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**Editors**

K. Wörhoff, L. Agazzi,  
 N. Ismail, X. Leijtens

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## **Silicon-on-Insulator Microspectrometer**

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*Miniature optical spectrometers have huge potential for application in mobile sensors which are capable of real-time environmental monitoring at any time, in any place. In this paper, we demonstrate that the heterogeneous integration of InGaAs photodetectors onto very compact silicon-on-insulator echelle grating demultiplexers is an efficient approach for the fabrication of highly integrated, cost-effective and performant spectrometers-on-a-chip.*

### **Introduction**

Near-infrared spectroscopy is a technique which is widely used for highly sensitive measurements of the composition of unknown organic samples by exciting overtones and combinations of molecular vibrations. Typical applications include pharmaceutical, agricultural and biological analysis. Conventional photospectrometers in the labs are typically large and expensive and have a performance that often exceeds the requirements for typical industrial applications. For industrial applications, what counts are the cost, size, robustness, sample volume, measurement time, ... of the spectrometer. For these applications, miniaturized spectrometers [1] that can be mass fabricated are better suited and using these devices, a new range of applications such as real-time, mobile sensing becomes possible.

In this paper, we demonstrate that silicon (Si-) photonics is an interesting technology platform for these applications. We fabricated a very compact near-infrared spectrometer-on-a-chip without any moving parts. The heart of the spectrometer is a silicon-on-insulator (SOI) echelle grating demultiplexer, fabricated on 200mm SOI wafers using CMOS-compatible waferscale processes. The high index contrast of this material system allows to drastically reduce the size making it possible to produce hundreds of chips on a single wafer. For measuring the optical signal in the different wavelength channels, near-infrared InGaAs photodetectors are heterogeneously integrated. These detectors are lithographically aligned onto the Si chips and can be processed on a waferscale.

### **Wavelength demultiplexer**

The demultiplexer is a 30-channel planar concave grating (PCG) or echelle grating with a 3.2nm channel spacing and a 120nm free spectral range. It is fabricated on a 200mm SOI wafer with a 220nm thick Si top layer using 193nm deep-UV lithography in combination with ICP-RIE etching. The fabricated device is shown in figure 1. The design is based on the Rowland geometry [2]: the input and output waveguides are positioned on a circle with a radius of 554 $\mu$ m and the curved grating sits on an 1108 $\mu$ m radius circle. The order of diffraction is 10 and the entrance and exit waveguides are 2 $\mu$ m wide with a spacing of 5 $\mu$ m between the centers of the output waveguides along

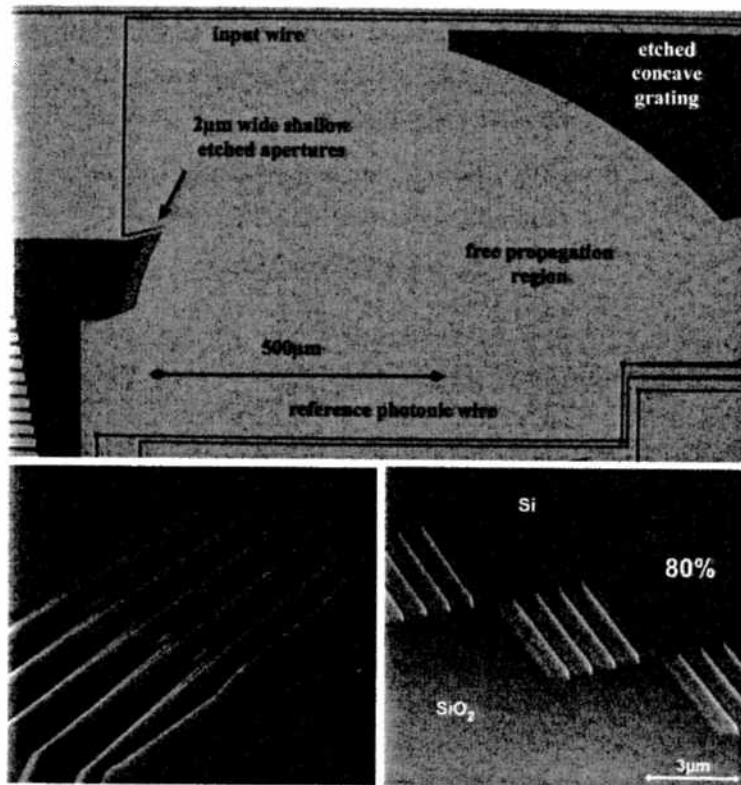


Fig.1: Top view of a 30-channel grating demultiplexer. Detailed photographs of the tapers which convert a 500nm wide photonic wire into a 2µm wide shallowly etched waveguide (left) and DBR grating facets (right) are also shown.

