

IMPEDANCE CONTROLLED ELECTRICAL INTERCONNECTION EMPLOYING META-MATERIALS

5 FIELD OF THE INVENTION

The invention relates generally to electronic device fabrication and packaging and more particularly to the design of controlled impedance electrical bond wire interconnections.

BACKGROUND OF THE INVENTION

10 An integrated circuit typically includes a plastic or ceramic package that encapsulates an electronic circuit, or a plurality of electronic circuits, each of which are formed on a semiconductor substrate. Electrical interconnection between the electronic circuit(s) and the external connections of the package are typically provided by wire bonding, flip-chip soldering, or tape automated bonding (TAB). With increasing
15 complexity and functionality of electronic circuits, such electrical interconnections are commonly required across the surface of the semiconductor die as well as at the periphery of the semiconductor die. Additionally, electrical interconnects between the electronic circuits in a multi-chip module (MCM), where a plurality of electronic circuits have been co-packaged, require electrical interconnections similarly implemented within
20 the entire footprint of the package rather than the periphery.

Consider wire bonding, where such electrical interconnections to any portion of an integrated circuit are easily implemented and function well at low frequencies. Such bond wires can vary in shape (round or flat), width (typically 15 μ m to 200 μ m), and length (typically 100 μ m to 1000 μ m). These bond wires represent a high characteristic
25 impedance transmission line segment to a signal propagating within them. However, these wire bonded electrical interconnections become more problematic as data rates and signal frequencies increase, due to inductance, capacitance and resistance parasitics together with variations introduced from the manufacturing processes and equipment. Such parasitics manifest as excessive or variable impedance for the bond wire as signal
30 frequency increases. Such impedance mismatches result in propagating signals having significant attenuations, due to reflection from the controlled impedance environment of the package electrical traces or electrical circuit to the bond wire. Such reflected signals

5 can also cause degraded performance within the electronic circuits and result in distorted signal waveforms and increased noise.

Typically, the prior art solution has been to control or reduce parasitic effects by designing the device to reduce bond wire lengths, thereby reducing the bond wire inductance. Where a bond wire connection is desirable at the device edge, short bond
10 wire lengths are possible and have utility. However, there are device applications where a bond wire is required on the device interior. Surprisingly, despite the plethora of electronic circuits, packaging formats, semiconductor die technologies, operating requirements, and manufacturers worldwide, the prior solutions to addressing the problems of providing high performance electrical interconnections to the electronic
15 circuit have been relatively limited, and suffer significant drawbacks in design of the electronic circuit and package or in their reproducibility and manufacturability, especially for devices with very high electrical interconnect counts. Today packages may range from single transistor packages, such as the 4-pin SOT available from NXP Semiconductors (Package Identity SOT343F), through to multiple chip packages (MCP)
20 such as the 2,116-pin high density BGA available from Renesas Technology (Package Identity PRBG2116FA-A). Accordingly, controlled impedance may be required by one electrical interconnection or all electrical interconnections.

Equally, these requirements for controlled, reproducible electrical interconnections exist throughout the wide range of package formats, pin counts, and
25 signal frequencies present within today's electronic circuits. Examples of such devices range from NXP Semiconductors BFG424F NPN wideband transistor operating with analog input and output ports up to 25GHz in a 4-pin SOT package, to Analog Devices AD6534 Othello-G Single-chip Direct Conversion GSM/GPRS Transceiver packaged within a 32-lead Lead Frame Chip Scale Package in Very Low Quad format (LFCSP-
30 VQ) with dual analog input ports operating at the standard cellular frequencies of 800MHz / 900MHz / 1800MHz / 1900MHz and digital output ports providing 64kb/s digital audio, through to an Intel® Pentium® 4 Extreme processor implemented in 0.13µm silicon with core operating at 3.5GHz and packaged in a 775-pin LAND package with 64-bit digital data busses operating at 1066MHz.

5 The common solution to the bond wire problem is to reduce the size of the transition by using a flip chip concept or ball grid array (BGA) package, in which contacts of a semiconductor circuit are directly bonded to an adjacent circuit or substrate. Another known solution is filling the transition region with a high dielectric constant material, such as for example an epoxy containing a ceramic. Although these solutions
10 work, they are not applicable in all cases. For example, these solutions are not efficient in the sense that the high frequency signals in the transition might involve only a few of the interconnections in the transition. Therefore, the existing solutions become costly and inefficient to implement when only a few transition interconnections require special treatment for high frequency parasitic effects, or the materials within the semiconductor
15 circuit cannot withstand the temperatures from the solder ball reflow operations in the above flip-chip and BGA solutions.

 Techniques to reduce or control parasitic effects in bond wire configurations have included providing a plurality of parallel layers of bond wires, for example Grellman et al [US Patent 4,686,492], such that the inductive reactance of the bond wire is compensated
20 by the capacitive reactance of the parallel bond wires. However, such a technique requires that the bonding pads on each end of the bond wire be capable of supporting three, four or more wire bonds, resulting in very large bond pads and increased semiconductor die footprints and cost. Equally, providing such parallel layers over long distances, with semiconductor die footprints reaching 25mm square or more, results in
25 fragile interconnects that cannot withstand the environmental requirements of electronic packaging. Finally, a 2,116pin package with a 4-layer bond wire configuration as depicted by Grellman et al requires 8,464 bond wires to be placed, and 16,928 individual bond landings of the wire bonding tool to the package and semiconductor die, resulting in reduced yields, increased manufacturing times, and increased cost.

