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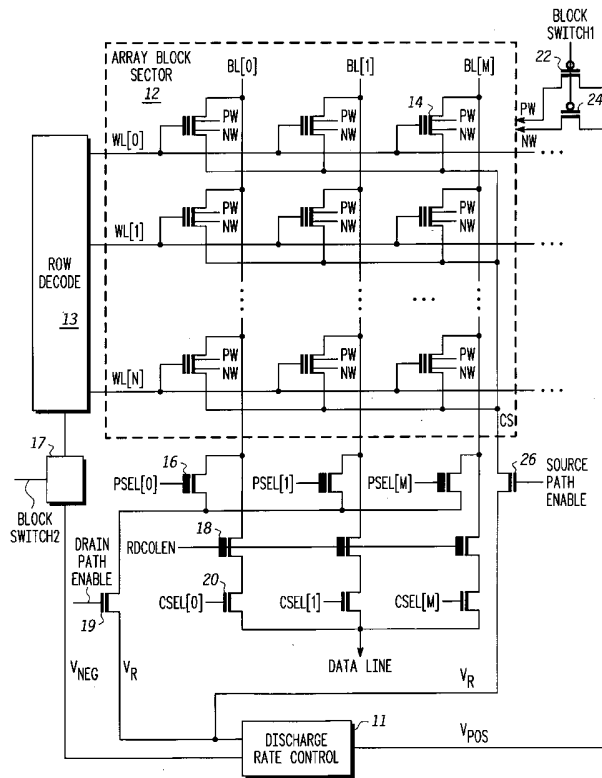
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(54) Title: INTEGRATED CIRCUIT HAVING A NON-VOLATILE MEMORY WITH DISCHARGE RATE CONTROL AND METHOD THEREFOR



(57) Abstract: An integrated circuit includes a memory (10). The memory (10) includes an array (12) of non-volatile memory cells. Each memory cell (14) of the array (12) includes a plurality of terminals comprising: a control gate, a charge storage region, a source, a drain, a well terminal, and a deep well terminal. Following an erase operation of the array (12), the erase voltages are discharged from each of the memory cells. A discharge rate control circuit (11) controls the discharging of terminals of the memory cell. The discharge rate control circuit (11) includes, for example, a plurality of parallel-connected transistors (112) coupled between the array (12) of non-volatile memory cells and a power supply terminal.

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INTEGRATED CIRCUIT HAVING A NON-VOLATILE MEMORY WITH DISCHARGE RATE CONTROL AND METHOD THEREFOR

Field of the Invention

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This invention relates generally to integrated circuits, and more particularly to an integrated circuit having a non-volatile memory with discharge rate control of erase voltages.

Background of the Invention

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Floating gate non-volatile memories such as erasable programmable read only memories (EPROMs), electrically erasable programmable read only memories (EEPROMs), block erasable ("flash") EEPROMs, and one time programmable read only memories (OTPROMs) are popular for many electronic applications such as automotive control, consumer products such as tapeless answering machines, and the like. In floating gate memories, the state of each memory cell is determined by the amount of charge stored on a floating gate. The floating gate is isolated from an underlying channel by a region of tunnel oxide. Typically, the floating gate transistor is programmed and erased by processes known as Fowler-Nordheim tunneling and hot carrier injection. One process that uses Fowler-Nordheim tunneling for erasing a flash memory is called "channel erase".

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A typical flash memory cell manufactured using a "triple well" process may have five terminals that must be properly biased for program and erase operations: a control gate, a source, a drain, a P-well terminal, and a deep N-well terminal. An array of flash memory cells is formed in the P-well. The P-well is isolated within the deep N-well. One technique for performing a channel erase operation on the memory cells of the flash memory array involves applying a relatively high negative voltage, for example about -9 volts, to the control gate, while applying a relatively high positive voltage, for example about +9 volts, to the P-well and the deep N-well. The drain and source of the memory cell are allowed to "float", that is, the drain and source are not directly coupled to a source of potential. However, due to capacitive coupling between the five terminals around the floating gate as well as the diode formed between the drain/source and P-well, the drain and source may float no lower than a diode drop below the P-well/deep N-well voltage.

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At the end of an erase operation, the voltage on the five terminals is discharged. If the terminals are allowed to discharge too quickly, an effect of discharging the relatively high negative voltage on the control gate can cause drain, source, and P-well potentials to peak a voltage higher than 10 volts because of the capacitive coupling. The application of a voltage
5 higher than 10 volts may cause the gate oxide of high voltage transistors connected to the nodes of the memory cells to break down, drain source punch through of the transistors connected to the nodes of the memory cell, or other forms of high voltage damage, thus shortening the life of the flash memory.

What would be desirable therefore are a method, and a non-volatile memory using
10 such a method, which prevents the exposure of the high voltage transistors to high voltage beyond the reliability limits. Such a method and a non-volatile memory using that technique is provided by the present invention, whose features and advantages will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings.

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Brief Description of the Drawings

FIG. 1 illustrates, in schematic diagram form, a portion of a non-volatile memory according to the present invention.

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FIG. 2 illustrates, in schematic diagram form, a first embodiment of a discharge rate control circuit for the memory of FIG. 1.

FIG. 3 illustrates, in schematic diagram form, a second embodiment of a discharge rate control circuit for the memory of FIG. 1.

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FIG. 4 illustrates, in schematic diagram form, a third embodiment of a discharge rate control circuit for the memory of FIG. 1.

FIG. 5 illustrates, in schematic diagram form, a fourth embodiment of a discharge rate control circuit for the memory of FIG. 1.

FIG. 6 illustrates, in schematic diagram form, a fifth embodiment of a discharge rate control circuit for the memory of FIG. 1.

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Detailed Description

Generally, the present invention provides an integrated circuit having a memory. The memory includes an array of non-volatile memory cells. Each memory cell of the array includes a plurality of terminals comprising: a control gate, a charge storage region, a source, a drain, a well terminal, and a deep well terminal. Following an erase operation of the array, the erase voltages are discharged from each of the memory cells. A discharge rate control circuit controls the discharging of the terminals of the erased memory cell. The erase voltages are discharged at a rate in which the capacitive coupling from one of the terminals of the memory cell to other terminals of the memory cell are essentially nulled out, or minimized, for voltage overshoot. After a predetermined time, the erase voltages will be discharged to a level that is safe for devices which are connected to any of the terminals of the memory cell. In one embodiment, all five terminals of a memory cell are recovered, or discharged, at the same time. In other embodiments, less than all of the five terminals may be discharged at the same time. Also, in another embodiment, a discharge circuit is described that recovers the negative voltage against some of the positive voltages that are on the source and drain. This eliminates the need to use charge from other positive power supplies.

In one embodiment, the discharge rate control circuit includes a reference current generator for providing a reference current; a first current mirror, coupled to the reference current generator for providing a first predetermined discharge current for discharging the control gate, drain, and source; and a second current mirror, coupled to the reference current generator, for providing a second predetermined discharge current for discharging the well terminals after the erase operation. In another embodiment, the discharge rate control circuit includes a plurality of parallel-connected transistors coupled between the array of non-volatile memory cells and a power supply terminal. The discharge rate is controlled by selecting which of the parallel-connected transistors are conductive.

Controlling the discharge rate using the discharge rate control circuit in accordance with the illustrated embodiments prevents transistors that are coupled to the memory cells from being damaged because they are exposed to a voltage higher than the reliability limits of the transistors.

