to avoid mechanical contact with the detector array and to reduce the heat loss from the IR detector to the bulk of the grating wafer. The bottom of the grating wafer is cut in 300 µm with a dicing saw prior to bonding to provide access to the bond pads located on the detector wafer. After completing the wafer-to-wafer bonding, the remaining 225 µm is cut for wire bonding to reveal the bond pads.

Designing a grating with a line width equal to the space between lines is essential for eliminating the second-order diffraction.

P- and n-type polysilicon thermopiles are fabricated in the second wafer using low-pressure, chemical vapor deposition (LPCVD), ion implantation, and reactive ion etching (RIE). When the wafer-processing of both wafers is done, the two wafers are aligned and bonded using silicon-to-silicon low-temperature (<400 °C) fusion bonding, followed by KOH etching, to release the membrane area needed for thermal isolation of the hot junctions of the thermopile. Fig. 3 shows the top view of a fabricated device. The upper half shows the detector array.

Fabry-Perot Interferometers

The simplest realization of Fabry-Perot interferometers uses bulk micromachining of the two wafers followed by wafer-to-wafer bonding [6]. Fig. 4 shows the basic device structure. The wafer-level processing is the same for both wafers [3], [4]. A special spacer prevents the aluminum electrodes from touching after bonding. Applying a voltage tunes the resonance cavity to the desired wavelength. A silicon frame ensures a flat membrane at the mirror area.

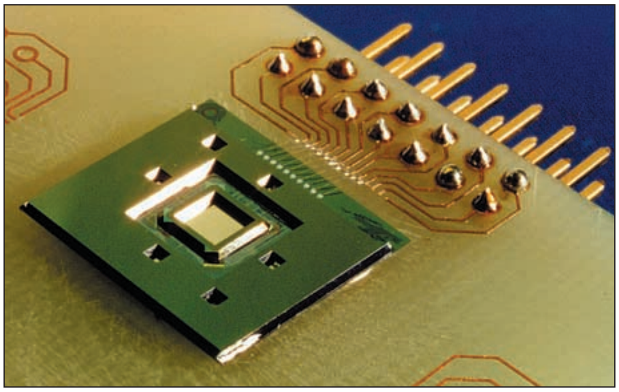


Fig. 5. Photograph of the two-wafer bulk-micromachined Fabry-Perot interferometer. A frame is used to keep the membrane flat.

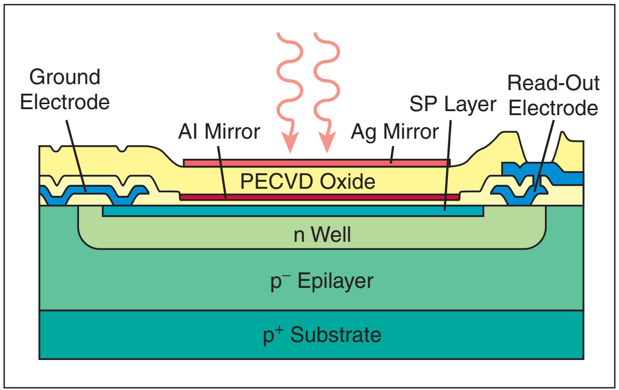


Fig. 6. A CMOS compatible Fabry-Perot resonator with a dielectric thin-film to determine the optical path between the mirrors.

The main design challenges of this Fabry-Perot interferometer are:

- Tuning the movable mirror over a sufficiently large spectrum with acceptable voltage levels,
- Fabrication of mirror surfaces of sufficient reflectivity and flatness,
- Achieving parallelism between the two mirrors.

An electrostatic force acting on the membrane deforms the area outside the frame. This technique prevents reduced optical performance that results from the curvature of a simple suspended membrane with a mirrored surface. It does so by requiring a higher voltage to deflect the same membrane area. Beam suspension [1] and corrugations [6] also reduce curvature. Fig. 5 shows a fabricated microspectrometer.

