Fiber Optic Coupler for VHSIC/VLSI Interconnects

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Abstract - A new optical interconnect technique, suitable for very high packing densities, is proposed for implementation in VHSIC/VLSI circuits. The approach allows vertical bonding.

Introduction

The performance of VHSIC/VLSI circuits is impaired by limitations in the communication capacity between gates, chip and boards [1]. Fiber optic interconnects are widely recognized as a potential solution to this communication problem [2-7]. However, no satisfactory means exists of coupling a fiber to a detector on a VLSI chip. We demonstrate a new optical interconnection technique which, relative to previous methods, offers several advantages such as very high packing density, accurate alignment, and mechanically stable coupling.

The advantages of optical over electronic interconnections include increased transmission bandwidth, immunity to mutual interference, freedom from capacitive loading, and freedom from planar constraints [5]. Optical interconnections also have the potential for reconfigurable switching and optically controlled electronic logic [3].

A significant limitation of electronic interconnection is known as the "pinout" problem. According to Rent's rule, a circuit with 100,000 gates requires 2,000 interconnection [3]. However, the perimeter of a typical 10 mm by 10 mm chip provides space for at most 300 pins, a gross undersupply [2]. Stated differently, the minimum allowed pin spacing to avoid signal corss coupling is approximately 100 µm, wheras Rent's rule implies a required maximum spacing of 20 µm [3]. Therefore, if optical interconnections are to solve the present electrical pinout problem, a connection spacing of less than 20 µm must be achieved.

Using standard fiber coupling techniques such as silicon V-groove or butt-coupling, it would be difficult to achieve a 20 µm interconnection spacing, since the cladding diameter of typical optical fibers is greater than 100 µm. Also butt-coupling may be mechanically unstable, provide poor alignment, and is not suited for high packing densities. V-groove coupling is not easily aligned with a detector array on a chip, and there are problems associated with multigroove splicing [8]. The disadvantages of butt-coupling and V-groove coupling would be accentuated by attempting to use smaller diameter fibers.

The proposed optical interconnect technique has the potential to solve the "pinout" problem by reducing the interconnect spacing nearly to the size of a single mode waveguide. The basic idea [see Fig. 1] is to etch a cylindrical hole, slightly larger than a single-mode optical fiber core, into a semiconductor wafer. A p-n junction, which serves as a detector is then formed on the inside of the hole. A single mode fiber core (or a tapered multimode fiber) is inserted into the hole and affixed using epoxy. Light emanating from the fiber is collected by the reverse biased p-n junction and converted into an electrical signal. This signal is utilized by the circuitry on the surface of the wafer. An additional advantage of this technique is that interconnects are not confined to the perimeter of the chip, but can be located at any point on the surface of the chip.

In section 2, the fabrication processes is described. In section 3, measurements of the perforamnce are reported. In section 4, the results are discussed.

Fabrication Process

The seat for the optical fiber is fabricated by using laser assisted etching of deep high aspect wells in the silicon substrate. The technique, which has been described elsewhere [9], consists of using the 257 nm light from a frequency-doubled Argon ion laser to accomplish low temperature light-assisted etching in a 5% aqueous solution of HF. In this process, the hole diameter is controlled to first order by the diameter of the nearly focused beam at the surface of the substrate. A limited variation about this diameter can be effected by changing the beam power. Wells as narrow as 4 μm have been made in the course of this project. Figure 2 shows the resulting cross-section of a typical etched fiber well. Note that the side walls of the etch are nearly vertical. This is a result of light guiding during the etching process. In general, the well walls are smooth and nearly circular. This insures good mechanical and optical coupling to the silicon substrate.

Following the etching of the well the detector is made using standard semiconductor device fabrication techniques. The well was doped using a spin-on dopant film followed by a high temperature drive-in. Although the formation of a p-n junction is evident from the detector's current-voltage characteristics, the details of junction formation in the cavity are still under investigation. For metalization, aluminum was thermally evaporated and then delineated using a wet etch. Backside aluminum was also deposited.

