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### Scan architecture for interconnect testing in 3D integrated circuits

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#### Abstract

In one embodiment, a device comprises: a first die having disposed thereon a first plurality of latches wherein ones of the first plurality of latches are operatively connected to an adjacent one of the first plurality of latches; and a second die having disposed thereon a second plurality of latches wherein ones of the second plurality of latches are operatively connected to an adjacent one of the second plurality of latches. Each latch of the first plurality of latches on said first die corresponds to a latch in the second plurality of latches on said second die. Each set of corresponding latches are operatively connected. A scan path comprises a closed loop comprising each of said first and second plurality of latches. One of the second plurality of latches is operatively connected to another one of the second plurality of latches via an inverter.

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a continuation of U.S. patent application Ser. No. 18/080,680, filed Dec. 13, 2022, now U.S. Pat. No. 11,899,064, issued Feb. 13, 2024, which is a continuation of U.S. patent application Ser. No. 16/724,787, filed Dec. 23, 2019, now U.S. Pat. No. 11,549,984, issued Jan. 10, 2023, which is a divisional of U.S. patent application Ser. No. 15/171,531, filed on Jun. 2, 2016, now U.S. Pat. No. 10,539,617, issued Jan. 21, 2020, each of which are incorporated by reference herein in their entireties.

### BACKGROUND

- (1) The 3D-IC approach uses a combination of standard single damascene techniques, wafer thinning, and direct Cu—Cu thermo-compression bonding. Hybrid bonding is a cost-effective, die-to-wafer integration processes for vertical stacking and high density die-to-die interconnecting.
- (2) In general, direct hybrid bonding is compatible with both die-to-die (D2D) and wafer-on-wafer (WoW) bonding. In direct hybrid bonding, a dual damascene copper and silicon oxide hybrid interface between dies serves as both the full-area substrate bonding mechanism and the electrical connection between pads and/or vias on respective dies.
- (3) Design-for-Testing or Design for Testability (“DFT”) refers to integrated circuit design techniques that add certain testability features to a hardware product design. The DFT features make it easier to develop and apply various manufacturing tests for the designed hardware. The purpose of manufacturing tests is to validate that the hardware products contain no manufacturing defects that could adversely affect the product's proper functioning. Scan chain is one example of a technique implemented in a DFT process.

## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. Various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
- (2) FIG. 1A is a cross-sectional view of the hybrid bonded 3DIC in accordance to some embodiments.
- (3) FIG. 1B is a schematic diagram of a serial cross-bar scan architecture in accordance with some embodiments.
- (4) FIG. 2A is a schematic diagram of a serial cross-bar scan architecture with D flip-flops and scan flops in accordance with some embodiments.
- (5) FIG. 2B is a schematic illustration of a scan flip-flop in accordance with some embodiments.
- (6) FIG. 2C is a schematic illustration of a D flop in accordance with some embodiments.
- (7) FIG. 3 is a schematic diagram of a serial cross-bar scan architecture with D flip-flops and multiplexers in accordance with some embodiments.

- (8) FIG. 4 is a schematic diagram of a scan architecture with non-equal number of inputs and outputs between dies in accordance with some embodiments.
- (9) FIG. 5 is a schematic diagram of a scan architecture with connections between flip-flops which are within the same die but not adjacent to each other in accordance with some embodiments.
- (10) FIG. 6 is a schematic diagram of a scan architecture with multiple scan outputs in accordance with some embodiments.
- (11) FIG. 7 is a schematic diagram of a scan architecture with shared functional flip-flops in accordance with some embodiments.
- (12) FIG. 8 is a schematic diagram of a scan architecture with level shifters in accordance with some embodiments.
- (13) FIG. 9A is a schematic diagram of a scan architecture with on-chip test generation and comparison in accordance with some embodiments.
- (14) FIG. 9B is a schematic diagram of a test pattern generator for on-chip test generation in accordance with some embodiments.
- (15) FIG. 9C is a schematic diagram of a test response comparison unit for on-chip test generation and comparison in accordance with some embodiments.
- (16) FIG. 10 is a schematic diagram of a deterministic circular built-in self-test architecture in accordance to some embodiments.
- (17) FIG. 11 is a block diagram of a deterministic circular built-in self-test architecture in accordance with some embodiments.
- (18) FIG. 12 is a schematic diagram of a fault free circuit of four flip-flops and its corresponding logic table in accordance with some embodiments.
- (19) FIG. 13 is a schematic diagram of a circuit with a stuck-at-1 fault at a first location of four flip-flops and its corresponding logic table in accordance with some embodiments.
- (20) FIG. 14 is a schematic diagram of a circuit with a stuck-at-1 fault at a second location of four flip-flops and its corresponding logic table in accordance with some embodiments.
- (21) FIG. 15 is a schematic diagram of a circuit with a stuck-at-1 fault at a third location of four flip-flops and its corresponding logic table in accordance with some embodiments.
- (22) FIG. 16 is a schematic diagram of a circuit with a stuck-at-1 fault at a fourth location of four flip-flops and its corresponding logic table in accordance with some embodiments.
- (23) FIG. 17 is a schematic diagram of a circuit with a stuck-at-0 fault at a first location of four flip-flops and its corresponding logic table in accordance with some embodiments.
- (24) FIG. 18 is a logic table of a circuit with 7 flip-flops under hold faults in accordance with some embodiments.
- (25) FIG. 19 is a logic table of a circuit with 7 flip-flops under setup faults in accordance with some embodiments.
- (26) FIG. 20 is a schematic diagram of a fault-free on-chip scan-chain with 7 flip-flops and its corresponding logic waveforms in accordance with some embodiments.
- (27) FIG. 21 is a schematic diagram of an on-chip scan-chain having a hold violation with 7 flip-flops and its corresponding logic waveforms in accordance with some embodiments.
- (28) FIG. 22 is a schematic diagram of an on-chip scan-chain having a setup violation with 7 flip-flops and its corresponding logic waveforms in accordance with some embodiments.
- (29) FIG. 23 is a flowchart illustrating the method for deterministic circular built-in self-test in accordance with some embodiments.

#### DETAILED DESCRIPTION

(30) The following disclosure provides many different embodiments, or examples, for implementing different features of the subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and

second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

(31) Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

(32) FIG. 1A is a cross-sectional view of a hybrid bonded 3D stack in accordance to some embodiments. The top die **100** includes a semiconductor (e.g., silicon) substrate **101**, and the bottom die includes a semiconductor (e.g., silicon) substrate **201**. Both the substrates **101** and **201** include functional circuits in them. The functional circuits include active devices, such as transistors, shown in substrates **101** and **102** and interconnects **110**, **210** in each die. The interconnect layer **110** of the top die **100** and the interconnect layer **210** of the bottom die **200** are connected by hybrid bonding structures **301** and **302**. FIG. 1B is a schematic diagram of a serial cross-bar scan architecture in accordance with some embodiments. The serial cross-bar scan architecture includes an upper die **1100** and a lower die **1200**. The upper die **1100** is stacked above the lower die **1200**. According to some embodiments, the bonding between the upper die **1100** and the lower die **1200** is hybrid bonding, which is a cost-competitive solution for vertical stacking and provides high density die-to-die interconnect. According to some embodiments, the pitch between the interconnections is, for example, 1  $\mu\text{m}$  or less. Hybrid bonding reduces leakage, power consumption and device footprint compared to a 3DIC in which connections between active devices on stacked dies include through-substrate-vias (TSV). Each of the lines **1302**, **1303**, **1304**, . . . **1309** represents a combination of one or more vias and/or one or more pads in each of the upper die **1100** and lower die **1200**.

(33) In other embodiments (not shown), interconnections between stacked dies in the 3DIC include TSVs. In other embodiments (not shown), the 3DIC is a stacked CMOS package, in which interconnections between tiers include inter-tier vias (ITV) also referred to as inter-level vias (ILV).

(34) Some embodiments of a scan chain include the following set of signals in order to control and observe the scan mechanism. Scan\_In (SI) and Scan\_Out(SO) are the input and output of a scan chain, respectively. A shift enable pin (SE) is a special signal that is added to a design. When SE is asserted, every latch in the scan chain is connected to a respective bit of a shift register. A clock signal is used for controlling all the latches, or flip-flops, in the chain during testing of the IC. An arbitrary test pattern (for example, a vector of random zeroes and ones) can be entered into the chain of latches, and the state of every latch can be read out.

