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DIRECT CONNECTION OF OPTICAL FIBERS TO INTEGRATED CIRCUITS

BY

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Introduction

Conventional metallic conductors carrying electronic signals between integrated circuits are susceptible to electromagnetic coupling which can result in parasitic capacitance, inductance, and noise pick-up. Consequently, overall system performance suffers, especially at high bit rates. Signals transmitted photonically are immune to these effects, which accounts for much of the current interest in optical interconnections.

Ideally, one would like to interconnect integrated circuits with optical fibers instead of metallic wires. These circuits could be located on the same chip, on the same circuit board, or on different boards; they could also be physically separated by a significant distance. Several technological hurdles must be overcome in order to achieve this goal. For example, a suitable means must be found to directly connect an optical fiber to an integrated circuit in a manner analogous to wire bonding or solder-bump technology. It must feature a small real-estate footprint, be assembled reliably, and be mechanically stable. This paper describes a new technique which satisfies these requirements.

The Integrated Fiber-Optic Coupler Concept

For directly coupling optical fibers to integrated circuits, an integrated fiber-optic coupler (IFOC) concept has been developed.[1,2] In the IFOC, a cavity is formed in the integrated circuit, and a photon detector or emitter is fabricated at the bottom of the cavity. An optical fiber is inserted into the cavity and, in a receiver structure, the light emanating from the fiber generates a photocurrent in the detector. In an optical source structure, light emitted by the transmitter is launched into the fiber. For front-side connections, the detector/emitter must be electrically connected from the bottom of the cavity to the front-side circuitry. For back-side connections, the cavity extends to just below the front surface on which the detector/emitter structure is fabricated. This is illustrated in Fig. 1. If the emitter were an LED and the cavity much larger in diameter, the structure would resemble a Burrus-type LED.[3]

The IFOC concept satisfies the requirements for the direct connection of optical fibers described above. The cavity approach insures accurate and reproducible alignment between the optical fiber and the detector/emitter, and also serves to mechanically stabilize the connection against vibration or shock. The vertical nature of the interconnect also implies the smallest possible real-estate footprint for the connection. In fact, since the cavity diameter need only be as large as the optical fiber cladding (or smaller for front-side connections), the projected footprint of the optical fiber jacket can be used for front-end signal processing circuitry including amplification and thresholding.

Prototype IFOC Device Fabrication

In order to demonstrate the IFOC concept, a prototype front-side silicon detector IFOC was fabricated and characterized. A cross-section of the device is shown in Fig 2. Fabrication of the device consists of two major stages: the formation of the detector, and the preparation of the optical fiber. In the first stage, a 10 ohm-cm, n-type, (100) silicon wafer is cleaned and oxidized in steam at 900°C. Windows are opened in the oxide and the cavities are etched. For this device, a non-thermal laser-assisted wet etching process[4] was used. A 10 W/cm^2 257 nm UV beam is focused onto the silicon substrate at the site of a previously opened window, which is covered by a drop of dilute (10 %) HF. Chemical etching of the silicon is stimulated by the photon beam and an anisotropic cavity 25 um deep and 15 um in diameter is formed after a 20 min. exposure. Deeper cavities can be etched by increasing the laser power or increasing the exposure time, and the diameter of the cavity can be controlled by the laser spot size. Other techniques can be used to form the cavity, such as reactive ion etching, but the laser-assisted process is a gentle one and does not damage the substrate, thus yielding low dark current, high mobility devices.

After etching, the oxide is stripped and a new oxide is grown in steam. Diffusion windows centered on the cavities are opened, and a boron-containing spin-on dopant is applied to the surface. Impurity drive-in is performed for 110 minutes at approximately 1000°C in a 95% N_2/ 5% O_2 gas ambient. Reproducible and consistent results have been obtained with this technique. A contact window is opened to the diffusion and 3000 A of aluminum is thermally evaporated. The metal is then patterned photolithographically with a wet etch. Removal of aluminum deposited in the cavity has not been a problem. A backside aluminum contact is evaporated and the device is annealed for 12 min. in forming gas at 400°C.

