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Inventor(s)

O'Connell; Cormac Michael

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### USING BUILT-IN SELF TEST OR TEST RESULTS TO IDENTIFY WEAK MEMORY BITS AND ENABLE ASSIST CIRCUITS WHEN NECESSARY

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#### Abstract

A semiconductor device and a method of operating the semiconductor device and circuit are disclosed. In one aspect, the semiconductor device includes a memory array comprising a first memory cell and a second memory cell. The second memory cell has an operational characteristic different than that of the first memory cell. The semiconductor device includes a first write circuit configured to write first data to the first memory cell. The semiconductor device includes a second write circuit configured to write second data to the second memory cell, wherein the second write circuit is selectively configured to compensate for the operational characteristic of the second memory cell.

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**Inventors:** O'Connell; Cormac Michael (Hsinchu, TW)

**Applicant:** Taiwan Semiconductor Manufacturing Company Ltd. (Hsinchu, TW)

**Family ID:** 1000007700947

**Assignee:** Taiwan Semiconductor Manufacturing Company Ltd. (Hsinchu, TW)

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# Background/Summary

## BACKGROUND

[0001] The semiconductor industry has experienced rapid growth due to continuous improvements in the integration density of a variety of electronic components (e.g., transistors, diodes, resistors, capacitors, etc.). For the most part, this improvement in integration density has come from repeated reductions in minimum feature size, which allows more components to be integrated into a given area.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, 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.

[0003] FIG. 1 illustrates a schematic block diagram of a memory array that implements selectively activated write assist circuits based on memory test results, in accordance with some embodiments.

[0004] FIG. 2 illustrates a schematic block diagram of another memory array that implements selectively activated write assist circuits according to a specified column address, in accordance with some embodiments.

[0005] FIG. 3 illustrates a schematic block diagram of another memory array that implements selectively activated write assist circuits according to a specified row address, in accordance with some embodiments.

[0006] FIG. 4 illustrates a schematic block diagram of another memory array that implements selectively activated write assist circuits according to a specified row address and a specified column address, in accordance with some embodiments.

[0007] FIG. 5 illustrates a flowchart of an example method to operate the disclosed memory arrays including selectively activated write assist circuits described herein, in accordance with some embodiments of the present disclosure.

### DETAILED DESCRIPTION

[0008] The following disclosure provides many different embodiments, or examples, for implementing different features of the provided 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.

[0009] Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” “top,” “bottom” 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.

[0010] Design specifications provide constraints on various operational characteristics for operating memory circuits, including word line pulse width and memory write voltage, among others. As design specifications begin to utilize higher sigma values, such as six-sigma values, for smaller and denser memory circuits, these design constraints begin to affect the aggregate write performance of the memory. Even when implementing such design constraints, defects in memory cells are still possible. One such defect includes a “weak” memory cell, which are memory cells that have difficulty holding or maintaining a desired state during write operations due to various factors such as process variations, degradation over time, or other environmental conditions.

[0011] These design constraints require activating write assist circuits for the entire memory array even when only a small number of memory cells are identified as weak memory cells. Various testing approaches can be used to identify defects in manufactured memory devices, including built-in self-test (BIST) circuits or external testing circuits. However, there is a significant downside to this approach for memory device design and manufacture. The use of high sigma values means that the resulting designs are very conservative in terms of power consumption and performance, resulting in wasted active power (e.g., write word line pulse width much wider to compensate for potentially defective cells) and extended cycle time, which can be significant for some memory operations. Additionally, write assist circuits are added to every access even when they may not actually be required for non-defective memory cells, further increasing the overall power consumption of the device.

[0012] To address these and other issues, the devices, circuits, and methods described herein provide techniques for selectively activating write assist circuits only when needed to compensate for a defective memory cell. Advantages of such techniques include lower active power, reduced cycle time, higher performance memory cells, and more efficient usage of the available space on the wafer to manufacture memory chips. Selectively activating write assist circuits can be implemented in various configurations, including activating a write assist upon detecting a write operation to a specified memory block, a specified memory column, a specified memory row, or combinations thereof. Various testing approaches can be utilized to identify defective memory bits (and any block, column, or row addresses thereof), including BIST techniques or external testing techniques, among others.

[0013] These techniques can improve overall device performance and power consumption by reducing the number of write assist circuits that are activate during normal operation. Active power can be reduced by disabling certain portions of the circuits when they are not needed, thereby reducing average device power consumption. Reducing this constant activate power consumption by allowing write assist circuitry to be selectively activated enables more relaxed design constraints (e.g.,  $5.5\sigma$ ), leading to improved timing and reduced active power.

[0014] FIG. 1 illustrates a schematic block diagram of a memory circuit **100** that implements selectively activated write assist circuits **106A-106N** based on memory test results, in accordance with some embodiments. As shown, the memory circuit **100** includes an array of memory cells **110** (sometimes referred to herein as “bit cells,”) which may store digital data. Each of the components shown in the memory circuit **100** may receive power from one or more voltage sources. The memory circuit **100** may include one or more logic gates and sub-circuits, each of which may be constructed from one or more logic gates. Logic gates are electronic devices that perform logical operations on one or more input signals to produce a single output signal.

[0015] Various embodiments of the circuits and logic gates that implement the memory circuit **100** may include various transistors. The transistors described herein may have a certain type (n-type or p-type), but embodiments are not limited thereto. The transistors can be any suitable type of transistor including, but not limited to, metal oxide semiconductor field effect transistors (MOSFET), complementary metal oxide semiconductors (CMOS) transistors, P-channel metal-oxide semiconductors (PMOS), N-channel metal-oxide semiconductors (NMOS), bipolar junction

transistors (BJT), high voltage transistors, high frequency transistors, P-channel and/or N-channel field effect transistors (PFETs/NFETs), FinFETs, planar MOS transistors with raised source/drains, nanosheet FETs, nanowire FETs, or the like.