(35) As shown in FIG. 1B, the architecture includes a wrapper around the interface between the upper die **1100** and lower die **1200**. The wrapper includes a respective wrapper cell (e.g., flip-flops **1121-1128** and **1221-1228**) in each of the dies **1100**, **1200** on each side of each inter-die connection **1302-1309**. Additional intra-die connections **1151-1154** and **1251-1253** are added to form a scan path **1900**, which functions as a shift register during scan chain testing. The scan shift path (scan path) is the route that the signal follows during a scan test. According to some embodiments, the scan shift path includes latches in the upper die and the lower die, their corresponding interconnections between dies and connections between latches in the same die. According to some embodiments, the scan shift path starts with a scan input, and ends with at least one scan output. The scan path includes a continuously connected set of latches and interconnections between and

within dies, for shifting data from the scan input to the scan output.

(36) The upper die **1100** includes a test and clock control unit **1110** and a plurality of flip-flops **1121, 1122, 1123, 1124, 1125, 1126, 1127** and **1128**. According to some embodiments, the flip-flops **1121 . . . 1128** are of the same type, according to other embodiments, the flip-flops **1121 . . . 1128** are of two or more different types. The test and clock control unit **1110** transmits a clock signal **CLK1** through the line **1140**. The clock signal **CLK1** controls the flops **1121 . . . 1128** through **1141, 1142, 1143, 1144, 1145, 1146, 1147** and **1148**, respectively. The test and clock control unit **1110** controls the flip-flops **1121 . . . 1128** through **1131, 1132, 1133, 1134, 1135, 1136, 1137** and **1138**, respectively. The output of the flip-flop **1121** is transmitted to the input of flip-flop **1122** through line **1151**; the output of the flip-flop **1123** is transmitted to the input of the flip-flop **1124** through line **1152**; the output of the flip-flop **1125** is transmitted to the input of the flip-flop **1126** through line **1153**; the output of the flip-flop **1127** is transmitted to the input of the flip-flop **1128** through line **1154**.

(37) Similarly, the lower die **1200** includes a test and clock control unit **1210** and a plurality of flops **1221, 1222, 1223, 1224, 1225, 1226, 1227** and **1228**. According to some embodiments, the flip-flops **1221 . . . 1228** are of the same type of flip-flops, according to other embodiments, the flip-flops **1221 . . . 1228** are of different types of flip-flops. The test and clock control unit **1210** transmits a clock signal **CLK2** through line **1240**, the clock signal **CLK2** controls the flip-flops **1221 . . . 1228** through **1241, 1242, 1243, 1244, 1245, 1246, 1247** and **1248** respectively. The test and clock control unit **1210** controls the flip-flops **1221 . . . 1228** through **1231, 1232, 1233, 1234, 1235, 1236, 1237** and **1238** respectively. The scan in signal **1301** is transmitted to the flip-flop **1221**. The output of the flip-flop **1222** is transmitted to the input of flip-flop **1223** through line **1251**, the output of the flip-flop **1224** is transmitted to the input of the flip-flop **1225** through line **1252**, the output of the flip-flop **1226** is transmitted to the input of the flip-flop **1227** through line **1253**, the output of the flip-flop **1228** is the scan out **1310**. The test and clock control unit **1110** in the upper die **1100** and the test and clock control unit **1210** in the lower die **1200** communicate through line **1312**.

(38) An inter-die scan path **1900** designated by dashed line can be created by embedding at least one functional path in a scan shift path. A functional path is a path that is not dedicated to the scan chain for testing purposes only, but rather is included in a functional circuit that performs other non-testing functions. The functional path can include one or more interconnect lines and/or interconnect vias within one of the dies. According to some embodiments, the embedded functional path includes other passive and/or active elements. The scan chain acts as a shift register during scan chain testing. In some embodiments, a functional path connected to a circuit is connected to a multiplexer in the scan shift path, and the multiplexer can be used to select either a test pattern input or a signal on the functional path connected to the functional circuit. This allows scan chain testing across functional paths, in addition to the interconnections shown in FIG. 1B. The inter-die scan path **1900** starts at the scan in signal **1301**, then passes through, in order, flip-flop **1221**, line **1302**, flip-flop **1121**, line **1151**, flip-flop **1122**, line **1303**, line **1303**, flip-flop **1222**, line **1251**, flip-flop **1223**, line **1304**, flip-flop **1123**, line **1252**, flip-flop **1124**, line **1305**, flip-flop **1224**, line **1252**, flip-flop **1225**, line **1306**, flip-flop **1125**, and so forth. The inter-die scan path **1900** crosses between the upper die **1100** and the lower die **1200** until it reaches the flip-flop **1228** in the lower die **1200**. The output of the flip-flop **1228** is transmitted to the scan out **1310** to complete the inter-die scan path **1900**. As discussed above, a functional path is a path included in a circuit that performs non-scan-chain-testing functions, and such a functional path is not dedicated to the scan chain wrapper cell structure. Functional paths **1302, 1303, 1304, 1305, 1306, 1307, 1308** and **1309** are embedded in the shift path of scan path **1900**. **CLK1** and **CLK2** are kept the same and synchronized during the scan. According to some embodiments, the shift clock frequency is swept during scan chain testing, to check timing-related defects caused by weak short or opens and DC defects. According to some embodiments, the clock frequencies **CLK1** and **CLK2** are swept through a range from 50 MHz to 2

GHz during scan chain testing. According to some embodiments, dummy connections are added to form a continuous chain of wrapper cells between the upper and lower dies, effectively forming a single shift register that is used during scan chain testing. According to some embodiments, testing is performed through shift operation at several different clock frequencies. Each time the clock is changed to a new frequency, a new clock leading edge occurs. Each flip-flop can use the leading edge of this new clock to trigger a capture. At the leading edge of this new clock, the flip-flops output the captured value from their respective D inputs to their respective Q outputs, shifting the data along the shift path. As a result, there is no requirement for a separate capture function to trigger the capture by setting scan enable ( $SE=0$ ). According to some embodiments, scan chain test patterns are generated, for example, by a general purpose processor programmed to execute a program such as an automatic test pattern generator (ATPG). If the scan chain test fails at low speed, then a hard defect is detected. If the scan chain test fails at high speed, then a resistive or weak defect is detected. According to some embodiments, a speed lower than 50 MHz is considered as low speed, the range between 50 MHz and 500 MHz is considered as high speed, 500 MHz and above is considered very high speed. If the 3DIC fails the DC test, this is an indication that the 3DIC contains at least one hard open circuit or short circuit defect. If the 3DIC passes the DC test, then the AC test is performed at a first frequency. If the 3DIC passes the AC test at the first frequency, the shift frequency is increased and the AC test is repeated. One or more iterations of the shift frequency increase and testing are repeated, until the 3DIC fails the AC test. The maximum frequency at which the 3DIC passes the scan chain test. The presence of AC defect is computed by correlating the measured passing frequency and expected shift frequency. Test or shift frequency is the speed at which data is transferred from the bottom die **1200** to the top die **1100** through the interconnections or the functional paths. As a result, the maximum passing shift frequency reflects the actual speed of the interconnections, or the functional path. FIG. 2A is a schematic diagram of a serial cross-bar scan architecture with D flops and scan flops in accordance with some embodiments. The schematic diagram in FIG. 2 has the same sequence of connections **2302-2308** as shown in the embodiment in FIG. 1, but the embodiment of FIG. 2 has two different kind of flip-flops. Flip-flops **2121**, **2123**, **2125**, **2127**, **2222**, **2224**, **2226** and **2228** are D flops, while flops **2122**, **2124**, **2126**, **2128**, **2221**, **2223**, **2225** and **2227** are “scan flip-flops.” The scan flip-flops **2800** of FIG. 2 all include a regular D flip-flop **2801** and a multiplexer **2802**, as shown in FIG. 2B. The scan flops are used for inter-die scan testing and the D flops are used for intra-die scan testing. The scan chain follows the same shift path as the implementation in FIG. 1. The details of the D flops and the scan flops are illustrated in FIG. 2B.

