GUIDED-WAVE SI CMOS PROCESS-COMPATIBLE OPTICAL INTERCONNECTS

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We report the formation of polyimide-based H-tree waveguides for a multi-GBit/sec optical clock signal distribution in a Si CMOS process compatible environment. Such a clock distribution system is to replace the existing electronic counterpart associated with high-speed supercomputers such as Cray T-90 machine. A waveguide propagation loss of 0.21 dB/cm at 850 nm was experimentally confirmed for the 1-to-48 waveguide fanout device. The planarization requirement of the optical interconnection layer among many electrical interconnection layers makes the employment of tilted grating a choice of desire. Theoretical calculation predicts the 1-to-1 free-space to waveguide coupling with an efficiency as high as 95%. Currently, a coupling efficiency of 35% was experimentally confirmed due to the limited index difference between guiding and cladding layers. Further experiments aimed at structuring a larger guiding/cladding layer index differences are under investigation. To effectively couple an optical signal into the waveguide through the titled grating coupler, the accuracy of the wavelength employed is pivotal. This makes the usage of the vertical cavity surface-emitting lasers (VCSELs) and VCSEL arrays the best choice when compared with edge-emitting lasers. Modulation bandwidth as high as 6 GHz was demonstrated at 850 nm. Such a wavelength is compatible with Si-based photodetectors.

The speed and complexity of integrated circuits are increased rapidly as integrated circuit technology advances from very large scale integrated (VLSI) circuits to ultra large scale integrated (ULSI) circuits. As the number of components per chip, the number of chips per board, the modulation speed and the degree of integration continue to increase, electrical interconnects are facing their fundamental bottle-necks, such as speed, packaging, fanout, and power dissipation. Multichip module (MCM) technology is employed to provide higher clock speeds and circuit densities [1-2]. However, the state-of-the-art technologies based on electrical interconnects fail to provide the required multi-GBit/sec clock speed and communication distance in intra-MCM and inter-MCM hierarchies.

For a multiprocessor computer system, such as a Cray T-90 supercomputer, it is extremely difficult to obtain high-speed (>500 MHz) synchronous clock distribution using electrical interconnections due to large fanouts (48x2) and long interconnection lengths (>15 cm) [3-7]. A fanout chip is required to provide the massive electrical fanout. The synchronous global clock signal distribution is highly desirable to simplify the architecture and enable a higher speed performance. High-speed, large-area massive fanout optoelectronic interconnects may overcome many of the problems associated with electrical interconnects in this interconnection scenario [3-11]. An array of novel optical interconnect architecture has been proposed and then demonstrated by earlier researchers [11-14], which may partially satisfy the above requirements for a massive clock signal distribution in intra-MCM and inter-MCM hierarchies.

In this paper, we report the development of a planarized guided-wave optoelectronic interconnect network for optical clock signal

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distribution on a board-level multi-processor system. The electrical interconnect network currently employed by Cray Research is shown in Fig. 1, which shows the existing 500 MHz 1-to-48 clock signal distribution (one side) realized in one of the 52 vertical integration layers (not shown) within the Cray-T-90 supercomputer board.

To further upgrade the clock speed, an appropriate optical interconnect scheme has to be incorporated. In this paper, an integrated board-level optoelectronic interconnection layer is constructed by using polyimide-based optical channel waveguides in conjunction with tilted waveguide gratings. This guided-wave optoelectronic interconnect network is to be inserted into the Cray supercomputer boards to become an additional optical interconnection layer among many other electrical interconnection layers.

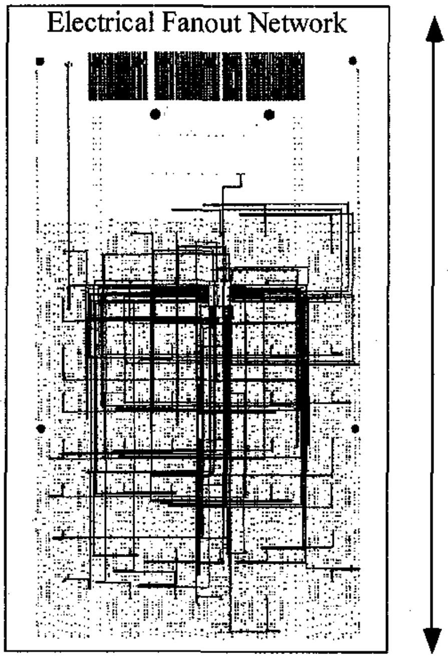

Fig. 1. Schematic diagrams of massive clock signal distribution networks using an electrical clock signal transmission line network that forms one of the 52 layers of Cray T-90 Supercomputer board. The holes indicate the feed-through marks of the on-board 3-D interconnect.supercomputer system may have a clock speed more than ten times higher than current systems.

