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INTEGRATED VOLTAGE REGULATOR AND PASSIVE COMPONENTS

Abstract

It is highly desirable in electronic systems to conserve space on printed circuit boards (PCB). This disclosure describes voltage regulation in electronic systems, and more specifically to integrating voltage regulators and associated passive components into semiconductor packages with at least a portion of the circuits whose voltage(s) they are regulating.

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Background/Summary

RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 18/399,504, filed Dec. 28, 2023, which continuation of U.S. patent application Ser. No. 18/058,677, filed Nov. 23, 2022, now U.S. Pat. No. 11,894,345, which is a continuation of U.S. patent application Ser. No. 16/397,202, filed Apr. 29, 2019, now U.S. Pat. No. 11,515,291, which claims priority to U.S. Provisional Patent Application No. 62/723,897, filed Aug. 28, 2018. The content of each of these applications is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

[0002] The invention pertains to voltage regulation in electronic systems, and more specifically to integrating voltage regulators and associated passive components into semiconductor packages with at least a portion of the circuits whose voltage(s) they are regulating.

BACKGROUND OF THE INVENTION

[0003] FIG. 1A illustrates a block diagram of a portion of a conventional system **100** which is suitable for use in, for example, a device such as a cellphone or computer. System **100** may comprise printed circuit board (PCB) **110**. Mounted on PCB **110** are components which may include a data processing integrated circuit (DPIC) **112** which may be, for example, a central processing unit (CPU), a microprocessor unit (MPU), a microcontroller unit (MCU), an Applications Processor (AP), a Digital Signal Processor (DSP), a System-on-a-Chip (SOC), an Application Specific Integrated Circuit (ASIC), or some other type of integrated circuit. Also mounted on PCB **110** may be an optional battery **114**, an external connector **116**, one or more RLC passive components **118**, and a Power Management Integrated Circuit (PMIC) **120**.

[0004] Active components (as opposed to passive components) are considered to be circuits or circuit elements that provide electrical gain and/or switching. Examples of active components are, for example, transistors, amplifiers, oscillators, pass transistors, transmission gates, etc.

[0005] Passive components are circuits or circuit elements that do not provide electrical gain. The common acronym RLC stands for Resistors, Inductors and Capacitors, all of which are examples of passive components. (Since “I” is by convention an abbreviation for current in electrical engineering, the letter “L” is by convention used as an abbreviation for inductance, hence “RLC” instead of “RIC.”) RLC may be, and herein is, used as a generic stand-in for one or more passive components regardless what mix of components are actually present. Other examples of passive components may include, for example, fuses or antifuses, resistors through-silicon vias (TSVs), etc., and may be included along with resistors, inductors, and capacitors in any combination as part of generic phrases like, for example, “RLC passive components” or “RLC passives” or “RLC components” or simply “RLC.”

[0006] PMIC **120** may be coupled to DPIC **112**, the optional battery **114**, the external connector **116**, and the RLC passives **118**. External connector **116** may be one of many types known in the art. It may supply one or more power and ground connections to other components and/or to PMIC **120**

which in turn may regulate or supply power to some or all of the other components on PCB **110**. [0007] The RLC passive components **118** may perform a variety of different functions for system **100**. They may, for example, provide diodes to protect PCB **110** from power surges, hot insertions, and electrostatic discharge (ESD) events related to the external connector **116**. They may also provide decoupling capacitors for DPIC **112**, PMIC **120**, and other chips in the system not shown in FIG. **1A**, as well as other components needed for other functions in system **100** (not shown). [0008] PMIC **120** may have a variety of circuits providing different sorts of power control to different parts of the system. For example, battery tender circuit **122** may control the battery charging, discharging, leakage, and maintenance as is known in the art in systems where battery **114** is present. [0009] Also present may be any of a variety of power supplies and/or regulators known in the art like, for example, switching supply **124** and Low Drop Out regulators (LDOs) **126** and **128**. Switching supply **124** may be any of a number of types known in the art like, for example, a buck converter, a boost converter, a switched capacitor converter, etc. These circuits often require external capacitors and inductors with values larger than may be practical to implement as a portion of PMIC **120**. They may also generate significant noise so care must be taken in their design and use. [0010] Low Drop Out (LDO) regulators like **126** and **128** are known in the art. They are a type of linear regulator that provides a small step down from a power supply voltage to a regulated lower voltage. They may also be present in PMIC **120** to provide different voltages to DPIC **112** and/or other integrated circuits in system **100** not shown in FIG. **1A**. [0011] FIG. **1B** illustrates a physical cross section of a portion of system **100**. It is intended for illustrative purposes and is not drawn to scale. Present in the figure are PCB **110**, PMIC **120**, and a package **130**, the latter further comprising data processing integrated circuit **112** and details of other physical elements. [0012] Package **130** may comprise DPIC **112** which may be bonded to a package substrate **132** with solder bumps **138**. Data processing integrated circuit **112** may be surrounded by die seal **134** to protect it from physical, chemical and/or electrical damage, but this may not be the case in some applications. In some technologies die seal **134** may not be present at all like, for example, in a die scale package. In other technologies, die seal **134** may be present as a layer between DPIC **112** and the package substrate **132** (and is known as under-fill). Package **130** itself may be bonded to PCB **110** by means of solder balls **136** coupled to the package substrate **132**. [0013] PMIC **120** is also shown in the figure, but without any internal package detail. It may be bonded to PCB **110** by solder bumps **140**, and coupled to package **130** though metal traces **142** present in PCB **110**, though many other configurations are possible. [0014] It is highly desirable for the circuitry comprising PMIC **120** and RLC passives **118** (not shown in FIG. **1B**) to be located in the same package as DPIC **112** to improve electrical performance and save area on PCB **110**.

Description

DESCRIPTION OF THE DRAWINGS

[0015] FIG. **1A** illustrates a block diagram of portion of a conventional system **100**. [0016] FIG. **1B** is not drawn to scale and illustrates a cross section of a portion of the conventional system **100**. [0017] FIG. **2A** is not drawn to scale and illustrates a portion of a system **200-A** with details of a cross section of a package **230-A** according to an embodiment of the present invention. [0018] FIG. **2B** is not drawn to scale and illustrates a portion of a system **200-B** with details of a cross section of a package **230-B** according to an embodiment of the present invention.

[0019] FIG. 2C is not drawn to scale and illustrates a portion of a system **200-C** with details of a cross section of a package **230-C** according to an embodiment of the present invention.

[0020] FIG. 3A is not drawn to scale and illustrates a portion of a system **300-A** with details of a cross section of a package **330-A** according to an embodiment of the present invention.

[0021] FIG. 3B is not drawn to scale and illustrates a portion of a system **300-B** with details of a cross section of a package **330-B** according to an embodiment of the present invention.

[0022] FIG. 3C is not drawn to scale and illustrates a portion of a system **300-C** with details of a cross section of a package **330-C** according to an embodiment of the present invention.

[0023] FIG. 4A is not drawn to scale and illustrates a portion of a system **400-A** with details of a cross section of a package **430-A** according to an embodiment of the present invention.

[0024] FIG. 4B is not drawn to scale and illustrates a portion of a system **400-B** with details of a cross section of a package **430-B** according to an embodiment of the present invention.

[0025] FIG. 4C is not drawn to scale and illustrates a portion of a system **400-C** with details of a cross section of a package **430-C** according to an embodiment of the present invention.

[0026] FIG. 4D is not drawn to scale and illustrates a portion of a system **400-D** with details of a cross section of a package **430-D** according to an embodiment of the present invention.

[0027] FIG. 5A is not drawn to scale and illustrates a top view of an integrated inductor **500** according to an embodiment of the present invention.

[0028] FIG. 5B is not drawn to scale and illustrates a cross section of the integrated inductor **500** according to an embodiment of the present invention.

[0029] FIG. 5C is not drawn to scale and illustrates a top view an integrated inductor **520** according to an embodiment of the present invention.

[0030] FIG. 5D is not drawn to scale and illustrates a cross section of the integrated inductor **520** according to an embodiment of the present invention.