(39) FIG. 2B is a schematic illustration of a scan flip-flop, and FIG. 2C is a schematic illustration of a D flop in accordance with some embodiments. The scan flip-flop **2800** includes a regular D flip-flop **2801** and a multiplexer **2802**. The multiplexer **2802** has two inputs: the scan input **2803** and the functional path input **2804**. The output **2805** of the multiplexer **2802** is transmitted to the D flip-flop **2801**, the output **2806** of the D flip-flop is transmitted to another die by way of one or more conductive vias and/or one or more conductive pads (not shown). In comparison, D flip-flop **2901** receives a functional path signal from a path included in a functional circuit, which is located on another die, by way of an input **2902** and the D flip-flop **2901** has an output **2903**. A functional circuit is a circuit in one of the dies that performs a function and is not exclusively used during scan chain testing operations.

(40) FIG. 3 is a schematic diagram of a serial cross-bar scan architecture with D flops and multiplexers in accordance with some embodiments. The embodiment in FIG. 3 is similar to the embodiment in FIG. 1, except that in the embodiment of FIG. 3, multiplexers are used to select either a functional path signal from a connecting path with a functional circuit in the same die as the flip-flop or a scan chain value output from the flip-flop. The value selected by the multiplexer is then provided to the other die.

(41) According to some embodiments, a multiplexer **3161** is inserted at the output of the flip-flop

**3122**. One input **3161A** of the multiplexer **3161** receives the output of the flip-flop **3122**, the other input **3161B** of the multiplexer **3161** receives a signal from a functional path of a functional circuit **3170** within the upper die **3100**. The output of the multiplexer **3161** is transmitted through inter-die functional path **3303** to flip-flop **3222** in the lower die **3200**. Similarly, multiplexers **3162**, **3163** and **3164** are inserted at the outputs of respective flops **3124**, **3126** and **3128** in the upper die **3100**, and multiplexers **3261**, **3262**, **3263** and **3264** are inserted at the outputs of the respective flops **3221**, **3223**, **3225** and **3227** in the lower die **3200**. The multiplexer inputs **3161B**, **3162B**, **3163B** and **3164B** are all connected to a functional path of a functional circuit in the upper die **3100**, the functional circuit **3170**. Similarly, the multiplexers' inputs **3261B**, **3262B**, **3263B** and **3264B** in the lower die **3200** are all connected to another functional circuit (not shown) in the lower die **3200**. The scan path **3900** of the scan chain is indicated by a dashed line.

(42) FIG. 4 is a schematic diagram of a serial cross-bar scan architecture with non-equal number of inputs and outputs between dies in accordance with some embodiments. For example, the upper die **4100** and lower die **4800** can be of different types. In an example, shown in FIG. 4, the upper die **4100** has one inter-die output **4309** illustrated in solid line, but the lower die **4800** has four inter-die outputs **4302**, **4304**, **4306**, **4308** illustrated in solid lines. Compared to FIG. 1, there are only five flops in the upper die, four of which are D flops (i.e., **4121**, **4122**, **4123** and **4124**) receiving inputs from lower die; the fifth flip-flop **4125** of the upper die is a scan flip-flop which provides an output to the lower die. The lower die has five corresponding flops, four of which are scan flops (i.e., **4221**, **4222**, **4223** and **4224**) providing outputs to corresponding D flops (i.e., **4121**, **4122**, **4123** and **4124**) in the upper die; The fifth flip-flop **4225** in the lower die is a D flip-flop receiving an input from scan flip-flop **4125** in the upper die.

(43) In some embodiments, as shown in FIG. 4, dummy interconnects **4303**, **4305** and **4307** (illustrated in dashed lines) are added to enable flow of scan chain test data between the upper die and the lower die. According to some embodiments, dummy connections are added to form a continuous chain of wrapper cells between the upper and lower dies, effectively forming a single shift register that is used during scan chain testing. A dummy connection is an interconnection provided for scan chain testing, but not used by any functional circuits during other operations (besides scan chain testing). Because the dummy interconnections between die are only used during scan chain testing (but not during normal operations), the adjacent wrapper cells providing signals to the dummy interconnections do not use multiplexers to select between a test pattern input signal and a functional path input signal. The adjacent wrapper cells providing signals to the dummy interconnections can contain a latch without a multiplexer. The dummy interconnects **4303**, **4305**, and **4307** allow the flip-flops **4121-4125** and **4201-4205** to operate as a shift register during scan-chain testing. The scan path **4900** of the scan chain is illustrated by arrows in FIG. 4, and includes, in order, flip-flops **4201**, **4121**, **4222**, **4122**, **4223**, **4123**, **4224**, **4124**, **4125** and **4225**.

(44) FIG. 5 is a schematic diagram of a scan architecture with connections between flip-flops which are within the same die but not adjacent to each other, in accordance with some embodiments. There are three D flops (**5121**, **5122** and **5124**) in the upper die **5100** for receiving inputs from corresponding scan flops (i.e., **5221**, **5222**, **5224**) in the lower die **5200**. There are two scan flip-flops (**5123** and **5125**) in the upper die **5100** for sending outputs to the corresponding D flip-flops (**5223** and **5225**) in the lower die **5200**. In this case, the flip-flop immediately adjacent to the D flip-flop **5121** within the upper die **5100** is another D flip-flop **5122**. In some 3DIC designs it may be impractical or undesirable for the designer to insert a dummy interconnect to direct the output of D flip-flop **5121** to the adjacent scan flip-flop **5222** in the lower die **5200**. Using a method as shown in FIG. 5, the output **5303** of the D flip-flop **5121** can be directed to a non-adjacent scan flip-flop (e.g., **5123**) in the upper die, such that the output **5304** of the non-adjacent flip-flop **5123** crosses to the lower die **5200** and is connected to a D flip-flop **5223** in the lower die **5200**. Similarly, the output **5305** of the D flip-flop **5223** is directed to a scan flip-flop **5222** in the lower die **5200**. The output **5306** of the scan flip-flop **5222** then crosses to the upper die **5100** and



connects to a D flip-flop **5122**. The output **5307** of the D flip-flop **5122** crosses to the lower die **5200** again the connects to a non-adjacent scan flip-flop **5224** in the lower die **5200**. The shift path then continues to cross to the upper die **5100** through **5308** to reach D flip-flop **5124**, then through **5309** to scan flip-flop **5125**. After crossing to the D flip-flop **5225** in the lower die **5200** through **5310**, the shift path completes with scan out **5311**. The scan path **5900** of the scan chain is illustrated with dashed line. The scan path **5900** includes, in order, flip-flops **5221**, **5121**, **5123**, **5223**, **5222**, **5122**, **5224**, **5124**, **5125** and **5225**.

(45) FIG. **6** is a schematic diagram of a scan architecture with multiple scan outputs in accordance with some embodiments. The embodiment in FIG. **6** is similar to the embodiment in FIG. **2A** except that instead of having only one scan out **2310**, there are four different taps for scan outputs **6310A**, **6310B**, **6310C** and **6310D**. The first scan output **6310A** is taken from the path between the D flip-flop **6222** and the scan flip-flop **6223**, the second scan out **6310B** is taken from the path between the D flip-flop **6224** and the scan flip-flop **6225**, the third scan out **6310C** is taken from the path between the D flip-flop **6226** and the scan flip-flop **6227**, and finally the fourth scan out **6310D** is taken from the output of the D flip-flop **6228**. Multiple scan outputs permit the user of a larger variety of fault diagnosis algorithms, to identify the specific location of a defect. The scan path **6900** of the scan chain is illustrated with dashed line, and is the same as that discussed above with reference to FIG. **2A**.

