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(54) **DEAPROM HAVING AMORPHOUS SILICON CARBIDE GATE INSULATOR**

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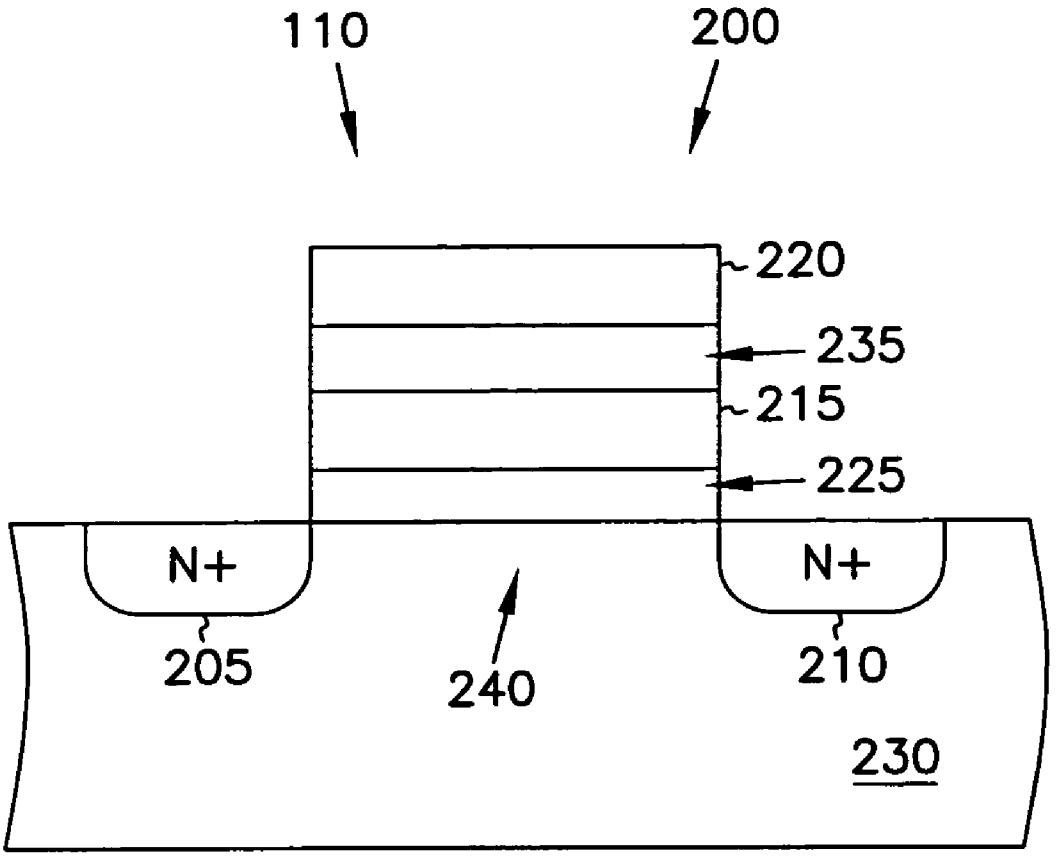
(57) **ABSTRACT**

A floating gate transistor has a reduced barrier energy at an interface with an adjacent amorphous silicon carbide (a-SiC) gate insulator, allowing faster charge transfer across the gate insulator at lower voltages. Data is stored as charge on the floating gate. The data charge retention time on the floating gate is reduced. The data stored on the floating gate is dynamically refreshed. The floating gate transistor provides a dense and planar dynamic electrically alterable and programmable read only memory (DEAPROM) cell adapted for uses such as for a dynamic random access memory (DRAM) or a dynamically refreshed flash EEPROM memory. The floating gate transistor provides a high gain memory cell and low voltage operation.



