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# United States Patent [19]

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[54] **METHOD OF FORMING A LOGIC ARRAY FOR A DECODER**

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[\*] Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

[21] Appl. No.: **09/313,049**

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### Related U.S. Application Data

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[51] Int. Cl.<sup>7</sup> ..... **H01L 21/336**; H01L 21/84

[52] U.S. Cl. .... **438/257**; 438/157; 438/268;  
438/269

[58] Field of Search ..... 438/257, 268,  
438/269, 157, 193; 365/230.06, 185.01;  
257/328, 365, 329, 330, 331

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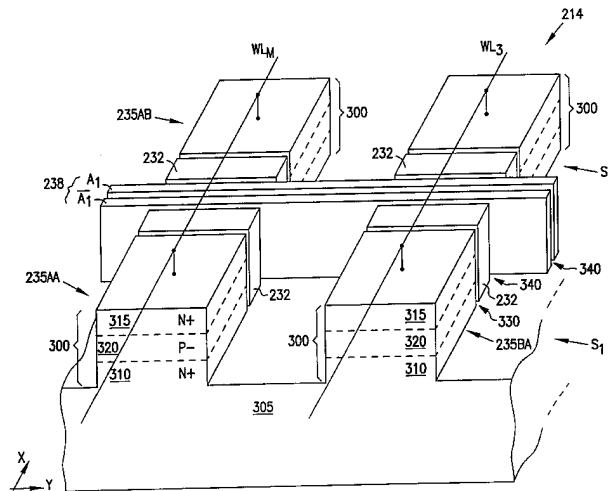
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[57] **ABSTRACT**

A programmable memory address decode array with vertical transistors having single or split control lines is used to select only functional lines in a memory array. The transistor is a field-effect transistor (FET) having an electrically isolated (floating) gate that controls electrical conduction between source regions and drain regions. If a particular floating gate is charged with stored electrons, then the transistor will not turn on and will act as the absence of a transistor at this location in a logic array within the decoder. The decoder is programmed at memory test to select an output line responsive to the bits received via the address input lines. A logic array includes densely packed logic cells, each logic cell having a semiconductor pillar providing shared source and drain regions for two vertical floating gate transistors that have individual floating gates and control lines distributed on opposing sides of the pillar. The control lines are formed together with interconnecting address input lines. The source regions share a common ground while the drain regions are connected to the output lines. Both bulk semiconductor and silicon-on-insulator embodiments are provided. If a floating gate transistor is used to represent a logic function, an area of only  $2F^2$  is needed per bit of logic, where F is the minimum lithographic feature size.

**18 Claims, 17 Drawing Sheets**



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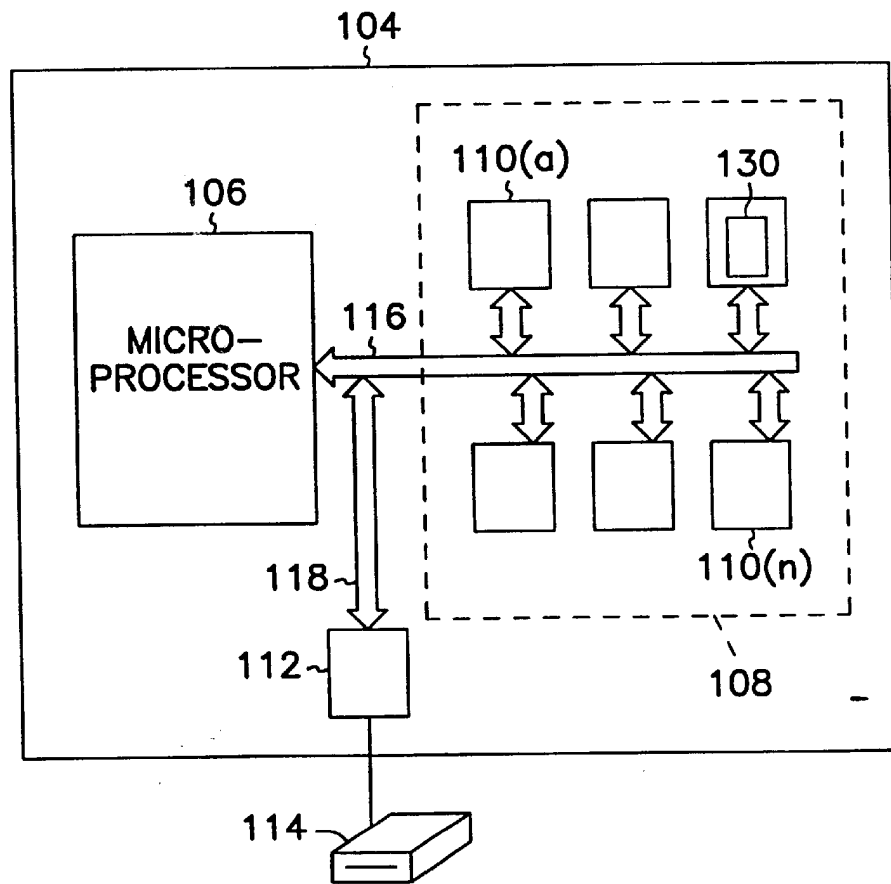
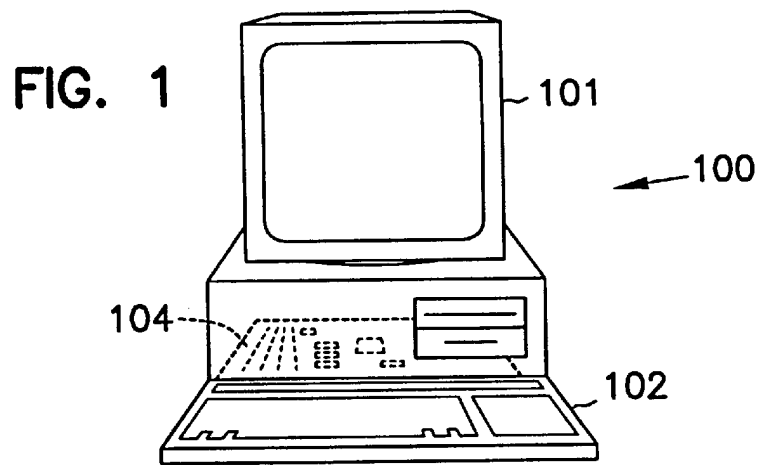
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**FIG. 2**

