

CO-PACKAGED OPTICS WITH OPTICALLY TRANSPARENT MOLDING COMPOUND

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of priority to Provisional Application No.
5 63/672,160, filed on July 16, 2024, the contents of which are hereby incorporated by
reference.

BACKGROUND OF THE DISCLOSURE

Co-packaged optics refers to the integration of optical components directly with
10 electrical integrated circuits (EICs), such as processing units and other application
specific integrated circuits (ASICs), to provide packages that use a combination of
electrical and optical signals to communicate and process data. In many designs, a
photonic integrated circuit (PIC) is used to communicate optical data within a package
and optical fibers are commonly used to relay optical data between packages. An optical
15 interface, e.g., for receiving a pluggable module, is used to facilitate connecting an end of
an optical fiber to a package. Such interfaces can couple light from the fiber into a
waveguide in a PIC via a port on the surface of the PIC or at an edge of the PIC. In either
case, arrangement of components in a package should provide ample access to the PIC to
accommodate the optical interface for robust and reliable attachment of the optical
20 fiber(s).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic cross-sectional view of an example system that includes a circuit package with co-packaged optics.

FIG. 1B is a schematic cross-sectional view of the examine system shown in FIG.
5 1A with a heat sink.

FIG. 2 is a schematic cross-sectional view of another example system that includes a circuit package with co-packaged optics.

FIG. 3 is a flow chart showing a series of steps for an example method for manufacturing and/or fabricating a circuit package with co-packaged optics.

10

DETAILED DESCRIPTION

The present disclosure relates to circuit packages with optically accessible co-packaged optics and methods for making such packages. Indeed, implementations herein relate to improving off-chip photonic links, e.g., bidirectional photonic links, by
5 providing a package that includes a transparent molding compound over optical couplers in the surface of a PIC that couple light into waveguides in the PIC. Such a molding compound can facilitate optical access to the waveguides through optical openings that are smaller than the interfaces typically used to couple optical fibers to a PIC and/or facilitate access to optical couplers that are close to other components in a package that
10 includes the PIC.

As will be discussed in further detail below, examples described herein include circuit packages with co-packaged optics that include an optical path between an active element, e.g., a photodetector or modulator, in a photonic integrated circuit (PIC) and an optical interface, e.g., a fiber array unit (FAU), that connects to an optical fiber.

15 Conventional circuit packages that include a PIC can be difficult and costly to manufacture because the optical interface is a relatively large component, e.g., similar in dimensions to the PIC, and needs to be robustly and precisely attached to the PIC to ensure reliable alignment between the optical fiber(s) and the coupler(s) through which optical signals are transmitted to and from the PIC.

20 One approach to managing these constraints when attaching an EIC to the PIC surface is to use an EIC die which is physically smaller in at least one dimension than the PIC. This ensures at least a portion of the PIC surface is clear of the EIC. Waveguides in the PIC can be routed to couplers in this portion and the optical interface can be attached to the exposed surface, however this manufacturing step can be difficult. Moreover, such
25 optical interface attachment often takes place after EIC attachment so any yield loss due to faulty interface attachment results in a loss of both the PIC and the EIC, which are often the most expensive part of a package. Indeed, packaging often involves encapsulating components with a molding compound, e.g., an epoxy, that is injection molded at high pressure. Maintaining precise alignment of an optical interface to a PIC
30 during such a process can be challenging and can create impediments to economical mass production of such packages.

However, using an optically transparent molding compound allows attachment of an optical interface to the package after encapsulation of the PIC, ensuring that the optical interface is not subject to the encapsulating process which can otherwise subject the optical interface to significant stress, e.g., thermal and/or mechanical stress, lowering yield.

Accordingly, examples of co-packaged optics are described that feature a PIC at least partially encapsulated, e.g., partially encapsulated or completely encapsulated, by a molding compound that includes at least a portion that is optically transparent. The optically transparent portion is proximate to one or more optical couplers in the PIC providing optical access to the optical couplers through the molding compound.