the Rowland circle. These waveguides are shallowly etched (70nm deep) and a double adiabatic taper is used to convert to deeply etched 500nm wide photonic waveguides as can be seen in figure 1. The design has one stigmatic point at the center of the output waveguides with a corresponding stigmatic wavelength of 1.55µm.

To avoid excessive reflection loss at the grating facets, we replaced the 141 flat facets with second order distributed Bragg reflector (DBR) facets [3] (Figure 2b). This method allows reducing the on-chip loss without the need of additional processing steps [3].

The on-chip transmission spectrum, referenced to a photonic wire waveguide and for

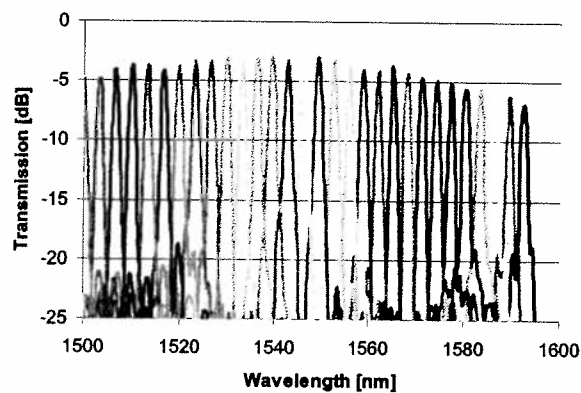


Fig. 2: Transmission spectrum of PCG demux for TE-polarization.

TE-polarized light is shown in figure 2. The on-chip loss is 2.5dB, the channel non-uniformity is 4dB and the near-channel crosstalk ranges from -25dB to -15dB.

### InGaAs-on-SOI photodetectors

As silicon is transparent for wavelengths above  $1.1\mu\text{m}$ , other materials need to be integrated on the SOI wafer in order to obtain efficient photodetection. We fabricated metal-semiconductor-metal (MSM) InAlAs/InGaAs photodetectors which are integrated by means of bonding unprocessed III-V dies (epitaxial layers facing down) onto the processed SOI wafer using DVS-BCB as an intermediate adhesive layer. After removal of the InP substrate, the detectors can be fabricated on a wafer scale and lithographically aligned to the underlying SOI waveguides [4].

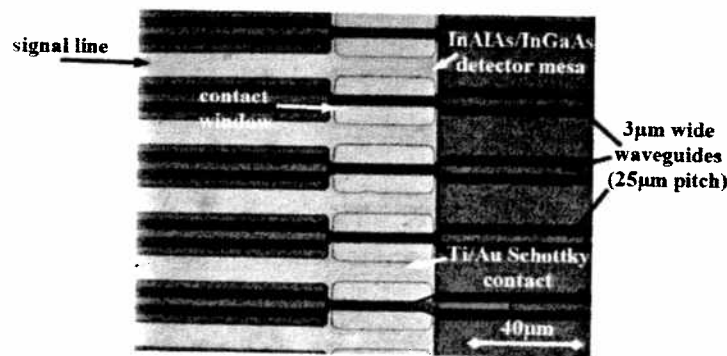


Fig. 3: Top view on MSM detectors on top of  $3\mu\text{m}$  wide SOI waveguides. Light enters from the right and the detectors are  $40\mu\text{m}$  long. The waveguide pitch is  $25\mu\text{m}$ .

As the DVS-BCB bonding layer is only 100nm thick, light is evanescently coupled from the SOI waveguide into the photodetector on top of it. Coupling lengths are in the order of 10 micrometer. Processing, simulation and measurements of these photodetectors are described elsewhere [5]. Detectors with a length of  $30\mu\text{m}$  have a responsivity of  $1.0\text{A/W}$  at  $1.55\mu\text{m}$  and a dark current of  $4.5\text{nA}$  at 5V bias. The detector pitch is  $25\mu\text{m}$  as can be seen in figure 3.

