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### Bit Line Pre-Charge Circuit for Power Management Modes in Multi Bank SRAM

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#### Abstract

Systems and methods are provided for controlling a wake-up operation of a memory circuit. The memory circuit is configured to precharge the bit lines of a memory array sequentially during wakeup. A sleep signal is received by the first bit line of a memory cell and then a designed delay occurs prior to the precharge of a second complementary bit line. The sleep signal may then precharge the bit lines of a second memory cell with further delay between the precharge of each bit line. The memory circuit is configured to precharge both bit lines of a memory cell at the same time when an operation associated with that cell is designated.

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 18/585,184, filed on Feb. 23, 2024, which is a continuation of U.S. patent application Ser. No. 18/188,523, filed on Mar. 23, 2023, entitled “Bit line pre-charge circuit for power management modes in multi bank SRAM,” now U.S. Pat. No. 11,935,589, issued on Mar. 19, 2024, which is a continuation of U.S. patent application Ser. No. 17/246,822, filed on May 3, 2021, entitled “Bit Line Pre-charge Circuit for Power Management Modes in Multi Bank SRAM,” now U.S. Pat. No. 11,626,158, issued on Apr. 11, 2023, which claims priority to U.S. Provisional Application No. 63/106,400, filed on Oct. 28, 2020, entitled “Bit Line Precharge Circuit,” each of which is incorporated herein by reference in their entirety.

### TECHNICAL FIELD

[0002] The technology described in this patent document relates generally to semiconductor memory systems, and more particularly to power management systems and methods for a semiconductor memory system.

### BACKGROUND

[0003] A memory bank is a logical unit of storage. A memory bank typically includes multiple rows and columns of storage units (memory cells). Sleep signals are routed to memory banks to precharge bit cells for wake-up or operations. A wake-up signal may be generated which has associated power costs to prepare memory cells for operation after a low power or sleep state.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0004] 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.

[0005] FIG. 1 is a diagram depicting a memory circuit that is configured to receive sleep and wake-up commands in an embodiment.

[0006] FIG. 2 is a block diagram depicting a memory architecture that includes sleep signal and delay elements in accordance with an embodiment.

[0007] FIG. 3 is a diagram of an example power management circuit for a semiconductor memory (e.g., SRAM) in an embodiment.

[0008] FIG. 4 is a timing diagram showing an example operation of the power management circuit of FIG. 3 in an embodiment.

[0009] FIGS. 5A-B depict an example of a delay element and associated logic table that may, for example, be utilized as one or more of the delay elements in FIG. 3 in an embodiment.

[0010] FIG. **6** is a diagram of another example power management circuit for a semiconductor memory (e.g., SRAM) in an embodiment.

[0011] FIG. **7** is a further example of a power management circuit for a semiconductor memory (e.g., SRAM) in an embodiment.

[0012] FIG. **8** is an additional example of a power management circuit for a semiconductor memory (e.g., SRAM) in an embodiment.

[0013] FIG. **9** is another example of a power management circuit for a semiconductor memory (e.g., SRAM) in an embodiment.

[0014] FIGS. **10A-B** are flow diagrams of an example method for controlling a wake-up operation for a memory array in an embodiment.

[0015] FIG. **11** is a flow diagram of an example method for controlling a wake-up operation for a memory array in an embodiment.

#### DETAILED DESCRIPTION

[0016] 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. 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.

[0017] Power gates are often used to turn off periphery and memory array in a low power SRAM. When memory comes out of a sleep mode (e.g., shut-down, deep sleep, and light sleep), large power gates may be used to ramp up the internal supply voltage of the memory. Power gates that provide a short wake-up time for the internal supply voltage may lead to large in-rush current. Large in-rush current may be sub-optimal because it can cause component failure and excess power draw in constrained devices.

[0018] The word line internal power supply and bit line pre-charge circuit of a memory system may be turned off during light sleep mode. Memory design criteria might suggest maintaining a wake-up peak current that is smaller than the mission mode (R/W operation) peak current, particularly during light sleep mode. A design might fail to meet this criteria during light sleep wake-up where bit lines are pre-charged at almost the same time within a memory bank.

[0019] Sequential wakeup is a technique that could be used to reduce wake-up peak current in a memory system. But it may be difficult to match the bit line pre-charge signal and sleep signal delay across all memory macros and PVTs. Without careful management, multiple bit lines could be pre-charged at substantially the same time, resulting in undesirable peak current levels being realized.

[0020] Systems and methods for power management in a memory system are described herein. In embodiments, a delay element (such as a pair of inverters) is utilized in a semiconductor memory system (e.g., SRAM) to track the bit line pre-charge signal in order to reduce peak current when coming out of power management mode (e.g., shut-down, deep sleep, and light sleep). In this way, a sequential bit line pre-charge operation within a memory bank may be achieved, and consequentially, wake-up peak current may be reduced to prevent high peak power draw which may cause component failures in constrained devices. Wake-up peak current may cause component failures when it is greater than mission mode peak current.

[0021] FIG. **1** is a diagram depicting a memory circuit that is configured to receive sleep and array signals in an embodiment. The example SRAM memory **102** includes a plurality of input pins configured to receive sleep and addressing signals. In the example of FIG. **1**, the memory **102** is configured to receive a clock (CLK) **115**, a chip enable (CEB) signal **117**, a shut-down mode (SD) signal **109**, a deep sleep mode (DSLP) signal **111**, and a light sleep mode (LSLP) signal **113**. The SRAM memory **102** is further configured to receive an address input (ADR[N:0]) **118**. In

embodiments, the address received at the address input indicates an address in the memory bank. The memory bank is made up of two or more memory arrays.