Here, an optically transparent compound refers to a compound that exhibits sufficient optical transmission that optical signals at the operative wavelength of the PIC can be transmitted through a layer of the compound overlying the PIC with sufficiently low loss to allow delivery of optical signals to the PIC and receipt of optical signals from the PIC. In other words, an optically transparent compound has low absorption, reflection, and/or scattering of light at the operative wavelength(s). Optical attenuation of a light signal through a layer of the molding compound at an operative wavelength of the PIC can be 1 dB or less, e.g., 0.5 dB or less, 0.2 dB or less, 0.1 dB or less, 0.05 dB or less, 0.02 dB or less, 0.01 dB or less, 0.005 dB or less, 0.002 dB or less, such as 0.001 dB or more, such as between 0.1 dB and 0.01 dB.

Referring to FIG. 1, a system 100 includes a circuit package 101 connected by a bundle of optical fibers 104 to another component 102, e.g., a light source or another circuit package. The circuit package 101, only a portion of which is shown, includes a PIC 110, an EIC 150, an optical interface 140, and a base 132. A molding compound 134 at least partially encapsulates the PIC 110, and the EIC 150 against the base 132. A portion of the molding compound 134 provides a continuous, flat surface 135 on which the optical interface 140 is mounted. FIG. 1 also shows a Cartesian coordinate system, for ease of reference. The z-direction may be referred to as the vertical direction while the x-direction and y-direction are lateral directions.

The optical interface 140 includes a connector for connecting to fiber connector 106 and optical elements, such as lenses 144, for directing light emitted from the ends of

optical fibers of the fiber bundle 104 through the portion of molding compound 134 to the PIC 110 and/or light emitted from the PIC 110 through the spacer 130 to the end of an optical fiber. The fiber connector 106 can be detachable from the optical interface 140 or can be permanently attached, e.g., using an optically transparent adhesive. In some
5 examples, the fiber connector 106 is integrated with the optical interface 140.

The PIC 110 includes a modulator 112, such as an electro-absorptive modulator (EAM), micro-ring resonator, or any suitable optical modulator having sufficient thermal stability, and a photodetector 114, such as a photodiode. Generally, a PIC includes more than two active components, and can include other types of active components too. The
10 PIC 110 also includes grating couplers 116 and 118, which are located at the top surface of the PIC 110. The grating couplers 116, 118 can be surface relief gratings with grating lines arranged to direct light that is normally incident or near normally incident into guided modes in planar gratings that are in the lateral plane of the PIC 110. The grating coupler 116 is optically connected to modulator 112 by a waveguide 124 and grating
15 coupler 118 is optically connected to photodetector 114 by a waveguide 126.

The EIC 150 is mounted in the package overlapping a portion of the top surface of the PIC 110. The EIC 150 includes a driver 152 and a transimpedance amplifier 154 which are electrically connected to the modulator 112 and photodetector 114 via electrical interconnects 156 and 158, respectively. The electrical interconnects 156 and
20 158 each include a copper pillar 162 and 164, which form electrical connections between the bottom surface of the EIC 150 and the top surface of the PIC 110. Generally, the copper pillars are relatively short, e.g., 100 μm or less, 50 μm or less, so that the bottom surface of the EIC 150 and the top surface of the PIC 110 are close to each other in the overlapping portion. The space between the copper pillars is filled with the molding
25 compound 134.

The molding compound is composed of a material that is transparent to light having the wavelengths at which the optical components of system 100 operate. In other words, the amount of absorption and/or scattering of light at these wavelengths by the layer of molding compound between the optical interface 140 and the top surface of the
30 PIC is sufficiently low to permit scatter-free passage of light at these wavelengths through the spacer to allow optical signals to be reliably transmitted back and forth

between the PIC and the optical interface during operation of the system 100. The molding compound should also be compatible with the manufacturing processes used to make circuit package 101 and have mechanical and chemical properties compatible with the other components of the package and the expected operational lifetime of the package.

Generally, the molding compound is a composite material that includes a curable binder and one or more structural materials dispersed through the binder. The curable binder can be an organic material, such as a plastic. In some examples, the curable binder is an epoxy, an acrylate, a silicone, and/or a urethane. The binder material can be a two-stage material that cures once the two stages are combined. In certain cases, the binder is a thermoset material or a radiation curable material. Thermoset materials and/or radiation curable materials can be cross-linkable materials. Cross-linkable materials can be readily flowable before curing, and solid after, providing ease of processing and structural stability once set.

