PACKAGING TECHNOLOGY FOR III-V PHOTONIC DEVICES AND INTEGRATED CIRCUITS

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Semiconductor device packages provide mechanical protection, an electrical interface between their chips and the outside world, a means of removing heat, and in the case of photonic devices, a means of coupling the photons to or from their detectors or source chips. Because III-V devices are often used for their optical properties or their high-frequency characteristics, or both, this paper focuses on optical and electrical interfaces rather than on the mechanical and thermal interfaces.

Introduction

The role of the semiconductor-device package is to provide mechanical protection, an electrical interface between the chip and the outside world, a means of removing heat, and, for photonic devices, a means of coupling the photons to or from the detector or source chip. The III-V device packages illustrated in Figure 1 are:

- Integrated circuit (IC) packages. Frequently, III-V IC package design concerns are dominated by the high-frequency characteristics of electrical connections between the IC and external circuitry.
- Lightwave (fiber-optic communication) devices. Lightwave sources and detectors must be optically coupled to the lightguide fiber. In single-mode laser packages, the need for precise fiber/laser alignment dominates package design.

Throughout this paper, specific examples will be drawn from two packages: the Astrotec® laser package and the gallium arsenide (GaAs) laser driver IC package, both of which are used in AT&T's FT Series G 1700 [1.7 gigabit per second (Gb/s)] lightwave transmission system.

A package provides a chip with a mounting surface as well as with physical and environmental protection. The package's exterior dimensions and electrical connections may be set by industry or military standards so that it can be handled by automatic assembly and test equipment and printed circuit boards can be laid out more readily. The package must carry visible information so that the user can identify the device code. Finally, the appearance of the package is important

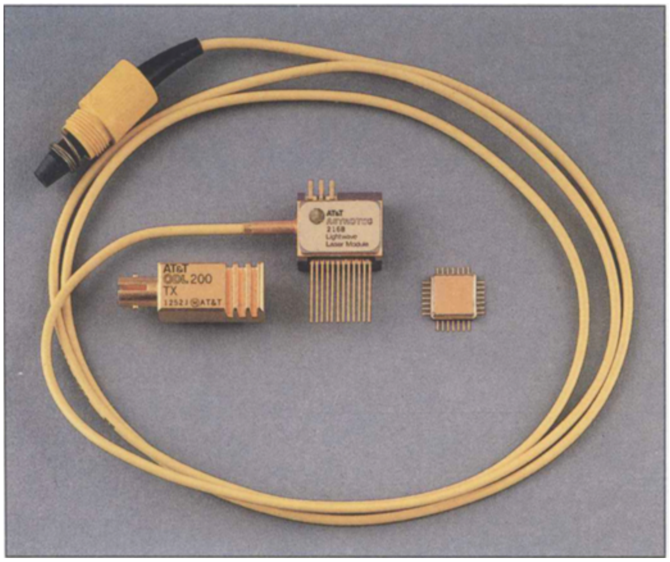

Figure 1. Packages for III-V devices come in a variety of shapes and sizes. IC packages provide multiple electrical connections, some designed to have good electrical characteristics at frequencies of several gigahertz. Lightwave packages for optical-fiber communication systems must provide optical coupling between the semiconductor device and the optical fiber's core, which is approximately 8 micrometers in diameter.

because it gives the user a first impression of the device's quality.

The device's temperature influences its performance and reliability. In some cases, a critical parameter, such as laser wavelength, is a strong function of temperature. To assure satisfactory system performance, temperature must be maintained within a few degrees. In other cases, the exact temperature is less important, but because the semiconductor device's lifetime decreases exponentially as its temperature rises, a good thermal path between the chip and the external heat sink is an important design consideration.

The device's electrical interface is no less important. III-V devices are frequently used when high-frequency performance is paramount. Conventional packages designed for frequencies of tens of megahertz are completely inadequate for applications requiring bandwidths of many gigahertz. Package designers are applying the principles of microwave design to achieve adequate performance in both analog and digital applications.

III-V photonic devices for lightwave systems require light to be coupled either from the optical fiber into detector chips [p-i-n diodes and avalanche photodetectors (APDs)], or from sources [lasers and light-emitting diodes (LEDs)] into the optical fiber. Maximizing the optical coupling and maintaining its stability despite variations in temperature and over periods of years are frequently the most demanding requirements imposed on lightwave package designs.