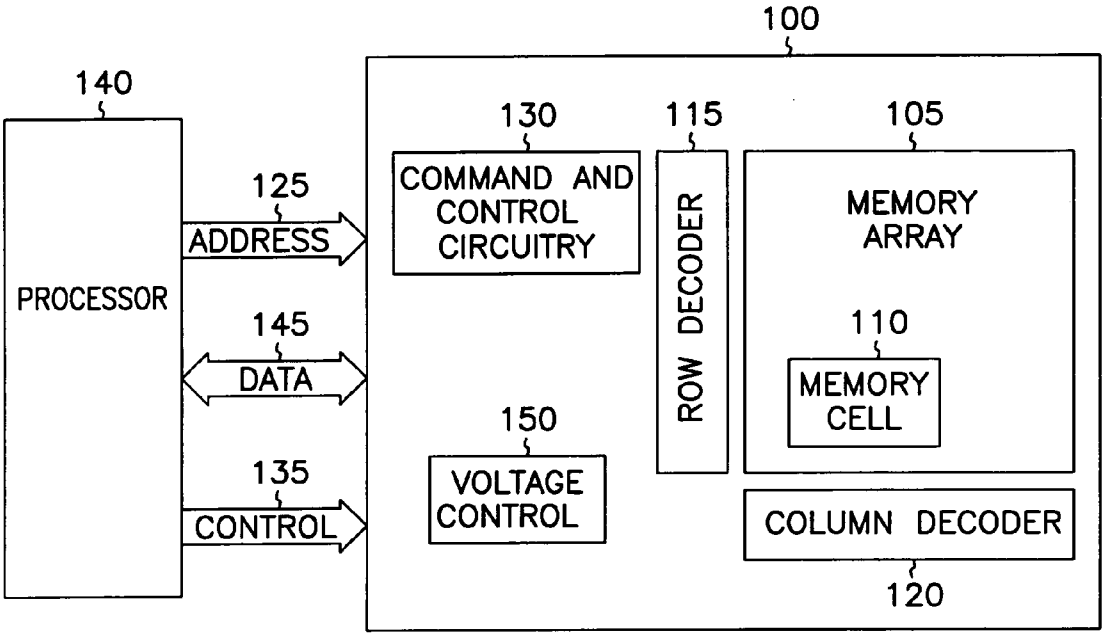

100
140
PROCESSOR
125
ADDRESS
145
DATA
135
CONTROL
130
COMMAND AND CONTROL CIRCUITRY
115
ROW DECODER
105
MEMORY ARRAY
110
MEMORY CELL
150
VOLTAGE CONTROL
COLUMN DECODER
120