30 An alternative presented by Kwark et al [US Patent Application 2005/0,116,013] involves providing a second bond, using a wider flat bond (commonly referred to as ribbon bonding), beneath the main wire bond. The resulting electrical connection provides a microstrip structure. As with Grellman et al the approach suffers from requiring increased die footprint, typically in dimensionally sensitive areas for high speed
35 interconnections; requires providing additional ground bond pads adjacent to every

5 bonding pad featuring the microstrip structure; and doubles the number of mechanical bonding operations.

Each of the solutions taught by Kwark and Grellman solve the issue of controlling the impedance individually for each bond wire. In contrast, Wyland [US Patent 7,217,997] teaches to provide a wide electrical plane above the wire bonds, with a
10 dielectric spacer between to prevent an electrical short circuit between the signal wire bond and the wide electrical plane. As taught by Wyland the impedance of a wire bond can be reduced from the approximately 125Ω of a discrete wire bond to a typical 50Ω of an analog signal input / output by providing the wide electrical plane approximately $32\mu\text{m}$ from the bond wire. Advantageously the approach taught by Wyland provides a
15 single feature, the wide electrical plane, allowing a plurality of wire bonds to be managed simultaneously.

However, Wyland teaches that the wide electrical plane above the wire bonds can reduce the impedance to 50Ω but not significantly lower, due to the already small gap of $32\mu\text{m}$ resulting in both tight tolerances and substantial variations in impedance for small
20 variations or deviations in this gap. Further, the provision of such impedance controlled structures is best suited to designs wherein the bond wires are connected solely to the periphery of the semiconductor circuit and bonded directly to the package electrical traces. It would also be evident that the structure does not allow the semiconductor circuit designer latitude to provide bond wires close together but of different impedance, such as
25 may be required in providing multiple outputs of different impedance such as 50Ω and 75Ω or the interconnection of very low impedance electronic circuits, such as amplifier gain stages of a few ohms within an MCM in close proximity to a 50Ω output port.

Accordingly it would be beneficial to provide a method of providing controlled impedance for bond wires irrespective of their placement within the semiconductor die or
30 package. It would be further beneficial if the method allowed the impedance of different bond wires to be individually established whilst allowing provisioning of a single additional element during manufacturing and assembly. Additional benefit may be further obtained if the additional element was capable of integration with an electrical signal interconnection to provide the bond wires as a single-piece part, in order to reduce the
35 complexity of the packaging process of the semiconductor circuit, MCM, etc. Further, a

- 5 method allowing the required structures to be pre-manufactured and including the effect of additional dielectric materials present within the finished device, such as encapsulants, would be advantageous.

SUMMARY OF THE INVENTION

In accordance with the invention there is provided a method of providing at least
10 an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length. The method further comprising providing an overlay, the overlay comprising at least a first meta-material structure and being disposed approximately parallel to the at least an electrical interconnection of a plurality of electrical interconnections for at least a
15 predetermined portion of the interconnection length.

In accordance with another embodiment of the invention there is provided a circuit comprising at least an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length. The circuit further comprising an overlay, the overlay
20 comprising at least a first meta-material structure and being disposed approximately parallel to the at least an electrical interconnection of a plurality of electrical interconnections for at least a predetermined portion of the interconnection length.

In accordance with another embodiment of the invention there is provided a computer readable medium having stored therein data according to a predetermined
25 computing device format, and upon execution of the data by a suitable computing device a method of electrically interconnecting a circuit is provided. The method comprising providing at least an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length; and providing an overlay, the overlay comprising at least a first
30 meta-material structure and being disposed approximately parallel to the at least an electrical interconnection of a plurality of electrical interconnections for at least a predetermined portion of the interconnection length.

In accordance with another embodiment of the invention there is provided a computer readable medium having stored therein data according to a predetermined
35 computing device format, and upon execution of the data by a suitable computing device

5 a circuit for electrically interconnecting a circuit is provided. The circuit comprising at least an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length; and an overlay, the overlay comprising at least a first meta-material structure and being disposed approximately parallel to the at least an electrical interconnection of a
10 plurality of electrical interconnections for at least a predetermined portion of the interconnection length.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the invention will now be described in conjunction with the following drawings, in which:

15 Fig. 1 illustrates a typical prior art electrical interconnection between two electronic elements using conventional wire bonds.

Fig. 2 illustrates the prior art layered wire bond approach to controlling impedance of the wire bonds according to Grellman et al.

20 Fig. 3 illustrates the prior art approach of a co-dispensed ground plane to form a microstrip transition according to Kwark et al.

Fig. 4 illustrates the prior art approach of a ground arch according to Wyland.

Fig. 5 illustrates an exemplary embodiment of the invention for providing a meta-material overlay to an array of wire bonds.