FIG. 1 illustrates, in schematic diagram form, a portion of a non-volatile memory in accordance with the present invention. Non-volatile memory 10 is implemented on an integrated circuit and includes an array 12 of non-volatile memory cells coupled at the

intersections of word lines and bit lines. Array 12 includes N word lines, where N is an integer, represented by word lines labeled WL[0], WL[1], and WL[N]. Array 12 includes M bit lines, where M is an integer, represented by bit lines labeled BL[0], BL[1], and BL[M]. A non-volatile memory cell 14 is illustrative of the memory cells of the array and includes a control gate coupled to the word line WL[0], a drain coupled to bit line BL[M], a floating gate, a P-well terminal labeled "PW" and a deep N-well terminal labeled "NW". The well terminal PW is coupled to a P-well region of a semiconductor substrate on which the integrated circuit is implemented. Source terminals of all of the memory cells of the array are coupled together and labeled "CS". In the illustrated embodiment, array 12 is a flash memory and is manufactured using a conventional triple-well process and includes a deep N-well for isolating the array. The deep N-well surrounds the P-well within the semiconductor substrate. In another embodiment, the array 12 may be manufactured using a different process that does not include a deep N-well. Also, in another embodiment, the conductivity types of the wells may be different. In addition, the array 12 of the illustrated embodiment includes floating gate transistors. In another embodiment, the array 12 may include another non-volatile memory cell type, such as for example, a SONOS structure where a charge storage layer may include, for example, nitride, nanocrystals, or a combination of nitride and nanocrystals. In addition, the non-volatile memory 10 may be implemented on an integrated circuit as a stand-alone memory, or may be implemented with other circuitry, such as for example, in a microprocessor, or in a microcontroller having a central processing unit (CPU) and one or more peripheral circuits.

A row decoder 13 is coupled to all of the word lines of the array 12. Row decoder 13 is a conventional row decoder and is for selecting one or more word lines, depending on the type of access operation, in response to receiving a row address. A program select transistor is coupled to each of the bit lines and receives one of a decoded program select signal labeled PSEL[0], PSEL[1], and PSEL[M]. For example, a program select transistor 16 has a drain coupled to the bit line BL[0], a gate coupled to receive the program select signal PSEL[0], and a source coupled to the drain of an N-channel transistor 18. Because the N-channel transistors 16 and 18 are exposed to relatively high voltages during program and erase operations, they are implemented using a high voltage CMOS (complementary metal-oxide semiconductor) process as indicated by the thickly drawn gate in FIG. 1. The transistors not exposed to the high program and erase voltages are implemented with thinner gate oxides. Transistors 18 are coupled between the program select transistors and the N-channel column

select transistors 20 are for isolating the column select transistors 20 from the relatively higher program and erase voltages. Transistors 18 are always enabled during a read operation and serve as a high voltage isolation device for thinner oxide transistors during program and erase and may not be necessary in other embodiments. Each of the column select transistors, such as transistor 20, is for coupling a corresponding bit line to a data line in response to an asserted one of the column select signals CSEL[0], CSEL[1], and CSEL[M]. In the illustrated embodiment, sense amplifiers (not shown) are coupled to the data lines and are shared between a predetermined number of bit lines. The sense amplifiers are for sensing and amplifying the relatively small currents conducting through the bit lines.

A discharge rate control circuit 11 is provided to discharge the voltages on the terminals of the non-voltage memory cells after an erase operation. The discharge rate control circuit 11 has a first conductor labeled VNEG coupled to the row decoder 13 through the negative block switch 17, and a second conductor labeled VR coupled to the source terminals of the program select transistors through an N-channel transistor 19 that is activated with a signal labeled "DRAIN PATH ENABLE". The negative block switch 17 receives an enable signal labeled "BLOCK SWITCH 2". The second conductor is also coupled to the common source CS of array 12 via an N-channel transistor 26 when a signal labeled "SOURCE PATH ENABLE" is asserted. In addition, the discharge rate control circuit 11 includes a third conductor labeled VPOS coupled to the P-well terminal and the deep N-well terminal via P-channel transistors 22 and 24 in response to a signal labeled "BLOCK SWITCH 1" being asserted. Note that the conductivity type of the illustrated transistors is not important for purposes of describing the invention, and may be different in other embodiments. Also, the transistors 22 and 24 may be separately controlled in other embodiments.

The memory array 12 is erased using a channel erase operation. A relatively high negative voltage, for example about -9 volts, is applied to the control gate of each of the memory cells of the array, while applying a relatively high positive voltage, for example about +9 volts, is applied to the P-well and the deep N-well. The drain and source are allowed to "float" no lower than a diode drop below the P-well, that is, the drain and source are not directly coupled to a source of potential. However, due to capacitive coupling between the five terminals around the floating gate and charging through the junction from the P-well to the drain and source, the drain and source float at a diode drop below the P-well/deep N-well voltage. These voltages are applied to the array 12 for a predetermined

amount of time. In other embodiments, the erase voltages may be different and may be applied to different terminals of the memory cells depending on the erase mechanism used.

After the erase operation, it is necessary to discharge the erase voltages from the memory array 12. To prevent high voltage damage to transistors connected to the nodes of the memory cell, the discharge rate control circuit 11 causes the high (or low) negative erase voltage on the gate and the high positive erase voltage on the wells, drains and sources, to be discharged at a rate which will suppress coupling voltage higher than 10V on any of the five terminals from any of the other five terminals. Because the array 12 is a flash memory in the illustrated embodiment, all of the transistors of array 12 are erased at the same time.

Likewise, the erase voltages are discharged from all of the transistors at the same time. In one embodiment, array 12 may represent the entire memory array. In other embodiment, array 12 may represent only one of two or more blocks, or sectors, of a non-volatile memory array. The operation of various embodiments of the discharge rate control circuit 11 will be described in more detail below.

FIG. 2 illustrates, in schematic diagram form, a first embodiment of a discharge rate control circuit 70 for the memory 10 of FIG. 1. Discharge rate control circuit 70 is substituted for the discharge rate control circuit 11 of FIG. 1. Note that throughout the drawings the same reference numbers will be used for the same or similar elements. Discharge rate control circuit 70 includes current source 34, current mirrors 36, 39, and 46, protection circuit 54, P-channel transistor 32, and N-channel transistors 42 and 52. Current mirror 36 includes N-channel transistors 38 and 44. Current mirror 39 includes N-channel transistors 38 and 40. Current mirror 46 includes P-channel transistors 48 and 50. Protection circuit 54 includes P-channel transistor 56 and N-channel transistors 58 and 60. N-channel transistors 42 and 52 and P-channel transistor 32 function as switches.

Current source 34 has a first terminal coupled to a supply voltage terminal labeled V_{FL} , and a second terminal for providing a reference current labeled " I_{REF} ". P-channel transistor 32 has a source coupled to a second terminal of current source 34, a gate coupled to receive a control signal labeled " V_{SW1} ", and a drain. In the illustrated embodiment, current source 34 is generated based on the bandgap voltage of silicon. In other embodiments, current source 34 may be generated differently. N-channel transistor 38 has a gate and a drain both coupled to the drain of transistor 32, and a source coupled to a supply voltage terminal labeled " V_{SS} ". N-channel transistor 40 has a drain, a gate coupled to the drain of transistor 32, and a source coupled to V_{SS} . N-channel transistor 42 has a drain coupled to a boosted

positive voltage terminal labeled " V_{POS} ", a gate for receiving a control signal labeled " V_{SW} ", and a source. N-channel transistor 44 has a drain coupled to the source of transistor 42, a gate coupled to the drain of transistor 32, and a source coupled to V_{SS} . P-channel transistor 48 has a source coupled to a supply voltage terminal labeled " V_R ", and a gate and a drain coupled to the drain of N-channel transistor 40. P-channel transistor 50 has a source coupled to V_R , a gate coupled to the drain of N-channel transistor 40, and a source. N-channel transistor 52 has a drain coupled to V_R , a gate for receiving a control signal labeled " V_{SW2} ", and a source coupled to the drain of P-channel transistor 50. P-channel transistor 56 has a source coupled to the drain of P-channel transistor 50, a gate coupled to V_{SS} , and a drain. N-channel transistors 58 and 60 are diode connected and in series between the drain of transistor 56 and a boosted negative voltage terminal labeled " V_{NEG} ".

