BASIC OPTO-ELECTRONICS ON SILICON FOR SENSOR APPLICATIONS

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A general platform for integrated opto-electronic sensorsystems on silicon is proposed. The system is based on a hybridly integrated semiconductor laser, ZnO optical waveguides and monolithic photodiodes and electronic circuitry.

I. INTRODUCTION

The development of innovative, miniaturized sensorsystems is widely recognized as being important for a modern and competitive industry. Therefore large national and international activities in the fields of electrical, mechanical and optical microsystems are being performed. Silicon has proved itself to be an excellent material for the signal processing part of an integrated sensorsystem. Besides, the fabrication technologies for silicon based systems are highly developed. It is therefore attractive to use silicon in various sensor integration schemes [1].
Integrated optic microsensors are very attractive for detecting (bio-) chemical substances as well as for many physical quantities [2]. Integrated optical sensors combine high sensitivity with the possibility of easy guidance and processing of the optical signal by the use of waveguides. They are small and rugged and offer a wide choice of materials used for sensing. In combination with silicon this gives

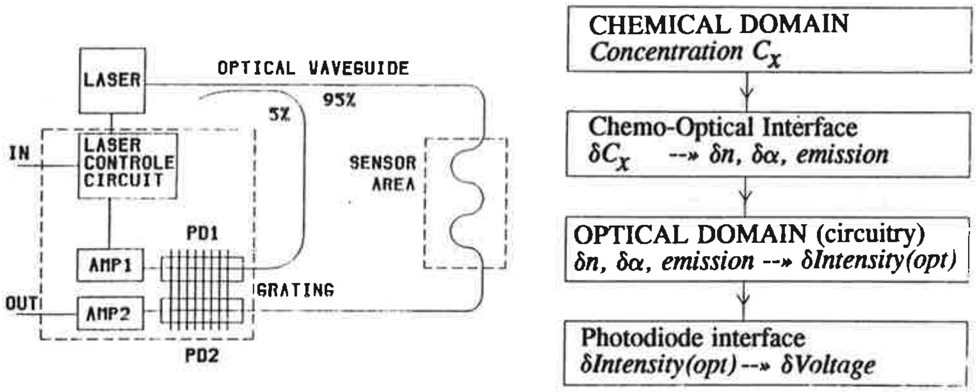

Figure 1: *(a) Possible layout of the proposed integrated opto-electronic sensorsystem, (b) Functional framework of the sensor*

the prospect of monolithic smart multisensor systems and batchwise production. Chemo-optical sensors are most commonly based on a chemo-optical transduction layer. The optical properties of this transduction layer, like the real or imaginary parts of the refractive index, change while detecting the chemical compound. By using e.g. the evanescent field of an optical waveguide mode, the presence of the chemical substance can be detected as an intensity- or phaseshift of the optical signal. This paves the way for compact integrated optical sensors for chemical detection and analysis.

Ideally, a chemo-optical sensor has to be integrated with an optical source and detector and microelectronics. In a cooperation of the TNO Physics and Electronics Laboratory and several groups of the University of Twente a silicon opto-electronic sensor platform is pursued. This cooperation is partly funded by the IOP Electro-Optics in a six years programme, initiated in 1992. By suitable design of this platform a compact, flexible basic opto-electronic sensor circuit will be created. The actual implementation of a specific sensing principle will only affect some final fabricationsteps of the chip. In this way we expect to achieve a high degree of standardization and cost effectiveness.

II. BASIC OPTO-ELECTRONIC SENSOR PLATFORM

According to current ideas, the sensor platform will consist of a hybridly integrated semiconductor lasersource with a stabilizing optical feedback loop, an optical waveguide system based on ZnO, a monolithic detector subsystem using a coupling grating, a monolithic photodiode and UT-BiCMOS electronics for driving the laserdiode and amplification of the detector signal (figure 1). The specific optical sensing system will be implemented in the ZnO optical waveguide part of the chip.

