

ACTIVE THERMAL CONTROL FOR STACKED IC DEVICES

TECHNICAL FIELD

[0001] This disclosure relates to integrated circuits (ICs). More specifically, the disclosure relates to multi-tiered IC devices and even more specifically to systems and methods for active thermal control within the multi-tiered IC devices.

BACKGROUND

[0002] In IC technology there is a need to stack chips together to form multi-tiered (3-D) IC devices (also referred to as multi-layered IC devices or stacked IC devices). One challenge that arises when chips are stacked is that thermal conductivity is reduced. Thus, hot spots could exist with little ability to move the heat away from the heat source. Because of the reduced size of stacked ICs, (substrate thickness going from 100 microns to about 6-50 microns), the power density rises while lateral thermal conductivity is reduced.

[0003] One method for increasing lateral thermal conductivity is to increase the substrate thickness. This, in turn, negatively impacts the desired form factor of the stacked IC device and degrades performance.

[0004] An additional challenge exists when more than two tiers are stacked. In such situations, the stacked IC device may contain multiple layers of oxide, one between each pair of stacked tiers. Oxide, being a poor thermal conductor, adds to the heat dissipation problem.

[0005] There are several approaches for addressing the thermal conductivity issues. One approach positions a heat conducting layer between the tiers. Typically, heat conducting layers are metallic and thus could interfere with inter-layer electrical connections. Another approach uses Through Silicon Vias (TSVs) to move the heat from an inner tier to a surface tier of the stacked IC device and then remove the heat from the surface tier using traditional methods, such as positioning a high thermal conductivity material on the surface tier. Challenges arises with such a solution. For example, it is not always possible to position a TSV at the necessary location because of circuitry layout requirements in the various tiers.

[0006] Another approach is to circulate cooling material through the stacked IC device to cool the hot spots. A cooling circulation solution is costly to

manufacture and, because of the moving liquid, requires a pumping mechanism and tight tolerances for liquid channels. Also, because of circuitry layout requirements, it may not be possible to “plumb” the device to channel the cooling material to the necessary location. The plumbing problem could be overcome, to some extent, by forcing cooling liquid through the substrate itself, but this method is not without a further set of problems and costs.

BRIEF SUMMARY

[0007] Thermal conductivity in stacked IC devices can be improved by constructing one or more active temperature control devices within the stacked IC device. In one embodiment, the control devices are thermal electric (TE) devices, such as Peltier devices. The TE devices can then be selectively controlled to remove or add heat as necessary to maintain the stacked IC device within a defined temperature range or otherwise bring the stacked IC device to a desired temperature. The active temperature control elements can be P-N junctions created in the stacked IC device and can serve to move the heat laterally and/or vertically as desired.

[0008] The foregoing has outlined, rather broadly, the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims. The novel features, which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages, will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0010] FIGURE 1 is a schematic drawing of a multi-tiered IC device having a hot spot therein;

[0011] FIGURE 2 shows one example of a prior art solution for relieving heat from the hot spot;

[0012] FIGURE 3 shows one embodiment of a stacked IC device having active temperature control in accordance with the teachings of the invention; and

[0013] FIGURES 4A through 4G show one method of manufacturing a multi-tiered IC device having active cooling capability in accordance with the teachings of the invention.

DETAILED DESCRIPTION

[0014] FIGURE 1 is a schematic drawing of multi-tiered IC device 10 having top tier 11 and bottom tier 12. Top tier 11 has an active circuit (face) 102 and substrate (back) 101. Bottom tier 12 has active circuit (face) 103 and substrate (back) 104. Faces 102/103 contain connections 108 which serve to connect components (or terminals) such a component 109 on the respective tiers. These connections are made using connector paths, such as path 107 and a via, such as via 106

[0015] For illustrative purposes, location 110 is thermally troubled in this embodiment. That is, location 110 is a “hot spot” that exists, or could exist, from time to time in stacked IC device 10. A hot spot, in this context, means that as stacked IC device 10 is operating, the temperature of the area in and around location 110 can become undesirably higher than other portions of tier 12. Because of the stacking of tier 11 on tier 12 and, preferably, reduced thickness of each tier, the lateral heat spread in tier 12 is reduced. In addition, air gap 111 can be formed between the tiers 11, 12 thereby reducing thermal flow upward from the hot spot.

