SILICON PHOTONICS: FROM RESEARCH TO MANUFACTURABLE PRODUCTS

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Abstract: The use of wafer-scale CMOS technologies holds great promise for the fabrication of high performance and high complexity photonic integrated circuits at moderate cost. In this paper we discuss some of the key challenges to make this promise come true.

1. INTRODUCTION

In the last decade, silicon photonics has gained substantial importance in the field of photonic integration. This is because of the combination of a very high index contrast (and thus strong potential for miniaturization) and the compatibility with CMOS fabrication technology.

Silicon nanophotonic waveguides can strongly confine light in a submicron waveguide core, allowing sharp bends and compact components. This allows for a dramatic reduction in footprint, which in turn enables larger-scale integration of photonic components. The attractiveness of silicon photonic wires also comes from the possibility of leveraging the industrial fabrication base of electronics. The fabrication of photonic circuits can be done with the same tools used for making CMOS-circuits. At the same time this CMOS-compatibility opens up interesting options for the integration of photonic functions with electronic functions, another key advantage of silicon photonics.

In this paper we address some of the key issues to be resolved in order to move from research to industrial manufacturing of silicon-based photonic-electronic ICs. These include manufacturing accuracy and reproducibility, wafer-level testing, integration with electronic circuitry and foundry access.

2. MANUFACTURING ACCURACY

The patterning of Silicon-on-Insulator based photonic devices in a CMOS environment is done by means of a combination of deep UV lithography tools and etching steps (possibly complemented by metallization, implantation etc.). While high index contrast brings great benefits for miniaturization it has a downside too: the dimensions of a waveguide need to be accurate down to the nm-level. In principle fabrication errors can be compensated by either trimming or tuning, but the extent by which that needs to happen should be minimized. A geometric accuracy (and reproducibility) at the level of a few nm is challenging – but feasible - for optical lithography processes operating at a wavelength of 193 nm.

Optical lithography has evolved with downsizing of the transistors in electronic circuits, bringing advanced functionalities for accurate pattern definition and uniformity. Using advanced manufacturing tools, namely 193nm optical lithography and dry etching, we have achieved sub-nm device uniformity. In any interferometric photonic device the waveguide geometry has an impact on the spectral response, hence controlling them is an absolute necessity. While the thickness is largely decided by the SOI wafer manufacturer (and process), the width is strictly controlled by the patterning process. In a 200mm wafer, we have achieved linewidth uniformity (standard deviation) of 2nm and 2.6nm after optical lithography and dry etching respectively. The fabrication process is developed to achieve high accuracy in combination with good reproducibility.

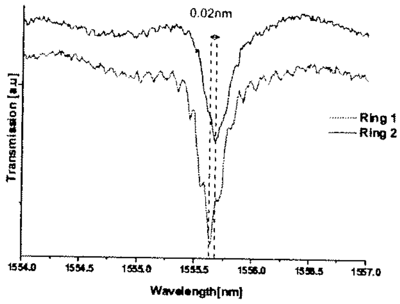

Fig.1 Non-uniformity of two ring resonators, which are 25µm apart.

There are two non-uniformities which are important for manufacturability: within chip and chip to chip uniformity. The device uniformity within a chip and between chips is tested by measuring wavelength selective devices (Mach-Zehnder interferometer and ring resonator). We have achieved an average spectral non-uniformity of ~0.4nm and ~1.5nm within a chip and between chips respectively [1]. Non-uniformity as low as 20pm (Fig.1) was obtained for devices which are placed 25µm apart. This value is better than the uniformity achieved using e-beam technology [2]. Fig. 2 shows the transmission spectrum of 12 identical (by design) MZI's from 3 chips in a 200mm wafer. Our characterization shows a correlation between non-uniformity and placement of the devices: the larger the distance between the devices, the higher the non-uniformity. Variation in the shorter length scale (μm) is largely influenced by pattern loading and optical lithography, while wafer thickness and dry etch process influence longer length scale (mm).

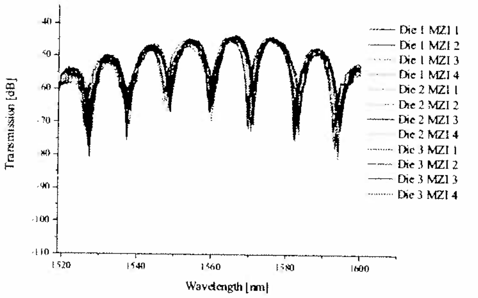

Fig.2 Chip to Chip non-uniformity of 12 MZI's from 3 chips

3. WAFER-LEVEL TESTING

Testing of photonic circuits can add considerably to their cost. Therefore there is a need for automated measurement tools that can test photonic circuits at the wafer-level, i.e. before dicing. This requires an approach whereby there is an out-of-plane optical access to the on-chip waveguides. This can be done either through the use of diffractive grating couplers integrated in the chip or by means of fiber probes with a grating integrated on the fiber tip. In the first case the grating coupler can not only be used for testing but also for packaged optical fiber access to the chip. That calls for couplers with low coupling loss and wide bandwidth. In the second case coupling efficiency is less critical and brings the extra asset of being able to probe the interior of complex circuits.