### Microspectrometer

Figure 4(a) shows the photocurrent spectrum of both the spectrometer and a detector which is processed on top of a reference waveguide. As the quantum efficiency of the detectors is almost constant from  $1.5$  to  $1.6\mu\text{m}$ , the spectrum of the reference detector is mainly determined by the fiber coupler transmission. Fiber couplers are 1-D gratings which allow coupling light from a single mode fiber into the SOI waveguides. These couplers have an estimated minimal coupling loss of 6dB at a wavelength of  $1590\text{nm}$  and a 3dB bandwidth of  $65\text{nm}$ . The on-chip loss (in respect to the reference detector) of the PCG ranges from 3dB for the central channels to 5dB for the longest wavelength channel as can be seen in figure 4(a). This corresponds with the results shown in figure 2. The power budget can be calculated as follows. By fine-tuning the fiber coupler, it is possible to make the central PCG wavelength and the maximum fiber coupler transmission coincide at  $1.55\mu\text{m}$ . The total loss for the central channels is about 6dB (fiber coupler loss) + 3dB (on-chip PCG loss). Waveguide loss can be neglected. Taking into account a detector responsivity of  $1\text{A/W}$  at  $1.55\mu\text{m}$ , the total responsivity

## Silicon-on-Insulator Microspectrometer

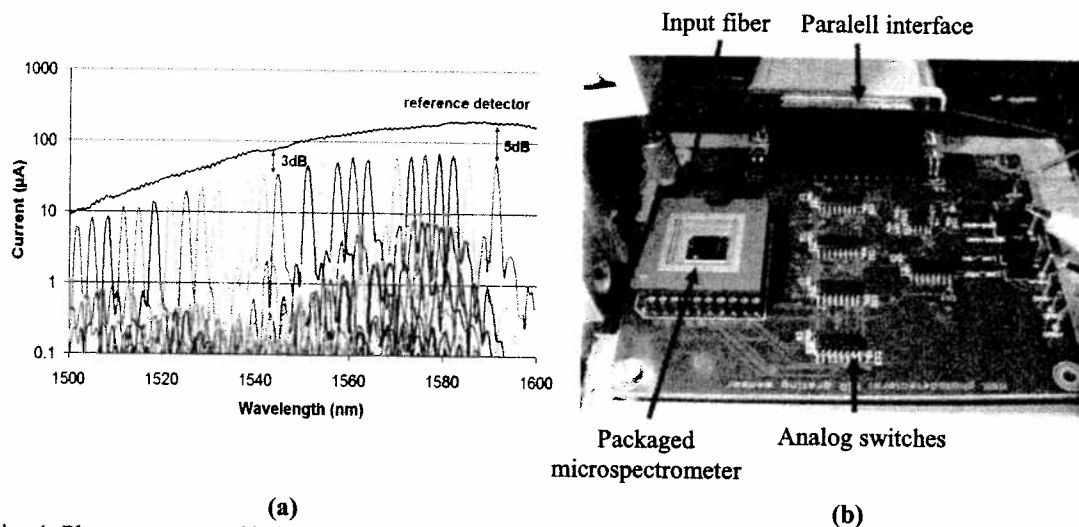


Fig. 4: Photoresponse of integrated spectrometer (a) and a picture of the spectrometer-on-a-chip mounted on a read-out board (b). Both the optical and electrical interfaces are visible.

for the central channels is  $\sim 0.1A/W$ . The size of the spectrometer including photodetectors, but excluding electrical probe pads is  $\sim 2\text{mm}^2$ .