[0016] As discussed above, there are a number of reasons to include cooling functionality or structures within a stacked IC device. But there are also reasons for heating a stacked IC device, or portions thereof. For example, when designing an adaptive voltage scaling circuit, it is desirable for the entire stacked IC device to have a

uniform temperature. Thus, if there are some localized areas of a tier in the stacked IC device that “run hot” (i.e., not a hot spot *per se*, but a localized area that operates at a warmer temperature than other areas in a tier) it might be desirable or necessary to heat the cooler areas of the tier so that the stacked IC device has a relatively constant or uniform temperature. In some situations, initialization of a stacked IC device to a required temperature is desired or important. For example, sensors may need to be hot to operate and a TE could be used to reduce initial heating time.

[0017] Additionally, selective heating and/or cooling may be required or desirable in a stacked IC device. For example, selective heating or cooling or a combination thereof may be used to even out the temperature gradients across silicon to alleviate stress caused by temperature differentials in the substrate. Also, selective temperature control can be used to allow the stacked IC device to operate, at least temporarily, in temperature environments that it otherwise would not be designed to operate in.

[0018] FIGURE 2 shows one example of a prior art solution for relieving heat from hot spot 110. In this solution, TSV array 200 is positioned above hot spot 110 so that the heat flowing from the hot spot 110 can be conducted through face 103, across gap 111, through face 102 and out through vias 201. In addition to the thermal conductivity problems, inherent with moving the heat through the various layers and gaps, in some situations circuitry or other elements, such as element 202, can be positioned in the heat flow path thereby reducing (and sometimes eliminating) the effectiveness of the TSV array 200.

[0019] FIGURE 3 shows one embodiment of a stacked IC device 30 having active temperature control in accordance with the teachings of the invention. A TE device 300 includes a pair of P-N junctions. Each P-N junction includes a P-type element 301 and N type element 302, as well as a bottom conductor 303. Depending on which direction current flows through the P-N junction, the bottom conductor 303 can either attract heat or provide heat. In one embodiment, the TE device 300 is a Peltier device. Although a pair of P-N junctions are shown, the invention is not limited to such a configuration. Rather, more or fewer P-N junctions can be provided.

[0020] Control circuit 304 is used to establish the current flow direction through the P-N junction. Control circuit 304 also controls current density. Circuit 304 provides selective current control to TE device 300 via an input, such as input 321. In

one embodiment, a TE device 300 operates such that a top side (top not designated with a reference number) heats while the other side, e.g., bottom 303, cools, based upon the current direction.

[0021] The thermal energy from hot spot 110 passes up through faces 103 and 102 to device 300. This thermal flow can be facilitated by constructing channels (vias) through the faces if desired. By selecting the proper current density, and current flow direction, device 300 serves to remove heat, thereby cooling the stacked IC device 30. Heat sink, or other heat transfer devices, not shown, may be located on the surface of tier 11 adjacent to TE device 300 to assist TE device 300 in heat removal from stacked IC device 30. Note that the stacked IC device 30 can have TE devices 300 provided in as many different areas as desired with some of the TE devices 300 injecting heat while others remove heat

[0022] Note that while the P-N junction material is shown going all the way through the substrate of tier 11, in another embodiment, the P-N material partially fills the substrate, with the junction being formed near the bottom conductor 303. In this embodiment, the top portion of each via is filled by metallization, creating a contact within the vias.

[0023] In some embodiments, the “hot spot” can be co-located in the same layer as the cooling device thereby resulting in lateral heat displacement. In such a situation, a horizontal trench could be constructed in the substrate to laterally transfer the heat within the same substrate. A first portion of the trench would include P-type material and another portion of the trench would include N-type material.

[0024] FIGURES 4A through 4G show an exemplary method of manufacturing a multi-layered IC device having active temperature control.