High efficiency on-chip grating couplers can be realized in several ways. The design of high efficiency grating couplers comprises the optimization of the directionality of the diffraction grating (the ratio of the power diffracted towards the optical fiber to the total diffracted optical power from the grating) and the optimization of the coupling length of the diffraction grating, since one needs to interface with a 10um diameter single mode optical fiber [3]. Uniform diffraction gratings result in an exponentially decaying diffracted field profile, which limits the overlap between the diffracted field and the Gaussian optical fiber mode to 84% (assuming perfect directionality of the grating). Optimization of the directionality of the grating can be achieved by defining a mirror below the waveguide grating to redirect the downwards diffracted power towards the optical fiber. Both a gold bottom mirror [4] and a DBR bottom mirror (comprising alternate Si and SiO_2 layers) can be used [5]. The phase difference between the upwards diffracted beam and the redirected beam needs to be well controlled in order to obtain constructive interference. This way 69% coupling efficiency between a standard single mode fiber and a silicon waveguide was realized [4]. An alternative approach to realize high directionality is to intrinsically modify the diffraction properties of the grating, by optimizing the silicon waveguide layer grating cross-section. A silicon overlay, defined on the silicon waveguide layer prior to grating definition as shown in figure 3, allows to achieve nearly perfect directionality. This silicon overlay can be amorphous, poly-crystalline or crystalline silicon. Experimentally 55% coupling efficiency was realized in this way [6]. However, optimization of the processing conditions promises to improve this number up to 80%.

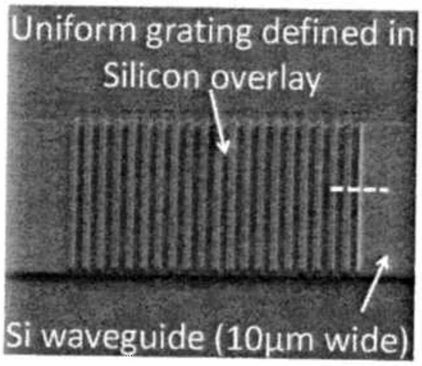

Fig. 3 SEM picture of a high efficiency grating coupler by defining a silicon overlay prior to grating definition

The alternative approach for wafer-scale testing is through the use of fiber probes with a grating on the fiber tip, brought in close proximity to the on-chip waveguides. We designed and fabricated gold grating fiber probes for silicon-on-insulator nanophotonic circuits. Due to the large refractive index contrast between the gold and the waveguide materials, strong diffraction will occur when light is incident on the grating, even when the grating is very thin [7]. Unlike grating couplers integrated in a chip, fiber probes offer a high degree of flexibility for testing. In particular, two probes allow to verify whether light can flow between any two points in a circuit while at the same time the spectral properties of the optical path established between those two points can be addressed.

Gold grating fiber probes were fabricated in a rather straightforward manner by a nanoimprint-and-transfer technique [8], as shown in fig. 4. 10 x 10μm gold gratings with a grating period of 630 nm were transferred from a mold to a single-mode fiber with a polymer as an intermediate layer. This technique allowed for alignment of the grating with respect to the fiber core and control of the angle between the grating plane and the fiber axis in order to maximize the coupling efficiency without suffering from second order Bragg reflections. 15% coupling efficiency between a gold grating fiber probe and a 220nm x 3µm SOI waveguide was obtained at a wavelength of 1545 nm with a 1dB bandwidth of 38nm. Testing of an integrated SOI ring resonator using two probes was experimentally demonstrated.

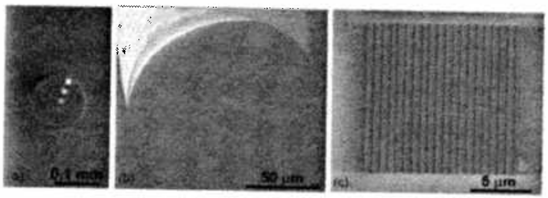

Fig.. 4. (a) Microscope image of the fiber probe facet containing 10 x 10 µm gold gratings. (b) SEM picture of the fiber facet. The middle grating is aligned to the fiber core. (c) Detail of the grating.