Figure 2 shows how these interfaces are accommodated in representative III-V device packages. The IC package (Figure 2a), a multilayer ceramic package with metallized electrical feedthroughs and a metal lid, contains a GaAs integrated circuit and passive components. The laser package (Figure 2b) contains an indium phosphide (InP) laser mounted on a beryllia (BeO) heat spreader. Behind the laser is an indium gallium arsenide (InGaAs) p-i-n diode that monitors the amount of light exiting the rear facet of the laser. The current from this diode is used in a control loop to stabilize the laser's light output. The light from the laser's front facet is coupled into an optical fiber by a microlens formed on the end of the fiber. The optical subassembly of fiber, laser, and monitor diode is mounted on a thermoelectric cooler that controls the laser's temperature. The package body, similar in construction to the IC package shown in Figure 2a, has an additional hermetically sealed port through which the fiber passes. A sheath protects the fiber from mechanical damage. The optical data link package (Figure 2c) contains an LED coupled to a connec-

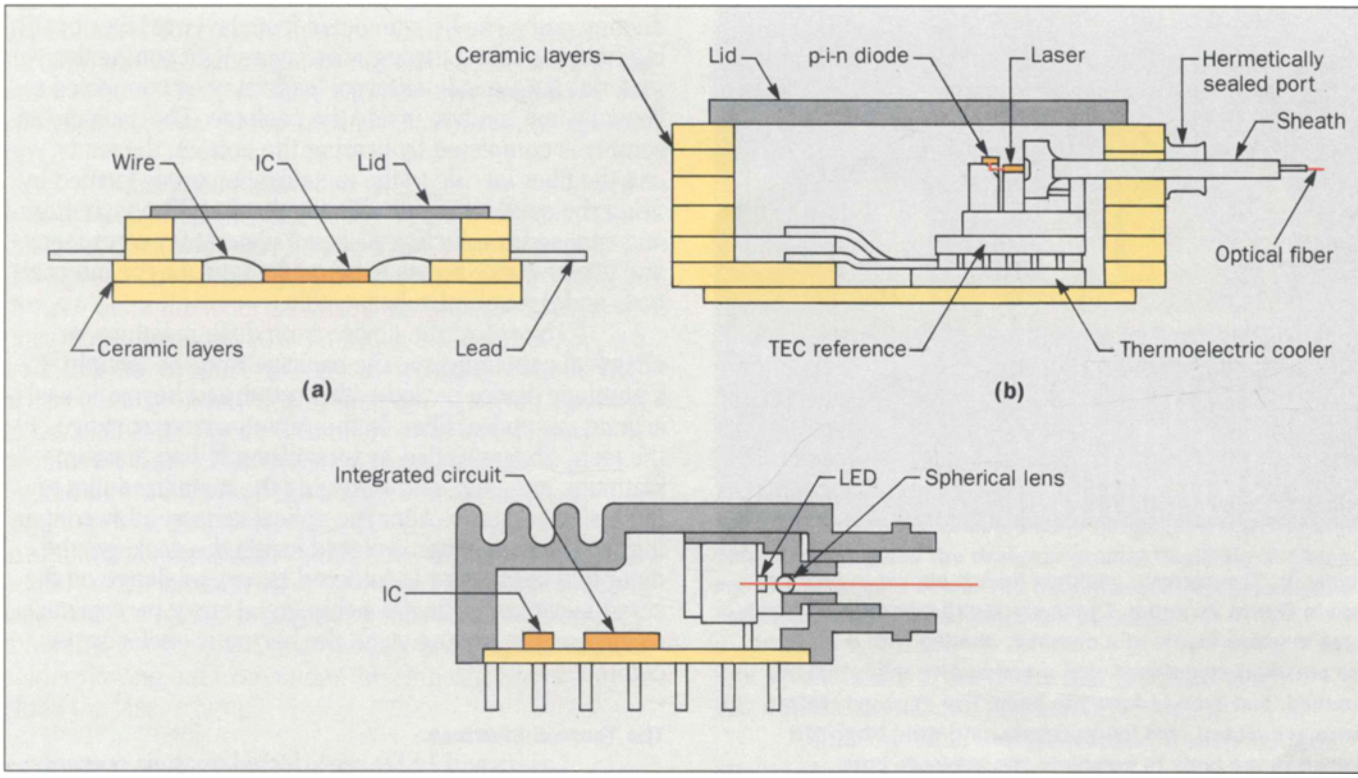

Figure 2. Cross sections of III-V device packages. (a) Integrated circuit package. (b) Laser package. (c) Light-emitting diode data-link package.