[0025] FIGURE 4A shows that tier 11 is stacked with respect to tier 12 and that some locations, such as locations 401-405 in the substrate of tier 11 are filled from top to bottom with sacrificial fill material. As will be seen, an active temperature control element will be constructed at location 400.

[0026] FIGURE 4B shows protective material 410 covering locations 401-404 in preparation for the next step in the process. Uncovered locations 405 will become standard TSVs as the process continues.

[0027] FIGURE 4C shows the metallization of the uncovered locations 405A by metal layer 420 to create standard TSVs 405A. Copper or any desired metal

can be used for this purpose consistent with other elements of the stacked IC device. Thus, as shown in FIGURE 4C the uncovered locations now contain metal as shown at 405A, whereas the elements 401-404 remains protected and filled with sacrificial material.

[0028] FIGURE 4D shows the removal of portions 410-2 and 410-4 of protective material 410 leaving portions 410-1 and 410-3 in place. The sacrificial material within vias 402 and 404 is also shown removed.

[0029] FIGURE 4E shows P-type thermal electric material deposited within locations 402 and 404. The P-type material has not been deposited within locations 401 and 403 because these locations remain protected by portions 410-1 and 410-3 and thus still contain the sacrificial material.

[0030] FIGURE 4F shows the removal of portions 410-1 and 410-3 of protective material 410 to expose vias 401 and 403. The sacrificial material is then removed from vias 401 and 403.

[0031] FIGURE 4G shows N-type thermal material deposited in locations 401 and 403 thereby completing the formation of the temperature control device within layer 11. Typical materials for a Peltier device are bismuth telluride, Sb_2Te_3 , PbTe and SiGe , but other materials, such as crystal-phonon glass or nano material, can be used as well. Also, it is possible to use two metals in a metal to metal junction such as Copper – Nickel. In this embodiment, Nickel fills the TSVs 401 - 404 and Copper is the standard metallization. Accordingly, every TSV 401-404 would be a potential Peltier device. There are two advantages of this Peltier structure. The first advantage is the masking steps for P and N type fill are removed. The second advantage is the density of the Peltier devices is increased as one side of the TSV 401 -404 would act as the cooling point while the other side would be the heating side. Of course heat transport in the Z direction is improved while heat transfer in the X and Y direction becomes more difficult.

[0032] Although the description has shown the P-type material being deposited first and the N-type material subsequently being deposited, the order is not critical. That is, the N-type material could be deposited first if it is more convenient.

[0033] It should be pointed out that the temperature differential created by the circuit elements in the substrate can be used to drive a voltage. The voltage thus created can be scavenged, for example, to drive other circuit elements as shown by

connection 320, FIGURE 3 from control circuit 304. This would effectively reverse the operation of the TE device 300. The TE device 300 will cool the thermally troubled area (in FIGURE 3 that would be hot spot 110) because heat energy is being removed from the hot spot by conversion into electrical energy. The net effect then would be that there would be no net cooling of the stacked IC device 30 as a whole (because energy is being returned to the stacked IC device 30 elsewhere) but there would be localized cooling at the "hot spot". Consequently, overall energy savings for the stacked IC device 30 results.

[0034] A Peltier device is a heat pump that requires energy to move heat from one point to another. As the disclosed embodiments have both points within the system, the heat energy is being moved from a point where it is difficult to remove (high thermal resistance) to a location where it is easier to remove so the heat is more uniformly distributed within the system. Thus, the total energy demand of the system is increased if the Peltier device is used to move the heat. Because the TE device can either remove or add heat depending upon current flow direction, a device could be used to selectively heat or cool the stacked IC device (or a portion thereof).

[0035] In one embodiment, the Peltier device is an energy scavenger: some of the heat generated by the stacked IC device operation can be recovered. The control system can switch the Peltier device to move heat from point A to point B (forward bias), or point B to point A (reverse bias) or scavenge heat from a temperature difference between points A and B to power the system. The energy balance of this TE system will depend on the efficiency of the Peltier device and the duty cycle of the system. Thus, the Peltier device can recover some energy from the overall system, based upon the temperature gradient within the system. In an embodiment in which more than two tiers exist, stacked Peltier devices can be provided to improve energy scavenging efficiency. For example, a cooling Peltier device could cool one tier, pumping heat to an adjacent tier. The adjacent tier could use the pumped heat to recover additional energy.