25 Fig. 6 illustrates an exemplary embodiment of the meta-material overlay structure according to Fig. 5.

Fig. 7A illustrates an exemplary cross-section of the meta-material overlay according to Figs. 5 and 6.

Fig. 7B illustrates another exemplary embodiment of the meta-material overlay.

30 Fig. 8 illustrates an exemplary six layer meta-material overlay according to an embodiment of the invention placed with respect to an array of wire bonds according to Figs. 6 and 7.

Fig. 9 illustrates an exemplary electrical interconnection using two seven layer meta-material overlays integrating both the six layer meta-material structure and wire bonds to provide a single interconnection element.

5 Fig.10 illustrates exemplary electrical interconnections from the exemplary seven layer meta-material overlay of Fig. 9 to a semiconductor circuit or package.

 Fig. 11 illustrates an exemplary thirteen layer meta-material overlay according to an embodiment of the invention wherein electrical signal interconnections are sandwiched between two six layer meta-material structures.

10 Fig. 12 illustrates three exemplary deployments of a meta-material overlay with respect to a semiconductor circuit within a package.

 Fig. 13 illustrates the transmission characteristics of a bond wire with meta-material overlay according to an embodiment of the invention compared to prior art solutions.

15 DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

 Illustrated in Fig. 1 is a typical prior art electrical interconnection 100 between two electronic elements 110 and 120 using conventional wire bonds 150. As shown, the first electronic element 110 has disposed upon its surface, close to its physical periphery, a plurality of first bond pads 130. Similarly, the second electronic element 120 has
20 disposed upon its surface, close to its physical periphery, a plurality of second bond pads 140. Between each first bond pad 130 and second bond pad 140 a conventional wire bond 150 has been made. The wire bonds 150 typically are formed using thermosonic bonding, ball bonding or wedge bonding using gold, aluminum, or copper wire of diameter between 15 μ m and 50 μ m. The typical separation L160 between the first bond pads 130
25 and the second bond pads 140 is 100 μ m to 250 μ m.

 A prior art layered wire bond approach to controlling impedance of the wire bonds according to Grellman et al is shown in layered interconnection 200 in Fig. 2. As shown a first device 210 having first bond pads 240 is electrically interconnected to second device 220 having second wire bonds 230. Each electrical interconnection being a
30 parallel layered wire bond stack 250 from one first bond pad 240 to one second bond pad 230. The parallel layered wire bond stack 250 comprises a first bond 201, comparable to the wire bond 150 in Fig. 1, second bond 202, third bond 203, and fourth bond 204. Each of the second through fourth bonds 202 to 204 are respectively disposed such that the wire bonds are parallel to first bond 201 and spaced vertically above it. Each subsequent
35 bond wire within the parallel layered wire bond stack 250 contribute a finite capacitance

5 to compensate for the inductance of the first bond 201. As outlined supra the approach of Grellman et al increases the manufacturing complexity and cost of the electronic circuit containing the first and second devices 210 and 220, because of the multiple wire bonding operations required for each electrical interconnection and the increased footprint consumed with the multiple bond feet, especially with wedge bonding.

10 Now referring to Fig. 3, illustrated is the prior art approach of a co-dispensed ground plane interconnection 300 to form a microstrip transition 370 according to Kwark et al. Shown are a first device 310 with first bond pads 340 and first ribbon pads 345, in close proximity to a second device 320 having second bond pads 330 and second ribbon pads 335. Each microstrip transition comprising a wire bond 350 between first bond pad
15 340 and second bond pad 330 with a ribbon bond 360 between first ribbon pad 345 and second ribbon pad 335. Typical dimensions for ribbon used in forming the ribbon bond 360 are widths between 20 μ m and 100 μ m and thicknesses between 6 μ m and 20 μ m, although standard ribbons are available up to 1000 μ m wide and 100 μ m thick (see for example Bonding Ribbon manufactured by Kulicke and Soffa Industries, Fort
20 Washington, Pennsylvania, USA). As with Grellman et al supra Kwark et al requires multiple bonds per required bond wire 350 and increased footprint to accommodate the wire bond pad and ribbon bond pad for each. The fact that the ribbon bond pads 335 and 345 are significantly wider than the bond pads 330 and 340 constitutes a limitation to the reduction of bond pad pitch L380. This limitation adds to the drawbacks of Kwark over
25 Grellman for implementing controlled impedance bond wire interconnections.

The requirement for multiple bonds per bond wire of Kwark and Grellman presented above in respect of Figs. 2 and 3 is ameliorated with a ground arch structure 400 according to Wyland. Shown is a base of a package 405, the remainder of which is not shown for clarity, upon which a semiconductor die 410 has been mounted, having
30 disposed upon its surface device bond pads 420. Also disposed on the surface of the base 405 are package traces 440 and ground plane connections 450. In common with the other prior art approaches outlined supra the semiconductor die 420 is electrically interconnected to the package by wire bonds 430 between each device bond pad 420 and package trace 440.