[0031] FIG. 5E is not drawn to scale and illustrates a cross section of two portions of an integrated inductor **540** prior to assembly according to an embodiment of the present invention.

[0032] FIG. 5F is not drawn to scale and illustrates a cross section of the integrated inductor **540** after assembly according to an embodiment of the present invention.

[0033] FIG. 6A is not drawn to scale and illustrates a top view of an annular integrated inductor **600** according to an embodiment of the present invention.

[0034] FIG. 6B is not drawn to scale and illustrates a cross section of the annular integrated inductor **600** according to an embodiment of the present invention.

[0035] FIG. 6C is not drawn to scale and illustrates a cross section of an annular integrated inductor **620** according to an embodiment of the present invention.

[0036] FIG. 6D is not drawn to scale and illustrates a cross section of an annular integrated inductor **640** according to an embodiment of the present invention.

[0037] FIG. 6E is not drawn to scale and illustrates a cross section of an annular integrated inductor **660** according to an embodiment of the present invention.

[0038] FIG. 6F is not drawn to scale and illustrates a cross section of an annular integrated inductor **680** according to an embodiment of the present invention.

[0039] FIG. 7 is not drawn to scale and illustrates cross sections and circuit symbols of exemplary passive components which may be present in an RLC passives die **700** according to an embodiment of the present invention.

[0040] FIG. 8A is not drawn to scale and illustrates a cross section of an RLC passives die **800-A** according to an embodiment of the present invention.

[0041] FIG. 8B is not drawn to scale and illustrates a cross section of an RLC passives die **800-B** according to an embodiment of the present invention.

[0042] FIG. 8C is not drawn to scale and illustrates a cross section of an RLC passives die **800-C** according to an embodiment of the present invention.

[0043] FIG. 8D is not drawn to scale and illustrates a cross section of an RLC passives die **800-D**

according to an embodiment of the present invention.

[0044] FIG. **9** is not drawn to scale and illustrates several package cross sections with illustrative internal arrangements of semiconductor dies according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0045] Those of ordinary skill in the art will realize that the following figures and descriptions of exemplary embodiments and methods of the present invention are illustrative only and not in any way limiting. Other embodiments will readily suggest themselves to such skilled persons after reviewing this disclosure.

[0046] Reference numbers are generally keyed to the figure in which they first appear. For example, a reference number in the range **700-799** will typically appear first in FIG. **7**. Reference numbers in the **400-499** range will typically appear first in one of the FIG. **4A**, **4B**, **4C**, or **4D**. Identical reference numbers in different figures indicate identical, similar, or analogous structures or features. In many figures, multiple instances of a particular element or feature may be shown, but only a single example may be given a reference numeral to avoid overcomplicating the drawings.

[0047] FIG. **2A** is not drawn to scale and illustrates a portion of a system **200-A** with details of a cross section of a package **230-A** according to an embodiment of the present invention. System **200-A** comprises PCB **210** with package **230-A** mounted onto it by means of solder balls **236**. Package **230-A** further comprises top integrated circuit **212-A** and bottom integrated circuit **214-A**. Top integrated circuit **212-A** comprises a circuit portion **212-U** and a substrate portion **212-V**. Similarly, bottom integrated circuit **214-A** comprises a circuit portion **214-U** and a substrate portion **214-V**.

[0048] Top integrated circuit **212-A** may be both physically and electrically coupled to bottom integrated circuit **214-A** at interface **250-A** using, for example, a die-to-die or wafer-to-wafer bonding technology. Dies or wafers may be bonded in a stacked arrangement using various bonding techniques like, for example, DBI®, a hybrid direct bonding technology that allows semiconductor wafers or dies to be bonded with exceptionally fine pitch 3D electrical interconnect, available from Invensas Bonding Technologies, Inc. (formerly Ziptronix, Inc.), an Xperi company (see for example, U.S. Pat. Nos. 6,864,585 and 7,485,968, which are incorporated herein in their entirety). Thus a high density of power and signal interconnections may be available between integrated circuits **212-A** and **214-A**.

[0049] The two integrated circuits **212-A** and **214-A** bonded together at interface **250-A** may be mounted on package substrate **232** by solder bumps **238**, and may be surrounded by die seal **234** to protect them from physical, chemical, and electrical damage. Coupling between the circuit portions **212-U** and **214-U** (of the bonded integrated circuits **212-A** and **214-A**, respectively) and the solder bumps **238** may be made by, for example, through-silicon vias (TSVs) passing through integrated circuit **214-A** (not shown in FIG. **2A**). While this particular packaging configuration and technology has been chosen for ease of explanation of exemplary embodiments, persons skilled in the art will realize that there are many other packaging configurations and technologies that may be used within the scope of the present invention.

[0050] The circuit portion **212-U** further comprises an integrated voltage regulator (IVR) circuit **216-A**, while circuit portion **214-U** further comprises integrated RLC passive components **215**. IVR circuit **216-A** may comprise some, all, or different regulatory circuitry, partially or completely replacing similar circuits like, for example, portions of a chip like, for example, PMIC **120** in FIG. **1A**. Similarly, RLC **215** may comprise some, all, or different components, partially or completely replacing similar circuit components like, for example, the ones comprising RLC passive components **118** in FIG. **1A**.

[0051] Integrated circuits **212-A** and **214-A** may be manufactured using different semiconductor fabrication processes. For example, integrated circuit **212-A** might be manufactured in a process more favorable for producing circuits like those found, for example, in data processing integrated

circuit **112** and/or PMIC **120** in FIG. **1A**, while integrated circuit **214-A** might be fabricated in a process more suitable for producing RLC passives with much larger component values than could normally be produced on a process more suitable for manufacturing integrated circuits like **212-A**. This approach has the advantage over the background art of saving space on PCB **210** as well better electrical performance by placing IVR **216-A** and RLC **215** closer to each other as well as to the other circuits they might be coupled to.

[0052] FIG. **2B** is not drawn to scale and illustrates a portion of a system **200-B** with details of a cross section of a package **230-B** according to an embodiment of the present invention. System **200-B** comprises PCB **210** with package **230-B** mounted onto it by means of solder balls **236**. Package **230-B** further comprises top integrated circuit **212-B** and bottom integrated circuit **214-B**. Top integrated circuit **212-B** comprises a circuit portion **212-W** and a substrate portion **212-X**. Similarly, bottom integrated circuit **214-B** comprises a circuit portion **214-W** and a substrate portion **214-X**. Top integrated circuit **212-B** may be both physically and electrically coupled to bottom integrated circuit **214-B** at interface **250-B** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®, a hybrid direct bonding technology available from Invensas Bonding Technologies, Inc.

[0053] The two integrated circuits **212-B** and **214-B** bonded together at interface **250-B** may be mounted on package substrate **232** by solder bumps **238**, and may be surrounded by die seal **234** to protect them from physical, chemical, and electrical damage. Coupling between the circuit portions **212-W** and **214-W** (of the bonded integrated circuits **212-B** and **214-B**, respectively) and the solder bumps **238** may be made by, for example, through-silicon vias (TSVs) passing through integrated circuit **214-B** (not shown in FIG. **2B**). While this particular packaging configuration and technology has been chosen for ease of explanation of exemplary embodiments, persons skilled in the art will realize that there are many other packaging configurations and technologies that may be used within the scope of the present invention.

[0054] The circuit portion **212-W** further comprises an integrated voltage regulator (IVR) circuit **216-B** and RLC passive components **217**. IVR circuit **216-B** comprises some, all, or different regulatory circuitry, partially or completely replacing similar circuits like, for example, those comprising portions of a chip like, for example, PMIC **120** in FIG. **1A**. Similarly, RLC **217** may comprise some, all, or different components, partially or completely replacing similar circuit components like, for example, the ones comprising RLC passive components **118** in FIG. **1A**.

