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### **ELECTRONIC DEVICES WITH SIDEWALL ANTENNAS AND METHODS OF FABRICATING SUCH DEVICES**

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#### **Abstract**

An electronic device includes a device substrate with a mounting surface, an electronic circuit coupled to the mounting surface, and encapsulant material over the electronic circuit and the mounting surface. The encapsulant material has an upper encapsulant surface and a plurality of encapsulant sidewalls extending between the mounting surface of the device substrate and the upper encapsulant surface. The electronic device also includes a sidewall antenna coupled to one of the encapsulant sidewalls, and a shield structure embedded within the encapsulant material between the sidewall antenna and the electronic circuit. The sidewall antenna is electrically coupled to the electronic circuit through the device substrate. The shield structure extends from the mounting surface of the device substrate toward the upper surface of the encapsulant material. The sidewall antenna may be selected from an end-fire type of antenna and a broadside-fire type of antenna.

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## Background/Summary

### TECHNICAL FIELD

[0001] Embodiments of the subject matter described herein relate generally to electronic devices that include antennas.

### BACKGROUND

[0002] Various types of electronic systems include antennas that radiate and receive electromagnetic signals over the air. Some systems include electronic devices that include antennas and circuitry within a same device package. When antennas and circuitry are integrated within the same package, it is important to design the device so that electromagnetic signal interference associated with the antenna does not detrimentally affect the performance and proper functioning of the circuitry. Accordingly, system designers continue to develop structures and methods that make electronic systems less prone to performance degradation due to interfering electromagnetic radiation.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0003] A more complete understanding of the subject matter may be derived by referring to the detailed description and claims when considered in conjunction with the following figures, wherein like reference numbers refer to similar elements throughout the figures.

[0004] FIG. 1 is a top, external view of an antenna-in-package electronic device that includes an electronic circuit coupled to first and second sidewall antennas, in accordance with an example embodiment;

[0005] FIG. 2 is a side, cross-sectional view of the electronic device of FIG. 1 or FIG. 4 along line 2-2;

[0006] FIG. 3 is a side, external view of the electronic device of FIG. 1, in accordance with an example embodiment;

[0007] FIG. 4 is a top, external view of an antenna-in-package electronic device, in accordance with another example embodiment;

[0008] FIG. 5 is a side, external view of the electronic device of FIG. 4, in accordance with an example embodiment;

[0009] FIG. 6 is an example of a planar Yagi-Uda antenna, in accordance with an example embodiment;

[0010] FIG. 7 is an example of a planar patch antenna, in accordance with an example embodiment; and

[0011] FIG. 8 is a flowchart of a method for fabricating the electronic device embodiments of FIGS. 1-5, in accordance with an example embodiment.

### DETAILED DESCRIPTION

[0012] Embodiments of the inventive subject matter described herein include antenna-in-package electronic devices that allow for good radio frequency (RF) isolation of the antennas by use of directional antennas (e.g., end-fire type antennas and/or broadside-fire type antennas) located on opposed package sidewalls to provide broadside radiation patterns. The sidewall orientation of the antennas results in radiation patterns that are directed away from the top of the device (laterally from the sidewall) in a broadside fashion, thus substantially preventing or reducing interference

between antennas on opposite sidewalls of the package. Additionally, embodiments of antenna-in-package electronic devices include vertically-oriented grounded shields between the antennas and the rest of the package (e.g., circuitry between the antennas), which ground shields function to isolate radiation associated with the antenna functioning from transmitting within the package. According to one or more embodiments, a ground plane can be formed horizontally and below the antennas to act as an antenna back stop.

[0013] FIG. 1 is a top, external view of an antenna-in-package electronic device **100** that includes an electronic circuit **180** coupled to first and second sidewall antennas **121**, **122**, in accordance with an example embodiment. To enhance understanding, FIG. 1 should be viewed simultaneously with FIG. 2, which is a side, cross-sectional view (along line 2-2 of FIG. 1) and with FIG. 3, which is a side, external view of the electronic device **100** of FIG. 1.

[0014] Briefly, device **100** includes a device substrate **110** with a first substrate surface **111**, a second substrate surface **112**, and substantially-planar first, second, third, and fourth substrate sidewalls **101**, **102**, **103**, **104** that extend between the first and second substrate surfaces **111**, **112**. The second substrate surface **112** of the device substrate **110** corresponds to a bottom surface **105** of the device **100**.

[0015] In addition, device **100** includes an electronic circuit **180** coupled to the first substrate surface **111**, and encapsulant material **190** covering the electronic circuit **180**. The encapsulant material **190** is defined by an upper encapsulant surface **192** and substantially-planar first, second, third, and fourth encapsulant sidewalls **141**, **142**, **143**, **144** that extend from the first substrate surface **111** to the upper encapsulant surface **192**. According to one or more embodiments, the encapsulant material **190** may include a material that supports a laser direct structuring (LDS) process, as will be described in more detail in conjunction with block **810** of FIG. 8.

[0016] As will be described in detail below, planar first and second sidewall antennas **121**, **122** are coupled to the encapsulant sidewalls (e.g., to sidewalls **141**, **143**), and are electrically coupled through the device substrate **110** to the electronic circuit **180**. According to one or more embodiments, the first and second sidewall antennas **121**, **122** are directional antennas.

Accordingly, during system operation, the device **100** is configured to transmit RF signals with power concentrated in a first radiation pattern **187** that extends from the first sidewall antenna **121**, as indicated with ovals that extend from antenna **121**. Further, the device **100** is configured to have the highest sensitivity to receiving RF signals through a second radiation pattern **189** that extends from the second sidewall antenna **122**, as indicated by ovals that extend from antenna **122**. The transmit and receive RF signals may be processed by the embedded electronic circuit **180** (e.g., a transceiver circuit), as will be described in more detail below.

[0017] According to one or more embodiments, the electronic device **100** may be a discrete, surface-mountable device, and conductive features on the second substrate surface **112** (and thus the bottom surface **105** of device **100**) may be configured to provide for physical and electrical attachment to external circuitry (e.g., to a system substrate, not shown, associated with a radar or communications system). Accordingly, the second substrate surface **112** may be referred to herein as a “terminal surface” of the device **100**. According to an embodiment, a plurality of conductive device terminals (e.g., terminals **160**, **161**, **166**, FIG. 2) are exposed at the terminal surface **105**, **112**, and these device terminals facilitate communication of electrical signals and voltages between circuitry within the device **100** (e.g., electronic circuit **180**) and the external circuitry (not shown). More specifically, the device terminals at the terminal surface **105**, **112** may be aligned with corresponding terminals (not shown) on a system substrate (not shown), and the device terminals and the system substrate terminals may be physically and electrically connected using conductive attachment material (e.g., solder balls **170**, FIG. 2). Accordingly, device **100** essentially is a surface-mountable, ball grid array (BGA) type of device. In other embodiments, a different type of electronic and mechanical interface may be used to connect the device **100** to a system substrate (e.g., device **100** may be a land grid array (LGA), a pin grid array (PGA) device, or have another

type of interconnect structure).

[0018] The device substrate **110** may, in various embodiments, take the form of a redistribution layer (RDL) structure, a multiple-layer printed circuit board (PCB) or another suitable structure. Regardless of the form it takes, the device substrate **110** includes multiple conductive layers **113**, **114**, **115**, **116** (FIG. 2) separated by multiple dielectric layers **117**, **118**, **119** (FIG. 2). In the below description, each of the conductive layers **113-116** may be referred to as a “patterned” conductive layer, meaning that the conductive layer may include multiple conductive features that are separated by non-conductive gaps. The use of the term “patterned” is not meant to limit how the conductive features of the conductive layer are formed. The conductive features may be formed by a subtractive process (e.g., blanket deposit the conductive layer and subsequently remove conductive material to create non-conductive gaps) or by an additive process (e.g., by printing the conductive features).

[0019] A first patterned conductive layer **113** is referred to herein as an “upper” conductive layer, a fourth patterned conductive layer **116** is referred to herein as a “lower” conductive layer, and second and third patterned conductive layers **114**, **115** are referred to herein as “intermediate” conductive layers. Conductive vias (not numbered), may extend through the dielectric layers **117-119** to connect various sets of conductive features within adjacent conductive layers **113-116**. Although four conductive layers **113-116** and three dielectric layers **117-119** are depicted in the drawings, alternate embodiments of a routing structure may include more or fewer conductive and dielectric layers.