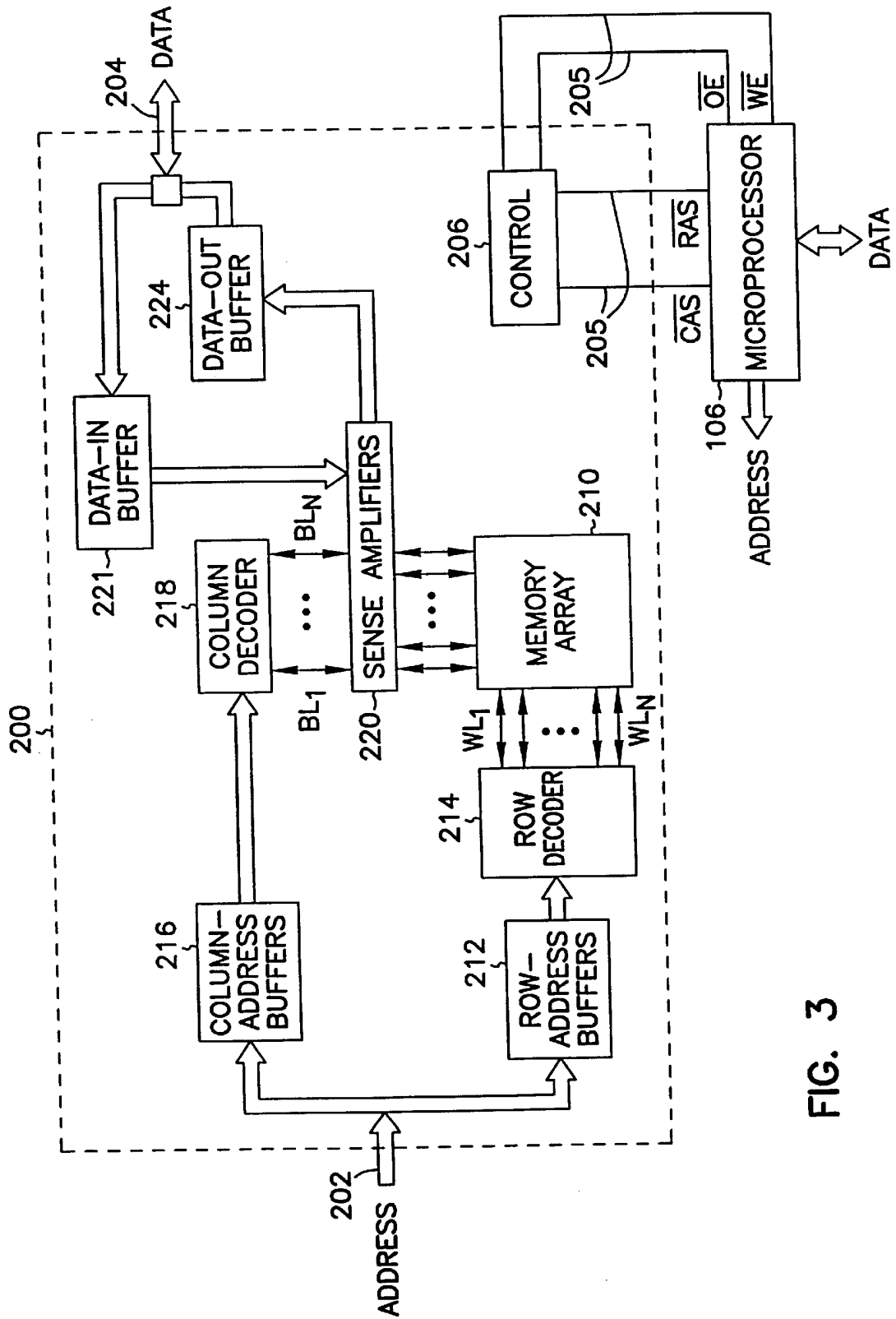


FIG. 3



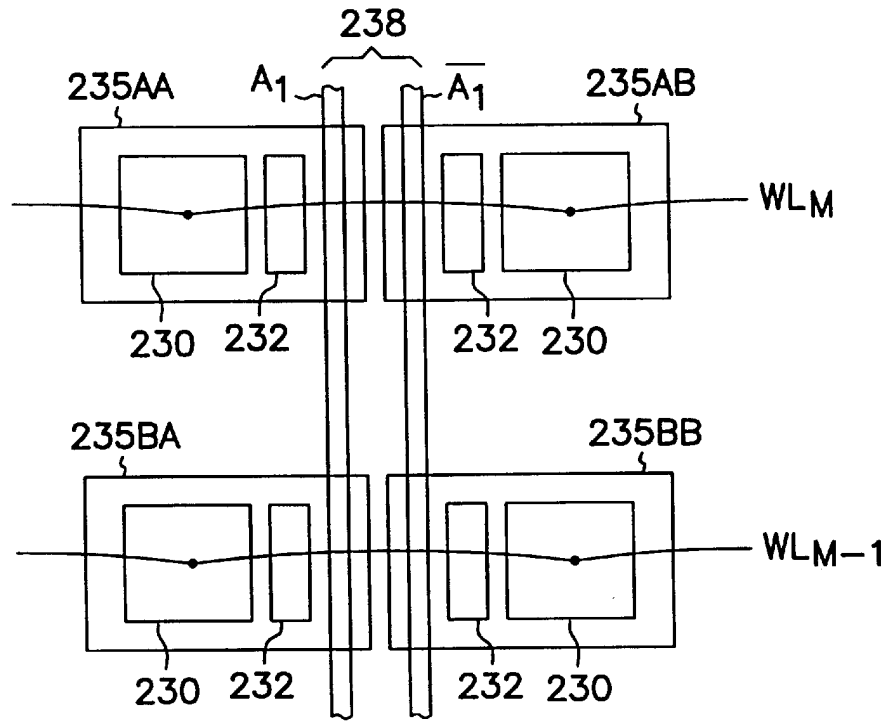


FIG. 5A

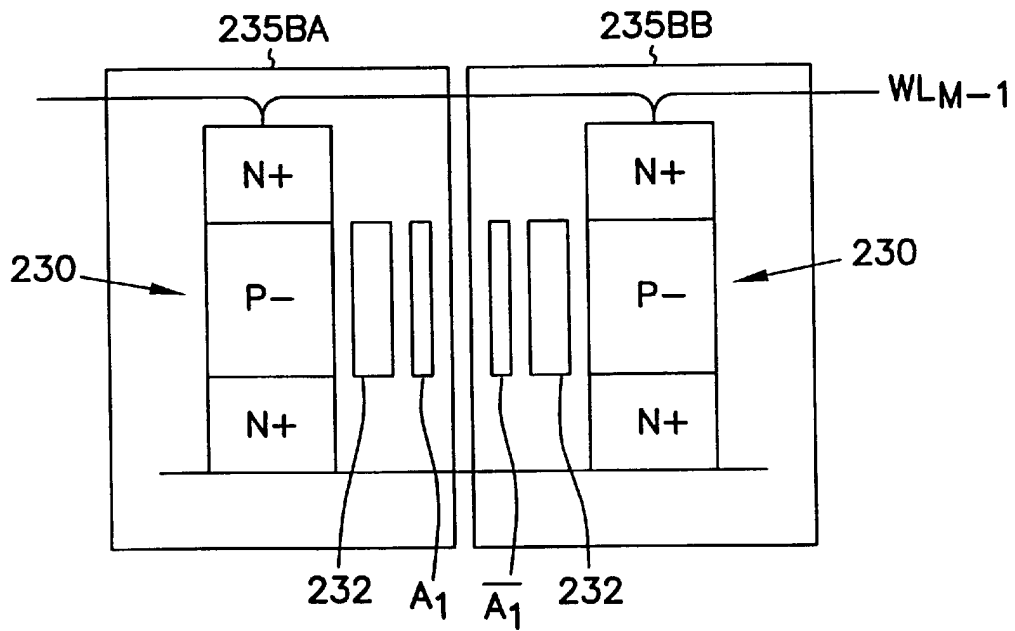


FIG. 5B

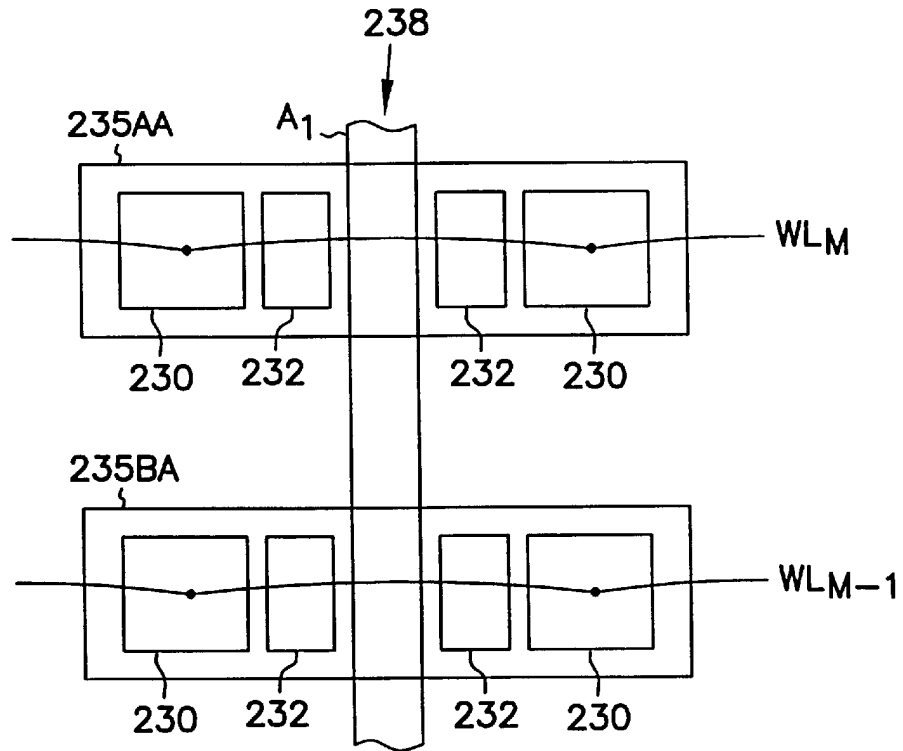


FIG. 5C

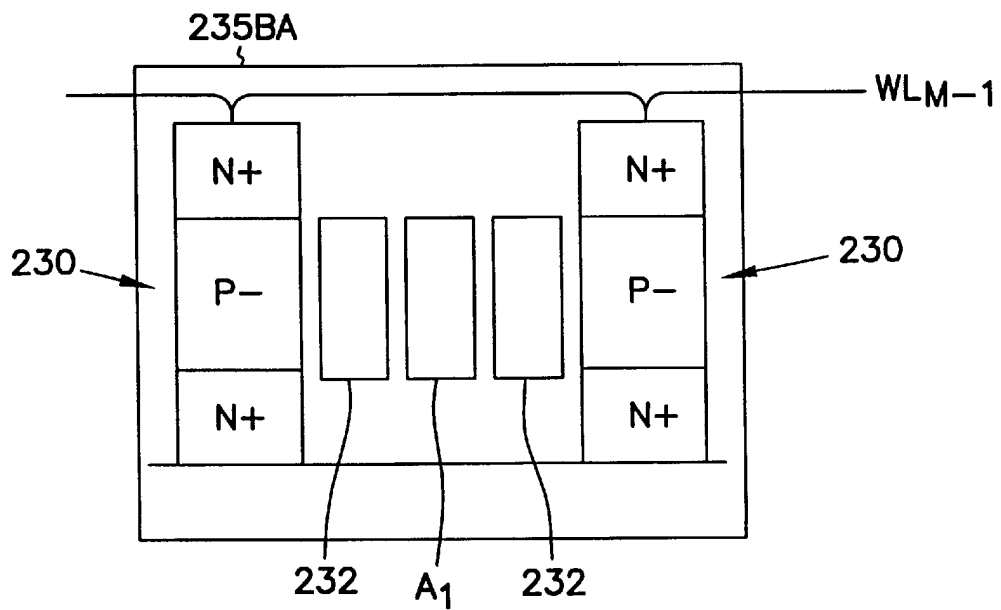


FIG. 5D



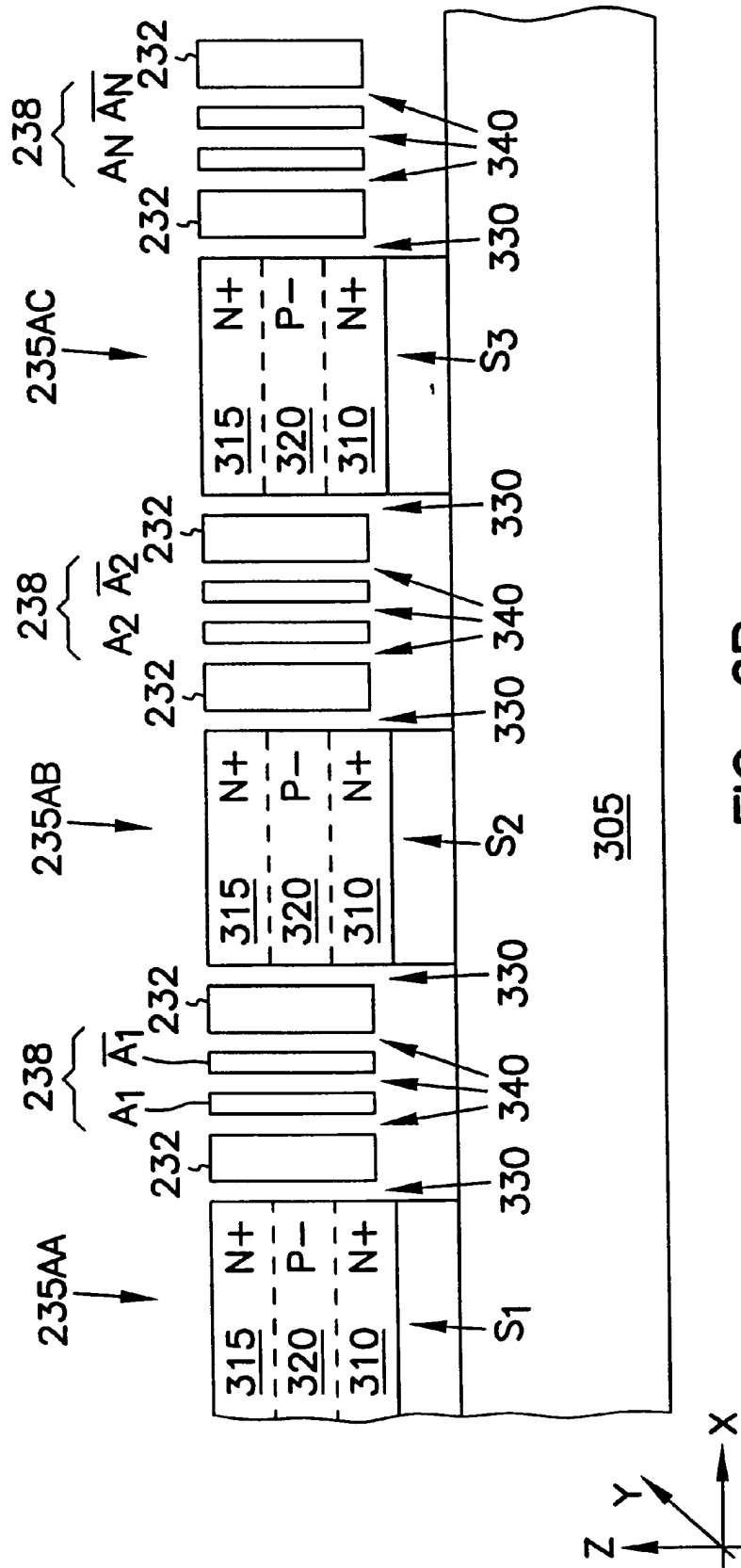


FIG. 6B

