Silicon-Organic Hybrid Fabrication Platform for Integrated Circuits

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ABSTRACT
The combination of CMOS compatible Silicon-On-Insulator (SOI) fabrication technology with organic cover materials constitutes the Silicon-Organic Hybrid (SOH) fabrication platform, which shows innovative functionality for the making of integrated optical circuits. We report on experimental demonstrations of essential building blocks for transceivers, while relying only on well-known SOI processing steps and simple post processing of the organic materials.
Keywords: Silicon-organic hybrid, silicon-on-insulator, photonic integrated circuits, modulators, electro-optic devices.

1. INTRODUCTION

Silicon-Organic Hybrid (SOH) technology [1] offers new active optical waveguides and integrated optoelectronic circuits to address rising demands on energy consumption, speed and ease of fabrication for applications in communication. Any functionality not available from pure silicon waveguides is created from the combination of Silicon-On-Insulator (SOI) structures and organic cladding materials, which are chosen according to their often unique properties.

There is a competition between photonic integrated circuit (PIC) platforms based on material systems such as III-V semiconductors, III-V components on silicon, germanium on silicon, lithium niobate, silicon nitride and more. The choice of the platform depends on the specific application and target parameters, but a detailed analysis is beyond the scope of this paper. Here we assume a desire to use SOI technology, because of highest practical integration density, existing infrastructure (scalability, potential high volume, low unit costs) and the potential for future integration with electronics. The choice is also influenced by the range of available devices, i.e. available building blocks to make complete integrated circuits.

In this paper we present the SOH platform as a solution to provide signal processing with high-speed SOH electro-optic phase modulators and SOH low voltage phase shifters for tuning passive structures such as filters (e.g. delay interferometers). Also an SOH technology-compatible detector option is discussed, which is based on sub-bandgap or surface state absorption in silicon. We elaborate the SOH concept by showing experimental results for each device, listing particular advantages and discuss challenges ahead of the road.

2. Available Building Blocks

2.1 Modulators

High-speed modulators remain the core component in advanced signal processing, especially for electrical to optical data signal conversion. Plasma effect based devices based on pn/pin junctions [2-6] present a direct solution.

The SOH platform [7-9] is an alternative solution offering large bandwidth, low energy consumption and suitability for advanced phase encoded modulation.

Aiming to employ the fast linear electro-optic effect known from non-linear optics, the lack of a second order nonlinearity in silicon has to be compensated by the cover material. For this purpose a set of process steps is introduced during fabrication at post-processing stage. We simply spin-coat a commercially available electro-optic polymer on SOI chips (produced in a standard CMOS line by 193 nm deep-UV lithography). The nonlinearity is created after spin-coating by aligning the functional molecules in a host polymer matrix by means of a poling procedure. Subsequently any voltage applied over the polymer covering a silicon waveguide not only changes the refractive index of the polymer but also the effective refractive index of this waveguide, but not its absorption.

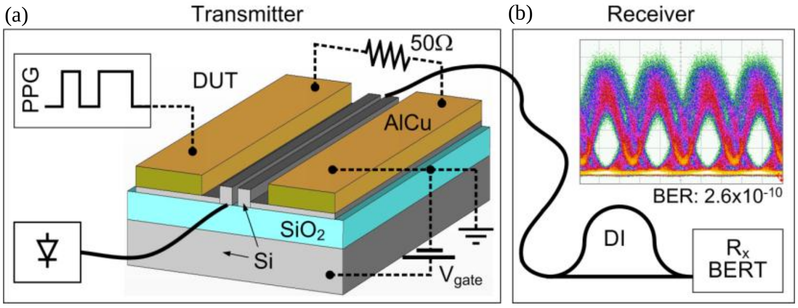

Figure 1. *(a) SOH modulator covered with electro-optic polymer (cover layer not shown) based on slot waveguide connected with* 70 nm *high silicon slabs to coplanar waveguide electrodes. Gate voltage on substrate increases conductivity of silicon slabs, similar to a channel in a field effect transistor. Sending* 42.7 Gbit/s *phase-modulated data with on-off keying employing the transmitter (a) allows to obtain Bit-Error-Ratio (BER) measurements as low as* 2.6E-10 *with a delay interferometer (DI) and BER-tester (BERT) in the receiver (b).*