[0020] According to some embodiments, the upper conductive layer **113** of the device substrate **110** includes a plurality of conductive features on or exposed at the mounting surface **111** of the device substrate **110**. For example, the upper conductive layer **113** may include conductive features in a roughly central portion of the upper surface **111** that correspond to conductive circuitry pads (e.g., pads **123**, **124**, **125**, **126**, FIG. 2) to which an electronic circuit **180** is physically and electrically coupled, as will be described in more detail below. Portions of the upper conductive layer **113** also may provide additional conductive structures. For example, the upper conductive layer **113** may include conductive ground pads **127** that are configured to be coupled to first and second shield structures **150** (described below), and may include conductive antenna pads **128**, **129** configured to be coupled to first and second antennas **121**, **122** (also described below), respectively. In addition, patterned portions of the upper conductive layer **113** may form conductive antenna ground planes **130** (also described below).

[0021] The one or more intermediate conductive layers **114**, **115** may function as routing layers that facilitate electrical connection between features of the upper conductive layer **113** (e.g., pads **123-129** and antenna ground planes **130**) and device terminals (e.g., terminals **160**, **161**, **166**) formed from portions of the lower conductive layer **116** at the second substrate surface **112** (and thus at the terminal surface **105** of the device **100**). Although two intermediate conductive layers **114**, **115** are shown in FIG. 2, more or fewer intermediate conductive layers may be included, in other embodiments.

[0022] The lower conductive layer **116** may provide the above-mentioned conductive device terminals **160**, **161**, **166**. According to one or more embodiments, some of the device terminals **160** are configured to be coupled to ground (or to another voltage reference) of a larger electrical system, and thus the device terminals **160** may be referred to herein as “ground terminals.” For example, according to one or more embodiments, the above-mentioned antenna ground planes **130** and the ground pads **127** are electrically coupled through conductive routing paths **131** to the ground terminals **160** at the terminal surface **105** of the device **100**. This enables the ground pads **127** and the antenna ground planes **130** to be grounded during system operation.

[0023] Other ones of the device terminals **161**, **166** are configured as input/output (I/O) terminals, which are configured to be coupled to signal inputs from the larger electrical system or to signal outputs to the larger electrical system. This enables the device **100** to receive input signals from and

provide output signals to the larger electrical system. Still other ones of the device terminals (not numbered) are configured as control or bias terminals.

[0024] As mentioned above, device **100** also includes circuitry coupled to the upper substrate surface **111**. Accordingly, the upper substrate surface **111** of the device substrate **110** may be referred to as a “mounting surface.” As will be described in more detail below, the circuitry coupled to the mounting surface **111** of the device substrate **110** includes an electronic circuit **180**, which is embedded within the above-mentioned encapsulant material **190**. The upper surface **192** of the encapsulant material **190** corresponds to the upper surface **106** of the device **100**. Again, substantially-planar first, second, third, and fourth encapsulant sidewalls **141**, **142**, **143**, **144** extend from the mounting surface **111** of the device substrate **110** to the upper encapsulant surface **192**. In some embodiments, the substantially-planar first, second, third, and fourth encapsulant sidewalls **141-144** may be oriented in parallel planes to the substantially-planar first, second, third, and fourth substrate sidewalls **101-104**, respectively. In other embodiments, the encapsulant sidewalls **141-144** and the substrate sidewalls **101-104** may be oriented in non-parallel planes.

[0025] Device **100** also includes first and second sidewall antennas **121**, **122** coupled to at least two of the encapsulant sidewalls **141-144** (e.g., to encapsulant sidewalls **141** and **143**, as shown in FIGS. 1-3). In the illustrated embodiments, the first sidewall antenna **121** is coupled to the first encapsulant sidewall **141**, and the second sidewall antenna **122** is coupled to the third encapsulant sidewall **143**, which is parallel to but on the opposite side of the device **100** from the first encapsulant sidewall **141**. During operation of the device **100**, the first sidewall antenna **121** is used to transmit RF signals, and thus, the first sidewall antenna **121** may be referred to herein as a “transmit antenna.” The second sidewall antenna **122** is configured to receive RF signals, and thus, the second sidewall antenna **122** may be referred to herein as a “receive antenna.” Encapsulant sidewalls **141**, **143** may be considered to be “radiation surfaces” of the device **100**, because the sidewall antennas **121**, **122** on those sidewalls **141**, **143** are configured to radiate and/or receive radio frequency (RF) signals at the sidewalls **141**, **143**.

[0026] Although the embodiments described herein include one transmit antenna **121** coupled to the first sidewall **141** of the device **100**, and one receive antenna **122** coupled to the opposed, third sidewall **143** of the device **100**, other configurations are intended to be encompassed by the inventive subject matter. For example, in other embodiments, both transmit and receive antennas may be coupled to a same encapsulant sidewall (e.g., one or more transmit antennas and one or more receive antennas may be coupled to any one or more of sidewalls **141-144**). In still other embodiments, multiple transmit or receive antennas may be coupled to an encapsulant sidewall (e.g., multiple transmit antennas or multiple receive antennas may be coupled to any one or more of sidewalls **141-144**). In still other embodiments, rather than having antennas coupled to exactly two encapsulant sidewalls, as shown in the figures, one or more transmit and/or one or more receive antennas may be coupled to only one of the encapsulant sidewalls (e.g., only to sidewall **141**), or alternatively, transmit and/or receive antennas may be coupled to three or four of the encapsulant sidewalls (e.g., to sidewalls **141-143**). In still other embodiments, antennas may be coupled to adjacent encapsulant sidewalls, in addition to or instead of being coupled to opposed sidewalls.

[0027] According to one or more embodiments, the first and second sidewall antennas **121**, **122** are directional antennas. In some embodiments, the transmit and receive antennas **121**, **122** are characterized by substantially upwardly-extending radiation patterns **187**, **189**. As used herein, “upwardly” means that the main lobes of the radiation patterns **187**, **189** extend from the antennas **121**, **122** beyond the upper surface **192** of the encapsulant material **190** in a direction that is substantially parallel to the encapsulant sidewalls **141**, **143**, as indicated by arrows **196**. More specifically, the power of the RF signals that are transmitted by the transmit antenna **121** is strongest in a substantially upwardly-extending direction encompassed by radiation pattern **187**. Conversely, the receive antenna **122** is configured to have a highest sensitivity to RF signal power from other sources in a direction encompassed by radiation pattern **189**. Said another way, the

sensitivity as a function of direction of the receive antenna **122** is highest within a substantially upwardly-extending radiation pattern **189**. According to such embodiments, as will be described in more detail in conjunction with FIG. **6**, the transmit and receive antennas **121**, **122** may include planar, end-fire types of antennas that are characterized by the above-described, upwardly-extending radiation patterns **187**, **189**.

[0028] According to one or more alternate embodiments, the transmit and receive antennas **121**, **122** may be characterized by substantially laterally-extending radiation patterns (not shown), where “laterally,” as used herein, means that the main lobes of the radiation patterns extend from the antennas **121**, **122** in opposite directions that are substantially perpendicular to the encapsulant sidewalls **141**, **143**. More specifically, the power of the RF signals that are transmitted by the transmit antenna **121** is strongest in a substantially laterally-extending direction indicated by arrow **197**. Conversely, the receive antenna **122** is configured to have a highest sensitivity to RF signal power from other sources in an opposite, substantially laterally-extending direction indicated by arrow **198**. Said another way, the sensitivity as a function of direction of the receive antenna **122** is highest within a substantially laterally-extending radiation pattern. According to such embodiments, the transmit and receive antennas **121**, **122** may include planar, broadside-fire types of antennas that are characterized by the above-described, laterally-extending radiation patterns, as will be described in more detail in conjunction with FIG. **8**.