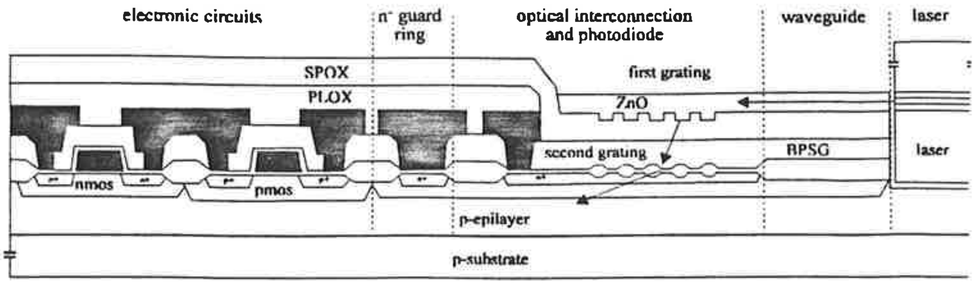

***Figure 2:** Schematic cross section of the basic opto-electronic circuit*

For defining the specifications and a general process sequence of this device many aspects have to be studied. These include process compatibility and cross-talk effects. The sensor platform will be designed at 675 nm wavelength, although the hybrid integration scheme for the semiconductor laserdiode allows for other wavelengths. Although a fast detector system is feasible, emphasis will be on sensitivity and dynamic range as required for the anticipated sensor applications.

III. SYSTEM INTEGRATION

A. Process Compatibility

It was recognized in an early stage, that because of the reliability and flexibility of the BiCMOS technology all electronic elements have to be manufactured, with only minor adjustments, before the optical ones. Therefore the compatibility studies focussed on possible influences on the electronics caused by the optical fabrication steps. Besides possible influences on the electronics by the subsequent process steps, several physical interferences in the system were identified. These include aspects of thermal dissipation, electrical and optical isolation and ZnO deposition on non-thermally oxidized substrates. In an accompanied paper these investigations are further elaborated [3]. It can be concluded, that, although several influences have been identified, we anticipate, that these influences can be taken care of.

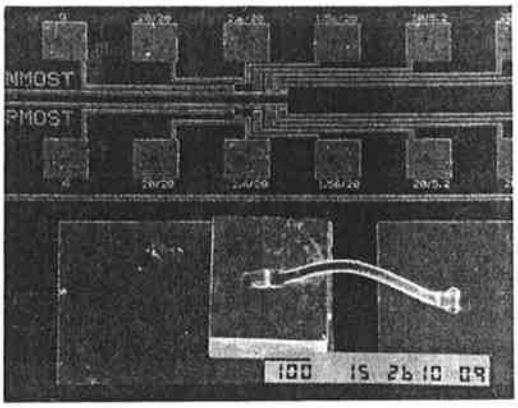

Figure 3: Electron microscope picture of a laserdiode mounted on a Program Control Module chip containing several electronic test structures

B. Lightsource Subsystem

Because a lightsource cannot be fabricated in silicon, a semiconductor laserdiode must be integrated hybridly. In earlier work [4] a new coupling mechanism was introduced, based on a straight well, accurately etched into the optical waveguide. A bare semiconductor laserchip was placed epi-down in the well. In this way the active layer of the laserchip can be moved to the vicinity of the waveguide, thus allowing for an efficient coupling. For the laserbonding a new method has been investigated. It appeared that a semiconductor laserdiode could be bonded to a silicon substrate by thermocompression.

Quantum Well ridge waveguide type semiconductor lasers (850 nm) were pressed epi-down on metallized silicon substrates at 250 °C for ten minutes. In this way a bond was established between the gold layer on the laserdiode and a Cr/Al/Pt/Au metallization on the substrate. In this stack the chromium serves as an adhesion layer to the silicon, the aluminium prevents damage to the chips by serving as a soft cushion and the platinum is a diffusion barrier between the aluminium and the gold top layer. Bonding experiments show excellent laser characteristics and CW operation. Coupling of laserdiodes to ZnO waveguides is currently under investigation. It is anticipated, that the thermocompression process can be applied in this sensor system and that coupling efficiencies up to 50% are feasible.

The laserdiode control circuitry will be integrated on the same chip. The aim is to produce a constant laser output by an optical feedback system. This system will consist of an optical waveguide element, where a small part of the optical power is tapped off, an optical grating interconnect as discussed elsewhere in this paper, a monolithic photodiode, a current comparator and a reference current source. The photocurrent is compared with a stable reference current. The difference current will controle the laser forward current for constant optical power on the photodiode. The grating and the photodiode will be of the same type as required for the detector side of the chip, as is described below.

C. Detector Subsystem

The detector subsystem chip will consist of a monolithic photodiode, amplifier electronics and an optical interconnect between the waveguide and the photodiode. In case of technological difficulties a hybrid solution for the detector subsystem is anticipated.

