Unidirectional surface-normal waveguide grating couplers for wafer-scale MCM interconnect

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Abstract

We report the fabrication of tilted gratings on polyimide waveguides. The reported gratings provide an effective unidirectional surface-normal optical couple-in and couple-out for polymer-based optoelectronic interconnects. Such a planarized grating is particularly suitable for wafer-scale MCM optoelectronic interconnects due to its unique non-blocking fanout feature. Both surface-normal input and output grating couplers have been demonstrated for the first time on polyimide waveguides on silicon substrate.

Keyword: waveguide grating coupler, optical interconnect, MCM interconnect

2. Introduction

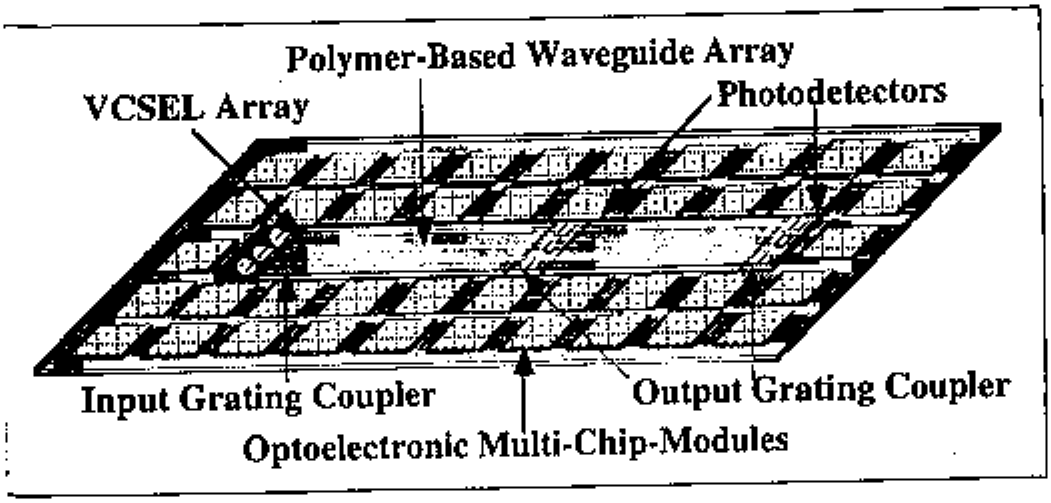
The speed and complexity of integrated circuits are increased rapidly as integrated circuit technology advances from very large scale integrated (VLSI) circuits to ultra large scale integrated (ULSI) circuits. As the number of components per chip, the number of chips per board, the modulation speed and the degree of integration continues 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, as cycle time and pulse widths generated by silicon VLSI circuit shrink, the bandwidth needed to preserve the rising and falling edges of the signals increases, the state-of-the-art technologies based on electrical interconnects fail to provide the required clock speed and communication distance in intra-MCM and inter-MCM hierarchies.

Implementation of optoelectronic elements to provide high speed, large fanout interconnects has already been a major thrust for many high performance systems where electrical interconnects failed to provide the bandwidth requirement. Employment of optoelectronic devices and components has become a necessity in high speed (200 MHz), wafer-scale interconnections. To make optical interconnects acceptable to microelectronics industry, it is pivotal to make the insertion of optics compatible with silicon CMOS fabrication process such that technology improvement and cost effectiveness are coupled together. Unlike the electrical interconnect network, the fabrication cost of an optoelectronic interconnect network is independent of the interconnect functionality and complexity. Polymer-based optical waveguide technology, is particularly suitable for wafer-scale MCM interconnect applications for its high density and potential low cost. If optical waveguide can be fabricated, integrated, and packaged into the MCM with existing electrical MCM fabrication technologies, further economies can be introduced by implementing optical interconnect within established electronic capital infrastructure.