torized fiber through a spherical lens. The LED is driven by a silicon integrated circuit mounted on the multilayer printed-circuit substrate that forms the bottom of the package. The heat generated by both the IC and LED is removed through the package's leads to the circuit board and through the die-cast metal body to the air. High temperature affects LED performance less strongly than laser performance.

The Mechanical Interface

The construction and materials for III-V device packages are similar to those for silicon device packages. Figure 3 illustrates two high-frequency multilayer ceramic packages, one a laser package and the other an IC package.

Multilayer ceramic packages offer unique advantages for both high-speed and photonic packages. They give the designer greater flexibility in choosing practical shapes and readily accommodate electrical signal routing throughout the package. For example, controlled-impedance signal lines can be incorporated in the package for high-frequency applications.

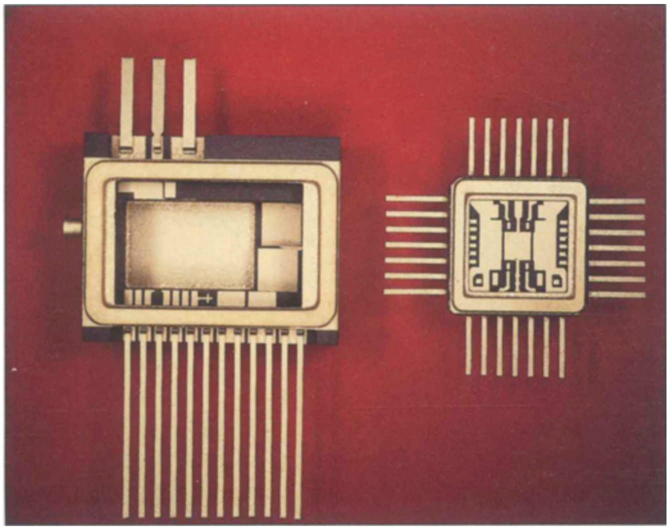

Figure 3. The ceramic package bodies shown in cross section in Figure 2a and b. These are multilayer ceramic packages in which layers of a ceramic, bonded with a polymer, are punched, metallized with a conductive ink, stacked, pressed, and fired to form the body. The exposed metal lands are plated, and leads, bases, and weld rings are brazed to the body to complete the package body.

Figure 4, which shows construction details of the multilayer ceramic body for the Astrotec laser package, illustrates these advantages. The sidewalls of the package are formed by punching out layers of ceramic tape and stacking, pressing, and firing them to form a monolithic ceramic body. The tape contains ceramic particles in a flexible polymer binder that is easily cut and handled. Because the thickness and shape of each layer may be different, the package may be designed to simplify the subsequent assembly of the optical components inside the package body. In addition, each layer of the ceramic tape may be printed with a conducting ink to form conductors through the package wall. These conducting paths can be connected from layer to layer by filling holes punched through the layers with conductive material. As a result, external leads may be connected to virtually any location inside the package. The package assembly is completed by brazing the bottom, the leads, and the fiber ferrule to the metallization areas formed by firing the conducting ink. Finally the metal leads, bottom, and exposed conducting pads are plated to protect them and to allow wire bonds to be made between the internal pads and the optical subassembly.

To protect the device from dust, moisture, or chemical contaminants, the package must be airtight. In a photonic device package, this requires a hermetic seal around the optical fiber. In the Astrotec laser package, the glass fiber is sealed by metallizing it with titanium, platinum, and gold, and soldering the metallized film to the inside of a tube. After the optical subassembly containing the laser and fiber is placed inside the package, the outer end of the tube is soldered to a metal flange on the ceramic package. Finally, a thin metal cover is resistance-welded on the package, and the hermetic enclosure is complete.