[0029] According to an embodiment, at least some of the encapsulant sidewalls **141-144** are recessed or set back from the substrate sidewalls **101-104** with which they are oriented in parallel planes (e.g., encapsulant sidewall **141** is recessed from substrate sidewall **101**, encapsulant sidewall **143** is recessed from substrate sidewall **103**, and so on). Such a configuration results in portions of the mounting surface **111** being exposed between at least some of the encapsulant sidewalls **141-144** and at least some of the substrate sidewalls **101-104**. According to one or more embodiments, substantially-planar, horizontally-oriented, first and second antenna ground planes **130** are provided at or below the mounting surface **111** in the exposed portions of the mounting surface **111** between encapsulant sidewall **141** and substrate sidewall **101**, and between encapsulant sidewall **143** and substrate sidewall **103**. The antenna ground planes **130** are oriented perpendicular to the encapsulant sidewalls **141**, **143** to which they are adjacent. The antenna ground planes **130** are configured, during operation of device **100**, to act as an antenna back stop, and thus to shield the device substrate **110** from electromagnetic radiation produced by sidewall antenna **121**, and from electromagnetic radiation that impinges upon sidewall antenna **122**. Further, the antenna ground plane **130** that is adjacent to the sidewall antenna **121** is configured to reflect signals produced by the sidewall antenna **121** in a generally upward direction. Further still, the antenna ground plane **132** that is adjacent to the sidewall antenna **122** is configured to reflect electromagnetic radiation that impinges on the ground plane **130** upward toward the sidewall antenna **122**. Any such energy is conveyed from the antenna ground planes **130** through the device substrate **110** (e.g., through routing paths **131**) to the ground terminals **160**. Accordingly, potential interference from the transmit and receive RF signals within the radiation patterns **187**, **189**, which may otherwise impinge upon the device substrate **110**, is reduced or substantially eliminated through the inclusion of the antenna ground planes **130**.

[0030] As best seen in FIG. **1**, the antenna ground planes **130** may be electrically separated from (isolated from) the antenna pads **128**, **129** (and thus from the antennas **121**, **122**) by virtue of non-conductive gaps in the upper conductive layer **113**. The antenna ground planes **130** may substantially cover all portions of the upper substrate surface **111** between the antenna pads **128**, **129** (and the antennas **121**, **122**) and the substrate sidewalls **101**, **103**, extending also to sidewalls **102** and **104**. During operation of the device **100**, this configuration may substantially prevent the electromagnetic energy emanating from the transmit antenna **121** or being received by the receive antenna **122** from being conveyed into the device substrate **110**. In alternate embodiments (not illustrated), some or all of the encapsulant sidewalls **141-144** may be co-planar with the substrate

sidewalls **101-104**, and the antenna ground planes **130** may be excluded.

[0031] According to one or more embodiments, the electronic device **100** also includes vertically-oriented, first and second shield structures **150** embedded in the encapsulant material **190** behind the sidewall antennas **121**, **122** (i.e., between the sidewall antennas **121**, **122** and the electronic circuit **180**). The shield structures **150** extend in a perpendicular direction from the mounting surface **111** of the system substrate **110** toward (or to) the upper encapsulant surface **192**. The shield structures **150** are configured, during operation of device **100**, to shield the embedded electronic circuit **180** within the device **100** from electromagnetic radiation produced by sidewall antenna **121**, and from electromagnetic radiation that impinges upon sidewall antenna **122**. The shield structures **150** may convey any such energy from the shield structures **150** through the device substrate **110** (e.g., through routing paths **131**) to the ground terminals **160**. Accordingly, potential interference from the transmit and receive RF signals within the radiation patterns **187**, **189**, which may otherwise affect the operation or performance of the electronic circuit **180**, is reduced or substantially eliminated through the inclusion of the shield structures **150**.

[0032] First portions **193** (FIG. 2) of encapsulant material **190** are present between the shield structures **150** and the encapsulant sidewalls **141**, **143**, and second portions **194** (FIG. 2) of the encapsulant material **190** are present between the shield structures and the electronic circuit **180**.

[0033] As most clearly seen in FIGS. 1 and 3, according to one or more embodiments, the shield structures **150** may be implemented as a plurality of conductive vias **152** (or conductive posts) that have proximal ends coupled to the ground pads **127** at the mounting surface **111** of the device substrate **110**, and distal ends that extend towards or to the upper encapsulant surface **192**. The conductive vias **152** may be arranged along a straight line between encapsulant sidewalls **142** and **144**, thus forming a row as shown in FIG. 1. In other embodiments, adjacent ones of the conductive vias **152** may be offset from each other (e.g., the vias **152** may be arranged in a zigzag, sinusoidal, sawtooth, or other pattern between encapsulant sidewalls **142** and **144**). In still other embodiments, multiple rows of conductive vias **152** may be implemented. Regardless of the arrangement of the conductive vias **152**, the lateral sides of each of the conductive vias **152** are surrounded by the encapsulant material **190**, in some embodiments.

[0034] The cumulative length **153** (FIG. 1) of the set of conductive vias **152** that make up each shield structure **150** may be slightly shorter than the width **191** (FIG. 1) of the encapsulant material **190** between sidewalls **142** and **144** so that third portions **195** (FIG. 3) of the encapsulant material **190** are present between the lateral sides of the outermost (leftmost and rightmost, in FIG. 3) conductive vias **152** and encapsulant sidewalls **142**, **144**, which are adjacent to the encapsulant sidewalls **141** and **143**. For example, the cumulative length **153** of each shield structure **150** may be in a range of about 400 microns to about 4000 microns.

[0035] According to one or more embodiments, a width **363** (FIG. 3) of the third portions **195** of the encapsulant material **190** may be selected to avoid a potential phenomenon of signal energy from the antennas **121**, **122** reflecting inward from the encapsulant sidewalls **142**, **144** through the space between the encapsulant sidewalls **142**, **144** and the lateral sides of the outermost conductive vias **152**. For example, the selected width **363** may be in a range of about  $\lambda/16$  to about  $\lambda/8$  (i.e., less than or equal to  $\lambda/8$ ), where  $\lambda$  is the wavelength associated with the frequency of operation of the device **100**, or the lower bandwidth limit. In general, when a signal waveform strikes an interface between two materials with different physical properties, some of the waveform energy may be reflected, and the rest may be transmitted through the interface. By selecting a width **363** that is a fraction of the wavelength, any reflected waveform energy is prevented from bypassing the conductive vias **152**.

[0036] In addition, adjacent vias **152** within each shield structure **150** are separated from each other by an inter-via spacing **362** (FIG. 3), that is filled with the encapsulant material **190**. For example, the inter-via spacing **362** may be in a range of about 100 microns to about 1000 microns, although the inter-via spacing **362** may be smaller or larger, as well. The inter-via spacing **362** may be

selected based on the frequency or bandwidth of operation of the device **100**. More particularly, the inter-via spacing **362** may be selected to block signal energy from traveling from the transmit and receive antennas **121**, **122** toward the electronic circuit **180**. For example, the selected inter-via spacing **362** may be in a range of about  $\lambda/16$  to about  $\lambda/8$  (i.e., less than or equal to  $\lambda/8$ ), where  $\lambda$  is the wavelength associated with the frequency of operation of the device **100**, or the lower bandwidth limit. Again, by restricting the inter-via spacing **362** to a fraction of the wavelength of the signal waveform, the conductive vias **152** may block waveform energy from reaching the embedded electronic circuit **180**.

[0037] According to one or more embodiments, the heights **159** of the conductive vias **152** within the shield structures **150** are at least as high as the height (not numbered) of the electronic circuit **180** (or at least those components of the electronic circuit **180** that are susceptible to electromagnetic interference). Further, in some embodiments, the heights **159** of the conductive vias **152** may be about equal to the height (not numbered) of the encapsulant material **190**. In some embodiments, the distal ends of the vias **152** are exposed at the upper encapsulant surface **192** (and thus exposed at the upper surface **106** of the device **100**). In other embodiments, the heights **159** of the conductive vias **152** may be less than the height of the encapsulant **190**, although not significantly less to avoid a potential phenomenon of signal energy from the antennas **121**, **122** reflecting downward from the interface associated with the upper encapsulant surface **106** through the space between the upper encapsulant surface **106** and the tops of the conductive vias **152**. For example, the maximum difference in the heights of the encapsulant **190** and the vias **152** may be selected dependent on the bandwidth or frequency of operation of the device **100** (e.g., the maximum difference in height may be less than  $\lambda/8$ , where  $\lambda$  is the wavelength associated with the frequency of operation of the device **100**, or the lower bandwidth limit).