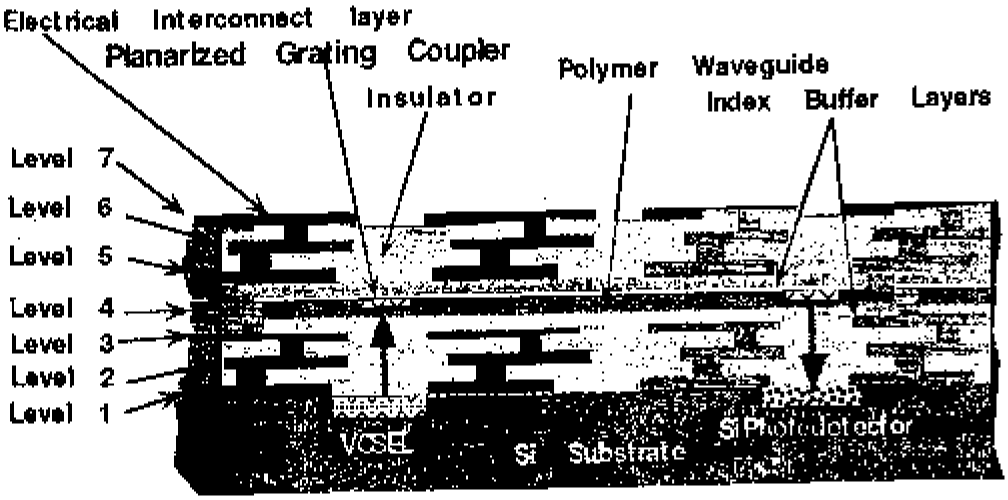
There are two major problems that impeded the progress of the insertion of optoelectronic components. The first problem is the requirement of planarization for silicon CMOS VLSI circuit due to the necessity of existing three-dimensional (3D) integrated on-chip electrical interconnects. The second problem is the requirement of the non-blocking communication among many modules. Currently, based on the state-of-the-art optical waveguide technology, insertion of optical interconnects for module-to-module connections is realized by using 45° total internal reflection mirrors in conjunction with vertical cavity surface emitting lasers (VCSELs) and high-speed photodetectors. Such a non-planarized coupling configuration is contradictory to the existing 3D electrical interconnects that are fabricated through microlithography. The depth of the 45° mirror is in the order of 25 μm that is well-above the depth of focus of any submicron microlithographic machines. As a result, there is no interconnection layer can be added after the optical waveguide layer involving the non-planarized 45° mirror coupler. Further more, due to the transmission blocking nature of the 45° total internal reflection mirror, only point-to-point optical interconnection can be constructed. This severely limits its applications for high density MCM interconnections.

3. Optoelectronic Interconnect for MCMs

In this paper, we report our efforts to fabricate non-blocking optoelectronic interconnects for wafer-scale MCMs based on polymer-based waveguides and unidirectional surface-normal waveguide grating couplers involving VCSELs and high-speed silicon photodetectors. Fig.1(a) shows the schematic diagram of the optoelectronic interconnect presented, together with its cross section in Fig.1(b). An planarized optical interconnection layer is inserted between the conventional VLSI electrical interconnects. There are four building blocks that are essential to this approach. The first is the formation of high performance polymeric waveguides on silicon wafer where MCMs are fabricated. The second is the formation of planarized waveguide grating couplers to interface the VCSELs to waveguides, and the waveguides to photodetectors. The third is the fabrication of high-speed photodetectors on silicon wafer together with MCMs. The final one is the integration of VCSELs to MCMs fabricated on silicon wafer, which currently is fabricated on GaAs substrate. The key to success is to be able to accomplish these building blocks in a cost effective and manufacturable fashion based on technologies that are compatible to established electrical industry.



(a)



(b)

Fig. 1. (a) Schematic of an optoelectronic interconnection link for wafer-scale MCMs using polymer-based waveguides. (b) Cross section of the proposed optical vias for 3D optoelectronic interconnects that will be compatible with Si CMOS fabrication