4. INTEGRATION WITH ELECTRONICS

While die-level technologies, such as flip-chip mounting, provide a viable solution for integration of photonics and electronics in some applications, there is a strong push towards wafer-scale integration technologies. There are three main approaches to achieve this each with their pros and cons. The photonic functions can be integrated in the electronic layer or they can be fabricated above CMOS by means of back-end processes or they can be built on a separate wafer which is then integrated with the electronic wafer. Here we discuss the two latter approaches.

Taking advantage of the layered approach of CMOS fabrication processes, building photonic circuits on top of CMOS circuits is a straightforward approach. As the photonic circuit layer has to be fabricated above the CMOS metallization the temperature of the fabrication process is restricted below 400°C.

Plasma enhanced chemical vapor deposition allows us to deposit low-loss amorphous silicon (a-Si) below 400°C [9,10] . We have achieved a propagation loss of 3.5dB/cm and 1.7dB/cm for a-Si photonic wires (450X220nm) and shallow etched ridge waveguide respectively (Fig. 5) [11]. From these measurements we have extracted a material loss of 0.7dB/cm. The deposition temperature is kept at 300°C to enable back-end CMOS compatibility.

The stability of a-Si:H over time and with respect to subsequent processing steps is important. Different environmental parameters such as temperature and pressure can change the film property. We have tested the stability by depositing silicon dioxide top cladding at 400°C, and we did not observe any change in the propagation loss. The stability (shelf life) of the film over time showed no change. Using our a-Si we have fabricated basic wavelength selective devices, such as ring resonators and MZI's (Fig. 6). These characterizations demonstrate the feasibility of using a-Si as waveguide medium in electronic-photonic integration.

Furthermore, a-Si opens a wide range of photonic devices, such as multilayer circuits and devices. Tunable thickness, low temperature, doping and, multi layer staking can open a wide range of application for a-Si.

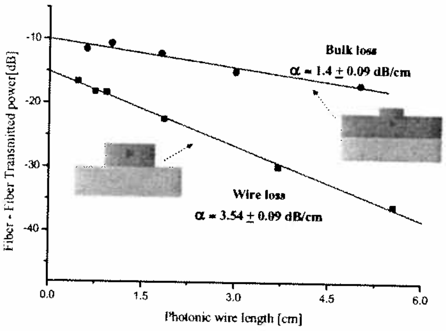

Fig.5 Propagation loss of a-Si wires extraction

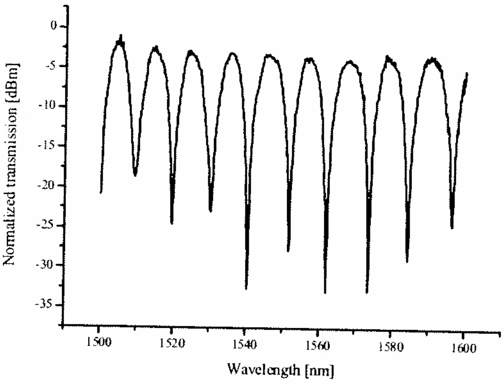

Fig. 6 Transmission spectrum of an a-Si MZI.

Another approach to integration of photonic and electronic functions is to decouple the fabrication of the photonics and electronics, by processing them on

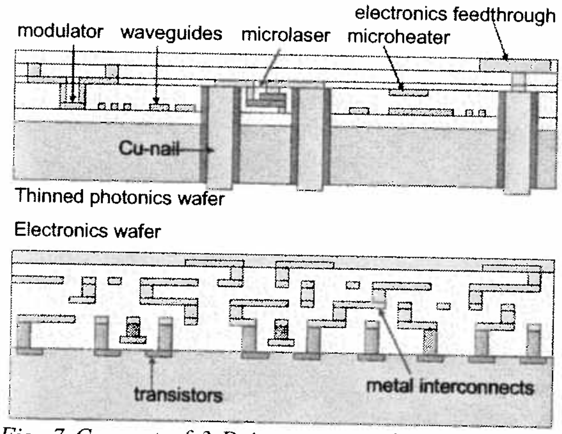

Fig. 7 Concept of 3-D integration of photonics and electronics with Cu-nail TSVs

separate wafers, and join them together at the final stage of the foundry process. For this purpose, a 3-D integration technology can be used, where photonic dies can be integrated on top of photonic wafers, or vice-versa. Using Cu-nail through-silicon vias (TSV), which can be arranged with pitches of 10m, thousands up to millions of interconnects between integration layers are possible [12]. This is conceptually shown in fig. 7. By choosing for die-to-wafer integration, this approach can improve yield by selecting only known-good dies for bonding [13].