[0016] As shown, the memory circuit **100** includes a number of memory blocks **101A-101N** (sometimes generally referred to as memory block(s) **101**), each of which include various memory cells **110**. The memory cell **110** can be any type of memory device capable of storing at least one bit of memory data, including but not limited to a static random access memory (SRAM) cell or a dynamic random access memory (DRAM) cell, among others. The memory cell **110** may, due to the nature of the manufacturing process used to create the memory cell, be manufactured with one or more defects. Such defects may cause the memory cell to be a “weak memory” cell, which have difficulty holding or maintaining a desired (e.g., written) state during write operations due to various factors such as process variations, degradation over time, or other environmental conditions. Memory cells **110** that have such defects may be referred to herein as a weak memory cell **112**.

[0017] As shown, each memory block **101** can include one or more columns of memory cells **110**, which are arranged in corresponding rows. Each column of a memory block **101** may include one or more weak memory cells **112**. In this example, each memory block **101** is shown as including two columns of memory cells **110** (or weak memory cells **112**). However, it should be understood that each block may include any number of columns, designated in this example by the identifier C (e.g., the total number of columns in the block). Each column in the memory block **101** can be addressed by a corresponding set of bit lines, such as the bit line BLO and its corresponding logical inverse bit line. If multiple columns are included in the memory block **101**, the memory block **101** can include a corresponding multiplexer circuit.

[0018] In this example, the memory block **101A** includes two memory columns, and therefore includes a 1:2 multiplexer circuit **108A** (sometimes generally referred to as a multiplexer circuit **108**), which switches between the bit lines BLO and the bit lines BLC based on an input column address (shown as Col ADDR) signal received from a memory control circuit. In this example, each memory block **101** includes two columns of memory cells **110**, and therefore the multiplexer circuits **108** (e.g., the multiplexer circuits **108A-108N**) are each 1:2 multiplexer circuits. The multiplexer circuits **108** receive corresponding bit line signals from a write driver circuit **104** of the corresponding memory block **101** (e.g., one of the write driver circuits **104A-104N**) and provide respective output bit line signals to the selected column. The multiplexer circuit **108** can select between each column based on a column address (shown here as Col ADDR), which may be received from a memory control circuit.

[0019] As shown, the memory cells **110** (and weak memory cells **112**) are arranged in one or more rows, each of which may be selected using a corresponding row address (shown here as a Row ADDR, spanning from 0 to R rows as the Row 0 ADDR to the Row R ADDR). Each row address can be provided by a memory control circuit for the memory blocks **101** of the memory, which can select a corresponding row and column the column address and row address signals. The memory control circuit may include any type of control circuit that provides signals to coordinate read or write operations via the circuitry of the memory circuit **100**. For example, the memory control circuit may provide a write enable signal (shown here as “Write”), which activates various components of the write enable driver. For example, the write enable signal may activate a corresponding write driver circuit **104**, write assist circuit **106**, and/or write assist enable circuit **102**, of the memory block **101**.

[0020] As shown, each memory block **101** is shown as including one of the write driver circuits **104A-104N** (sometimes generally referred to as a write driver circuit **104**). Each write driver circuit **104** can generate one or more signals to writing input data (shown here as “Data 0” for the first memory block **101A**, and “Data N” for the N-th memory block **101N**) to selected memory cells **110**. To do so, a write driver circuit **104** can drive the bit lines corresponding to the selected

memory cell **110** (e.g., the bit lines BLC and !BLC, where the ! designator indicates the logical inverse of the corresponding signal) for a write operation to store the input data (e.g., Data 0) within an addressed memory cell **110** (or weak memory cell **112**). In some implementations, the write driver **104** includes a level shifter circuit, which can adjust voltage levels of the output signals to align them with voltage requirements of the memory cell **110** to be written. The write driver circuit **104** can include write enable logic, which causes the write driver circuit **104** to remain deactivated until a write enable signal is received (shown here as the “Write” signal).

[0021] As shown, the write driver circuits **104A-104N** are integrated with corresponding write assist circuits **106A-106N** (sometimes generally referred to as “write assist circuit(s) **106**”). A write assist circuit **106** can be used to compensate for the defective weak memory cells **112**, which may include different operational characteristics than the memory cells **110**. For example, the weak memory cells **112** may require a higher voltage across its corresponding storage element to effectively write data to the weak memory cell **112**, as compared to the memory cells **110**. Each write assist circuit **106** may therefore selectively increase the voltage provided by its corresponding write driver circuit **104**, when the write assist circuit **106** is activated. The write assist circuit **106** may apply negative voltage write assist and positive voltage write assist to increase the voltage difference across the weak memory cell **112**, when selected for a write operation.

[0022] A negative voltage write assist operation involves applying a temporary negative voltage to at least one of the bit lines during the write operation (e.g., reducing what would otherwise be a ground voltage), thereby effectively increasing the total voltage potential across the weak memory cell **112** to compensate for its operational characteristics. A positive voltage write assist operation includes boosting the positive voltage to at least one bit line during the write operation, thereby increasing the voltage potential across the weak memory cell **112**. To implement these operations, the write assist circuit **106** may include one or more boost circuits, charge pump circuits, or other circuits to raise or lower the voltage of one or more bit lines (e.g., the bit line BLC, the bit line !BLC, etc.).

[0023] Each of the memory blocks **101A-101N** is shown as including corresponding write assist enable circuits **102A-102N** (sometimes generally referred to as write assist enable circuit(s) **102**). The write assist enable circuit **102** can include logic (e.g., transistors, logic gates, latches, flip-flops, registers, etc.) that cause the write assist circuits **106** to be selectively activated or deactivated according to an input signal from the write assist configuration circuit **120**. For example, the write assist enable circuit **102** can produce a signal that selectively activates the write assist circuit **106** for a corresponding memory block **101** when the write assist enable circuit **102** receives a programming signal from the write assist configuration circuit **120** that indicates the memory block **101** includes a defective memory cell (shown here as the weak memory cell **112** in the second column).