A boosted negative voltage provided to V_{NEG} is used for program and erase operations and is provided by a charge pump (not shown), or may be provided by a voltage source external to the memory 10 in other embodiments. Likewise, a boosted positive voltage provided to V_{POS} is used for the program and erase operations and is provided by another charge pump (not shown), or in other embodiments, may be provided by a voltage source external to memory 10. Because N-channel transistor 42 is exposed to the boosted positive voltage used for the erase operation, it is a high voltage transistor as indicated by the relatively thicker gate in FIG. 2. Protection circuit 54 functions to protect the transistors of current mirror 46 from the boosted negative erase voltage received to V_{NEG} . Therefore, the transistors 56, 58, and 60 are also high voltage transistors.

As stated above, the discharge rate control circuit 70 is used to control the discharge of the voltages on the memory cells of array 12 after an erase operation. For example, during the erase operation, a positive 9 volts may be applied to the P-well of each memory cell of the array 12 via V_{POS} . The positive 9 volts is discharged through transistors 42 and 44 to V_{SS} . Also, during the erase operation a negative 9 volts may be applied to the control gate of each memory cell via V_{NEG} . The negative 9 volts is discharged through the protection circuit 54 and transistor 50 and 52 to V_R . The discharge rate for each terminal of a memory cell is determined based on a mirror ratio to a known reference. In FIG. 2, the reference current is I_{REF} which is provided by current source 34 to transistor 38 of current mirror 36 & 39. In current mirror 36 & 39, the current through transistor 38 is determined by I_{REF} . The current through transistor 40 is determined by adjusting the gate width (W) to gate length (L) ratio relative to the W_1/L ratio of transistor 38 by using a factor "K" as illustrated in FIG. 2.

Likewise, the discharge current through transistor 44 is determined by a gate width to gate length ratio factor "J" times W_1/L . The factors K and J are generally determined by capacitive loading, and in some embodiments, may be substantially the same. Also, the current through transistor 50 is "X" times W_2/L , where W_2 is the gate width of transistor 48 and L is the gate length of transistor 48. The current through transistor 48 is determined by the current through transistor 40. Note that in the illustrated embodiment, gate length L is the same for all of the transistors. However, in other embodiments, gate length L may be different for the various transistors.

In operation, discharge rate control circuit 70 is activated when control signal V_{SW1} is asserted as a logic low voltage, V_{SS} . Concurrent with, or following the assertion of V_{SW1} , control signal V_{SW} is asserted as a logic high, V_{FL} , at the gate of transistor 42. Transistor 42 is provided to protect transistor 44 from the relatively high erase voltages as well as to limit the drain source voltage of transistor 44 for more accurate mirroring of the current through transistor 38 and may not be necessary in some embodiments. A current through transistor 38 is mirrored by transistors 40 and 44. A current through transistor 48 is mirrored by transistor 50. The voltage on V_{NEG} is then discharged to V_R and the voltage on V_{POS} is discharged to V_{SS} . The factors J, K, and X are chosen to ensure that the memory cell erase voltages begin to discharge at a rate in which the capacitive coupling from one of the terminals of the memory cell to other terminals of the memory cell are essentially nulled out or minimized for voltage overshoot. After a predetermined time, the erase voltages will be discharged to a level that is safe for devices which are connected to any of the terminals of the memory cell. At a later time, the control signal V_{SW2} is asserted as a logic high voltage V_{FL} to make transistor 52 conductive, thus providing another current path for rapidly discharging V_{NEG} and V_R .

Discharge rate control circuit 70 will discharge all of the terminals of the memory cells at a rate which will track together and have very little variation due to process, temperature, and supply. Also, discharge rate control circuit 70 provides two recovery, or discharge, rates for V_{NEG} relative to V_R ; an initial relatively slow recovery to a safe voltage and then a faster recovery rate to shorten recovery time. The illustrated embodiments are especially useful for memories that are operating close to their voltage reliability limits.

FIG. 3 illustrates, in schematic diagram form, a discharge rate control circuit 30 in accordance with a second embodiment of the present invention. Discharge rate control circuit 30 is substituted for the discharge rate control circuit 11 of FIG. 1. Discharge rate control

circuit 30 differs from discharge rate control circuit 70 in that discharge rate control circuit 30 does not have a transistor 52. In circuit 30, the discharge rate remains at the initial rate. However, with careful attention to the determination of the ratio factors J, K, and X, the discharge rate may be relatively quick, especially for those embodiments where there is
5 relatively more margin for device parameters such as oxide breakdown, gate induced junction breakdown, drain-source punch through, and the like.

FIG. 4 illustrates, in schematic diagram form, a discharge rate control circuit 80 in accordance with a third embodiment of the present invention. Discharge rate control circuit 80 replaces the discharge rate control circuit 11 in the memory of FIG. 1. Discharge rate
10 control circuit 80 differs from discharge rate control circuit 30 in that discharge rate control circuit 80 includes a plurality of current sources selectively coupled to current mirrors 36 and 39 to provide different rates for discharging the erase voltages from the terminals of the memory cells. FIG. 4 shows two additional current sources 66 and 68 coupled to current
15 mirror 36 and 39 via P-channel transistors 62 and 64, respectively. The P-channel transistor 62 is conductive when control signal V_{SW3} is asserted as a logic low voltage. The P-channel transistor 64 is conductive when control signal V_{SW2} is asserted as a logic low voltage. When control signal V_{SW3} is asserted, current source 66 provides a current I_{REF1} to current mirrors
20 36 and 39. Likewise, when control signal V_{SW2} is asserted, current source 68 provides a current I_{REF2} to current mirror 36 and 39. Currents I_{REF1} and I_{REF2} may be the same as I_{REF} , or different, depending on the desired discharge rates. Note that in other embodiments, there may be more or fewer than three current sources. Each of the current sources is coupled to a
25 separately controlled switch. In the illustrated embodiment, the erase voltages are initially discharged at a low rate by asserting only V_{SW1} for a predetermined time period. After the predetermined time period, control signal V_{SW2} is asserted to add current I_{REF1} to I_{REF} to
30 discharge the memory cells at a second, faster rate. Finally, control signal V_{SW3} is asserted to add the current I_{REF2} to I_{REF} and I_{REF1} to discharge the memory cell nodes at a third rate. Like current source 34, current sources 66 and 68 are bandgap generated. However, in other
embodiments, current sources 66 and 68 may be generated in other ways.

FIG. 5 illustrates, in schematic diagram form, a discharge rate control circuit 90 in
30 accordance with a fourth embodiment. Discharge rate control circuit 90 replaces the discharge rate control circuit 11 in the memory of FIG. 1. Discharge rate control circuit 90 differs from discharge rate control circuit 30 in that discharge rate control circuit 90 includes a current mirror 92 coupled to the drain of N-channel transistor 44. Current mirror 92

includes P-channel transistors 94 and 96, and N-channel transistor 100. Transistors 98 and 100 function to enable current flow through transistors 94 and 96. The voltage on transistor 98 must be high enough to disable current from V_{POS} to V_{FL} . In this embodiment, transistor 98 is a thick oxide transistor to help it sustain larger gate voltages. N-channel transistor 100 has a source coupled to the drain of N-channel transistor 44, a gate for receiving a control signal V_{SW3} , and a drain. P-channel transistor 96 includes a source coupled to V_{POS} , and a gate and a drain coupled to the drain of transistor 100. P-channel transistor 94 has a source coupled to V_{POS} , a gate coupled to the drain of transistor 100, and a drain. P-channel transistor 98 has a source coupled to the drain of transistor 94, a gate for receiving control signal V_{SW2} , and a drain coupled to V_{FL} . A width/length ratio of transistor 94 differs from a width/length ratio of transistor 96 (W_3/L) by a factor "Y".