As described above, the fabrication of the IFOC cavity and detector is compatible with normal integrated circuit processing. We have recently fabricated a charge-coupled device test chip configured to accept both electronic and optical fiber inputs. Ongoing tests indicate that the inclusion of IFOC sites has no detrimental effect on adjacent circuitry.

The second stage of fabrication begins with the preparation of the optical fiber. The tip of a single-mode Corning fiber with a core diameter of 9 um and a cladding outer diameter of 125 um is tapered to approximately 12 um in a continuously stirred solution of HF buffered with ammonium fluoride. This technique results in a conically tapered profile with a half angle of 12-15 degrees.

The fiber is inserted into the IFOC cavity using a dedicated work station, which is shown schematically in Fig. 3. The insertion station consists of a mount for the microcircuit package, an X-Y-Z translational stage with a vacuum chuck fitting to hold the optical fiber, and an Olympus SZH microscope which gives reasonable magnification while maintaining a long focal length for maximum working distance. Electrical connection is made to the photodiode through the mounting box, and live photocurrent monitoring supplements visual observation in the determination of the best final resting postion for the fiber. Figure 4 shows two photographs taken through the microscope during the insertion process. Following insertion, the fiber tip remains in place despite small movements of the vacuum chuck, indicating the lateral alignment stability provided by the cavity approach.

To prevent stress on the taper, a UV-cured adhesive is used to bond the fiber to the edge of a glass slide affixed to the top of the microcircuit package, in this case a standard 16 pin DIP. No adhesive is needed at the surface of the chip, as in other fiber- optic coupler designs[3,5,6] because the cavity itself prevents lateral misalignment. Other techniques in which the fiber is vertically stabilized above the surface of the integrated circuit might also be considered. For example, an array of holes etched in a silicon wafer could be used to guide an array of fibers to an array of IFOC cavities. Such a "spaghetti extruder" would then be mounted as a lid on the circuit package. This is shown conceptually in Fig. 5.

Prototype IFOC Device Characterization

Electrical characterization of the photodetectors included measurement of series resistance, capacitance, and dark current, both before and after device packaging. The sheet resistance of diffused areas was 25 ohms/square, leading to detector series resistance of less than 100 ohms if contact resistance effects are included. A significant portion of the series resistance is due to the diffused sidewalls of the cavity, which connect the detector active region to the front-side metallization. The IFOC capacitance was measured to be 10 pF at

-5 volts. This can be reduced substantially by improved layout. Dark current, which can also be substantially reduced, was still very low at less than 2 nA at -10 volts.

Opto-electronic characterization of the device was carried out at 633 nm and 825 nm wavelengths. These were chosen for convenience and optimal performance was not expected. At 633 nm, DC measurements were performed both by directly focusing the laser beam into the IFOC cavity, and by launching the beam into one end of an optical fiber whose other end was tapered and inserted into the cavity. In the first case, a responsivity of 0.23 A/W was obtained corresponding to a quantum efficiency of 45%. In the second, a responsivity (adjusted for launching losses) of 0.21 A/W was obtained, indicating excellent coupling of the optical signal in the fiber to the detector. The measurement made at 825 nm yielded a responsivity of 0.10 A/W, lower because the longer absorption length results in recombinative loss of carriers generated far from the collection field in the detector. The 825 nm source was modulated to measure the response time of the detector. A characteristic time of 125 nsec was obtained, which agrees with the diffusion time of carriers generated far from the collection field. Since this time increases with the absorption length, the use of shorter wavelength photons would significantly improve the apparent performance of the p-n junction detector.