An optical fiber is then tapered and inserted into the detector cavity. A Corning dBF graded index fiber, with 85 μm core diameter and 125 μm cladding diameter is used for the optical interconnection. At $\lambda = 0.633$ μm, the cladding index of refraction is $n_c = 1.457$ and the core center index of refraction is $n_o = 1.486$, corresponding to a numerical aperature of 0.26. The attenuation is 4dB/km at $\lambda = 0.850$ μm. The fiber is suspended vertically (with a weight of a few grams on its end) and passed briefly through a 2000 volt electric discharge arc, causing the fiber to melt and stretch uniformly. The tip of the stretched fiber is examined under a Vanox optical microscope at 1000 x magnification and an outer cladding diameter of 5 um is recorded. Since the ratio of core to cladding diameters is maintained after stretching the fiber, the final core diameter is 3.4 μm. The main tapered section of the fiber is shown in Figure 3.

In order to facilitate mechanical insertion of the tapered fiber into the detector cavity the fiber is first pulled through a glass capillary tube until only the tip protrudes. The capillary tube is then mounted on a machined metal holder, which in turn is connected to a Rucker and Kolls micromanipulator at an adjustable tile angle to facilitate the fiber insertion. The Si chip containing the detector cavity is mounted beneath the 8X microscope objective, on the x-y stage of the Rucker and Kolls probe station. While viewing through the zoom microscope, the portion of the fiber tip is manipulated manually and inserted into the detector cavity.

Experimental results

The perfromance of the completed optical interconnect is measured by injecting light into the fiber and measuring the photocurrent generated on the Si chip. The light from a 7 mW cw HeNe laser, operating at $\lambda = 0.63$ um, is focused on the cleaved untapered fiber end using a 5 x microscope objective rated at a numerical aperature of 0.13. The output from the tapered fiber end was measured to be 2.4 μW, using a NRC Model 815 Si photodetector. After insertion of the tapered fiber end into the hole, using a curve tracer, the IV characteristics of the photodiode was measured. The IV characteristic is shown in Figure 4, under the conditions of no illumination (upper curve) and illumination from the tapered fiber end (lower curve). The downward shift of the IV vharacteristic under illumination corresponds to a photon-generated current of 100 nA for an optical power of 2.4 μW inside the hole. The responsivity of the photodiode (in the hole) is therefore 0.04 A/W.

Discussion

The power loss between the laser and the fiber output is attributed largely to improper alignment of the laser with the fiber. In subsequent measurement, 1.33 mW is coupled from the 7 mW laser source into the fiber and an output power of 1.18 mW is recorded at the tapered fiber output.

Though the tapered fiber was a convenient method to match the fiber to the hole size in this initial demonstration, theoretically less loss is anticipated using a single-mode fiber with the core diameter constant [10]. It will also be desirable to etch the single-mode fiber cladding to a small diameter in order to provide high packing density. Thus, in the future, the well will be etched slightly larger in diameter than a single mode fiber core (approximately 9 μm). The minimum thickness cladding (perhaps 1-2 μm) needed for isolation will surround the core, bringing the total diameter of the coupler to about 12 μm.

The net responsivity measured of the detector is 41 mA/W, corresponding to a quantum efficiency of approximately 7.5%. Such efficiency is reasonable for non-optimized p-n junction diode. With improvements in processing techniques for detector fabrication and single-mode fiber etching, it is expected that higher efficiency will be obtained. Though the technique described here has been experimentally tested with Si circuits, the same technique can be applied to the ultra-high speed circuitry made possible by using GaAs.

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Since the completion of this report more efficient means for modifying and inserting a single-mode fiber into the detector cavity have been tried. The results showing improved light coupling efficiency at the detector and higher responsivity will be published in the February issue of Optics Letters

