Intrachip Optical Interconnect :An above IC approach .

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Abstract

This paper describes a new approach for optical interconnects, based on an above IC clock signal distribution with high compacity, using polymers with high refractive index difference. We investigate the design and its feasibility study and show the results on the firsts components obtained with similar materials. We demonstrate a high level of integration using materials compatible with microelectronic process, allowing an intra-chip optical distribution.

Introduction:

According to the ITRS Roadmap (1), increase in density and performances of Integrated Circuits (IC) with device down scaling will soon lead to drastic limitations on the interconnect point of view.In a few years, new architectures or technological solutions such as 3D integration, nanotubes or optical links will be needed to overcome the performance limitations of traditional metallic interconnects. Optical interconnect appears now as a promising candidate to replace conventional metallisation. Indeed, using light instead of electricity to transport information brings improvments associated to the shorter wavelength, the higher speed and elimination of RC delay (2). However, different types of optical interconnects are possible, from free space links to integrated waveguides. While integrated interconnect appears as the most promising solution, two different approaches are existing, with specific advantages.

Previously, optical links have been developed on the top of IC's wafers, with technological solutions derivated from the telecom domain. The waveguides, situated above the upper interconnection levels, are made of transparent polymers (3). This technique show an easy compatibility with microelectronics technology, considering the low deposition temperatures, and some clock distributions for supercomputer have been demonstrated (4). However, the polymer materials used have low index differences ($10^{-4}<\Delta N<10^{-2}$), leading to large waveguides dimensions and very low compacity. Intra chip optical distribution is hardly possible with this technique.

More recently, many researches are focused on photonics on Silicon On Insulator wafers, using the silicon layer as the guiding medium for infrared light. The index difference between silicon and silicon oxyde is very high ($\Delta N=2.06$), allowing a high compacity with very small dimension waveguides. However, losses in the waveguides are linked to sidewall roughness, requiring critical technological steps to reduce it (5). Moreover, integration of SOI based waveguides on an IC is not straightforward. The location of the optical waveguide at the level of the transistors introduces space constraints. The integration on top of the IC requires critical 3D integration with wafer bonding.

In this work, a new approach based on an above IC optical clock signal distribution with materials showing a medium index difference is proposed. This method combines an easy integration with microelectronics technology and a good density of integration, allowing intra-chip signal distribution. In order to avoid any perturbations on the operating conditions of the electrical part, infrared light (1.3 or 1.55µm) is chosen. Using two dielectric materials with a medium refractive index difference ($\Delta N\#0.5$), sub-micrometer width waveguides and radius bends less than 10 µm can then be fabricated. Moreover, an optical circuit for clock signal distribution must include other components such as: compact light sources coupled to an integrated light modulator to generate the optical clock signal, photodiodes at the output of the passive optical distribution, compact beam splitters to distribute the initial optical clock signal towards N blocks of the integrated circuit. This paper deals with the passive part of the distribution.

In a first section, the modelling and design of the integrated optical components for optical interconnects in IC are discussed. Experimental results on the components developed using Plasma Enhanced Chemical Vapor Deposited (PECVD) Si_3N_4 as guiding medium are then exposed. Optical characterization of a 1 to 4 MultiMode Interference (MMI) device is shown. A good correlation between simulation and experimental results is demonstrated. Finally, preliminary results on the development of PECVD organic polymers (a-CH for the guide and a-CF for the cladding) that show a high index contrast and low optical losses in the IR range are presented.

Experiment

Silicon oxide and silicon nitride films are deposited by PECVD, using a Precision 5000 from Applied Material. Films are characterized using a spectroscopic ellipsometer (GESP5 SOPRA) in the range 0.2 to 1.8µm. Optical devices are fabricated using a standard CMOS technology on 8" wafers.Optical characterization of the components is performed using an integrated optical bench, composed with 3D nano-handlers. The beam is focused by achromatic lens on the grating to obtain a beam waist of 20 µm. The collect is done with a multimode fiber linked to an optical spectrum analyser (Agilent 86140B). The observation is performed using an infrared linear response Hamamatsu video camera.