[0024] In some implementations, the write assist enable circuit **102** may be part of a shift register (e.g., a chain of flip flops). For example, the write assist enable circuit **102** of each memory block may provide an output to the next write assist enable circuit **102** of the following memory block **101** in the memory array. Configuration data can be iteratively shifted through each of the write assist enable circuits **102** in the memory circuit **100** to configure the circuit. The configuration data can indicate which write assist enable circuits **102** are to enable corresponding write assist circuits **106** of the memory circuit **100** during a write operation, and which write assist circuits **106** are to remain deactivated during the write operation. In this example, the write assist enable circuit **102A** can be configured via configuration data to activate the write assist circuit **106A** because the memory block **101A** includes the weak memory cell **112**, while the write assist enable circuit **102N** may receive to deactivate the write assist circuit **106N** because the memory block **101N** is shown as not including any defective memory cells.

[0025] The configuration data for the write assist enable circuits **102** can be stored in the write assist configuration circuit **120**, which may include any suitable programmable storage device for

configuring the memory circuit **100**. In some implementations, the configuration data stored in the write assist configuration circuit **120** may be provided to (e.g., shifted through) each of the write assist enable circuits **102** after reset, power-on, or another predetermined event. For example, upon receiving a resent signal, the write assist enable circuits **102** of the memory circuit **100** can iteratively shift through configuration data until all of the write assist enable circuits **102** are configured.

[0026] The write assist configuration circuit **120** may include any type of storage device that is suitable for storing the configuration data for each of the write assist enable circuits **102**. In this example, the configuration data indicates whether the write assist circuit **106** for a particular memory block **101** is to be activated in the event of a write operation to a memory cell **110** included in that memory block **101**. Additional implementations of the configuration data that may be stored in the write assist configuration circuit **120** are described in connection with FIGS. 2, 3, and 4. The write assist configuration circuit **120** may include any suitable type of programmable memory, including eFuse memory, flash memory, or the like. The write assist configuration circuit **120** may include logic to configure each of the write assist enable circuits **102**, for example, by iteratively shifting data through each of the write assist enable circuits **102** until all write assist enable circuits **102** are configured.

[0027] The write assist configuration circuit **120** may include or may be in communication with one or more testing circuits, such as a BIST circuit or a built-in self-test and repair (BISTR) circuit that operates to test the operational characteristics of the memory circuit **100**. In some implementations, the write assist configuration circuit **120** may be in communication with an external testing circuit that performs similar operations as a BIST or BISTR circuit. Results from such testing circuits may be stored in the programmable memory of the write assist configuration circuit **120** as the configuration data for the write assist enable circuits **102**. The testing circuits can include test pattern generators, response analyzers, and control logic that enables the testing circuits to execute a series of the memory array to identify any memory cells that are defective (e.g., the weak memory cell **112**).

[0028] The testing process may be performed as part of the manufacturing process to identify the weak memory cells **112**. Corresponding configuration data can then be generated that identifies which memory cells are defective or have normal operating characteristics. In some implementations, and as described in further detail in connection with FIGS. 2, 3, and 4, the configuration data may include row addresses and/or column addresses of identified weak memory cells **112** in the memory circuit **100**. In some implementations, an indication of whether each memory block **101** includes at least one weak memory cell **112**. In the example shown in FIG. 1, such indications may be provided to configure each write assist enable circuit **102** to selectively enable the write assist circuits **106** to write to any identified weak memory cells **112**.

[0029] In some implementations, the write assist configuration circuit **120** may dynamically update the configuration data stored in its programmable memory. For example, the write assist configuration circuit **120** may utilize BIST or BISTR circuits to periodically test the memory cells **110** of the memory circuit **100** to determine whether any memory cells **110** have become weak memory cells **112**. Upon identifying any additional weak memory cells **112**, the write assist configuration circuit **120** can update the configuration data with identifier(s) of a memory block **101**, column address, and/or row address of the weak memory cell **112**, which can be used to configure the write assist enable circuits **102** as described herein. The write assist configuration circuit **120** provides the configuration signal to the write assist enable circuits **102** as the “WA shift” signal, which can be propagated through each of the write assist enable circuits **102** via at least one shift register included in the write assist enable circuits **102**. Each storage flip-flop in the shift register can be included in a respective write assist enable circuit **102** and can include an indication identifying whether the corresponding memory block **101** includes at least one weak memory cell **112**. Additional implementations for selectively activating write assist circuits are

described in connection with FIGS. 2, 3, and 4.

[0030] Referring to FIG. 2, illustrated is a schematic block diagram of memory circuit **200** that implements selectively activated write assist circuits (e.g., the write assist circuits **206A-206N**, sometimes generally referred to as the write assist circuit(s) **206**) according to a specified column address, in accordance with some embodiments. As shown, the memory circuit **200** includes an array of memory cells **210** which may store digital data and may include any of the structure and functionality of the memory cells **110** of FIG. 1. Each of the components shown in the memory circuit **200** may receive power from one or more voltage sources. The memory circuit **200** may include one or more logic gates and sub-circuits, each of which may be constructed from one or more logic gates. Logic gates are electronic devices that perform logical operations on one or more input signals to produce a single output signal.

[0031] Various embodiments of the circuits and logic gates that implement the memory circuit **200** may include various transistors. The transistors described herein may have a certain type (n-type or p-type), but embodiments are not limited thereto. The transistors can be any suitable type of transistor including, but not limited to, MOSFET, CMOS transistors, PMOS, NMOS, BJT, high voltage transistors, high frequency transistors, PFETs/NFETs, FinFETs, planar MOS transistors with raised source/drains, nanosheet FETs, nanowire FETs, or the like.

[0032] As shown, the memory circuit **200** includes memory blocks **201A-201N** (sometimes generally referred to as memory block(s) **201**), each of which include memory cells **210**. Each of the memory blocks **201** and memory cells **210** may be similar to, and include any of the structure and functionality of, the memory blocks **101** and memory cells **110** described in connection with FIG. 1, respectively. As described herein, a memory cell **210** may, due to the nature of the manufacturing process used to create the memory cell, be manufactured with one or more defects. Such defects may cause the memory cell to be a “weak memory cell,” which have difficulty holding or maintaining a desired (e.g., written) state during write operations due to various factors such as process variations, degradation over time, or other environmental conditions. Memory cells **210** that have such defects may be referred to herein as a weak memory cell **212**.