[0038] In the embodiment of FIG. 1, each conductive via **152** has a substantially circular cross-sectional shape. Accordingly, a height **159** of each via **152** is significantly greater (e.g., from 5 to 50 times greater) than its diameter (e.g., diameter **360**, FIG. 3). For example, but not by way of limitation, each conductive via **152** may have a height **159** in a range of about 20 microns to about 2000 microns. In other embodiments, the heights **159** may be smaller or larger than the above-given range. Further, the diameter **360** (FIG. 3) of each via **152** may be in a range of about 20 microns to about 200 microns, although the diameter **360** may be smaller or larger, as well.

[0039] In various embodiments, as will be described in more detail later in conjunction with FIG. 8, each conductive via **152** may include a conductive pillar (e.g., pillar **152**, step **804**, FIG. 8) that is built up upon or attached to the mounting surface **111** of the device substrate **110** (and more specifically to a ground pad **127**). The encapsulant material **190** may then be applied over the mounting surface **111** of the device substrate **110**. In other embodiments, each conductive via **152** may consist of an elongated hole in the encapsulant material **190** that is lined or filled with conductive material.

[0040] FIGS. 4 and 5 are top and side views of an alternate embodiment of an antenna-in-package electronic device **100'** that includes an electronic circuit **180** coupled to first and second sidewall antennas **121**, **122**. In FIGS. 4 and 5, the same reference numbers are used for features that are identical to the same-numbered features of FIGS. 1-3, and the above description of those same-numbered features is incorporated into this description of FIGS. 4 and 5.

[0041] In the alternate embodiment of device **100'** illustrated in FIGS. 4 and 5, rather than implementing shield structures (e.g., structures **150**, FIGS. 1-3) with conductive vias (e.g., vias **152**, FIGS. 1-3), each shield structure **150'** instead includes a continuous conductive trench or wall that has a "bar-shaped" (e.g., rectangular) cross-section. In this example, each shield structure **150'** is coupled to one or more conductive ground pads **127** at the upper surface **111** of the device substrate **110**, and each shield structure **150'** extends from the upper surface **111** toward or to the upper encapsulant surface **192**. In some embodiments, the cross-section of device **100'** in FIG. 4 along line 2-2 would appear substantially the same as the cross-section of device **100** of FIG. 1



along line 2-2, with shield structures **150'** (FIGS. 4 and 5) replacing conductive vias **152** (FIG. 2). [0042] The lateral sides of each shield structure **150'** are completely surrounded by the encapsulant material **190**, in some embodiments. Similar to vias **152** (FIGS. 1-3), each shield structure **150'** has a height **159** that is at least as high as the height (not numbered) of the electronic circuit **180** (or at least those components of the electronic circuit **180** that are susceptible to electromagnetic interference). Further, in some embodiments, the height **159** of the shield structures **150'** may be about equal to the height (not numbered) of the encapsulant material **190**. The distal ends of the shield structures **150'** are exposed at the upper encapsulant surface **192** (and thus exposed at the upper surface **106** of the device **100'**). In other embodiments, the heights **159** of the shield structures **150'** may be less than the height of the encapsulant **190**, although not significantly less to avoid the phenomenon of signal energy from the antennas **121**, **122** reflecting downward from the upper encapsulant surface **106** through the space between the upper encapsulant surface **106** and the tops of the shield structures **150'**. For example, the difference in the heights of the encapsulant **190** and the shield structures **150'** may be selected dependent on the bandwidth or frequency of operation of the device **100'** (e.g., the difference in height may be less than  $\lambda/8$ , where  $\lambda$  is the wavelength associated with the frequency of operation of the device **100'**, or the lower bandwidth limit).

[0043] The length **453** (FIG. 4) of each shield structure **150'** may be slightly shorter than the width **191** (FIG. 4) of the encapsulant material **190** between sidewalls **142** and **144** so that third portions **195** (FIG. 5) of the encapsulant material **190** are present between the lateral sides of the shield structures **150'** and encapsulant sidewalls **142**, **144**. For example, the length **453** of each shield structure **150'** may be in a range of about 400 microns to about 4000 microns.

[0044] According to one or more embodiments, a width **563** (FIG. 5) of the third portions **195** of the encapsulant material **190** may be selected to avoid a potential phenomenon of signal energy from the antennas **121**, **122** reflecting inward from the encapsulant sidewalls **142**, **144** through the space between the encapsulant sidewalls **142**, **144** and the lateral sides of the shield structures **150'**. For example, the selected width **563** may be in a range of about  $\lambda/16$  to about  $\lambda/8$  (i.e., less than or equal to  $\lambda/8$ ), where  $\lambda$  is the wavelength associated with the frequency of operation of the device **100'**, or the lower bandwidth limit.

[0045] In various embodiments, each shield structure **150'** may include a conductive wall that is built up upon or attached to the mounting surface **111** of the device substrate **110** (and more specifically to a ground pad **127**) before the encapsulant material **190** is applied over the mounting surface **111** of the device substrate **110**. In other embodiments, each shield structure **150'** may consist of an elongated trench in the encapsulant material **190** that is lined or filled with conductive material.

[0046] As discussed above, and referring to all of the embodiments illustrated in FIGS. 1-5, the electronic circuit **180** is coupled to mounting surface **111** of the device substrate **110** between the shield structures **150** (or **150'**) and between the transmit and receive antennas **121**, **122**. More particularly, the electronic circuit **180** includes a plurality of terminals (e.g., first, second, third, and fourth terminals **181**, **183**, **184**, **186**, FIG. 2), which are physically and electrically coupled to corresponding circuitry pads (e.g., first, second, third, and fourth circuitry pads **123**, **124**, **125**, **126**, FIG. 2) at the mounting surface **111** of the device substrate **110**. For example, as shown in FIG. 2, a first terminal **181** of the electronic circuit **180** is coupled to a first circuitry pad **123** of the device substrate **110**. Similarly, a second circuitry pad **124** is coupled to a second terminal **183**, a third circuitry pad **125** is coupled to a third terminal **184**, and a fourth circuitry pad **126** is coupled to a fourth terminal **186**.

[0047] According to one or more embodiments, and as indicated above, the electronic circuit **180** may be a transceiver circuit that includes transmitter circuitry **182** and receiver circuitry **185**. The terminals **181**, **183**, **184**, **186** of the electronic circuit **180** are electrically coupled to the transmitter and receiver circuitry **182**, **185**. For example, the first terminal **181** may function as an input

terminal to the transmitter circuitry **182**, and the second terminal **183** may function as an output terminal from the transmitter circuitry **182**. Further, the third terminal **184** may function as an input terminal to the receiver circuitry **185**, and the fourth terminal **186** may function as an output terminal from the receiver circuitry **185**.

[0048] According to an embodiment, the first circuitry pad **123** and the first terminal **181** of the electronic circuit **180** are electrically coupled through a conductive routing path **132** in the device substrate **110** to an input terminal **161** at the terminal surface **105** of the device **100, 100'**. The second circuitry pad **124** and the second terminal **183** of the electronic circuit **180** are electrically coupled through another conductive routing path **133** in the device substrate **110** to the antenna pad **128** and, thus, to the transmit antenna **121**. The third circuitry pad **125** and the third terminal **184** of the electronic circuit **180** are electrically coupled through yet another conductive routing path **134** in the device substrate **110** to the antenna pad **129** and, thus, to the receive antenna **122**. Finally, the fourth circuitry pad **126** and the fourth terminal **186** of the electronic circuit **180** are electrically coupled through yet another conductive routing path **135** in the device substrate **110** to an output terminal **166** at the terminal surface **105** of the device **100, 100'**.