The Thermal Interface

Lasers and LEDs are affected by their operating temperature in several ways:

- Both are subject to wear-out mechanisms that are exponential functions of temperature.
- Both suffer a decrease in emission efficiency (light power per ampere) with an increase in temperature.
- The laser threshold current increases with increasing temperature.
- The emission wavelength increases with increasing temperature.

As a result of these temperature sensitivities, a lightwave system's performance and reliability depend on the laser package's thermal design. High-performance (high-power, high-data-rate) laser packages use thermoelectric coolers (TECs) to control the laser's temperature. TECs are Peltier-effect coolers in which a current passing through the TEC elements causes one end to cool and the other to heat. Thus, the laser can be either heated or cooled as necessary to maintain it at a constant temperature.

Because low-cost laser packages can not afford to use TECs, their thermal design is more difficult. The designer must consider the amount of heat generated in the laser's active region and the thermal path from the active region to the external heat sink. Because indium phosphide, the material from which lasers are made, is a poor thermal conductor, lasers in packages without TECs are frequently mounted with their active region attached to the heat sink. Figure 5 compares the temperature profiles for laser chips mounted with the active regions up and down. Although the temperature of the laser mounted with its active region down is significantly lower, this configuration complicates the design and assembly of the package in other ways. For instance, the laser's active region is only a few micrometers from the mounting surface, so a dust particle or a small amount of solder flowing out from under the chip can completely occlude the laser's light.

The Electrical Interface

When III-V semiconductors are used for their high-frequency characteristics, the package must be designed to pass electrical signals between the chip and the outside world unaltered. When the frequencies of interest were tens of megahertz, little thought was required for the package's electrical design. However, at frequencies greater than 1 gigahertz (GHz), microwave techniques must be used to analyze, design, and measure the package's electrical interface. Powerful computerized tools have been developed to assist in the design and measurement of high-frequency devices and systems. With them, the designer can analyze and characterize a simple device such as a coaxial cable-to-cable connector by applying a signal to an input and measuring the power

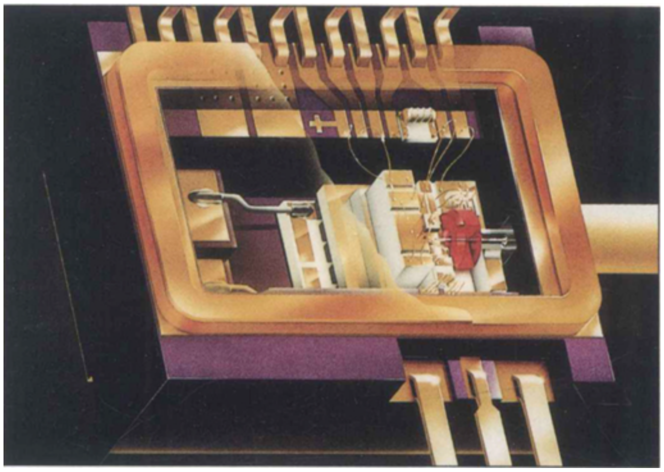

Figure 4. In AT&T's Astrotec laser package, a multilayer ceramic body gives the designer greater flexibility in choosing the package's shape and readily accommodates electrical signal routing throughout the package.

that is reflected and the power that is transferred through the device as a function of frequency.

The four chief measurements on such a device are known as *S* parameters:

- *S*11 is the ratio of power reflected to port 1 to that of a signal applied to port 1, in decibels. *S*11 is referred to as *return loss*.
- *S*21 is the ratio of power at port 2 to that of a signal applied to port 1, in decibels. *S*21 is referred to as *insertion loss*.
- *S*22 and *S*21 are similar to *S*11 and *S*21 except that the signal is applied to port 2.

In a package, electrical reflections result from a change in the characteristic impedance of the conductor as the signal progresses from the external leads through the package wall and then across the wire bonds to the chip. If there are no discontinuities in the impedance and the chip terminates the line in its characteristic im-