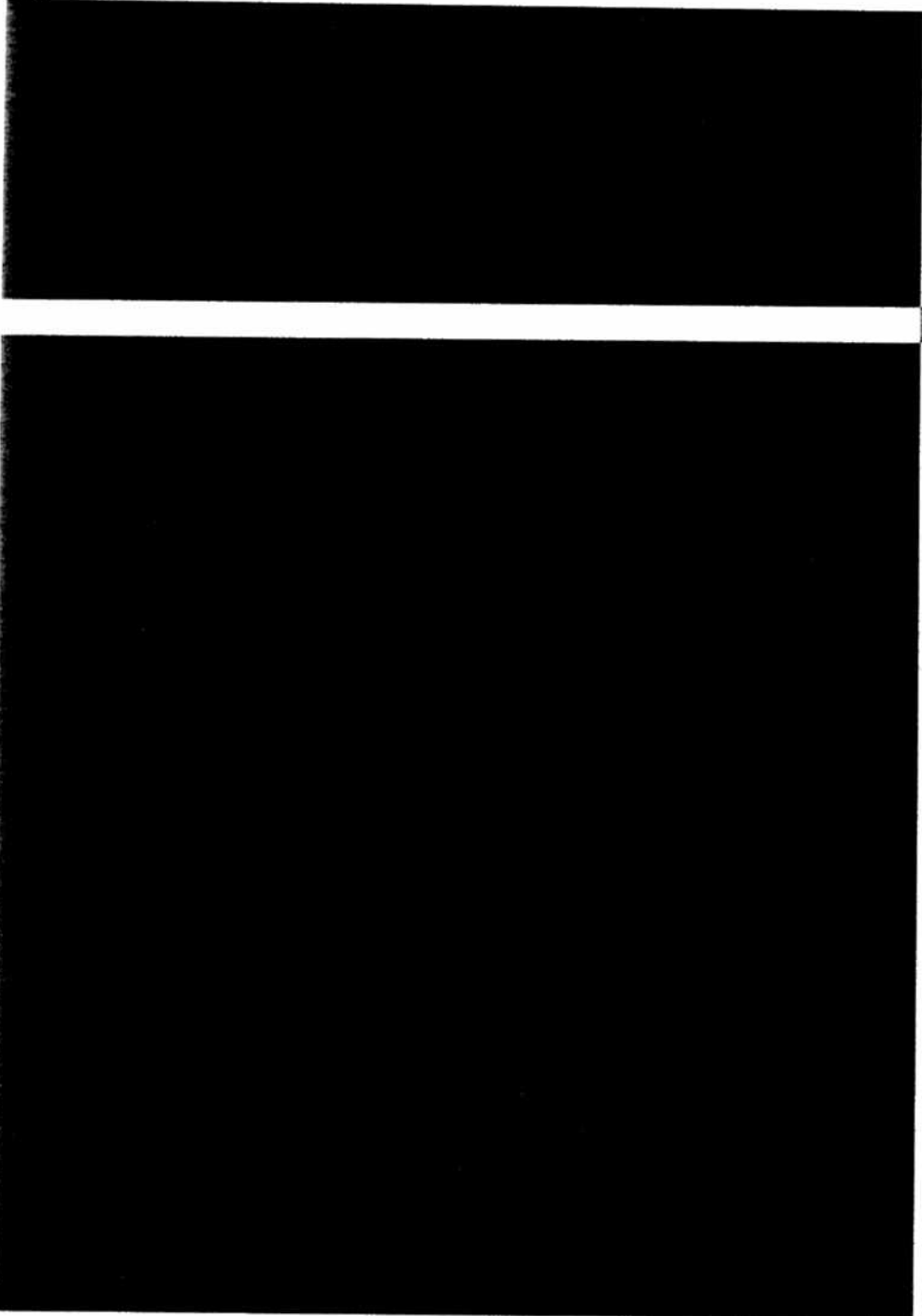
The spectrometer chip was also mounted and wire-bonded into a ceramic PGA (Pin Grid Array) package as can be seen in figure 4(b). This PGA was mounted on a read-out printed circuit board which contains some analog switches, a transimpedance amplifier and a parallel PC interface. The optical input fiber can be seen on the left side of the picture. A Labview program was used to sequentially read-out the photodetector signals.

### Conclusion

We demonstrated a very compact ( $2\text{mm}^2$ ) near-infrared 30-channel spectrometer based on the heterogeneous integration of InGaAs photodetectors on SOI PCGs. This integration technique, in combination with the fabrication of the passive circuitry on low-cost SOI wafers using CMOS compatible processes can result in a compact, highly integrated and low-cost miniature photospectrometer that can be mass-fabricated.

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