FIG. 1

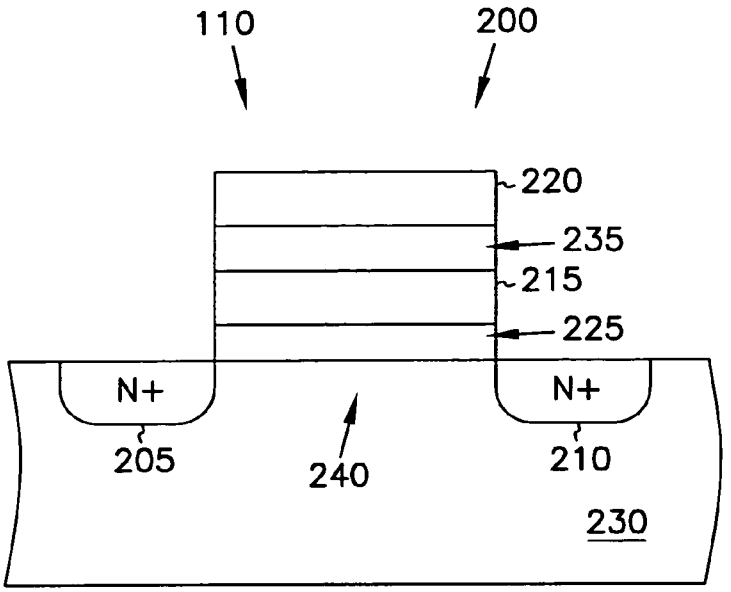

110
200
220
235
215
225
N+
N+
205
240
210
230

FIG. 2

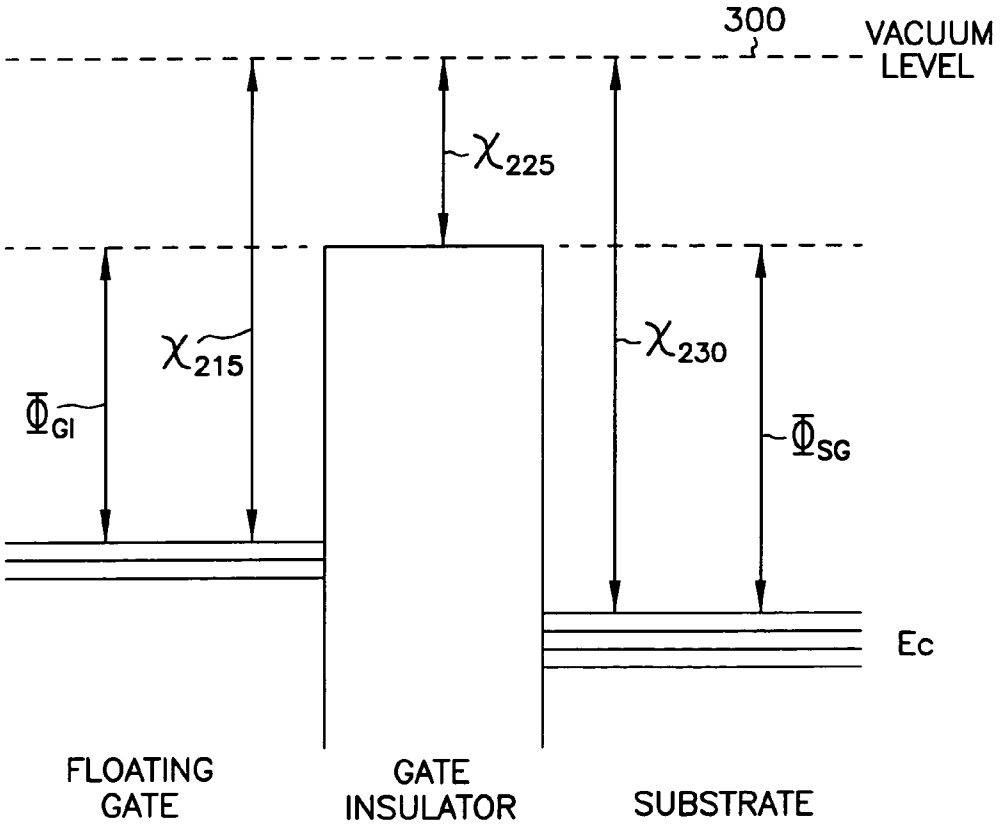

300
VACUUM LEVEL
χ_{225}
χ_{215}
χ_{230}
Φ_{GI}
Φ_{SG}
Ec
FLOATING GATE
GATE INSULATOR
SUBSTRATE

FIG. 3

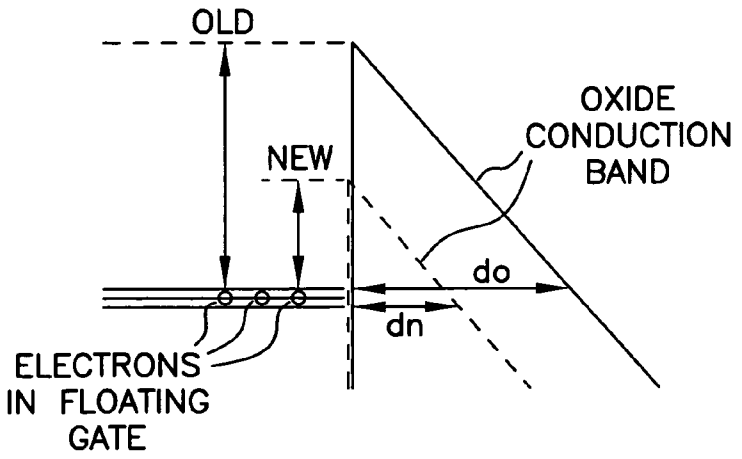

OLD
NEW
OXIDE
CONDUCTION
BAND
do
dn
ELECTRONS
IN FLOATING
GATE

FIG. 4

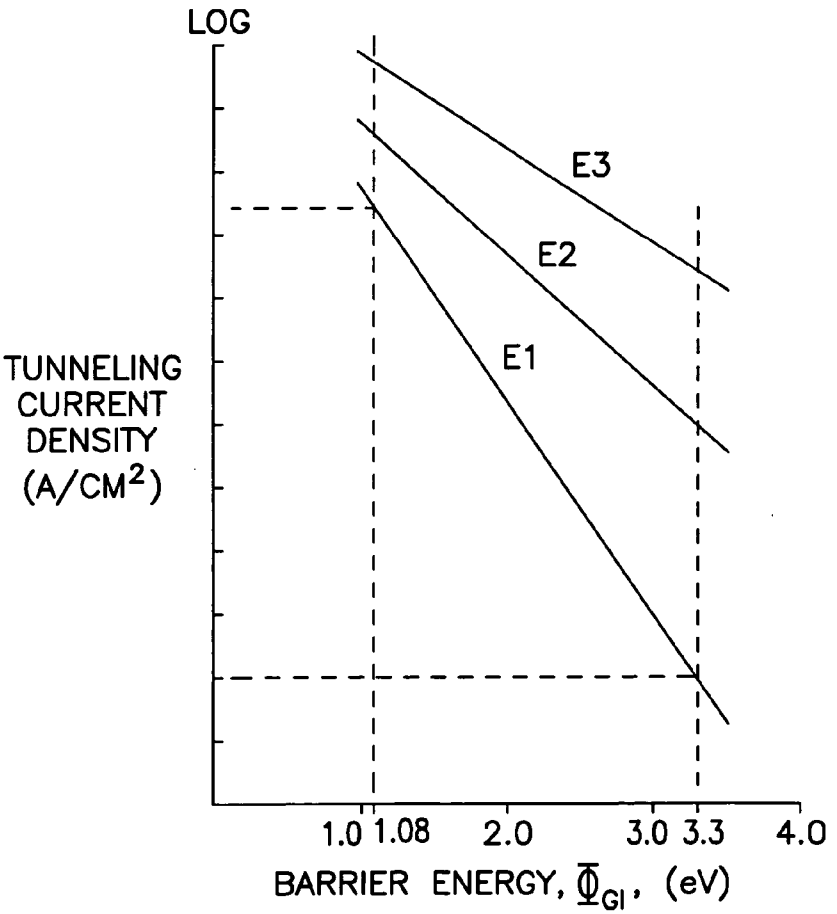

LOG
E3
E2
E1
TUNNELING
CURRENT
DENSITY
(A/CM2)
1.0
1.08
2.0
3.0
3.3
4.0
BARRIER ENERGY, ΦGI, (eV)