Discussion

The cavity approach advocated in the IFOC concept facilitates reliable and high-density direct connection of optical fibers to integrated circuits. Vertical connections have the advantage over lateral connections in that one is not constrained to the perimeter of the chip while maintaining minimal real-estate consumption. It is felt that back-side connections are preferred over the front-side prototype device described above. There are several reasons for this. First, in the front-side approach, the detector/emitter device is necessarily located below the plane of the surface circuitry and a low resistance vertical connection to the surface is required. Second, the fabrication of an optimal detector at the bottom of the cavity is difficult. Third, isolation of the detector from surface circuitry and adjacent detectors to prevent minority carrier cross-talk and latch-up is difficult at IFOC cavity depths. Back-side connection, on the other hand, (provided the etching can be accurately controlled to stop a few microns from the front surface) eliminates all three of these difficulties.

Direct connection of optical fibers to silicon integrated circuits for receiver applications has been demonstrated. However, silicon is a poor material in which to build efficient emitter structures. Direct band-gap semiconductors such as binary and ternary compounds are preferred materials for opto-electronic integrated circuits. Assuming that silicon continues to be the dominant material used in electronic circuits, the widespread use of optical fiber interconnections may therefore depend on hybrid approaches. For example, the growth of direct-band-gap materials on silicon[7,8] may be one solution. Another possibility is to fabricate IFOC devices in a direct band gap material (either individually, or as an array) and then hybridize such an IFOC "optical ribbon" connector onto the silicon chip, perhaps using solder bump technology. The advantage to this latter approach is that the manufacturing yields of the III-V material IFOC and the silicon integrated circuit are decoupled.

Several other technological hurdles must be overcome in order to make optical interconnections economically viable for general application. These include development of techniques to daisy-chain connections (e.g. a low-loss optical tap), and to route optical signals around sharp corners with low loss (e.g. a micro-mirror right angle fiber). Although current applications would not require it, a technique for fully utilizing the terahertz bandwidth potential of optical fibers within the constraints of the gigahertz bandwidth of the fastest electronic integrated circuits would also be useful. For example, two circuit boards which need several hundred interconnections, each with a 1 GHz bandwidth, might be interconnected with <u>one</u> optical fiber with a THz bandwidth if an appropriate and economical multiplexing scheme could be devised.

Summary

The integrated fiber-optic coupler concept has been described. The use of a cavity to mechanically stabilize the tip of the fiber offers potential for making real-estate efficient coupling of optical fibers to integrated circuits. Techniques for routinely inserting the fiber into the microscopic cavity have also been described. A prototype front-side silicon detector IFOC has been fabricated and characterized. The performance of the prototype IFOC is satisfactory for a number of optical interconnection applications, including skewless distribution of clock signals. Finally, new ideas for future research and the implications for electronics packaging have been discussed.