5 However, now disposed over the wire bonds 430 is a ground arch 470 providing a capacitive correction for the inductive impedance of the wire bond 430. The ground arch 470 has disposed on its lower inner surface a dielectric 480, to prevent shorting of the ground arch 470 to the wire bond 430 in the event of deformation of the ground arch 470 or detachment of the wire bond 430. The ground arch 470 is electrically connected to the
10 ground plane connection 450 by a conductive epoxy 460. As noted supra, to provide 50Ω impedance for the wire bond, as opposed to 120Ω without the ground arch 470, the separation L490 between the wire bond 430 and the ground arch 470, is 32μm. As noted supra the ground arch 470 does not provide flexibility in implementing multiple bond wire impedances simultaneously, does not support multiple bond pad locations within the
15 footprint of the semiconductor die 410 unless spaced consistently in a row at fixed distance from the periphery of the semiconductor die 410, and does not support very low impedances, which for example are required to interconnect multiple high frequency semiconductor devices such as low noise GaAs, InP or SiGe amplifiers within microwave MCMs.

20 As such shown in Fig.5 is an exemplary embodiment of the invention for providing a solution to the drawbacks and limitations of the prior art: a meta-material overlay 560 overlaying an array of wire bonds 530. Similarly to Fig. 1, a first device 510 is shown having a plurality of first bond pads 520, as well as a second device 550 with a plurality of second bond pads 540. Each of the first bond pads 520 is electrically
25 connected to one of the second bond pads 540 via a wire bond 530. Overlaying the array of wire bonds 530 is the meta-material overlay 560 that provides the appropriate correction and control of the wire bond 530 environment such that the wire bond 530 impedance meets the desired target value. The meta-material overlay 560 is one of a plurality of materials that are designed to make the signal act in such a way as to make
30 the shape of the signal behave as though the permittivity and permeability are different than the real component permittivity and permeability of the insulator used. It should be noted that the relative permittivity and relative permeability include both real and imaginary components, that is $\epsilon_R = \epsilon_R + j \epsilon_I$ and $\mu_R = \mu_R + j \mu_I$. It is possible to design meta-materials so as to have the signal respond as if the permittivity and permeability
35 have negative values. The meta-material within the exemplary embodiments, such as

5 meta-material overlay 560, is an arrangement of conductors in the insulator that reduces the resonant response of the line on the signal. Optionally these meta-material designs are replaced with other meta-material designs.

Though current approaches to impedance matching rely on positive impedance, it is also possible to use negative impedances to perform impedance matching. A. F. Starr
10 et al. write in their paper titled, "Fabrication and Characterization of a Negative-Refractive-Index Composite Meta-Material," Physical Review B 70, 113102 (2004) of the American Physical Society, "while there have not been many suggested paths toward the design of a material whose effective index-of-refraction is negative, a rigorous approach is to design a material whose electric permittivity (ϵ) and magnetic permeability
15 (μ) are simultaneously negative. While there are no known naturally occurring materials or compounds that exhibit simultaneously negative ϵ and μ , such materials can be designed to provide effective ϵ and μ , as derived from effective medium arguments, which are singly or both negative over a finite frequency band."

Unlike Wyland, as presented supra in Fig. 4, in the meta-material overlay 560 the
20 permittivity and permeability of the wire bond 530 is influenced in a negative direction, allowing the impedance of the wire bond 530 to be substantially lower than 50Ω if required, increasing the tolerances of spacing between the wire bond 530 and meta-material overlay 560 compared with the ground arch 470 of ground arch structure 400, and allowing for the meta-material overlay 560 to be employed wherever a wire bond 530
25 is required between first and second bond pads 520 and 540 irrespective of location within the semiconductor die or package.

Referring to Fig. 6 shown is a first exemplary meta-material structure 600 suitable for providing the meta-material overlay 560 of Fig. 5. A substrate 610 has been configured as a meta-material. As such within the substrate 610 is a pattern of conductive
30 material 635 (i.e., a motif) arranged as concentric "square-circles" 625 that are hereinafter described as rectangular-like shapes. Such shapes include but are not limited to, rectangles and squares. Also within the substrate 610 is a pattern of straight sections of metal 630 and a meta-material conductor plane 615, shown on the surface of the substrate 610. According to an embodiment of the invention consider that the substrate
35 610, and therein meta-material conductor plane 615, are 14mm long in the y-direction

5 and that the meta-material is designed to enhance a signal transmission line, such as the wire bond 530 of Fig. 5, by controlling the impedance to reduce reflections, enhance power transfer and reduce signal noise. The sum of the lengths of the rectangular-like shapes 635 is comparable to (and often may match) the length of the meta-material conductor plane 615. Optionally, this length of the meta-material conductor plane 615 is
10 an integer division of the length of the wire bond 530 or a quarter fractional division thereof. The straight sections of metal 630 match the width of the rectangular-like shapes 635. In this embodiment the open rectangular-like shapes 635 are square in nature with a “diameter” of 2.5mm; each element of the conductive material 635 being characterized by a conductor width of 0.1mm and conductor thickness of 25 μ m. Gaps 645 and 650
15 within the rectangular-like shapes 625 are 0.2mm. The meta-material conductor plane 615 thickness is 25 μ m. The metal in this meta-material structure 600 is typically gold, copper or aluminum but optionally is selected from a range of materials including other metals, metal alloys and conductive polymers. The insulator in this meta-material structure 600 is typically a high heat resistant thermosetting resin such as bismaleimide triazine (BT) resin, a resin employed in glass type copper clad laminates for circuit
20 boards.