[0022] FIG. 2 is a block diagram depicting a bit line precharge circuit **200** that includes a sleep signal with sequential delay elements in accordance with an embodiment. The example SRAM memory circuit includes a memory array with two memory cells a first (bottom) memory cell and a second (top) memory cell. The bottom memory cell including a first bit line and a second complementary bit line. The top memory cell includes a first bit line and a second complementary bit line. The second bit line is also called a bit line bar. The memory circuit further includes a global control within the global input/output. The global control includes sleep logic circuitry and a clock generator and address decoder. The sleep logic circuitry has input pins for the shut-down mode (SD) signal **109**, a deep sleep mode (DSL<sub>LP</sub>) signal **111**, and a light sleep mode (LSLP) signal **113**. The clock generator and decoder has input pins for a clock (CLK) signal **115**, a chip enable (CEB) signal **117**, and the address input (ADR[N:0]) **118**. The sleep logic circuitry is configured to generate a sleep signal (SLP) if a shut down (SD) signal **109**, deep sleep mode (DSL<sub>LP</sub>) signal **111**, or light sleep mode (LSLP) signal **113** is present. The sleep signal or wake-up signal path includes a plurality of delay elements configured in series. The sleep signal is configured to precharge each of the bit lines sequentially with a delay element between each connection between the wake-up signal path and the bit line.

[0023] FIG. 3 is a diagram of an example power management circuit **300** for a semiconductor memory (e.g., SRAM) in accordance with an embodiment. The power management circuit **300** is an example embodiment of the bit line precharge circuit **200** as diagramed in FIG. 2. The example power management circuit **300** includes a memory array **302** having a plurality of memory cells that are controlled by a local input/output (I/O) system **304** and a global I/O system **306**. The global I/O system **306** includes logic circuitry **308** that generates a sleep signal **301** (SLP), and a clock generator and address decoder **310** that generates clock (ICLK) and addressing signals (TOP, BOT) for selecting a memory cell in the memory array **302** for read or write operations. Specifically, in the illustrated embodiment, the global I/O system **306** includes the logic (OR) gate **308** that generates the sleep signal **301** (SLP) as a function of power management signals that include a shut-down mode (SD) signal **109**, a deep sleep mode (DSL<sub>LP</sub>) signal **111**, and a light sleep mode (LSLP) signal **113**. These three modes (SD, DSL<sub>LP</sub> and LSLP) control power management for the memory system. For example, in light sleep mode, the bit line pre charge circuit and word line drivers may be turned off, in deep sleep mode, the memory logic may be turned off, and in shut-down mode, the entire memory circuit may be turned off. The clock generator and address decoder **310**, in the illustrated embodiment, generates the clock signal (ICLK) as function of a global clock signal **115** (CLK) and a chip enable signal **117** (CEB), and generates address signals (TOP, BOT) as function of an address word **118** (ADR[N:0]) and the chip enable signal **117** (CEB).

[0024] In the illustrated embodiment, the memory array **302** includes a first (bottom) memory cell **312** and a second (top) memory cell **314**. The sleep signal (SLP) from the global I/O system **306** is received in the local I/O system **304** as a first delayed sleep signal **316** (SLP\_BOT\_BL) and a second delayed sleep signal **319** (SLP\_BOT\_BLB) for the bottom memory cell **312** in the illustrated embodiment.

[0025] The local I/O system **304** includes logic circuitry for each of the memory cells in the memory array **302** that generate bit line pre-charge (BPCHB) signals for controlling power to the bit lines of the respective memory cells as a function of the sleep signal **301** (SLP) and clock (ICLK) and address (TOP, BOT) signals. The local I/O system **304** further includes a plurality of delay elements **307**, **324**, **334**, **337**, **344** that are connected in series within the sleep signal bit causing a delay between the sleep signal **301** (SLP) and logic circuitry for each of a plurality of memory cell bit lines **321**, **325**, **333**, **335**. The sleep signal **301** (SLP) is delayed prior to the first logic (OR) gate **322** of the bottom memory cell **312** by the first delay element **307**. The output of the first delay element is the first delayed sleep signal **316** (SLP\_BOT\_BL). The delay elements are

positioned along the wake up signal path. The delay elements **307**, **324**, **334**, **337**, **344** may, for example, be buffers that each include a series of an even number of inverters. The delay elements are connected in sequence with the sleep signal **301** (SLP) such that a transition of the sleep signal **301** (SLP) indicating a memory wake-up operation (e.g., coming out of shut-down, deep sleep, or light sleep) causes the plurality of memory cells in the memory array **302** to receive power in a sequential manner. The sleep signal (SLP) inputs into the first delay element **307** which generates the first delayed sleep signal **316** (SLP\_BOT\_BL). The first delayed sleep signal **316** (SLP\_BOT\_BL) inputs into the second delay element **324** which generates the second delayed sleep signal **319** (SLP\_BOT\_BLB). The second delayed sleep signal **319** (SLP\_BOT\_BLB) inputs into the third delay element **334** which generates a third delayed sleep signal **329** (SLP\_TOP\_BL). The third delayed sleep signal **329** (SLP\_TOP\_BL) inputs into the fourth delay element **337** which generates a fourth delayed sleep signal **339** (SLP\_TOP\_BLB). The fourth delayed sleep signal **339** (SLP\_TOP\_BLB) inputs into the fifth delay element **344** which then outputs from the local I/O **304**.

[0026] The clock (ICLK) and address (TOP, BOT) signals are input to the first logic (AND) gate **320** and a second logic (AND) gate **330**. The first delayed sleep signal **316** (SLP\_BOT\_BL) is input to a first logic (OR) gate **322** for the bottom memory cell **312**, along with the output of the first logic (AND) gate **320** clock (ICLK) and addressing (BOT) signal as a bit line pre charge signal **303** (BPCHB\_BOT) for the bottom memory cell **312**. The clock (ICLK) and address (TOP) signal are input to the second logic (AND) gate **330** which outputs the bit line pre charge signal (BPCHB\_TOP) for the top memory cell **314**.

[0027] The bit line pre charge signal **303** (BPCHB\_BOT) for the bottom memory cell **312** is input into the first logic (OR) gate **322** and a second logic (OR) gate **327**. The first logic (OR) gate **322** and the second logic (OR) gate **327** generate the bit line precharge signals (BPCHB\_BOT\_BL and BPCHB\_BOT\_BLB) for the bottom memory cell **312**. Specifically, a bit line pre-charge signal **323** (BPCHB\_BOT\_BL) is received at the gate terminal of a first PMOS transistors **326**, which include source terminals that are coupled to a supply voltage, and a drain terminal that is coupled to the bit line **321** (BL\_BOT). A bit line bar pre-charge signal **331** (BPCHB\_BOT\_BLB) is received at the gate terminal of a second PMOS transistor **328**, which include source terminals that are coupled to a supply voltage, and a drain terminals that is coupled to the bar bit line **325** (BLB\_BOT). As described above, the bit line pre charge signal **303** (BPCHB\_BOT) is configured such that during an operation associated with the bottom cell **312** the bit lines for bottom cell **321**, **325** (BL\_BOT and BLB\_BOT) are precharged at essentially the same time.