5. ACCESS TO FOUNDRIES

Access to advanced CMOS fabrication facilities - with processes optimized for photonic devices - is non-trivial both at the research and the manufacturing level. To this end an initiative has been taken to organize a Multi-Project-Wafer service for silicon photonics through which users can have their designs fabricated in a cost-sharing mode.

This service runs under the name of *ePIXfab* (www.epixfab.eu). Three times a year, a multi-project wafer run is scheduled to which users can sign up with one or multiple designs. ePIXfab checks and integrates the designs into CMOS masks. The designs are then jointly fabricated in a single process flow. By sharing the expensive CMOS masks as well as the processing costs between 10 to 15 users, the cost of research and prototyping with CMOS technology is made affordable.

ePIXfab aims to set up a system for fabless silicon photonics, where a full food chain is available from design and fabrication to packaging and testing. Complemented by training of designers from academia and industry on design for the available technologies, the barriers for fabless access will be greatly reduced so that the transfer from R&D to products is made considerably easier.

ACKNOWLEDGEMENT

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MONDAY, DECEMBER 15, 2008

FORENOON

	Plenary Session *Chair:* **A.K. Ghatak** Venue: Stein Auditorium (Session-A)
9:30	The revolution in Fiber Optics, **D. N. Payne**, ORC, University of Southampton, UK
10:45	Ultrafast Nonlinear Optics on a Photonic Chip, **B. Eggleton**, University of Sydney, Australia