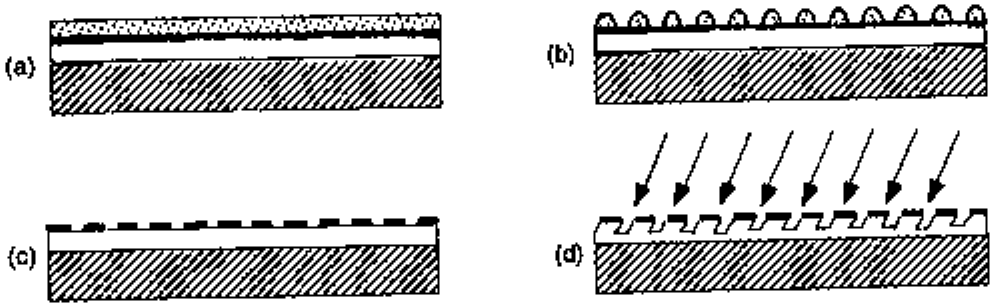
As shown in Fig.1, the electrical signals are converted into optical signals by an array of VCSELs, provided by Honeywell and MCC. Compared to conventional edge emitting laser diodes, VCSELs offer very low threshold current (1~3 mA) with much less temperature sensitivity, moderate optical power (a few mW or more), very high direct modulation bandwidth (> 14 GHz), and wide operating temperature range (-55 to +125 °C). More importantly, the unique surface normal output feature allow a convenient face-to-face coupling and packaging to in-plane optical waveguides using waveguide grating couplers, which is exactly same coupling and packaging scheme for coupling light from waveguide to photodetectors. The surface-normal feature of the grating coupler provide an effective coupling to the photodetectors. As shown in Fig.1, the converted optical signals from a VCSEL array are launched into the polymer-based waveguide bus array through a surface-normal waveguide grating coupler. Compared with the 45-degree end facet, the surface-normal waveguide grating is process-compatible to current VLSI technologies, having a planarized feature highly desired for the integration of multiple interconnection layers. More importantly, it allows multi-stage communication due to the non-blocking feature of grating (see Fig.1). The optical signal can be delivered over a long distance (~45 cm) and finally coupled out of the waveguide into a desired photodetector [3].

4. Fabrication of tilted gratings

For the optoelectronic interconnect network presented, the planarized grating coupler is the most crucial element that has been thoroughly investigated. There are a large number of publications in grating design and fabrications[4,5]. However, the surface-normal coupling scenario in optical waveguides has not been carefully investigated so far. In order to improve the coupling efficiency, a tilted grating profile in a planarized structure within a thin waveguide layer has been investigated. The tilted angle of the grating corrugation creates the vertical component of the required grating **K** vector, to provide the required phase-matching condition. These tilted gratings under investigation are fabricated by the well-established planar microfabrication processes, such as photo and holographic lithographies. They are mass-producible with excellent accuracy and reproducibility. In order to verify the presented concept, tilted waveguide gratings was fabricated and tested using optical polyimide waveguides.

The polyimide waveguide was first fabricated on silicon substrate by spin-coating. An A600 primer layer was spin-coated first on the substrate with a spin speed of 5000 rpm, and prebaked at 90 ^{0}C for 60 seconds. The Amoco polyimide 9020D cladding layer was then spin-coated on Si substrate, followed by a 9120D core layer. A final curing at 260 ^{0}C in nitrogen atmosphere was carried out for more than three hours. Typical thickness of the waveguide was 7 μm. The channel waveguide has also been successfully fabricated on Si substrate by photolithography patterning.

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.2. First, a 500 Angstroms aluminum layer was coated on top of the waveguide by electron beam evaporation deposition, followed by a layer of 5206E photoresist with spin speed of 3000 rpm. The grating patterns on photoresist was recorded by interfering two beam of the λ=442 nm He-Cd laser line. In order 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 has 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 etch the aluminum in the opening window of the photoresist pattern. The gases used were $BCl_3/SiCl_4$ with a pressure of 20 millitorr. However, it was found that there were still some photoresist residuals in the grating groove which could block the aluminum RIE process. In order to clean these residuals, an additional step of RIE etching using oxygen was applied before removing the Al layer. 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[6] was used. The sample inside the cage was placed at a tilted angle of 40 degrees with respect to the incoming oxygen ions. The final step was to remove the aluminum mask by another step of RIE process.



(a) coating: polyimide, Al, photoresist
(b) hologram exposure, develop
(c) BCl3/SiCl4 RIE
(d) oxygen tilted RIE

Fig. 2. The schematic diagram for the fabrication of tilted grating on polyimide waveguide.