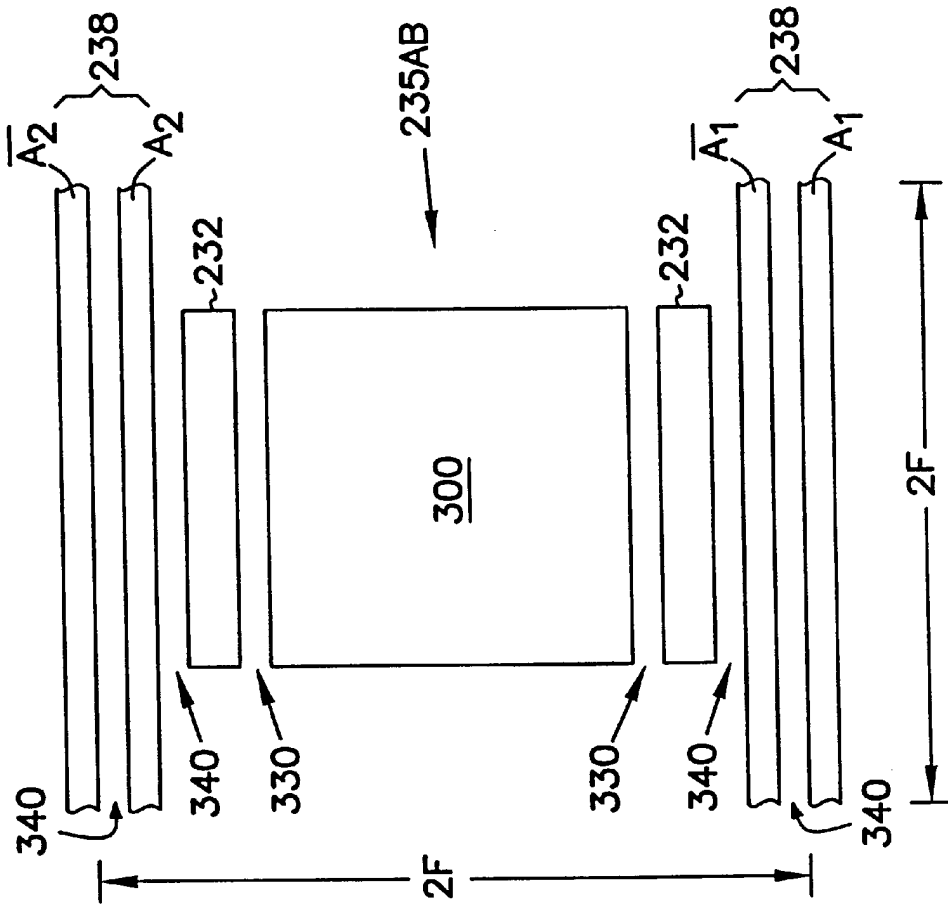


FIG. 7

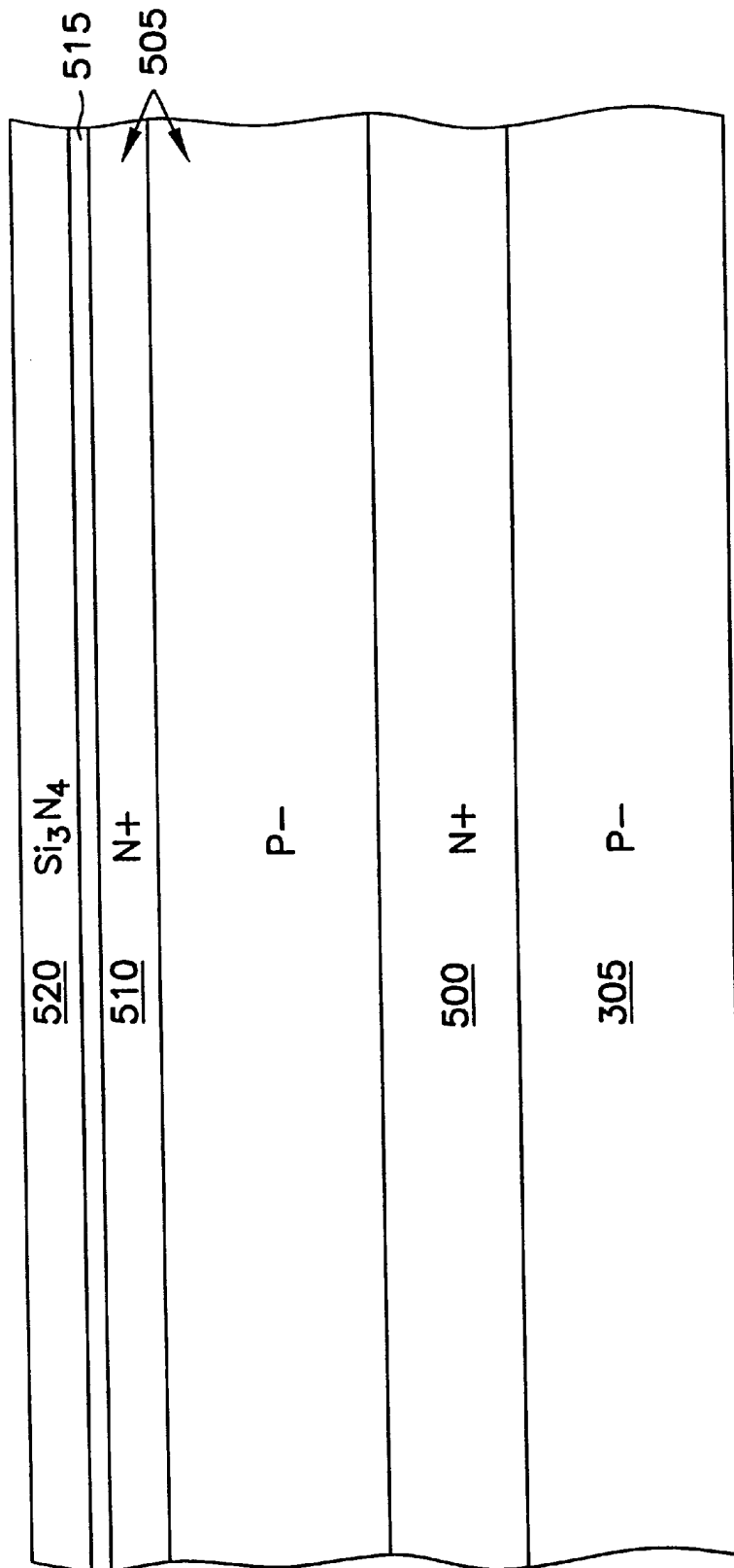


FIG. 8

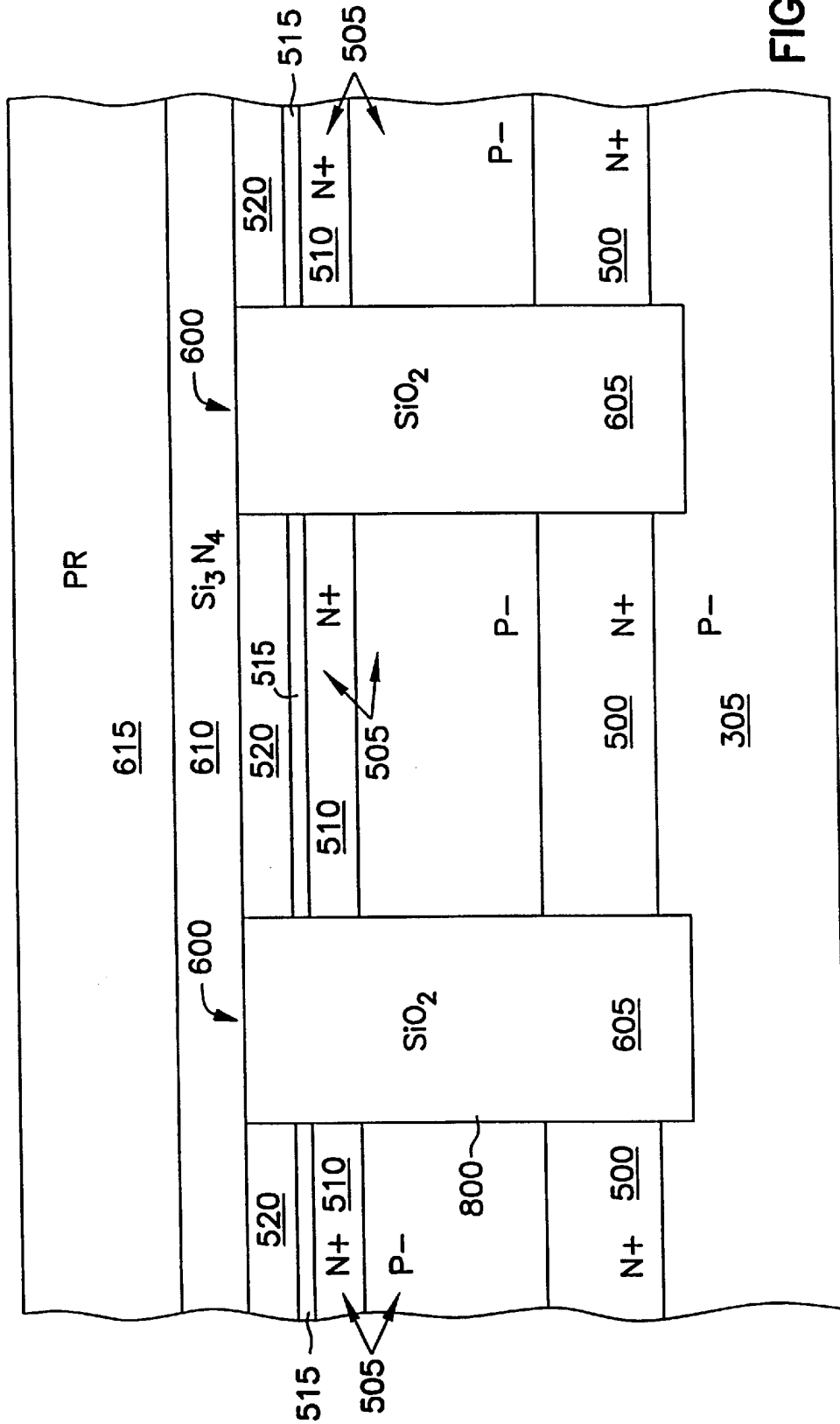


FIG. 9

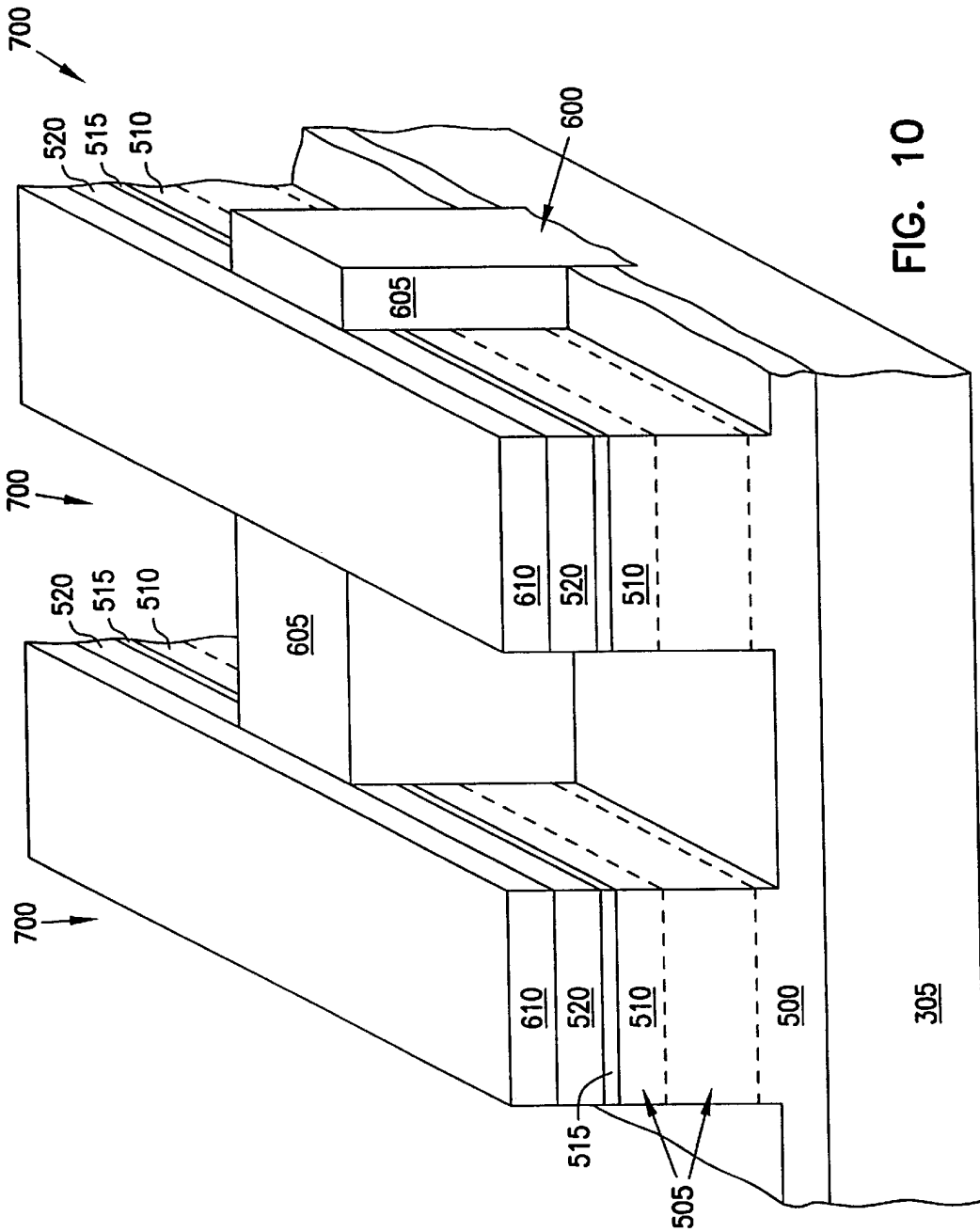


FIG. 10

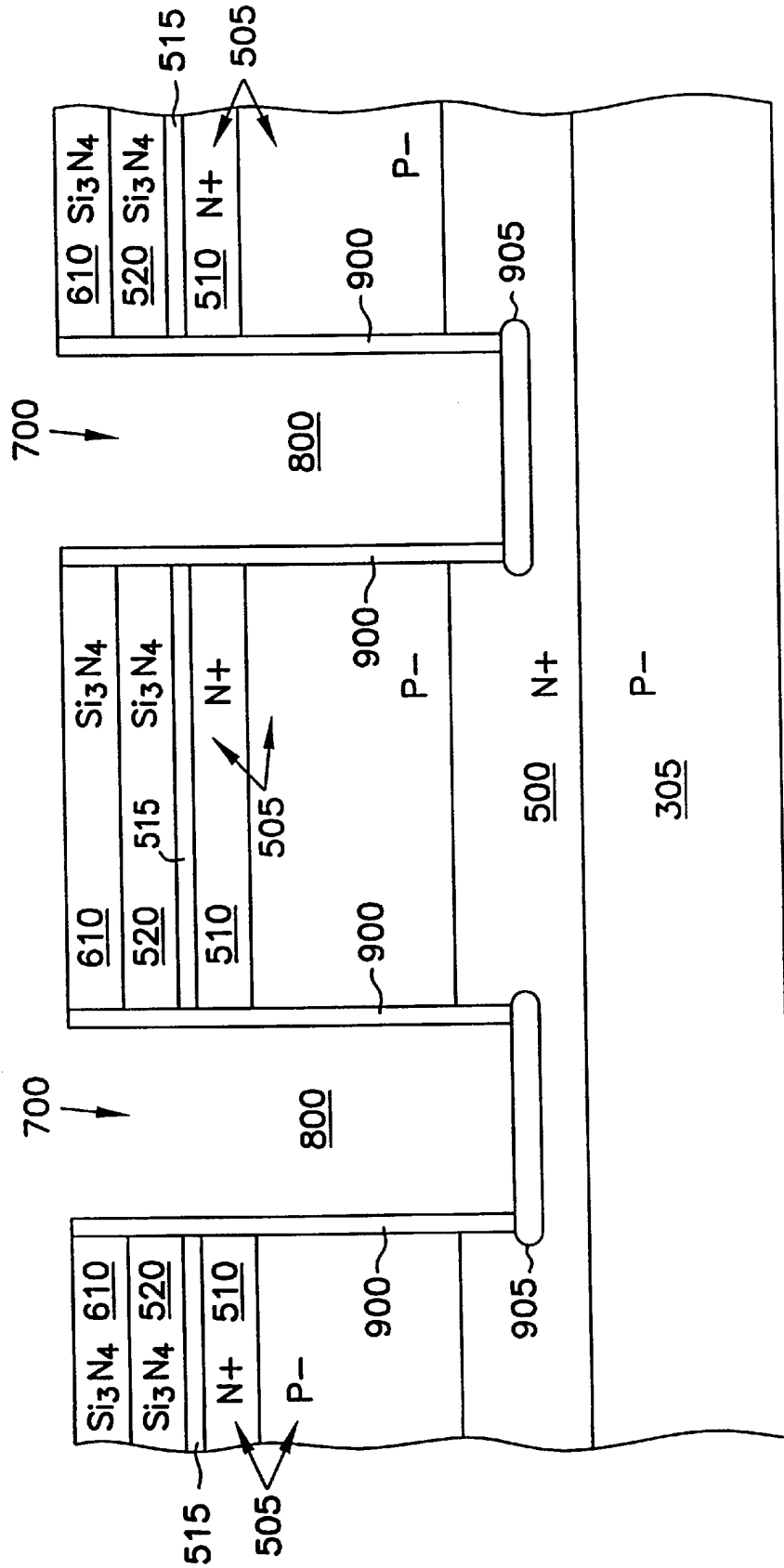


FIG. 11

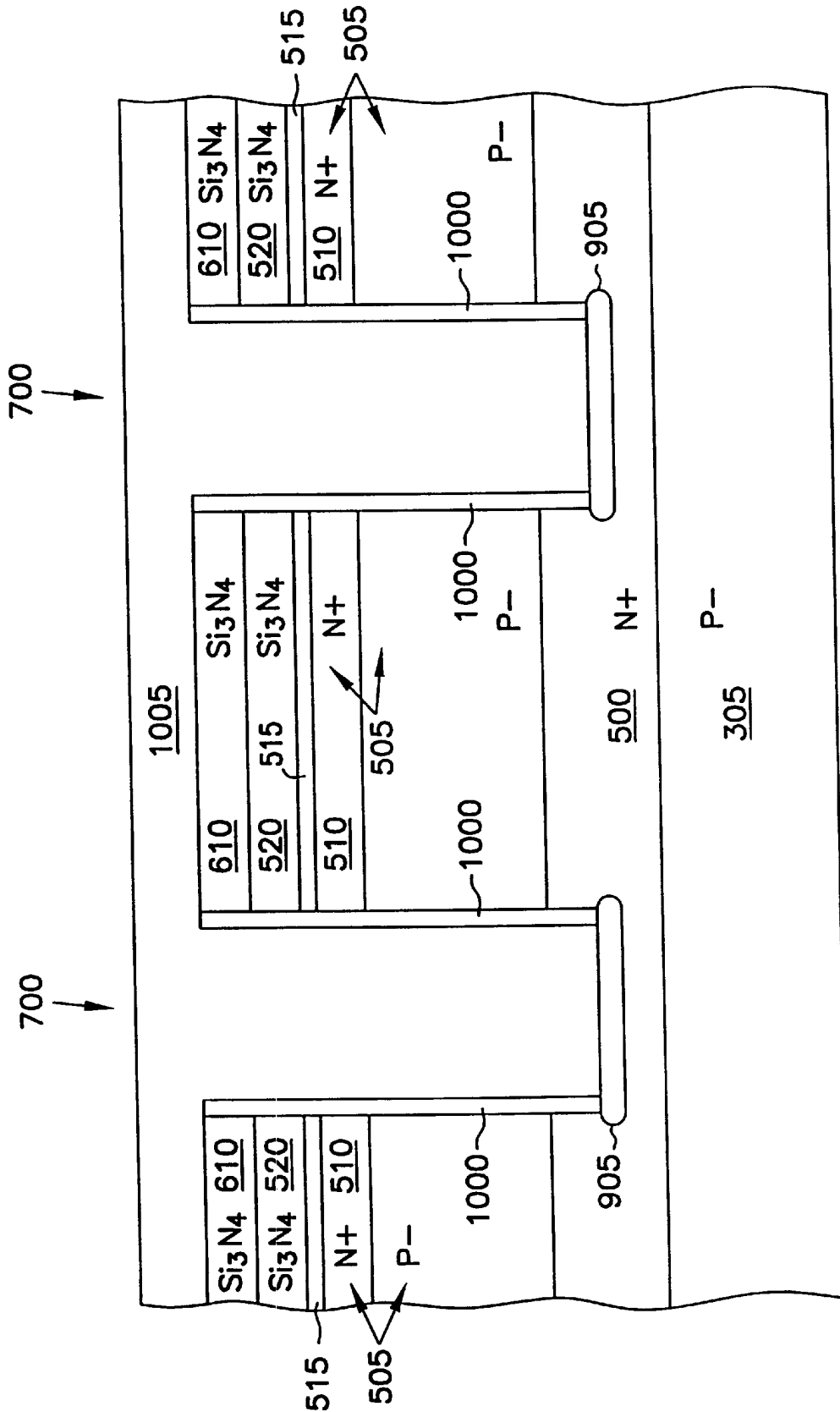


FIG. 12