[0028] A bit line pre charge signal **305** (BPCHB\_TOP) for the top memory cell **314** is input into a first logic (OR) gate **332** and a second logic (OR) gate **342** for the top memory cell. The first logic (OR) gate **332** and the second logic (OR) gate **342** generate the bit line precharge signals (BPCHB\_TOP\_BL and BPCHB\_TOP\_BLB) for the top memory cell **314**. Specifically, a bit line pre-charge signal **341** (BPCHB\_TOP\_BL) is received at the gate terminal of a first PMOS transistors **336**, which include source terminals that are coupled to a supply voltage, and a drain terminal that is coupled to the bit line **333** (BL\_TOP). A bit line bar pre-charge signal **343** (BPCHB\_TOP\_BLB) is received at the gate terminal of a second PMOS transistor **338**, which include source terminals that are coupled to a supply voltage, and a drain terminals that is coupled to the bar bit line **335** (BLB\_TOP). As described above, the bit line pre charge signal **305** (BPCHB\_TOP) is configured such that during an operation associated with the top cell **314** the bit lines for the top cell **333**, **335** (BL\_TOP and BLB\_TOP) are precharged at essentially the same time.

[0029] The clock (ICLK) and address (TOP, BOT) signals are input to the first logic (AND) gate **320**. The first delayed sleep signal **316** (SLP\_BOT\_BL) is input to the first logic (OR) gate **322** for the bottom memory cell **312**, along with the output of the first logic (AND) gate **320** clock (ICLK) and addressing (TOP, BOT) signals as the bit line pre charge signal **303** (BPCHB\_BOT) for the

bottom memory cell **312**. More particularly, the logic circuit for the bottom memory cell **312** includes the first logic (AND) gate **320** with inputs that receive the addressing (BOT) signal and clock (ICLK) signals, and the first logic (OR) gate **322** with inputs that receive the output of the first logic (AND) gate **320** and the first delayed sleep signal **316** (SLP\_BOT\_BL). The output of the first logic (OR) gate **322** provides the bit line pre-charge signal **323** (BPCHB\_BOT\_BL) for switching circuitry memory cell. The output of the second logic (OR) gate **327** provides the bit line bar pre-charge signal **331** (BPCHB\_BOT\_BLB) for the bit line bar **325** of the bottom memory cell **312**. Specifically, the bit line pre-charge signal **323** (BPCHB\_BOT\_BL) is received at the gate terminal of the first PMOS transistors **326**, which include source terminals that are coupled to a supply voltage, and a drain terminal that is coupled to the bit line **321** (BL\_BOT). The bit line bar pre-charge signal **331** (BPCHB\_BOT\_BLB) is received at the gate terminal of the second PMOS transistor **328**, which include source terminals that are coupled to a supply voltage, and a drain terminals that is coupled to the bit line bar **325** (BLB\_BOT).

[0030] In response to a transition of the first delayed sleep signal **316** (SLP\_BOT\_BL) indicating a memory wake-up operation, the first logic (OR) gate **322** for the bottom memory cell **312** generates a logic state on the bit line pre-charge signal **323** (BPCHB\_BOT\_BL) that causes power to be supplied to pre-charge the memory cell bit line **321** (BL\_BOT). The sleep signal further passes through the delay element **324** which generates the second delayed sleep signal **319** (SLP\_BOT\_BLB). In response to a transition of the second delayed sleep signal **319** (SLP\_BOT\_BLB) indicating a memory wake-up operation, the second logic (OR) gate **327** for the bottom memory cell **312** generates a logic state on the bit line pre-charge signal for the bit line bar **331** (BPCHB\_BOT\_BLB) that causes power to be supplied to pre-charge memory cell bit line for the bit line bar **325** (BLB\_BOT). More specifically, the first PMOS transistor **326** is controlled by the bit line pre-charge signal **323** (BPCHB\_BOT\_BL) to provide power to the memory cell **312** bit line **321** (BL\_BOT). The second PMOS transistor **328** is controlled by the bit line pre-charge signal **331** (BPCHB\_BOT\_BLB) to provide power to the memory cell **312** bit line **325** (BLB\_BOT) in order to initialize the bit line voltages as the memory array **302** is powered on in response to a memory wake-up operation (e.g., coming out of shut-down, deep sleep, or light sleep.) An example of this operation is illustrated in the timing diagram **400** shown in FIG. **4**.

[0031] FIG. **4** is the timing diagram **400** for the example power management circuit **300** for a semiconductor memory (e.g., SRAM) in accordance with an embodiment. With reference to FIG. **4**, the wake-up operation is initiated by a logic high to logic low transition **401** in the sleep signal **113** (LSLP) received by the global I/O system **306**. The logic state transition **401** of the sleep signal **113** (LSLP) causes a corresponding logic state transition **403** in the sleep signal **301** (SLP) received by the local I/O system **304**. The initial sleep signal **301** (SLP) passes through a first delay element which generates the bit line first delayed sleep signal **316** (SLP\_BOT\_BL). As detailed above with reference to FIG. **3**, the logic state transition **403** in the first delayed sleep signal **316** (SLP\_BOT\_BL) causes the first logic (OR) gate **322** for the bottom memory cell **312** to a high to low transition **405** of the logic state of the bit line pre-charge signal **323** (BPCHB\_BOT\_BL), which causes power to be supplied to pre-charge the memory cell bit line **321** (BL\_BOT). The precharging of the memory cell bit line **321** (BL\_BOT) can be seen in the timing diagram **400** of FIG. **4** by the voltage transition **405** that occurs in response to the logic state transition **405** of the bit line pre-charge signal **323** (BPCHB\_BOT\_BL). This generates a first peak in the wakeup current **407** i(VDD). This first peak of wakeup current **407** i(VDD) is less than the wakeup current in memory circuits that precharge bit lines at the same time by, for example, one fourth.