[0055] Integrated circuits **212-B** and **214-B** may be manufactured using different semiconductor fabrication processes. For example, integrated circuit **212-B** might be manufactured in a process more favorable for producing both analog circuits like those found, for example, in PMIC **120** in FIG. **1A**, as well as for RLC passives like those found, for example in RLC **116** in FIG. **1A**. Integrated circuit **214-B** might be fabricated in a process more suitable for producing data processing integrated circuits like, for example, DPIC **112** in FIG. **1A**. This approach has the advantage over the background art of saving space on PCB **210** as well better electrical performance by placing IVR **216-B** and RLC **217** closer to each other as well as to the other circuits they might be coupled to.

[0056] FIG. **2C** is not drawn to scale and illustrates a portion of a system **200-C** with details of a cross section of a package **230-C**, according to an embodiment of the present invention. System **200-C** comprises PCB **210** with package **230-C** mounted onto it by means of solder balls **236**. Package **230-C** further comprises top integrated circuit **212-C** and bottom integrated circuit **214-C**. Top integrated circuit **212-C** comprises a circuit portion **212-Y** and a substrate portion **212-Z**. Similarly, bottom integrated circuit **214-C** comprises a circuit portion **214-Y** and a substrate portion **214-Z**. Top integrated circuit **212-C** may be both physically and electrically coupled to bottom integrated circuit **214-C** at interface **250-C** like, for example, DBI®.

[0057] The two integrated circuits **212-C** and **214-C** bonded together at interface **250-C** may be mounted on package substrate **232** by solder bumps **238**, and may be surrounded by die seal **234** to

protect them from physical, chemical, and electrical damage. Coupling between the circuit portions **212-Y** and **214-Y** (of the bonded integrated circuits **212-C** and **214-C**, respectively) and the solder bumps **238** may be made by, for example, through-silicon vias (TSVs) passing through integrated circuit **214-C** (not shown in FIG. 2C). While this particular packaging configuration and technology has been chosen for ease of explanation of exemplary embodiments, persons skilled in the art will realize that there are many other packaging configurations and technologies that may be used within the scope of the present invention.

[0058] The circuit portion **212-Y** further comprises an integrated voltage regulator (IVR) circuit **216-C** and RLC passive components **218**, while the circuit portion **214-Y** further comprises RLC passive components **219**. IVR circuit **216-C** comprises some, all, or different regulatory circuitry, partially or completely replacing similar circuits like, for example, those comprising portions of a chip like PMIC **120** in FIG. 1A. Similarly, RLC **218** and RLC **219** may comprise some, all, or different components, partially or completely replacing similar circuit components like, for example, the ones comprising RLC passive components **118** in FIG. 1A.

[0059] Integrated circuits **212-C** and **214-C** may be manufactured using different semiconductor fabrication processes. For example, integrated circuit **212-C** might be manufactured in a process more favorable for producing both analog circuits like those found, for example, in PMIC **120** in FIG. 1A, as well as for RLC passives like those found, for example in RLC **118** in FIG. 1A, with much larger component values, while integrated circuit **214-C** might be fabricated in a process more suitable for producing data processing integrated circuits like, for example, DPIC **112** in FIG. 1A.

[0060] In this configuration, individual passive components may be formed in two parts via the connections at the interface **250-C** between RLC **218** and RLC **219**. This approach has the advantage over the background art of saving space on PCB **210** as well better electrical performance by placing IVR **216-C** and RLCs **218** and **219** closer to the circuits they are coupled to. In addition, the interface **250-C** can be made extremely thin to enhance the electric and/or magnetic coupling to more efficiently make passive components formed in two parts.

[0061] FIG. 3A is not drawn to scale and illustrates a portion of a system **300-A** with details of a cross section of a package **330-A** according to an embodiment of the present invention. System **300-A** comprises PCB **310** with package **330-A** mounted onto it by means of solder balls **336**. Package **330-A** further comprises top integrated circuit (IC) **312-A**, RLC passives die **318-A**, and bottom integrated circuit die **314-A**. Top IC **312-A** may be physically and electrically coupled to RLC **318-A** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®, a hybrid direct bonding technology available from Invensas Bonding Technologies, Inc. Similarly, RLC **318-A** may also be physically and electrically coupled to IC **314-A** using, for example, DBI®. IC **312-A**, RLC **318-A**, and IC **314-A** may be mounted to package substrate **332** by solder bumps **338**. Further, IC **312-A**, RLC **318-A**, and IC **314-A** may be electrically coupled together and to the solder bumps **338** with TSVs passing through RLC **318-A** and IC **314-A** (not shown in FIG. 3A).

[0062] Top IC **312-A**, RLC **318-A**, and bottom IC **314-A** may be manufactured using different semiconductor fabrication processes appropriate to the circuitry therein. For example, IC **312-A** may be manufactured in a process tuned to produce ICs like, for example, PMIC **120** in FIG. 1A, while RLC **318-A** may be manufactured in a process tuned to produce passive components, and IC **314-A** may be manufactured in a process tuned to produce ICs like, for example, DPIC **112** in FIG. 1A. Persons skilled in the art will appreciate many other configurations and combinations are possible as a matter of design choice and fall within the scope of the present invention. For example, the side with the circuitry of each die may be either be facing towards (down) or away from (up) the package substrate **332**. If the active circuitry of top IC **312-A** faces away from package substrate **332**, TSVs through IC **312-A** may also be needed (not shown in FIG. 3A).

[0063] This approach improves over the background art because in many embodiments it allows a

system like system **100** in FIG. **1A** to incorporate DPIC **112**, RLC passives **118**, and PMIC **120** into a single package improving electrical performance and saving valuable space on PCB **110**.

[0064] FIG. **3B** is not drawn to scale and illustrates a portion of a system **300-B** with details of a cross section of a package **330-B** according to an embodiment of the present invention. System **300-B** comprises PCB **310** with package **330-B** mounted onto it by means of solder balls **336**. Package **330-B** further comprises RLC passives die **318-B**, top integrated circuit (IC) die **312-B**, and bottom integrated circuit die **314-B**. RLC **318-B** may be physically and electrically coupled to IC **312-B** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBIR. Similarly, IC **312-B** may also be physically and electrically coupled to IC **314-B** like, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®. RLC **318-B**, IC **312-B**, and IC **314-B** may be mounted to package substrate **332** by solder bumps **338**. Further, RLC **318-A**, IC **312-A**, and IC **314-A** may be electrically coupled together and to the solder bumps **338** with TSVs passing through IC **312-B** and IC **314-B** (not shown in FIG. **3B**).

[0065] RLC **318-B**, top IC **312-B**, and bottom IC **314-B** may be manufactured using different semiconductor fabrication processes appropriate to the circuitry therein. For example, RLC **318-B** may be manufactured in a process tuned to produce passive components, while IC **312-B** may be manufactured in a process tuned to produce ICs like, for example, PMIC **120** in FIG. **1A**, and IC **314-B** may be manufactured in a process tuned to produce ICs like, for example, data processing integrated circuit **112** in FIG. **1A**. Persons skilled in the art will appreciate many other configurations and combinations are possible as a matter of design choice and fall within the scope of the present invention. For example, the side with the circuitry of each die may be either be facing towards (down) or away from (up) package substrate **332**. Depending on the design of its components and circuitry, if RLC **318-B** faces away from package substrate **332**, TSVs through RLC **318-C** may also be needed (not shown in FIG. **3B**).

[0066] This approach improves over the background art because in many embodiments it allows a system like system **100** in FIG. **1A** to incorporate DPIC **112**, RLC passives **118**, and PMIC **120** into a single package improving electrical performance and saving valuable space on PCB **110**.

[0067] FIG. **3C** is not drawn to scale and illustrates a portion of a system **300-C** with details of a cross section of a package **330-C** according to an embodiment of the present invention. System **300-C** comprises PCB **310** with package **330-C** mounted onto it by means of solder balls **336**. Package **330-C** further comprises top integrated circuit (IC) **312-C**, bottom integrated circuit die **314-C**, and RLC passives die **318-C**. IC **312-C** may be physically and electrically coupled to IC **314-C** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®, a hybrid direct bonding technology available from Invensas Bonding Technologies, Inc. Similarly, IC **314-C** may also be physically and electrically coupled to RLC **318-C** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®. IC **312-C**, RLC **318-C**, and IC **314-C** may be mounted to package substrate **332** by solder bumps **338**. Further, IC **312-C**, IC **314-C**, and RLC **318-C**, may be electrically coupled together and to the solder bumps **338** with TSVs passing through IC **314-C** and RLC **318-C** (not shown in FIG. **3C**).