[0033] As described herein, if multiple columns of memory cells **210** (or weak memory cells **212**) are included in a memory block **201**, the memory block **201** can include a corresponding multiplexer circuit. In this example, the memory blocks **201A-201N** each include two memory columns, and the memory blocks **201A-201N** include 1:2 multiplexer circuits **208A-208N** (sometimes generally referred to as multiplexer circuit(s) **208**). The multiplexor circuits **208** may be similar to, and include any of the structure and functionality of, the multiplexor circuits **108** of FIG. 1. The multiplexer circuit **208** can select between each column in a memory block **201** based on a column address (shown here as Col ADDR), which may be received from a memory control circuit.

[0034] As shown, the memory cells **210** (and weak memory cells **212**) are arranged in one or more rows, each of which may be selected using a corresponding row address (shown here as a Row ADDR, spanning from 0 to R rows as the Row 0 ADDR to the Row R ADDR). Each row address can be provided by a memory control circuit for the memory blocks **201** of the memory, which can select a corresponding row and column the column address and row address signals. The memory control circuit may include any type of control circuit that provides signals to coordinate read or write operations via the circuitry of the memory circuit **200**. For example, the memory control circuit may provide a write enable signal (shown here as “Write”), which activates various components of the write enable driver. For example, the write enable signal may activate a corresponding write driver circuit **204**, write assist circuit **206**, and/or write assist enable circuit **202**, of the memory block **201**.

[0035] Each memory block **201** is shown as including one of the write driver circuits **204A-204N** (sometimes generally referred to as the write driver circuit(s) **204**). The write driver circuits **204** may be similar to, and include any of the structure and functionality of, the write driver circuits **104**

of FIG. 1. For example, as described herein, the write driver circuits **204** can drive the bit lines corresponding to an addressed memory cell **210** (e.g., the bit lines BLC and !BLC) for a write operation to store the input data (e.g., Data 0) within the addressed memory cell **210** (or weak memory cell **212**). As shown, the write driver circuits **204A-204N** are integrated with corresponding write assist circuits **206A-206N** (sometimes generally referred to as “write assist circuit(s) **206**”), which may include any of the structure or functionality of the write assist circuits **106** of FIG. 1. For example, the write assist circuits **206** may perform negative voltage write assist or positive voltage write assist operations to increase the voltage across a selected weak memory cell **212**.

[0036] Each of the memory blocks **201A-201N** is shown as including corresponding write assist enable circuits **202A-202N** (sometimes generally referred to as write assist enable circuit(s) **202**). The write assist enable circuit **202** can include logic (e.g., transistors, logic gates, latches, flip-flops, registers, etc.) that cause the write assist circuits **206** to be selectively activated or deactivated according to an input signal from the write assist configuration circuit **220**.

[0037] In the example shown in FIG. 2, the write assist enable circuits **202** can perform a match operation between one or more stored column addresses and an input column address for a write operation (e.g., a Col ADDR). The stored column addresses to which the input column address is compared may be columns of the corresponding memory block **201** that have been determined to include at least one defective memory cell **212**. The comparison may be performed via one or more logic gates or comparison circuits of the corresponding write assist enable circuit **202**. Upon detecting a match between the input column address and the column address for a column that includes a weak memory cell **212**, the write assist enable circuit **202** can selectively activate the write assist circuit **206** to compensate for the operational characteristics of the weak memory cell **212**. In this example, the right-hand column of the memory block **201A** includes a weak memory cell **212**.

[0038] When a write operation addresses the right-most column of the memory block **201A** to perform a write operation, the write assist enable circuit **206A** detects a match between the input column address and the address of the right-most column and produces a signal to activate the write assist circuit **206A**. The write assist circuit **206A** can then produce an increased voltage potential across the bit lines BLC and !BLC (e.g., relative to a normal write operation). This increased voltage potential is provided via the second output **214** of the multiplexer circuit **208A**. The increased voltage enables a successful write operation at the weak memory cell **212**. In this example, the write assist enable circuit **202** selectively activates the write assist circuit **206** only when a corresponding column of the memory block **201** that includes a weak memory cell is being written to. The write assist circuit **206** is disabled, and normal voltage is applied, when a column of the same memory block **201** that does not include a weak memory cell **212** is written to.

[0039] As described herein, the configuration data for the write assist enable circuits **202** can be stored in the write assist configuration circuit **220**, which may be similar to and include any of the structure and functionality of the write assist configuration circuit **120** of FIG. 1. In this example, the configuration data that is provided to (e.g., shifted through) one or more registers of the write assist enable circuits **202A-202N** can include column addresses of each of any columns in the memory blocks **201A-201N** that are determined (e.g., via the testing processes described herein) to include at least one weak memory cell **212**. The configuration data may be provided to the write assist enable circuits **202** in response to a reset, power-on, or a configuration signal. Additional implementations for selectively activating write assist circuits based on row addresses (e.g., the row addresses Row 0 ADDR through Row R ADDR) are described in connection with FIGS. 3 and 4.

[0040] Referring to FIG. 3, illustrated is a schematic block diagram of a memory circuit **300** that implements selectively activated write assist circuits (e.g., the write assist circuits **306A-306N**) according to specified row addresses (e.g., the row addresses Row 0 ADDR through Row R ADDR), in accordance with some embodiments. The memory circuit **300** may be similar to, and



include any of the structure and functionality of, the memory circuit **200** of FIG. **2** or the memory circuit **100** of FIG. **1**. As shown, the memory circuit **300** includes an array of memory cells **310** which may store digital data, and may include any of the structure and functionality of the memory cells **110** of FIG. **1**. Each of the components shown in the memory circuit **300** may receive power from one or more voltage sources. The memory circuit **300** may include one or more logic gates and sub-circuits, each of which may be constructed from one or more logic gates. Logic gates are electronic devices that perform logical operations on one or more input signals to produce a single output signal.