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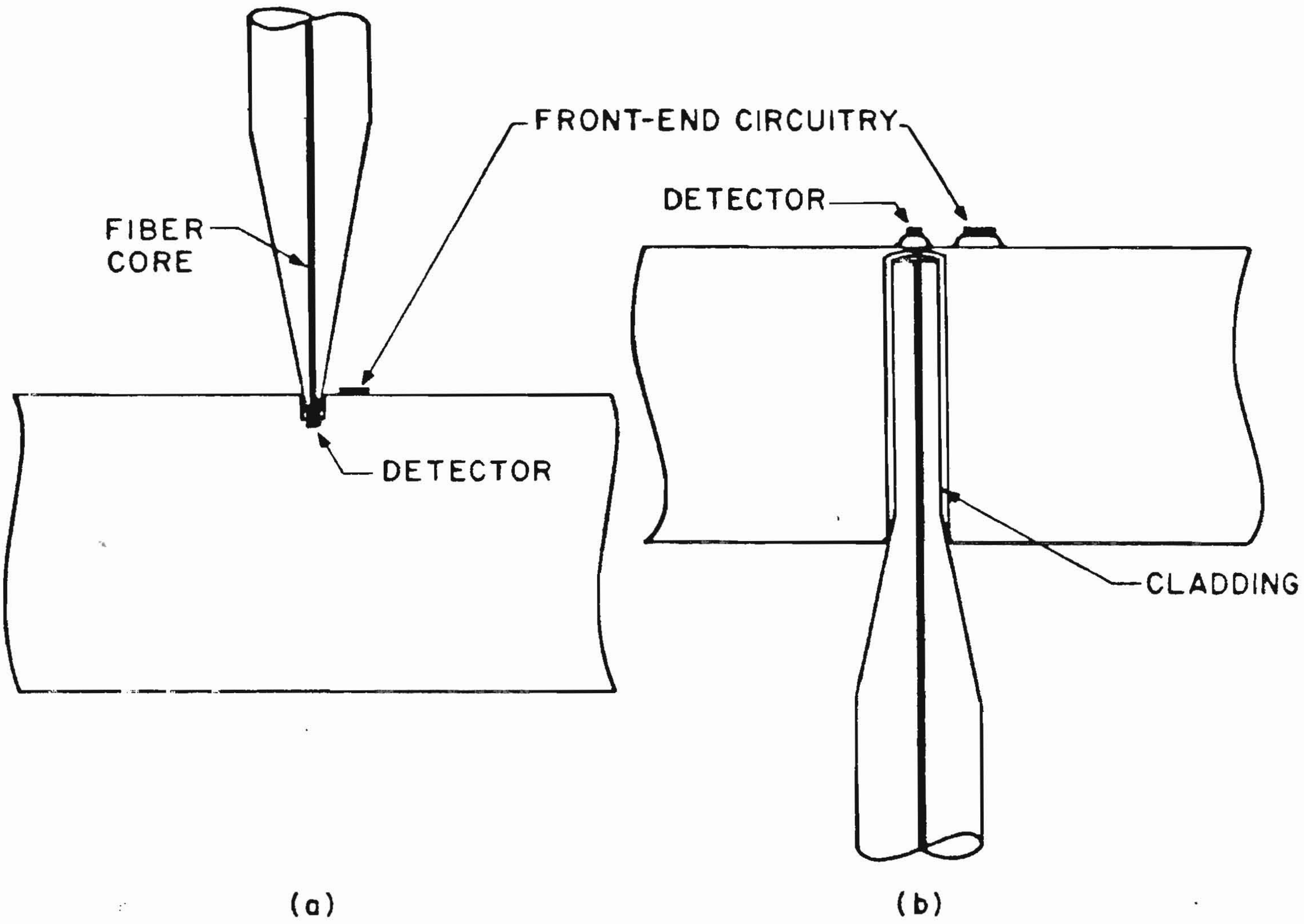

Figure 1. Illustration of (a) front-side and (b) backside integrated fiber-optic coupler concepts.