FIG. 5

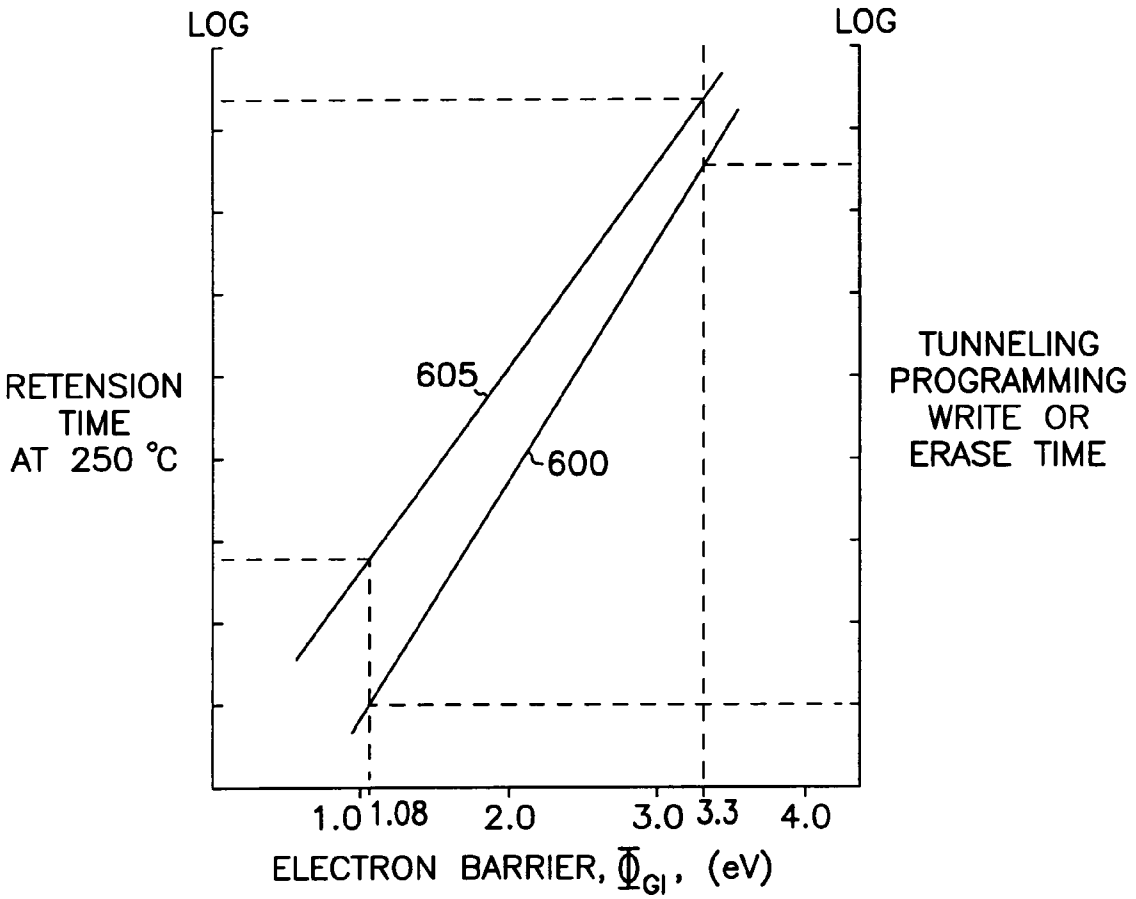

LOG
LOG
RETENSION TIME AT 250 °C
TUNNELING PROGRAMMING WRITE OR ERASE TIME
605
600
1.0
1.08
2.0
3.0
3.3
4.0
ELECTRON BARRIER, Φ_{GI}, (eV)