Time	Session-A	Session-B	Session-C	Session-D	Session-E	Session-F
	MA1: SENSORS FOR CIVIL STRUCTURES *Chairs:* KTV Grattan & P. Radhakrishnan	**MB1: MICRO-STRUCTURED FIBERS** *Chairs:* K. Yasumoto & J Kobelke	**MC1: SILICON PHOTONICS** *Chairs:* A Basu & R Baets	**MD1 : MICROWAVE PHOTONICS** *Chairs:* EK Sharma & DK Paul	**ME1: DOPED FIBERS-1** *Chairs:* R Kashyap & R Sen	**MF1: SLOW LIGHT & EIT** *Chairs:* K Thyagarajan & Y. Kivshar
11:30	**Invited:** Hollow-core optical fiber sensors and devices **Wei Jin,** The Hong Kong Polytechnic University, Kowloon ,Hong Kong	**Invited:** Recent developments of microstructured fibers for active and passive applications **J Kobelke, J Kirchhof, S Unger, K Schuster, A Schwuchow** Institute of Photonic Technology, Jena, Germany	**Invited:** Silicon photonics: from research to manufacturable products **R Baets, S Selvaraja, G Roelkens, S Scheerlinck, P Dumon, W Bogaerts, D Van Thourhout** Ghent University, Gent, Belgium	**Invited:** MW/mmW photonics technology: state-of-the-art and applications **Dilip K Paul,** ACES, Inc., Bethesda, USA	**Invited:** Erbium emission properties in nanostructured fibres **B Dussardier[1], W Blanc[1], G Monnom[1], R Peretti[2], A M Jurdyc[2], B Jacquier[2], M Foret[3]** [1] LPMC, Université de Nice, Nice, France, [2] LPCML, Université Lyon [1]/CNRS, France [3] Université de Montpellier 2, Montpellier, France	**Invited:** Shape preserving pulses in two-mode fibers doped with 3-level atoms **T N Dey[1], S Dutta Gupta[2] and G S Agarwal[3]** [1]Indian Institute of Technology Guwahati, India [2]University of Hyderabad, India [3]Oklahoma State University, USA
12:00	**Invited:** Developments in fiber optic techniques for structural monitoring **K T V Grattan[1], T Sun[1], S K T Grattan[2], S E Taylor[2], D O McPolin[2] and P A M Basheer[2]** [1]City University London, UK [2]The Queen's University of Belfast, UK	Design of modified micro-structured optical fiber for dispersion-shifted application **S C Gowre, P K Sahu, S Mahapatra, and J C Biswas** IIT Kharagpur, India	**Invited:** Silicon photonics: The impact of silicon-organic hybrid systems **W Freude[1], C. Koos[1,2], J-M Brosi[1], P Vorreau[1], P Dumon[3], R Baets[3], B Esembeson[4], I Biaggio[4], T Michinobu[5,] F Diederich[5], and J. Leuthold[1]** [1]University of Karlsruhe, Karlsruhe, Germany, [2]Now with Carl Zeiss AG, Corporate Research and Technology, Oberkochen, Germany [3]Ghent University, Gent, Belgium [4] Lehigh University, Bethlehem, USA [5]Laboratorium für Organische Chemie, ETH Zürich, Switzerland	**Invited:** Low-loss waveguides for THz propagation **B M A Rahman, N Kejalakshmy, C Themistos, H Tanvir and K T V Grattan** City University London, London, UK	**Invited:** Rare earth doped optical fibers- fabrication technology **R Sen and A Dhar** Central Glass and Ceramic Research Institute, Kolkata, India	Electromagnetically induced transparency and slow light in a hot vapor of ^{4}He undergoing collisions **J Ghosh[1], F Goldfarb[2], M David[2], J Ruggiero[2], T Chanelière[2], J L Le Gouët[2], H Gilles[3], F Bretenaker[2] and R Ghosh[1]** [1]Jawaharlal Nehru University, New Delhi, India, [2] CNRS Université, Orsay , France, [3]Centre de Recherche sur les Ions, Caen, France
12.15		Single-modeness in Bragg fibers **D A Gaponov [1], A S Biriukov [1], A D Pryamikov [1], M E Likhachev [1], and S Février [2]** [1] Fibre Optics Research Center, Moscow, Russia [2] Xlim, UMR CNRS, Limoges, France				Ultrafast carrier relaxation and nonlinear absorption in $Bi_{12}SiO_{20}$ single crystal **P P Kiran[1],G R Kumar[2] and D N Rao[1]** [1] University of Hyderabad, India [2] Tata Institute of Fundamental Research, Mumbai, India
12:30	Fibre optic relative humidity sensor for monitoring civil engineering structures **S Srinivasan[1], P A M Basheer[1], R Mandamparambil[2], S E Taylor[1], K T V Grattan[2], T Sun[3], B J Smith[1] and M Gomez-Heras[2]** [1]Queens University, Belfast, UK [2]City University London, UK	Dispersion properties and infrared broadband generation in square lattice photonic crystal fiber made of highly nonlinear glasses **S Roy and P Roy Chaudhuri** Indian Institute of Technology Kharagpur, India	3x10 Gbit/s wavelength division multiplexing using silicon microring electrooptic modulators **S Manipatruni[1], B G Lee[2], A Biberman[2], B Schmidt[1], K Bergman[2], M Lipson[1]** [1]Cornell University, NY, USA [2] Columbia University, NY, USA	Reflective 3x3 coupler-based double recirculating delay line microwave photonic filter **J Q Zhou, H Dong, S Aditya, P Shum, L Xia, and B P Parhusip** Nanyang Technological University, Singapore	Spectroscopic properties and laser gain characteristics of Tm^{3+}-Yb^{3+} and Tm^{3+}-Ho^{3+}-Yb^{3+} tellurium oxide fibres **A Jha[1], B Richards[1], J Lousteau[1], Y Tsang[2], and D J Binks[2]** [1]The Institute for Materials Research, Leeds,UK, [2] School of Physics and Astronomy, Manchester, UK	
12:45	Condition monitoring of steel rope and water barrier pillar using FBG sensors **V Kumar[1], J S Bhadoria[1], N Singh[2], V Mishra[2], S C Jain[2], and P Kapur[2]** [1] ISM University, Dhanbad, India [2]Central Scientific Instruments Organization, Chandigarh, India	Fluorescent response of dye filled suspended-core microstructured polymer optical fiber, **J Vanda[1], J Skapa[1], V Vasinek[1], A Argyros[2], Martijn A van Eijkelenborg[2], M Large[2]** [1]VSB-TU Ostrava, Dept. of Telecommunications, Czech Republic, [2]University of Sydney, Australia	Demonstration of optical via and low-loss optical crossing for vertical integration of silicon photonic circuit **S. K. Selvaraja, P. Dumon, E. Sleeckx*, Marc Schaekers*, W. Bogaerts, D. Van Thourhout and R. Baets** Gent University-IMEC, Department of Information Technology, Gent, Belgium. *IMEC, Leuven, Belgium.	Continuous multiband microwave photonic phase shifter based on lightwave polarization control **O L Coutinho[1], C S Martins[1], V R Almeida[2], J E B Oliveira[1]** [1]Pça. Mal. Eduardo Gomes. SP - Brazil [2]Instituto de Estudos Avançados, S Campos, Brazil		
13.00				Optical generation of low-noise phase-modulated terahertz signal **T Chattopadhaya[1] and BMA Rahman[2]** [1]Visva-Bharati University, Santiniketan, India [2] City University London, UK		