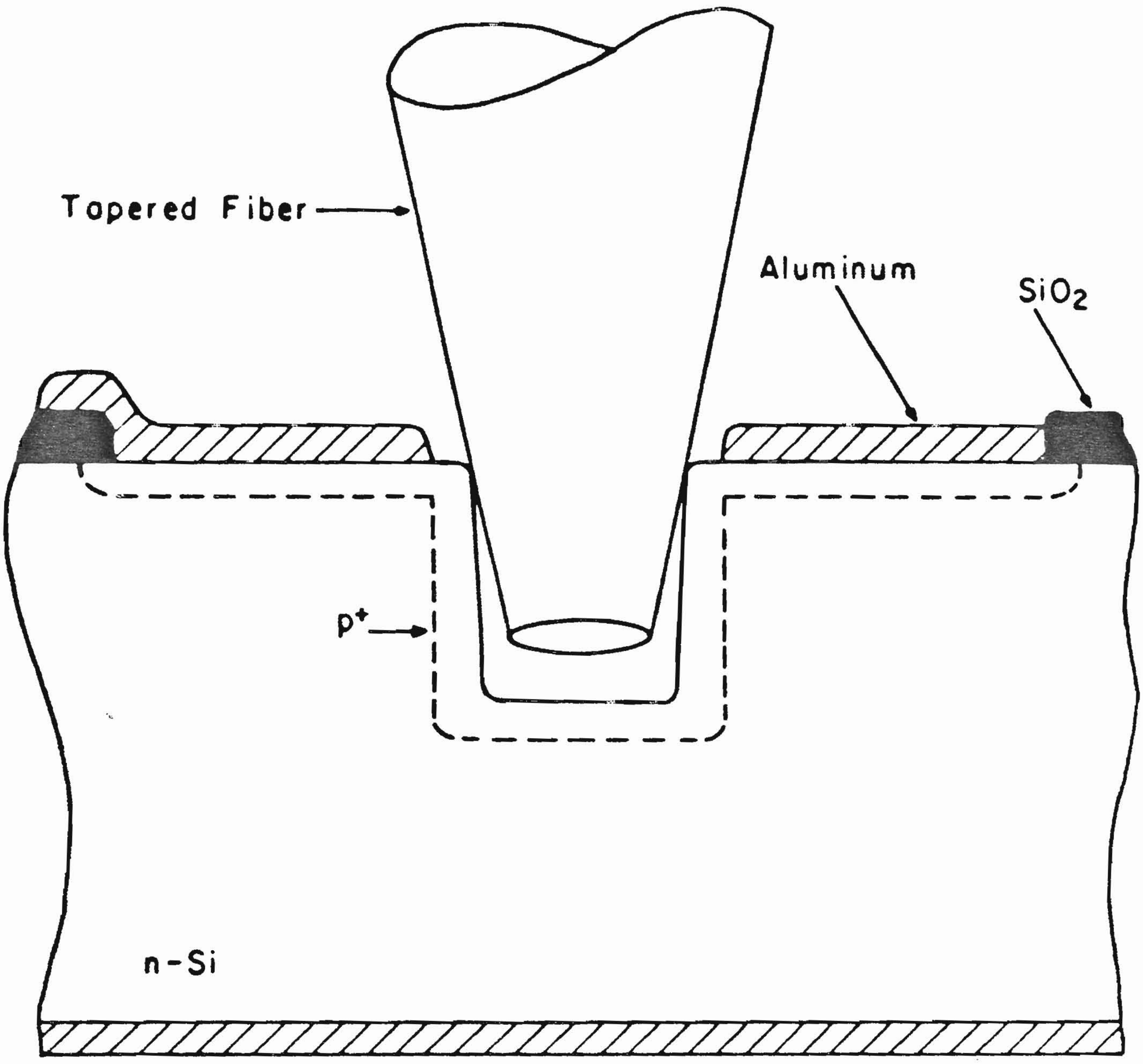

Figure 2. Cross-section of prototype front-side silicon detector IFOC structure.