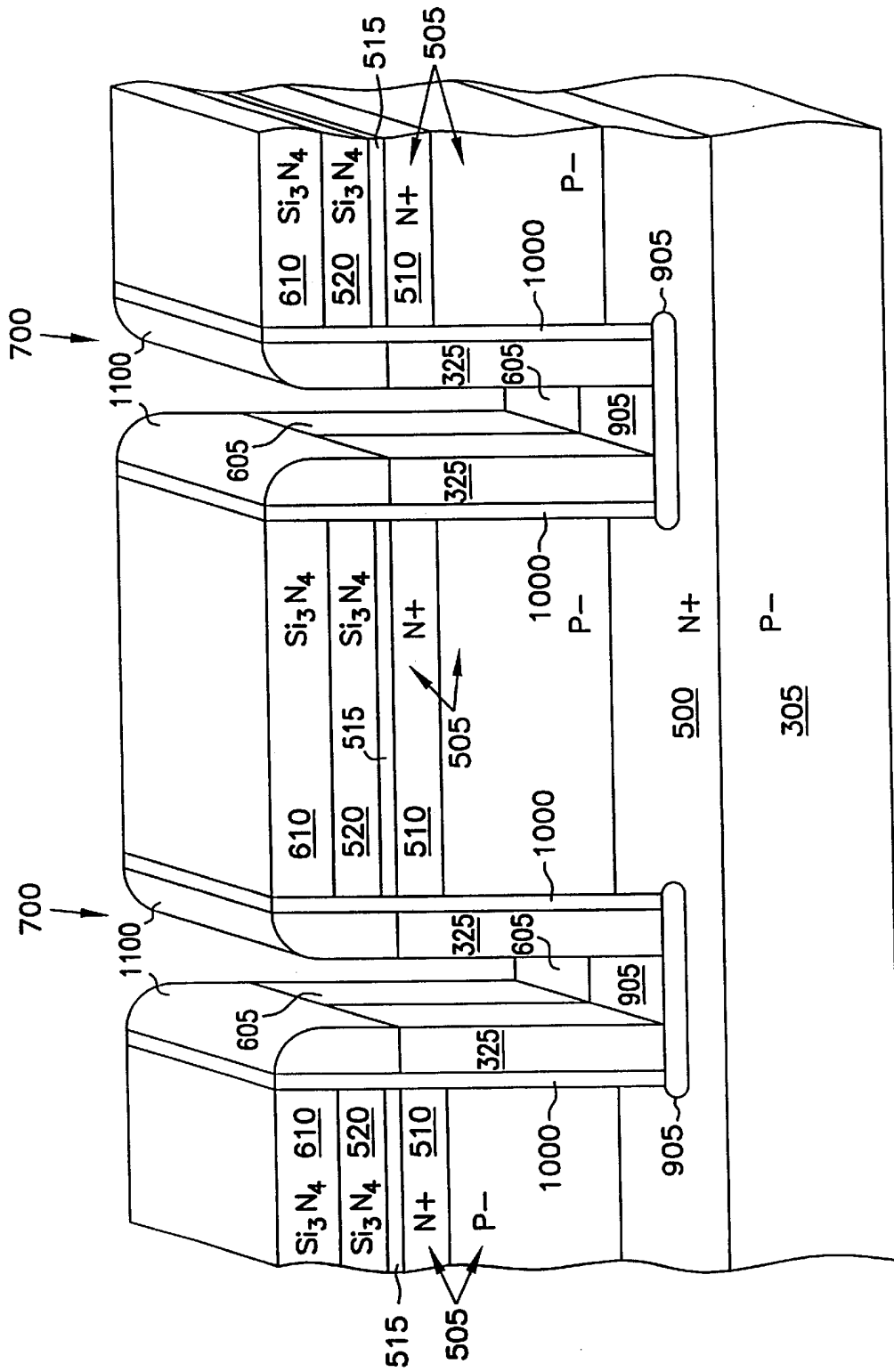


FIG. 14

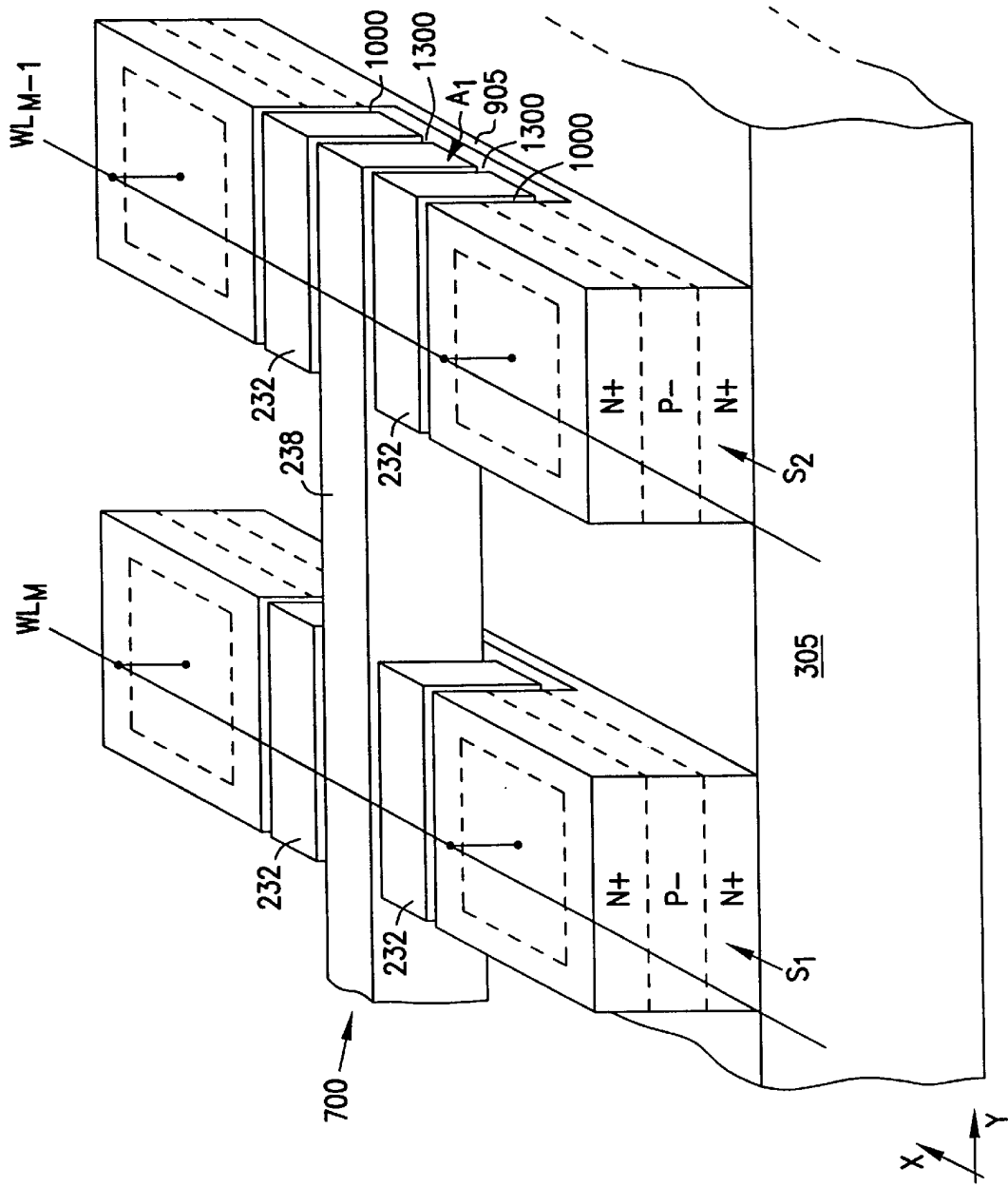


FIG. 15

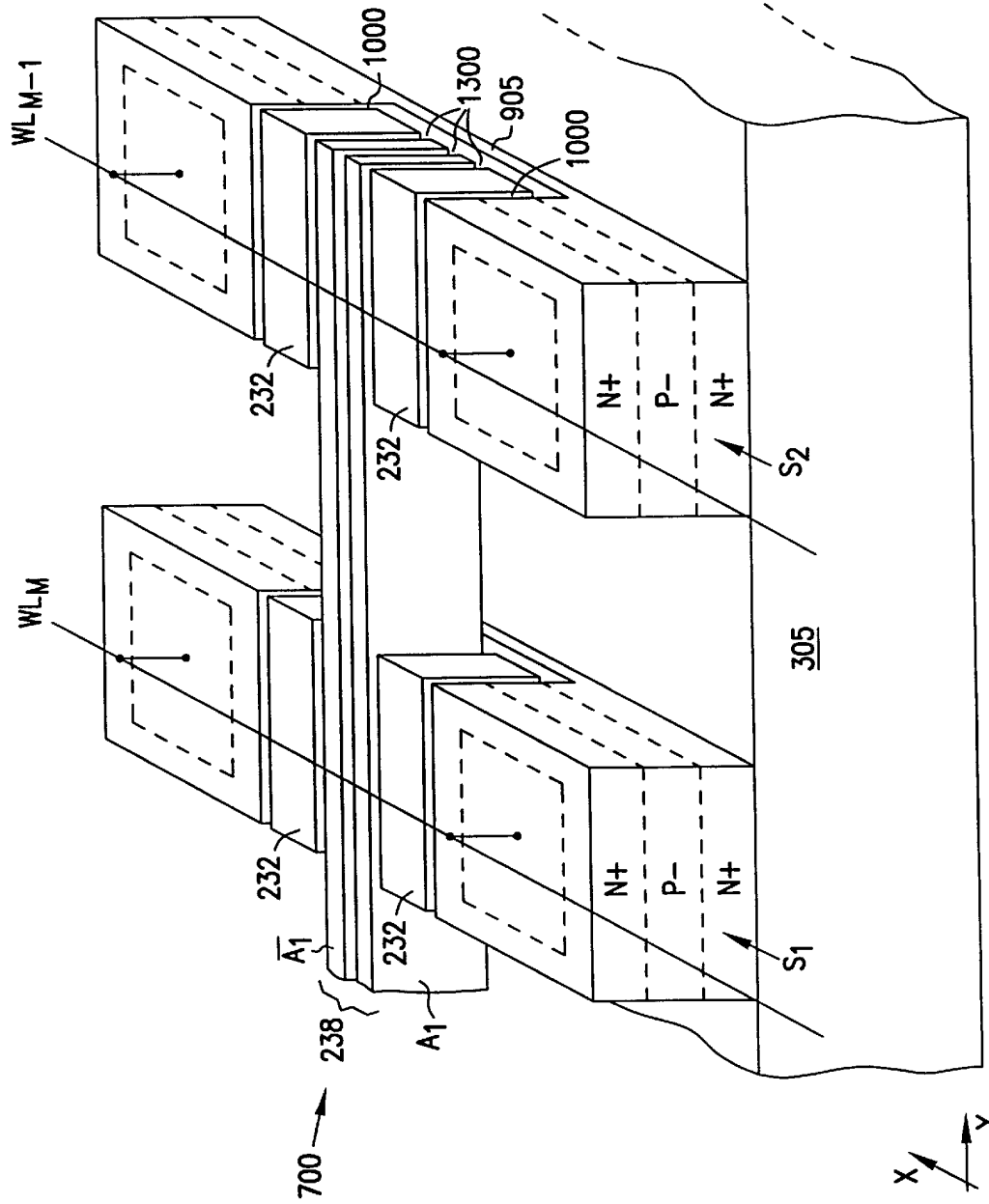


FIG. 16

## METHOD OF FORMING A LOGIC ARRAY FOR A DECODER

This application is a divisional of U.S. Ser. No. 09/031,621 filed Feb. 27, 1998 now U.S. Pat. No. 5,991,225.