(46) FIG. **7** is a schematic diagram of a scan architecture with shared functional flip-flops in accordance with some embodiments. The embodiment in FIG. **7** is similar to the embodiment in FIG. **2A** except that intra-die flip-flops **7123**, **7125**, **7222** and **7224** are “shared functional flip-flops” rather than dedicated D flip-flops. A shared functional flip-flop is used during scan chain testing, and is also used by a functional circuit within one of the dies while that die is performing an operation other than scan chain testing. The D flip-flops **7123** and **7125** are part of a functional circuit **7810** in the upper die. The D flip-flops **7222** and **7224** are part of a logic unit **7820** in the lower die. The intra-die flops **7123**, **7125**, **7222** and **7224** are not dedicated for scan chain testing. Instead, each of the flip-flops **7123**, **7125**, **7222** and **7224** are included in separate logic circuitry (e.g., in their own logic units **7810** and **7820** respectively). Sharing flops for use both during scan chain testing and during normal operation is usually possible from a functional point of view, but providing dedicated flip-flops for scan chain testing may simplify routing in some IC designs. In some embodiments, flip-flop sharing as shown in FIG. **7** can be used to reduce die size, for example. The scan path **7900** of the scan chain in FIG. **7** is illustrated with dashed line, and includes, in order, flip-flops **7221**, **7121**, **7122**, **7222**, **7223**, **7123**, **7124**, **7224**, **7225**, **7125**, **7126**, **7226**, **7227**, **7127**, **7228**, and **7128**.

(47) FIG. **8** is a schematic diagram of a scan architecture with level shifters in accordance with some embodiments. The embodiment in FIG. **8** is similar to the embodiment in FIG. **4**, with four D flip-flops, **8121**, **8122**, **8123** and **8124**, in the upper die **8100** for receiving inputs from scan flip-flops, **8221**, **8222**, **8223** and **8224**, respectively, in the lower die **8200**, and a scan flip-flop **8125** in the upper die **8100** for sending signal to the D flip-flop **8225** in the lower die **8200**. The scan path **8900** is similar to the scan path **4900** in FIG. **4**, and includes flip-flops **8221**, **8121**, **8222**, **8122**, **8223**, **8123**, **8224**, **8124**, **8125** and **8225**. The difference is that eight level shifters **8401**, **8402**, **8403**, **8404**, **8405**, **8405**, **8407** and **8408** are inserted along the scan path **8900** in the connections between the upper die and the lower die. Although the level shifters **8401-8408** are shown schematically between the dies **8100** and **8200**, the individual level shifters can be included within the upper die **8100** and/or the lower die **8200**. The implementation of level shifters between the upper die and the lower die permits inclusion of dies having two or more different voltage levels within the same 3DIC. When the upper die and the lower die implement different technologies, their voltage levels may differ. According to some embodiments, with level shifters, an upper die and lower die of different technologies can be stacked within the same 3DIC. Level shifters can be included in any of the embodiments from FIG. **1** through FIG. **7**. The scan path **8900** of the scan

chain is illustrated with dashed line, and includes the flip-flops **8221**, **8121**, **8222**, **8122**, **8223**, **8123**, **8224**, **8124**, **8125**, and **8225**.

(48) FIG. **9A** is a schematic diagram of a scan architecture with on-chip scan chain test data generation and comparison in accordance with some embodiments. The embodiment in FIG. **9** is similar to the embodiment in FIG. **3A**, with eight flops, **9121**, **9122**, **9123**, **9124**, **9125**, **9126**, **9127** and **9128** in the upper die **9100**, and eight flops, **9221**, **9222**, **9223**, **9224**, **9225**, **9226**, **9227** and **9228** in the lower die **9200**. The test and clock control unit **9210** is different from the test and clock controls **3110** and **3210**. Instead of receiving tests from scan in **3301** from outside the upper and the lower dies, according to some embodiments as shown in FIG. **3A**, test patterns are generated inside the test and clock control unit **9210** in the die including the first flip-flop in the scan chain shift pattern (e.g., the lower die **9200** in the example of FIG. **9**). The scan chain test data sequence is generated on-chip and then transmitted to the first flip-flop through interconnection **9301**. Then a scan path similar to scan path **3900** is followed, and the scan output **9310** is transmitted into the test and clock control unit **9210** where a comparison can be conducted on-chip. According to some embodiments, the on-chip test generation and comparison facilitates scan chain testing without external test generation and comparison. In other embodiments, external test generation and comparison can reduce the time for test generation and comparison. The on-chip test generation and comparison can be implemented to any of the embodiments in FIG. **1** through FIG. **8**. Scan path **9900** of the scan chain is illustrated with dashed line, and includes flip-flops **9221**, **9121**, **9122**, **9222**, **9223**, **9123**, **9124**, **9224**, **9225**, **9125**, **9126**, **9226**, **9227**, **9127**, **9128**, and **9228**.

(49) FIG. **9B** is a schematic diagram of a test pattern generator for on-chip test generation in accordance with some embodiments. The D flip-flop **901** has an output **902**, which is fed to the input of an inverter **903**. The output **904** of the inverter is fed back to the input of the D flip-flop **901**. The output **902** can be used as the scan input **9301** in FIG. **9A**. In other embodiments, other test pattern generators are used.

(50) FIG. **9C** is a schematic diagram of a test response comparison unit for on-chip test generation and comparison in accordance with some embodiments. The scan output **910** is fed through the counter **905** as an input **906** to the comparator **907**. The other input **909** of the comparator **907** is calculated based on scan length and the generated pattern. The values of input **906** and input **909** are compared in the comparator **907**, and the output **908** indicates whether the 3DIC passes or fails the scan chain test.

(51) The embodiments in FIG. **1** through **9C** can be combined with each other, the inclusion of one embodiment does not exclude the other embodiments. Although the examples described above include two dies for simplicity of illustration, the methods and structures described herein can be applied to 3DICs including more than two dies (e.g., four, six, or eight dies).

(52) FIG. **10** is a schematic diagram of a deterministic circular built-in self-test architecture in accordance to some embodiments. The embodiment in FIG. **10** is similar to the embodiment in FIG. **9A**. The upper die **10100** is stacked on the top of the lower die **10200**. According to some embodiments, there are eight flip-flops(**10121**, **10122**, **10123**, **10124**, **10125**, **10126**, **10127** and **10128**) implemented in the upper die **10100**, and there are eight flip-flops(**10221**,**10222**, **10223**, **10224**, **10225**, **10226**, **10227** and **10228**) in the lower die **10200**. The eight flip-flops in the upper die **10100** and the eight flip-flops in the lower die **10200** are inter-connected in a similar fashion to those flip-flops shown in FIG. **9A**. The test and clock control unit **10110** in the upper die **10100** is connected to the eight flip-flops in the upper die in a similar fashion to that of FIG. **9A**. The difference between FIG. **10** and FIG. **9A** is in the lower die **10200**. The output **10255** of the eighth flip-flop **10228** in the lower die **10200** is connected to an inverter **10230**. The output signal from flip-flop **10228** is inverted by the inverter **10230** and is then transmitted to two different places: first, the inverted signal **10251** is transmitted back to the input of the first flip-flop **10221** of the lower die **10200**; second, the inverted signal **10251** is transmitted to the analyzer unit **10213** in the lower die **10200**.

(53) The test and clock control unit **10110** of the upper die is connected to the clock control unit **10211** in the lower die **10200**. The phase lock loop (PLL) unit **10212** controls the clock and control unit **10211**. The output of the clock and control unit **10211** is also transmitted to the analyzer unit **10213** in the lower die **10200**. The clock and control unit **10211** transmits clock signal to each of the eight flip-flops in the lower die **10200**. The clock and control unit **10211** also transmits set and rest signals to each of the eight flip-flops in the lower die **10200**. The set and rest signals are implemented to initialize the flip-flops. The analyzer unit **10213** accepts signals from the flip-flop scan chain and the clock and control unit **10211** to perform analytical tasks to diagnose the types of the faults present in the flip-flop scan chain and to locate such faults therein. The scan path **10900** includes a continuously connected set of latches and interconnections between and within dies, for shifting data from the scan input to the scan output. According to some embodiments, the scan path **10900** includes flip-flop **10221**, interconnect **10301**, flip-flop **10121**, connect **10151**, flip-flop **10122**, interconnect **10302**, flip-flop **10222**, connect **10252**, flip-flop **10223**, interconnect **10303**, flip-flop **10123**, connect **10152**, flip-flop **10124**, interconnect **10304**, flip-flop **10224**, connect **10253**, flip-flop **10225**, interconnect **10305**, flip-flop **10125**, connect **10153**, flip-flop **10126**, interconnect **10306**, flip-flop **10226**, connect **10254**, flip-flop **10227**, interconnect **10307**, flip-flop **10127**, connect **10154**, flip-flop **10128**, interconnect **10308**, flip-flop **10228**, output **10255**, inverter **10230** that inverts the output signal, and connect **10251** that feed the inverted output to the input of the first flip-flop **10221** for form a scan path. The details of the analyzing and diagnosing steps will be discussed below.