[0041] Various embodiments of the circuits and logic gates that implement the memory circuit **300** may include various transistors. The transistors described herein may have a certain type (n-type or p-type), but embodiments are not limited thereto. The transistors can be any suitable type of transistor including, but not limited to, MOSFET, CMOS transistors, PMOS, NMOS, BJT, high voltage transistors, high frequency transistors, PFETs/NFETs, FinFETs, planar MOS transistors with raised source/drains, nanosheet FETs, nanowire FETs, or the like.

[0042] As shown, the memory circuit **300** includes memory blocks **301A-301N** (sometimes generally referred to as memory block(s) **301**), each of which include memory cells **310**. Each of the memory blocks **301** and memory cells **310** may be similar to, and include any of the structure and functionality of, the memory blocks **101** and memory cells **110** described in connection with FIG. **1**, respectively. As described herein, a memory cell **310** may, due to the nature of the manufacturing process used to create the memory cell, be manufactured with one or more defects. Such defects may cause the memory cell to be a “weak memory cell,” which have difficulty holding or maintaining a desired (e.g., written) state during write operations due to various factors such as process variations, degradation over time, or other environmental conditions. Memory cells **310** that have such defects may be referred to herein as a weak memory cell **312**.

[0043] As described herein, if multiple columns of memory cells **310** (or weak memory cells **312**) are included in a memory block **301**, the memory block **301** can include a corresponding multiplexer circuit. In this example, the memory blocks **301A-301N** each include two memory columns, and the memory blocks **301A-301N** include 1:2 multiplexer circuits **308A-308N** (sometimes generally referred to as multiplexer circuit(s) **308**). The multiplexor circuits **308** may be similar to, and include any of the structure and functionality of, the multiplexor circuits **108** of FIG. **1**. The multiplexer circuit **308** can select between each column in a memory block **301** based on a column address (shown here as Col ADDR), which may be received from a memory control circuit.

[0044] As shown, the memory cells **310** (and weak memory cells **312**) are arranged in one or more rows, each of which may be selected using a corresponding row address (shown here as a Row ADDR, spanning from 0 to R rows as the Row 0 ADDR to the Row R ADDR). Each row address can be provided by a memory control circuit for the memory blocks **301** of the memory, which can select a corresponding row and column the column address and row address signals. The memory control circuit may include any type of control circuit that provides signals to coordinate read or write operations via the circuitry of the memory circuit **300**. For example, the memory control circuit may provide a write enable signal (shown here as “Write”), which activates various components of the write enable driver. For example, the write enable signal may activate a corresponding write driver circuit **304**, write assist circuit **306**, and/or write assist enable circuit **302**, of the memory block **301**.

[0045] Each memory block **301** is shown as including one of the write driver circuits **304A-304N** (sometimes generally referred to as the write driver circuit(s) **304**). The write driver circuits **304** may be similar to, and include any of the structure and functionality of, the write driver circuits **104** of FIG. **1**. For example, as described herein, the write driver circuits **304** can drive the bit lines corresponding to an addressed memory cell **310** (e.g., the bit lines BLC and !BLC) for a write operation to store the input data (e.g., Data 0) within the addressed memory cell **310** (or weak

memory cell **312**). As shown, the write driver circuits **304A-304N** are integrated with corresponding write assist circuits **306A-306N** (sometimes generally referred to as “write assist circuit(s) **306**”), which may include any of the structure or functionality of the write assist circuits **106** of FIG. **1**. For example, the write assist circuits **306** may perform negative voltage write assist or positive voltage write assist operations to increase the voltage across a selected weak memory cell **312**.

[0046] Each of the memory blocks **301A-301N** is shown as including corresponding write assist enable circuits **302A-302N** (sometimes generally referred to as write assist enable circuit(s) **302**). The write assist enable circuits **302** can include any of the structure or functionality as the write assist enable circuits **102** of FIG. **1**. The write assist enable circuit **302** can include logic (e.g., transistors, logic gates, latches, flip-flops, registers, etc.) that cause the write assist circuits **306** to be selectively activated or deactivated according to an input signal from the write assist configuration circuit **320**.

[0047] In the example shown in FIG. **3**, the write assist enable circuits **302** can enable corresponding write assist circuits **306** in response to a signal from the address match circuit **314**. For example, as described in connection with FIG. **1**, each write assist enable circuit **302** may include a register or other storage device that stores an indication of whether the memory block **301** corresponding thereto includes at least one weak memory cell **301**. As described herein, the write assist configuration circuit **320** (which may be similar to and include any of the structure and functionality of the write assist configuration circuit **120** of FIG. **1**) provides configuration data to the write assist enable circuits **302** as the “WA shift” signal, which can be propagated through each of the write assist enable circuits **302** via at least one shift register included in the write assist enable circuits **302**. Each storage flip-flop in the shift register can be included in a respective write assist enable circuit **302** and can include an indication identifying whether the corresponding memory block **301** includes at least one weak memory cell **312**.

[0048] Additionally, the write assist configuration circuit **320** can provide data to a row address match circuit **314**. The row address match circuit **314** can provide an activation signal to the write assist enable circuits **302** in response to detecting a match between an input row address of the memory circuit **300** and a stored row address that is identified as including a weak memory cell **312**. For example, in addition to providing an indication of whether each memory block **301** includes at least one weak memory cell **312**, the write assist configuration circuit **320** can additionally provide addresses of rows within which weak memory cells **312** have been detected. The row addresses can be determined, in some implementations, based on the testing techniques described herein. The write assist configuration circuit **320** can provide the detected row addresses to the row address match circuit **314**, for example, in response to a reset, a power-on, or in response to a configuration signal. The write assist configuration circuit **320** can therefore provide configuration data to both the address match circuit and the write assist enable circuit **302**.

[0049] The row address match circuit **314** can include logic gates, transistors, or any other device or circuit that can compare an input row address for a write operation and a stored row address provided by the write assist configuration circuit **320**. In some implementations, the row address match circuit **314** can include one or more storage devices, registers, or memory devices that store the row addresses provided by the write assist configuration circuit **320**. The comparison performed by the row address match circuit **314** can produce a signal that indicates whether the input row address matches a stored (or provided) row address of a row (e.g., the Row 1 ADDR in this example) that includes a weak memory cell **312**.