The structural material is generally a different material than the binder and can include microparticles and/or nanoparticles. In some examples, the structural material includes an organic material, such as an epoxy, an acrylate, a silicone, and/or a urethane. In certain examples, the structural material includes one or more inorganic materials, such as Ge, Si, ZnS, ZnSe, AlO, MgF, GaAs, CaF₂, and BaF₂. Inorganic glasses, such as BK7 and fused silica, can be used. The structural materials can constitute 50 wt.% or more, e.g., 60 wt.% or more, 70 wt.% or more, 80 wt.% or more, 85 wt.% or more, 90 wt.% or more, 95 wt.% or less, of the molding compound.

Generally, the binder and structural materials are selected so that their optical properties are sufficient similar to provide a transparent layer of compound once cured. For example, a refractive index of the binder at an operative wavelength and a refractive index of each of the one or more structural materials at the operative wavelength can be mismatched by 0.02 or less (e.g., 0.01 or less, 0.005 or less, 0.001 or less, 0.0005 or less, 0.0001 or less). The two materials can be substantially index matched at the operative wavelength band. Use of two or more materials can provide an ability to adjust the refractive index of the composite, e.g., by varying the ratio of one material to another.

Generally, in the present example, the vertical thickness, T , of the layer of the molding compound over the PIC is approximately the same as or slightly greater than the vertical thickness of the EIC 150. T can be in a range from 100 μm to 5 mm, depending on the implementation. Furthermore, while the top surface 135 is coplanar with the top surface of the EIC 150 in the present example, more generally, a slight mismatch in the surface heights is permissible provided the surface is appropriate for attachment of the interface 140. In some examples, the surface heights can be mismatched by an amount in a range from 10 nm to 10 μm , e.g., from 100 nm to 1 μm .

The base 132 can include, for example, one or more interposers, redistribution layers, printed circuit boards, and/or other components used in a circuit package.

In general, the operative wavelength band of the system 100 can be one of a variety of commonly used bands for optical communications. Generally, the operative wavelength(s) are in the near infrared (NIR) part of the spectrum, e.g., 1300 nm to 1650 nm, and can be, for example, C-band wavelengths, i.e., 1530 nm to 1565 nm.

Together, the waveguide 124, grating coupler 116, the layer of molding compound 134 and lens 144 compose an optical path through the package 101 between the modulator 112 and an end of a first optical fiber in the bundle 104. During operation, the driver 154 drives modulator 114 to modulate an optical signal in the PIC which is carried over the optical path from the PIC 110 to the other component 102 via the first optical fiber. The waveguide 126, grating coupler 118, the layer of molding compound 134, and lens 142 compose a second optical path through the package 101 from a second optical fiber to the photodetector 114. This optical path is used to received optical signals from the other component 102 at the photodetector 114, which then converts them to electrical signals which are detected and processed in the EIC 150 via the TIA 152. Collectively, the two optical paths provide a bidirectional photonic link between the circuit package 101 and the other component 102.

The optical interface 140, the layer of molding compound 134, and optical couplers 116 and 118 constitute an interface block which facilitates transfer of light to and from the fiber bundle 104 and the waveguides in the PIC 110. In general, the size, length, material, and number of optical elements, e.g., lenses, that may be included an interface block depends on specific requirements of the implementation, such as the

wavelength of light, the coupling efficiency, and the cost. Generally, interface blocks can include a variety of mechanisms of providing an optical interface between the fiber(s) and/or the fibers and PIC, for example, an edge coupler; a grating coupler (GC), a graded index (GRIN) lens coupler, a fiber Bragg grating (FBG) coupler, a micro-lens array (MLA) coupler, an evanescent wave (EW) coupler, an adiabatic coupler, a wavelength division multiplexing (WDM) coupler, a prism coupler, a butt coupler, an end-fire coupler, and a V-groove coupler. In certain examples, the interface block includes a polarizing beam splitter to separate light into orthogonal polarization states. Such beam splitters can be used to combine two orthogonally polarized signals exiting the PIC and/or to split an unpolarized signal into two orthogonal polarization states before the signal enters the PIC. In some examples, the interface block includes a fiber array unit (FAU) for connecting the PIC with an array of optical fibers. For example, the fiber connector 106 and optical interface 140 can constitute a FAU that is bonded to the surface 135 of the package 101. The FAU may be one of a variety of types of FAUs including linear and circulate. FAUs are typically made from precision-molded plastic or ceramic material and may have anywhere from a few to hundreds of fibers arranged in a specific pattern, e.g., 30 fibers or more, 40 fibers or more, 80 fibers or more, such as 200 fibers or less. The choice of FAU or FAU type may depend on specific requirements of an application, such as the number of fibers, the arrangement of the fibers, the wavelength of light being used, and the coupling efficiency desired.