(54) FIG. **11** is a block diagram of a deterministic circular built-in self-test architecture in accordance with some embodiments. The deterministic circular built-in self-test architecture **11000** includes a plurality of interconnect segments, labeled as interconnect segment **1 (11100)**, through interconnect segment **X (11200)**. The deterministic circular built-in self-test architecture **11000** also includes a multiplexer **11300**, a first counter unit **11301** for counting the number of hold violations, a second counter unit **11302** for counting the number of setup violations, a compare unit **11303** for comparing the output of the first counter unit **11301** and the output of the second counter unit **11302**. According to some embodiments, a hold violation happens when the flip-flop holds the old value and cannot change from 1 to 0, or from 0 to 1 when it is supposed to change. According to some embodiments, a setup violation happens when the new data comes to a flip-flop earlier than the new data is supposed to be there. The deterministic circular built-in self-test architecture **11000** further includes a control logic unit **11304**, a test access port (TAP) unit **11305**, a phase lock loop (PLL) unit **11306**, a clock controller **11307**, and a single pulse unit **11308**. The TAP unit **11305** is connected to a JTAG bus. A JTAG bus is the Standard Test Access Port and Boundary Scan Architecture according to IEEE standard 1149.1.

(55) The first interconnect segment **11100** includes a first multiplexer **11101**, a second multiplexer **11102**, a plurality of flip-flops **11103, 11104, 11105, 11106, 11107, 11108, 11109, 11110**, and a diagnosis unit **11111**. According to some embodiments, the first input **11101A** of the first multiplexer **11101** is connected to the scan-in signal **11309**, and the second input **11101B** of the first multiplexer **11101** is connected to the second inputs of all subsequent interconnect segments, up to the second input **11201B** of the first multiplexer **11201** of the **X**th interconnect segment **11200**. The output of the first multiplexer **11101** is connected to the first input **11102A** of the second multiplexer **11102**, and the second input **11102B** of the second multiplexer **11102** is connected to the QB (QB represents “Q bar”, the inversion of Q) output the last flip-flop **11110QB**. The output **11102C** is connected to the D input **11103D** of the first flip-flop **11103**, and the Q output **11103Q** is connected to the D input **11104D** of the subsequent flip-flop **11104**. The Q output of each of the flip-flops are connected to the D input of the subsequent flip-flops in a similar way. The clock signal **11112** provide clock signal to each of flip-flops **11103, 11104, 11105, 11106, 11107, 11108, 11109** and **11110**. The output **11110Q** of the last flip-flop **11110** is transmitted as an input to the multiplexer **11300**. The output **11110Q** of the last flip-flop **11110** in the first interconnect segment

**11100** is also connected to the first input of the first multiplexer in the second interconnect segment (not shown in the figure). The diagnosis unit **11111** further includes an OR gate **11111A** as a setup detector, and a XOR gate **11111B** as a hold detector. The detailed operations of OR gate **11111A** as a setup detector, and a XOR gate **11111B** as a hold detector is discussed in FIGS. **21** and **22**.

(56) All subsequent interconnect segments up to interconnect segment X **11200** are configured similarly to the interconnect segment **1 11100**. The second inputs of the first multiplexers of the plurality of interconnect segments from 1 to X are connected together. The Q outputs of the last flip-flops in each of the plurality of flip-flops are transmitted to the multiplexer **11300** as inputs in a similar way to **11110Q**. The output of the diagnosis units are also connected to the multiplexer **11300** in a similar way to diagnosis unit **11111**. The Q outputs of the last flip-flops of each of the interconnect segment (except the last interconnect segment X) is connected to the first input of the first multiplexer in the subsequent interconnect segment.

(57) The output **11300A** is transmitted to both the first counter unit **11301** and the second counter unit **11302** for counting hold setup fault respectively. The output of the first counter unit **11301** and the second counter unit **11302** are transmitted to the compare unit **11303** for comparison to determine pass or fail of the test, a detailed discussion regarding the test is presented in the description of FIG. **23** in the step **2303**. The output **11300B** of the multiplexer **11300** is transmitted to the control logic unit **11304** for further processing. The clock control unit **11307** provides a first control signal **11307A** to control the single pulse unit **11308**, a second control signal **11307B** to provide clock signals to all interconnect segments by connecting to the flip-flops' clock inputs in a similar way to clock signal **11112**. The third control signal **11307C** controls the first counter **11301** and the second counter **11302**.

(58) The control logic unit **11304** provides a start and stop signal **11304A** to control the starting and stopping of the clock controller unit **11307**. The control logic unit **11304** provides diagnosis signal **11304B** connecting to the selector signals of the first multiplexers in each of the interconnect segment for setup and hold diagnosis. The details of the setup and hold diagnosis are discussed in the following figures. The control logic unit **11304** provides a set and rest signal **11304C** to the single pulse unit **11308**, the first counter unit **11301**, the second counter unit **11302** and each of the flip-flops in each of the interconnect segment. The control logic unit **11304** also provides a selector signal **11304D** to control the selectors of the second multiplexers in each of the interconnect segments. In addition, the control logic unit **11304** is also coupled to the first counter unit **11301**, the second counter unit **11302**, and the TAP unit **11305**. The PLL unit **11306** accepts an external slow clock to control the clock controller **11307**.

(59) FIG. **12** is a schematic diagram of a fault free circuit of four flip-flops and its corresponding logic table in accordance with some embodiments. There are four flip-flops **1201**, **1202**, **1203** and **1204** in the interconnect segment **1205** according to some embodiments. According to some embodiments, the interconnect segment **1205** is the first interconnect segment in FIG. **11**. The first flip-flop **1201**'s output **1201Q(Q1)** is connected to the D input **1202D** of the second flip-flop **1202**, the output **1202Q(Q2)** is connected to the D input **1203D** of the third flip-flop, the Q output **1203Q(Q3)** is connected to the D input **1204D** of the fourth flip-flop, the Q output of the fourth flip-flop **1204** is **1204Q(Q4)**. The QB output **1204QB** of the fourth flip-flop **1204** is connected to the D input of the first flip-flop **1201**. QB means Q-bar, or the inversion of Q. The Set signals "S" of all of the four flip-flops are connected to Set signal **11304C** of the control logic unit **11304** illustrated in FIG. **11**. Similarly, the Reset signal "R" of all of the four flip-flops are connected to the Reset signal **11304C** of the control logic unit **11304** illustrated in FIG. **11**. The clock of all of the flip-flops are controlled by the clock signal **11307B** of the clock controller unit **11307** illustrated in FIG. **11**.

(60) According to some embodiments, the circuit implemented by flip-flops **1201** through **1204** is a fault-free circuit. According to some embodiments, table **120** is a table illustrating the Q output values of the flip-flops **1201** through **1204** at clock cycles 0, 1, 2, 3, 4, 5, 6, 7 and 8. According to

some embodiments, for a circuit with  $N$  flip-flops, it takes  $2N$  clock cycles to go back to its initial state, and this circuit is a  $2N$ -state finite state machine. In FIG. 12,  $N=4$ , thus  $2N=8$ . Accordingly, the circuit with 4 flip-flops is a finite state machine with 8 states. In Table 120, for each clock cycle 0 through 8, there are 4 Q values, Q1, Q2, Q3 and Q4 corresponding to the Q outputs of the flip-flops. At clock cycle 0, all Q values are 0, at clock cycle 8, the circuit goes back to the initial state with all Q values equal to 0. At clock cycle 1, the value 1 is shifted out on Q1; at clock cycle 2, value ones are shifted out on Q1 and Q2; at clock cycle 3, value ones are shifted out on Q1, Q2, and Q3; at clock cycle 4, value ones are shifted out on all Q's from Q1 to Q4. At clock cycle 4, four value ones are shifted to the fault free circuit 1205. Because there is no fault in the circuit 1205, it takes another 4 cycles for the circuit to return back to its initial state with all Q values equal to 0. The output sequence on Q4 during the 0 through 8 clock cycles are: 0, 0, 0, 0, 1, 1, 1, 1, 0, as illustrated in the last column in the Table 120 marked Q4. The number of zeroes and ones play a key role in the determination of the fault states of the flip-flops in the interconnect segment 1205. According to some embodiments, for a fault-free circuit with  $N$  flip-flops of  $2N$  cycles, there are  $N$  ones and  $N$  zeroes in the Q output of the last flip-flop. In the fault-free circuit example illustrated in FIG. 12, the 8 cycles in the Q4 data has 4 zeroes and 4 ones.