Results and discussion

Realisation of a complete passive clock distribution involves the design of different components: waveguides, compact bends and efficient splitters. The design of waveguides with a strong field confinement is performed using a full vectorial finite difference mode solver (6) including symmetries and transparent conditions at the limits. To avoid information losses due to multimode potential parasitic coupling in the waveguides, monomode guides are mandatory. Fig.1 highlights thickness boundaries to obtain monomode operation for different width of the waveguides, according to the refractive index difference between the guiding medium and the cladding. Sub-micrometer waveguides are designed, with cross-section 0,4 x 0,8µm, in the same order as the one obtained on SOI technology (typically 0.3 x 0.4) (7). In the same way, crosstalk between waveguides has to be determined in order to avoid any coupling between waveguides in cm range. It is here estimated by the modal analysis of parallel waveguides. With this technology, simulation results leads to a minimum spacing of 1.5µm .

Due to the small size of the waveguides, butt-coupling method shows limited efficiency on the order of few percent, and a very poor reproducibility. The grating coupler is a good alternative. Indeed, it can be monolithically integrated, at any point of the circuit. To design this type of coupler, we used a grating mode solver coupled to a plane wave decomposition method (8) to calculate the coupling efficiency of the grating for an incident Gaussian beam. Efficiency more than 50% is reported. The losses by optical tunnel effect trough the substrate are a critical parameter. As silicon substrate has a higher refractive index than the core of the waveguide, the cladding layer thickness has to be sufficient. Fig. 2 presents simulation results of the losses in the Si-substrate function of the thickness of the insulation layer. With our medium index waveguides, an increase of the insulation layer to 2 µm is necessary to have losses under 10^{-2} $dB.cm^{-1}$, compared to the value of 1µm for a high index silicon waveguide.

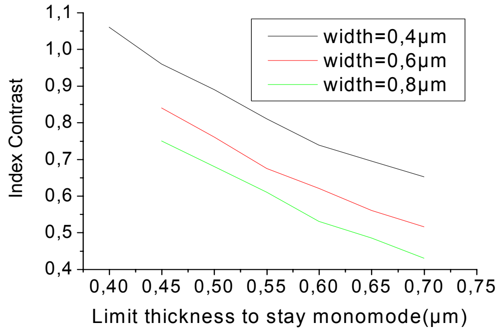

Fig. 1 : Evaluation of the monomodal waveguiding conditions for a strip waveguide with a full vectorial mode solver.

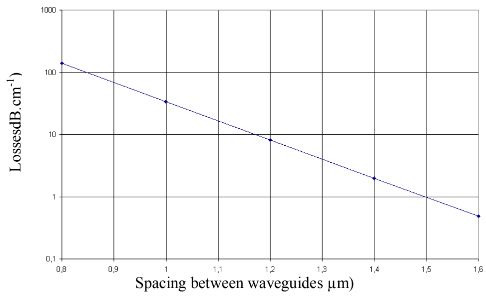

Fig.2: Optical tunelling losses through the substrate versus the insulation layer e thichness. For a 0.4 x0.8 µm waveguide. Index of the guiding/cladding material:1.95/1.447

Design of beam splitters and compact directional changes are performed using beam propagation method associated with the effective index method. For optimising, more accurate 3D FDTD (Finite difference in Time Domain) calculations have then be used (9). Even requiring large memory size and long computing time, they take into account diffraction effects in high refractive index contrast components.

For compact directional changes of directions, the medium index difference forbid the use of integrated micro mirrors contrary to silicon waveguides (10). Simulation results on bends reveals that curvature radius as low as 8µm exhibits negligible losses.

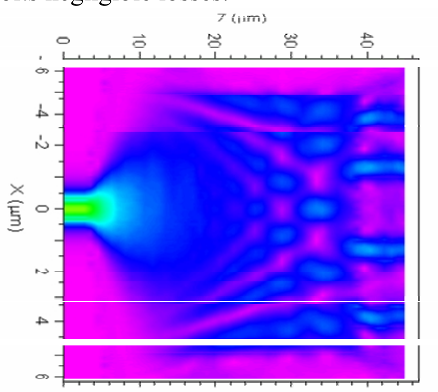

Fig. 3 :FDTD simulation of a MMI (10 x35 µm) 1 to 4 beamsplitter. Refractive index of the guiding\ cladding medium: 1.95\1.447