A cross-sectional view of a first exemplary meta-material substrate 700 is shown in Fig. 7A. The cross-sectional view being along the section AA-AA of meta-material substrate 600 of Fig. 6. The meta-material substrate 600 may be constructed as multiple
25 layers 755. Layer 1 (755L1) is a ground plane 730, equivalent to the meta-material conductor plane 615 of Fig. 6 and is 25 μ m thick. Upon the ground plane 730 is placed layer 2 (755L2); insulating material 750 of 100 μ m thickness. Layer 3 (755L3) is where the straight sections of metal 720 are implemented within the meta-material substrate 700 and is also 25 μ m thick. Layer 4 (755L4) is another 100 μ m thick layer of insulating
30 material 750. Layer 5 (755L5) includes an arrangement of metallic conductors 725 that form the concentric rectangular-like shapes 625 of Fig. 6 and have a thickness of 25 μ m.

Upon layer 5 (755L5) there is a further layer 6 (755L6) of insulating material 750 of 100 μ m thickness. Thus, for an exemplary embodiment the meta-material is implemented as the addition of two metallic layers 755L3 and 755L5 into the
35 conventional ground plane 730 (755L1) and insulator material 750 of a copper tape.

5 Alternative embodiments with reduced or additional processing complexity are optionally implemented to provide the meta-material substrate 700. One such alternative embodiment is presented in Fig. 7B as meta-material substrate 700B, having a signal conductor plane 790 on an insulating material. At a predetermined distance below the signal conductor plane 790, an isolated metal structure 760 having concentric squares is defined. In contrast with the previous embodiment, the squares are regions with an
10 absence of metal.

Fig. 8 illustrates the exemplary six layer meta-material substrate 700 deployed according to an embodiment of the invention: as meta-material overlay placed with respect to an array of wire bonds according to Fig. 5. Hence, shown are a first device 510,
15 having a plurality of first bond pads 520; as well as a second device 550 with a plurality of second bond pads 540. Each of the first bond pads 520 is electrically connected to one of the second bond pads 540 via the wire bond 530. In place of the meta-material overlay 560 there is placed the six layer meta-material substrate 700 comprising, in listed order: layer 755L6 of insulating material 750, layer 755L5 consisting of the arrangement of
20 metallic conductors 725, layer 755L4 of insulating material 750, layer 755L3 including straight sections of metal 720, layer 755L2 of insulating material 750, and layer 755L1 being the ground plane 730.

In the exemplary embodiments presented supra the meta-material overlay (such as meta-material overlay 700, 600 or 560) is separate from the wire bonds. Alternatively, the
25 meta-material overlay may be implemented as a complete electrical interconnection.

Such an arrangement is shown in Fig. 9 wherein seven layer meta-material overlays 910 and 920 provide controlled impedance electrical interconnection for arrayed interconnections. Accordingly, shown are a first device 510 with a plurality of first bond pads 520 and a second device 550 with a plurality of second bond pads 540.

30 Interconnecting the array of first bond pads 520 and second bond pads 540 is the first seven-layer meta-material substrate 910, which consists initially of an electrical trace layer 917, wherein multiple electrical traces disposed within this layer replace the previous plurality of discrete wire bonds 530. The remaining layers of first seven-layer meta-material overlay 910 are: first insulating layer 916, metallic conductors 725 in first
35 conductor layer 915, second insulating layer 914, straight sections of metal 720 in second

5 conductor layer 913, third insulating layer 912, and signal conductor plane 911. First seven-layer meta-material substrate 910 has a length L910 sufficient to provide coverage of the plurality of first and second bond pads 520 and 540 respectively.

Also shown is second seven-layer meta-material 920, of length L920, which provides interconnection for a single electrical interconnection between a first bond pad
10 520 and a second bond pad 540. Optionally, the second seven-layer meta-material 920 has variations in the thickness, composition, and layout for the layers 911 through 916 with respect to the first seven-layer meta-material 910. This second design optionally: reduces material consumption by addressing only specific interconnections; provides specific bandwidth performance; or provides specific impedance characteristics, meta-
15 material overlay shape characteristics or interconnection distance characteristics that are different from those of the first seven-layer meta-material 910.

The exemplary seven-layer meta-materials 910 and 920 require the attachment of electrical traces disposed within electrical trace layer 917 (the electrical traces replacing the discrete wire bonds 530) to the first and second bond pads 520 and 540 respectively.
20 Similarly, the signal conductor plane 911 requires electrical interconnection to at least one of the two ground contacts provided within at least the first and second devices 510 and 550. Exemplary approaches to providing these electrical interconnections from the exemplary seven-layer meta-material overlay of Fig. 9 to a semiconductor circuit or package are shown in Fig. 10. The exemplary seven-layer meta-material interconnection
25 1000 is shown with respect to cross-sections 1000A through 1000C.