(61) FIG. 13 is a schematic diagram of a circuit with a stuck-at-1 fault at a first location of four flip-flops and its corresponding logic table in accordance with some embodiments. FIG. 13 illustrates a similar configuration to FIG. 12, with the interconnect 1305 including four flip-flops 1301, 1302, 1303 and 1304. FIG. 13 is different from FIG. 12 in that there is a stuck-at-1 (SA1) fault at the first flip-flop 1301, as illustrated as SA1 in FIG. 13. The SA1 fault could be at D1, between D1 and Q1 or at Q1. The “Reset” signal resets the output of the flip-flops to 1 at appropriate clock cycles.

(62) Similarly, the Table 130 illustrates the Q output states of the flip-flops 1301 through 1304 from clock cycles 0 through 8. When the circuit is not fault-free, as illustrated in FIG. 12, the circuit is no longer a finite state machine and the circuit does not go back to its initial state after  $2N$  cycles. The number of ones and number of zeroes are no longer equal in the Q4 output from clock cycles 1 through 8. According to some embodiments, for  $2N$  cycles, there are  $N-1$  zeros and  $N+1$  ones on the Q4 output. As illustrated in the Table 130, because there is an SA1 fault at flip-flop 1301, the Q output value Q1 is “stuck-at” 1, which propagates to the next flip-flop at the next clock cycle. For the rest of the 8 clock cycles, the Q1 value remains at 1. Once Q2 reaches 1, the 1 also propagates to the next flip-flop after another clock cycle. Eventually the value 1 reaches Q4 and because Q1 is “stuck at” 1, it keeps Q2, Q3 and Q4 all at the value 1 after 4 clock cycles. After 8 clock cycles, the number of ones is  $4+1=5$ , and the number of zero's is  $4-1=3$ .

(63) FIG. 14 is a schematic diagram of a circuit with a stuck-at-1 fault at a second location of four flip-flops and its corresponding logic table in accordance with some embodiments. FIG. 14 illustrates another similar configuration 1405 with four flip-flops 1401, 1402, 1403 and 1404, and the difference between FIG. 14 and FIG. 13 is that there is a Stuck-At-1 fault at a second location in FIG. 14.

(64) The difference between the Tables 140 and 130 is that instead of Q1 being stuck at 1 for all 8 clock cycles, as in the Table 130, in Table 140, Q2 is stuck at 1 for all 8 clock cycles. According to some embodiments, there are  $N-2$  zeroes and  $N+2$  ones in the Q4 output after  $2N$  clock cycles. Similar to FIG. 13, the configuration in FIG. 14 is not a  $2N$  finite state machine either. According to some embodiments, when  $N=4$ , there are two ( $4-2=2$ ) zero's and six ( $4+2=6$ ) ones in the Q4 output.

(65) FIG. 15 is a schematic diagram of a circuit with a stuck-at-1 fault at a third location of four flip-flops and its corresponding logic table in accordance with some embodiments. Another stuck-at-1 fault at a third location is illustrated in FIG. 15 in a similar configuration of interconnect segment 1505 that includes four flip-flops 1501, 1502, 1503 and 1504. The difference between the Table 150 and the Table 130 is that Q3 values are stuck at 1 for all eight clock cycles. According to

some embodiments, there are  $N-3$  zero's and  $N+3$  ones in the Q4 output data for  $2N$  clock cycles. The interconnect segment configuration **1505** is not a finite state machine and the circuit does not go back to its initial state. When  $N$  is equal to 4 as illustrated in FIG. **15**, there are one ( $4-3=1$ ) zero and seven ( $4+3=7$ ) ones for Q4 in the Table **150**.

(66) FIG. **16** is a schematic diagram of a circuit with a stuck-at-1 fault at a fourth location of four flip-flops and its corresponding logic table in accordance with some embodiments. Another stuck-at-1 fault is illustrated at a fourth location illustrated in FIG. **16** in a similar configuration of interconnect segment **1605** that includes four flip-flops **1601**, **1602**, **1603** and **1604**. The difference between the Table **160** and the Table **130** is that Q4 values are stuck at 1 for all eight clock cycles. According to some embodiments, there are  $N-4$  zeroes and  $N+4$  ones in the Q4 output data for  $2N$  clock cycles. The interconnect segment configuration **1605** is not a finite state machine and the circuit does not go back to its initial state. When  $N$  is equal to 4 as illustrated in FIG. **16**, there are zero ( $4-4=0$ ) zero and eight ( $4+4=8$ ) ones for Q4 in the Table **160**.

(67) In summary, for a fault-free flip-flop chain of length  $N$ , there are equal numbers of zeroes and ones after  $2N$  clock cycles. When the flip-flop chain is initialized to all zeroes (which is called “reset”), after  $2N$  cycles, if the number of ones is larger than the number of zeroes on the output of the last flip-flop, a conclusion can be drawn that there is a stuck-at-1 fault in the flip-flop chain path. The location of the stuck-at-1 fault can be further identified by the number of ones observed at the last flip-flop ( $Q_N$ , the Q output of the  $N$ th flip-flop). If the number of ones is  $2N$ , then the stuck-at-1 fault is at the input of the last (or  $N$ -th) flip-flop in the flip-flop chain; if the number of ones is  $2N-1$ , then the stuck-at-1 fault is at the input of the  $(N-1)$ -th flip-flop; if the number of ones is  $2N-2$ , then the stuck-at-1 fault is at the input of the  $(N-2)$ -th flip-flop; if the number of ones is  $N+1$ , then there is either a stuck-at-1 fault, or a setup violation at the first flip-flop of the flip-flop scan chain.

(68) If the number of ones is smaller than the number of zeroes, then there is a setup/hold violation in the flip-flop chain. A hold violation happens when the flip-flop holds the old value and cannot change from 1 to 0, or from 0 to 1 when it is supposed to change. A setup violation happens when the new data comes to a flip-flop earlier than the new data is supposed to be there.

(69) When the number of zero's is equal to  $2N$ , then there is a stuck-at-0 fault in the flip-flop scan chain. The location of the stuck-at-0 fault can be located by initializing the flip-flop scan chain to ones.

(70) FIG. **17** is a schematic diagram of a circuit with a stuck-at-0 fault at a first location of four flip-flops and its corresponding logic table in accordance with some embodiments. Similar to FIG. **13** discussed above, the interconnect segment **1705** includes four flip-flops **1701**, **702**, **1703** and **1704**. The first difference is that a “Set” signal sets the output of the flip-flops to 0 at appropriate clock cycles. the second difference is that, instead of a stuck-at-1 fault, a stuck-at-0 fault is located at the first flip-flop **1701**. The Table **170** is similarly structured as the Table **130**. At clock cycle 0, all flip-flops are initialized to 1, then at clock cycle 1, 0 is “Set” to the first flip-flop **1701**, at each subsequent clock cycle, 0 is “set” to an additional subsequent flip-flop in the chain. It is clear by comparing the Tables **130** and **170**, that the Table **170** is a reverse of the Table **130** because when all ones are placed by zeroes, and zeroes by ones, in Table **170**, it becomes identical to Table **130**, and vice versa. According to some embodiments, when the stuck-at-0 fault is located between the first flip-flop **1701** and the second flip-flop **1702**, a corresponding table can be derived by reversing the Table **140**. Following the same logic, when the stuck-at-0 fault is located between the second flip-flop **1702** and the third flip-flop **1703**, a corresponding table can be derived by reversing the Table **150**; when the stuck-at-0 fault is located between the third flip-flop **1703** and the fourth flip-flop **1704**, a corresponding table can be derived by reversing the Table **160**.

(71) Similar to the method for determining the existence and location of the stuck-at-1 fault discussed above, a method for determining the existence and location of the stuck-at-0 fault is discussed below.