[0032] With reference again to FIG. **3**, the first delayed sleep signal **316** (SLP\_BOT\_BL) is received by as input to the second delay element **324** and generates the second delayed sleep signal **319** (SLP\_BOT\_BLB). The second delayed sleep signal **319** (SLP\_BOT\_BLB) is received by the third delay element **334** and generates the third delayed sleep signal **329** (SLP\_TOP\_BL). The first logic circuitry (OR) gate **332** of the top memory cell **314** generates the bit line pre-charge signal

**341** (BPCHB\_TOP\_BL), such that the logic state of the second delayed sleep signal does not transition (indicating a wake-up operation) until after the bit line voltages **321**, **325** (BL\_BOT and BLB\_BOT) of the bottom memory cell **312** have been initialized.

[0033] As shown in the timing diagram **400** of FIG. **4**, the second delayed sleep signal **319** (SLP\_BOT\_BLB) begins a logic state transition **409** only after the bit line pre-charge signal **323** (BPCHB\_BOT\_BL) has transitioned from logic high to logic low **405**. This causes a time delay **410** between precharging of the bit line voltage **321** (BL\_BOT) of the first PMOS transistor **326** and the initiation of wake-up for the complementary PMOS transistor **328** for the bit line voltage **325** (BLB\_BOT) of the bottom memory cell **312**.

[0034] With reference again to FIG. **3**, the third delayed sleep signal **329** (SLP\_TOP\_BL) is provided as a sleep signal input to the logic circuits **330**, **332** for the top memory cell **314** and also as an input to the fourth delay element **337**. The logic circuit for the top memory cell **314** includes a first logic (AND) gate **330** with inputs that receive the addressing (TOP) signal and clock (ICLK), and the first logic (OR) gate **332** with inputs that receive the output of the first logic gate **330** and the third delayed sleep signal **329** (SLP\_TOP\_BL). The output of the first logic (AND) gate **330** for the top memory cell **314** is the bit line precharge bar **305** (BPCHB\_TOP). The output of the first logic (OR) gate **332** provides the bit line pre-charge signal **341** (BPCHB\_TOP\_BL) for switching circuitry in the top memory cell **314**. Specifically, the bit line pre-charge signal **341** (BPCHB\_TOP\_BL) is received at the gate terminal of the first PMOS transistors **336**, which includes source terminal that is coupled to a supply voltage, and drain terminals is coupled to the bit line **333** (BL\_TOP) input of the top memory cell **314**. The output of the second logic (OR) gate **342** provides the bit line bar pre-charge signal **343** (BPCHB\_TOP\_BLB) for the top memory cell **314**. The bit line bar pre-charge signal **343** (BPCHB\_TOP\_BLB) is received at the gate terminal of the second PMOS transistors **338**, which includes source terminal that is coupled to a supply voltage, and drain terminals is coupled to the bit line bar **335** (BLB\_TOP) input of the top memory cell **314**.

[0035] In response to a transition of the third delayed sleep signal **329** (SLP\_TOP\_BL) indicating a memory wake-up operation, the first logic (OR) gate **332** for the top memory cell **314** generates a logic state on the bit line pre-charge signal **341** (BPCHB\_TOP\_BL) that causes the first PMOS transistor **336** of the top memory cell **314** to supply power to pre-charge the memory cell bit line **333** (BL\_TOP). Subsequently, in response to a transition of the fourth delayed sleep signal **339** (SLP\_TOP\_BLB) indicating a memory wake-up operation, the second logic (OR) gate **342** for the top memory cell **314** generates a logic state on the bit line pre-charge signal **343** (BPCHB\_TOP\_BLB) that causes the second PMOS transistor **338** to supply power to pre-charge the memory cell bit line bar **335** (BLB\_TOP). As shown in the timing diagram of FIG. **4**, a logic state transition **413** in the third delayed sleep signal **329** (SLP\_TOP\_BL) causes the first logic (OR) gate **332** for the top memory cell **314** to transition **415** the logic state of the bit line pre-charge signal **341** (BPCHB\_TOP\_BL), which causes power to be supplied to pre-charge memory cell bit line **333** (BL\_TOP). As shown in the timing diagram of FIG. **4**, the logic state transition **417** in the fourth delayed sleep signal **339** (SLP\_TOP\_BLB) causes the second logic (OR) gate **342** for the top memory cell **314** to transition **419** the logic state of the bit line bar pre-charge signal **343** (BPCHB\_TOP\_BLB), which causes power to be supplied to pre-charge memory cell bit line bar **335** (BLB\_TOP). The precharging of memory cell bit lines **333**, **335** (BL\_TOP and BLB\_TOP) can be seen in the timing diagram **400** of FIG. **4** by voltage transitions **411**, **413** that occurs in response to the logic state transitions **415**, **419** of the bit line pre-charge signals **341**, **343** (BPCHB\_TOP\_BL and BPCHB\_TOP\_BLB) respectively.

[0036] With reference again to FIG. **3**, the second delayed sleep signal **319** (SLP\_BOT\_BLB) is received as inputs to the third delay element **334**, which generates the third delayed sleep signal **329** (SLP\_TOP\_BL). The generation of the third delayed sleep signal **329** (SLP\_TOP\_BL) by the third delay element **334** is delayed such that the logic state of the third delayed sleep signal **329**

(SLP\_TOP\_BL) does not transition (indicating a wake-up operation) until after the bit line voltages **321**, **325** (BL\_BOT and BLB\_BOT) of the bottom memory cell **312** have been initialized.

[0037] As shown in the timing diagram **400** of FIG. **4**, the third delayed sleep signal **329** (SLP\_TOP\_BL) begins the high-to-low logic state transition **413** only after the bit line pre-charge signal **331** (BPCHB\_BOT\_BLB) has the transition **411** from logic high to logic low. This causes a time delay **416** between precharging of the bit line bar voltage **325** (BLB\_BOT) of the bottom memory cell **312** and the initiation of wake-up operations for the first bit line **333** (BL\_TOP) of the top memory cell **314**.