### TECHNICAL FIELD OF THE INVENTION

This invention relates generally to integrated circuits and in particular to a programmable memory address decode array with vertical transistors.

### BACKGROUND OF THE INVENTION

Technological advances have permitted semiconductor integrated circuits to comprise significantly more circuit elements in a given silicon area. Reducing and eliminating defects in the circuit elements has, however, become increasingly more difficult with the increased number of circuit elements. To achieve higher population capacities, circuit designers strive to reduce the size of the individual circuit elements to maximize available die real estate. The reduced size makes these circuit elements increasingly susceptible to defects caused by material impurities during fabrication.

Nevertheless, defects are identifiable upon completion of the integrated circuit fabrication by testing procedures, either at the semiconductor chip level or after complete packaging. Scrapping or discarding defective integrated circuits when defects are identified is economically undesirable, particularly if only a small number of circuit elements are actually defective.

Relying on zero defects in the fabrication of integrated circuits is an unrealistic option. Therefore, redundant circuit elements are provided on integrated circuits to reduce the number of scrapped integrated circuits. If a primary circuit element is determined to be defective, a redundant circuit element is substituted for the defective primary circuit element. Substantial reductions in scrap are achieved by using redundant circuit elements without substantially increasing the cost of the integrated circuit.

One type of integrated circuit device using redundant circuit elements is integrated memory circuits, such as dynamic random access memories (DRAMs), static random access memories (SRAMs), video random access memories (VRAMs), and erasable programmable read only memories (EPROMs). Typical integrated memory circuits comprise millions of equivalent memory cells arranged in arrays of addressable rows and columns. The rows and columns of a memory cell array are the primary circuit elements of the integrated memory circuit. By providing redundant circuit elements, either as rows or columns, defective primary rows or columns can be replaced with functional ones.

Decoders perform an essential task by selecting the functional rows and columns of the integrated memory array. The memory cells within an integrated memory array are coupled to an electronic system through the address and data lines. Decoder circuits interface between the address lines and the array of memory cells.

A conventional decoder circuit of a semiconductor memory device comprises one or more separate decoder units which supply decode output signals according to an input address signal. A row decoder selects the appropriate row and the column decoder selects the appropriate column corresponding to a particular memory cell within the memory array. The pair of decoder output signals are also referred to wordlines, which corresponds to a row decoder, and bitlines, which correspond to a column decoder.

Decoders contain the required logic functions required to properly address desired memory cells within a memory cell array. Traditionally, decoder circuits are masked with a logic configuration for selecting rows and columns. Once the logic function has been masked, it is very difficult to make a correction. An improperly programmed decoder results in an integrated memory device functioning incorrectly.

A technique used to correct a decoder after it has been masked is to use ion beams or lasers. Making corrections to a decoder after it has been programmed is a very time consuming and cumbersome process using these common techniques.

To provide some level of programmability in a decoder, antifuses are used. To program an antifuse "on," a large programming voltage is applied across the antifuse terminals, breaking down the interposed dielectric and forming a conductive link between the antifuse terminals. An unprogrammed "off" state, in which the antifuse is fabricated, presents a high resistance between the antifuse terminals. The antifuse can be reprogrammed to an "on" state in which a low resistance connection between the antifuse terminals is desired, but only for a very limited number of times.

Therefore, a problem with current row and column decoders is that once they are programmed with a particular logic function, changes are often difficult and complex to make. If a decoder is not properly programmed, the integrated memory circuit will likewise not function properly, which defeats the purpose of having redundant circuit elements on an integrated memory array. There are elaborate techniques to reprogram a decoder, but these techniques are cumbersome and time consuming. Therefore, there is a need in the art for a decoder that can be easily reprogrammed.

Another problem with decoders is that as integrated circuit technology advances, the size of individual circuit elements decreases. Designers can include more storage cells in a memory array on a semiconductor substrate. As the number of storage cells increases, the number of components in a decoder likewise need to increase.

Increasing the storage capacity of a decoder array requires a reduction in the size of the transistors and other components in order to increase the decoder's density. However, memory density is typically limited by a minimum lithographic feature size (F) imposed by lithographic processes used during fabrication. For example, the present generation of high density decoders require an area of  $8F^2$  per bit of data. Therefore, there is a need in the art to provide even higher density decoders in order to further support the increased storage capacity of integrated memory circuits.

### SUMMARY OF THE INVENTION

A programmable memory address decode array with vertical transistors is implemented for selecting only functional lines in a memory array. The decoder is programmed at memory test and is easily reprogrammed.

In one embodiment, a decoder for a semiconductor memory comprises a number of address input lines, a number of output lines, and an array of logic cells connected between the address input and the output to select an output line responsive to address bits received via the address input. Each logic cell includes at least a pair of transistors formed on opposing sides of a common pillar of semiconductor material that extends outwardly from a working surface of a substrate to form source, drain and body regions for the transistors. A number of floating gates are also formed wherein each gate is associated with a side of the pillar and

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a number of control lines are also formed wherein each control line is associated with a floating gate.

In particular, a decoder for a semiconductor memory comprises an array of logic cells. Each logic cell includes at least a pair of transistors formed on opposing sides of a common pillar of semiconductor material that forms source, drain and body regions for the transistors. At least a pair of floating gates are disposed adjacent to the opposing sides of the pillar. At least one first source and drain interconnection line, interconnecting one of the first source and drain regions of one of the logic cells is formed. A plurality of output lines, each output line interconnecting one of the second source and drain regions of one of the memory cells is also formed. A plurality of address input lines for receiving address bits are formed, wherein the array of logic cells connected between the plurality of address input lines and the plurality of output lines selects an output line responsive to the received address bits.

In another illustrative embodiment, a memory device comprises an array of memory cells, each memory cell includes a transistor, a capacitor, and a bit contact. Addressing circuitry is coupled to the array of memory cells via wordlines for accessing individual memory cells in the array of memory cells. The addressing circuitry includes a row decoder having a number of address input lines, a number of output lines, and an array of logic cells connected between the address input and the output to select a wordline responsive to address bits received via the address input. A read circuit is coupled to the array of memory cells via bitlines for reading individual memory cells in the array of memory cells. The read circuit includes a column decoder having a number of address input lines, a number of output lines, and an array of logic cells connected between the address input and the output to select a bitline responsive to address bits received via the address input.

In another embodiment, a computer system comprises a memory device. The memory device includes an array of memory cells, each memory cell includes a transistor, a capacitor, and a bit contact. Addressing circuitry is coupled to the array of memory cells via wordlines for accessing individual memory cells in the array of memory cells. The addressing circuitry includes a row decoder having an address input having  $N$  input lines, an output having  $2^N$  output lines, and an array of logic cells connected between the address input lines and the output lines to select a wordline responsive to address bits received via the address input lines. A read circuit is coupled to the array of memory cells via bitlines for reading individual memory cells in the array of memory cells. The read circuit includes a column decoder having an address input having  $N$  input lines, an output having  $2^N$  output lines, and an array of logic cells connected between the address input and the output to select a bitline responsive to address bits received via the address input.

In yet another embodiment, a method of forming a logic array for a decoder is provided. The method includes several steps as described below. A plurality of first conductivity type semiconductor pillars are formed upon a substrate, each pillar having top and side surfaces. Next, a plurality of first source and drain regions are formed, of a second conductivity type, each of the first source and drain regions formed proximally to an interface between the pillar and the substrate. Forming a plurality of second source and drain regions, of a second conductivity type, each of the second source and drain regions formed within one of the pillars and distal to the substrate and separate from the first and source drain region. Forming a gate dielectric on at least a portion

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of the side surface of the pillars. A plurality of floating gates is formed, each of the floating gates formed substantially adjacent to a portion of the side surface of one of the pillars and separated therefrom by the gate dielectric. A plurality of control lines are formed, each of the control lines formed substantially adjacent to one of the floating gates and insulated therefrom, such that there are two control lines between the common pillars. Forming an intergate dielectric, interposed between ones of the floating gates and one of the control lines. Forming an intergate dielectric, interposed between the two control lines between the common pillars. Forming a plurality of address input lines that interconnect the control lines. At least one first source/drain interconnection line interconnecting ones of the first source/drain regions is formed and a plurality of data lines are formed, each data line interconnecting ones of the second/source drain regions.

In a still further embodiment, a method of forming a decoder logic array on a substrate is provided. The method comprises the steps of forming a first source/drain layer at a surface of the substrate. Then a semiconductor epitaxial layer on the first source/drain layer is formed. Next, a second source/drain layer at a surface of the epitaxial layer is formed. Etching is performed, in a first direction, for a plurality of substantially parallel first troughs in the epitaxial layer. The steps continue with forming an insulator in the first troughs, etching, in a second direction that is substantially orthogonal to the first direction, a plurality of substantially parallel second troughs in the epitaxial layer, forming a gate dielectric layer substantially adjacent to sidewall regions of the second troughs, and forming a conductive layer in the second troughs. A portion of the conductive layer is removed in the second troughs such that floating gate regions are formed along the sidewall regions therein and separated from the sidewall regions by the gate dielectric layer. Finally, the steps include forming an intergate dielectric layer on exposed portions of the floating gate regions in the second troughs, and forming control line regions and address input lines between opposing floating gate regions in the second troughs and separated from the floating gate regions in the second troughs by the intergate dielectric layer.

In another embodiment, a method of forming a decoder logic array on a substrate is provided, comprising the steps of forming a first source/drain layer at a surface of the substrate, forming a semiconductor epitaxial layer on the first source/drain layer, forming a second source/drain layer at a surface of the epitaxial layer, etching, in a first direction, a plurality of substantially parallel first troughs in the epitaxial layer. The steps also include forming an insulator in the first troughs, etching, in a second direction that is substantially orthogonal to the first direction, a plurality of substantially parallel second troughs in the epitaxial layer, forming a gate dielectric layer substantially adjacent to sidewall regions of the second troughs, forming a conductive layer in the second troughs and removing a portion of the conductive layer in the second troughs such that floating gate regions are formed along the sidewall regions therein and separated from the sidewall regions by the gate dielectric layer. Finally, the following steps are performed. Forming an intergate dielectric layer on exposed portions of the floating gate regions in the second troughs, forming split control line regions and address input lines between opposing floating gate regions in the second troughs, separating from the floating gate regions in the second troughs by the intergate dielectric layer, and separating the split control lines by the intergate dielectric layer.

Therefore, bulk semiconductor and semiconductor-on-insulator embodiments of the present invention provide a high density programmable memory address decode device. If a floating gate of transistor data is used to represent a logic function, an area of only  $2F^2$  is needed, where F is the minimum lithographic feature size. The programmability of the decoder device is particularly advantageous for selecting functional lines in a memory array without having to program a logic array with a mask. If a logic change needs to be made to the decoder, selected transistors in the logic array are simply reprogrammed.

A programmable memory decode device thus allows a user to define a selected output line in response to address bits received via an address input. The logic function is defined without having to actually mask a logic array. In different embodiments of the invention, bulk semiconductor, semiconductor-on-insulator, single control lines, split control lines and floating gates of varying scope are described. Still other and further embodiments, aspects and advantages of the invention will become apparent by reference to the drawings and by reading the following detailed description.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a personal computer of the present invention.

FIG. 2 illustrates a block diagram of an interface for a microprocessor and a memory device of FIG. 1.

FIG. 3 is a block diagram illustrating generally an architecture of a DRAM integrated memory circuit.

FIG. 4 is a schematic diagram illustrating generally an architecture of one embodiment of a programmable decode array.

FIG. 5A illustrates a top view of a portion of an array of logic cells having a split control line.

FIG. 5B illustrates a front view of a portion of an array of logic cells having a split control line.

FIG. 5C illustrates a top view of an alternative embodiment of the array of logic cells of FIG. 5A having a single control line.

FIG. 5D illustrates a front view of an alternative embodiment of the array of logic cells of FIG. 5A having a single control line.

FIG. 6A is a perspective view illustrating generally one embodiment of a completed programmable decode array, including portions of four transistors having split control lines.

FIG. 6B is a cross-sectional view of the completed programmable row decoder of FIG. 6A looking perpendicular to wordlines  $WL_1$ - $WL_m$ .

FIG. 7 is a plan view looking toward the working surface of a substrate, illustrating generally by way of example one embodiment of a logic cell.

FIG. 8 illustrates a side view of a substrate material having a plurality of source/drain layers on top of the substrate material for forming a programmable row decoder.

FIG. 9 illustrates a plurality of parallel first troughs extending through a plurality of layers formed on top of a substrate material.