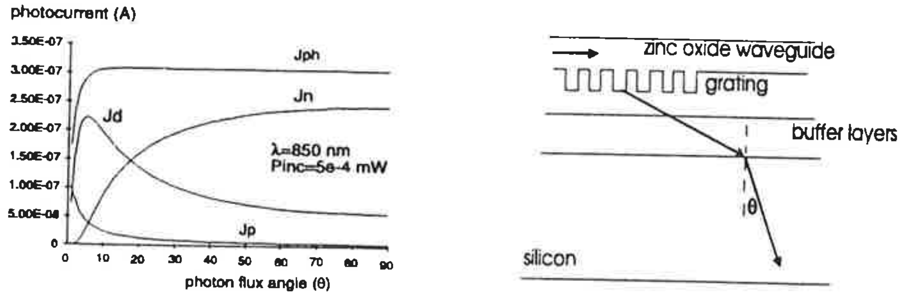

Figure 4: *(a) Fast (Jd) and slow (Jp, Jn) contributions to the photocurrent, (b) grating interconnect. N.B.* $\Theta(a)=90-\Theta(b)$

A PIN photodiode has been designed and modelled concerning quantum efficiency, absorption, responsivity, noise and bandwidth. Boundary conditions for the design were dictated by the UT-BiCMOS process, among others substrate choice and several standard doping levels. An efficient photodiode can be realized. A considerable part of the generated photocurrent however is transported via diffusion currents (Jp and Jn in figure 4a), because the absorption length is larger than the thickness of the depletion layer. This could restrict the effective bandwidth to 1 MHz.

To improve this bandwidth a grating coupler can be employed. Normally, the waveguide will be optically isolated from the silicon substrate by a SiO_2-like layer to prevent unwanted optical attenuation. So, a special interconnect is required in the photodiode area to disturb the confined light in the waveguide and to redirect it into the underlying photodiode. For establishing a short detectorsystem a coupling based on evanescent coupling in a thinned region of the waveguide appeared to be unsuited. Instead, a coupling based on an output grating was investigated (figure 3b). In order to have a fast and efficient photodetector it is desirable that almost all the photons are absorbed within the depletion layer of the photodiode. This can be achieved by introducing an angle between the direction of the light and the photodetector as induced by a coupling grating. Calculations show however, that this solution is only effective for wavelengths much shorter than 850 nm. Around 850 nm a second grating is required [5]. A wavelength of 675 nm will be pursued for this sensorsystem, because of, among others, this technical difficulty.

The photodiode signal will be amplified on chip by a transimpedance amplifier. This amplifier combines high bandwidth and high dynamic range with relatively low noise. The equivalent inputnoise current will be a few nA at a bandwidth of 100 kHz. The maximum input current of the amplifier is about 50 μA.

D. ZnO Waveguide Technology

ZnO is a popular material for sensor applications, because of its piezo-electricity and gas sensing properties. A major advantage of the utilization of ZnO in opto-electronic integration schemes is its low growth temperature in a RF sputtering proces. Optimized sputterparameters were investigated. Channel ridge waveguides have been fabricated by sputter etching of ZnO. Although these waveguides showed only a small increase in attenuation compared to slab waveguides (1 dB/cm @ 633 nm), they suffered from non-uniformity of the etch. First results indicate that ZnO waveguides toploaded with SiO_2 are preferable. In an accompanied paper these investigations are further elaborated [6].

V. CONCLUSIONS

A general platform for integrated opto-electronic sensorsystems on silicon is proposed. The system is based on a hybridly integrated semiconductor laser, ZnO optical waveguides and monolithic photodiodes and electronic circuitry. Key experiments concerning compatibility aspects and subsystems of the sensor indicate, that realization of the concept is feasible.

REFERENCES

1. E. Voges, H. Bezzaoui and M. Hoffmann, European Conference on Integrated Optics '93, Neuchatel, April 18-22 (1993).
2. P.V. Lambeck, Sensors and Actuators B, **8**, pp. 103-116 (1992).
3. M.J. Zhou, T. Ikkink, J. Chalmers, H. van Kranenburg, H. Albers, J. Holleman, P.V.Lambeck, J.L. Joppe, H.H.P.Th. Bekman, A.J. T de Krijger, these proceedings (1994).
4. J.L. Joppe, A.J.T. de Krijger and O.F.J. Noordman, Elec. Lett., 27, pp. 162-163 (1991).
5. J. Chalmers et al., these proceedings (1994).
6. H.H.P.Th. Bekman, K.W. Benoist, J.A.G. van Bezooijen, J.L. Joppe, R.G. Heideman and P.V. Lambeck, these proceedings (1994), and references therein.

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