Referring to first cross-section 1000A the 7-layer meta-material overlay 910 is shown overlaid on a bond pad, either first bond pad 520 or second bond pad 540, comprising metallization 1010 on a substrate 1020. The electrical trace layer 917 is shown in contact with the metallization 1010, such contact being implemented by
30 standard techniques including conductive adhesive and solder. Second cross-section 1000B shows a first electrical interconnection of the signal conductor plane 911 of the seven-layer meta-material overlay 910 to a metallization 1010 on substrate 1020. As shown, the direct connection from the metallization 1010 to the seven-layer meta-material overlay 910 is a via metallization 1030 which forms a discrete portion of the
35 electrical trace layer 917. The via metallization 1030 is electrically connected to the

5 signal conductor plane 911 through a via 1040 which routes through first insulating layer 916, first conductor layer 915, second insulating layer 914, second conductor layer 913, third insulating layer 912, and signal conductor plane 911.

The via metallization 1030 to metallization 1010 contact is implemented by standard techniques such as outlined supra. The formation of via 1040 as outlined is
10 compatible with industry standard techniques for the fabrication of the seven-layer meta-material overlay 910 as a variant of tape used within tape automated bonding (TAB). An alternate embodiment of the seven-layer meta-material overlay 910 is shown with third cross-section 1000C, which removes the via metallization 1030, offering a simplified interconnection for the signal conductor plane 911. As shown, in this embodiment the
15 seven-layer meta-material overlay 910 interconnects the electrical trace layer 917 to a bond pad 1010 on a substrate 1020 in a manner similar to that in the first cross-section 1000A. The signal conductor plane 911, rather than terminating proximate to bond pad 1010 as in the previous cross-sections, extends with a free region 1050 formed to interconnect with a signal plane bond pad 1060. This interconnection is made via
20 standard techniques such as those providing interconnection of electrical trace layer 917 to bond pad 1010 outlined supra, but optionally includes thermo-compression wedge bonding or other variants of bonding.

The exemplary embodiments supra employ either six-layer or seven-layer meta-material, the latter incorporating the electrical trace layer into the layer arrangement and
25 thereby removing the requirement for separate wire bonds. In some instances the electrical signals are sensitive to noise arising from coupling from electrical interconnections in proximity to the overlay, or the electrical interconnections over which the overlay lies are sensitive to noise coupled from the overlay electrical traces. Further, in some instances the tolerances for implementing an overlay or the absolute magnitude
30 of the desired impedance reach a threshold where an alternative overlay implementation is appropriate. In these situations a 13-layer meta-material overlay 1100, such as shown in Fig. 11, provides either additional shielding of the electrical traces, design flexibility or relaxed tolerances.

As shown the 13-layer meta-material overlay 1100 comprises a lower six-layer
35 meta-material structure 1155A, electrical trace layer 1110, and upper six-layer meta-

5 material structures 1155B. The lower six-layer meta-material structure 1155A formed from first signal conductor plane 1155L1A, first insulating layer 1155L2A, straight sections of metal 720 in first conductor layer 1155L3A, second insulating layer 1155L4A, metallic conductors 725 in second conductor layer 1155L5A, and third insulating layer 1155L6A.

10 The upper six-layer meta-material structure 1155B is formed from second signal conductor plane 1155L1B, fourth insulating layer 1155L2B, straight sections of metal 720 in third conductor layer 1155L3B, fifth insulating layer 1155L4B, metallic conductors 725 in fourth conductor layer 1155L5B, and sixth insulating layer 1155L6B.

Throughout the exemplary embodiments supra the deployment scenarios for each
15 of the meta-material overlays have been presented in respect of replacing wire bonds between the peripheries of first and second devices; including but not limited to semiconductor die, package, and printed circuit boards. Alternatively, the meta-material overlay is configured to provide an overlay to electrical interconnections disposed within the footprint of the package, semiconductor die, etc. Three such exemplary deployments
20 of a meta-material overlay with respect to a semiconductor circuit within a package are shown in Fig. 12 by cross-sections 1200A through 1200C.

First cross-section 1200A depicts a scenario wherein a meta-material overlay 1210 lands directly onto the upper surface of a semiconductor die 550, originating on the left upper surface 510A of a circuit package, not shown for clarity, and terminating on the right upper surface of the circuit package 510B. As such the meta-material overlay 1210
25 forms two arcuate surfaces under which are bond wires 530. Each arcuate surface 1210A and 1210B is approximately parallel to its respective bond wire 530 for a substantial portion of the length of the bond wire 530. Whilst this exemplary cross-section 1200A depicts the meta-material overlay 1210 forming two arcuate surfaces,
30 alternative embodiments may offer three or more such regions to provide the requisite impedance control for the bond wire interfaces either across a single die or an MCM. Further, the overlay is optionally shaped prior to deployment according to the requirements of the design or shaped during placement and bonding. Also, the meta-material overlay optionally is designed to not interconnect to the upper surface of the
35 semiconductor die 550, but be spaced away with an air gap.