[0068] Top IC **312-C**, bottom IC **314-C**, and RLC **318-C**, may be manufactured using different semiconductor fabrication processes appropriate to the circuitry therein. For example, IC **312-C** may be manufactured in a process tuned to produce ICs like, for example, data processing integrated circuit **112** in FIG. **1A**, while IC **314-C** may be manufactured in a process tuned to produce ICs like, for example, PMIC **120** in FIG. **1A**, and RLC **318-C** may be manufactured in a process tuned to produce passive components. Persons skilled in the art will appreciate many other configurations and combinations are possible and a matter of design choice and fall within the scope of the present invention. For example, the side with the circuitry of each die may be either be facing towards (down) or away from (up) package substrate **332**. If the active circuitry of top IC **312-C** faces away from package substrate **332**, TSVs through IC **312-C** may also be needed (not shown in FIG. **3C**).

[0069] This approach improves over the background art because in many embodiments it allows a system like system I **00** in FIG. **1A** to incorporate DPIC **112**, RLC passives **118**, and PMIC **120** into a single package improving electrical performance and saving valuable space on PCB **110**.

[0070] FIG. **4A** is not drawn to scale and illustrates a portion of a system **400-A** with details of a cross section of a package **430-A** according to an embodiment of the present invention. System **400-A** comprises PCB **410** with package **430-A** mounted onto it by means of solder balls **436**. Package **430-A** further comprises top integrated circuit die **412-A**, RLC passives die **415-A**, bottom integrated circuit die **414-A**, and die seal **434**. Top integrated circuit **412-A** comprises a circuit portion **412-U** and a substrate portion **412-V**. Similarly, bottom integrated circuit **414-A** comprises a circuit portion **414-U** and a substrate portion **414-V**.

[0071] Top integrated circuit **412-A** may be both physically and electrically coupled to RLC **415-A** at interface **450-K** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®. a hybrid direct bonding technology available from Invensas Bonding Technologies, Inc. Similarly, RLC **415-A** may also be both physically and electrically coupled to bottom integrated circuit **414-A** at interface **450-L** using, for example, DBI®.

[0072] The circuit portion **412-U** of top IC **412-A** further comprises integrated voltage regulator (IVR) **416-A**. This allows better electrical performance because of the proximity of IVR **416-A** to a select portion of the components of RLC **415-A** that are directly coupled between them at interface **450-K**, while other passive components with less critical layout constraints may be placed elsewhere on RLC **415-A**. Further, it allows IVR **416-A** to be placed in a location that is optimal for the circuits it regulates power for in either IC **412-A** or IC **414-A**.

[0073] FIG. **4B** is not drawn to scale and illustrates a portion of a system **400-B** with details of a cross section of a package **430-B** according to an embodiment of the present invention. System **400-B** comprises PCB **410** with package **430-B** mounted onto it by means of solder balls **436**. Package **430-B** further comprises top integrated circuit (IC) **412-B**, RLC passives die **415-B**, bottom integrated circuit die **414-B**, and die seal **434**. Top integrated circuit **412-B** comprises a circuit portion **412-W** and a substrate portion **414-X**. Similarly, bottom integrated circuit **414-B** comprises a circuit portion **414-W** and a substrate portion **414-X**.

[0074] Top integrated circuit **412-B** may be both physically and electrically coupled to RLC **415-B** at interface **450-M** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®. Similarly, RLC **415-B** may also be both physically and electrically coupled to bottom integrated circuit **414-B** at interface **450-N** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®.

[0075] The circuit portion **412-W** of top IC **412-B** further comprises integrated voltage regulator (IVR) **416-B** and RLC passives **418-B**. This allows better electrical performance because of the proximity of IVR **416-B** to a select portion of the components of RLC **415-B** that are directly coupled between them at interface **450-M**, while other components with less critical layout constraints may be placed elsewhere on RLC **415-B**. Further, it allows IVR **416-A** to be placed in a location that is optimal for the circuits it regulates power for in either IC **412-A** or IC **414-A**. The proximity of RLC passives **418-B** on IC **412-B** to RLC die **415-B** further allows the creation of unique passive components having two portions coupled together at interface **450-M**. Such unique two-die passive components may have advantages over components formed in a single die due to the reduced complexity of processing one or both of IC **412-B** and RLC **415-B**.

[0076] FIG. **4C** is not drawn to scale and illustrates a portion of a system **400-C** with details of a cross section of a package **430-C** according to an embodiment of the present invention. System **400-C** comprises PCB **410** with package **430-C** mounted onto it by means of solder balls **436**. Package **430-C** further comprises top integrated circuit die **412-C**, RLC passives die **415-C**, bottom integrated circuit die **414-C**, and die seal **434**. Top integrated circuit **412-C** comprises a circuit portion **412-Y** and a substrate portion **412-Z**. Similarly, bottom integrated circuit **414-C** comprises a circuit portion **414-Y** and a substrate portion **414-Z**.

[0077] Top integrated circuit **412-C** may be both physically and electrically coupled to RLC **415-C** at interface **450-0** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®, a hybrid direct bonding technology available from Invensas Bonding Technologies, Inc. Similarly, RLC **415-C** may also be both physically and electrically coupled to bottom integrated circuit **414-C** at interface **450-P** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®.

[0078] The circuit portion **412-Y** of top IC **412-C** further comprises integrated voltage regulator (IVR) **416-C** and RLC passives **418-C**. This allows better electrical performance because of the proximity of IVR **416-C** to a select portion of the components of RLC **415-C** that are directly coupled between them at interface **450-0**, while other components with less critical layout constraints may be placed elsewhere on RLC **415-C**. The proximity of RLC passives **418-C** on IC **412-C** to RLC die **415-C** allows the creation of unique passive components having two portions coupled together at interface **450-0**. Such unique two-die passive components may have advantages over components formed in a single die like, for example, due to reduced complexity of processing one or both of IC **412-C** and RLC **415-C**.

[0079] Further, the proximity of RLC passives **418-C** on IC **412-C** to RLC passives **419-C** on IC **414-C** opposite each other across RLC die **415-C** allows the creation of unique passive components having three portions coupled together at interfaces **450-0** and **450-P**. Such unique three-die passive components may have advantages over components formed in a single die like, for example, due to reduced complexity of processing one, two, or all three of IC **412-C**, RLC **415-C**, and IC **412-C**.

[0080] FIG. **4D** is not drawn to scale and illustrates a portion of a system **400-D** with details of a cross section of a package **430-D** according to an embodiment of the present invention. The other reference numbers in the figure are identical to FIG. **4C** except that die seal has been removed and replaced with an underfill-type of die seal **440**. Persons skilled in the art will appreciate that while the technology employing die seal **434** has been used in many figures for simplicity of presentation, the invention may be practiced with many other packaging technologies known in the art. Further, the use of this method of presentation in no way limits the scope of invention.

[0081] FIG. **5A** is not drawn to scale and illustrates a top view of an integrated inductor **500** according to an embodiment of the present invention. Inductor **500** comprises a magnetically enhanced material **502**, wires on a bottom metal layer **504**, wires on a top metal layer **506**, and via contacts **508** coupling together the wires on metal layers **504** and **506**. Inductor **500** has two terminals **T1** and **T2** which may be used to couple it to other electronic components and circuits not shown in FIG. **5A**. The wires on metal layers **504** and **506** are coupled together by vias **508** to form a coil-like connection between **T1** and **T2** that wraps around the magnetically enhanced material **502**. A cross section line between **510'** and **510''** is shown to define the cross section of FIG. **5B**.