[0050] If the row address match circuit **314** detects a match, the row address match circuit **314** can provide an activation signal to the write assist enable circuits **302**. If, during the write operation, the write assist enable circuit **302** also has received an indication (e.g., via the WA Shift signal) that its corresponding memory block **301** includes at least one weak memory cell **312**, the write assist enable circuit **302** can activate the write assist circuit **306** integrated with the corresponding write

driver circuit **304**, to compensate for the operational characteristics of the weak memory cell **312**. In this example, if a write operation occurs to write to Row 1 (e.g., as designated by the write address) and to the memory block **301A**, the write enable assist circuit **302A** can provide a signal to activate the write assist circuit **306A** integrated with the write driver circuit **304A**, as shown. This approach selectively activates the write assist circuit **306** only when a row and a memory block **301** to which a write operation is to be performed includes at least one weak memory cell **312**. For example, as the memory block **301N** is not shown as including any weak memory cells, the write assist enable circuit **302** will not activate the write assist circuit **306**, thereby conserving power when write operations are performed to the memory block **301N**. An additional implementation in which both the row address and column address are used to selectively activate the write assist circuits is described in connection with FIG. 4.

[0051] Referring to FIG. 4, illustrated is a schematic block diagram of a memory circuit **400** that implements selectively activated write assist circuits **406A-406N** (sometimes generally referred to as the write assist circuit(s) **406**) according to a specified row address (e.g., one of the row addresses Row 0 ADDR through Row R ADDR) and a specified column address (e.g., the Col ADDR), in accordance with some embodiments. The memory circuit **400** may be similar to, and include any of the structure and functionality of, the memory circuit **300** of FIG. 3, the memory circuit **200** of FIG. 2, or the memory circuit **100** of FIG. 1. As shown, the memory circuit **400** includes an array of memory cells **410** which may store digital data, and may include any of the structure and functionality of the memory cells **110** of FIG. 1. Each of the components shown in the memory circuit **400** may receive power from one or more voltage sources. The memory circuit **400** may include one or more logic gates and sub-circuits, each of which may be constructed from one or more logic gates. Logic gates are electronic devices that perform logical operations on one or more input signals to produce a single output signal.

[0052] Various embodiments of the circuits and logic gates that implement the memory circuit **400** may include various transistors. The transistors described herein may have a certain type (n-type or p-type), but embodiments are not limited thereto. The transistors can be any suitable type of transistor including, but not limited to, MOSFET, CMOS transistors, PMOS, NMOS, BJT, high voltage transistors, high frequency transistors, PFETs/NFETs, FinFETs, planar MOS transistors with raised source/drains, nanosheet FETs, nanowire FETs, or the like.

[0053] As shown, the memory circuit **400** includes memory blocks **401A-401N** (sometimes generally referred to as memory block(s) **401**), each of which include memory cells **410**. Each of the memory blocks **401** and memory cells **410** may be similar to, and include any of the structure and functionality of, the memory blocks **101** and memory cells **110** described in connection with FIG. 1, respectively. As described herein, a memory cell **410** may, due to the nature of the manufacturing process used to create the memory cell, be manufactured with one or more defects. Such defects may cause the memory cell to be a “weak memory cell,” which have difficulty holding or maintaining a desired (e.g., written) state during write operations due to various factors such as process variations, degradation over time, or other environmental conditions. Memory cells **410** that have such defects may be referred to herein as a weak memory cell **412**.

[0054] As described herein, if multiple columns of memory cells **410** (or weak memory cells **412**) are included in a memory block **401**, the memory block **401** can include a corresponding multiplexer circuit. In this example, the memory blocks **401A-401N** each include two memory columns, and the memory blocks **401A-401N** include 1:2 multiplexer circuits **408A-408N** (sometimes generally referred to as multiplexer circuit(s) **408**). The multiplexor circuits **408** may be similar to, and include any of the structure and functionality of, the multiplexor circuits **108** of FIG. 1. The multiplexer circuit **408** can select between each column in a memory block **401** based on a column address (shown here as Col ADDR), which may be received from a memory control circuit.

[0055] As shown, the memory cells **410** (and weak memory cells **412**) are arranged in one or more

rows, each of which may be selected using a corresponding row address (shown here as a Row ADDR, spanning from 0 to R rows as the Row 0 ADDR to the Row R ADDR). Each row address can be provided by a memory control circuit for the memory blocks **401** of the memory, which can select a corresponding row and column the column address and row address signals. The memory control circuit may include any type of control circuit that provides signals to coordinate read or write operations via the circuitry of the memory circuit **400**. For example, the memory control circuit may provide a write enable signal (shown here as “Write”), which activates various components of the write enable driver **404**. For example, the write enable signal may activate a corresponding write driver circuit **404**, write assist circuit **406**, and/or write assist enable circuit **402**, of the memory block **401**.

[0056] As described in connection with FIGS. 1-3, each memory block **401** is shown as including one of the write driver circuits **404A-404N** (sometimes generally referred to as the write driver circuit(s) **404**). The write driver circuits **404** may be similar to, and include any of the structure and functionality of, the write driver circuits **104** of FIG. 1. For example, as described herein, the write driver circuits **404** can drive the bit lines corresponding to an addressed memory cell **410** (e.g., the bit lines BLC and !BLC) for a write operation to store the input data (e.g., Data 0) within the addressed memory cell **410** (or weak memory cell **412**). As shown, the write driver circuits **404A-404N** are integrated with corresponding write assist circuits **406A-406N** (sometimes generally referred to as “write assist circuit(s) **406**”), which may include any of the structure or functionality of the write assist circuits **106** of FIG. 1. For example, the write assist circuits **406** may perform negative voltage write assist or positive voltage write assist operations to increase the voltage across a selected weak memory cell **412**, as described herein.

[0057] Each of the memory blocks **401A-401N** is shown as including corresponding write assist enable circuits **402A-402N** (sometimes generally referred to as write assist enable circuit(s) **402**). The write assist enable circuits **402** can include any of the structure or functionality as the write assist enable circuits **102** of FIG. 1. The write assist enable circuit **402** can include logic (e.g., transistors, logic gates, latches, flip-flops, registers, etc.) that cause the write assist circuits **406** to be selectively activated or deactivated according to an input signal from the write assist configuration circuit **420**.