FIG. 6

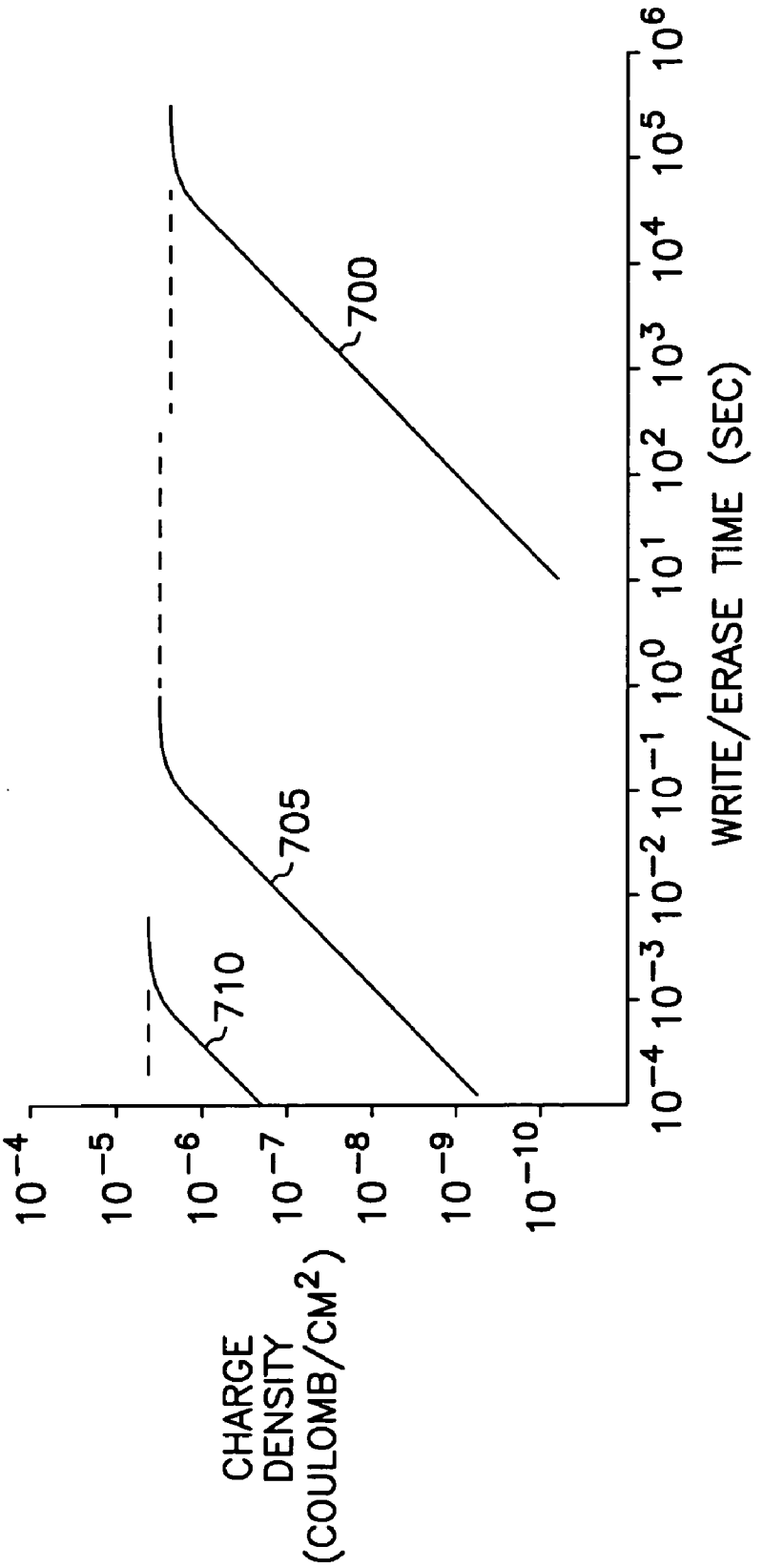

CHARGE DENSITY (COULOMB/CM^2)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
710
705
700
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
WRITE/ERASE TIME (SEC)

