A Wafer Scale Optical Bus Interconnection Prototype

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Abstract

Prototypes of a wafer wide optical bus interconnection technology are described. By optically coupling sub-systems on the wafer, faults normally found in electrically based interconnection topologies are avoided. Wire buses are more prone to errors (such as shorts and broken wires) than waveguides due to the nature of the material involved and requirements for connectivity. This is accomplished through the incorporation of a planar cylindrical waveguide which couples emitter/detector pairs. This waveguide supports an omnidirectional emission from an optical diode to all receivers on the wafer. This paper concentrates on the emitter properties of the light emitting diode and its coupling to the waveguide and not on the detector since current technology is adequate for detection. Details of the current prototypes are given along with data on the output of the waveguide. A photograph of the light emitted from the edge of the waveguide along with analysis and waveforms are included. Current work utilizes, but is not limited to, a single wavelength source from a light emitting diode transmitting at 1.4 Gbit/second. The only electrical connection between sub-systems on the wafer is power.

1: Introduction

Mangir and Avizienis have reported that given a set of equivalent components communicating, the overall yield is a product of the component yield times the interconnection yield [1], hence there is clearly a need for high interconnection yield. These same interconnections rear their ugly head when we apply built-in testing techniques to determine component faults at the wafer scale level [2, 3]. Chang and Fuchs recently reported an improved harvest rate at a given yield using a loop based approach to diagnose defects in linear arrays on the wafer but show that the harvest rate drops rapidly with Cneighbor loops when cell yield falls below 0.6 [3].

The need for high bandwidth, reliable communications leads one to optical interconnections. Some reasons for considering optics are: unlike electrons, photons suffer no coupling interactions such as capacitance and inductance, the indications that GaAs systems and wafers in the 100+ MHz range are a reality and that silicon based semiconductors have recently been shown to emit light [4]. A 350,000
transistor gallium arsenide device is expected to be in production by the end of this year [5].

Three basic techniques exist for optically communicating between elements on a semiconductor surface: direct connection with a point-to-point waveguide, free-space unfocused broadcast and finally free-space focused interconnection or imaging interconnections. We will concentrate on a direct connection of one-to-many using an omnidirectional optical emitter and an unfocused planar waveguide on the wafer.

The direct point to point method is efficient but fixes the topology in the same way as bus connections on the wafer. Free-space unfocused broadcast suffers from efficiency losses due to the free-space transmission. In spite of its limitations, at least one experimental computer system has been built using a common free space optical bus [6]. The use of holography as an approach to free-space focused interconnection has been promising but most work has utilized visible light and less is known concerning good holographic optical elements in the near infrared, where high speed optical technology has progressed [7, 8]. Work has also been reported on deformable mirrors as an approach to free-space focused interconnection [9, 10].

The prototype of a wafer scale optical interconnection technology (ORION) will be described. It provides topology insensitive coupling of devices on the wafer. These devices can be at any level of complexity from simple cells to complete RISC processors. Both global and local communications can be supported. In addition to providing communication, it can provide a clock channel and thus a global wafer wide clock with minimum skew (limited only by the speed of light thru the medium). Early work on clock distribution has been published by Dhar, Franklin, Wann, Fried, Clymer and Goodman [11-14]. Keezer and Jain [15] have published a useful survey of clock distribution strategies for WSI.

2: Interconnection Architecture

The complexity of interconnections and routing required to support WSI has been a severe problem and is a direct contributor to the overall system yield [1]. We have seen many compromises in interconnection structures on the wafer but most fail because of the error prone nature of the interconnection medium. Global wire buses with close etches tend to be easy targets for shorts and open connections. As an example of the seriousness of the problem, it was recently reported that an examination of 34 of the WASP 2A global buses showed that 28 were defect free, while 6 contained fatal defects [16]. The fine grain nature of the wire bus structure disappears when a waveguide is used in its place and much greater yields and reliability are achieved. ORION can be considered to provide a wafer-wide optical bus as a system interconnection resource. Extensions of the concept lead to multiple independent concurrent communicating regions on the wafer. This latter structure allows both local and global traffic to be accommodated optically. Prototypes have been build with a 1.4 Gbit optical source and a 0.3 micron thick SiN/SiO$_2$ waveguide and a 5 micron thick F:SiO$_2$/SiO$_2$ waveguide.

2.1: Wafer waveguide architecture

The communications architecture consists of a silicon or gallium arsenide wafer of diameter $W$ containing a cylindrical waveguide of diameter $D$ and height $H$ grown on top of the semiconductor material containing the electrical and electro-optic elements
as shown in Figure 1. The diameter of the waveguide D, is assumed to be equal to or very slightly less than W, while the height H, is less than three microns. The omni-directional optical transmitter consists of an emitter which generates an optical wavefront of equal energy in all directions of a plane created at the wafer surface (strictly speaking, within the waveguide). Even though the waveguide is a three dimensional object, it is considered to be a 2-D waveguide since light is confined in one dimension. Since light travels only 15 cm on a 6 inch wafer, dispersion, which is in the range of 10 to 50 nsec/km will be negligible. Light emitted from the omni-directional transmitter is coupled into the waveguide and the propagation follows a pattern of concentric rings as shown in Figure 2.