5 An alternative embodiment provides for the number of arcuate surfaces to vary according to position, such that for a portion of the interconnections there is a single arcuate surface whilst for other portions there are two, three or more arcuate surfaces. Also whilst the meta-material overlay 1210 is shown as a six-layer meta-material overlay, such as six-layer meta-material overlay 560, alternatives include but are not limited to the
10 seven-layer and 13-layer meta-material overlays described supra such as the seven-layer meta-material overlay 910 and the 13-layer meta-material overlay 1100.

 In second cross-section 1200B the meta-material overlay 1220 is again employed for impedance control of bond wires 530 between the upper surface of semiconductor die 550 and left and right upper surfaces 510A of a circuit package, not shown for clarity.

15 The upper surface of semiconductor die 550 includes landing zone 1230, upon which the meta-material overlay 1220 is interconnected rather than interfacing directly to the upper surface of the semiconductor die 550. The landing zone 1230 vertically offsets the meta-material overlay 1220 over the semiconductor die 550, thereby modifying the shape of the arcuate surfaces 1220A and 1220B. Landing zone 1230 is formed according to
20 standard semiconductor processes from a range of dielectric materials and metals, according to the requirements of the semiconductor die 550 and whether an electrical interconnection to the signal conductor plane of the meta-material overlay is made in the landing zone 1230. Typical materials for the landing zone 1230 include silicon dioxide, silicon nitride, silicon oxynitride, spin-on-glass, bisbenzocyclobutene, gold, and
25 aluminum, each of these being optionally employed discretely or in combination.

 Now referring to the third cross-section 1200C, the meta-material overlay 1240 again provides an overlay for the left wire bond 540A, originating on the left upper surface 510A of the circuit package, over semiconductor die 550, and for right wire bond 540B terminating on the right upper surface 510B of the circuit package. In contrast to
30 first and second cross-sections 1200A and 1200B the meta-material overlay 1240 provides a single arcuate surface, wherein the left and right surface portions 1240A and 1240B are approximately parallel to wire bonds 540A and 540B for a predetermined region of each. Hence, whilst meta-material overlay 1240 typically does not provide as controlled an impedance environment for the wire bonds 540A and 540B when compared
35 to the meta-material overlays 1220 and 1210 of first and second cross-sections 1200A

5 and 1200B respectively, the formation of the structure in situ has reduced complexity. Accordingly the exemplary deployment embodiment in the third cross-section 1200C presents a different tradeoff between cost of implementation and performance to that of the first and second cross-sections 1200A and 1200B respectively.

Now referring to Fig. 13 there are shown simulation results 1300 for the
10 transmission characteristics of electrical interconnections according prior art solutions and an embodiment of the invention, a bond wire with meta-material overlay. For each result the ratio of electrical signal received at the end of the electrical interconnection to electrical signal applied is shown as a function of frequency. A first curve 1310 plots this ratio for a single discrete bond wire, 14,500 μ m long, according to the prior art, which
15 essentially provides a linearly degrading transmission of the electrical interconnection with increasing frequency, having a 1dB loss for the 14,500 μ m bond wire length at approximately 1.3GHz, a 2dB loss at approximately 2.4GHz, and 3dB loss at approximately 3.3GHz.

Second curve 1320 plots the results for a single 14,500 μ m bond wire length
20 according to the prior art of Wyland [US Patent 7,217,997] wherein a ground arch is placed over the bond wire with air dielectric. In contrast to the single discrete bond wire, the second curve 1320 drops approximately linearly until 2GHz and then flattens out to a maximum loss of approximately 1.6dB at 2.6GHz. Shown finally is third curve 1330, representing an exemplary electrical interconnection according to an embodiment of the
25 invention wherein a meta-material overlay is employed in conjunction with the 14,500 μ m bond wire. Now the loss increases approximately linearly to a maximum loss of approximately 1dB at 2.2GHz whereupon it decreases to a loss of approximately 0.6dB at 4GHz.

The effectiveness of the exemplary embodiment against the prior art is clearly
30 evident. For example at 3.3GHz the third curve 1330 shows a loss of only 0.75dB versus 3dB for the discrete bond wire in first curve 1310, a 2.25dB improvement; and an improvement of 0.6dB from 1.55dB to 0.95dB when compared to second curve 1320 for the bond wire with an electrical ground plane.

Numerous other embodiments may be envisaged without departing from the spirit
35 or scope of the invention.

CLAIMS

1. A method comprising:

providing at least an electrical interconnection of a plurality of electrical
interconnections to a first device, each electrical interconnection being characterized
by at least an interconnection length;

providing an overlay, the overlay comprising at least a first meta-material
structure and being disposed approximately parallel to the at least an electrical
interconnection of a plurality of electrical interconnections for at least a
predetermined portion of the interconnection length; and

providing an underlay, the underlay comprising at least a second meta-material
structure and being disposed approximately parallel to the electrical interconnection
for at least another predetermined portion of the interconnection length.

2. A method according to claim 1 wherein,

providing the first meta-material structure comprises providing at least a
continuous conductor layer and a dielectric layer, the dielectric layer having
embedded therein at least one isolated conductor of a plurality of isolated conductors.

3. A method according to claim 2 wherein,

providing the continuous conductor comprises providing the continuous
conductor at least one of at a ground potential, at a predetermined potential, and
floating.