We choose a particular waveguide geometry which maximises the overlap (and hence the desired effect) between the optical mode and the active material: Two silicon strips (220 nm height) separated by a slot guide light polarized in parallel to the substrate to a large part in the polymer, because of the high refractive index step of the materials involved. 70 nm high silicon slabs connect the coplanar waveguide electrodes (AlCu alloy) with the slot waveguide, as shown in Figure 1(a). Here, in a proof-of-principle demonstration, the slot width is 160 nm, the active device length is 1.7 mm resulting in a phase shift of $V_{\pi}L$ = 9 Vmm at DC. Contacting with pico-probes which feed PRBS (2^{31}-1) data at 42.7 Gbit/s (driven with 4 V RF voltage swing) and applying an off-chip 50 Ohm termination a data transmission at 1550 nm with Bit-Error-Ratio (BER) of 2.6E-12 is achieved [10]. At the same time a voltage is applied to the silicon substrate to increase the conductivity of the silicon slabs, similar to creating a conductive channel in a field effect transistor.

The SOH modulator has the advantage of simplifying the on-chip RF signal termination, as there are no bias voltages applied which otherwise would be short-circuited at the on-chip ohmic resistance or require more RF components. Furthermore the pure electro-optic phase shift and virtual absence of amplitude modulation predestine SOH modulators for more advanced modulation formats, whereas plasma effect based modulators by nature will show a change in amplitude to a certain extend. Plasma-effect based modulators face the fabrication challenge to reliably obtain p and n implantations close to each other and exactly at the right position. The SOH approach avoids these demanding doping resolution constraints.

The choice of cover material is open and any material having a large second order non-linearity can be considered. We hence pursue the SOI functionalization with organic electro-optic single crystals [11] grown epitaxially. The crystal orientation is fixed during growth, which makes this cover layer ready for use right after growth and potentially more stable than polymers when choosing appropriate crystalline materials.

2.2 Phase shifters for adjusting passive SOI structures

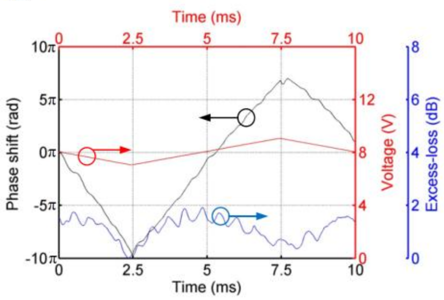

Figure 2*. Slow but highly efficient phase shifter based on orienting nematic liquid crystals, i.e. aligning birefringent molecules. Diagram shows the obtained phase shift from an SOH slot structure with silicon slabs as in Figure 1(a) (without gate voltage) when covered with nematic liquid crystals and measured in external Mach-Zehnder setup. Black curve depicts the phase shift caused by the applied, slowly varying voltage shown red. Resulting excess loss is depicted in blue.*

Some signal processing can be done optically with passive silicon structures instead of using energy to perform it in the electrical domain. Especially filter structures based on Delay Interferometers (DI) and Arrayed

Waveguide Gratings (AWG) or switches are easy to produce, as well as circuits for an optical Fourier transform, which is useful for orthogonal frequency division multiplexing (OFDM). However, often active phase control is unavoidable and frequently done with heaters. Instead of applying a constant current, providing just an electrical potential is more energy efficient. Nematic Liquid Crystals (LC) are bi-refringent and can be aligned with an electrical field. When used as a cladding on a silicon waveguide they can provide a much stronger, slower phase shift compared to the electro-optic materials described before [12]. This allows for shorter devices, and when measuring LCs (see Figure 2) in the very same structure as the SOH modulator explained above a better $V_\pi L = 0.085$ Vmm.