Current mirror 92 is used in FIG. 5 to divert some of the discharged erase voltage from V_{POS} to V_{FL} to "recycle" some of the charge and reduce power consumption of device having memory 10. To discharge V_{POS} after an erase operation, control signals V_{SW2} and V_{SW3} are asserted to make transistors 98 and 100 conductive. Some of the discharge current is provided to V_{SS} through transistors 96, 100, and 44, and some of the discharge current is provided to V_{FL} through transistors 94 and 98. The amount of current from V_{POS} that is provided to V_{FL} is determined, at least in part, by the width/length ratio of transistors 94 and 96 as illustrated in FIG. 5.

FIG. 6 illustrates, in schematic diagram form, a discharge rate control circuit 110 in accordance with a fifth embodiment. Discharge rate control circuit 110 is another embodiment of the discharge rate control circuit 11 in the memory of FIG. 1. Discharge rate control circuit 110 includes a plurality of parallel-connected N-channel transistors 112 and a protection circuit 114. The plurality of transistors 112 includes transistors 116, 118, 120, and 122. The protection circuit 114 includes a P-channel transistor 124, diode-connected N-channel transistors 126 and 130, and an N-channel transistor 128. Each of the plurality of transistors 112 has a current electrode (drain) connected to the power supply voltage terminal V_R , a control electrode (gate) for receiving one of control signals V_{SW1} , V_{SW2} , V_{SW3} , and V_{SW4} , and a current electrode (source) connected to a node labeled "N1".

In protection circuit 114, P-channel transistor 124 has a source connected to node N1, a gate connected to power supply voltage terminal V_{SS} , and a drain. N-channel transistor 126 has a gate and a drain connected to the drain of transistor 124, and a source. N-channel transistor 128 has a drain connected to the source of transistor 126, a gate for receiving a bias

voltage labeled " V_{TN} ", and a source. N-channel transistor 130 has a gate and a drain connected to the source of transistor 128, and a source connected to V_{NEG} . Protection circuit 114 functions to protect the plurality of transistors 112 from the boosted negative erase voltage V_{NEG} . Therefore, the transistors 124, 126, 128, and 130 are high voltage transistors as indicated in FIG. 6 by the relatively thicker gates. Note that unlike the embodiments illustrated in FIGs. 2 - 5, discharge rate control circuit 110 does not require the use of voltages V_{POS} or V_{FL} .

In operation, discharge rate control circuit 110 discharges the erase voltages from the terminals of the memory cells in FIG. 1 using one or more of the plurality of transistors 112 by asserting one or more of control signals V_{SW1} , V_{SW2} , V_{SW3} , and V_{SW4} . In one embodiment of FIG. 6, each of transistors 116, 118, 120, and 122 have the same length and width and will therefore provide substantially the same current flow. In this embodiment, the discharge rate is determined by how many of transistors 116, 118, 120, and 122 are made conductive. Generally, the erase voltage should be initially discharged at a relatively low rate by first asserting only one of the control signals V_{SW1} , V_{SW2} , V_{SW3} , and V_{SW4} , for example control signal V_{SW1} . After a predetermined time, one or more of the other control signals are asserted in addition to V_{SW1} to increase the discharge rate as desired. The use of four parallel-connected transistors in the illustrated embodiment allows up to four different discharge rates. In other embodiments, there may be more than four or fewer than four parallel-connected transistors to discharge the erase voltages. In another embodiment, the transistors 116, 118, 120, and 122 are each sized to provide different currents. In this embodiment, each of the transistors may be sequentially made conductive to provide additive currents, or may be controlled so that only one transistor is conductive at a time. The discharge charge rate is determined by the combination of transistors 116, 118, 120, and 122 chosen to be conductive. The control logic necessary to provide control signals V_{SW1} , V_{SW2} , V_{SW3} , and V_{SW4} is determined by the application. In one embodiment, the control signals may be provided by a data processor (not shown) used to control operation of memory 10. In another embodiment, the control signals may be provided by a separate control circuit (not shown) used to control memory 10.

As stated above, protection circuit 114 provides high voltage protection to protect the plurality of transistors 112 from damage caused by exposure to the relatively high erase and programming voltages. Because of protection circuit 114, transistors 116, 118, 120, and 122 can use a thinner gate oxide that is rated at a relatively lower voltage than the transistors of

protection circuit 114. This results in a lower threshold voltage (V_T) and a higher conductance (G_m). Also, the lower V_T provides for smaller process variation between transistors 116, 118, 120, and 122. The smaller process variation results in less impedance variation.

5 In protection circuit 114, N-channel transistor 128 is provided to prevent a voltage at node N1 from ever being positive. In the illustrated embodiment, the bias voltage V_{TN} is an N-channel threshold voltage of about 0.6 volts. In other embodiments, the bias voltage V_{TN} may be different and depends on the particular process technology used to manufacture memory 10.

10 In the foregoing specification, the invention has been described with reference to specific embodiments. However, one of ordinary skill in the art will appreciate that various modifications and changes can be made without departing from the scope of the present invention as set forth in the claims below. Accordingly, the specification and figures are to be regarded in an illustrative rather than a restrictive sense, and all such modifications are
15 intended to be included within the scope of the present invention.

Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature or element
20 of any or all the claims. As used herein, the terms "comprises," "comprising," or any other variations thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

Claims

What is claimed is:

1. An integrated circuit comprising:
5 an array of non-volatile memory cells, each memory cell of the array having a
 charge storage region and a plurality of terminals; and
 a discharge rate control circuit for controlling a discharge rate of one or more
 of the plurality of terminals of an erased memory cell, the discharge
10 rate control circuit comprising a plurality of parallel-connected
 transistors coupled between the one or more of the plurality of
 terminals and a power supply terminal.

2. The integrated circuit of claim 1, wherein the array of non-volatile memory cells
15 comprises an array of flash memory cells.

3. The integrated circuit of claim 1, wherein one or more transistors of the plurality of
 parallel-connected transistors are conductive for a first predetermined time to provide
 a first discharge rate, and one or more transistors of the plurality of parallel-connected
20 transistors are conductive for a second predetermined time to provide a second
 discharge rate higher than the first discharge rate.

4. The integrated circuit of claim 1, wherein the plurality of terminals comprises a
 control gate, a drain, and a source.

- 25 5. The integrated circuit of claim 1, wherein the drain of each of the memory cells of the
 array is coupled to a corresponding bit line and all of the sources of the array are
 coupled together.

- 30 6. The integrated circuit of claim 1, further comprising a high voltage protection circuit
 for protecting the plurality of parallel-connected transistors from damage due to
 exposure to relatively high erase voltages.