[0058] In the example shown in FIG. 4, the write assist enable circuits **402** can enable corresponding write assist circuits **406** in response to a signal from the address match circuit **414** indicating a match between an input row address and an address of a row including at least one weak memory cell **412**. Additionally, the write assist enable circuit **402** conditions activation of the corresponding write assist circuit **406** on matching an input column address (e.g., Col ADDR) to an identifier of at least one column in the memory block **401** that includes at least one weak memory cell **412**. As such, write assist enable circuit **402** can condition activation of the write assist circuit **406** on writing to both a row and column that includes a weak memory cell **412**, based on the techniques described herein.

[0059] The write assist enable circuit **402** can include logic that performs a comparison operation between one or more stored column addresses and an input column address for a write operation (e.g., a Col ADDR). The stored column addresses to which the input column address is compared may be columns of the corresponding memory block **401** that have been determined to include at least one defective memory cell **412**. The comparison may be performed via one or more logic gates or comparison circuits of the corresponding write assist enable circuit **402**.

[0060] The stored column addresses may be provided as part of configuration data for the write assist enable circuit **402**, as described in connection with FIGS. 1-3. The configuration data for the write assist enable circuits **402** can be stored in the write assist configuration circuit **420**, which may be similar to and include any of the structure and functionality of the write assist configuration circuit **220** of FIG. 2. In this example, the configuration data that is provided to (e.g., shifted through) one or more registers of the write assist enable circuits **402A-402N** can include column

addresses of each of any columns in the memory blocks **401A-401N** that are determined (e.g., via the testing processes described herein) to include at least one weak memory cell **412**. The configuration data may be provided to the write assist enable circuits **402** in response to a reset, power-on, or a configuration signal.

[0061] Additionally, the write assist enable circuits **402** can further condition activation of the write assist circuits **406** on a signal from the address match circuit **414**. For example, the write assist configuration circuit **420** can provide data to a row address match circuit **414**. The row address match circuit **414** can include logic gates, transistors, or any other device or circuit that can compare an input row address for a write operation and a stored row address provided by the write assist configuration circuit **420**. The row address match circuit **414** can include any of the structure of, and implement any of the functionality of, the row address match circuit **314** of FIG. 3.

[0062] The row address match circuit **414** can provide an activation signal to the write assist enable circuits **402** in response to detecting a match between an input row address of the memory circuit **400** and a stored row address that is identified as including a weak memory cell **412**. The write assist configuration circuit **420** can provide addresses of rows that are determined to include at least one weak memory cell **412** (e.g., the Row 1 ADDR, as shown) to the row address match circuit **414**, for example, in response to a reset, a power-on, or in response to a configuration signal. The write assist configuration circuit **420** can therefore provide configuration data to both the address match circuit and the write assist enable circuit **402**. When the write assist enable circuit **402** selectively activates the write assist circuit **406**, the increased voltage produced by the write assist circuit **406** can be provided via the output of the multiplexor **404** that corresponds to the respective Col ADDR of the write operation. For example, as shown, if a write operation occurs on at the Row 1 ADDR and the second column of memory block **401A**, the write assist enable circuit **402A** activates the write assist circuit **406A**, which provides corresponding outputs via the second output **416** of the multiplexor **404A**.

[0063] FIG. 5 illustrates a flowchart of an example method **500** to operate the disclosed memory circuits **100**, **200**, **300**, and **400** of FIGS. 1-4, respectively, in accordance with some embodiments of the present disclosure. The method **500** may be used to operate a memory circuit or device (e.g., the memory circuit **100**, the memory circuit **200**, the memory circuit **300**, the memory circuit **400**, etc.) to selectively active write assist circuits. For example, at least some of the operations described in the method **500** use layouts and schematics described in FIGS. 1-4. It is noted that the method **500** is merely an example and is not intended to limit the present disclosure. Accordingly, it is understood that additional operations may be provided before, during, and after the method **500** of FIG. 5, and that some other operations may only be briefly described herein.

[0064] In brief overview, the method **500** starts with operation **502** of providing an indication (e.g., via the WA Shift signal) that a memory cell (e.g., the weak memory cell **112**) of a memory array has a predetermined operational characteristic (e.g., being a weak memory cell, as opposed to a normally operating memory cell). The method **500** proceeds with operation **504** of detecting a write operation (e.g., via the "Write" signal) for a row or column (e.g., identified by a Row ADDR or Col ADDR, as described herein) of the memory array including the memory cell having the predetermined operational characteristic. The method **500** concludes with operation **506** of selectively activating a write assist circuit to compensate for the predetermined operational characteristic of the memory cell during the write operation.

[0065] Referring to operation **502**, an indication (e.g., via the WA Shift signal) that a memory cell (e.g., the weak memory cell **112**) of a memory array has a predetermined operational characteristic (e.g., being a weak memory cell, as opposed to a normally operating memory cell) is provided. The indication may be generated by one or more test circuits, which may be included in one or more write assist configuration circuits (e.g., the write assist configuration circuits **120**, **220**, **320**, or **420**, etc.). The indication may include a row and/or column address for any memory cells identified as a weak memory cell. The indication may include indications of each memory block of the memory

array that includes at least one weak memory cell. The indications may be stored in one or more storage devices, such as programmable memory (e.g., flash memory, eFuse memory, etc.). Weak memory cells may be identified using a testing circuit, such as a BIST or BISTR circuit, or an external testing circuit.

[0066] Referring to operation **504**, a write operation (e.g., via the “Write” signal) for a row or column (e.g., identified by a Row ADDR or Col ADDR, as described herein) of the memory array including the memory cell having the predetermined operational characteristic is detected. The write operation may be detected as corresponding to the memory block, column, and/or row that includes at least one weak memory cell. For example, a row address match circuit (e.g., the row address match circuit **314**, the row address match circuit **414**) can detect a write operation to a row that includes at least one weak memory cell. A write assist enable circuit can detect a write operation to a memory block and/or a column including at least one weak memory cell.