(72) The first step is the determination of the existence of the stuck-at-0 fault. When the number of ones is smaller than the number of zeroes, then there is a stuck-at-0 fault in the flip-flop scan chain path. Then the location of the stuck-at-0 fault can be further determined by the number of zero's observed at the last flip-flop. Similar to the setting discussed above, assuming there are  $N$  flip-flops in the scan chain, if the number of zeroes is  $2N$ , then the stuck-at-0 fault is located at the input of the last flip-flop (or the  $N$ -th flip-flop); if the number of zeroes is  $2N-1$ , then the stuck-at-0 fault is located at the input of the  $(N-1)$ -th flip-flop in the scan chain; if the number of zeroes is  $2N-2$ , then the stuck-at-0 fault is located at the input of the  $(N-2)$ -th flip-flop in the scan chain; if the number of zeroes is  $N+1$ , then the stuck-at-0 fault is located at the input of the first flip-flop in the scan chain.

(73) According to some embodiments, if the number of ones is larger than the number of zeroes, then there is a stuck-at-1 fault and its location can be determined by initializing the scan chain to all zeroes and then implementing the method discussed following FIG. 16.

(74) FIG. 18 is a logic table of a circuit with 7 flip-flops under hold faults in accordance with some embodiments. A hold violation, or a hold fault, happens when a certain flip-flop cannot hold data for a long enough period of time (e.g., because of a delayed clock signal). Effectively, a single flip-flop hold violation is equivalent to a scan chain of one bit shorter as illustrated in FIG. 21 below. In order to detect a hold violation, the entire flip-flop scan chain of length  $N$  is initialized to all zeroes and then the test run for  $2N$  cycles. If the number of ones is smaller than the number of zeroes observed on the last flip-flop, then there is a hold fault (or a setup fault as illustrated in FIG. 19) in the flip-flop scan chain. In the example illustrated in Table 180, the flip-flop scan chain has 7 flip-flops ( $N=7$ ). After 14 ( $2N$ ) clock cycles, six ones and 8 zeroes are observed on the last (7th) flip-flop. Because the number (6) of ones is smaller than the number (8) of zeroes, a possible hold fault is detected in the flip-flop chain.

(75) FIG. 19 is a logic table of a circuit with 7 flip-flops under setup faults in accordance with some embodiments. A setup violation, or a setup fault, happens when the data in the flip-flop arrives earlier than it is supposed to. Effectively, a single flip-flop setup violation is equivalent to a scan chain of one bit longer as illustrated in FIG. 22 below. Using a similar method to that discussed above for FIG. 18, the entire flip-flop scan chain is initialized to zeroes, after  $2N$  clock cycles, if the number of ones is smaller than the number of zeroes, then there is either a setup fault or a hold fault in the scan chain. In the example illustrated in Table 190, the flip-flop scan chain has 7 flip-flops ( $N=7$ ). After 14 ( $2N$ ) clock cycles, six ones and 8 zeroes are observed on the last (7th) flip-flop. Because the number (6) of ones is smaller than the number (8) of zeroes, a possible setup fault is detected in the flip-flop chain. According to some embodiments, the methods illustrated in FIG. 18 and FIG. 19 produce the same results for both hold and setup faults, so additional steps are implemented to differentiate setup fault and hold fault after the number of ones is determined to be smaller than the number of zeroes after  $2N$  clock cycles on the last flip-flop.

(76) According to some embodiments, a ring counter is a type of counter composed of a type of circular shift register. The output of the last shift register is fed to the input of the first register. A Johnson counter is a ring counter with an inversion. The interconnect segments illustrated in FIGS. 12-17 are all Johnson counters because the QB ( $Q$ -bar, the inversion of the  $Q$  output) is fed to the input of the first flip-flop.

(77) According to some embodiments, the Johnson counter is implemented to diagnose setup and hold faults. According to some embodiments, built-in self-test (BIST) based solutions are implemented to meet scan out timing and high speed scan shift clock specifications.

(78) FIG. 20 is a schematic diagram of a fault-free on-chip scan-chain with 7 flip-flops and its corresponding logic waveforms in accordance with some embodiments. According to some embodiments, seven flip-flops 2001 through 2007 are implemented in the flip-flop scan chain, and each flip-flop has a D input (e.g., 2001D), a Q output (e.g., 2001Q), a clock (e.g., 2001CLK), and a reset (e.g., 2001CLR). In the case of the last flip-flop, there is an additional QB ( $Q$ -bar, the

inversion of Q) signal for implementation of Johnson Counter. A signal pulse generator unit **2010** generates clock signals for all flip-flops in the flip-flop scan chain, a line **200** connects the single pulse generator unit **2010** with the first flip-flop **2001**, and connects each flip-flop with its successor (except the last one). Signal **2021** is the clock signal and signal **2022** is the corresponding shift chain. Signal **2023** is the initial pulse signal generated by the single pulse generator unit **2010**. Signals **2024**, **2025**, **2026**, **2027**, **2028**, **2029** and **2030** are the corresponding pulse signals shifted along the flip-flop scan chain path. FIG. **20** is an illustration of a fault-free flip-flop scan chain in which there is no fault and there is one and only one flip-flop holding a value of one in any clock cycle.

(79) FIG. **21** is a schematic diagram of an on-chip scan-chain having a hold violation with 7 flip-flops and its corresponding logic waveforms in accordance with some embodiments. According to some embodiments, FIG. **21** illustrates a similar configuration to that shown in FIG. **20**, except that there is a hold fault at the third flip-flop in FIG. **21**. As discussed above, a scan chain with a hold fault is equivalent to a scan chain of one bit shorter. Similar to the description of FIG. **20**, signal **2121** is the clock cycle signal and the signal **2122** is the shift signal. The signals **2123** through **2130** are the signals observed on the flip-flops **2101** through **2107**. The signal **2131** is a logic XOR of signals **2123** through **2130**. Between the signal **2126** and the signal **2127**, there is an overlap. Accordingly, the XOR signal **2131** produces a pulse at the corresponding location and the shift counter is frozen on this signal. As a result, the value of the shift counter identifies the location of the flip-flop (i.e., the third flip-flop) with the hold fault. According to some embodiments, long flip-flop scan chains can be divided into shorter chains with one flip-flop overlap to reduce XOR tree timing impact.

(80) FIG. **22** is a schematic diagram of an on-chip scan-chain having a setup violation with 7 flip-flops and its corresponding logic waveforms in accordance with some embodiments. According to some embodiments, FIG. **22** illustrates a similar configuration as FIG. **20** except that there is a setup fault at the fourth flip-flop. As discussed above, a scan chain with a setup fault is equivalent to a scan chain of one bit longer. Similar to the discussion in FIG. **20**, signal **2221** is the clock cycle signal and the signal **2222** is the shift signal. The signals **2223** through **2230** are the signals observed on the flip-flops **2201** through **2207**. The signal **2231** is a logic OR of signals **2223** through **2230**. Between the signal **2226** and the signal **2227**, the OR signal **2231** produces a pulse at the corresponding location and the shift counter is frozen on this signal. As a result, the value of the shift counter identifies the location of the flip-flop (i.e., the third flip-flop) with the setup fault. According to some embodiments, similar to the discussion in FIG. **21**, long flip-flop scan chains can be divided into shorter chains with one flip-flop overlap to reduce OR tree timing impact.

(81) FIG. **23** is a flowchart illustrating the method for deterministic circular built-in self-test in accordance with some embodiments. According to some embodiments, the flow-chart in FIG. **23** summarizes the discussion of the method above. According to some embodiments, the method for deterministic circular built-in self-test is implemented on the circuit structure illustrated in FIG. **11**.