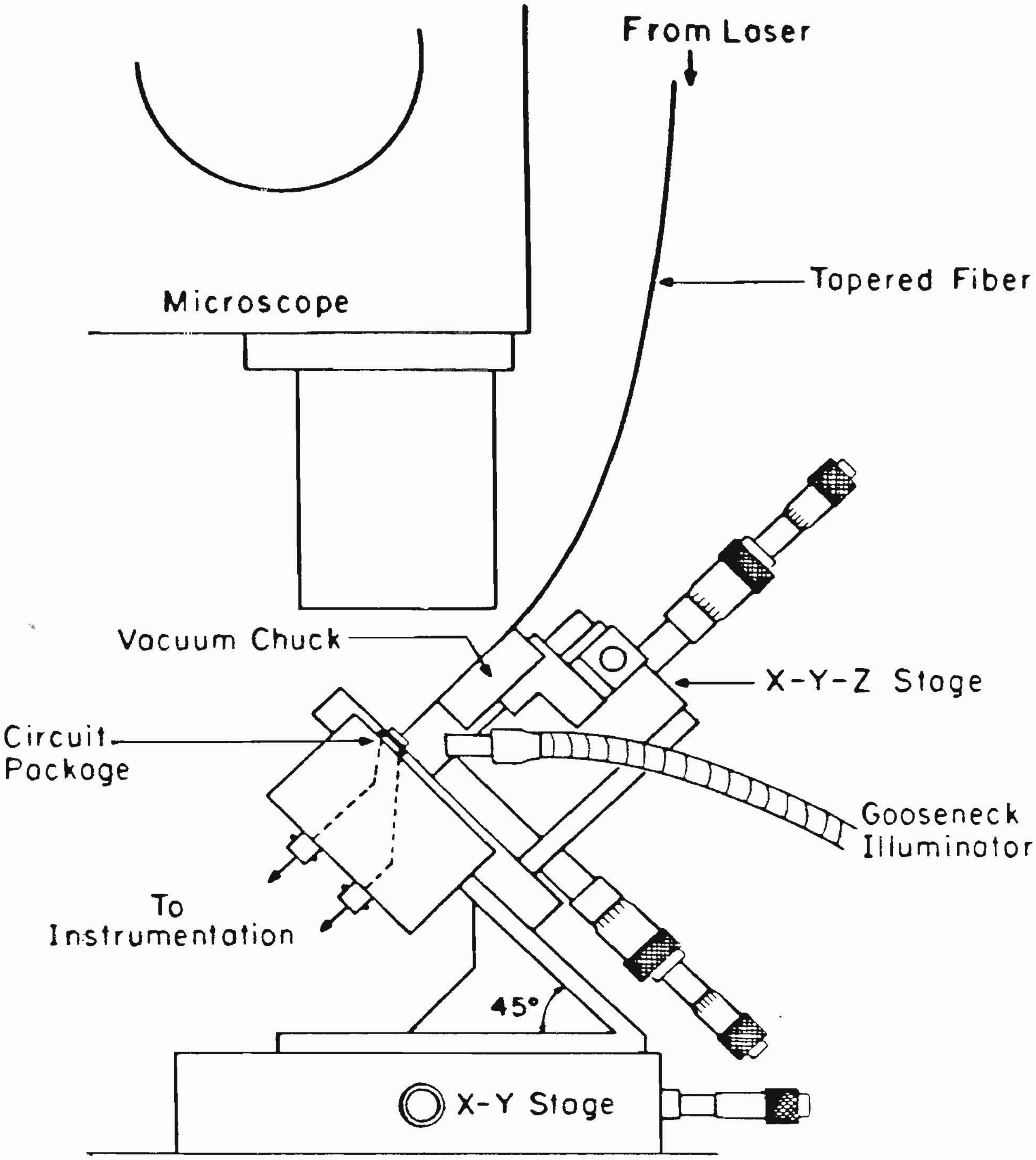

Figure 3. Schematic drawing of the work station used to insert optical fibers into the IFOC cavity.

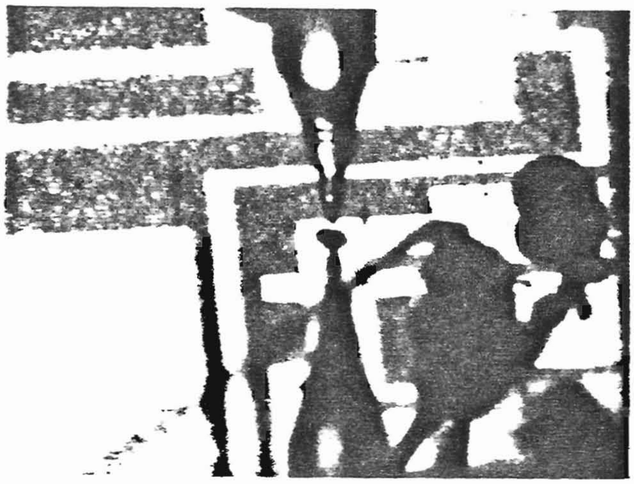

Figure 4(a). Tapered optical fiber about to be inserted into IFOC cavity.