[0036] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process,

machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

CLAIMS

1. A stacked integrated circuit device comprising, in combination:
a first tier having a substrate and a face, with circuit elements at the face, and a thermal electric device, wherein the thermal electric device is positioned at the first tier; and
a second tier having a substrate and a face with circuit elements, wherein the circuit elements of the first tier are electrically connected to the circuit elements of the second tier, and a thermally troubled area is in the second tier;
wherein the thermal electric device is adapted to generate electricity in response to a thermal gradient between the thermally troubled area and the thermal electric device.
2. The stacked integrated circuit device of claim 1 wherein the thermal electric device comprises a Peltier device.
3. The stacked integrated circuit device of claim 1 further comprising:
at least one electrical connection from the thermal electric device to the circuit elements, and the thermal electric device is adapted to supply generated electricity to the circuit elements.
4. The stacked integrated circuit device of claim 1 wherein the thermal electric device comprises at least one P-N junction.
5. The stacked integrated circuit device of claim 1 wherein a control circuit controls the thermal electric device and selective application of a control signal from the control circuit to

the thermal electric device changes the temperature gradient between the thermally troubled area and the thermal electric device.

6. The stacked integrated circuit device of claim 1 wherein the thermally troubled area is a hot spot created by circuit elements in the second tier.

7. The stacked integrated circuit device of claim 5 wherein the thermal electric device is adapted to selectively heat or cool the thermally troubled area in response to the control signal.

8. The stacked integrated circuit device of claim 7 wherein the control circuit controls electric current flow direction through the thermal electric device.

9. A stacked integrated circuit device comprising, in combination:
a tier having active circuits;
a substrate; and
a thermal electric device positioned within the substrate;
wherein the thermal electric device is adapted to enhance thermal flow from a thermally troubled area of the stacked integrated circuit device.

10. A stacked integrated circuit device comprising, in combination:
a first tier having active circuits and a substrate;
a second tier having active circuits and a substrate; and
at least one P-N junction positioned within one of the first tier and the second tier,
wherein the at least one P-N junction is adapted to transfer thermal energy from a thermally

troubled area of the other of the first tier and the second tier in response to application of current to the at least one P-N junction.

11. An integrated circuit device comprising:

a tier having active circuits and a thermal electric device formed within vias in a layer of the tier, wherein the thermal electric device enhances thermal flow from a thermally troubled area of the integrated circuit device.

12. A method for reducing a temperature gradient in an integrated circuit device, comprising, in combination, the steps of:

providing a first tier of the integrated circuit having a substrate and a face, with circuit elements at the face, and a thermal electric device, wherein the thermal electric device is positioned at the first tier;

providing a second tier having a substrate and a face with circuit elements, wherein the circuit elements of the first tier are electrically connected to the circuit elements of the second tier, and a thermally troubled area is in the second tier;

generating electricity with the thermal electric device in response to the thermal gradient between the thermally troubled area and the thermal electric device; and

controlling current flow to the thermal electric device with a control circuit so as to selectively control the temperature gradient.

13. The method of claim 12 wherein the step of controlling comprises:

providing a control signal from the control circuit to enable the thermal device to remove heat from the thermally troubled area or to deliver heat to the thermally troubled area.

14. The method of claim 12 wherein a gap is maintained between the thermal electric device and the thermally troubled area.
15. The method of claim 12 further comprising:
routing electricity from the thermal device to power circuit elements.
16. The method of claim 12 wherein the thermally troubled area is a hot spot and further comprising
removing heat from the hot spot by allowing heat to pass from the second tier to first tier; and
using the thermal electric device to transfer the heat out of the tiers of the integrated circuit device.
17. The method of claim 12 further comprising the step of selectively heating or cooling the thermally troubled area using the thermal electric device.
18. The stacked integrated circuit device of claim 1 wherein the face on the first tier faces the face on the second tier, and a gap is maintained between the faces.
19. The stacked integrated circuit device of claim 1 wherein the thermal electric device is positioned in vias in the first tier.