2.3 Detectors

Using silicon for waveguiding infrared light implies that using the very same material for detection is challenging [13]. Sub-band gap detection by means of deliberately created defects from silicon implantation [14] or relying on surface states [15] presents a solution. Another option is again introducing a material with the desired properties as done with germanium [16] or using polycrystalline silicon [17]. An organic material for high-speed detection at IR wavelengths remains to be found. In search of an option using processes already employed in the SOH platform we consider the following alternative in a proof-of-principle:

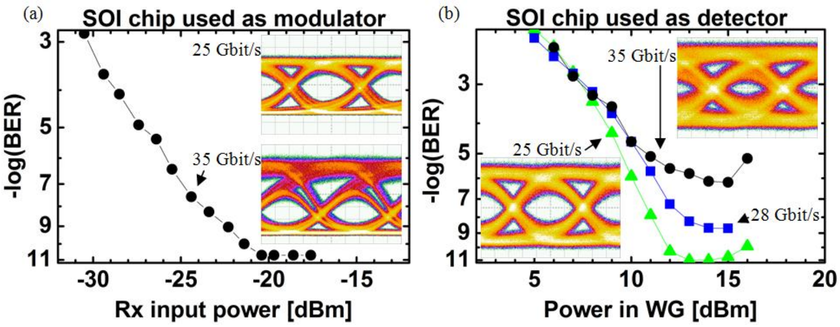

Figure 3 *Modulation and detection of sub-band gap light with the same pin-silicon diode fabricated in an SOH platform compatible process. Characterization of pin-silicon diode around 1550 nm by data transmission of a PRBS (2^7-1) using NRZ OOK. (a) BER and open eye diagrams for modulation with diode on SOI chip (reverse biased at 5.7 V) using commercial receiver. (b) BER and open eye diagrams for detection with the very same diode (reverse biased at 7.1 V) of optical signal (generated with LN modulator) using an electronic amplifier.*

As ion implantation is essential in any case for the SOH modulator a p dopant can easily be added. Using a ridge waveguide with p doping on one side and n doping on the other side constitutes a pin diode, i.e. an SOI modulator based on carrier depletion can be fabricated [18]. In Figure 3(a) the resulting capability of transmitting a Pseudo Random Bit Sequence (PRBS) of length 2^7-1 at 35 Gbit/s is demonstrated. Not only is this modulator allowing for an extension of application range (note that this modulator cannot compete with the SOH modulator in terms of bandwidth and can only be implemented at the expense of high spatial implantation accuracy, but nevertheless without additional process complexity), but also it turns out that the very same device can be used for detection.

Instead of applying an RF voltage and reverse bias to modulate incoming cw light, PRBS amplitude modulated light is send into the reverse biased device (near break-down voltage) and the resulting, received RF signal is amplified and tested for bit errors. In Figure 3(b), the resulting Bit-Error-Ratio (BER) is plotted in dependence of average optical input power. The latter quantity needs to be reduced further for most applications.

3. FROM BUILDING BLOCKS TO A PHOTONIC INTEGRATED CIRCUIT

To unite the building blocks on one chip to make a packaged unit, the tremendous range of choice for cover materials is best addressed by using a standard and flexible approach for packaging. Grating couplers are and active alignment of fibers is used for pigtailing to the off-chip light source and other optical in- and outputs. Electrical lines and waveguides are bonded to an alumina based mount.

4. CONCLUSIONS

To establish the Silicon-Organic Hybrid (SOH) fabrication platform proof-of-principle experiments have been performed for signal processing (modulation, phase shifters) and detection. We present a demonstration for each one of them and point out the peculiarities of the SOH concept in positive as in negative respects. The SOH platform can be considered versatile and disruptive because of the unlimited choice of organic cover materials.

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