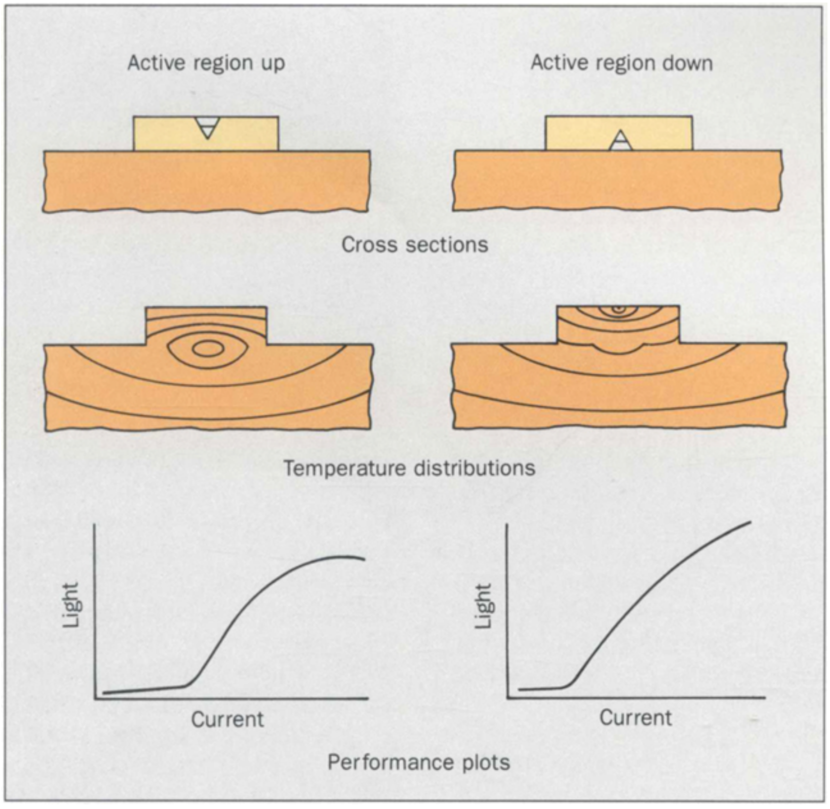

Figure 5. Mounting laser chips with the active (heat-generating) region adjacent to the heat sink enhances their thermal performance. The temperature distributions are the results of finite-element analyses. Each line represents a 1°C change in temperature. The performance plots show light output versus current input when the bottom of the heat sink is held at 85°C.

pedance, no reflections will occur. One way to evaluate a package's high-frequency characteristics is to connect two of its high-frequency ports internally and to measure its S parameters versus frequency. A perfect package will have no reflections or insertion loss at any frequency. Unfortunately, this is never achieved. Figure 6a shows $S11$ and $S21$ for an integrated circuit package in which two of the high-frequency leads have been tied together inside the package.

The relevant measurements for a laser package are more difficult because the electrical input signal is converted into an optical output. In addition, the laser chip is not a perfect resistive termination for the controlled impedance line. In the Astrotec laser package, a resistor is mounted next to the laser and connected in series with it to terminate the line. See Figure 4. $S21$ for the laser package is illustrated in Figure 6b. For the $S21$ measurement, the input signal (port 1) is the modulation current and the output signal (port 2) is the optical power coupled into the fiber. The latter includes the effects of both the frequency response of the laser chip and the frequency response of the laser package. In this case the frequency response of the laser does not limit the laser/package performance, and $S21$ represents the

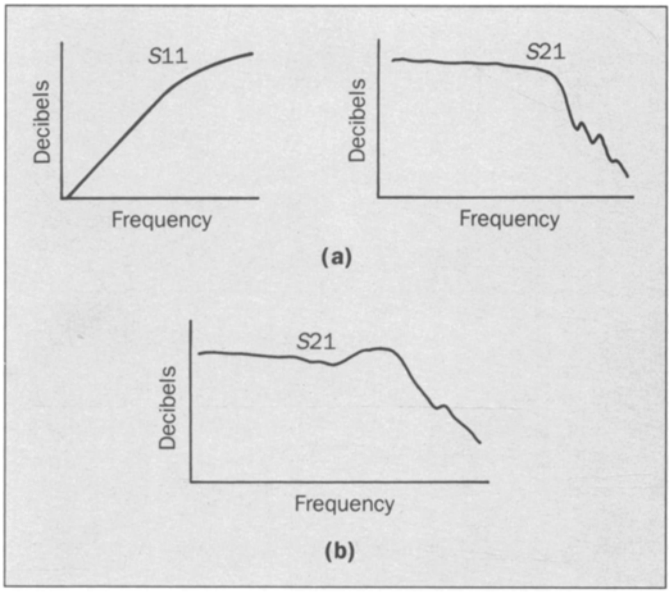

Figure 6. *S* characteristics. (a) *S*11 and *S*21 for the 1.7-Gb/s laser driver IC package with two of its high-frequency ports connected with five parallel wire bonds (to minimize inductance). Fewer wire bonds significantly degrade the *S*11 performance. (b) Current-in, light-out *S*21 performance of the laser chip and laser package combination.

package's frequency response.