7. The integrated circuit of claim 1, wherein each transistor of the plurality of parallel-connected transistors has a first current electrode coupled to a first power supply voltage terminal, a control electrode for receiving a control signal, and a second current electrode.
- 5
8. The integrated circuit of claim 7, further comprising:
- a first transistor having a first current electrode coupled to the second current electrode of each transistor of the plurality of parallel-connected transistors, a control electrode for receiving a first bias voltage, and a
 - 10 second current electrode;
 - a second transistor having a first current electrode and a control electrode both coupled to the second current electrode of the first transistor, and a
 - second current electrode;
 - a third transistor having a first current electrode coupled to the second current electrode of the second transistor, a control electrode for receiving a
 - 15 second bias voltage, and a second current electrode; and
 - a fourth transistor having a first current electrode and a control electrode both coupled to the second current electrode of the third transistor, and a
 - second current electrode coupled to a second power supply voltage
 - 20 terminal.
9. The integrated circuit of claim 8, wherein the first, second, third, and fourth transistors have a relatively thicker gate oxide than a gate oxide of the plurality of parallel-connected transistors.
- 25
10. The integrated circuit of claim 1, wherein the charge storage region is a floating gate of a flash memory cell.
11. An integrated circuit comprising:
- 30 an array of non-volatile memory cells, each memory cell of the array having a control gate, a source, a drain, a first well terminal, and a second well terminal; and

a discharge rate control circuit for controlling discharging of erase voltages from the control gate, the source, the drain, the first well terminal and the second well terminal of an erased memory cell after an erase operation of the array of non-volatile memory cells, the discharge rate control circuit comprising a plurality of parallel-connected transistors coupled between the array of non-volatile memory cells and a power supply terminal.

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12. The integrated circuit of claim 11, wherein the array of non-volatile memory cells comprises an array of flash memory cells.

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13. The integrated circuit of claim 11, wherein one or more transistors of the plurality of parallel-connected transistors are conductive for a first predetermined time to provide a first discharge rate, and one or more transistors of the plurality of parallel-connected transistors are conductive for a second predetermined time to provide a second discharge rate higher than the first discharge rate.

20

14. The integrated circuit of claim 11, wherein the drain of each of the memory cells of the array is coupled to a corresponding bit line and all of the sources of the array are coupled together.

25

15. The integrated circuit of claim 11, further comprising a high voltage protection circuit for protecting the plurality of parallel-connected transistors from damage due to exposure to relatively high erase voltages.

30

16. The integrated circuit of claim 11, wherein each transistor of the plurality of parallel-connected transistors has a first current electrode coupled to a first power supply voltage terminal, a control electrode for receiving a control signal, and a second current electrode.

17. The integrated circuit of claim 16, further comprising:

a first transistor having a first current electrode coupled to the second current electrode of each transistor of the plurality of parallel-connected

transistors, a control electrode for receiving a first bias voltage, and a second current electrode;

a second transistor having a first current electrode and a control electrode both coupled to the second current electrode of the first transistor, and a second current electrode;

a third transistor having a first current electrode coupled to the second current electrode of the second transistor, a control electrode for receiving a second bias voltage, and a second current electrode; and

a fourth transistor having a first current electrode and a control electrode both coupled to the second current electrode of the third transistor, and a second current electrode coupled to a second power supply voltage terminal.

18. The integrated circuit of claim 17, wherein the first, second, third, and fourth transistors have a relatively thicker gate oxide than a gate oxide of the plurality of parallel-connected transistors.

19. A method for controlling a discharge rate of an erase voltage applied to a non-volatile memory cell, the non-volatile memory cell having a plurality of terminals, the method comprising:

providing a plurality of parallel-connected transistors coupled between one or more terminal(s) of the plurality of terminals;

erasing the non-volatile memory cell by applying the erase voltage to the non-volatile memory cell;

discharging the erase voltage through one or more transistors of the plurality of parallel-connected transistors at a first discharge rate for a first time period; and

discharging the erase voltage through one or more transistors of the plurality of parallel-connected transistors at a second discharge rate for a second time period, wherein the second discharge rate is higher than the first discharge rate and the second time period follows the first time period.

20. The method of claim 19, wherein the plurality of terminals comprises a control gate, a floating gate, a source, a drain, and a well region, the well region being in a semiconductor substrate.
- 5 21. An integrated circuit, comprising:
an array of non-volatile memory cells, each memory cell of the array having a charge storage region and a plurality of terminals; and
a discharge rate control circuit for controlling a discharge rate of one or more of the plurality of terminals of an erased memory cell, the discharge rate control circuit comprising:
10 a reference current generator for providing a reference current; and
a first current mirror, coupled to the reference current generator, for providing a first predetermined discharge current for discharging a first predetermined terminal of the plurality of terminals after the erase operation.
- 15 22. The integrated circuit of claim 21, wherein the discharge rate control circuit is for discharging all of the plurality of terminals at a rate determined to reduce voltage overshoot due to capacitive coupling between one or more of the plurality of terminals.
- 20 23. The integrated circuit of claim 22, wherein the plurality of terminals comprises a control gate, a drain, and a source.
- 25 24. The integrated circuit of claim 21, wherein the first and second predetermined terminals are both discharged at a first rate for a first predetermined time period and discharged at a second rate for a second predetermined time period, wherein the second rate is higher than the first rate.
- 30 25. The integrated circuit of claim 21, wherein the first predetermined terminal of the plurality of terminals is discharged at a first rate for a first predetermined time period and discharged at a second rate for a second predetermined time period, wherein the second rate is higher than the first rate.

26. The integrated circuit of claim 21, further comprising a second current mirror, coupled to the reference current generator, for providing a second predetermined discharge current for discharging a second predetermined terminal of the plurality of terminals after the erase operation.
- 5
27. The integrated circuit of claim 26, wherein the second current mirror comprises:
- a first transistor having a first current electrode and a control electrode both coupled to the reference current generator, and a second current electrode coupled to a first supply voltage terminal;
 - a second transistor having a first current electrode capable of being selectively coupled to the well terminal of each of the array of memory cells, a control electrode coupled to the reference current generator, and a second current electrode coupled to the first supply voltage terminal.
- 10
- 15
28. The integrated circuit of claim 21, wherein the first current mirror comprises:
- a third transistor having a first current electrode and a control electrode both coupled to the reference current generator, and a second current electrode selectively coupled to the source and drain of each memory cell of the array of memory cells; and
 - a fourth transistor having a having a first current electrode coupled to a source of each memory cell of the array of memory cells, a control electrode coupled to the reference current generator, and a second current electrode selectively coupled to the control gate of each memory cell of the array of memory cells.
- 20
- 25
29. The integrated circuit of claim 21, further comprising a third current mirror, the third current mirror having an input for receiving the second predetermined discharge current, the third current mirror providing a discharge path from predetermined terminals of each memory cell of the array, for recycling charge from the predetermined terminals to a supply voltage terminal.
- 30

30. The integrated circuit of claim 21, wherein the discharge rate control circuit further comprises a second reference current generator coupled to the first and second current mirrors.
- 5 31. The integrated circuit of claim 21, wherein the drain of each of the memory cells of the array is coupled to a corresponding bit line and all of the sources of the array are coupled together.
- 10 32. The integrated circuit of claim 21, wherein the charge storage region is a floating gate of a flash memory cell.
- 15 33. An integrated circuit, comprising:
an array of non-volatile memory cells, each memory cell of the array having a control gate, a source, a drain, and a well terminal;
a reference current generator for providing a reference current;
15 a first current mirror, coupled to the reference current generator, for providing a first predetermined discharge current for discharging the control gate of each memory cell of the array of non-volatile memory cells after an erase operation of the array; and
a second current mirror, coupled to the reference current generator, for
20 providing a second predetermined discharge current for discharging the well terminal of each memory cell of the array of non-volatile memory cells after the erase operation of the array.
- 25 34. The integrated circuit of claim 33, wherein the array is erased by applying a positive voltage to the well terminal of each memory cell while applying a negative voltage to the control gate of each memory cell.
- 30 35. The integrated circuit of claim 33, wherein the array comprises a plurality of flash memory cells.
36. The integrated circuit of claim 33, wherein the control gate, the drain, the source and the well terminal are all discharged at a rate whereby a discharge voltage overshoot,

caused by capacitive coupling between one or more memory cell terminals, is minimized.