[0038] As shown in the timing diagram **400** of FIG. **4**, the fourth delayed sleep signal **339** (SLP\_TOP\_BLB) begins a high-to-low logic state transition **417** only after the bit line pre-charge signal **341** (BPCHB\_TOP\_BL) has transitioned **415** from logic high to logic low. This causes a time delay **418** between precharging of the bit line voltage **333** (BL\_TOP) of the top memory cell **314** and the initiation of wake-up operations for the bit line bar **335** (BLB\_TOP) of the top memory cell **314**.

[0039] In this manner, the bit lines of the two memory cells **312**, **314** in the example embodiment **300** are pre-charged in a sequential fashion, as illustrated in the example timing diagram **400** shown in FIG. **4**. Specifically, each bit line pre-charge signal **323**, **331**, **341**, **343** is received at the gate terminals of the four PMOS transistors **326**, **328**, **336**, **338** sequentially. As further shown in FIG. **4**, the sequential wake-up operation causes the resulting wake-up current draw **430** to occur during four separate intervals, reducing the peak wakeup current in comparison to systems that perform simultaneous wake-up operations on multiple memory cells.

[0040] FIGS. **5A-5B** depict an example of a buffer **500** that may, for example, be utilized as one or more of the delay elements **307**, **324**, **334**, **337**, **344** in FIG. **3** in accordance with an embodiment. As shown in FIG. **5A**, the buffer **500** includes a pair of inverters **502**, **504**. A first inverter **502** has an output **506** that is the input of the second inverter **504**. The output **506** of the first inverter **502** is inverse to the input such that if the input is logic high state then the output is logic low state. A sleep signal (e.g., SLP\_BOT\_BL) is the input to the first inverter **502** and the output **506** of the first inverter **502** is the input for the second inverter **504**. The output of the second inverter **504** provides a delayed sleep signal (e.g., SLP\_BOT\_BLB) that matches the logic state of the input sleep signal.

[0041] A logic state table **510** for the example delay element is shown at FIG. **5B**. As shown in table **510**, when the first sleep signal (e.g., SLP\_BOT\_BL) is in a logic low state, the delayed sleep signal (e.g., SLP\_BOT\_BLB) will also be in a logic low state. As detailed above with reference to FIG. **4**, when the first sleep signal (e.g., SLP\_BOT\_BL) is in a logic high state the delayed sleep signal (e.g., SLP\_BOT\_BLB) will be logic state high.

[0042] FIG. **6** is a diagram of another example power management circuit **600** for a semiconductor memory (e.g., SRAM) in accordance with an embodiment. The example **600** shown in FIG. **6** is the same as the example power management circuit **300** shown in FIG. **3**, except that the example **600** shown in FIG. **6** utilizes additional delay elements **610**, **612**, **614** between the sleep signals **316**, **319**, **329** and subsequent delayed sleep signals **319**, **329**, **339**. The fourth additional delay element **616** is connected in series between the fourth delayed sleep signal **339** (SLP\_TOP\_BLB) the bit line sleep signal output from the local I/O **304**. The delay elements **610**, **612**, **614**, **616** may, for example, be buffers that each include a series of an even number of inverters. The length of the signal delay caused by each delay element **610**, **612**, **614**, **616** may, for example, be determined by the number of inverter pairs included in the buffer circuit. Multiple delay elements may be connected in series with delay elements located on the edge of the local I/O **304**. Additional delay elements may, for example, provide additional delay in the bit line tracking for pre charge when line resistance is high.

[0043] When a memory wake-up operation is initiated by one or more of the SD **109**, DSLP **111**, and LSLP **113** signals received by the global I/O system **306**, the bit line **321** (BL\_BOT) is precharged and then the second delayed sleep signal **319** (SLP\_BOT\_BLB) is generated by the



second delay element which precharges the bit line bar **325** (BLB\_BOT). Once the bottom memory cell **312** is pre-charged, the third delayed sleep signal **329** (SLP\_TOP\_BL) is generated by third delay element **334** in the same way as described above with reference to the embodiment shown in FIG. **3**. The third delayed sleep signal **329** (SLP\_TOP\_BL) also causes the first bit line of the top memory cell **333** (BL\_TOP) to be precharged and then inputs into the fourth delay element **337** and sequentially pre-charges the second bit line of the top memory cell **335** (BLB\_TOP), as describe above with reference to FIG. **3**. However, the subsequent delayed sleep signals **319**, **329**, and **339** (SLP\_BOT\_BLB, SLP\_TOP\_BL, and SLP\_TOP\_BLB) in this embodiment **600** are respectively generated by the delay elements **610**, **612**, and **614**. In this way, initiation of the memory wake-up operation for the bottom memory cell second bit line **325** is delayed by an amount of time (D1) from initiation of the memory wake-up operation of the bottom memory cell first bit line **321**, and the top memory cell first bit line **333** (BL\_TOP) is delayed by an amount of time (D2) from initiation of the memory wake-up operation for the bottom memory cell second bit line **325**, and initiation of the memory wake-up operation for the top memory cell second bit line **335** is delayed by an amount of time (D3) from initiation of the memory wake-up operation for the top memory cell first bit line **333** (BL\_TOP). The length of the time delays (D1, D2, and D3) may be determined by the size of the respective delay elements, **324** and **610** for D1, **334** and **612** for D2, and **337** and **614** for D3 (e.g., by selecting the number of inverter pairs), and may be configured such that the bit lines **321**, **325**, **333**, **335** of the memory cells **312**, **314** are pre-charged in a sequential fashion, similar to (or the same as) the sequential bit line precharging that results from the embodiment of FIG. **3**. In this way, a sequential bit line pre-charge operation within a memory bank may be achieved. Consequentially, wake-up peak current may be significantly reduced (e.g., by one fourth) in comparison to existing SRAM architectures.