The devices represented in Figure 6 are used in AT&T's 1.7-Gb/s lightwave transmission system, and their characteristics are adequate for this application. For future systems, faster packages will have to be developed. This is being done with the help of an analytical model of the current package that includes estimates of all the stray capacitances and inductances. A computer-aided design program for microwave circuit design is used to analyze the model, and the results are compared with the S-parameter measurements of the actual package. The model is adjusted until its performance matches that of the package. The designer can then modify the model to improve performance. When the model's performance is adequate, the designer must attempt to realize the same improvements in the physical design.

The Optical Interface

The difficulty of maximizing the optical coupling and minimizing the changes in coupling that result from variations in temperature or the passage of time depends on the nature of the source (LED or laser), the size of the detector, and the type of fiber (single-mode or multimode). The most demanding problem is coupling single-mode fibers to lasers, where motions of a few tenths of a micrometer result in significant coupling changes. The least demanding problem is coupling single-mode fiber to a detector, where several micrometers of motion will have no effect on the coupling.

Because the subject is so broad, we will discuss only the coupling of lasers to single-mode fibers. In this case, there are two requirements for the coupling optics between the laser and the fiber: the design must match the optical mode size of the laser to that of the fiber and it must project the light emerging from the laser into the core of the optical fiber. Typically, the mode size of the light emerging from the laser is between 1 and 2 micrometers (μm) in diameter, and the mode size of the light in the fiber is 6 to 8 μm. Therefore, the optical system must magnify the laser's mode by a factor of about 5 and project it into the core of the fiber. (Single-mode fiber has an 8-μm core surrounded by a 125-μm-diameter glass cladding layer, which is coated with a flexible plastic coating to prevent damage to the glass.)

Figure 7 illustrates several approaches to coupling light into a single-mode fiber. The simplest is to cleave the fiber and align it with the laser. With this arrangement, the maximum coupling efficiency is only 10 percent because it makes no attempt to match the mode sizes of the laser and fiber. (Coupling efficiency is the ratio of the amount of light coupled into the fiber's core to

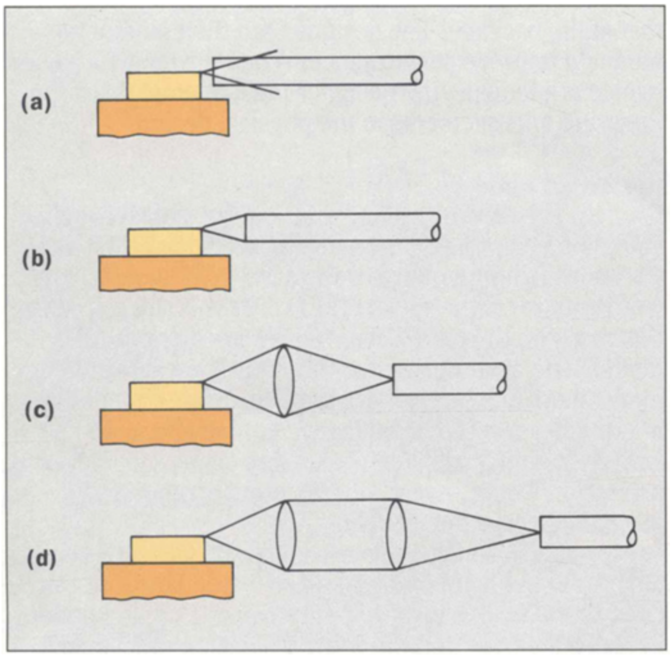

Figure 7. Coupling light from a laser into a single-mode fiber is maximized when the optical mode sizes of the laser and the fiber are equal. The coupling setup in (a) suffers a 10-decibel loss because of mode-size mismatch. The lenses in (b), (c), and (d) are intended to magnify the laser's optical mode size.