[0082] FIG. **5B** is not drawn to scale and illustrates the cross section between **510'** and **510''** viewed from the side of the integrated inductor **500** according to an embodiment of the present invention. Present in FIG. **5B** are magnetically enhanced material **502**, metal layers **504** and **506**. Vias **508** are absent since they do not fall along the cross section line. At each location where there are metal wires, there is wire on bottom metal layer **504** and a parallel wire on top metal **506**.

[0083] Returning to FIG. **5A**, each of the wires on top metal layer **506** jogs one wire pitch as it approaches the end of its loop around magnetically enhanced material **502**. This creates the coil-like structure wrapped around magnetically enhanced material **502** needed to create a high inductance value for the inductor **500**.

[0084] FIG. **5C** is not drawn to scale and illustrates a top view an integrated inductor **520** according to an embodiment of the present invention. Inductor **520** comprises a magnetically enhanced material **522**, wires on a bottom metal layer **524**, wires on a top metal layer **526**, and via contacts **528**, which couple together the wires on metal layers **524** and **526**. Inductor **520** has three terminals **T1**, **T2**, and **T3** which may be used to couple it to other electronic components and circuits not shown in FIG. **5C**. The wires on metal layers **524** and **526** are coupled together by vias **528** to form

a coil-like connection between terminals T1 and T2 that wraps around the magnetically enhanced material 522. The terminal T3 may allow the inductor 520 to be separated into two inductors sharing a common node, a configuration that may be used as a transformer. A cross section line between 530' and 530'' is shown to define the cross section of FIG. 5D.

[0085] FIG. 5D is not drawn to scale and illustrates the cross section between 530' and 530'' viewed from the side of the integrated inductor 520 according to an embodiment of the present invention. Present in FIG. 5D are magnetically enhanced material 522, metal layers 524 and 526, and vias 528. At each location where there is a via 528, there is the end of a wire on bottom metal layer 524 and the end of a parallel wire on top metal 526 coupled together by the via 528.

[0086] Returning to FIG. 5C, each of the wires on top metal layer 526 jogs one wire pitch as it approaches the end of its loop around magnetically enhanced material 522. This creates the coil-like structure wrapped around magnetically enhanced material 522 needed to create a high inductance value for the inductor 520.

[0087] FIG. 5E is not drawn to scale and illustrates a cross section of two portions of an inductor 540 prior to assembly according to an embodiment of the present invention. Inductor 540 has top view like the one illustrated for inductor 520 in FIGS. 5A and 5B—with reference numerals in the format 52x being replaced by reference numerals in the format 54x (i.e., by adding 20 to each). The reference numerals for the cross section between 530' and 530'' viewed from the side are the same.

[0088] When assembled, inductor 540 comprises a magnetically enhanced material 542, wires on a bottom metal layer 544, wires on a top metal layer 546, and via contacts 548, which couple together the wires on metal layers 544 and 546. Inductor 540 has three terminals T1, T2, and T3 which may be used to couple it to other electronic components and circuits not shown in FIG. 5E. The wires on metal layers 544 and 546 are coupled together by vias 548 to form a coil-like connection between terminals T1 and T2 that wraps around the magnetically enhanced material 542. The terminal T3 may allow the inductor 540 to be separated into two inductors sharing a common node, a configuration that may be used as a transformer.

[0089] Inverter 540 is shown in two parts in FIG. 5E with top metal 546 in a circuit IC die 552 currently separated from the remainder of inductor 540 present in RLC passives die 554. Also present in RLC 554 are metal bond pads 547 coupled to vias 548. This allows for the two portions of inductor 540 to be electrically coupled when IC 552 and RLC 554 are physically coupled together at a future time. Persons skilled in the art will appreciate that little or no special processing may be required for IC 552 beyond that needed for the bonding process employed like, for example, DBI®, and that the normal thick top metal on circuit die 552 may be used as metal layer 546.

[0090] FIG. 5F is not drawn to scale and illustrates a cross section of the inductor 540 after assembly according to an embodiment of the present invention. Present in FIG. 5F are all the elements previously described with respect to FIG. 5E.

[0091] In FIG. 5F, circuit IC die 552 may be physically and electrically coupled together with RLC die 554 at interface 556 using, for example, DBIR. At the interface 556, when DBI® technology is used, the oxide on the bottom of IVR 552 and the oxide on the top of RLC 554 bond together, physically coupling them together. Then a low temperature anneal process causes enough metal migration for top metal wires 546 and bond pads 547 to electrically couple together with high reliability. When the process is complete, inductor 540 is fully formed and functional.

[0092] Inductor 500 in FIGS. 5A and 5B and inductor 520 in FIGS. 5C and 5D are illustrated generically without any indication of how they are physically constructed. For example, they could be completely within an RLC die or formed across multiple dies. Inductor 540 in FIG. 5F is an example of the two-die passive components discussed previously in regards to FIGS. 4B and 4C.

[0093] FIG. 6A is not drawn to scale and illustrates a top view of an embedded annular inductor 600 according to an embodiment of the present invention. Embedded annular inductor 600 comprises a circular ring 602 of magnetically enhanced material, wires on a bottom metal layer

604, wires on a top metal layer **606**, and vias **608** coupling together the wires on metal layers **604** and **606**. Embedded annular inductor **600** has two terminals **T1** and **T2** which may be used to couple it to other electronic components and circuits not shown in FIG. **6A**. The wires on metal layers **604** and **606** are coupled together by vias **608** to form a coil-like connection between **T1** and **T2** that wraps around the magnetically enhanced material **502** to create a high inductance value. A cross section line between **610'** and **610''** is shown to define the cross sections illustrated in the FIGS. **6B**, **6C**, **6D**, **6E**, and **6F**.

[0094] FIG. **6B** is not drawn to scale and illustrates a cross section of the embedded annular inductor **600** according to an embodiment of the present invention. Present in FIG. **6B** are all the elements previously described with respect to FIG. **6A**. Embedded annular inductor **600** is an example of a passive component constructed entirely embedded in RLC passives die **612**.

Embedded annular inductor **600** has two terminals **T1** and **T2** (not shown in FIG. **6B**) which may be used to couple it to other electronic components and circuits not shown in FIG. **6B**.

[0095] In FIG. **6B**, ring **602** passes through the cross section plane defined by **610'** and **610''** in two places. At the crossing near **610'**, a wire of top metal **606** is shown passing over ring **602** and coupled to two different wires of bottom metal **604** through two vias **608**. Similarly, at the crossing near **610''**, a wire of bottom metal **604** is shown passing under ring **602** and coupled to two different wires of top metal **606** through two vias **608**. A series of these connections around ring **602** coupled between **T1** and **T2** (not shown in FIG. **6B**) create the coil-like structure needed to create a high inductance value.

[0096] FIG. **6C** is not drawn to scale and illustrates a cross section of an embedded annular inductor **620** according to an embodiment of the present invention. The top diagram of embedded annular inductor **620** is not shown, but it would be identical to that of embedded annular inductor **600** in FIG. **6A** except that all reference numbers in the range **600** to **609** would be increased by a value of 20 to become reference numbers in the range **620** to **629**. The cross section reference labels **610'** and **610''** remain the same.

[0097] Embedded annular inductor **620** comprises a circular ring **622** of magnetically enhanced material, wires on a bottom metal layer **624**, wires on a top metal layer **626**, and vias **628** coupling together the wires on metal layers **624** and **626**. Embedded annular inductor **620** has two terminals **T1** and **T2** (not shown in FIG. **6C**) which may be used to couple it to other electronic components and circuits not shown in FIG. **6C**. The wires on metal layers **624** and **626** are coupled together by vias **628** to form a coil-like connection between **T1** and **T2** that wraps around the magnetically enhanced material **622** to create a high inductance value.