5. Experimental results

The microstructure of the tilted grating is shown in Fig.3 from a scanning electron microscope (SEM) picture. The grating period can be tuned from 0.6 micron to 4 micron by changing the hologram recording angle. The schematic of coupling a surface-normal input light into waveguide using the device fabricated is shown in Fig.4(a), together with an experimental photograph in Fig.4(b). In Fig.4(b), the grating is designed to surface-normally couple the laser beam into the waveguide with an operating wavelength at 1.3 μm. The coupling to the planar waveguide with the unidirectional propagation can be clearly observed with a measured efficiency of 5%. This is our first device which realized the surface-normal waveguide input coupling.

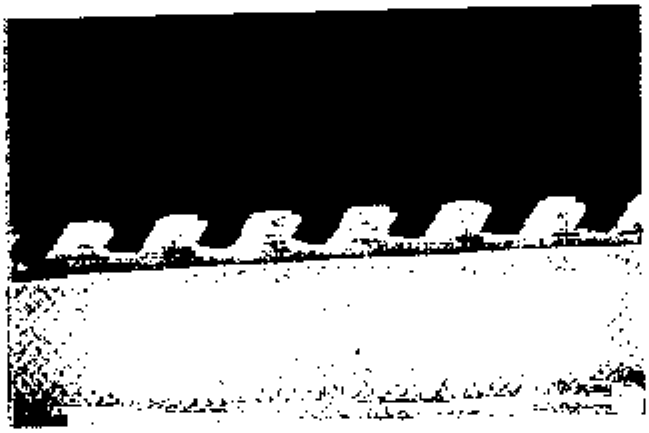


Fig. 3. SEM picture of the 4 micron period tilted grating.

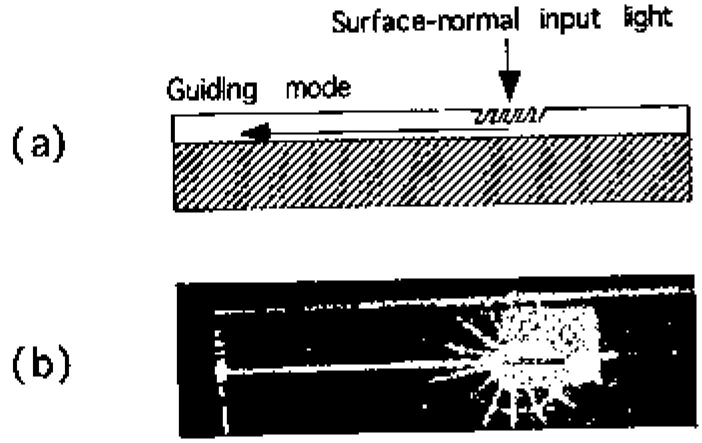


Fig.4 (a) The schematic of coupling a surface-normal input light into waveguide using the tilted grating. (b) The experimental photograph of coupling a surface-normal input light into the polyimide waveguide.

Fig.5 Photograph of surface normal output coupling

The demonstration of surface-normal output coupling is shown in Fig.5. The 1.3 micron laser light was coupled into the guided mode by prism input coupling and coupled out of the waveguide by grating. The length of output coupling grating is 3 mm. From the surface scattering light intensity of the guiding path, we can see that most part of the light was coupled out by the grating. It is desirable that this output coupling length is as short as the order of 50 microns, because high speed transmission requires a small size photodetector. We are working right now to increase the coupling efficiency. From the theoretical calculation, it is found that the waveguide parameters, such as the difference of the refractive index between the core and cladding layer, and the grating depth are critical to the coupling efficiency. For input coupling, not only the grating phase-matching, but also the mode profile matching are important. The input laser beam profile needs to be considered.

6. Conclusion

In conclusion, we have successfully fabricated the tilted grating for unidirectional surface-normal waveguide grating couplers in polyimide waveguides. The demonstrated waveguide grating coupler is particularly suitable for wafer-scale MCM optoelectronic interconnections. Both input and output grating couplers have been experimentally demonstrated. Compared with the 45 degree mirror coupling, grating input and output couplers are more desirable because of the possibility to realize 1-to-many fanouts in the MCM interconnect applications.

7. References

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