FIG. 10 is a perspective view of a plurality of parallel second troughs orthogonal to the first troughs illustrated in FIG. 9.

FIG. 11 is a cross-sectional view looking in the direction of the second troughs illustrated in FIG. 10.

FIG. 12 is a cross-sectional view looking in the direction of the second troughs provided in FIG. 11 illustrating a barrier layer stripped from the sidewalls of the second troughs.

FIG. 13 is a cross-sectional view looking in the direction of the second troughs provided in FIG. 12 illustrating a conductive layer in the second troughs.

FIG. 14 is a perspective view of the second troughs provided in FIG. 13 illustrating spacers positioned for use as a mask.

FIG. 15 is a perspective view illustrating a single control line formed between opposing floating gates in the second troughs provided in FIG. 14.

FIG. 16 is a perspective view illustrating split control lines formed between opposing floating gates in the second troughs provided in FIG. 14.

#### DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description of the invention, reference is made to the accompanying drawings which form a part hereof, and in which is shown, by way of illustration, specific embodiments in which the invention may be practiced. In the drawings, like numerals describe substantially similar components throughout the several views. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the present invention. The terms wafer and substrate used in the following description include any structure having an exposed surface with which to form the integrated circuit (IC) structure of the invention. The term substrate is understood to include semiconductor wafers. The term substrate is also used to refer to semiconductor structures during processing, and may include other layers that have been fabricated thereupon. Both wafer and substrate include doped and undoped semiconductors, epitaxial semiconductor layers supported by a base semiconductor or insulator, as well as other semiconductor structures well known to one skilled in the art. The term conductor is understood to include semiconductors, and the term insulator is defined to include any material that is less electrically conductive than the materials referred to as conductors. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims, along with the full scope of equivalents to which such claims are entitled.

A personal computer **100** is illustrated in FIGS. 1 and 2, and includes a monitor **101**, a keyboard input **102**, and a central processing unit **104**. The processing unit **104** typically includes a microprocessor **106**, a memory bus circuit **108** having a plurality of memory slots **110(a-n)**, and other peripheral circuitry **112**. Peripheral circuitry **112** permits various peripheral devices **114** to interface the processor-memory bus **116** over the input/output (I/O) bus **118**.

The microprocessor **106** produces control and address signals to control the exchange of data between the memory bus circuit **108** and the microprocessor **106**, and between the memory bus circuit **108** and the peripheral circuitry **112**. This exchange of data is accomplished over the high speed memory bus **116** and over the high speed I/O bus **118**.

A plurality of memory slots **110(a-n)** are coupled to the memory bus **116** for receiving memory devices **130** well known to those skilled in the art. Memory devices include, but are not limited to the following types: static random access memory (SRAM), dynamic random access memory (DRAM), synchronous dynamic random access memory (SDRAM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only

memory (EEPROM), or Flash memories. A memory device **130** is illustrated in FIG. 2 in one of the memory slots **110(a-n)**. A memory device **130** may be packaged as a single in-line memory module (SIMM) or a dual in-line memory module (DIMM), or any other packaging schemes well known in the art.

Furthermore, these memory devices **130** can be produced in a variety of designs which provide different methods of reading from and writing to a memory cell of a memory device **130**. For example, a preferred method of reading and writing to a dynamic random access memory (DRAM) device is a page mode operation. Page mode operations in a DRAM access a row of a memory cell arrays and randomly access different columns of the array. Data stored at the row and column intersection can be read and output while that column is accessed.

Another type of memory device **130** is an extended data output (EDO) memory which allows data stored at a memory array address to be available as output after the addressed column has been closed. EDO memory can increase some communication speeds by allowing shorter access signals without reducing the time in which memory output data is available on the memory bus **116**.

Those skilled in the art will recognize that a wide variety of memory devices **130** may be used in the implementation of the present invention. The DRAM implementation described herein is illustrative only and not intended to be exclusive or limiting. A DRAM device compatible with the memory slots **110(a-n)** is illustrated generally at **200** in block diagram form in FIG. 3. The description of the DRAM **200** has been simplified for purposes of illustrating a DRAM memory device and is not intended to be a complete description of all the features of a DRAM. Those skilled in the art will recognize that a wide variety of memory devices **130** may be used in the implementation of the present invention.

In referring to the DRAM **200** device illustrated in FIG. 3, address information is provided on input line **202**, data information is provided on input line **204**, and control input is provided on a variety of input lines **205** directed to a control logic **206**. Control lines **205** are discussed in more detail within the following paragraphs. Input lines **202**, **204**, and **205** correspond to individual inputs from the memory bus **116** illustrated in FIG. 2.

As is well known in the art, the DRAM **200** includes a memory array **210** which in turn comprises rows and columns of addressable memory cells. Each memory cell in a row is coupled to a common wordline, as illustrated by lines  $WL_1-WL_m$ . Additionally, each memory cell in a column is coupled to a common bitline, as illustrated by lines  $BL_1-BL_n$ . Each cell in the memory array **210** includes a storage capacitor and an access transistor as is conventional in the art.

The DRAM **200** interfaces with, for example, the microprocessor **106** through address lines **202** and data lines **204**. Alternatively, DRAM **200** may interface with a DRAM controller, a micro-controller, a chip set or other electronic system. The microprocessor **106** also provides a number of control signals to the DRAM **200** via the control lines **205**, including but not limited to, row and column address strobe signals RAS\* and CAS\*, write enable signal WE\*, an output enable signal OE\* and other conventional control signals.

The illustrative embodiments described herein concern electrical circuitry which uses voltage levels to represent binary logic states—namely, a “high” logic level and a “low” logic level. Further, electronic signals used by the various embodiments of the present invention are generally

considered active when they are high. However, an asterisk (\*) following the signal name in this application indicates that the signal is negative or inverse logic. Negative or inverse logic is considered active when the signal is low.

A row address buffer **212** and a programmable decode array **214** receive and decode row addresses from row address signals provided on address lines **202** by the microprocessor **106**. Each unique row address corresponds to a row of cells in the memory array **210**. The programmable decode array **214** includes a wordline driver, an address decoder tree, and circuitry which translates a given row address received from the row address buffers **212** and selectively activates the appropriate wordline of the memory array **210** via the wordline drivers.

A column address buffer **216** and a column decoder **218** receive and decode column address signals provided on the address lines **202** by the microprocessor **106**. Each unique column address corresponds to a column of cells in the memory array **210**. The column decoder **218** also determines when a column is defective. The column decoder **218** is coupled to sense amplifiers **220**. The sense amplifiers **220** are coupled to complementary pairs of bitlines of the memory array **210**.

The sense amplifiers **220** are coupled to a data-in buffer **221** and a data-out buffer **224**. The data-in buffers **221** and the data-out buffers **224** are coupled to the data lines **204**. During a write operation, the data lines **204** provide data to the data-in buffer **221**. The sense amplifier **220** receives data from the data-in buffer **221** and stores the data in the memory array **210** as a charge on a capacitor of a cell at an address specified on the address lines **202**.

During a read operation, the DRAM **200** transfers data to microprocessor **106** from the memory array **210**. Complementary bitlines for the accessed cell are equilibrated during a precharge operation to a reference voltage provided by an equilibration circuit and a reference voltage supply. The charge stored in the accessed cell is then shared with the associated bitlines. A sense amplifier of the sense amplifiers **220** detects and amplifies a difference in voltage between the complementary bitlines. The sense amplifier passes the amplified voltage to the data-out buffer **224**.

The control logic **206** is used to control the many available functions of the DRAM **200**. In addition, various control circuits and signals not detailed herein initiate and synchronize the DRAM **200** operation as known to those skilled in the art. As stated above, the description of DRAM **200** has been simplified for purposes of illustrating the present invention and is not intended to be a complete description of all the features of a DRAM.

Bitlines  $BL_1-BL_n$  are used to write to and read data from the memory cells within the memory array **210**. The wordlines  $WL_1-WL_m$  are used to access a particular row of the memory cells that is to be written or read. The programmable row decode array **214** and the column decoder **218** selectively access the memory cells in response to address signals that are provided on the address lines **202** from the microprocessor **106** during write and read operations.

In operation, the DRAM memory **200** receives an address of a particular memory cell at the address buffers **212** and **216**. For example, the microprocessor **106** may provide the address buffers **212** and **216** with the address for a particular cell within the memory array **210**. The row address buffer **212** identifies wordline  $WL_1$ , for example, for the appropriate memory cell to the row decoder **214**. The row decoder **214** selectively activates the wordline  $WL_1$  to activate an access transistor of each memory cell connected to the

wordline  $WL_1$ . The column address buffer **216** identifies bitline  $BL_1$ , for example, for the appropriate memory cell to the column decoder **218**. The column decoder **218** selectively activates the bitline  $BL_1$  to activate an access transistor of each memory cell connected to the bitline  $BL_1$ .

FIG. 4 is a schematic diagram illustrating generally an architecture of one embodiment of the programmable row decoder **214**. The architecture of the programmable column decoder **218** is substantially the same and is not discussed in detail. Array type memory address decode circuits which are not programmable are well known in the art. The programmable NOR row decoder **214** of FIG. 4 is implemented with plurality of transistors **230** each having a corresponding floating gate **232**.

The transistors **230** are arranged in logic cells, such as cells **235AA**, **235BA**, . . . , **235NA**, in a first dimension, e.g., in the Y-dimension of the decoder output lines  $WL_1$ – $WL_m$ , and in cells such as **235AA**, **235AB**, . . . , **235AN** in a second dimension, e.g., in the X-dimension of the memory address interconnection lines  $A_1$ – $A_n$ . Each logic cell **235** thus includes one of the plurality of transistors **230** having a corresponding floating gate **232**. Each logic cell **235** further includes a control line **238**. The control lines **238** receive address signals provided via the address line **202**. Received address signals are directed to selected floating gates **232** of a transistor **230** via the control lines **238**. The control lines **238** are further identified more specifically as memory address input lines  $A_1$ – $A_n$ . Therefore, address input lines  $A_1$ – $A_n$  are interchangeable with the general reference term control lines **238**.

The transistor **230** is a floating gate transistor, which is a field-effect transistor (FET) having an electrically isolated (floating) gate **232** that controls electrical conduction between source regions  $S1$ – $SN$  and drain regions **242**. Drain regions **242** are interconnected with wordlines  $WL_1$ – $WL_m$ . Source regions  $S1$ – $SN$  share a common ground for operation of the row decoder **214**. As an alternative embodiment to a common ground, sources  $S1$ – $SN$  do not share a common ground.

The programmable decode array **214** is programmed at memory test to select only functional wordlines within the memory array **210**. The NOR row decoder **214** serves as an illustrative embodiment of programmable memory address decoders using the transistors **230** described herein. Other decoding schemes are acceptable, such as AND, OR, and NAND, etc.

The programmable decode array **214** has address lines  $A_1$ – $A_n$  as inputs and wordlines  $WL_1$ – $WL_m$  as output lines. For  $N$  address input lines, there are a maximum of  $2^N$  outputs lines. However, the number of outputs in the programmable decode array **214** could be less than  $2^N$ . Depending on the combination of high and low signals received via the corresponding  $A_1$ – $A_n$  input lines, any one of the  $2^N$  possible outputs corresponding to the wordlines  $WL_1$ – $WL_m$  may be selected.

Programmability of the transistor **230** is achieved by charging the corresponding floating gate **232**. When the floating gate **232** is charged, the transistor **230** remains in an off state until the transistor **230** is reprogrammed. Applying and removing a charge to the floating gate **232** is discussed in more detail within the following description. A transistor **230** in an off state is represented by a dotted circle **244** instead of actually displaying the full transistor. A transistor programmed in an off state remains in that state until the charge is removed from the floating gate **232**.

Transistors **230** not having their floating gate **232** pre-charged are fully illustrated in FIG. 4. These transistors **230**

operate in either an on state or an off state, wherein address signals received on their respective address input lines  $A_1$ – $A_n$  determine the applicable state. Each transistor **230** has a source, drain region fabricated using a semiconductor pillar on a substrate. Source  $S1$ – $SN$  is connected to a common ground for all the transistors **230** and the drain **242** is tied to a wordline row, e.g.,  $WL_1$ .

If any transistor **230** is turned on, then a ground is provided to a pull up transistor **250**. The pull up transistor **250** is attached to a wordline row, e.g.,  $WL_m$ . The transistor **250** provides a low voltage level when any one of the transistors **230** connected to the corresponding wordline row is activated. When the transistor **230** is in an off state, an open is provided to the source of the pull up transistor **250**, wherein the  $V_{DD}$  voltage level is applied to the memory array **210** when the pull up transistor **250** is turned on by a clock signal received via input line **252**.

FIGS. 5A and 5B illustrate a top view and a front view, respectively, of the logic cells **235AA**, **235BA**, **235AB** and **235BB** having a split control line **238**, e.g.,  $A_1$  and  $A_1$ . The advantage of split control lines **238** is that this requires only one transistor **230** per logic cell **235**. Since the split control lines **238** are isolated from each other, this allows a single transistor **230** to be selected.

FIGS. 5C and 5D illustrate a top view and a front view, respectively, of an alternative embodiment of logic cells **235AA** and **235BA** of FIG. 5A having a single control line, e.g.,  $A_1$ . When a single control line  $A_1$  is high, the two transistors **230** on each side of the control line **238** are activated at the same time. The advantage is that there is redundancy in the selection of a wordline, but the drawback is the loss of circuit density because of this duplication.