As noted above, the molding compound 134 at least partially encapsulates the PIC 110, the EIC 150, and the spacer 130 within the package 101 against the base 132. In other words, the molding compound 134 at least partially encloses the PIC 110, and the EIC 150 by filling in the space between these components and the base 132.

While the partially encapsulated EIC 150 in package 101 has an exposed top surface that is coplanar with the top surface of the layer of molding compound 134, other implementations are possible. For example, referring to FIG. 1B, in some implementations a heat sink 130 is thermally coupled, e.g., using a thermal interface material (TIM) to the top surface of the EIC 150 to provide a circuit package 100'.

Referring to FIG. 2, another example circuit package 101 includes a layer of molding compound 234 that extends over the top surface of the EIC 150.

In general, the co-packaged optics described herein (for FIG. 1A, FIG. 1B, and FIG. 2, and below) can be used in an artificial intelligence (AI) accelerator, a bridge, a chiplet, or any other configuration that can benefit from photonic links on and off the package or within the package. Examples can include packages with more than one EIC
 5 that share a common PIC interposer and communicate via a plurality of intra-chip bidirectional photonic channels. Other examples include circuit packages that include an EIC which can communicate with external components via a plurality of inter-chip bidirectional photonic channels as discussed in further detail herein.

In addition, it will be noted that features and functionality of the circuit package
 10 may be implemented within a variety of implementations and configurations of packages having different components and configurations. Indeed, the circuit package may be implemented as part of any of a variety of optical blocks that form a portion of an inter-package photonic channel passing between a grating coupler region and an optical interface (or other interface block component), and which may be coplanar with a top
 15 surface of the package, e.g., the top surface of the electrical layer of the circuit package. In one or more examples, the circuit package is part of an optical bridge like the one described in Application No. 18/123,083 entitled "Optical Multi-Die Interconnect Bridge (OMIB)", the entirety of which is incorporated by reference.

In general, the EICs of circuit packages described above can be, at least a portion
 20 of, a memory device, a computing device, a storage device, or a combination thereof. Examples include, but are not limited to, a random-access memory (RAM) device (such as a static RAM (SRAM) device, a magnetic RAM (MRAM) device, a resistive RAM (RRAM) device, or a conductive-bridging or a conductive-bridging RAM (CBRAM) device), a logic device, e.g., an AND, OR, NANO, NOR, or EXOR gate), a NANO flash
 25 memory, a solid state drive (SSD) memory, a NOR flash memory, a CMOS memory, a thin film transistor-based memory, a phase-change memory (PCM), a storage class memory (SCM), a magneto-resistive memory (MRAM), a resistive RAM. a DRAM, a high bandwidth memory (HBM), a DOR-based DRAM, a DIMM memory, a CPU, a GPU, an MPU, a tensor engine, a load/store unit (LDSU), a neural compute engine, a dot-
 30 product and/or convolution engine, a field programmable gate array (FPGA), an AI accelerator, or any other suitable circuit element. Multiple instances of these devices may

be combined on a single die. For example, the EIC can include a memory including multiple memory arrays, one or more processors, other logic, communication circuits, and power management functions, and execute instructions stored in the memory array, or otherwise interact with the memory array using the processors on the EIC.

5 FIG. 3 illustrates an example manufacturing process for fabricating the packages described herein includes series of steps 300. In particular, FIG. 3 is a flowchart including a series of example steps for manufacturing and implementing a circuit package 100'. Alternative examples may omit, add to, reorder, and/or modify any of the steps shown in FIG. 3. The steps of FIG. 3 may be performed as part of a method (e.g., a
10 method for manufacturing a circuit package). In one or more examples, one or more machines may perform one or more of the steps of FIG. 3 with the aid of a processor(s) and computing device(s).