[0098] Embedded annular inductor **620** is an example of the three-die passive components discussed previously in regards to FIG. **4C**. Also present in FIG. **6C** are top die IC **630**, RLC die **632**, and bottom die IC **634**. Bottom layer metal **624** is present in bottom die **634**, top layer metal **626** is present in top die **630**, and the magnetically enhanced ring **622** and vias **628** are present in RLC **632**. Also present in RLC **632** are bond pads **625** and **627**, which allow electrical coupling to bottom metal **624** and top metal **626**, respectively, when the dies are physically and electrically coupled together to form the complete and functional embedded annular inductor **620**.

[0099] Ring **622** is illustrated as completely spanning RLC **632** from top to bottom. This can be accomplished by etching a circular trench and filling it with the magnetically enhanced material. This has the advantage of allowing the top and bottom of ring **622** to be extremely close to top metal **626** and bottom metal **624** respectively with little more than, for example, the thin bonding oxide used as part of the DBI® process previously discussed. As persons skilled in the art will appreciate, both metal layer **624** and metal layer **626** can be implemented using the thick top metal layers typically present in IC **634** and IC **630**, respectively. Such skilled persons will also appreciate that the final thickness of RLC die **632** is less than its thickness when the magnetically enhanced ring **622** is defined and the circular trench is etched. This prevents the material in the center of ring **622** from detaching. Ultimately, RLC die **632** is then thinned to its final thickness

later in the manufacturing process.

[0100] FIG. 6D is not drawn to scale and illustrates a cross section of an embedded annular inductor **640** according to an embodiment of the present invention. The top diagram of embedded annular inductor **640** is not shown, but it would be identical to that of embedded annular inductor **600** in FIG. 6A except that all reference numbers in the range **600** to **609** would be increased by a value of 40 to become reference numbers in the range **640** to **649**. The cross section reference labels **610'** and **610''** remain the same.

[0101] Embedded annular inductor **640** comprises a circular ring **642** of magnetically enhanced material, wires on a bottom metal layer **644**, wires on a top metal layer **646**, and vias **648** coupling together the wires on metal layers **644** and **646**. Embedded annular inductor **640** has two terminals **T1** and **T2** (not shown in FIG. 6D) which may be used to couple it to other electronic components and circuits not shown in FIG. 6D. The wires on metal layers **644** and **646** are coupled together by vias **648** to form a coil-like connection between **T1** and **T2** that wraps around the magnetically enhanced material **642** to create a high inductance value.

[0102] Embedded annular inductor **640** is another example of the three-die passive components discussed previously in regards to FIG. 4C. Also present in FIG. 6D are top die IC **650**, RLC die **652**, and bottom die IC **654**. Bottom layer metal **644** is present in IC **654**, top layer metal **646** is present in IC **650**, and the magnetically enhanced ring **642** and vias **648** are present in RLC **652**. Also present in RLC **652** are bond pads **645** and **647**, which allow electrical coupling to bottom metal **644** and top metal **646**, respectively, when the dies are physically and electrically coupled together to form the complete and functional embedded annular inductor **640**.

[0103] FIG. 6E is not drawn to scale and illustrates a cross section of an embedded annular inductor **660** according to an embodiment of the present invention. The top diagram of embedded annular inductor **660** is not shown, but it would be identical to that of embedded annular inductor **600** in FIG. 6A except that all reference numbers in the range **600** to **609** would be increased by a value of 60 to become reference numbers in the range **660** to **669**. The cross section reference labels **610'** and **610''** remain the same.

[0104] Embedded annular inductor **660** comprises a ring **662** of magnetically enhanced material, wires on a bottom metal layer **664**, wires on a top metal layer **666**, and vias **668** coupling together the wires on metal layers **664** and **666**. Embedded annular inductor **660** has two terminals **T1** and **T2** (not shown in FIG. 6E) which may be used to couple it to other electronic components and circuits not shown in FIG. 6E. The wires on metal layers **664** and **666** are coupled together by vias **668** to form a coil-like connection between **T1** and **T2** that wraps around the magnetically enhanced material **662** to create a high inductance value.

[0105] Embedded annular inductor **660** is an example of the two-die passive components discussed previously in regards to FIGS. 4B and 4C. Also present in FIG. 6E are top die IC **670** and RLC die **672**. Bottom layer metal **664** is present in RLC **672**, top layer metal **666** is present in IC **670**, and the magnetically enhanced ring **662** and vias **668** are present in RLC **672**. Also present in RLC **672** are bond pads **667**, which allow electrical coupling to top metal **666** when the dies are physically and electrically coupled together to form the complete and functional embedded annular inductor **660**.

[0106] FIG. 6F is not drawn to scale and illustrates a cross section of an embedded annular inductor **680** according to an embodiment of the present invention. The top diagram of embedded annular inductor **680** is not shown, but it would be identical to that of embedded annular inductor **600** in FIG. 6A except that all reference numbers in the range **600** to **609** would be increased by a value of 80 to become reference numbers in the range **680** to **689**. The cross section reference labels **610'** and **610''** remain the same.

[0107] Embedded annular inductor **680** comprises a ring **682** of magnetically enhanced material, wires on a bottom metal layer **684**, wires on a top metal layer **686**, and vias **688** coupling together the wires on metal layers **684** and **686**. Embedded annular inductor **680** has two terminals **T1** and

T2 (not shown in FIG. 6F) which may be used to couple it to other electronic components and circuits not shown in FIG. 6F. The wires on metal layers **684** and **686** are coupled together by vias **688** to form a coil-like connection between T1 and T2 that wraps around the magnetically enhanced material **682** to create a high inductance value.

[0108] Embedded annular inductor **680** is an example of the two-die passive components discussed previously in regards to FIGS. 4B and 4C. Also present in FIG. 6F are RLC die IC **692** and bottom die **694**. Bottom layer metal **684** is present in IC **694**. Top layer metal **686**, the magnetically enhanced ring **682** and vias **688** are present in RLC **692**. Also present in RLC **692** are bond pads **685**, which allow electrical coupling to bottom metal **684** when the dies are physically and electrically coupled together to form the complete and functional embedded annular inductor **680**.

[0109] FIG. 7 is not drawn to scale and illustrates a variety of exemplary passive components which may be present in RLC passives die **700** according to an embodiment of the present invention. Top integrated circuit **702** may be both physically and electrically coupled to RLC **700** at interface **704** using, for example, a die-to-die or wafer-to-wafer bonding technology like, for example, DBI®. Also present in FIG. 7 are capacitors **710** and **720**, resistor **730**, and fuse **740**.

[0110] The schematic symbol for capacitor **710** is present in FIG. 7 with first and second terminals indicated by squares containing crossed lines. A physical representation of capacitor **710** is shown constructed with a top metal plate **712** coupled to the first terminal, a bottom metal plate **714** coupled to the second terminal, and a dielectric insulator **716** coupled in between. The terminals here are also indicated by squares containing crossed lines. Capacitor **710** is preferably a metal-insulator-metal (MIM) capacitor and with the dielectric insulator **716** preferably comprising a high-K dielectric, though other types of capacitors and insulators may be used as is known in the art. MIM capacitors are advantageous because they are very thin in the vertical direction and a plurality of them may be stacked one above another to increase the capacitance per area in RLC-**700**.

[0111] The schematic symbol for capacitor **720** is present in FIG. 7 with first and second terminals indicated by squares containing crossed lines. A physical representation of capacitor **720** is shown constructed with a top metal plate **722** coupled to the first terminal, a bottom metal plate **724** coupled to the second terminal, and a dielectric insulator **726** coupled in between. The die-to-die or wafer-to-wafer bond **704**, like, for example, DBI®, serves as the dielectric insulator **726** in the region between metal plates **722** and **724**. The thickness of bond **704** will control the capacitance per unit area for capacitor **720**. In one embodiment, the DBI interconnect oxide thickness is about 1 μm (micro meter) on each side giving bond **704** a total thickness of 2 μm . In other embodiments, bond **704** may be thinner with increased anneal temperature or thicker with lower anneal temperature. The actual limits are unknown and may be gated on the thinner side by anneal temp and on the thicker side by mechanical stress. The practical limits may be in the range 0.3 μm -2 μm per side, but the theoretical limits may be in the range of 0.1 μm -5 μm per side. The terminals here are also indicated by squares containing crossed lines.