An alternative approach that circumvents these problems uses 16 fixed Fabry-Perot resonators with different spacing between cavities. Oxide layers space the mirrors to keep them parallel. Four subsequent masked oxide-etch steps fabricate cavities of 16 different thicknesses. The 16 channels cover the entire visible spectrum. The fabrication of each of these Fabry-Perot resonators, shown in Fig. 6, is compatible with a standard complimentary metal-oxide-semiconductor (CMOS) process which enables the integration of circuits on-chip for selection and readout of the array photodiodes covered by the different resonators [13]. Fig. 7 shows the resulting device [2]. An additional channel compensates for dark current and scattering, both caused by the roughness of the mirrors. The Fabry-Perot oxide etalons on top of the photodetectors are deposited by plasma-enhanced chemical vapour deposition (PECVD) on an aluminium lower mirror surface. The upper mirror, on top of this oxide, is subsequently deposited at the very end of processing. For this reason silver, with a better optical performance but with poor integrated circuit (IC) compatibility, can be used for the upper mirror only.

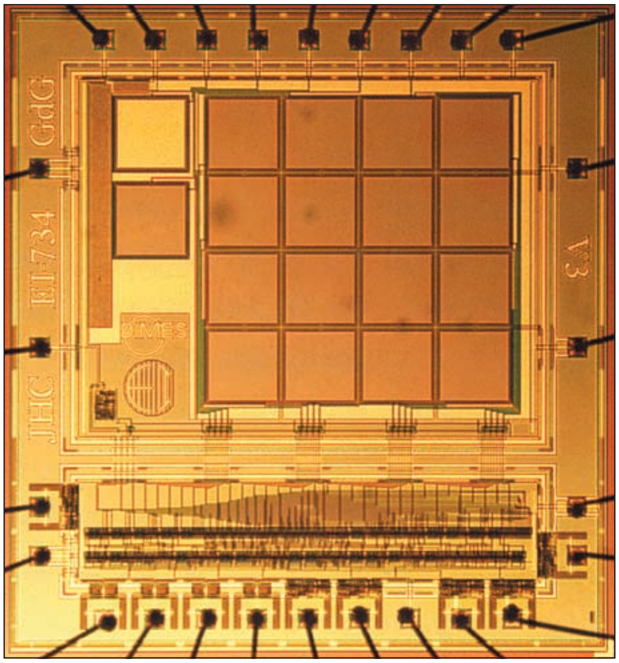


Fig. 7. Photograph of the 16-channel CMOS integrated microspectrometer.

Summary

Microspectrometers have been fabricated using standard microelectronic processing, with additional compatible post-processing steps, for either a grating or a Fabry-Perot resonator which is used as dispersion element. The spectral resolution ranges between 20 and 50 channels in the selected operating range. Combining a standard microelectronic process with additional microelectromechanical systems (MEMS) processing for optical components results in small and low-cost solutions for many industrial and consumer applications.

References

[1] K. Aratani, P.J. French, P.M. Sarro, D.P. Poenar, and R.F. Wolffenbuttel, "Surface micromachined tuneable interferometer array," *Sens. Actuators A, Phys.*, vols. 41-42, pp. 17-23, 1994.

[2] J.H. Correia, G. de Graaf, S.-H. Kong, M. Bartek, and R.F. Wolffenbuttel, "Single-chip CMOS optical micro-interferometer," *Sens. Actuators A, Phys.*, vol. 82, pp.191-197, 2000.

[3] J.H. Correia, M. Bartek, and R.F. Wolffenbuttel, "Bulk micromachined tunable Fabry-Perot micro-interferometer for the visible spectral range," *Sens. Actuators A, Phys.*, vol. 76, pp. 191-196, 1999.

[4] J.H. Correia, M. Bartek, and R.F. Wolffenbuttel, "High-selectivity single-chip spectrometer in silicon for operation in the visible part of the spectrum," *IEEE Trans. Electron Devices,* vol. 47, pp. 553-559, Mar. 2000.