FIG. 7

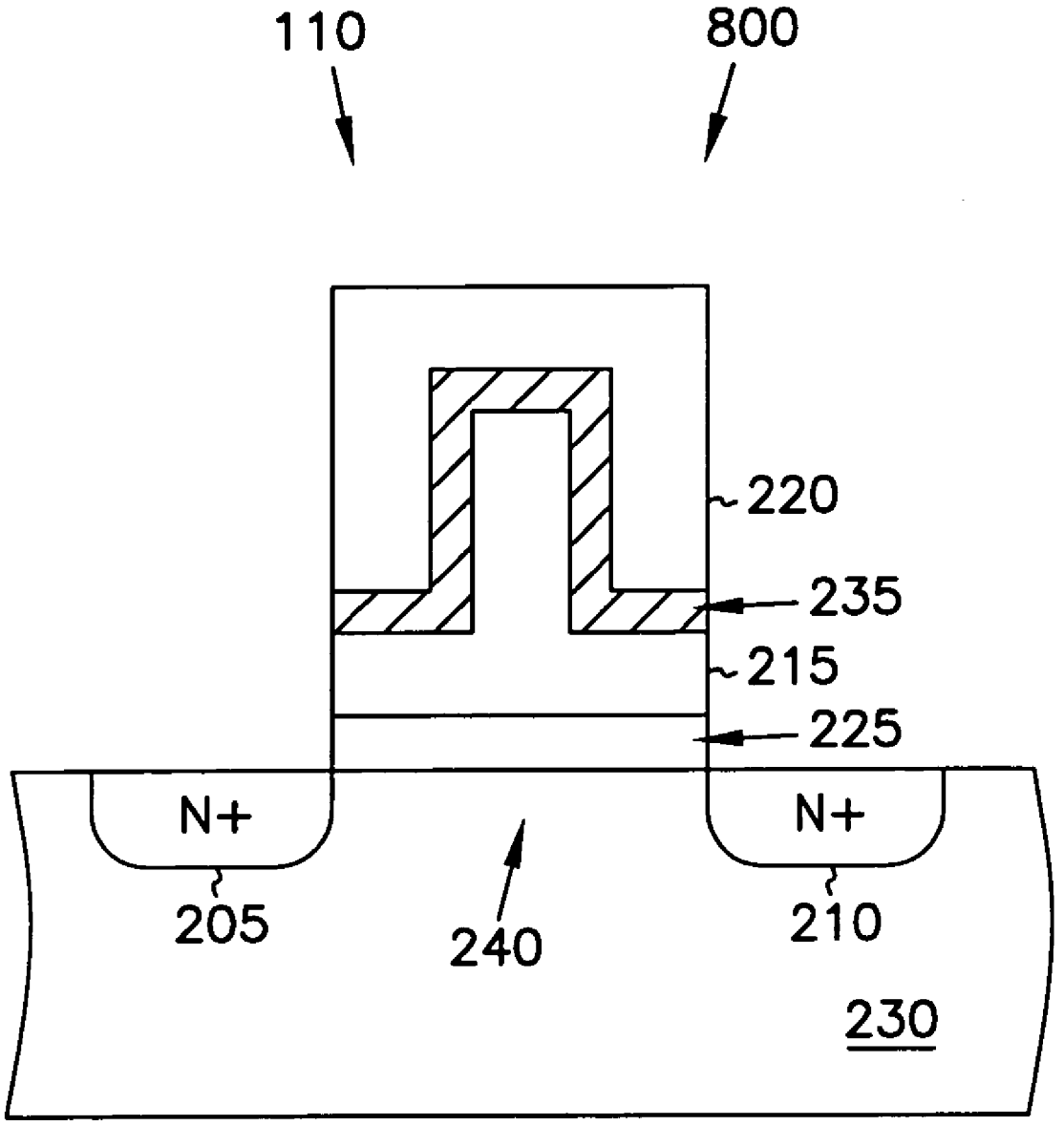


FIG. 8

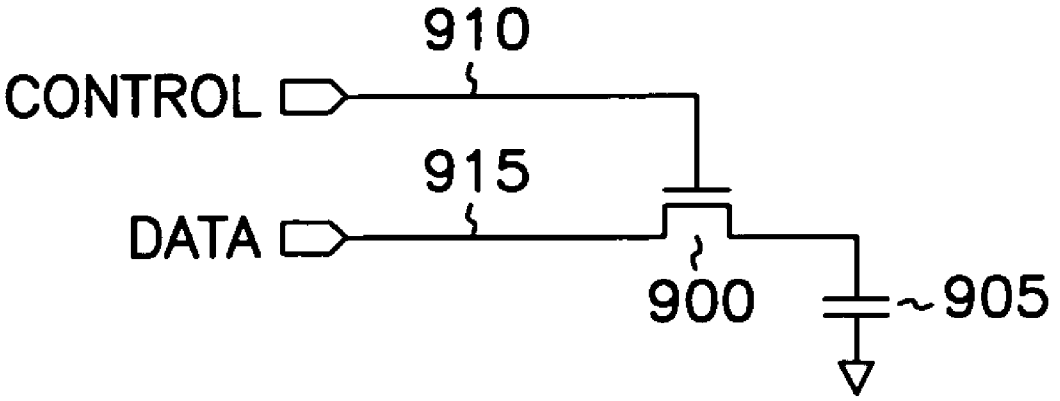


FIG. 9A (PRIOR ART)

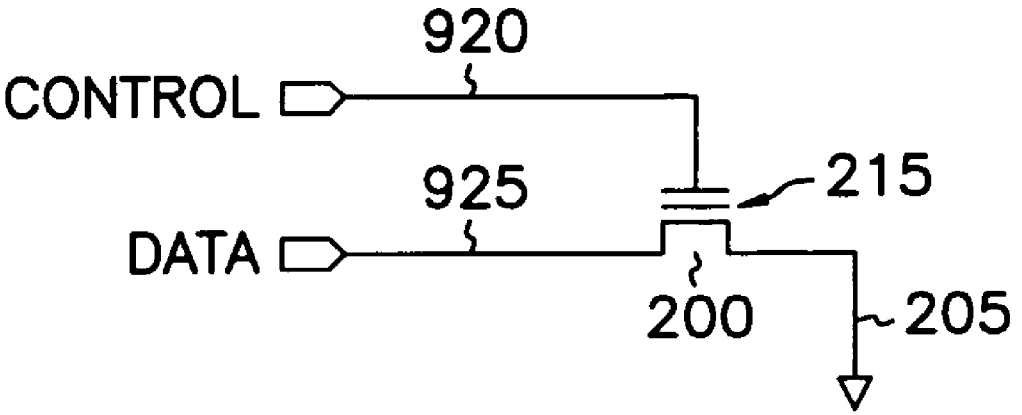


FIG. 9B

DEAPROM HAVING AMORPHOUS SILICON CARBIDE GATE INSULATOR

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation of U.S. Ser. No. 09/134,713, filed on Aug. 14, 1998; which is a divisional of U.S. Ser. No. 08/902,843, filed Jul. 29, 1997, now abandoned; each of which is incorporated herein by reference in its entirety.

[0002] This application is related to the following co-pending, commonly assigned U.S. patent applications: "MEMORY DEVICE," Ser. No. 08/902,133; "DEAPROM AND TRANSISTOR WITH GALLIUM NITRIDE OR GALLIUM ALUMIUM NITRIDE GATE," Ser. No. 08/902,098, now issued as U.S. Pat. No. 6,031,263; "CARBURIZED SILICON GATE INSULATORS FOR INTEGRATED CIRCUITS," Ser. No. 08/903,453; "TRANSISTOR WITH VARIABLE ELECTRON AFFINITY GATE AND METHODS OF FABRICATION AND USE," Ser. No. 08/903,452, now abandoned; "SILICON CARBIDE GATE TRANSISTOR AND FABRICATION PROCESS," Ser. No. 08/903,486, now issued as U.S. Pat. No. 6,936,849; and "TRANSISTOR WITH SILICON OXYCARBIDE GATE AND METHODS OF FABRICATION AND USE," Ser. No. 08/902,132, now issued as U.S. Pat. No. 5,886,368; each of which was filed on Jul. 29, 1997, and each of which disclosure is herein incorporated by reference.

FIELD OF THE INVENTION

[0003] The present invention relates generally to integrated circuit technology, including dynamic random access memories (DRAMs) and electrically erasable and programmable read only memories (EEPROMS), and particularly, but not by way of limitation, to a floating gate transistor memory that is dynamically electrically alterable and programmable.

BACKGROUND OF THE INVENTION

[0004] Dynamic random access memories (DRAMs) are data storage devices that store data as charge on a storage capacitor. A DRAM typically includes an array of memory cells. Each memory cell includes a storage capacitor and an access transistor for transferring charge to and from the storage capacitor. Each memory cell is addressed by a word line and accessed by a bit line. The word line controls the access transistor such that the access transistor controllably couples and decouples the storage capacitor to and from the bit line for writing and reading data to and from the memory cell.