[0112] The schematic symbol for resistor **730** is present in FIG. 7 with first and second terminals indicated by squares containing crossed lines. A physical representation of resistor **730** is shown constructed as a sheet of resistive material **732** between the first and second terminals as is known in the art. The terminals here are also indicated by squares containing crossed lines.

[0113] The schematic symbol for fuse **740** is present in FIG. 7 with its terminals indicated by squares containing crossed lines. A physical representation of fuse **740** is shown constructed with a top metal plate **742** coupled to the first terminal, a bottom metal plate **744** coupled to the second terminal, and fuse layer (or layers) **746** coupled in between. The terminals here are also indicated by squares containing crossed lines. Fuse **740** may be either a programmable fuse or a programmable antifuse as is known in the art. Fuse **470** is illustrated as spanning the interface **704** between RLC die **700** and top die **702**, but other configurations are possible.

[0114] A fuse is normally conductive until it is programmed, so fuse layer **746** will initially be a conductive material electrically coupling top metal plate **742** and bottom metal plate **744**. When

programmed, fuse layer **746** will disintegrate or change in some other way breaking the connection between top metal plate **742** and bottom metal plate **744** creating an open circuit as is known in the art.

[0115] An antifuse is normally non-conductive until it is programmed, so fuse layer **746** will initially be an insulating material electrically isolating top metal plate **742** and bottom metal plate **744**. When programmed, metal from top metal plate **742** and bottom metal plate **744** will fuse together into a conductive filament through fuse layer **746** making an electrical connection between top metal plate **742** and bottom metal plate **744** as is known in the art.

[0116] FIG. **8A** is not drawn to scale and illustrates a cross section of an RLC passives die **800-A** according to an embodiment of the present invention. This embodiment is similar to the IC stack of package **330-C** illustrated in FIG. **3C**. Present in FIG. **8A** is RLC passives die **800-A**, bottom circuit die **802-A**, and top circuit die **804-A** coupled together with bonding techniques of the sort discussed in conjunction with other embodiments. Also present in the figure are solder bumps **806**, **832**, and **834** which may be used to couple RLC **800-A** to, for example, a package substrate or a printed circuit board (neither shown in FIG. **8A**).

[0117] Through silicon via (TSV) **810** may allow electrical coupling through RLC **800-A** between solder bump **806** and bottom circuit die **802-A**. TSV **810** comprises lower bond pad **812**, upper bond pad **814**, and via **816**. Lower bond pad **812** is metal that may couple solder bump **806** to via **816**, and upper bond pad **814** is metal may couple bottom die **802-A** to via **816**.

[0118] TSV **818** may allow electrical coupling through bottom circuit die **802-A** between RLC die **800-A** and top circuit die **804 A**. TSV **818** comprises upper bond pad **820**, lower bond pad **822**, and via **824**. Lower bond pad **822** is metal that may couple bond pad **814** to via **824**, and upper bond pad **820** is metal that may couple via to **824** top die **804-A**. Lower bond pad **826** may be present in top die **804-A** to electrically couple to upper bond pad **820**.

[0119] Circuit **830** is present in the diagram and coupled to solder bumps **832** and **834** through two TSVs **831** and **833** (shown as wires for simplicity in FIG. **8A** and further diagrams). Solder bump **834** is also coupled to ground through the package substrate and/or PCB (not shown in FIG. **8A**). Circuit **830** can be any circuit needing electrostatic discharge (ESD) protection. While circuit **830** is illustrated as present in bottom die **802-A**, persons skilled in the art will realize that it may also be present in whole or in part in RLC **800-A** or top circuit die **804-A**.

[0120] Diode **836** has its cathode terminal coupled to circuit **830**, solder bump **832**, and a first terminal of optional capacitor **840**, while its anode terminal is coupled to circuit **830**, solder bump **834** and an internal ground node **838**. Optional capacitor **840** has a second terminal coupled to solder bump **834**.

[0121] When a negative ESD event occurs at solder bump **832**, the voltage on the cathode goes negative (i.e., below ground) until diode **836** turns on and safely steers the ESD current from ground by means of solder bump **834** and out of the device through solder bump **832**.

[0122] When a positive ESD event occurs at solder bump **832**, the voltage on the cathode goes positive (i.e., above ground) until diode **836** breaks down and safely steers the ESD current from solder bump **832** and out of the device to ground through solder bump **834**.

[0123] In a typical ESD protection scheme, an ESD event on any pin will have the current (positive or negative depending on the positive or negative voltage polarity of the ESD event) steered to or from the internal ground **838** which is coupled to solder bump **834** in the figure. Thus, any event between any two pins is treated as a positive ESD event on one pin and a negative ESD event on the other. Typically, internal ground node **838** is present near every bond pad and/or ESD device like diode **836** and provides a low resistance path (typically through both thick metal and/or the substrate) between all pairs of pins to prevent the ESD current from damaging the device.

[0124] Optional capacitor **840** may provide a temporary current source or sink during an ESD event on solder bump **832**. By sourcing or sinking some of the ESD current during the initial stages of an ESD event, it provides additional time for diode **836** to turn on or break down before the

voltage on solder bump **832** can rise or fall to a level where circuit **830** or other internal components are damaged.

[0125] Also present in FIG. **8A** is inductor **844**, switching power supply **846** coupled to inductor **844**, and metal shield **848**, the latter being coupled to internal ground **838**. Depending on the application like, for example, a switching power supply as in this embodiment, inductor **844** may generate substantial electro-magnetic interference (EMI). In such embodiments, EMI shielding like metal shield **848** can be placed between inductor **844** (or any other noisy circuit or component on RLC **800-A**) to prevent interference with sensitive circuits or nodes anywhere in the die stack comprising **800-A**, **802-A**, and **804-A** (or anywhere else in the package or system). Persons skilled in the art will realize that FIG. **8A** is a two dimensional cross section of a three dimensional structure and that most of shield **848** will extend further into or out of the illustrated cross-section of RLC die **800-A** in the third physical dimension and that typically all portions of metal shield **848** will be coupled to internal ground **838** though this is not illustrated in the figure.

[0126] FIG. **8B** is not drawn to scale and illustrates a cross section of an RLC passives die **800-B** according to an embodiment of the present invention. This embodiment is similar to the IC stack of package **330-C** illustrated in FIG. **3C**. Present in FIG. **8B** is RLC passives die **800-B**, bottom circuit die **802-B**, and top circuit die **804-B** coupled together with bonding techniques of the sort discussed in conjunction with other embodiments. Also present in the figure are solder bumps **858**, **862**, and **868** which may be used to couple RLC **800-B** to, for example, a package substrate or a printed circuit board (neither shown in FIG. **8B**).

[0127] Also present in FIG. **8B** are switching power supply **850** of a type known in the art, like, for example, a switched capacitor supply, and transistor switch **852**, both present in bottom circuit die **802-B**. Transistor switch **852** has a gate terminal coupled to switching power supply **850**, a first source/drain terminal coupled to a first terminal of capacitor **854** in RLC die **800-B**, and a second source/drain terminal coupled to switching power supply **850** and to a first terminal of capacitor **856** in RCL die **800-B**. Transistor switch **852** is shown as an N-channel MOSFET in FIG. **8B**, but could also be a P-channel MOSFET or some other type of device like, for example, a bipolar junction transistor as a matter of design choice.

[0128] Solder bump **858** is coupled to a second terminal of capacitor **854**. Switching power supply **850** is further coupled to a second terminal of capacitor **856**. Also present in the figure is solder bump **862** coupled to external ground, internal ground **864**, and to switching power supply **850** by means of TSV **866**. Also shown is solder ball **868** coupled to an external power supply and switching power supply **850** by means of TSV **869**.