- 5 37. The integrated circuit of claim 33, wherein the control gate is discharged at a first rate for a first predetermined time period and discharged at a second rate for a second predetermined time period, wherein the second rate is higher than the first rate.
- 10 38. The integrated circuit of claim 33, wherein the control gate and the well terminal are both discharged at a first rate for a first predetermined time period and discharged at a second rate for a second predetermined time period, wherein the second rate is higher than the first rate.
- 15 39. The integrated circuit of claim 33, wherein each of the memory cells further comprises a deep well terminal coupled to the second current mirror, wherein the deep well terminal is discharged by second discharge current after the erase operation.
- 20 40. An integrated circuit comprising:
an array of non-volatile memory cells, each memory cell of the array having a control gate, a source, a drain, a first well terminal, and a second well terminal; and
a discharge rate control circuit for controlling discharging of erase voltages from the control gate, the source, the drain, the first well terminal and the second well terminal of an erased memory cell after an erase operation of the array of non-volatile memory cells.
- 25
- 30 41. The integrated circuit of claim 40, wherein the discharge rate control circuit comprises:
a reference current generator for providing a reference current; and
a plurality of current mirrors for providing a plurality of discharge currents in response to the reference current, the plurality of current mirrors for discharging the erase voltages at a plurality of predetermined rates.

42. The integrated circuit of claim 40, wherein a discharge rate of the erase voltages is determined to reduce voltage overshoot due to capacitive coupling between one or more of the control gate, the source, the drain, the first well terminal and the second well terminal.
- 5
43. The integrated circuit of claim 40, wherein the array of non-volatile memory cells comprises an array of flash memory cells.
44. The integrated circuit of claim 40, wherein the control gate is discharged at a first rate for a first predetermined time period and discharged at a second rate for a second predetermined time period, wherein the second rate is higher than the first rate.
- 10
45. The integrated circuit of claim 40, wherein the control gate and the first well terminal are both discharged at a first rate for a first predetermined time period and discharged at a second rate for a second predetermined time period, wherein the second rate is higher than the first rate.
- 15
46. A method for controlling a discharge rate of an erase voltage applied to a non-volatile memory cell, the non-volatile memory cell having a plurality of terminals, the method comprising:
- 20
- providing a reference current;
 - mirroring the reference current to provide a first mirrored current for discharging a first terminal of the plurality of terminals at a first discharge rate for a first predetermined time; and
 - 25 mirroring the reference current to provide a second mirrored current for discharging a second terminal of the plurality of terminals at a second discharge rate for a second predetermined time.
47. The method of claim 46, wherein the plurality of terminals comprises a control gate, a floating gate, a source, a drain, and a well region, the well region being in a semiconductor substrate.
- 30

48. The method of claim 46, wherein the first discharge rate is approximately equal to the second discharge rate and the first predetermined time is approximately equal to the second predetermined time.

5 49. The method of claim 46, further comprising:
discharging the first terminal at a third discharge rate for a third predetermined
time; and
discharging the second terminal at a fourth discharge rate for a fourth
predetermined time.

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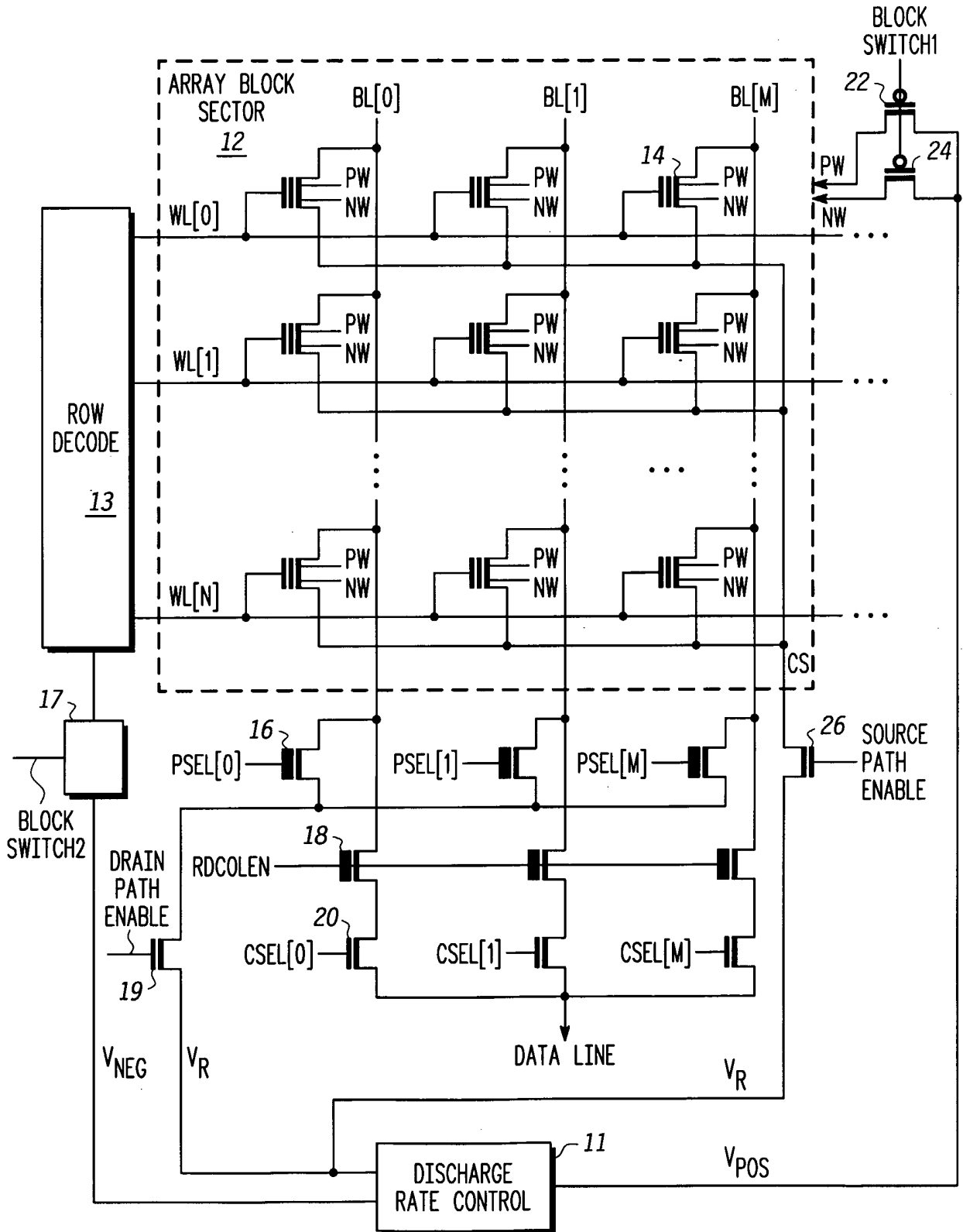