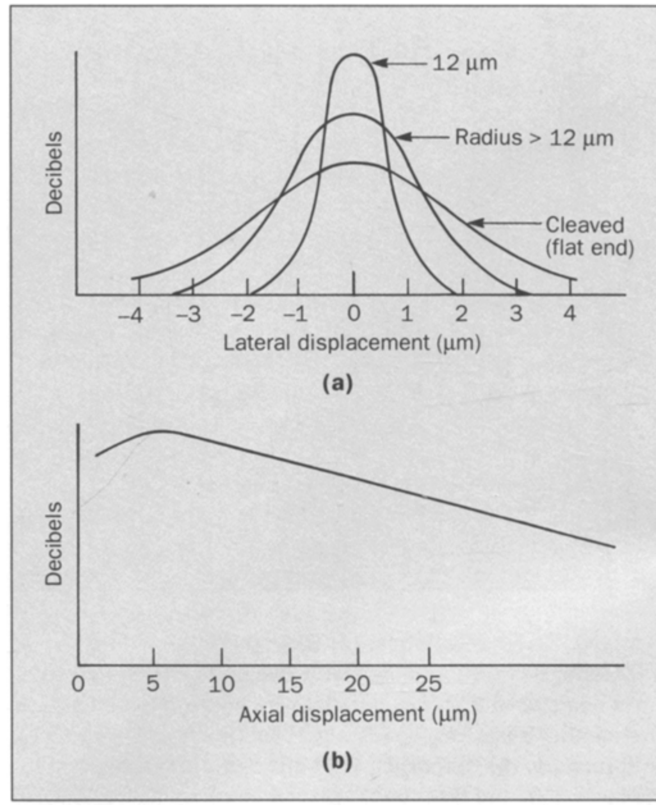

Figure 8. The amount of light coupled from a laser into a single-mode fiber is a function of fiber alignment and optical magnification. (a) Coupling efficiency as a function of lateral displacement for various lens radii. (b) Coupling efficiency as a function of axial displacement of the fiber from the laser facet.

the amount of light that can be captured by a large-area detector placed close to the laser's output facet.) The coupling can be improved by forming a lens on the end of the fiber to act as a magnifying element. Figure 8a illustrates the effects of lens radius and radial misalignment on coupling efficiency. Figure 8b shows that the coupling efficiency is only a weak function of the fiber tip's axial location. With a lensed fiber, about 50 percent coupling can be expected. Further improvements are limited by lens aberrations.

A more sophisticated optical approach is the confocal design shown in Figure 7d. This optical design is used in the more demanding applications because it has a higher coupling efficiency—greater than 70 percent—and it provides a region of collimated light into which