[0005] The storage capacitor must have a capacitance that is large enough to retain a charge sufficient to withstand the effects of parasitic capacitances, noise due to circuit operation, and access transistor reverse-bias junction leakage currents between periodic data refreshes. Such effects can result in erroneous data. Obtaining a large capacitance typically requires a storage capacitor having a large area. However, a major goal in DRAM design is to minimize the area of a DRAM memory cell to allow cells to be more densely packed on an integrated circuit die so that more data can be stored on smaller integrated circuits.

[0006] In achieving the goal of increasing DRAM array capacity by increasing cell density, the sufficient capacitance levels of the DRAM storage capacitors must be maintained. A "stacked storage cell" design can increase the cell density to some degree. In this technique, two or more capacitor conductive plate layers, such as polycrystalline silicon (polysilicon or poly), are deposited over a memory cell access transistor on a semiconductor wafer. A high dielectric constant material is sandwiched between these capacitor plate layers. Such a capacitor structure is known as a stacked capacitor cell (STC) because the storage capacitor plates are stacked on top of the access transistor. However, formation of stacked capacitors typically requires complicated process steps. Stacked capacitors also typically increase topographical features of the integrated circuit die, making subsequent lithography and processing, such as for interconnection formation, more difficult. Alternatively, storage capacitors can be formed in deep trenches in the semiconductor substrate, but such trench storage capacitors also require additional process complexity. There is a need in the art to further increase memory storage density without adding process complexity or additional topography.

[0007] Electrically erasable and programmable read only memories (EEPROMs) provide nonvolatile data storage. EEPROM memory cells typically use field-effect transistors (FETs) having an electrically isolated (floating) gate that affects conduction between source and drain regions of the FET. A gate dielectric is interposed between the floating gate and an underlying channel region between source and drain regions. A control gate is provided adjacent to the floating gate, separated therefrom by an intergate dielectric.

[0008] In such memory cells, data is represented by charge stored on the polysilicon floating gates, such as by hot electron injection or Fowler-Nordheim tunneling during a write operation. Fowler-Nordheim tunneling is typically used to remove charge from the polysilicon floating gate during an erase operation. However, the relatively large electron affinity of the polysilicon floating gate presents a relatively large tunneling barrier energy at its interface with the underlying gate dielectric. The large tunneling barrier energy provides longer data retention times than realistically needed. For example, a data charge retention time at 85 □ C is estimated to be in millions of years for some floating gate memory devices. The large tunneling barrier energy also increases the voltages and time needed to store and remove charge to and from the polysilicon floating gate. "Flash" EEPROMs, which have an architecture that allows the simultaneous erasure of many floating gate transistor memory cells, require even longer erasure times to accomplish this simultaneous erasure. The large erasure voltages needed can result in hole injection into the gate dielectric. This can cause erratic overerasure, damage to the gate dielectric, and introduction of trapping states in the gate dielectric. The high electric fields that result from the large erasure voltages can also result in reliability problems, leading to device failure. There is a need in the art to obtain floating gate transistors that allow the use of lower programming and erasure voltages and shorter programming and erasure times.

SUMMARY OF THE INVENTION

[0009] The present invention includes a memory cell that allows the use of lower programming and erasure voltages

and shorter programming and erasure times by providing a storage electrode for storing charge and providing an adjacent amorphous silicon carbide (a-SiC) insulator.

[0010] In one embodiment, the memory cell includes a floating gate transistor, having a reduced barrier energy between the floating gate and an amorphous silicon carbide (a-SiC) insulator. A refresh circuit allows dynamic refreshing of charge stored on the floating gate. The barrier energy can be lowered to a desired value by selecting the appropriate material composition of the a-SiC insulator. As a result, lower programming and erasure voltages and shorter programming and erasure times are obtained.

[0011] Another aspect of the present invention provides a method of using a floating gate transistor having a reduced barrier energy between a floating gate electrode and an adjacent a-SiC insulator. Data is stored by changing the charge of the floating gate. Data is refreshed based on a data charge retention time established by the barrier energy. Data is read by detecting a conductance between a source and a drain. The large transconductance gain of the memory cell of the present invention provides a more easily detected signal and reduces the required data storage capacitance value and memory cell size when compared to a conventional dynamic random access memory (DRAM) cell.

[0012] The present invention also includes a method of forming a floating gate transistor. Source and drain regions are formed. An a-SiC gate insulator is formed. A floating gate is formed, such that the floating gate is isolated from conductors and semiconductors. The a-SiC gate insulator provides a relatively short data charge retention time, but advantageously provides a shorter write/programming and erase times, making operation of the present memory speed competitive with a DRAM.

[0013] The present invention also includes a memory device that is capable of providing short programming and erase times, low programming and erase voltages, and lower electric fields in the memory cell for improved reliability. The memory device includes a refresh circuit and a plurality of memory cells. Each memory cell includes a transistor. Each transistor includes a source region, a drain region, a channel region between the source and drain regions, and a floating gate that is separated from the channel region by an a-SiC gate insulator. The transistor also includes a control gate located adjacent to the floating gate and separated therefrom by an intergate dielectric. The memory device includes flash electrically erasable and programmable read only memory (EEPROM), dynamic random access memory (DRAM), and dynamically electrically alterable and programmable read only memory (DEAPROM) embodiments.