4. A method according to claim 1 wherein,

providing the electrical interconnection and overlay comprises providing a
single structure.

5. A method according to claim 1 wherein,

providing an electrical interconnection of a plurality of electrical
interconnections comprises providing an electrical interconnection terminating at least
one of approximately at the periphery of the first device and within the footprint of the
first device.

6. A method according to claim 5 wherein,

at least a first predetermined portion of the plurality of electrical interconnections terminate at a location other than that of a second predetermined portion of the plurality of electrical interconnections.

5 7. A method according to claim 1 wherein,
 providing the overlay, underlay, and at least an electrical interconnection of a plurality of electrical interconnections comprising providing a single integrated structure.

 8. A method according to claim 1 wherein,
10 providing the second meta-material comprises providing at least one of the first meta-material, a meta-material with a predetermined relationship to the first meta-material, and a meta-material other than the first meta-material.

 9. A method according to claim 1 wherein,
 providing the overlay additionally comprises providing at least the first meta-
15 material and a second meta-material, wherein the first meta-material is associated with a first predetermined portion of the plurality of electrical interconnections and the second meta-material is associated with a second predetermined portion of the plurality of electrical interconnections.

 10. A method according to claim 1 wherein,
20 providing the first meta-material comprises providing a first meta-material having material properties selected to improve an electrical characteristic of the at least an electrical interconnection of the plurality of electrical interconnections, the electrical characteristic selected from a group comprising impedance, propagation loss, radiation loss, frequency response, rise time and fall time.

25 11. A circuit comprising:
 at least an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length;

 an overlay, the overlay comprising at least a first meta-material structure and
30 being disposed approximately parallel to the at least an electrical interconnection of a plurality of

electrical interconnections for at least a predetermined portion of the interconnection length; and

an underlay, the underlay comprising at least a second meta-material structure and being disposed approximately parallel to the electrical interconnection for at least another predetermined portion of the interconnection length.

12. A circuit according to claim 11 wherein,

providing the first meta-material structure comprises providing at least a continuous conductor layer and a dielectric layer, the dielectric layer having embedded therein at least one isolated conductor of a plurality of isolated conductors.

13. A circuit according to claim 12 wherein,

providing the continuous conductor comprises providing the continuous conductor at least one of electrically interconnected to ground, electrically interconnected to a predetermined potential, and electrically isolated.

14. A circuit according to claim 11 wherein,

providing the electrical interconnection and overlay comprises providing a single integrated structure.

15. A circuit according to claim 11 wherein,

providing an electrical interconnection of a plurality of electrical interconnections comprises providing an electrical interconnection terminating at least one of approximately the periphery of the first device and within the footprint of the first device.

16. A circuit according to claim 15 wherein,

at least a first predetermined portion of the plurality of electrical interconnections terminate at a location other than that of a second predetermined portion of the plurality of electrical interconnections.

17. A circuit according to claim 11 wherein,

providing the overlay, underlay, and at least an electrical interconnection of a plurality of electrical interconnections comprising providing a single integrated structure.

18. A circuit according to claim 11 wherein,

providing the second meta-material comprises providing at least one of the first metamaterial, a meta-material with a predetermined relationship to the first meta-material, and a meta-material other than the first meta-material.

19. A circuit according to claim 11 wherein,

5 providing the overlay additionally comprises providing at least the first meta-material and a second meta-material, wherein the first meta-material is associated with a first predetermined portion of the plurality of electrical interconnections and the second metamaterial is associated with a second predetermined portion of the plurality of electrical interconnections.

10 20. A circuit according to claim 11 wherein,

providing the first meta-material comprises providing a first meta-material having material properties selected to improve an electrical characteristic of the at least an electrical interconnection of the plurality of electrical interconnections, the electrical characteristic selected from a group comprising impedance, propagation
15 loss, radiation loss, frequency response, rise time and fall time.

21. A computer readable medium having stored therein data according to a predetermined computing device format, and upon execution of the data by a suitable computing device a method of electrically interconnecting a circuit is provided, comprising:

20 providing at least an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length;

providing an overlay, the overlay comprising at least a first meta-material structure and being disposed approximately parallel to the at least an electrical
25 interconnection of a plurality of electrical interconnections for at least a predetermined portion of the interconnection length; and

providing an underlay, the underlay comprising at least a second meta-material structure and being disposed approximately parallel to the electrical interconnection for at least another predetermined portion of the interconnection length.

30 22. A computer readable medium having stored therein data according to a predetermined computing device format, and upon execution of the data by a suitable

computing device a circuit for electrically interconnecting a circuit is provided, comprising:

at least an electrical interconnection of a plurality of electrical interconnections to a first device, each electrical interconnection being characterized by at least an interconnection length;

an overlay, the overlay comprising at least a first meta-material structure and being disposed approximately parallel to the at least an electrical interconnection of a plurality of electrical interconnections for at least a predetermined portion of the interconnection length; and

an underlay, the underlay comprising at least a second meta-material structure and being disposed approximately parallel to the electrical interconnection for at least another predetermined portion of the interconnection length.