[0044] FIG. **7** is a further example of a power management circuit **700** for a semiconductor memory (e.g., SRAM) in accordance with an embodiment. The example **700** shown in FIG. **7** is the same as the example power management circuit **300** shown in FIG. **3**, except that in the example **700** shown in FIG. **7** the memory cells respectively include equalizer devices **710**, **712** between bit lines **321**, **325** (BL\_BOT and BLB\_BOT) and bit lines **333**, **335** (BL\_TOP and BLB\_TOP) respectively. The equalizer device may, for example, comprise a PMOS transistor. The equalizer device **710** for the bottom memory cell **312** receives the bit line pre-charge signal **331** (BPCHB\_BOT\_BLB) at the gate terminal of the PMOS transistor, which includes a source terminal that is coupled to a bit line and a drain terminal that is coupled to the complementary bit line. The bit line pre-charge signal **331** (BPCHB\_BOT\_BLB) that is received by the gate terminal results from the second logic (OR) gate **327** with inputs from the second delayed sleep signal **319** (SLP\_BOT\_BLB) and the bit line pre-charge signal **303** (BPCHB\_BOT). As shown in the timing diagram **400** of FIG. **4**, the second delayed sleep signal **319** (SLP\_BOT\_BLB) begins the logic state transition **409** only after the bit line pre-charge signal **323** (BPCHB\_BOT\_BL) has transitioned from logic high to logic low. This causes a time delay **410** between precharging of the bit line voltage **321** (BL\_BOT) of the first PMOS transistor **326** and the initiation of wake-up for the complementary PMOS transistor **328** for the bit line voltage **325** (BLB\_BOT) of the bottom memory cell **312**. The additional equalizer device, when (BPCHB\_BOT\_BLB) transitioned from logic high to logic low during initiation of wake-up, equalizes the complementary bit lines **321**, **325** (BL\_BOT and BLB\_BOT) such that the voltage on the source terminals of the first PMOS transistor **326** and second PMOS transistor **328** of the bottom memory cell **312** is essentially the same.

[0045] The equalizer device **712** for the top memory cell **314** receives the bit line pre-charge signal **343** (BPCHB\_TOP\_BLB) at the gate terminal of the PMOS transistor, which includes a source terminal that is coupled to a bit line and a drain terminal that is coupled to the complementary bit line **333**, **335** (BL\_TOP and BLB\_TOP). The bit line pre-charge signal **343** (BPCHB\_TOP\_BLB) is received by the gate terminal which results from the second logic (OR) gate **342** with inputs from

the fourth delayed sleep signal **339** (SLP\_TOP\_BLB) and the bit line precharge signal **305** (BPCHB\_TOP). As shown in the timing diagram **400** of FIG. **4**, fourth delayed sleep signal **339** (SLP\_TOP\_BLB) begins the logic state transition **417** only after the bit line pre-charge signal **341** (BPCHB\_TOP\_BL) has transitioned from logic high to logic low. This causes a time delay between precharging of the bit line voltage **333** (BL\_TOP) of the first PMOS transistor **336** and the initiation of wake-up for the complementary PMOS transistor **338** for the bit line voltage **335** (BLB\_TOP) of the top memory cell **314**. The additional equalizer device, when the bit line pre-charge signal **343** (BPCHB\_TOP\_BLB) transitioned from logic high to logic low during initiation of wake-up, equalizes the complementary bit lines **333**, **335** (BL\_TOP and BLB\_TOP) such that the voltages on the source terminals of the first PMOS transistor **336** and second PMOS transistor **338** of the top memory cell **314** are essentially the same.

[0046] FIG. **8** is a diagram of an additional example of a power management circuit **800** for a semiconductor memory (e.g., SRAM) in accordance with an embodiment. The example **800** shown in FIG. **8** is the same as the example power management circuit **300** shown in FIG. **3**, except that the example **800** shown in FIG. **8** does not utilize a delay element between the sleep signal **301** (SLP) and the first logic (OR) gate **322**. In this embodiment there is no delay element connected in series between the sleep signal **301** (SLP) and the sleep signal **316** (SLP\_BOT\_BL) for the first bit line **321** of the bottom memory cell **312**.

[0047] FIG. **9** is a diagram of another example of a power management circuit **900** for a semiconductor memory (e.g., SRAM) in accordance with an embodiment. The example **900** shown in FIG. **9** is the same as the example power management circuit **700** shown in FIG. **7**, except that the example **900** shown in FIG. **9** includes additional equalizer delay elements **910**, **912**, **914**, **916** between sleep signals **316**, **319**, and **329** and delayed sleep signals **319**, **329**, **339**. The fourth additional delay element **916** is connected in series between the fourth delayed sleep signal **339** (SLP\_TOP\_BLB) the bit line sleep signal output from the local I/O **304**. The delay elements **910**, **912**, **914**, **916** may, for example, be buffers that each include a series of an even number of inverters. The length of the signal delay caused by each delay element **910**, **912**, **914**, **916** may, for example, be determined by the number of inverter pairs included in the buffer circuit. Multiple delay elements may be connected in series with delay elements located on the edge of the local I/O **304**. Additional delay elements may, for example, provide additional delay in the bit line tracking for pre charge when line resistance is high.

[0048] FIG. **10A** is a flow diagram depicting a method **1000** for controlling wake-up operations for a memory array that includes a plurality of memory cells. The steps of FIG. **10A** are provided with reference to previously described structures for ease of understanding, but it is understood that the steps could be performed using a variety of structures. The method **1000** may, for example, be performed by one of the example memory circuits **300**, **600**, **700**, **800**, **900** shown in FIGS. **3**, **6**, **7**, **8**, and **9**. The sleep signal **301** (SLP) is received by the memory circuit at **1001** indicating initiation of a memory wake-up operation. The sleep signal may, for example, be received by the logic circuitry **322**, **327**, **332**, **342** in FIGS. **3**, **6**, **7**, **8**, and **9**. A first bit line pre-charge signal (e.g., BPCHB\_BOT\_BL) for a first memory cell of the plurality of memory cells is generated in response to the sleep signal. The first bit line pre-charge signal may, for example, be generated by the logic circuitry **308** shown in FIGS. **3**, **6**, **7**, **8**, and **9**. At **1010**, a bit line of the first memory cell, such as bit line **321** shown in FIGS. **3**, **6**, **7**, **8**, and **9**, is pre-charged in response to the first bit line pre-charge signal. A delayed sleep signal (e.g., SLP\_BOT\_BLB) is generated in response to the sleep signal passing through a delay element **1015** such as **324** in series along the bit line. A second bit line pre-charge signal (e.g., BPCHB\_BOT\_BLB) for the first memory cell of the plurality of memory cells is generated in response to the sleep signal. At **1020**, a second bit line for the first memory cell, such as bit line **325** shown in FIG. **3**, **6**, **7**, **8**, or **9** is precharged in response to the second bit line pre-charge signal. The delayed sleep signal passes through a further delay element at **1025**, again delaying the signal such and generating a second delayed sleep signal. A third bit