[0049] During device operation, an input signal is conveyed from the input terminal **161** through the conductive path **132** to the first circuitry pad **123** and the first terminal **181**, and the transmitter circuitry **182** may process (e.g., amplify) the input signal, and provide a processed (e.g., amplified) version of the signal to the second terminal **183**. This signal, in turn, may be conveyed from the second circuitry pad **124** and conductive routing path **133** to the transmit antenna **121**, which then radiates the signal over the air as a transmit RF signal within radiation pattern **187**.

[0050] Conversely, during device operation, a receive RF signal with sufficient power within radiation pattern **189** may impinge upon the receive antenna **122**. The receive antenna **122** may convert the receive RF signal to an electrical signal that is conveyed from the receive antenna **122** through the conductive routing path **134** to the third circuitry pad **125** and the third terminal **184** of the electronic circuit **180**. The receiver circuitry **185** may then process (e.g., filter and amplify) the signal, and may provide a processed (e.g., filtered and amplified) version of the signal to the fourth terminal **186**. This signal, in turn, may be conveyed from the fourth circuitry pad **126** and the conductive routing path **135** to the output terminal **166** of the device **100, 100'**.

[0051] The electronic circuit **180** is depicted in the drawings as an integrated circuit (IC) device that includes terminals (e.g., terminals **181, 183, 184, 186**) that are coupled to corresponding conductive pads (e.g., pads **123, 124, 125, 126**) at the mounting surface **111** of the device substrate **110**. The IC device may be a flip-chip, ball grid array (BGA) device, which, in some embodiments, includes transmitter circuitry **182** and receiver circuitry **185**. In other embodiments, the electronic circuit **180** may be implemented with multiple ICs and/or discrete components, at least some of which are coupled to the mounting surface **111** of the device substrate **110**.

[0052] Although the illustrated embodiments of devices **100, 100'** each include one instance of transmitter circuitry **182** coupled to a single transmit antenna **121**, and one instance of receiver circuitry **185** coupled to a single receive antenna **122**, other embodiments may include only one instance of either the transmitter or receiver circuitry **182, 185**, and accordingly only one of either the transmit antenna **121** or the receive antenna **122**. In still other embodiments, a device may include multiple transmit antennas **121** and/or multiple receive antennas **122**, which may enable multiple-input, multiple-output (MIMO) operation.

[0053] As discussed above, the transmit and receive antennas **121, 122** may include one or more types of planar, end-fire antennas on the encapsulant sidewalls (e.g., on sidewalls **141, 143, FIG. 2**), which are configured to support radiation patterns **187, 189** with main lobes that extend substantially upward, as indicated by arrows **196** in FIG. 2. For example, either or both of the transmit and receive antennas **121, 122** may be selected from a planar Yagi-Uda antenna (as shown in FIGS. 3 and 5), a planar log periodic dipole antenna (LPDA), a planar Vivaldi (tapered slot) antenna, or another suitable planar, end-fire antenna.

[0054] Referring now to FIG. 6, a non-limiting example of a planar, Yagi-Uda antenna **600** is shown, which may be coupled to one or more of the encapsulant sidewalls (e.g., to sidewalls **141**, **143**) and used for either or both of the transmit and receive antennas **121**, **122**. According to an embodiment, the planar Yagi-Uda antenna **600** is a three-element antenna that includes an array of three parallel resonant antenna elements **612**, **614**, **616** (e.g., microstrip dipole elements) arranged in an antenna layout. In other embodiments, a suitable Yagi-Uda antenna may include more than three antenna elements **612**, **614**, **616**. Either way, centers of the antenna elements **612**, **614**, **616** are aligned with each other along a central axis **630**, and the antenna elements **612**, **614**, **616** are physically and electrically separated from each other by non-conductive gaps **613**, **615**. The length (horizontal dimension in FIG. 6) of each antenna element **612**, **614**, **616** is substantially greater than the width (vertical dimension in FIG. 6) of each antenna element **612**, **614**, **616**. According to one or more embodiments, each of the antenna elements **612**, **614**, **616** is formed from a relatively-thin stack of conductive material layers (e.g., comprising layers of copper, nickel, gold, and/or other suitable materials).

[0055] According to one or more embodiments, the antenna elements **612**, **614**, **616** include a driven element **612** and two director elements **614**, **616**. The length of the driven element **612** is relatively long, and the lengths of the director elements **614**, **616** become shorter, the farther the element **614**, **616** is from the driven element **612**. The director elements **614**, **616** are positioned, relative to the driven element **612**, in the intended direction of the radiation patterns (e.g., in directions indicated by arrows **196**, FIG. 2).

[0056] The director element **612** has a feed point **611** that is coupled to a proximal end **622** of a microstrip feed structure **620**. When integrated into a device (e.g., device **100**, **100'**, FIGS. 1-5), a distal end **624** of the microstrip feed structure **620** is coupled to an antenna pad (e.g., one of antenna pads **128**, **129**, FIG. 2). When the above-described Yagi-Uda antenna **600** is used in one of the above-described devices **100**, **100'** (FIGS. 1-5), the shield structure (e.g., shield structure **150**, **150'**) functions as a ground plane for the antenna **600**.

[0057] Although the Yagi-Uda antenna **600** described above has a particular arrangement of microstrip dipole elements **612**, **614**, **616**, the various elements may be differently arranged. For example, the driven element may be located between a reflector element and one or more director elements, according to other embodiments. Other variations also could be made.

[0058] As also described above, according to one or more alternate embodiments, the transmit and receive antennas **121**, **122** may include one or more types of planar, broadside-fire antennas on the encapsulant sidewalls (e.g., on sidewalls **141**, **143**, FIG. 2), which are configured to support radiation patterns with main lobes that extend substantially perpendicularly from the encapsulant sidewalls, as indicated by arrows **197**, **198** in FIG. 2. For example, either or both of the transmit and receive antennas **121**, **122** may be selected from a patch antenna, a slot antenna, a dipole antenna, a ring antenna, a spiral antenna, a bow tie antenna, or another suitable planar, broadside-fire antenna.

[0059] Referring now to FIG. 7, a non-limiting example of a planar patch antenna **720** is shown, which may be coupled to one or more of the encapsulant sidewalls (e.g., to sidewalls **141**, **143**) and used for either or both of the transmit and receive antennas **121**, **122**. According to an embodiment, the planar patch antenna **720** includes a planar microstrip element **712**, formed from a relatively-thin stack of conductive material layers (e.g., comprising layers of copper, nickel, gold, and/or other suitable materials) with a rectangular antenna layout. In other embodiments, the shape of the antenna layout for the patch antenna **720** may be different (e.g., round, hexagonal, triangular, etc.).

[0060] A feed point **711** along one edge of the microstrip element **712** is coupled to a proximal end **722** of a microstrip feed structure **720**. When integrated into a device (e.g., device **100**, **100'**, FIGS. 1-5), a distal end **724** of the microstrip feed structure **720** is coupled to an antenna pad (e.g., one of antenna pads **128**, **129**, FIG. 2). When the above-described patch antenna **700** is used in one of the above-described devices **100**, **100'** (FIGS. 1-5), the shield structure (e.g., shield structure **150**, **150'**)

functions as a ground plane for the antenna **700**.

[0061] Embodiments of methods for fabricating the above-described embodiments of devices **100**, **100'** will now be described. More specifically, FIG. **8** is a flowchart of a method for fabricating the electronic devices **100**, **100'** (FIGS. **1-5**), in accordance with one or more example embodiments. For enhanced understanding, small depictions of partially formed devices during the various fabrication stages are shown to the right of each corresponding flowchart block.

[0062] It should be mentioned here that devices **100**, **100'** may be fabricated individually. More likely, however, multiple instances of the devices **100**, **100'** may be fabricated simultaneously in a strip or panel form, where the individual devices **100**, **100'** are separated from the strip or panel (i.e., singulated) during a later fabrication step (e.g., in conjunction with block **812**). For ease of illustration, FIG. **8** depicts two devices that are formed in parallel in a strip that includes two device areas **801**. Those of skill in the art would understand, based on the description herein, how to form a single individual device, how to form a strip of more than two devices, and how to form a panel of devices.