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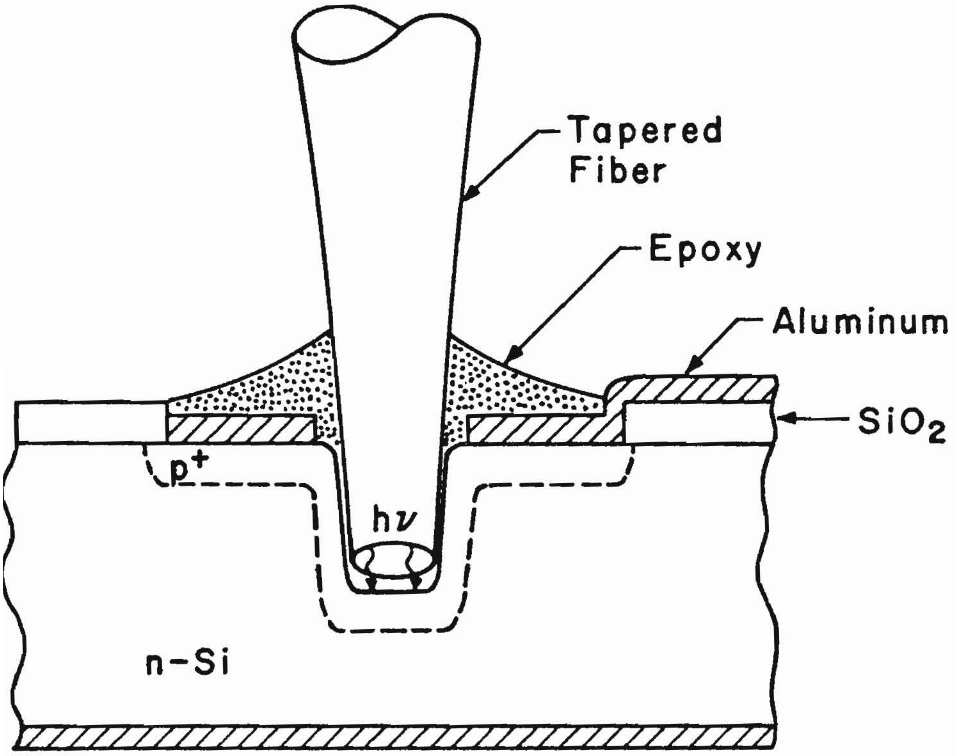

Fig. 1. Schematic cross-section of prototype integrated fiber optic coupler (IFOC) device.

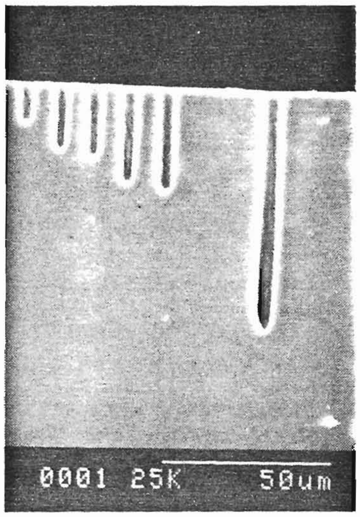

Fig. 2. Cross-section of holes etched in silicon by a laser-assisted photochemical process. Holes are variable in depth and 12 µm in diameter illustrating viable high-aspect-ratio hole etching technology. (Etching and cleaving: P.V. Podlesnik, SEM photo: S. Todorov).

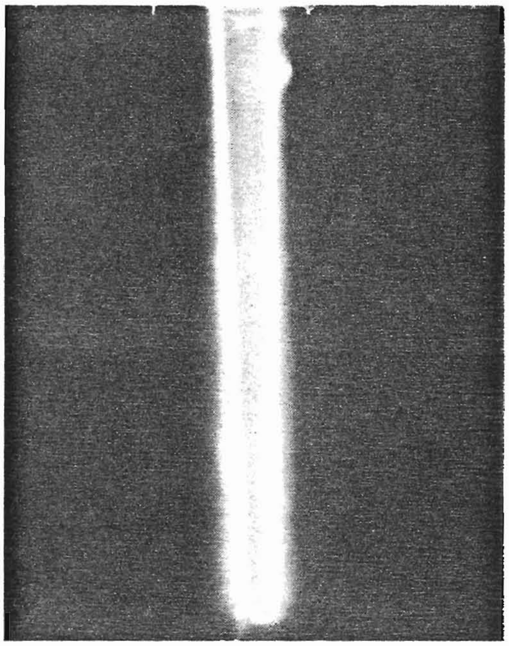

Fig. 3. Tapered fiber at X1000 magnification.

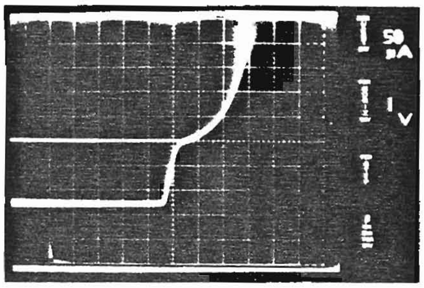

Fig. 4. Dark and illuminated I-V characteristic of prototype IFOC device.