line pre-charge signal is generated for a second memory cell of the plurality of memory cells in response to the second delayed sleep signal. The third bit line pre-charge signal may, for example, be generated by the logic circuitry **332** shown in FIG. **3**, **6**, **7**, **8**, or **9**. At **1030**, a bit line of the second memory cell, such as bit line **333** shown in FIG. **3**, **6**, **7**, **8**, or **9** is pre-charged in response to the third bit line pre-charge signal. The second delayed sleep signal passes through a third delay element at **1035**, again delaying the signal and generating a third delayed sleep signal. A fourth bit line pre-charge signal is generated for a second bit line in a second memory cell of the plurality of memory cells in response to the third delayed sleep signal. At **1040**, the second bit line of the second memory cell, such as bit line **335** shown in FIG. **1**, **4**, **5**, **6**, or **7** is pre-charged in response to the fourth bit line pre-charge signal.

[0049] FIG. **10B** is a flow diagram of an example method **1000** for precharging bit cells during an operation associated with a memory cell in a memory array that includes a plurality of memory cells. The steps of FIG. **10B** are provided with reference to previously described structures for ease of understanding, but it is understood that the steps could be performed using a variety of structures. The method **1000** may, for example, be performed by one of the example memory circuits **300**, **600**, **700**, **800**, **900** shown in FIGS. **3**, **6**, **7**, **8** and **9**. At **1002**, an operation signal is received from the clock generator and address decoder **310**, the logic circuitry **320**, **330** for each of the memory cells **312**, **314** generates the bit line pre-charge signal **303** (BPCHB\_BOT) for the bottom memory cell **312** or **305** (BPCHB\_TOP) for the top memory cell **314**. For an operation signal associated with the bottom memory cell **312**, the bit line pre-charge signal **303** (BPCHB\_BOT) is received by the logic (OR) gates **322**, **327** at the same time. At **1050**, the bit line pre-charge signals **323**, **331** (BPCHB\_BOT\_BL and BPCHB\_BOT\_BLB) pre charge the respective bit lines **321**, **325** (BL\_BOT and BLB\_BOT) at the same time. For an operation signal associated with the top memory cell **314**, the bit line pre-charge signal **305** (BPCHB\_TOP) is received by the logic (OR) gates **332**, **342** at the same time. At **1050**, the bit line pre-charge signals **341**, **343** (BPCHB\_TOP\_BL and BPCHB\_TOP\_BLB) precharge the respective bit lines **333**, **335** (BL\_TOP and BLB\_TOP) at the same time.

[0050] In an example method, one of two bit lines associated with a bit cell is at a high logic level and the complementary bit line is in a low logic level based on a prior operation. The global I/O **306** signals that the associated bit cell is the target of a next operation (e.g., a read or write operation), a precharge circuit precharges both bit lines to the high level (e.g., bringing the low level line high and restoring any small drop in the high level line to restore it to a proper high level). Specifically the clock generator and address decoder **310** inputs to logic circuitry which generates a bit line pre charge signal associated with a memory cell **1002**. The precharge circuit precharges both bit lines to the high level **1050**.

[0051] When a memory wake-up operation is initiated by one or more of the SD **109**, DSLP **111**, and LSLP **113** signals received by the global I/O system, the bit lines **321**, **325** (BL\_BOT and BLB\_BOT) for the bottom memory cell **312** are pre-charged, and the third delayed sleep signal **329** is generated by the third delay element **334** as described above with reference to the embodiment described above with reference to FIG. **3**. The third delayed sleep signal **329** also causes the bit lines **333**, **335** (BL\_TOP and BLB\_TOP) to be pre-charged in the same way as describe above with reference to FIG. **1**. In this way, initiation of the memory wake-up operation for the bottom memory cell second bit line **325** (BLB\_BOT) is delayed by an amount of time (D1) from initiation of the memory wake-up operation of the bottom memory cell first bit line **321** (BL\_BOT), and initiation of the memory wake-up operation for the top memory cell first bit line **333** (BL\_TOP) is delayed by an amount of time (D2) from initiation of the memory wake-up operation for the bottom memory cell second bit line **325** (BLB\_BOT), and initiation of the memory wake-up operation for the top memory cell second bit line **335** (BLB\_TOP) is delayed by an amount of time (D3) from initiation of the memory wake-up operation for the top memory cell first bit line **333** (BL\_TOP). The length of the time delays (D1, D2, and D3) may be determined by the size of the respective

delay elements **324**, **334**, and **337** (e.g., by selecting the number of inverter pairs), and may be configured such that the bit lines **321**, **325**, **333**, **335** of the memory cells **312**, **314** are pre-charged in a sequential fashion, similar to (or the same as) the sequential bit line precharging that results from the embodiment of FIG. 3.

[0052] FIG. 11 is a flow diagram depicting a method **1100** for controlling wake-up operations for a memory array that includes a plurality of memory cells. The steps of FIG. 11 are provided with reference to previously described structures for ease of understanding, but it is understood that the steps could be performed using a variety of structures. A wakeup operation is initiated at the memory input (e.g., SD, LSLP, DSLP) at **1110**. A sleep signal is propagated along a wake-up signal path to precharge a plurality of bit cells. The sleep signal precharges a first bit line of a first bit cell and then a second bit line of the first bit cell **1120**. There is a delay between the precharge of the first bit line and the second bitline. The delayed sleep signal (e.g., SLP\_TOP\_BL) next precharges a first bit line of a second bit cell and then a second bit line of the second bit cell **1130**. The delay elements (for example delay elements **307**, **324**, **334**, **337**, **344** in FIG. 3) cause each bit line to precharge at a different phase. In this method bit lines are not precharged simultaneously and peak in-rush current is reduced.