 The series of steps 300 includes step 310 of placing a photonic integrated circuit (PIC) over a carrier base. For instance, step 310 involves placing a photonic integrated
15 circuit (PIC) over a carrier base. The PIC includes one or more photonic channels.

 An EIC is attached 320 to the PIC on the surface of the PIC opposite the carrier base. The EIC can be flip chip bonded to the PIC, electrically connecting components in the EIC to components in the PIC via copper posts, for example.

 The EIC and the PIC are encapsulated 330 by molding compound. Typically, the
20 encapsulation process involves injection molding uncured molding compound around the PIC and the EIC at high pressure and curing the compound. Depending on the implementation, molding compound can be cure by a variety of possible mechanisms, including use of a two stage epoxy, thermal curing, or actinic radiation.

 A portion of the cured molding compound is removed 340, e.g., by grinding
25 and/or polishing. This process exposes the top surface of the EIC and ensures a planar surface of the layer of the molding compound over the optical couplers in the PIC.

 A heat sink is attached 350 to the exposed surface of the EIC. For example, the heat sink can be attached using a thermal paste to ensure good thermal coupling at the interface.

30 An optical interface is attached 360 to the surface of the molding compound after alignment of the optical interface with the optical couplers in the PIC.

While the foregoing examples feature co-packaged optics (CPO) in which an EIC is bonded to a surface of a PIC, more generally the packaging techniques described here can be applied to other CPO systems where an optical path is provided through a layer of molding compound. For example, in some examples, multiple EICs (e.g., one or more processor units and/or one or more memory units) can be bonded to a single PIC. In certain examples, electronic components can be integrated into the PIC, rather than (or in addition to) being in a separate EIC. For instance, the driver and/or TIA can be integrated into the PIC. Moreover, while the foregoing examples show arrangements in which light is coupled into and out of the PIC via a surface of the PIC, other coupling schemes are possible. For example, edge coupling can be used. In such examples, the optical path(s) for light from coupled fibers can traverse transparent molding at an edge of the PIC.

The following numbered paragraphs are non-limiting examples of innovative embodiments of the present disclosure.

What is claimed is:

1. An integrated circuit package, comprising:

a photonic integrated circuit (PIC) comprising an active element, an optical
5 coupling element arranged to receive light at a surface of the PIC and couple the light
into one or more waveguides in the PIC, the active element being located in a first
portion of the PIC, and the optical coupling element being in a second portion of the PIC
spaced apart from the first portion; and

a molding compound at least partially encapsulating the PIC, a layer of the
10 molding compound covering the surface of the PIC at the second portion,

wherein the molding compound at the second portion is transparent to light at in
an operative wavelength band of the PIC, the layer of the molding compound, optical
coupling element, and one or more waveguides providing an optical path through the
package to the active element for light in the operative wavelength band.

15 2. The package of claim 1, further comprising a first electrical integrated circuit
(EIC) electrically connected to the PIC.

3. The package of claim 2, wherein the first EIC is attached to the surface of the PIC
20 overlapping the first portion and non-overlapping the second portion.

4. The package of claim 3, wherein the first EIC is at least partially encapsulated by
the molding compound.

25 5. The package of claim 4, wherein a surface of the first EIC facing away from the
PIC is at least partially free of the molding compound.

6. The package of claim 5, further comprising a heat sink supported by the first EIC
at the surface at least partially free of the molding compound.

7. The package of claim 3, further comprising a second EIC attached to the surface of the PIC and overlapping a further portion of the PIC not overlapped by the first EIC or second portion of the PIC.

5 8. The package of claim 1, further comprising an optical interface for an optical fiber affixed to a surface of the layer of molding compound.

9. The package of claim 8, wherein the optical interface is affixed to the surface of the layer of the molding compound by an optical adhesive and the molding compound
10 comprises the optical adhesive.

10. The package of claim 8, wherein the optical interface comprises a fiber array unit (FAU).

15 11. The package of claim 1, further comprising an optical interface affixed to the molding compound on a surface of the layer of the molding compound opposite the PIC, the optical interface comprising a connector for receiving at least one optical fiber and one or more optical elements arranged to direct light in the operative wavelength band from the optical fiber to the optical coupling element.

20

12. The package of claim 11, wherein the optical interface comprises a polarizing beam splitter for splitting an optical signal into a pair of signals having orthogonal polarization states prior to the pair of optical signals entering the PIC or for combining a pair of orthogonal polarized optical signals exiting the PIC.