[0129] Capacitor **860** is present in RLC die **800-B** having a first terminal coupled to switching power supply **850** and a second terminal coupled to external ground by means of solder bump **862**. In this embodiment, RLC die has two different layers of embedded capacitors with capacitors **854** and **860** on a lower layer and capacitor **856** on an upper layer. Persons skilled in the art will appreciate that more than two layers of capacitors (or resistors, inductors, or any other passive component) may be present as a matter of design choice.

[0130] FIG. **8C** is not drawn to scale and illustrates a cross section of an RLC passives die **800-C** according to an embodiment of the present invention. Present in the figure are RLC die **800-C**, bottom circuit die **802-C**, and top circuit die **804-C** bonded together using bonding techniques like those described in previous embodiments of the present invention.

[0131] Programming circuit **870** is present in bottom circuit die **802 C**. It is coupled to external power and external ground by means of solder bumps **872** and **874** respectively, in series with TSVs **876** and **878** respectively.

[0132] Also coupled to programming circuit are both terminals of the fuses **880** and **882**.

Programming circuit **870** is configured apply the necessary electrical signals to program and read the contents of fuses **880** and **882**. The data stored in the fuses may be used for a variety of functions like, for example, operating or configuration parameters of any circuitry in RLC die **800-**

C, bottom circuit die **802-C** and top circuit die **804-C**.

[0133] FIG. **8D** is not drawn to scale and illustrates a cross section of an RLC passives die **800-D** according to an embodiment of the present invention. This embodiment is similar to the IC stack of package **330-C** illustrated in FIG. **3C**. Present in FIG. **8B** is RLC passives die **800-D**, bottom circuit die **802-D**, and top circuit die **804-D** coupled together with bonding techniques of the sort discussed in conjunction with other embodiments.

[0134] Also present in the figure is switching power supply **884**, two-part inductor **886**, two-part capacitors **888**, lower-layer capacitors **890**, solder bumps **892** and **896**, and TSVs **894** and **898**. Switching power supply **884** may be of a type known in the art like, for example, a buck converter. Two-part inductor **886** may be partially formed in bottom circuit die **802-D** and partially formed in RLC passives die **800-D** in a manner similar to the inductors disclosed in FIGS. **5E**, **5F**, **6C**, **6D**, **6E** and **6F**. Two-part capacitors **888** may be partially formed in bottom circuit die **802-D** and partially formed in RLC passives die **800-D** in a manner similar to capacitor **720** in FIG. **7**. Lower-layer capacitors **890** are stacked in two layers beneath the two-part capacitors **888** in a manner similar to that disclosed in FIG. **8B**. Persons skilled in the art will realize that the number of layers of the lower-layer capacitors **890** is a matter of design choice and there are embodiments comprising three or more such layers.

[0135] Switching power supply **884** is coupled to a first terminal of two-part inductor **886**, the first terminals of two-part capacitors **888**, the first terminals of lower-layer capacitors **890**, to an external ground by means of solder bump **892** and TSV **894**, and to an external power source by means of solder bump **896** and TSV **898**. The second terminal of two-part inductor **886** is coupled to switching power supply **884** and the first terminals of two-part capacitors **888** and the first terminals of lower-layer capacitors **890**. The second terminals of two-part capacitors **888** and the second terminals of lower-layer capacitors **890** are coupled to external ground by means solder bump **892**.

[0136] The advantages of the circuit configuration of FIG. **8D** are (1) high value capacitance values may be obtained using two-part capacitors **888** which use the thin bonding oxide as the insulator, (2) additional layers of lower-layer capacitors **890** like, for example, metal-insulator-metal (MIM) capacitors, may be added as needed to increase the total capacitance value, (3) as much surface area as needed can be used to increase the inductance of two-part inductor **886**, (4) the switching supply **884** is very close to the necessary capacitors and inductors which increases the power efficiency of the converter and keeps the interconnections lines between them short to minimize both resistance and EMI, and (5) any necessary shielding can be built close the converter and its passive components minimizing both area and the EMI emissions.

[0137] FIG. **9** is not drawn to scale and illustrates several package cross sections with illustrative internal arrangements of semiconductor dies according to embodiments of the present invention. Present in the figure is a simplified drawing of the embodiment of package **330-A** as described in conjunction with FIG. **3A**. Present in this representation of package **330-A** are some of the reference numerals from FIG. **3A** including package substrate **332**, solder bumps **338**, bottom die **314**, RLC passives die **318**, top die **312** and die seal **334**.

[0138] Package **900** comprises package substrate **932**, solder bumps **938**, bottom die **914**, RLC dies **918-A** and **918-B**, top die **912** and die seal **934**. These structures are roughly analogous to their counterparts substrate **332**, solder bumps **338**, bottom die **314**, RLC passives die **318**, top die **312** and die seal **334** respectively in package **330-A**, allowing for differences in design goals and choices.

[0139] Package **900** has two RLC dies **918-A** and **918-B** bonded together between top die **912** and bottom die **914**. All four die are bonded together in a manner similar to that discussed with respect to other embodiments. Together they are coupled to package substrate **932** by means of solder bumps **938**.

[0140] RLC dies **918-A** and **918-B** may be manufactured with different fabrication processes

allowing a greater variety of RLC passive components to be present in package **900** than in the device in package **330-A**.

[0141] Package **902** comprises package substrate **932**, solder bumps **938**, bottom die **914**, RLC dies **918-A** and **918-B**, top die **912** and die seal **934** though the reference numerals are not shown in the figure. These structures are roughly analogous to their counterparts in package **900**. The primary difference is that RLC dies **918-A** and **918-B** are bonded together at the top of the stack above top die **912** and bottom die **914**.

[0142] Package **904** comprises package substrate **932**, solder bumps **938**, bottom die **914**, RLC dies **918-A** and **918-B**, top die **912** and die seal **934** though the reference numerals are not shown in the figure. These structures are roughly analogous to their counterparts in packages **900** and **902**. The primary difference is that RLC dies **918-A** and **918-B** are bonded together at the bottom of the die stack below top die **912** and bottom die **914**.

[0143] Likewise, package **906** comprises package substrate **932**, solder bumps **938**, bottom die **914**, RLC dies **918-A** and **918-B**, top die **912** and die seal **934** though the reference numerals are not shown in the figure. These structures are roughly analogous to their counterparts in packages **900**, **902**, and **904**. The primary difference is that top die **912** and bottom die **914** are bonded together in the middle of the die stack, and bonded together with RLC dies **918-A** and **918-B** at the top and bottom of the stack respectively.

[0144] Persons skilled in the art will recognize that other combinations are possible and fall within the scope of the present invention. For example, such skilled persons will realize that more than four dies may be present as shown in package **908**.

[0145] Package **908** comprises package substrate **932**, solder bumps **938**, bottom die **914**, RLC die **918-A**, middle die **913**, RLC die **918-B**, top die **912** and die seal **934** though (except for middle die **913**) the reference numerals are not shown in the figure. These structures are roughly analogous to their counterparts in packages **900**, **902**, **904**, and **906**. Persons skilled in the art will realize that more than five die may be present and that many different combinations are available and within the scope of the present.

[0146] Those of ordinary skill in the art will realize that the above figures and descriptions are exemplary only. Many other embodiments will readily suggest themselves to such skilled persons after reviewing this disclosure. Thus, the invention is not to be limited in any way except by the issued claims.

Claims

1. A semiconductor package, comprising: (A) a package substrate comprising: (i) a first side, and (ii) a second side opposite the first side; (B) a first semiconductor die comprising: (i) a first side coupled to the second side of the package substrate, and (ii) a second side opposite the first side and comprising a first bonding layer; (C) a second semiconductor die comprising: (i) a first side comprising a second bonding layer coupled to the second side of the first semiconductor die, and (ii) a second side opposite the first side; (D) a voltage regulator circuit comprising at least one active component; and (E) a first passive component electrically coupled to the voltage regulator circuit, the first passive component comprising: (i) a first portion integrated into the first semiconductor die, and (ii) a second portion integrated into the second semiconductor die, wherein: the first portion and the second portion are coupled together to form the complete first passive component when the second side of the first semiconductor die is coupled to the first side of the second semiconductor die.