[0053] According to some embodiments, systems and methods are provided for a bit cell precharge circuit. In an example, the precharge circuit includes operational circuitry and wakeup precharge circuitry. The operational circuitry is configured such that a first bit line and a second bit line of a memory cell operate simultaneously. The wakeup precharge circuitry is configured to sequentially precharge the first bit line of a first bit cell and the second bit line of the first bit cell. In this example, the first bit line and the second bit line are each precharged through a bit line precharge signal. The bit line precharge signals having different phases because the signal is delayed between the precharging of the first bit line and the second bit line of the first bit cell. The wakeup circuitry may further precharge a first bit line of a second bit cell, and a second bit line of the second bit cell sequentially. The circuitry may, for example, precharge sequentially by positioning delay elements along the wake up signal path. In one example, the wake up signal path is configured to begin precharging the next bit line on the wake up signal path as soon as the prior bit line on the wake up signal path finishes precharging to maximize the speed of the wakeup operation while limiting peak power. In another example, the signal path is configured with additional delay elements along the wake up signal path such that additional delay occurs between the precharge of each bit line.

[0054] In an embodiment, a precharge circuit may precharge bit cells through an operational mode or a wake-up mode. The method of precharging bit lines of the bit cells results in staggering the precharging of bit lines during wake-up mode and precharging bit lines at the same time during operational mode. During operational mode, memory cells are precharged for an operation (for example a R/W operation) associated with the addressed memory cells. During operational mode, a control may precharge both bit lines of the memory cell at the same time to reduce wake-up time. The wake-up operation for a memory array may include precharging each bit line sequentially by charging one bit line, a delay occurring, and then charging a second complementary bit line of the bit cell. The time of the delay may be determined by the number of buffers, such as inverter pairs. The wake-up signal then charges the first bit line of a second memory cell, a delay occurs, and then charges a second complementary bit line of the second memory cell. The method of staggering precharging of the bit lines during wake-up operation may limit peak power consumption. This may prevent high peak power draw, reducing power for memory circuits with current maximums or permit other memory circuit components to draw power in constrained devices.

[0055] In an additional embodiment, a memory circuit includes a memory array with a plurality of memory cells, first logic circuitry, delay elements, and second logic circuitry. The first logic circuitry may be configured to generate a first bit line pre-charge signal for the first memory cell, where the first bit line pre-charge signal is generated in response to a sleep signal. The first bit line pre-charge signal is configured to charge a first bit line and then have the sleep signal propagate

through a delay element which generates a delayed sleep signal. The delayed sleep signal then charges the second complementary bit line. The second logic circuitry may be configured to generate a second bit line pre-charge signal for a second memory cell, where the second bit line pre-charge signal is generated in response to the delayed sleep signal. The second logic circuitry may be configured to provide power to one or more bit lines of the second memory cell in response to the second bit line pre-charge signal. The second logic circuitry may be configured to provide power to a first bit line and then to a second complementary bit line of the second memory cell in response to a delayed pre-charge signal.

[0056] 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 circuit comprising: circuitry configured to precharge a first bit line and a second bit line, wherein the circuitry includes: a delay element between the first bit line and the second bit line.
2. The circuit of claim 1, wherein the circuitry is a wakeup precharge circuitry configured to precharge the first bit line and the second bit line of a first bit cell, the wakeup precharge circuitry includes a wakeup signal path that includes the delay element, and the wakeup signal path further includes a second delay element between a first bit line of a second bit cell and a second bit line of the second bit cell.
3. The circuit of claim 1, wherein the delay element includes a pair of inverters.
4. The circuit of claim 1, wherein the circuitry is a wakeup precharge circuitry, and the wakeup precharge circuitry further includes an equalizer element configured to connect the first bit line and the second bit line.
5. The circuit of claim 2, wherein the circuitry is a wakeup precharge circuitry, and the wakeup precharge circuitry is configured to cause a logic state transition in a delayed sleep signal to occur after power has been provided to the first bit line.
6. The circuit of claim 1, wherein a time between precharging of the first bit line and the second bit line is based on a delay associated with the delay element.
7. A circuit comprising: a first bit line configured to receive a first precharge signal; and a second bit line configured to receive a second precharge signal, wherein the second precharge signal is generated by delaying the first precharge signal.
8. The circuit of claim 7, further comprising: a first bit cell having the first bit line and the second bit line; a first bit line of a second bit cell configured to receive a third precharge signal; and a second bit line of the second bit cell configured to receive a fourth precharge signal, wherein the third precharge signal and the fourth pre-charged signal have different phases.
9. The circuit of claim 8, wherein the first precharge signal, the second precharge signal, the third precharge signal, and the fourth precharge signal have different phases.
10. The circuit of claim 7, further comprising an equalizer device between the first bit line and the second bit line.
11. The circuit of claim 8, further comprising: a first equalizer device between the first and second bit lines of the first bit cell; and a second equalizer device between the first and second bit lines of the second bit cell.
12. The circuit of claim 7, further comprising a wake up signal path that includes a delay element.

- 13.** The circuit of claim 12, wherein the delay element includes a pair of inverters.
  - 14.** A method, comprising: generating, at a first delay element, a first delayed sleep signal from a sleep signal; and precharging a first bit line with the sleep signal and precharging a second bit line with the first delayed sleep signal.
  - 15.** The method of claim 14, wherein a wakeup operation of the method further includes: generating, at a second delay element, a second delayed sleep signal; and generating, at a third delay element, a third delayed sleep signal.
  - 16.** The method of claim 15, wherein the first delayed sleep signal, the second delayed sleep signal, and the third delayed sleep signal are generated sequentially.
  - 17.** The method of claim 15, wherein the sleep signal and the first delayed sleep signal precharge the first bit line and the second bit line of a first bit cell, respectively, and the second delayed sleep signal and the third delayed sleep signal precharge a first bit line of a second bit cell and a second bit line of the second bit cell, respectively.
  - 18.** The method of claim 14, wherein the first delay element includes a pair of inverters.
  - 19.** The method of claim 14, further comprising, during a wakeup operation, equalizing voltages on the first and second bit lines.
  - 20.** The method of claim 19, further comprising equalizing voltages on a first bit line of a second bit cell and a second bit line of the second bit cell.
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