[0063] The method begins, in block **802**, by mounting electronic circuits **180** to the mounting surface **111** of a device substrate panel **803** within each device area **801**. According to an embodiment, the device substrate panel **803** may be a multi-layer PCB, which includes multiple patterned conductive layers (e.g., layers **113-116**, FIG. **2**) separated by multiple dielectric layers (e.g., layers **117-119**, FIG. **2**). In other embodiments, the device substrate panel **803** may be another suitable substrate other than a PCB. Conductive vias (not numbered), may extend through the dielectric layers **117-119** to connect various sets of conductive features within adjacent conductive layers **113-116**. Within each device area **801**, a first patterned conductive layer (e.g., layer **113**) of the device substrate panel **803** may include a plurality of conductive features on or exposed at the mounting surface **111** of the device substrate panel **803**. For example, in each device area **801**, the first patterned conductive layer may include conductive features that correspond to conductive circuitry pads (e.g., pads **123**, **124**, **125**, **126**, FIG. **2**). The first patterned conductive layer also may include conductive features that correspond to ground terminals (e.g., ground terminals **127**, FIG. **2**), antenna terminals (e.g., antenna terminals **128**, **129**, FIG. **2**), and antenna ground planes (e.g., antenna ground planes **130**, FIG. **2**).

[0064] During the process of mounting the electronic circuits **180** onto the device substrate panel **803**, corresponding terminals (e.g., terminals **181**, **183**, **184**, **186**, FIG. **2**) of each electronic circuit **180** are physically and electrically coupled to the conductive circuitry pads (e.g., pads **123**, **124**, **125**, **126**). For example, the circuitry pads and device terminals may be coupled together using solder, electrically conductive adhesive, or other suitable materials.

[0065] In block **804**, shield structures (e.g., shield structures **150**, **150'**, FIGS. **1-5**) are then formed on or coupled to the mounting surface **111** of the device substrate **110** within each device area **801**. According to some embodiments, conductive posts or a conductive wall (corresponding to vias **152** of structure **150** or corresponding to the conductive wall of structure **150'**, FIGS. **1-5**) are connected to or built up on the ground pads **127**. For example, the conductive posts or the conductive walls may be formed from copper or one or more other electrically-conductive materials.

[0066] In block **806**, the electronic circuit **180** and the shield structures **150**, **150'** are then encapsulated by applying encapsulant material **190** over the electronic circuits **180**, over the shield structures **150**, **150'**, and over the mounting surface **111** of the device substrate panel **803**. Said another way, the encapsulant material **190** is coupled to the mounting surface **111**. The height of the encapsulant material **190** should be sufficient to cover the electronic circuits **180** and the shield structures **150**, **150'**.

[0067] In various embodiments, the encapsulant material **190** may include one or more epoxy molding compounds (EMC) or other suitable materials, which may be molded (e.g., compression or injection molded) or dispensed (e.g., screen printed) over the electronic circuits **180**, the shield structures **150**, **150'**, and the mounting surface **111**. Unless a subsequent grinding or polishing

process is performed to thin the encapsulant material **190**, the upper surface of the encapsulant material **190** corresponds to the upper surface **106** of the partially-formed device.

[0068] According to one or more further embodiments, the encapsulant material **190** may include a thermosetting mold compound material that supports a laser direct structuring (LDS) process, which later may be used (e.g., in block **810**) to form sidewall antennas (e.g., antennas **121**, **122**), as will be described below. For example, the encapsulant material **190** may include a polymer and an additive (e.g., 3 valent copper), which is configured to be activated by laser ablation (e.g., by thermal energy from a laser beam **811**, as discussed below).

[0069] In block **808**, a partial cutting process is then performed to form openings **809** in the encapsulant material **190** that expose portions of the mounting surface **111** of the device substrate panel **803**. This results in the exposure of the antenna pads **128**, **129** and the antenna ground planes **130**, while also defining the encapsulant sidewalls (e.g., sidewalls **141-144**, FIGS. 1-5).

[0070] In block **810**, the planar transmit and receive antennas **121**, **122** are then formed on the encapsulant sidewalls **141**, **143**, with distal ends of the antenna feeds (e.g., ends **624**, **724** of feeds **620**, **720**, FIGS. 6, 7) being connected to the antenna pads **128**, **129**. According to one or more embodiments, as mentioned above, the encapsulant material **190** may include a thermosetting mold compound material with a special additive (e.g., 3 valent copper), and the antennas **121**, **122** may be formed using an LDS process. More specifically, a laser activation process is performed, in which angled laser beams (e.g., laser beam **811**) are sequentially directed toward the encapsulant sidewalls **141**, **143** in order to write (or transfer) the layouts of the antennas **121**, **122** onto the encapsulant sidewalls **141**, **143**. Thermal energy from the laser beams **811** activates the additive in the encapsulant material **190**, which results in plateable antenna patterns on the encapsulant sidewalls **141**, **143**. For example, when the additive is 3 valent copper, a chemical reaction may occur (e.g., at about 1000 degrees Celsius) in which the 3 valent copper is converted to bulk copper, which may act as a catalyst at the encapsulant sidewalls **141**, **143** for subsequent electroless plating (e.g., of copper), as described below. The plateable antenna patterns are formed by the laser beam **811** as micro-rough surfaces on which conductive material (e.g., bulk copper) is firmly anchored.

[0071] On their own, the plateable antenna patterns may not be electrically conductive. Accordingly, in conjunction with one or more embodiments, the laser ablation process is followed by the performance of an electroless plating process, which results in metallization (e.g., copper) being applied onto the plateable antenna patterns. For example, the partially-formed devices may be submerged in copper baths, resulting in copper being additively built-up (e.g., in a range of 8 to 12 microns/hour) on the plateable antenna patterns. According to one or more embodiments, additional metal layers (e.g., one or more layers of nickel and/or gold) may be applied over the plated copper layers. In some embodiments, one or more layers of tin, silver, palladium/gold, or other materials also or alternatively may be formed as constituent parts of the sidewall antennas **121**, **122**.

[0072] Although the above-described LDS process may be used to form the sidewall antennas **121**, **122** on the encapsulant sidewalls **141**, **143**, other methods alternatively may be used to form the sidewall antennas **121**, **122**. For example, the patterns for the sidewall antennas **121**, **122** alternatively may be formed by printing conductive material layers (e.g., copper, nickel, gold, etc.) on the encapsulant sidewalls **141**, **143**. This may be most conveniently performed after singulation of the devices **100**, **100'** as described in the next fabrication step.

[0073] In block **812**, the individual devices **100**, **100'** are singulated from the device substrate panel **803** along the saw streets **813**. For example, a sawing process may be performed to separate the devices **100**, **100'** and to define the substrate sidewalls (e.g., sidewalls **101-104**). Fabrication of the devices **100**, **100'** is then complete.

[0074] Optionally, conductive attachment material (e.g., solder balls **170**) then may be applied to the device terminals (e.g., terminals **160**, **161**, **166**). At this stage, formation of the device **100**, **100'**

is complete. When the device has been formed in a strip or panel with other devices (not shown), a device singulation process may be performed to separate the devices into discrete units. The method may then end.

[0075] The fabrication method described in conjunction with FIG. 8 includes providing the device substrate **110** (or a panel **803** thereof) in the form of a multiple-layer PCB or other suitable structure. In other embodiments, the device substrate **110** may be formed as an RDL structure.

[0076] Alternate embodiments of fabricating devices **100**, **100'** could be used, rather than the process depicted in FIG. 8. For example, an alternative method of fabrication could include coupling multiple instances of an electronic circuit **180** (FIGS. 2, 4) to the upper surface of a temporary carrier, and encapsulating each electronic circuit **180** with encapsulant material **190** (FIGS. 2, 4). The partially-formed device could then be removed from the temporary carrier, and openings for the conductive vias (e.g., vias **152**, FIGS. 1-3) or conductive trench (e.g., structure **150'**, FIGS. 4, 5) could be formed in the encapsulant material **190** (e.g., using laser drilling or other suitable techniques). The depths of the via or trench openings may be controlled through control of the energy and/or time associated with the laser drilling process. The depths of the via or trench openings correspond to the ultimate heights (e.g., heights **159**, **559**, FIGS. 2, 5) of the to-be-formed conductive vias or conductive trenches. In some cases, the via or trench openings may be drilled all the way through the upper surface **192** (FIGS. 2, 3, 5) of the encapsulant material **190**, although these via or trench openings may stop short of the upper surface **192**, as well.