FIG. 6A is a perspective view illustrating generally one embodiment of a completed programmable decode array **214**, including portions of four transistors **230** having split control lines **238**, such as illustrated in FIGS. 5A and 5B. In FIG. 6A, the substantially identical transistors are illustrated by way of example through logic cells **235AA**, **235BA**, **235AB** and **235BB**. Each logic cell **235** includes a semiconductor pillar **300**, initially of a first conductivity type such as P-silicon, fabricated upon a monolithic substrate **305**. In one embodiment, substrate **305** is a bulk semiconductor, such as P-silicon. In another embodiment, a semiconductor-on-insulator (SOI) substrate **305** includes an insulating layer, such as silicon dioxide ( $SiO_2$ ), as described below.

Each pillar **300** includes a first source/drain region of a second conductivity type, such as N+ silicon source region **310**, formed proximally to a sub-micron dimensional interface between pillar **300** and substrate **305**. Each pillar **300** also includes a second source/drain region of the second conductivity type, such as N+ silicon drain region **315**, that is distal to substrate **305**, and separated from source region **310** by a first conductivity type region, such as P- body region **320**.

Each pillar **300** provides a source region **310**, a drain region **315**, and a body region **320** for floating gate transistor **230** of a particular logic cell, e.g., **235AA**. In one embodiment, the physical dimensions of each pillar **300** and the doping of P- body region **320** are both sufficiently small to allow operation of the floating gate transistors **230** that is characteristic of fully depleted body transistors. First source, drain region interconnection lines  $S1$ – $SN$  electrically interconnects the source region **310** of each pillar **300** of cells.

In one embodiment, the first source/drain interconnection lines  $S1$ – $SN$  comprise a conductively doped semiconductor

of the second conductivity type, such as N+ silicon, disposed at least partially within substrate **305**. For example, dopants can be ion-implanted or diffused into substrate **305** to form the first source/drain interconnection lines  $S1-SN$ .

In another embodiment, the first source, drain interconnection lines  $S1-SN$  are formed above substrate **305**. For example, a doped epitaxial semiconductor layer can be grown on substrate **305**, from which first source, drain interconnection lines  $S1-SN$  are formed. Alternatively, an undoped epitaxial semiconductor layer can be grown on substrate **305**, and dopants then introduced by ion-implantation or diffusion to obtain the first source, drain interconnection lines  $S1-SN$  of the desired conductivity.

Each pillar **300** is outwardly formed from substrate **305**, and is illustrated in FIG. **6A** as extending vertically upward from substrate **305**. Each pillar **300** has a top region that is separated from substrate **305** by four surrounding side regions. A floating gate **232** is formed substantially adjacent to two opposing side surfaces of pillar **300**, and separated therefrom by a gate dielectric **330**, such that there are two floating gates **232** per pillar **300**, though FIG. **6A** omits some of the floating gates **232** for clarity of illustration.

Each floating gate **232** has a corresponding substantially adjacent control line **238** from which it is separated by an intergate dielectric **340**. Except at the periphery of the array **214**, there are two control lines **238** interposed between two approximately adjacent pillars **300**. For example, in FIG. **6A**, address input lines  $A_1$  and  $\overline{A}_1$  are interposed between logic zones **235AA**, **235BA** on one side and logic zones **235AB** and **235BB** on the other side. Address input line  $A_1$  controls logic zones **235AA** and **235BA** while address input line  $\overline{A}_1$  controls logic zones **235AB** and **235BB**. Address input lines  $A_1$  and  $\overline{A}_1$  are separated by an intergate dielectric **340**.

In the single control line embodiment, a single control line **238** controls the two transistors **230** on each side of the control line, e.g., address input line  $A_1$ . A logic cell **235** has two transistors operated from a single control line **238**, as shown in FIG. **5D**. This is in contrast to the split control line **238** embodiment where only one transistor **230** is operated by a control line **238**.

Control lines **238** are interposed between approximately adjacent pillars **300**, wherein the memory address input lines  $A_1-A_n$  are substantially parallel to each other. In this embodiment, address input lines  $A_1-A_n$  are illustrated as running in the Y-dimension, e.g. perpendicular to wordlines  $WL_1-WL_m$ . Each of the memory address input lines  $A_1-A_n$  interconnects a plurality of transistors **230**. For example, address input line  $A_1$  electrically interconnects floating gate **232** of logic cells **235AA-235NA**. Having split control lines **238** allows the floating gates **232** to be independent between pairs of logic cells, **235AA** and **235BA**, **235AB** and **235BB**, . . . , **235AN** and **235BN**. In the embodiment of FIG. **6A**, the address input lines  $A_1-A_n$  are disposed above substrate **305**, as described below.

Drain regions **315** of the pillars **300** are interconnected by wordlines  $WL_1-WL_m$  that are substantially parallel to each other in the X-dimension, e.g. perpendicular to address input lines  $A_1-A_n$ . FIG. **6A** illustrates, by way of example, wordlines  $WL_m$  and  $WL_{m-1}$ , which are shown schematically for clarity. However, it is understood that wordlines  $WL_1-WL_m$  comprise metal or other interconnection lines that are isolated from the underlying topology, e.g. pillars **300**, floating gates **232**, address input lines  $A_1-A_n$  (control lines **238**), and wordlines  $WL_1-WL_m$ , by an insulating layer through which contact holes are etched to access the drain regions **315** of the pillars **300**.

FIG. **6B** is a cross-sectional view of FIG. **6A** looking in the Y-dimension, e.g. perpendicular to wordlines  $WL_1-WL_m$ . FIG. **6B** illustrates a row of logic cells **235AA**, **235AB**, . . . , **235AN**, having source regions **310** interconnected by one of first source/drain interconnection lines  $S1, S2, \dots, SN$ .

FIG. **7** is a plan view, looking toward the working surface of substrate **305**, illustrating generally by way of example one embodiment of logic cell **235AB**. Each of the two floating gates **232** is adjacent to one of opposing sides of pillar **300**, and separated therefrom by gate dielectric **330**. Each control line **238** is separated from a corresponding floating gate **232** by an intergate dielectric **340**. The control lines **238** are likewise separated by intergate dielectric **340**. Each control line **238** is integrally formed together with one of the address input lines  $A_1-A_n$ .

The center-to-center spacing ("pitch") between control lines **238** that are on opposite sides of pillar **300** is twice the minimum lithographic feature size  $F$ . Since two floating gate transistors **230** are contained within a logic cell **235** having an area of  $4F^2$ , an area of only  $2F^2$  is needed per logic cell.

In one embodiment, programming of one of the floating gate transistors **230** is by hot electron injection. For example, a voltage of approximately 10 volts is provided to a particular one of address input lines  $A_1, A_2, \dots, A_n$ , adjacent to a particular floating gate **232**. A resulting inversion region (channel) is formed in the body region **320** at the surface that is approximately adjacent to the particular one of address input lines  $A_1-A_n$ . A voltage of approximately 10 Volts is provided through a particular one of wordlines  $WL_1-WL_m$  to a particular drain region **315**. A voltage of approximately 0 Volts is provided, through a particular one of first source/drain interconnection lines  $S1-SN$ , to the particular source region **310** of the floating gate transistor **230**.

Electrons are injected onto the floating gate **232** interposed between the control line **238** and the pillar **300** in which the particular drain region **315** is disposed. The exact value of the voltages provided to the particular control line **238** and drain region **315** will depend on the physical dimension of the floating gate transistor **230**, including the thickness of the gate dielectric **330**, the thickness of the intergate dielectric **340**, and the separation between source region **310** and drain region **315**. Alternatively, if higher voltages are provided to control line **238**, and the gate dielectric **330** and intergate dielectric **340** are made thinner, the floating gate transistor **230** may be programmed instead by Fowler-Nordheim tunneling of electrons from the body region **320**, source region **310**, or drain region **315**.

In one embodiment, reading data stored on a particular floating gate transistor **230** includes providing a voltage of approximately 5 volts to a particular one of the address input lines  $A_1, A_2, \dots, A_n$  to the particular floating gate **232** of the corresponding floating gate transistor **230**. A voltage of approximately 0 Volts is provided common ground  $S1, S2, \dots, SN$  to the particular source region **310** of the particular floating gate transistor **230**. A particular one of wordlines  $WL_1-WL_m$  that is switchably coupled to the drain region **315** of the floating gate transistor **230** is precharged to a positive voltage by transistor **250**, then coupled to the drain region **315** to determine the conductivity state of the floating gate transistor **230** between its source region **310** and drain region **315**.

If there are no electrons stored on the floating gate **232**, the floating gate transistor **230** will conduct between its source region **310** and drain region **315**, decreasing the

voltage of the particular one of wordlines  $WL_1$ – $WL_m$  toward that voltage of its source region **310**, e.g. toward a “low” binary logic level voltage of approximately 0 Volts. If there are electrons stored on the floating gate **210**, the floating gate transistor **230** will not conduct between its source region **310** and drain region **315**. As a result, pull up transistor **250** will tend to increase the voltage of the particular one of wordlines  $WL_1$ – $WL_m$  toward a positive voltage, e.g. toward a “high” binary logic voltage level.

In one embodiment, erasure of floating gate transistors **230** includes providing an erasure voltage difference of approximately between 10 and 12 Volts from a source region **310** to a corresponding floating gate **232**. For example, a voltage of approximately 0 Volts is provided to source regions **310** of floating gate transistors **230** that are interconnected by one or several first source/drain interconnection lines  $S1, S2, \dots, SN$ . A voltage of approximately between 10 and 12 Volts is provided through a corresponding one or several of the address input lines  $A_1$ – $A_n$  to the floating gates **232** of the corresponding floating gate transistors **230** to be erased. As a result of the negative voltage applied to the floating gates **232**, electrons are removed from the corresponding floating gates **232** by Fowler-Nordheim tunneling, thereby removing the charge from one of the floating gate transistors **230**.

In another example, a voltage of approximately between –5 and –6 Volts is applied to the floating gate **232** and a voltage of approximately between +5 and +6 Volts is applied to the source regions **310** in order to obtain the erasure voltage difference of approximately between 10 and 12 Volts from a source region **310** to a corresponding floating gate **232**. The exact value of the erasure voltage difference will vary depending upon the physical dimensions of the floating gate transistor **230** and the thicknesses of gate dielectric **330** and intergate dielectric **340**.

In one embodiment, the entire programmable decode array **214** of floating gate transistors **230** is simultaneously erased by applying approximately between –10 and –12 Volts to each of address input lines  $A_1$ – $A_n$ , and also applying 0 Volts to each of first source/drain interconnection lines  $S1, S2, \dots, SN$ . In another embodiment, one or more sectors of the programmable decode array **214** are simultaneously erased by selectively applying approximately between –10 and –12 Volts to one or ore of control lines  $A_1$ – $A_n$ , and also applying 0 Volts to one or more of first source/drain interconnection lines  $S1, S2, \dots, SN$ .

FIGS. **8–16** illustrate generally one embodiment of a method of forming the programmable decode array **214**. In this embodiment, the programmable decode array **214** is formed using bulk silicon processing techniques and is described, by way of example, with respect to a particular technology having a minimum lithographic feature size  $F$ , which is also sometimes referred to as a critical dimension (CD), of 0.4 microns. However, the process steps described below can be scaled accordingly for other minimum feature sizes without departing from the scope of the invention.

The term “horizontal” as used in this application is defined as a plane parallel to the conventional plane or surface of a wafer or substrate, regardless of the orientation of the wafer or the substrate. The term “vertical” refers to a direction perpendicular to the horizontal as defined above. Prepositions, such as “on,” “side,” (as in sidewall), “higher,” “lower,” “over,” and under are defined with respect to the conventional plane or surface being on the top surface of the wafer or substrate, regardless of the orientation of the wafer or substrate.

In FIG. **8**, a P– silicon starting material is used for substrate **305**. A first source/drain layer **500**, of approximate thickness between 0.2 microns and 0.5 microns, is formed at a working surface of substrate **305**. In one embodiment, first source/drain layer **500** is N+ silicon formed by ion-implantation of donor dopants into substrate **305**. In another embodiment, first source/drain layer **500** is N+ silicon formed by epitaxial growth of silicon upon substrate **305**. On the first source/drain layer **500**, a semiconductor epitaxial layer **505**, such as P– silicon of 0.6 micron approximate thickness, is formed, such as by epitaxial growth.

A second source/drain layer **510**, such as N+ silicon of 150 nanometers approximate thickness, is formed at a surface of the epitaxial layer **505**, such as by ion-implantation of donor dopants into P– epitaxial layer **505** or by epitaxial growth of N+ silicon on P– epitaxial layer **505**. A thin layer of silicon dioxide ( $SiO_2$ ), referred to as pad oxide **515**, is deposited on the second source/drain layer **510**. Pad oxide **515** has a thickness of approximately 10 nanometers. A layer of silicon nitride ( $Si_3N_4$ ), referred to as pad nitride **520**, is deposited on the pad oxide **515**. Pad nitride **520** has a thickness of approximately 100 nanometers.

In the bulk silicon embodiment of FIG. **9**, photoresist masking and selective etching techniques are used to form, in the first dimension (e.g., the Y-dimension, which is perpendicular to the plane of the drawing of FIG. **9**), a plurality of substantially parallel first troughs **600** that extend through the pad nitride **520**, pad oxide **515**, second source/drain layer **510**, the underlying portion of epitaxial layer **505**, first source/drain layer **500**, and at least partially into underlying P– silicon substrate **305**.

The photoresist is then removed by conventional photoresist stripping techniques, and an insulator **605**, such as silicon dioxide deposited by chemical vapor deposition (CVD), is formed to fill first troughs **600**. The insulator **605** is planarized (e.g. exposing underlying portions of pad nitride **520**) such as by chemical mechanical polishing (CMP) or other suitable planarization technique. A masking layer **610** such as, for example, silicon nitride deposited by CVD and having an approximate thickness of 200 nanometers, is then formed on insulator **605** and elsewhere on the working surface of substrate **305**. A photoresist layer **615** is then formed on masking layer **610**.