(82) According to some embodiments, at the step **2301**, the deterministic circular built-in self-test circuit **11100** in FIG. **11** is switched to pass/fail mode by the control logic unit **11034**. At step **2302**, the control logic unit **11034** selects the interconnect segment under test through the controlling of multiplexers **11102B** through **11202B**. Once an interconnect segment is selected, for example the interconnect segment **11100**, at step **2303**, the deterministic circular self-test is run by initializing all flip-flops in the scan chain to zeroes. Then ones are shifted in consecutively for  $2N$  clock cycles, where  $N$  is the number of flip-flops in the scan chain of the interconnect segment. At step **2304**, a comparison is conducted between the number of ones and number of zeroes observed on the last flip-flop to determine whether the test result is a pass or fail. At the step **2305**, if the number of ones and zeroes are equal, then no fault is detected and the selected interconnected segment is a fault free circuit. If the numbers of ones and zeroes are not equal, at the step **2306**, the circuit **11100** is switched to diagnosis mode and a determination of stuck-at-1 fault or stuck-at-0 fault is



conducted. At step **2307**, if the number of ones is larger than the number of zeroes, then there is a stuck-at-1 fault in the path of the selected interconnect segment. At step **2308**, the location of the stuck-at-1 fault is determined. At step **2309**, if the number of zeroes is equal to  $2N$ , then there is a stuck-at-0 fault in the scan chain of the selected interconnect segment. At step **2310**, the location of the stuck-at-0 fault is determined. At step **2309**, if the number of ones is smaller than the number of zeroes, then there is a setup or hold fault. Then at step **2311**, the method determines whether there is a setup fault or a hold fault in the scan chain. At step **2311**, the scan chain is initialized to ones, and zeroes are shifted in consecutively for  $2N$  clock cycles, where  $N$  is the number of flip-flops in the scan chain of the interconnect segment. A comparison is conducted between the number of ones and number of zeroes observed on the last flip-flop. The diagnosis unit **1111** is activated to determine whether there is a setup fault or a hold fault according to the methods shown in FIG. **21** and FIG. **22**. At step **2312**, by using the OR gate **11211A**, the non-zero output signal on the OR gate **11211A** produces the location of a setup fault; at step **2313**, by using the XOR gate **11211B**, the non-zero output signal on the XOR gate **11211B** produces the location of a hold fault. According to some embodiments, the above steps are repeated for each of the interconnect segments in the circuit **1100** in FIG. **11** to determine the types of faults in each of the interconnect segment and the location of each fault.

(83) Various embodiments using the concepts provided herein can use clock synchronization with a single clock speed to ensure shift testing without requiring complex synchronization of two clocks or at-speed transition generation. This method allows use of a single pass flow for both DC and AC testing. The method can provide testing of actual functional inter-die connections (i.e., connections that are used during operations other than scan chain testing) as part of the scan chain shift test. Embodiments of this disclosure are suitable for designs with large or small numbers of interconnects. Although examples are described above using 3DICs with hybrid bonding, the architecture and methods described herein can be applied to any 3DIC and to any 2.5D IC (with an interposer).

(84) In some embodiments, a device comprises: a first die having disposed thereon a first plurality of latches wherein ones of the first plurality of latches are operatively connected to an adjacent one of the first plurality of latches; and a second die having disposed thereon a second plurality of latches wherein ones of the second plurality of latches are operatively connected to an adjacent one of the second plurality of latches. Each latch of the first plurality of latches on said first die corresponds to a latch in the second plurality of latches on said second die. Each set of corresponding latches are operatively connected. A scan path comprises a closed loop comprising each of said first and second plurality of latches. One of the second plurality of latches is operatively connected to another one of the second plurality of latches via an inverter.

(85) In some embodiments, a device comprises a first die and a second die with interconnections between the first die and the second die. Each of the first and second dies comprises: a plurality of latches, including a respective latch corresponding to each one of the interconnections; and a plurality of multiplexers. Each multiplexer is connected to a respective one of the plurality of latches and a respective functional path. Respective ones of the plurality of multiplexers in the first die are connected to a subset of latches within the plurality of latches in one of the first die and the second die. The subset of latches are non-adjacent from each other among the plurality of latches. A scan path comprises a closed loop comprising each of the plurality of latches in the first and second dies.

(86) In some embodiments, a device comprises a first die and a second die. At least one of the first die and second die includes level shifters and interconnections between the first die and the second die. Each of the first and second dies comprises: a plurality of latches, including a respective latch corresponding to each one of the interconnections, and a plurality of multiplexers. Each multiplexer is connected to a respective one of the plurality of latches and a respective functional path and is arranged for receiving and selecting one of a scan test pattern or a signal from the functional path

for outputting during a scan chain test of the first die and second die. The plurality of latches in the first die includes a first latch without a connection to a multiplexer. A scan path comprises a closed loop comprising each of the plurality of latches in the first and second dies.

(87) The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

## Claims

1. A device comprising: a first die having disposed thereon a first plurality of latches; and a second die having disposed thereon a second plurality of latches, wherein: each latch of the first plurality of latches on said first die operatively couple to a respective latch in the second plurality of latches on said second die, a scan path comprising each of said first and second plurality of latches, wherein the scan path goes consecutively through a first latch in the first plurality of latches in the first die, a second latch in the second plurality of latches in the second die, a third latch in the second plurality of latches in the second die, and a fourth latch in the first plurality of latches in the first die.
2. The device of claim 1, wherein the second die further comprises a clock and control unit.
3. The device of claim 1, wherein the second die further comprises a phase lock loop unit.
4. The device of claim 1, wherein the second die further comprises an analyzer unit.
5. The device of claim 1, wherein: the first latch and the fourth latch are adjacent to each other in the first die, and the second latch and the third latch are adjacent to each other in the second die.
6. The device of claim 1, further comprising a plurality of level shifters for changing an amplitude of signals transmitted between the first die and the second die.
7. The device of claim 1, wherein the first die has a first clock and the second die has a second clock, and the first clock and second clock are synchronized with each other.
8. The device of claim 1, wherein the first plurality of latches in the first die and the second plurality of latches in the second die are not of the same type.
9. The device of claim 1, wherein the first plurality of latches includes a subset of latches, each latch in the subset transmitting a signal from the first die to a corresponding latch in the second die.
10. The device of claim 1, wherein: the first plurality of latches includes a first number of latches; the second plurality of latches includes a second number of latches; and the first and second numbers are different from each other.
11. A device, comprising: a first die; and a second die, wherein each of the first and second dies comprises: a plurality of latches; and a plurality of multiplexers, each multiplexer connected to a respective one of the plurality of latches, wherein respective ones of the plurality of multiplexers in the first die are connected to a subset of latches within the plurality of latches in one of the first die and the second die, and wherein a scan path comprising each of said plurality of latches in the first and second dies, and wherein the scan path goes consecutively through a first latch in the first die, a second latch in the second die, a third latch in the second die, and a fourth latch in the first die.
12. The device of claim 11, wherein: the plurality of latches in the first die and the second die include D flip-flops, the first latch and the fourth latch are adjacent to each other in the first die, and the second latch and the third latch are adjacent to each other in the second die.
13. The device of claim 11, wherein respective ones of the plurality of multiplexers are connected to alternating ones of the plurality of latches in the first die.

14. The device of claim 11, wherein a respective one of the plurality of multiplexers receives one input from a corresponding one of the plurality of latches in the first die, receives another input from a functional path in the first die, and transmits an output to a corresponding one of the plurality of latches in the second die.

15. The device of claim 11, wherein one of the plurality of latches in the first die is connected to output a signal to one of the plurality of multiplexers in the second die and receives an input signal from an adjacent latch in the plurality of latches within the first die, wherein the adjacent latch does not output a signal to any of the plurality of multiplexers in the second die.

16. The device of claim 11, wherein the plurality of latches includes a subset of the plurality of latches, each latch in the subset transmitting a signal from one of the first and second dies to a corresponding latch in the other of the first and second dies, and each latch in the subset is connected to a first input of a corresponding one of the plurality of multiplexers.

17. A device, comprising: a first die; and a second die, at least one of the first die and second die including interconnections between the first die and the second die, wherein each of the first and second dies comprises a plurality of latches, including a respective latch corresponding to each one of the interconnections, a scan path comprising each of said plurality of latches in the first and second dies, and wherein the scan path goes consecutively through a first latch in the first die, a second latch in the second die, a third latch in the second die, and a fourth latch in the first die.

18. The device of claim 17, wherein the plurality of latches are connected in a chain having a first scan chain output, and an output of at least one latch other than a last one of the plurality of latches is transmitted to a second scan chain output.

19. The device of claim 17, wherein each of the first and second dies further comprises: a plurality of multiplexers, each multiplexer connected to a respective one of the plurality of latches, wherein respective ones of the plurality of multiplexers in the first die are connected to a subset of latches within the plurality of latches in one of the first die and the second die.

20. The device of claim 19, wherein two or more of the plurality of multiplexers have taps for outputting signals from the device.

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