FIG. 1

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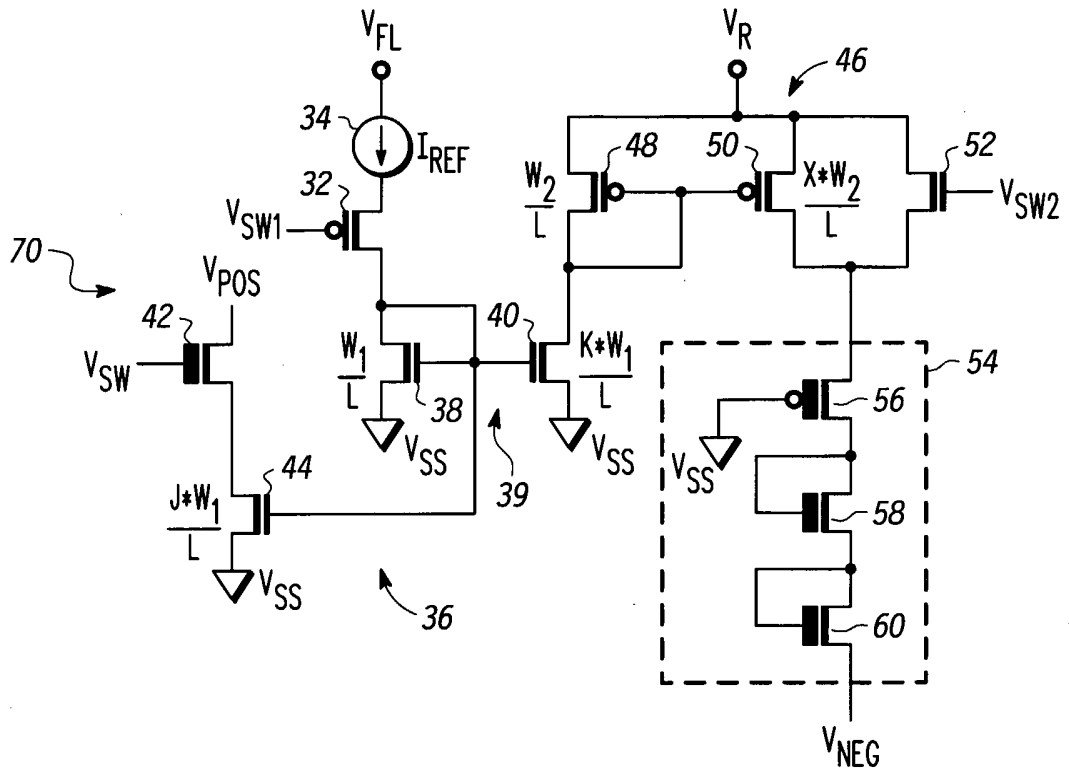