When a diode transmits its optical output into the waveguide, the signal is detectable anywhere on the wafer surface. This allows considerable flexibility in placement of architectural components on the wafer. The waveguide contains an optical terminator placed at its circumference to prevent reflections from interfering with the primary transmission. The terminator can be designed to either reflect the optical energy up and out of the waveguide or down and into the silicon substrate (highly doped). This combination of diode and waveguide, in effect, creates an optical bus which connects the transmitting diode with all detectors on the wafer. If the choice of optical termination was to reflect up and off the waveguide, an external detector would make an effective bus monitor.

The next issue is that of injection of the optical energy into the waveguide and the drive connections to the diode. By using an inverted mesa emitter, shown in Figures 3a and 3b, the diode couples its energy directly into the waveguide by what is called "end-fire" coupling. This type of coupling minimizes the losses and maximizes the optic energy output into the waveguide. Since the top electrical contact of the diode is in common to all others, they can be connected via metalization (or "wired" connections) on top of the waveguide and the drive circuit and current source can then be below the waveguide on silicon where the electronic components reside.

With this type of design each diode may cast a shadow when another diode is emitting. This places some restrictions on the topological placement of emitters and detectors, that is, all detectors must be in line-of-sight of all emitters. Even with this restriction, placement of small numbers of emitter/detector pairs on the wafer is not a problem. In Figure 4a, we see the placement of eight nodes (emitter/detector pairs) on a wafer such that all nodes are in line-of-sight of the emitter. In Figure 4b is shown an example of eight equal area square circuit regions with one emitter/detector pair each. In Figure 4c is shown an example with more efficient silicon usage. In this latter case circuit elements are of one of two types but the basic area of each are the same.

This line-of-sight restriction is only temporary since the next generation of emitters are expected to inject their optical signal into the waveguide via a recessed emitter as shown in Figure 5b. Now, since most of the emitter lies below the waveguide, the line-of-sight restriction disappears as the wavefront will continue to propagate beyond that intermediate emitter/detector pair. The optical signal is still injected into the waveguide directly as before but since the active region is less than 3 microns from the top of the diode, it should not obscure the transmission from another source, see Figure 5a. This type of injection will be called "recessed coupling". When the number of emitter/detector pairs are small, "end-fire" coupling is simpler while for large numbers of pairs "recessed" coupling should be employed.
2.2: Yield Considerations

One of the consequences of the non-directed optical interconnect structure is that components may fail without concern for the topology of their failure. This is, of course, because "optically connected" have power as the only electrical connection and the optics are omnidirectional within a region (where the region could be wafer-wide).

Swartzlander has recently reported on the use of pooled spares for fault circumvention at the macrocell level [17]. He developed yield formulas which included the number of spares along with the interconnection yield and macrocell yield. He showed how the total wafer yield could be substantially improved as a function of the pooling. He points out that this approach is only desirable when the interconnection yield is much greater than the macrocell yield. He further points out that in a Radix-2 butterfly function implementation, a four from six sparing for the multipliers and six from nine sparing for the adders gave a predicted total yield of 0.51. As he indicates, this low yield was due to a total interconnection yield of 0.58 and if the individual interconnection yield were 0.99 (instead of 0.97) the total yield would have been 0.76 (instead of 0.51). He concludes with: "The example demonstrates the advantage of m from n pooled sparing of macrocells if the interconnect yield can be keep high."

Since the inherent nature of the waveguide material is more reliable than long runs of multiple closely spaced wires, we should be able to achieve his objective with this optical technology. His butterfly example could have been implemented by creating two independently communicating regions bounded by an optical terminator, one containing the six multipliers and the other containing the nine adders.

2.3: External Connections

In all cases discussed above, the only electrical connections to the wafer system would be power. All external I/O including wafer to wafer traffic can be routed on and off the wafer through optical fiber connections. Load balancing can be accomplished by appropriate mixing of I/O requirements to processing elements with optical connection to the necessary wafers. For example, in a light I/O environment, all I/O connections may go to a single wafer for processing, while in a heavy I/O environment, I/O connections may be distributed to all wafers. The placement of I/O connections in general is an architectural decision, not a function of the optical connections.