[0077] Electrically conductive material then may be applied in the via openings or trench openings in order to form the vias (e.g., vias **152**, FIGS. 1-3) or the conductive trench (e.g., structure **150'**, FIGS. 4, 5). For example, the via or trench openings may be plated with copper or another conductive metal, or the via or trench openings may be filled with electrically conductive epoxy or another conductive material.

[0078] The device substrate **110** (FIG. 2) then may be build up on the surface of the encapsulant material **190** at which the electronic circuit **180** is exposed. For example, the device substrate **110** may be formed as a redistribution layer (RDL) structure using appropriate techniques. For example, in one or more embodiments, forming the device substrate **110** may include forming a first patterned conductive layer (e.g., layer **113**, FIG. 2) over the exposed surfaces of the encapsulant **190**, the electronic circuit **180**, and the proximal ends of the conductive vias or trenches. For example, the first patterned conductive layer may include circuitry pads (e.g., pads **123-126**, FIG. 2) in contact with the terminals (e.g., terminals **181**, **183**, **184**, **186**, FIG. 2) of the electronic circuit **180**, ground pads (e.g., pads **127**, FIG. 2) in contact with proximal ends of the vias or trenches (and thus in contact with the shield structures **150**, **150'**, FIGS. 1-5), antenna pads (e.g., pads **128**, **129**, FIG. 2), and antenna ground planes (e.g., ground planes **130**, FIGS. 1-5) overlying sacrificial portions of the encapsulant material **190**.

[0079] A first dielectric layer (e.g., layer **117**, FIG. 2) then may be formed over the first patterned conductive layer, and openings may be formed through the first dielectric layer to expose the circuitry pads **123-126**, the ground pads **127**, the antenna pads **128**, and the antenna ground planes **130**. The first dielectric layer and the first patterned conductive layer define the mounting surface (e.g., mounting surface **111**, FIG. 2) of the device substrate **110**. An iterative process of forming subsequent patterned conductive layers (e.g., layers **114-116**, FIG. 2) interleaved with subsequent dielectric layers (e.g., layers **118**, **119**, FIG. 2) may then be performed to complete formation of the device substrate **110**. Upon completion, a plurality of conductive device terminals (e.g., terminals **160**, **161**, **166**, FIG. 2) are exposed at the terminal surface (e.g., surface **112**, FIG. 2) of the device substrate **110**. Fabrication of the device **100**, **100'** may then proceed according to blocks **808** through **812** of FIG. 8.

[0080] An embodiment of an electronic device includes a device substrate with a mounting surface, an electronic circuit coupled to the mounting surface, and encapsulant material over the electronic circuit and the mounting surface. The encapsulant material is defined by an upper encapsulant

surface and a plurality of encapsulant sidewalls extending between the mounting surface of the device substrate and the upper encapsulant surface. The electronic device also includes a sidewall antenna coupled to a first encapsulant sidewall of the plurality of encapsulant sidewalls, and a shield structure embedded within the encapsulant material between the sidewall antenna and the electronic circuit. The sidewall antenna is electrically coupled to the electronic circuit through the device substrate. The shield structure extends in a perpendicular direction from the mounting surface of the device substrate toward the upper surface of the encapsulant material.

[0081] According to a further embodiment, the device substrate also includes a second surface and a plurality of substrate sidewalls that extend between the mounting surface and the second surface, and the first encapsulant sidewall and a first substrate sidewall of the plurality of substrate sidewalls are oriented in parallel planes. The first encapsulant sidewall is recessed from the first substrate sidewall to define an exposed portion of the mounting surface between the first encapsulant sidewall and the first substrate sidewall, and the electronic device further comprises an antenna ground plane at or below the exposed portion of the mounting surface. The antenna ground plane is configured to act as an antenna back stop.

[0082] According to another further embodiment, the encapsulant material includes a first portion of encapsulant material between the shield structure and the first encapsulant sidewall, a second portion of encapsulant material between the shield structure and the electronic circuit, and third portions of encapsulant material between the shield structure and other encapsulant sidewalls of the plurality of encapsulant sidewalls, where the other encapsulant sidewalls are adjacent to the first encapsulant sidewall.

[0083] According to yet another further embodiment, the sidewall antenna is a planar end-fire type of antenna, which is configured to support a radiation pattern with a main lobe that extends upward in a direction that is parallel to the first encapsulant sidewall. For example, the sidewall antenna may be an antenna selected from a planar Yagi-Uda antenna, a planar log periodic dipole antenna, and a planar Vivaldi antenna.

[0084] According to yet another further embodiment, the sidewall antenna is a planar broadside-fire type of antenna, which is configured to support a radiation pattern with a main lobe that extends laterally in a direction that is perpendicular to the first encapsulant sidewall. For example, the sidewall antenna may be an antenna selected from a patch antenna, a slot antenna, a dipole antenna, a ring antenna, a spiral antenna, and a bow tie antenna.

[0085] An embodiment of a method of fabricating an electronic device includes coupling an electronic circuit to a mounting surface of a device substrate, coupling a shield structure to the mounting surface of the device substrate, and applying encapsulant material over the electronic circuit and the mounting surface. The encapsulant material is defined by an upper encapsulant surface and a plurality of encapsulant sidewalls extending between the mounting surface of the device substrate and the upper encapsulant surface, and the encapsulant material surrounds lateral sides of the shield structure. The method further includes forming a sidewall antenna on a first encapsulant sidewall of the plurality of encapsulant sidewalls. The sidewall antenna is electrically coupled to the electronic circuit through the device substrate. The shield structure is embedded within the encapsulant material between the sidewall antenna and the electronic circuit, and the shield structure extends in a perpendicular direction from the mounting surface of the device substrate toward the upper surface of the encapsulant material.

[0086] According to a further embodiment, the encapsulant material includes a polymer and an additive that is configured to be activated by laser ablation, and forming the sidewall antenna on the first encapsulant sidewall includes directing a laser beam toward the first encapsulant sidewall to form a plateable antenna pattern associated with the sidewall antenna onto the first encapsulant sidewall, and performing an electroless plating process to apply metallization onto the plateable antenna pattern.

[0087] According to a further embodiment, the sidewall antenna is selected from a planar end-fire

type of antenna that is configured to support a first radiation pattern with a first main lobe that extends upward in a direction that is parallel to the first encapsulant sidewall, and a planar broadside-fire type of antenna that is configured to support a second radiation pattern with a second main lobe that extends laterally in a direction that is perpendicular to the first encapsulant sidewall. [0088] The preceding detailed description is merely illustrative in nature and is not intended to limit the embodiments of the subject matter or the application and uses of such embodiments. As used herein, the word “exemplary” means “serving as an example, instance, or illustration.” Any implementation described herein as exemplary is not necessarily to be construed as preferred or advantageous over other implementations. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, or detailed description.

[0089] The connecting lines shown in the various figures contained herein are intended to represent exemplary functional relationships and/or physical couplings between the various elements. It should be noted that many alternative or additional functional relationships or physical connections may be present in an embodiment of the subject matter. In addition, certain terminology may also be used herein for the purpose of reference only, and thus are not intended to be limiting, and the terms “first”, “second” and other such numerical terms referring to structures do not imply a sequence or order unless clearly indicated by the context.

[0090] The foregoing description refers to elements or features being “connected” or “coupled” together. As used herein, unless expressly stated otherwise, “connected” means that one element is directly joined to (or directly communicates with) another element, and not necessarily mechanically. Likewise, unless expressly stated otherwise, “coupled” means that one element is directly or indirectly joined to (or directly or indirectly communicates with, electrically or otherwise) another element, and not necessarily mechanically. Thus, although the schematic shown in the figures depict one exemplary arrangement of elements, additional intervening elements, devices, features, or components may be present in an embodiment of the depicted subject matter.