25

13. The package of claim 11, wherein the one or more optical elements comprise at least one focusing element for focusing light through the spacer to the optical coupling element.

30 14. The package of claim 11, wherein the optical interface comprising an array of lenses, at least one of the lenses in the array corresponding to the one or more optical

elements arranged to direct the light in the operative wavelength band from the optical fiber to the optical coupling element.

5 15. The package of claim 1, wherein the molding compound comprises a plastic material.

16. The package of claim 15, wherein the plastic material is a thermoset plastic material.

10 17. The package of claim 15, wherein the plastic material is an epoxy.

18. The package of claim 15, wherein the plastic material comprises an optical adhesive.

15 19. The package of claim 18, wherein the optical adhesive is an epoxy, an acrylate, a silicone, or a urethane.

20 20. The package of claim 15, wherein the plastic material is a single-component plastic material.

21. The package of claim 15, wherein the plastic material is a multi-component plastic material.

25 22. The package of claim 15, wherein the molding compound further comprises an inorganic component.

23. The package of claim 22, wherein the inorganic component comprises nanoparticles and/or microparticles.

30 24. The package of claim 23, wherein the inorganic component comprises silica.

25. The package of claim 23, wherein the inorganic component constitutes 50 wt.% or more of the molding compound.

26. The package of claim 23, wherein the inorganic component comprises particles
5 composed of a compound selected from the group consisting of Ge, Si, ZnS, ZnSe, AlO, and MgF.

27. The package of claim 23, wherein a refractive index of the plastic material at an operative wavelength and a refractive index of the inorganic component at the operative
10 wavelength are mismatched by 0.02 or less .

28. The package of claim 1, wherein the PIC further comprises a demultiplexer in the optical path between the optical coupling element and the active element.

15 29. The package of claim 28, wherein the active element is a photodiode or a modulator.

30. The package of claim 1, wherein the PIC further comprises a multiplexer in the optical path between the optical coupling element and the active element.

20

31. The package of claim 1, wherein the optical path is part of a bidirectional photonic channel between the first EIC and a component external to the package, the bidirectional photonic channel comprising the first optical path and a second optical path between another optical coupling element and another active element.

25

32. The package of claim 31, wherein the first EIC comprises an application-specific integrated circuit (ASIC).

33. The package of claim 31, wherein the first EIC comprises a memory interface.

30

34. The package of claim 1, wherein the operative wavelength band comprises a C-band.

35. A method of making an integrated circuit package, comprising:

5 providing a photonic integrated circuit (PIC) comprising an active element, an optical coupling element arranged to receive light at a surface of the PIC and couple the light into one or more waveguides in the PIC, the active element being located in a first portion of the PIC, and the optical coupling element being in a second portion of the PIC spaced apart from the first portion; and

10 encapsulating at least a portion of the PIC in a molding compound such that a layer of the molding compound covers the surface of the PIC at the second portion, wherein the molding compound at the second portion is transparent to light at in an operative wavelength band of the PIC, the layer of the molding compound, optical coupling element, and one or more waveguides providing an optical path through the
15 package to the active element for light in the operative wavelength band.

36. The method of claim 35, wherein encapsulating the PIC comprises injection molding an uncured molding compound around the PIC and curing the uncured molding compound to provide the molding compound.

20

37. The method of claim 36, further comprising removing a portion of the molding compound to provide a planar surface at the layer of the molding compound.

38. The method of claim 37, wherein removal of the portion of the molding
25 compound exposes a surface of an electrical integrated circuit (EIC) electrically connected to the PIC.

39. The method of claim 38, further comprising attaching a heat sink to the exposed surface of the EIC.

30

40. The method of claim 35, further comprising attaching an optical interface to a surface of the layer of the molding compound.

41. The method of claim 40, wherein the optical interface is attached using an optical
5 adhesive.

42. The method of claim 41, wherein the optical adhesive is the same as at least a component of the molding compound.

10 43. The method of claim 35, further comprising:
providing an electrical integrated circuit (EIC);
attaching the EIC to the surface of the PIC; and
encapsulating at least a portion of the EIC with the molding compound while
encapsulating at least a portion of the PIC.

15