3: The Prototypes

The emitter currently being utilized is an optically-coupled mirror-quantum well InGaAs-GaAs light emitting diode (LED). The intensity of these light-emitting diodes peaks near 1.0 μm. It has been shown that with a 410 angstrom spacing between the quantum well and the mirror on the surface a 3 dB roll-off frequency of 1.4 GHz was obtained [18]. These light emitting diodes have a mesa type structure with a diameter in the range of 20 to 100 microns. Two actual prototypes have been constructed, one with a 0.3 micron (3000 Å) high SiNx confinement layer (optical waveguide layer for confining emission) and another with a 5 micron (50000 Å) phosphorous doped SiO2 (P:SiO2) confinement layer.
The 0.3 μm-thick waveguide was formed by first depositing a 2.5 μm-thick cladding layer of SiO\textsubscript{2} on the Si substrate followed by the SiN\textsubscript{x} confinement layer (3000 Å). The 5 μm-thick thick waveguide was formed by first producing a 15 μm-thick cladding layer of HIPOX SiO\textsubscript{2} on the Si substrate followed by the deposition of a 5 μm-thick phosphorous dopped SiO\textsubscript{2} (P:SiO\textsubscript{2}) confinement layer. The attenuation of both of these waveguides has been determined to be less than 0.5 dB/cm. Each prototype consisted of a waveguide which was approximately 1 cm square on silicon as described above.

The work has concentrated on the development of prototypes which test the coupling to the waveguide, even dispersion in the waveguide and the quality of the signal waveform resulting from an "end-fire" coupling and transmission thru a planar waveguide. To test the coupling, the prototypes are constructed such that the emitting edge of the diode is vertically aligned with the guided layer and placed at one end of the waveguide. The optical output is then measured and recorded as it emerges from the opposite edge of the planar waveguide, thus allowing a measurement of the coupling and transmission characteristics.

Figure 6 contains a photograph of the actual optical output from the edge of the 0.3 micron waveguide as obtained with a Spiricon Laser Beam Analyzer. It displays the energy output emitted from the edge of the waveguide (opposite side of the waveguide from the LED). If one looks at the intensity (pixel display) pattern it can be seen that the output corresponds to the waveguide edge in the vertical direction. In this display the light pixels correspond to higher optical energy. The plot just to the left of the pixel display (Y axis) provides an average intensity profile in the vertical direction and it can be seen that all of the energy is emitted at the waveguide edge corresponding to the single peak on the vertical axis. The plot at the base of the pixel display shows the intensity variation along the waveguide edge (approximately 0.5 cm). As can be seen, there are two peaks and an area to the right which is not emitting. One would hope for a flat output on this axis indicating that there was an even dispersal of light all along the edge of the waveguide. As it turns out there are "hot" spots and voids in this 0.3 micron waveguide. The problem was that it is difficult to couple the emitter to the thin waveguide, but it did couple and provide a confinement on the top and bottom of the waveguide.

Figure 7 shows the optical output for the 5 micron waveguide. In this case it can be seen that there are no "hot" spots and a flat optical output is observed along the edge of the waveguide (X axis). Figure 8 shows the actual infrared output through a vidicon camera. The intensity of the output of this waveguide is higher than that of the 0.3 micron waveguide confirming a better coupling efficiency. This waveguide, hence, showed improvement in both coupling and lack of "hot" spots.

The pulse response of the 5 micron waveguide was then measured using a 1 KHz 50ns wide pulse source which has a rise time of 9.4 ns. Figure 9 shows a dual trace of the drive pulse (lower trace) and the detector output (upper trace), both with 20ns/div horizontal timebases. The detector was a silicon PIN photodiode and the detector output is displayed directly. The fall time was identical to the fall of the LED drive from the pulse source. The rise was initially identical but then decreased slightly. The main objective was to determine if "clean" waveforms were obtained with reasonable rise and fall times and that has been accomplished. Also the signal to noise margins were quite acceptable.
4: Conclusions

A prototype of the planar waveguide and emitter has been fabricated and has demonstrated the concept of omnidirectional unfocused communication on a planar waveguide. Photographs of the optical output at the edge of both the 0.3 and 5 micron waveguide shows that light was emitted all along the waveguide thus creating a two dimensional optical bus. The 5 micron waveguide provided improved coupling and quite flat output along the edge as compared to the 0.3 micron device. The signal response characteristics were acceptable in terms of both rise/fall times and signal quality. Subsequent work will provide more qualitative information on power distribution and signal to noise ratios. The diode used for signal measurement can be improved, without much effort, to provide even better response and optical efficiency.

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References:


Figure 1. Water waveguide

Figure 2. Omni-Directional Propagation on water
Top View of Waveguide

Figure 3a. End-fire inverted mesa emitter

Figure 3b. In-line waveguide
Figure 4. Emitter/detector placement:
(a) Eight node placement
(b) Eight equal area and geometry circuits
(c) Eight more efficiently allocated circuits

Figure 5a. Reformed Emitter with Waveguide

Figure 5b. Reformed Emitter

Figure 6. Optical output map from 0.3 micron waveguide