[0091] While at least one exemplary embodiment has been presented in the foregoing detailed description, it should be appreciated that a vast number of variations exist. It should also be appreciated that the exemplary embodiment or embodiments described herein are not intended to limit the scope, applicability, or configuration of the claimed subject matter in any way. Rather, the foregoing detailed description will provide those skilled in the art with a convenient road map for implementing the described embodiment or embodiments. It should be understood that various changes can be made in the function and arrangement of elements without departing from the scope defined by the claims, which includes known equivalents and foreseeable equivalents at the time of filing this patent application.

## Claims

1. An electronic device comprising: a device substrate with a mounting surface; an electronic circuit coupled to the mounting surface; encapsulant material over the electronic circuit and the mounting surface, wherein the encapsulant material is defined by an upper encapsulant surface and a plurality of encapsulant sidewalls extending between the mounting surface of the device substrate and the upper encapsulant surface; a first sidewall antenna coupled to a first encapsulant sidewall of the plurality of encapsulant sidewalls, wherein the first sidewall antenna is electrically coupled to the electronic circuit through the device substrate; and a first shield structure embedded within the encapsulant material between the first sidewall antenna and the electronic circuit, wherein the first shield structure extends from the mounting surface of the device substrate toward the upper surface of the encapsulant material.
2. The electronic device of claim 1, wherein: the device substrate further includes a second surface and a plurality of substrate sidewalls that extend between the mounting surface and the second



surface; the first encapsulant sidewall and a first substrate sidewall of the plurality of substrate sidewalls are oriented in parallel planes; the first encapsulant sidewall is recessed from the first substrate sidewall to define an exposed portion of the mounting surface between the first encapsulant sidewall and the first substrate sidewall; and the electronic device further comprises an antenna ground plane at or below the exposed portion of the mounting surface, wherein the antenna ground plane is configured to act as an antenna back stop.

**3.** The electronic device of claim 2, further comprising: a conductive antenna pad at the mounting surface of the device substrate, wherein the first sidewall antenna is electrically coupled to the conductive antenna pad; and a non-conductive gap between the conductive antenna pad and the antenna ground plane.

**4.** The electronic device of claim 1, wherein: a height of the first shield structure is at least as high as a height of the electronic circuit; and a length of the first shield structure is shorter than a width of the encapsulant material between second and third encapsulant sidewalls that are adjacent to the first encapsulant sidewall.

**5.** The electronic device of claim 1, further comprising: at least one ground pad at the mounting surface of the device substrate, wherein the first shield structure comprises a plurality of conductive vias electrically coupled to the at least one ground pad.

**6.** The electronic device of claim 5, wherein: adjacent vias of the plurality of conductive vias are separated by an inter-via spacing that is less than  $\lambda/8$ , where  $\lambda$  is a wavelength associated with a frequency of operation of the electronic device.

**7.** The electronic device of claim 1, further comprising: at least one ground pad at the mounting surface of the device substrate, wherein the first shield structure comprises a conductive wall electrically coupled to the at least one ground pad.

**8.** The electronic device of claim 1, wherein the encapsulant material comprises: a first portion of encapsulant material between the first shield structure and the first encapsulant sidewall; a second portion of encapsulant material between the first shield structure and the electronic circuit; and third portions of encapsulant material between the first shield structure and other encapsulant sidewalls of the plurality of encapsulant sidewalls, where the other encapsulant sidewalls are adjacent to the first encapsulant sidewall.

**9.** The electronic device of claim 1, wherein the first sidewall antenna is a planar end-fire type of antenna, which is configured to support a radiation pattern with a main lobe that extends upward in a direction that is parallel to the first encapsulant sidewall.

**10.** The electronic device of claim 9, wherein the first sidewall antenna is an antenna selected from a planar Yagi-Uda antenna, a planar log periodic dipole antenna, and a planar Vivaldi antenna.

**11.** The electronic device of claim 1, wherein the first sidewall antenna is a planar broadside-fire type of antenna, which is configured to support a radiation pattern with a main lobe that extends laterally in a direction that is perpendicular to the first encapsulant sidewall.

**12.** The electronic device of claim 11, wherein the first sidewall antenna is an antenna selected from a patch antenna, a slot antenna, a dipole antenna, a ring antenna, a spiral antenna, and a bow tie antenna.

**13.** The electronic circuit of claim 1, further comprising: a second sidewall antenna coupled to a second encapsulant sidewall of the plurality of encapsulant sidewalls, wherein the second sidewall antenna is electrically coupled to the electronic circuit through the device substrate; and a second shield structure embedded within the encapsulant material between the second sidewall antenna and the electronic circuit, wherein the second shield structure extends from the mounting surface of the device substrate toward the upper surface of the encapsulant material.

**14.** The electronic circuit of claim 13, wherein: the electronic circuitry includes transmitter circuitry and receiver circuitry; the electronic circuit further comprises a first conductive antenna pad and a second conductive mounting pad at the mounting surface of the device substrate; the first sidewall antenna is electrically coupled to the first conductive antenna pad; the second sidewall

antenna is electrically coupled to the second conductive antenna pad; the first conductive antenna pad is electrically coupled to the transmitter circuitry of the electronic circuitry through a first conductive routing path in the device substrate; and the second conductive antenna pad is electrically coupled to the receiver circuitry of the electronic circuitry through a second conductive routing path in the device substrate.

**15.** The electronic device of claim 1, wherein: the device substrate further includes a terminal surface at which a plurality of conductive device terminals are exposed; the electronic circuitry is electrically coupled to a first device terminal of the plurality of device terminals; and the first shield structure is electrically coupled to a second device terminal of the plurality of device terminals.

**16.** A method of fabricating an electronic device, the method comprising: coupling an electronic circuit to a mounting surface of a device substrate; coupling a first shield structure to the mounting surface of the device substrate; applying encapsulant material over the electronic circuit and the mounting surface, wherein the encapsulant material is defined by an upper encapsulant surface and a plurality of encapsulant sidewalls extending between the mounting surface of the device substrate and the upper encapsulant surface, and wherein the encapsulant material surrounds lateral sides of the first shield structure; and forming a first sidewall antenna on a first encapsulant sidewall of the plurality of encapsulant sidewalls, wherein the first sidewall antenna is electrically coupled to the electronic circuit through the device substrate, wherein the first shield structure is embedded within the encapsulant material between the first sidewall antenna and the electronic circuit, and wherein the first shield structure extends from the mounting surface of the device substrate toward the upper surface of the encapsulant material.

**17.** The method of claim 16, wherein: the encapsulant material includes a polymer and an additive that is configured to be activated by laser ablation; and forming the first sidewall antenna on the first encapsulant sidewall includes directing a laser beam toward the first encapsulant sidewall to form a plateable antenna pattern associated with the first sidewall antenna onto the first encapsulant sidewall, and performing an electroless plating process to apply metallization onto the plateable antenna pattern.

**18.** The method of claim 16, wherein: the device substrate further includes a second surface and a plurality of substrate sidewalls that extend between the mounting surface and the second surface; the first encapsulant sidewall and a first substrate sidewall of the plurality of substrate sidewalls are oriented in parallel planes; the first encapsulant sidewall is recessed from the first substrate sidewall to define an exposed portion of the mounting surface between the first encapsulant sidewall and the first substrate sidewall; and the method further includes forming an antenna ground plane at or below the exposed portion of the mounting surface, wherein the antenna ground plane is configured to act as an antenna back stop.

**19.** The method of claim 16, further comprising: coupling a second shield structure to the mounting surface of the device substrate; forming a second sidewall antenna on a second encapsulant sidewall of the plurality of encapsulant sidewalls, wherein the second sidewall antenna is electrically coupled to the electronic circuit through the device substrate, wherein the second shield structure is embedded within the encapsulant material between the second sidewall antenna and the electronic circuit, and wherein the second shield structure extends from the mounting surface of the device substrate toward the upper surface of the encapsulant material.

**20.** The method of claim 16, wherein: the first sidewall antenna is selected from a planar end-fire type of antenna that is configured to support a first radiation pattern with a first main lobe that extends upward in a direction that is parallel to the first encapsulant sidewall, and a planar broadside-fire type of antenna that is configured to support a second radiation pattern with a second main lobe that extends laterally in a direction that is perpendicular to the first encapsulant sidewall.

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