Our approach is to construct an additional optoelectronic interconnection layer (OIL) for the high-speed optical clock signal distribution using polymer-based guided-wave devices. The selection of guided-wave approach is mainly based on the system alignment and reliability concerns [15]. During the course of research, Si CMOS process compatibility and planarization of the OIL are the two major technical concerns. A polymer-based waveguide H-tree system is employed to replace the existing electrical fanout interconnect network shown in Fig. 2. The optical clock signal delivered by an optic fiber will be coupled into the OIL using an input surface-normal tilted grating coupler, and distributed through out the board by the polymer-based channel waveguide network. The distributed optical clock signal at each fanout end will be coupled into a Si photodetector by an output surface-normal grating coupler.

The building blocks required to necessitate such an optical H-tree system include high performance low-loss polymer-based channel waveguides, waveguide gratings, 1-to-2 3 dB waveguide splitters and curved waveguides. These components allow the formation of a waveguide H-tree for the required optical clock signal distribution, where all the optical paths have the same length to minimize the clock skew problem. The employment of optical channel waveguides and surface-normal waveguide gratings provides a compact, mechanically reliable system. Due to the nature of massive fanouts (48x2) over a large area, the waveguide propagation loss must be minimized while the waveguide grating coupling efficiency has to be maximized. These two factors are very important to ensure enough optical power at the end of photodetectors for high-speed operation. We have employed the highly purified version of the commercially available polyimides in order to fabricate low-loss polymeric waveguides. To improve the waveguide grating coupling efficiency, tilted waveguide gratings are employed to provide the required 1-to-1 surface-normal coupling. Note that a simple 45° waveguide end mirror is not suitable in this case because of the requirement of planarization imposed on the vertical integration of the other electrical interconnection layers [16-17].

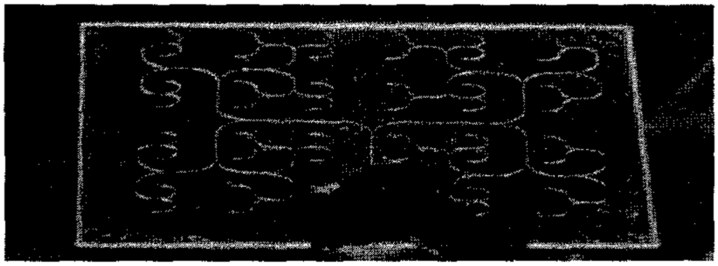

Fig. 2. Photograph of the 1-to-48 fanout H-tree Polyimide-based waveguide on quartz.

While fiber optics technology has successfully implemented among cabinets as replacements for coaxial cable point-to-point link, its application inside a cabinet on the MCM system is severely limited due to the bulkiness of fibers, fiber connectors, and significant labor and cost involved in parallelism of the interconnects. Polymer optical waveguide technology, on the other hand, is particularly suitable for wafer-scale MCM interconnect applications for its large area waveguide formation and potential low costs. It can be viewed as an optical equivalent of electrical printed wiring board technology in which the fabrication cost is independent of the interconnect functionality and complexity. In order to take the advantages of the polymer waveguides, we must be capable of implementing optoelectronic devices such as laser diodes, and photodetectors in the same MCM package. If optical waveguides can be fabricated, integrated, and packaged into the MCM with existing electronic MCM fabrication technologies, the insertion of optical interconnects becomes an acceptable approach to upgrade the microelectronics-based high performance computers.

Both the waveguides and the tilted gratings are polyimide-based to provide the high temperature processing requirement associated with Si CMOS fabrication. The modulation source that converts electrical signals to optical signals is realized using vertical cavity surface emitting lasers (VCSELs) and VCSEL arrays with a modulation bandwidth of 6 GBit/sec. The power budget consideration is also investigated with appropriate light source allocations to meet the bit error rate (BER) requirement.

In order to fabricate the grating coupler by reactive-ion-etching (RIE), a thin aluminum metal mask was deposited on top of the polyimide-based planar guide. The schematic diagram for the fabrication process is shown in Fig. 3. First, a 500-Angstrom aluminum layer was coated on top of the waveguide by electron beam evaporation, followed by a layer of 5206E photoresist with a spin speed of 3000 rpm. The grating patterns on photoresist were recorded by interfering two beams at λ=442 nm (a He-Cd laser line). To record a grating with a period of Λ, the cross angle θ of the two interference beams is determined through the formula of $\sin(\theta/2) = \left(\lambda/\Lambda\right)$. After the sample had been developed, a postbake at 120^{0}C for 30 minutes was followed. To transfer the photoresist grating patterns to aluminum, we used RIE to remove the aluminum in the window region of the photoresist pattern. The gases used were $BCl_3/SiCl_4$ with a pressure of 20 millitorr. To form the tilted grating pattern on the polyimide waveguide, we used a RIE process with a low oxygen pressure of 10 millitorr to transfer the grating pattern on aluminum layer to the polyimide layer. In order to get the tilted profile, a Faraday cage was used. The final step was to remove the aluminum mask by another step of RIE process. Microstructures of the tilted grating having a periodicity varying from 0.5 μm to 3 μm have been fabricated. Fig. 4 shows one of many gratings from a scanning electron microscope (SEM) picture.