FIG. 2

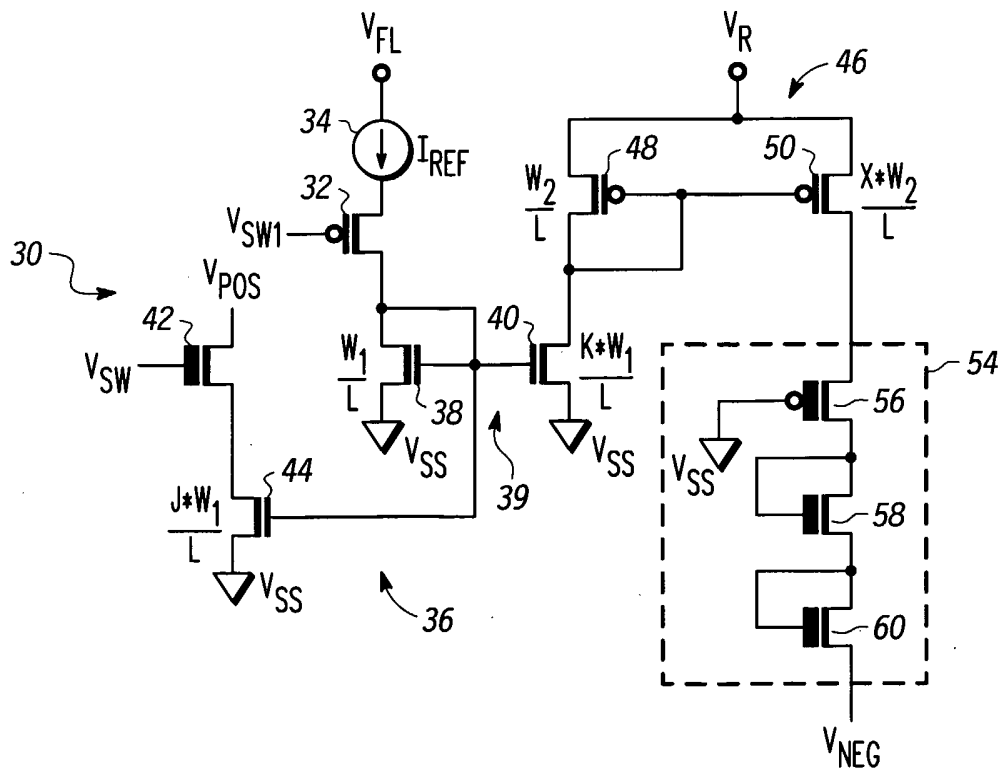


FIG. 3

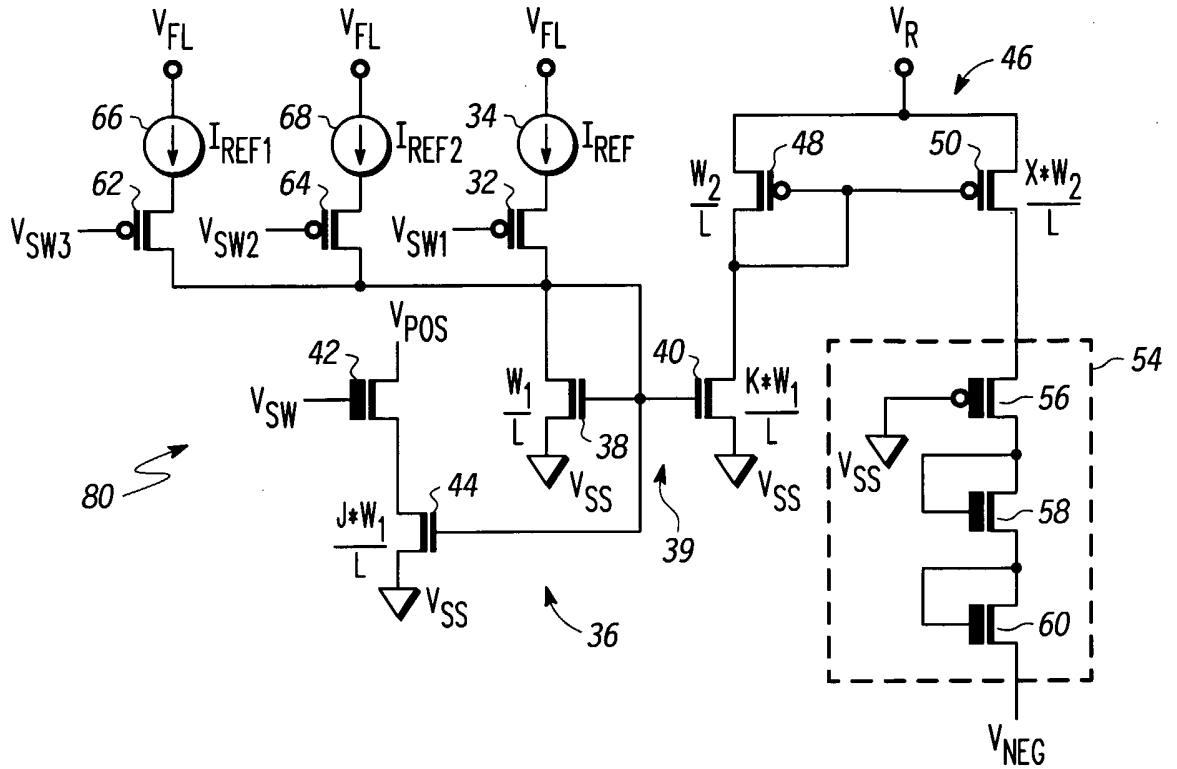


FIG. 4

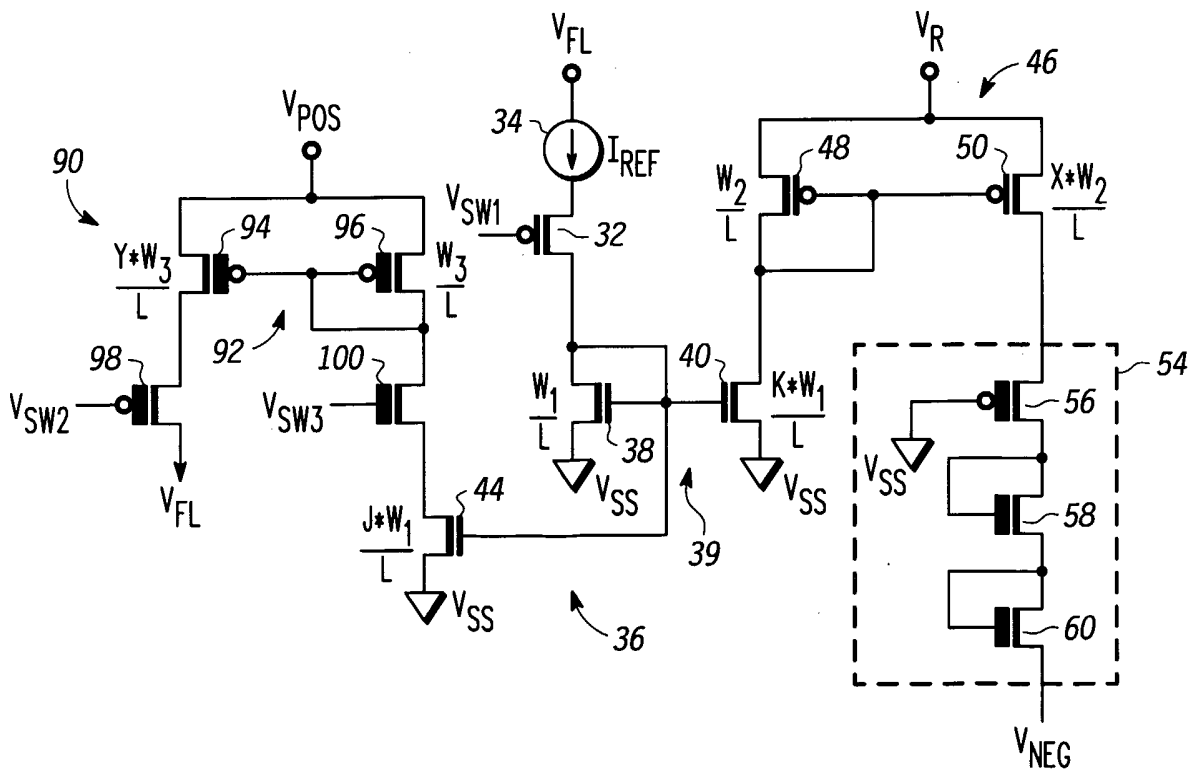


FIG. 5

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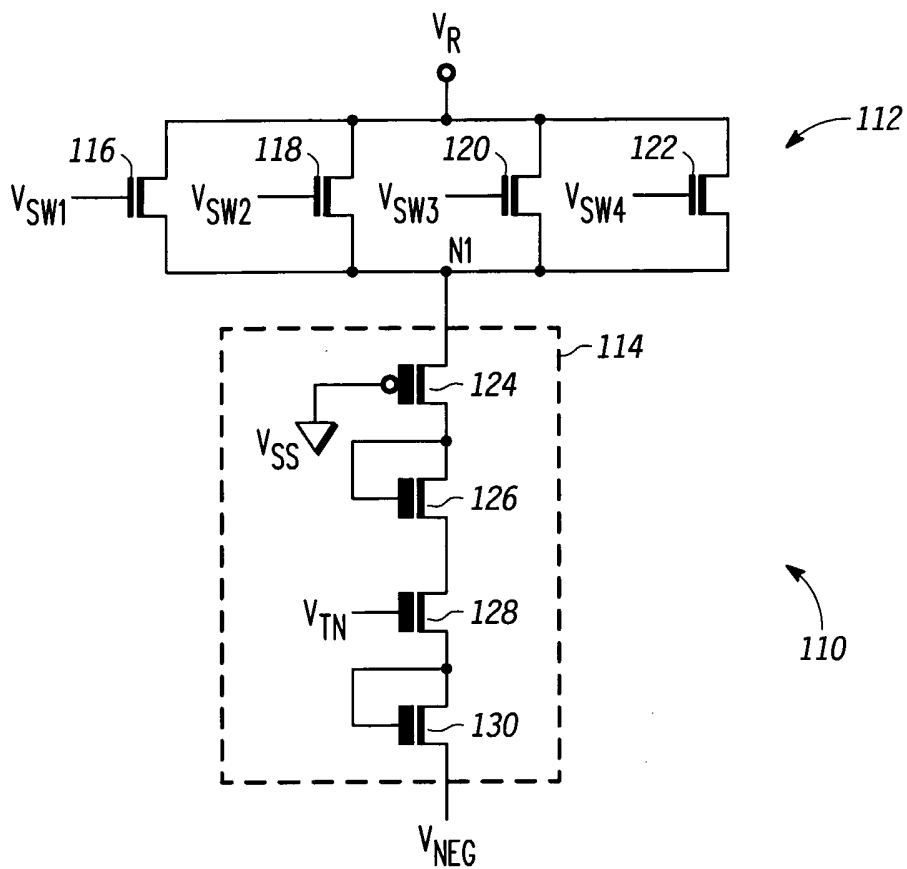


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US05/37070

A. CLASSIFICATION OF SUBJECT MATTER

IPC: **G11C 16/06**(2006.01),**16/04**(2006.01),**7/00**(2006.01)

USPC: 365/185.25,185.29,185.33,204,189.09

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 365/185.25, 185.29, 185.33, 204, 189.09

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,667,910 B2 (ABEDIFARD et al.) 23 December 2003 (23.12.3003), entire document.	1-2, 4-5, 7-10
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Y		3, 6, 19-20
X	US 5,999,456 (SALI et al.) 07 December 1999 (07.12.1999), entire document.	21-22, 24-25, 31-32
Y	US 5,701,090 (HIDAKA et al.) 23 December 1997 (23.12.1997), column 43, lines 28-60 and FIG. 43.	3, 19-20
Y	US 4,750,078 (GANGER et al.) 07 June 1988 (07.06.1988), the figure.	6

Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search

28 August 2006 (28.08.2006)

Date of mailing of the international search report

21 SEP 2006

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US05/37070

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Claims 1-20, drawn to apparatus and method of discharge erase voltage from erased memory cell with discharge control rate circuit comprising parallel-connected transistors.

Claims 21-49, drawn to apparatus and method of discharge erase voltage from erased memory cell with discharge control rate circuit comprising current mirror circuits.

1. As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of any additional fees.
3. As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

- Remark on Protest**
- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US05/37070

Continuation of B. FIELDS SEARCHED Item 3:

EAST

search terms: eras\$3 near10 discharg\$3 near10 control\$4, current adj2 mirror\$1, parallel near2 connect\$3, capacit\$4 near3 coupl\$3