FIG. **10** is a perspective view, illustrating the selective etching, in a second dimension (X-dimension) that is substantially orthogonal to the first dimension (Y-dimension), of a plurality of substantially parallel second troughs **700**, as described below. Forming second troughs **700** includes patterning photoresist layer **615**, selectively etching masking layer **610**, pad nitride **520**, and underlying pad oxide **515**, such that portions of silicon dioxide insulator **605** in the second troughs **700** are exposed, together with N+ silicon second source/drain layer **510**. A selective etch, which preferentially removes silicon but doesn’t substantially remove silicon dioxide, is used to etch through the exposed portions of second source/drain layer **510**, the underlying portions of epitaxial layer **505**, and approximately 100 nanometers into the underlying portions of first source/drain layer **500**. Photoresist **615** is then removed by conventional photoresist stripping techniques, leaving the structure illustrated in FIG. **10**.

FIG. **11** is a cross-sectional view looking in the direction of second troughs **700** (e.g. such that the X-dimension is orthogonal to the plane of the illustration of FIG. **11**). In FIG. **11**, a thin oxidation barrier layer **900**, such as silicon nitride of approximate thickness of 20 nanometers, is conformally

deposited by CVD to protect against the oxidation of sidewalls of second troughs **700**. Barrier layer **900** is anisotropically etched to expose bottom portions of second troughs **700**. A bottom insulation layer **905** is formed on the bottoms of second troughs **700**, such as silicon dioxide of approximate thickness of 100 nanometers formed by thermal oxidation of the exposed bottom portions of second troughs **700**.

In FIG. **12**, barrier layer **900** is stripped from the sidewalls of the second troughs **700**, such as by a brief phosphoric acid etch, which is timed to expose the sidewalls of the second troughs **700** but which avoids significant removal of the thick silicon nitride masking layer **610**. A gate dielectric layer **1000**, such as silicon dioxide of thickness approximately between 5 nanometers and 10 nanometers (sometimes referred to as "tunnel oxide"), is formed substantially adjacent to the exposed sidewalls of the second troughs **700**. A conductive layer **1005**, such as N+ doped polysilicon, is formed in the second troughs **700**, such as by CVD, to fill the second troughs **700**. The conductive layer **1005** is planarized, such as by chemical mechanical polishing (CMP) or other suitable planarization technique.

In FIG. **13**, the conductive layer **1005** is etched back in the second troughs **700** to approximately at or slightly above the level of the silicon surface, which is defined by the interface between the second source/drain layer **510** and the pad oxide **515** layer. A spacer layer, such as silicon nitride of an approximate thickness of 100 nanometers, is deposited by CVD and anisotropically etched by reactive ion etching (RIE) to leave nitride spacers **1100** along the sidewalls of the second troughs **700**, e.g. on the etched back portions of the conductive layer **1005**, on the portions of insulator **605** in the intersections of first troughs **600** and second troughs **700**, and against the second gate dielectric **1000**.

In the perspective view of FIG. **14**, spacers **1100** are used as a mask for the anisotropic etching in the second troughs **700** of the etched back portions of polysilicon conductive layer **1005** and the portions of silicon dioxide insulator **605**. A selective etch, which preferentially removes silicon dioxide but doesn't substantially remove polysilicon, is used to etch into portions of silicon dioxide insulator **605**, but not the portions of polysilicon conductive layer **1005** in second troughs **700**.

The portions of silicon dioxide insulator **605** in second troughs **700** are etched until they are approximately even with adjacent portions of bottom insulating layer **905**. Then, a selective etch, which preferentially removes polysilicon but doesn't substantially remove silicon dioxide, is used to etch through portions of conductive layer **1005** in second troughs until the bottom insulation layer **905** is exposed, thereby forming from the polysilicon conductive layer **1005** along the sidewalls of the second troughs **700**.

In the perspective view of FIG. **15**, which is orthogonal to the perspective view of FIG. **14**, an intergate dielectric **1300** is formed in the second troughs **700**, such that the intergate dielectric **1300** has an approximate thickness between 7 nanometers and 15 nanometers. In one embodiment, formation of intergate dielectric **1300** is by thermal growth of silicon dioxide. In another embodiment, formation of intergate dielectric **1300** is by deposition of oxynitride by CVD. Single control lines **238**, as illustrated in FIG. **15**, are formed between opposing floating gates **232** in the second troughs **700** and separated therefrom by the intergate dielectric **1300**. The control lines **238** in second troughs **700** are formed together with the output lines  $WL_1-WL_m$  in second troughs **700** by a single deposition greater than 150 nanometers of

N+ doped polysilicon that fills second troughs **700** and is planarized, such as by CMP down to the top level of silicon nitride masking layer **610**. Split control lines **238**, as illustrated in FIG. **16**, are formed between opposing floating gates **232** in the second troughs **700** and separated therefrom by the intergate dielectric **1300**. The control lines **238** in second troughs **700** are formed together with the output lines  $WL_1-WL_m$  in second troughs **700** by a single deposition of approximately 70 nanometers of N+ doped polysilicon that lines second troughs **700** and is then directionally etched to leave on vertical surfaces only.

Phosphoric acid is used to remove the remaining silicon nitride, such as spacers **1100**, masking layer **610**, and pad nitride **520**, leaving the structure illustrated in FIGS. **15** and **16**. An insulator such as silicon dioxide is then deposited, and subsequent processing follows conventional techniques for forming contact holes, terminal metal, and inter level insulator steps to complete wiring of the logic cells **235** and other circuits of memory **100**.

Though FIGS. **8-16** illustrate generally one embodiment of forming the memory array **105** using bulk silicon processing techniques, in another embodiment a semiconductor-on-insulator (SOI) substrate is formed from substrate **305**. In one such embodiment, a P- silicon starting material is used for substrate **305**, and processing begins similarly to the bulk semiconductor embodiment described in FIG. **8**. However, after the first troughs **600** are formed in FIG. **9**, an oxidation barrier layer is formed on the sidewalls of the first troughs **600**. An isotropic chemical etch is used to fully undercut the semiconductor regions separating the first troughs **600**, and a subsequent oxidation step is used to fill in the evacuated regions formed by the undercutting. As a result, an insulator is formed on the bottoms of first troughs **600**, bars of SOI are formed between first troughs **600**, and the topography on the working surface of substrate **305** is separated from substrate **305** by an insulating layer. The barrier layer is then removed from the sidewalls of first troughs **600**, which are then filled with insulator **605**, as illustrated in FIG. **9**. Thus, in the above described Figures, substrate **305** is understood to include bulk semiconductor as well as SOI embodiments in which the semiconductor integrated circuits formed on the surface of substrate **305** are isolated from each other and an underlying semiconductor portion of substrate **305** by an insulating layer.

One such method of forming bars of SOI is described in the Noble U.S. Patent application Ser. No. 08/745,708 which is assigned to the assignee of the present application and which is herein incorporated by reference. Another such method of forming regions of SOI is described in the Forbes U.S. patent application Ser. No. 08/706,230, which is assigned to the assignee of the present application and which is herein incorporated by reference.

Thus, the present invention provides a high density programmable memory address decoder device **214** that is easily programmed for selecting functional lines in a memory array **210**. Programmability is achieved with a field-effect transistor (FET) having an electrically isolated (floating) gate that controls electrical conduction between source regions and drain regions. Programmability is accomplished without having to mask the desired logic functions into an array structure. The floating gate transistor **230** needs an area of only  $2F^2$  to store a single bit of logic data.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of skill in the art

upon reviewing the above description. For example, though the logic cells **235** have been described with respect to a particular embodiment having two floating gate transistors **230** per pillar **300**, a different number of floating gate transistors per pillar could also be used. It is also understood that the above structures and methods, which have been described with respect to memory address decode devices having floating gate transistors **230**, are also applicable to other integrated circuits using vertically oriented field-effect transistors that do not have floating gates.

Thus, the scope of the invention is not limited to the particular embodiments shown and described herein.

What is claimed is:

**1.** A method of forming a logic array for a decoder, the method comprising:

forming a plurality of first conductivity type semiconductor pillars upon a substrate, each pillar having top and side surfaces;

forming a plurality of first source and drain regions, of a second conductivity type, each of the first source and drain regions formed proximally to an interface between a pillar and the substrate;

forming a plurality of second source and drain regions, of a second conductivity type, each of the second source and drain regions formed within one of the pillars and distal to the substrate and separate from the first source and drain region;

forming a gate dielectric on at least a portion of the side surface of one of the pillars;

forming a plurality of floating gates, each of the floating gates formed substantially adjacent to a portion of the side surface of one of the pillars and separated therefrom by the gate dielectric;

forming a plurality of control lines, each of the control lines formed substantially adjacent to one of the floating gates and insulated therefrom, such that there are two control lines between common pillars;

forming an intergate dielectric, interposed between the floating gates and the control lines;

forming an intergate dielectric, interposed between the two control lines between the common pillars;

forming a plurality of address input lines, each address input line interconnecting one of the control lines;

forming at least one first source and drain interconnection line interconnecting one of the first source and drain regions; and

forming a plurality of data lines, each data line interconnecting one of the second source and drain regions.

**2.** The method of claim **1**, further comprising forming an insulating layer between the semiconductor pillars and a semiconductor portion of the substrate.

**3.** The method of claim **1**, wherein forming at least one first source and drain interconnection line is carried out at least partially within the substrate.

**4.** The method of claim **1**, wherein forming the plurality of address input lines includes forming a plurality of substantially parallel address input lines.

**5.** The method of claim **1**, wherein forming the plurality of pillars further comprises:

growing an epitaxial layer on the substrate;

etching the epitaxial layer and a portion of the underlying substrate to form a plurality of first troughs therein for carrying an insulator; and

etching the epitaxial layer to form therein a plurality of second troughs, substantially orthogonal to the plurality

of first troughs, the second troughs for carrying the address input lines.

**6.** The method of claim **5**, wherein forming the plurality of floating gates comprises:

depositing polysilicon in the second troughs; and  
etching the deposited polysilicon in a median portion of the second troughs to form the floating gates on either side of the second troughs, each floating gate adjacent to one of the pillars but separated therefrom by the gate dielectric.

**7.** The method of claim **6**, wherein forming the plurality of address input lines comprises:

etching into the substrate in a median portion of the second troughs; and  
depositing conductive polysilicon in and above the substrate in the etched median portion of the second troughs to form the address input lines and one of the floating gates.

**8.** The method of claim **1**, wherein forming the plurality of second source and drain regions comprises ion-implanting a dopant of the second conductivity type.

**9.** The method of claim **1**, wherein forming the gate dielectric comprises growing on the side surface of each pillar a layer of silicon dioxide of thickness approximately between 5 nanometers and 10 nanometers.

**10.** The method of claim **1**, wherein forming the plurality of data lines comprises:

depositing an insulator over the pillars, the floating gates, and the address input lines;

forming contact holes in the insulator to contact the second source and drain regions of each pillar;

depositing a conductive layer on the insulator and in the contact holes; and

etching the conductive layer to form the data lines.

**11.** A method of forming a decoder logic array on a substrate, the method comprising:

forming a first source and drain layer at a surface of the substrate;

forming a semiconductor epitaxial layer on the first source and drain layer;

forming a second source and drain layer at a surface of the epitaxial layer;

etching, in a first direction, a plurality of substantially parallel first troughs in the epitaxial layer;

forming an insulator in the first troughs;

etching, in a second direction that is substantially orthogonal to the first direction, a plurality of substantially parallel second troughs in the epitaxial layer;

forming a gate dielectric layer substantially adjacent to sidewall regions of the second troughs;

forming a conductive layer in the second troughs;

removing a portion of the conductive layer in the second troughs such that floating gate regions are formed along the sidewall regions therein and separated from the sidewall regions by the gate dielectric layer;

forming an intergate dielectric layer on exposed portions of the floating gate regions in the second troughs; and

forming control line regions between opposing floating gate regions in the second troughs and separated from the floating gate regions in the second troughs by the intergate dielectric layer.

**12.** The method of claim **11**, wherein the substrate is a bulk semiconductor.

**13.** The method of claim **11**, wherein the substrate includes a semiconductor-on-insulator portion.

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14. The method of claim 11, further comprising forming an insulating layer undercutting semiconductor regions between the first troughs.

15. A method of forming a decoder logic array on a substrate, comprising:

forming a first source and drain layer at a surface of the substrate;

forming a semiconductor epitaxial layer on the first source and drain layer;

forming a second source and drain layer at a surface of the epitaxial layer;

etching, in a first direction, a plurality of substantially parallel first troughs in the epitaxial layer;

forming an insulator in the first troughs;

etching, in a second direction that is substantially orthogonal to the first direction, a plurality of substantially parallel second troughs in the epitaxial layer;

forming a gate dielectric layer substantially adjacent to sidewall regions of the second troughs;

forming a conductive layer in the second troughs;

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removing a portion of the conductive layer in the second troughs such that floating gate regions are formed along the sidewall regions therein and separated from the sidewall regions by the gate dielectric layer;

forming an intergate dielectric layer on exposed portions of the floating gate regions in the second troughs;

forming split control line regions between opposing floating gate regions in the second troughs;

separating from the floating gate regions in the second troughs by the intergate dielectric layer; and

separating the split control lines by the intergate dielectric layer.

16. The method of claim 15, wherein the substrate is a bulk semiconductor.

17. The method of claim 15, wherein the substrate includes a semiconductor-on-insulator portion.

18. The method of claim 15, further comprising forming an insulating layer undercutting semiconductor regions between the first troughs.

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