A test waveguide sample with a tilted grating as the surface-normal input coupler was built using 632.8 nm as the operating wavelength [18]. The schematic of coupling a surface-normal input light into a waveguide using the device fabricated is shown in Fig. 5(a), together with an experimental photograph in Fig. 5(b).

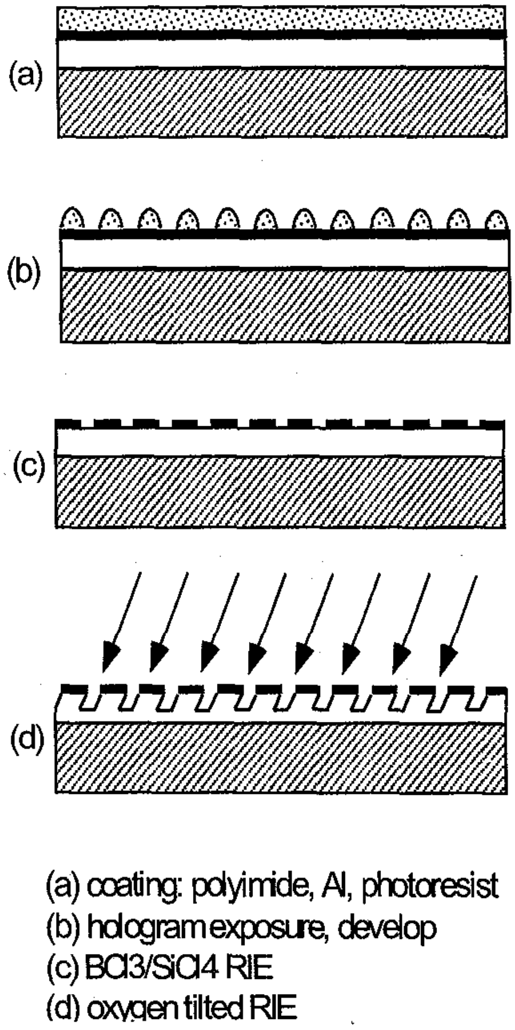

Fig. 3. The schematic diagram for the fabrication of tilted grating on polyimide waveguide.

The grating is designed to surface-normally couple the laser beam into the waveguide with an operating wavelength at 632.8 nm. The coupling to the planar waveguide with the unidirectional propagation can be clearly observed with a measured efficiency of 35%. This is our first device employing the surface-normal waveguide input coupling. Note that the index difference between the guiding layer and the substrate layer is less than 0.03 for the device shown in Fig. 4. Theoretical result shows that the index difference between the guiding and the cladding layers plays an important role in enhancing the coupling efficiency. Further research aimed at providing a larger index difference to increase the coupling efficiency is under investigation.

Fig. 4. SEM picture of a tilted grating which has a tilted angle of 32°. Grating periods from 0.5 μm to 3 μm have been successfully fabricated with an aspect ratio of 1.1.

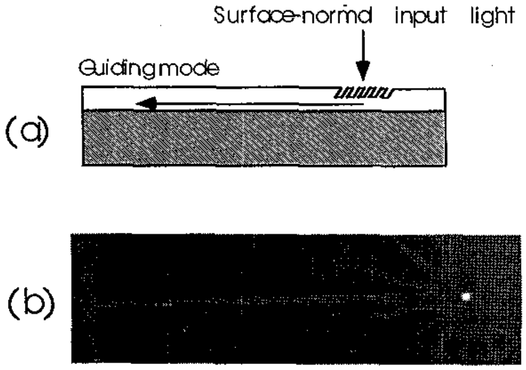

Fig. 5 (a) The schematic of coupling a surface-normal input light into waveguide using the tilted grating. (b) The experimental photograph of coupling a surface-normal input 632.8 nm He-Ne light into the polyimide waveguide.

Because the Cray supercomputer board is 26.67 cm in length, which is beyond the field size of the in-house microlithography, large-area optical waveguides are required to build an optical clock signal distribution layer. To meet the size requirement, a laser beam direct writing was employed to solve the problem. The laser-beam writing system consists of a dualwavelength HeCd laser (λ_1 = 325 nm and λ_2 = 442 nm), beam-shaping optics, an electronic shuttle and a computer-controlled X-Y-Z translation stage.

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http://www.ece.utexas.edu/projects/ece/mrc/groups/optic-inter/

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