[5] D. Goldman, P. White, and N. Anheier, "Miniaturized spectrometer employing planner waveguides and grating couplers for chemical analysis," *Appl. Opt.*, vol. 29, pp. 4583-4589, 1990.

[6] J.H. Jerman, D.J. Clift, and S.R. Mallinson, "A miniature Fabry-Perot interferometer with a corrugated silicon diaphragm support," *Sens. Actuators A, Phys.,* vol. 29, pp. 151-158, 1991.

[7] S.-H. Kong, D.D.L. Wijngaards, M. Bartek, and R.F. Wolffenbuttel, "Integrated microspectrometer based on a diffraction grating," in *Proc. Eurosensors,* Copenhagen, Denmark, 2000, vol. 14, pp. 321-324.

[8] T.A. Kwa and R.F. Wolffenbuttel, "Integrated grating/detector array fabricated in silicon using micromachining techniques," *Sens. Actuators A, Phys.*, vol. 31, pp. 259-266, 1992.

[9] T.A. Kwa, P.J. French, R.F. Wolffenbuttel, P.M. Sarro, L. Hellemans, and J. Snauwaert, "Anisotropically etched silicon mirrors for optical sensor applications," *J. Electrochem. Soc.*, vol. 142, pp. 1226-1233, 1995.

[10] T.A. Kwa, P.M. Sarro, and R.F. Wolffenbuttel, "Backside-illuminated silicon photodiode array for an integrated spectrometer," *IEEE Trans. Electron Devices*, vol. 44, pp. 761-765, May 1997.

[11] D. Rossberg, "Silicon micromachined infrared sensor with tunable wavelength selectivity for application in infrared spectroscopy," *Sens. Actuators A, Phys.*, vols. 46-47, pp. 413-416, 1995.

[12] G.M.Yee, N.I. Maluf, P.A. Hing, M. Albin, and G.T.A. Kovacs, "Miniature spectrometers for biochemical analysis," *Sens. Actuators A, Phys.*, vol. 58, pp. 61-66, 1997.

[13] R.F. Wolffenbuttel, Ed., *Silicon Sensors and Circuits: On-Chip Compatibility*. London, U.K.: Chapman & Hall, 1996.

Seong-Ho Kong received the M.Sc. degree from Tohoku University, Sendai, Japan, in 1996. Since 1997, he has been working towards the Ph.D. degree at Delft University, Delft, The Netherlands, studying integrated IR microspectrometers in silicon.

José Higino Correia graduated in physical engineering at University of Coimbra, Portugal, in 1990. He obtained his Ph.D. degree in 1999 at the Delft University of Technology, The Netherlands. Since May 1999, he has been Auxiliary Professor in the Department of Industrial Electronics at University of Minho, Portugal, and he is involved in the development of optical microsystems for biomedical applications.

Ger de Graaf is a staff member of the Department of Electrical Engineering of the Delft University of Technology. He received his BSEE degree in electrical and control engineering from the Technische Hogeschool in Rotterdam in 1983. He is currently working on electronic circuits for silicon sensors. He is also a consultant specializing in electronic design and computer-controlled measurement systems.

Marian Bartek received his M.Sc. degree in microelectronics and optoelectronics from the Slovak Technical University in Bratislava, Slovakia, 1988, and a Ph.D. degree in electrical engineering at the Delft University of Technology in The Netherlands, 1995. He was a post-doctoral Fellow between 1996 and 1999 dealing with research on technological aspects of integrated silicon sensor systems. Since 2000, he has been an Assistant Professor with the Electronic Components, Materials and Technology Laboratory, Delft University of Technology, working in the area of RF MEMS and wafer-level packaging.

Reinoud F. Wolffenbuttel received an M.Sc. degree in 1984 and a Ph.D. degree in 1988, both from the Delft University of Technology, The Netherlands. He is an Associate Professor at the Laboratory of Electronic Instrumentation of the Delft University of Technology. He is involved in instrumentation and measurement in general and on-chip functional integration of microelectronic circuits and silicon sensor, fabrication compatibility issues, and micromachining in silicon and microsystems in particular.