To split beam in 1 to 2 or 1 to 4, MMI are designed (fig 3). They show low losses and equilibrated outputs with compact (sizes 3x10µm and 10x35µm respectively).
For first demonstration, PECVD silicon nitride (N=1.87 @ 1.3µm) is used as the guiding medium and SiO_2 (N=1.447 @ 1.3µm) as the cladding. Silicon nitride was deposited at 400°C on thermal oxyde grown on silicon substrate. Waveguides, grating couplers, MMI splitters and micro-bends are defined using deep UV lithography (248nm). Strip waveguides and grating grooves are simultaneously etched by Reactive Ion Etching. Finally, a cladding layer of PECVD SiO_2 is deposited. A cross view of a waveguide is shown fig4.

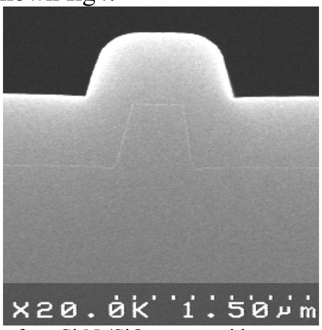

Fig. 4 : SEM view of an Si_3N_4/SiO_2 waveguide

Injection of light in such small devices is performed with grating assisted couplers. By varying the angle of incidence, a spectral analysis is made possible and an MMI 1 to 4 can be characterized. Fig. 5 shows the 4 decoupled beams output from the gratings associated to the MMI. A equilibrated energy repartition ($\Delta E<5\%$) on the outputs of the component is measured and this results is correlated to our simulations.

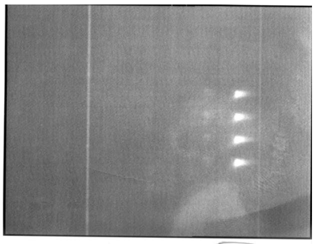

Fig. 5 : Infrared Image of the 4 decoupled beams output from the gratings associated to the MMI 1 to 4.

To our knowledge, it is one of the most compact MMI splitters. Using a linear response video camera, total losses of 3dB are measured. These losses can be attributed to the intrinsic losses of both nitride and cladding layer. In fact low absorption on both silicon-nitride and silicon oxide needs a high temperature annealing (11) which is not compatible with back-end technology. To avoid this problem, polymers are an interesting alternative due to their low deposition temperature and good transparency in the IR range.
Using PECVD techniques, a couple of polymer showing a high index difference has been developped. For the guiding medium, amorphous carbon (a-CH) shows high refractive index (higher than 1.85 at 1.3µm) and acceptable extinction coefficient ($k<10^{-4}$). Fig. 6 exhibits the refractive index variations in the wavelength range between 0.2 and 1.6µm. By varying plasma deposition conditions (gaz ratio, different precursors (aliphatic or aromatic hydrocarbons)), refractive indexes between 1.65 and 1.85 at 1.3µm can be obtained. For the cladding layer, amorphous fluorocarbon exhibits a very low index (1.35 @ 1.3µm), combined with a very low extinction coefficient $k<10^{-5}$). Using these two materials, a refractive index difference higher than 0.5 can be achieved, which is compatible with the approach proposed in this work.

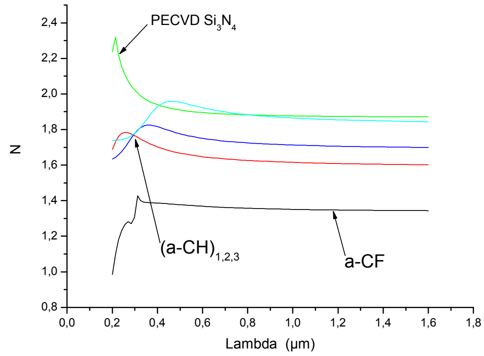

Fig. 4 :Refractive index of several optical materials according to the wavelength, i.e. PECVD SI_3N_4, a-CF and different a-CH.

Conclusion:

These results show the feasibility of a new type of optical interconnects, with a compacity comparable with SOI devices, and easily integrable with IC technology. Fabrication and characterization of extremely compact components with a Si_3N_4/SiO_2 technology prove the validity of this technical solution. New polymeric materials with much higher index difference are being developped, in order to decrease the losses of devices in the future.

Aknowledgment:

This work is financialy supported by an European Community trough the PICMOS program.

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