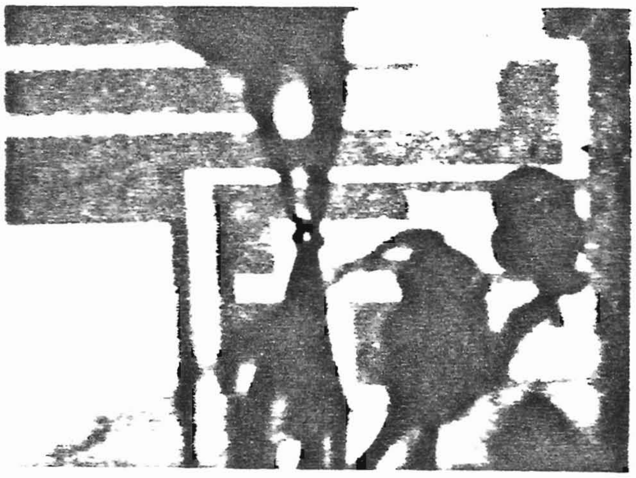

Figure 4(b). Fiber seated in cavity.

Note conventional wire bonds to detector pads used in monitoring photocurrent during insertion process. Fiber image is reflected from surface in both pictures.

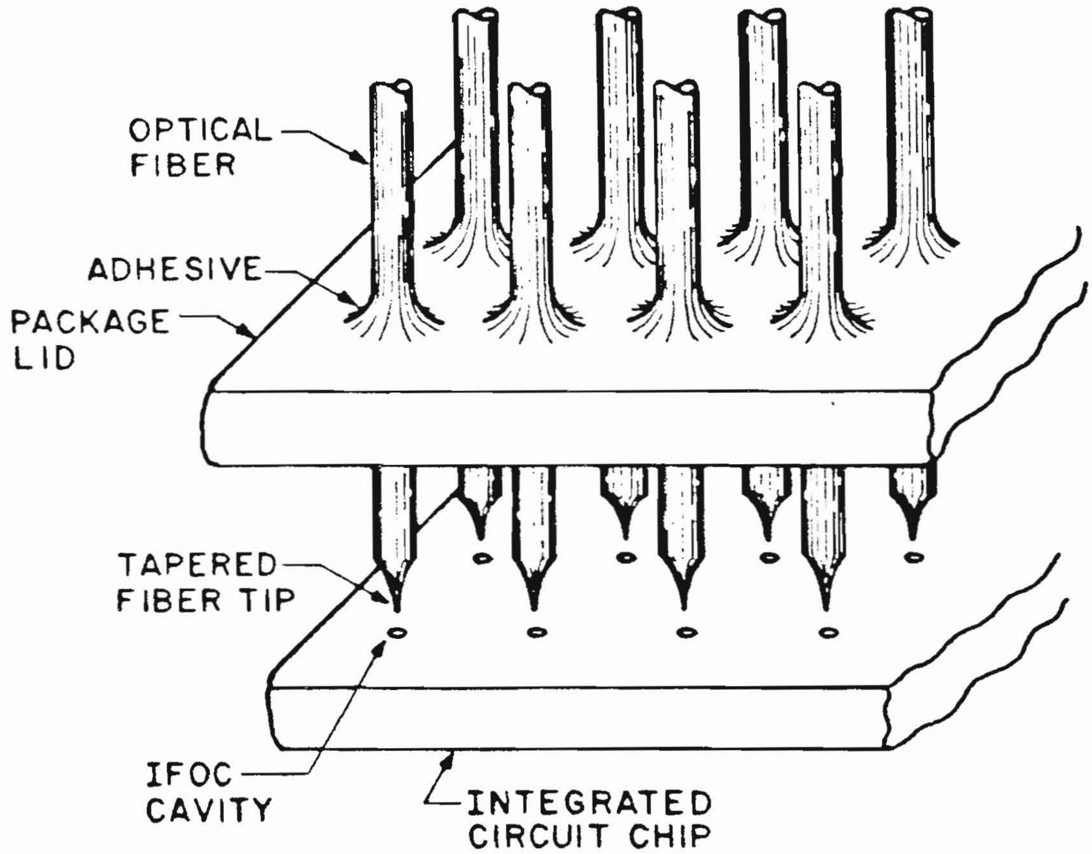

Figure 5. "Spaghetti extruder" package lid concept. Might be useful for aligning and vertically stabilizing arrays of optical fiber interconnections.