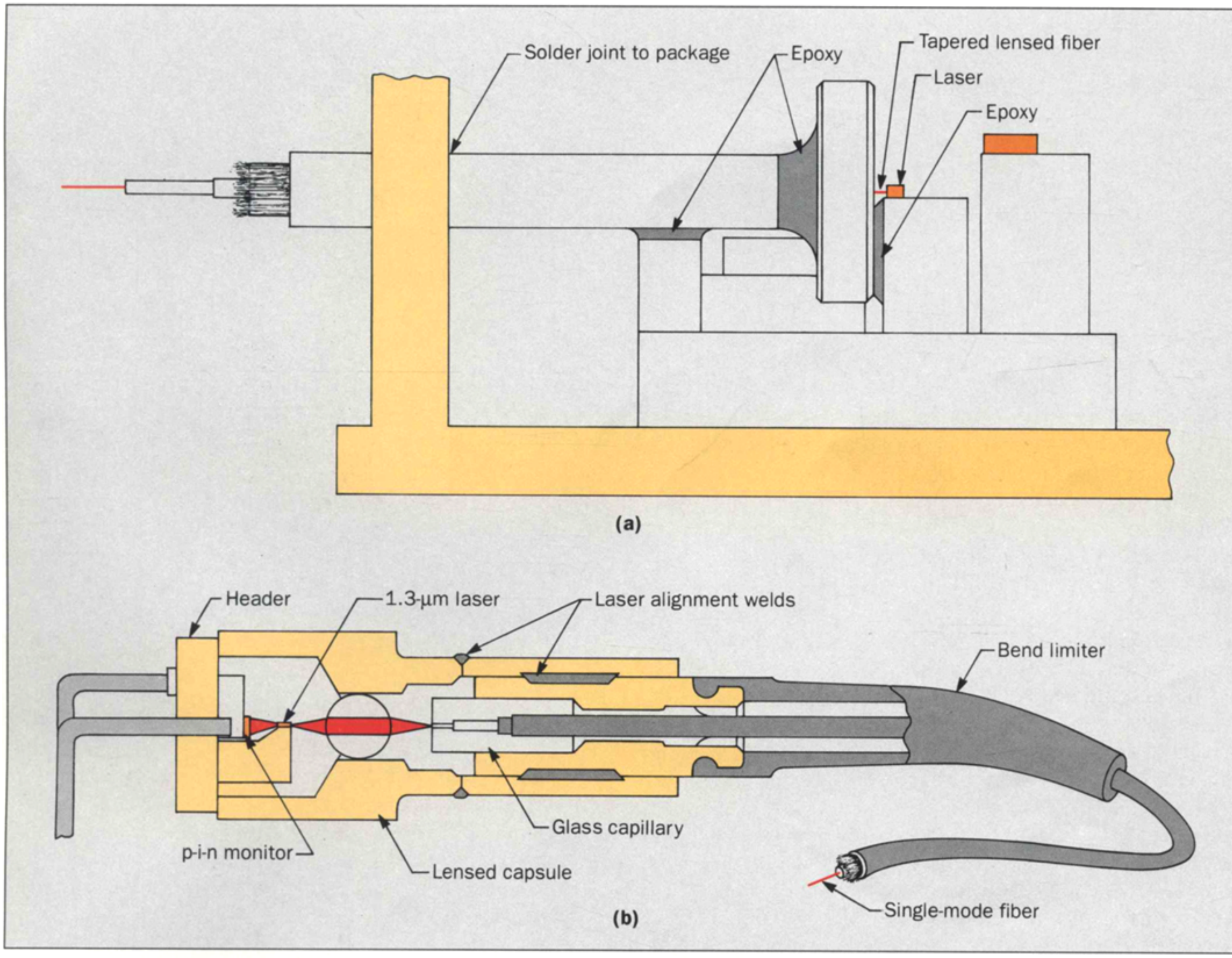

Figure 9. Several methods are used for fiber/laser alignment. (a) In the Astrotec laser package, a proprietary epoxy attaches the fiber to a jewel (similar to a watch jewel) and the jewel to the laser submount. (b) An uncooled package is laser-welded to secure the fiber/laser alignment. The two-step alignment process laser-welds the ferrule to establish the proper axial alignment, then welds the transverse alignment between the sleeve and the body.

other optical elements, such as an isolator, may be inserted. An additional benefit of the confocal design is that the alignment of the fiber is less critical than it is in the lensed fiber design because the mode has already been magnified to match the fiber's mode size. Although the alignment tolerance at the fiber is relaxed, the stability requirement for the laser-to-first-lens coupling is similar to that for the lensed fiber.

Manufacturers secure the fiber's position in a variety of ways. Soldering, epoxy bonding, and laser welding are used successfully. Two approaches are illustrated in Figure 9. In one, a lensed fiber is captured in a watch jewel with epoxy, and the face of the jewel is secured to the laser submount. In the other, the fiber, epoxied or soldered into the fiber ferrule, is secured to the body with two sets of laser welds. One set secures the fiber ferrule's axial location, and the other set of laser welds locks the fiber tip's radial position. Both approaches result in stable coupling over time and temperature, but laser welding will probably replace epoxy bonding because of its speed and because it is adaptable to automation.

Summary

The design of packages for III-V devices is similar to that for other electronic components except that many of the applications require more attention to the III-V device package's high-frequency performance, and an optical interface is rarely required in non-III-V device applications. Package designers continue their efforts to increase package bandwidths, to increase coupling efficiencies, to reduce thermal resistance, and to make packages smaller and less expensive.

Biographies (continued)

of integrated circuit packages. He received a B.S. in aeronautical engineering and an M.S. in applied mechanics from Polytechnic Institute of Brooklyn and an Eng.Sc.D. degree in engineering mechanics from Columbia University. He joined AT&T in 1970.

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