[0067] Referring operation **506**, of a write assist circuit (e.g., the write assist circuit **106**, the write assist circuit **206**, the write assist circuit **306**, and the write assist circuit **406**, etc.) is selectively activated to compensate for the predetermined operational characteristic of the memory cell during the write operation. For example, activation of a write assist circuit for a memory block may be conditioned on detection of a write operation to the memory block, a row, and/or column including at least one weak memory cell. The write assist circuit can produce an increased voltage across the weak memory cell during the write operation to compensate for its operational characteristics (e.g., manufacturing defects that affect its ability to retain its state during write operations).

[0068] In one aspect of the present disclosure, a semiconductor device is disclosed. The semiconductor device includes a memory array comprising a first memory cell and a second memory cell, the second memory cell having an operational characteristic different than that of the first memory cell. The semiconductor device a first write circuit configured to write first data to the first memory cell. The semiconductor device a second write circuit configured to write second data to the second memory cell. The second write circuit is selectively configured to compensate for the operational characteristic of the second memory cell.

[0069] In another aspect of the present disclosure, a memory circuit is disclosed. The memory circuit includes a write driver device configured to write input data to one of a first column or a second column of a memory array. The memory circuit includes a write assist circuit configured to cause the write driver device to selectively operate at one of a first voltage or a second voltage. The memory circuit includes a write assist enable circuit configured to activate the write assist circuit based on an indication that the first column or the second column comprises a memory cell having a defect.

[0070] Yet another aspect of the present disclosure is directed to a method. The method includes providing an indication that a memory cell of a memory array has a predetermined operational characteristic. The method includes detecting a write operation for a row or column of the memory array including the memory cell having the predetermined operational characteristic. The method includes selectively activating a write assist circuit to compensate for the predetermined operational characteristic of the memory cell during the write operation.

[0071] As used herein, the terms “about” and “approximately” generally mean plus or minus 10% of the stated value. For example, about 0.5 would include 0.45 and 0.55, about 10 would include 9 to 11, about 1000 would include 900 to 1100.

[0072] 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 semiconductor device, comprising: a memory array comprising a first memory cell and a second memory cell, the second memory cell having an operational characteristic different than that of the first memory cell; a first write circuit configured to write first data to the first memory cell; and a second write circuit configured to write second data to the second memory cell, wherein the second write circuit is selectively configured to compensate for the operational characteristic of the second memory cell.
2. The semiconductor device of claim 1, wherein the first memory cell and the second memory cell each comprise a respective bit cell in the memory array.
3. The semiconductor device of claim 1, wherein the first write circuit is configured to operate at a first voltage to write the first data to the first memory cell and the second write circuit is configured to operate at a second voltage to write the second data to the second memory cell.
4. The semiconductor device of claim 3, further comprising: a write-assist enable circuit configured to cause the second write circuit to selectively operate using the second voltage.
5. The semiconductor device of claim 4, wherein the write-assist enable circuit comprises a latch configured to selectively cause the second write circuit to operate using the second voltage.
6. The semiconductor device of claim 5, wherein the latch causes the second write circuit to operate using the second voltage based on a column address of the second memory cell.
7. The semiconductor device of claim 3, further comprising a register storing control data that indicates the first write circuit is to operate at the first voltage and the second write circuit is to operate at the second voltage.
8. The semiconductor device of claim 1, further comprising: an address match circuit configured to produce a write-assist enable signal upon receiving a write address corresponding to the second memory cell, wherein the second write circuit is configured to compensate for the operational characteristic of the second memory cell based on the write-assist enable signal.
9. The semiconductor device of claim 1, further comprising a multiplexer circuit configured to receive a write signal from the second write circuit and provide the write signal to one of a first column or a second column, the first column comprising the second memory cell.
10. A memory circuit, comprising: a write driver device configured to write input data to one of a first column or a second column of a memory array; a write assist circuit configured to cause the write driver device to selectively operate at one of a first voltage or a second voltage; and a write assist enable circuit configured to activate the write assist circuit based on an indication that the first column or the second column comprises a memory cell having a defect.
11. The memory circuit of claim 10, further comprising: a multiplexer device configured to receive a write signal from the write driver device and provide the write signal to one of the first column or the second column of the memory array, the first column or the second column selected based on a column address signal.
12. The memory circuit of claim 11, wherein the write assist enable circuit is configured to activate the write assist circuit further based on the column address signal matching a column address of the memory cell having the defect.
13. The memory circuit of claim 10, wherein the memory cell having the defect is defined within a first row of the memory array, the memory circuit further comprising: a row address match circuit configured to generate a row enable signal upon detecting a match between an input row address and an address of the first row, write assist enable circuit configured to activate the write assist circuit further based on the row enable signal.
14. The memory circuit of claim 13, further comprising: a multiplexer device configured to receive

a write signal from the write driver device and provide the write signal to one of the first column or the second column of the memory array, the first column or the second column selected based on a column address signal.

**15.** The memory circuit of claim 14, wherein the write assist enable circuit is configured to activate the write assist circuit further based on the column address signal matching a column address of the memory cell having the defect.

**16.** The memory circuit of claim 10, wherein the write assist circuit is further configured to cause the write driver to produce a boosted write voltage for writing to the memory cell having the defect.

**17.** The memory circuit of claim 10, wherein the write assist circuit is further configured to cause the write driver to reduce a ground voltage for writing to the memory cell having the defect.

**18.** A method, comprising: providing an indication that a memory cell of a memory array has a predetermined operational characteristic; detecting a write operation for a row or column of the memory array including the memory cell having the predetermined operational characteristic; and selectively activating a write assist circuit to compensate for the predetermined operational characteristic of the memory cell during the write operation.

**19.** The method of claim 18, wherein detecting the write operation comprises comparing an input column address for the write operation to a column address of the memory cell having the predetermined operational characteristic.

**20.** The method of claim 18, wherein detecting the write operation comprises comparing an input row address for the write operation to a row address of the memory cell having the predetermined operational characteristic.

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