[0014] The memory cell of the present invention provides a reduced barrier energy, large transconductance gain, an easily detected signal, and reduces the required data storage capacitance value and memory cell size. The lower barrier energy increases tunneling current and also advantageously reduces the voltage required for writing and erasing the floating gate transistor memory cells. For example, conventional polysilicon floating gate transistors typically require complicated and noisy on-chip charge pump circuits to generate the large erasure voltage, which typically far exceeds other voltages required on the integrated circuit. The present invention allows the use of lower erasure voltages that are more easily provided by simpler on-chip circuits. Reducing the erasure voltage also lowers the electric fields, minimizing reliability problems that can lead to device failure, and better accommodating downward scaling of device dimensions. Alternatively, the thickness of the gate insulator can be increased from the typical thickness of a silicon dioxide gate insulator to improve reliability or simplify processing, since the lower barrier energy allows easier transport of charge across the gate insulator by Fowler-Nordheim tunneling.

[0015] According to another aspect of the invention, the shorter retention time of data charges on the floating electrode, resulting from the smaller barrier energy, is accommodated by refreshing the data charges on the floating electrode. By decreasing the data charge retention time and periodically refreshing the data, the write and erase operations can be several orders of magnitude faster such that the present memory is speed competitive with a DRAM. In this respect, the memory operates similar to a memory cell in DRAM, but avoids the process complexity, additional space needed, and other limitations of forming stacked or trench DRAM capacitors.

[0016] The memory cell of the present invention can be made smaller than a conventional DRAM memory cell. Moreover, because the storage capacitor of the present invention is integrally formed as part of the transistor, rather than requiring complex and costly non-CMOS stacked and trench capacitor process steps, the memory of the present invention should be cheaper to fabricate than DRAM memory cells, and should more easily scale downward as CMOS technology advances.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] In the drawings, like numerals describe substantially similar components throughout the several views.

[0018] **FIG. 1** is a simplified schematic/block diagram illustrating generally one embodiment of a memory including reduced barrier energy floating electrode memory cells.

[0019] **FIG. 2** is a cross-sectional view that illustrates generally a floating gate transistor embodiment of a memory cell provided by the present invention.

[0020] **FIG. 3** is an energy band diagram that illustrates generally conduction band energy levels in a floating gate transistor provided by the present invention.

[0021] **FIG. 4** is a graph comparing barrier energy vs. tunneling distance for a conventional floating gate transistor and one embodiment of a the present invention having a lower barrier energy.

[0022] **FIG. 5** is a graph that illustrates generally the relationship between Fowler-Nordheim tunneling current density vs. the barrier energy Φ_{GI} at various parameterized values $E_1<E_2<E_3$ of an electric field.

[0023] **FIG. 6** illustrates generally how the barrier energy affects the time needed to perform write and erase operations by Fowler-Nordheim tunneling for a particular voltage.

[0024] **FIG. 7** is a graph that illustrates generally charge density vs. write/erase time for three different embodiments of a floating gate FET.

[0025] **FIG. 8** is a cross-sectional view, similar to **FIG. 2**, but having a larger area control gate-floating gate capacitor than the floating gate-substrate capacitor.

[0026] **FIG. 9A** is a schematic diagram, labeled prior art, that illustrates generally a conventional DRAM memory cell.

[0027] **FIG. 9B** is a schematic diagram that illustrates generally one embodiment of a floating gate FET memory cell according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0028] 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 semiconductor-based structure having an exposed surface with which to form the integrated circuit structure of the invention. Wafer and substrate are used interchangeably 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 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.

[0029] The present invention discloses a dynamic electrically alterable programmable read only memory (DEAPROM) cell. The memory cell has a floating electrode, which is defined as an electrode that is "electrically isolated" from conductors and semiconductors by an insulator such that charge storage upon and removal from the floating electrode depends upon charge conduction through the insulator. In one embodiment, described below, the floating electrode is a floating gate electrode in a floating gate field-effect transistor, such as used in flash electrically erasable and programmable read only memories (EEPROMs). However, a capacitor or any other structure having a floating electrode and adjacent insulator could also be used according to the techniques of the present invention described below. According to one aspect of the present invention, a barrier energy between the floating electrode and the insulator is lower than the barrier energy between polycrystalline silicon (polysilicon) and silicon dioxide (SiO_2), which is approximately 3.3 eV. According to another aspect of the present invention, the shorter retention time of data charges on the floating electrode, resulting from the smaller barrier energy, is accommodated by refreshing the data charges on the floating electrode. In this respect, the memory operates similar to a memory cell in a dynamic random access memory (DRAM). These and other aspects of the present invention are described in more detail below.

[0030] **FIG. 1** is a simplified schematic/block diagram illustrating generally one embodiment of a memory **100** according to one aspect of the present invention, in which reduced barrier energy floating electrode memory cells are incorporated. Memory **100** is referred to as a dynamic electrically alterable programmable read only memory (DEAPROM) in this application, but it is understood that memory **100** possesses certain characteristics that are similar to DRAMs and flash EEPROMs, as explained below. For a general description of how a flash EEPROM operates, see B. Dipert et al., "Flash Memory Goes Mainstream," IEEE Spectrum, pp. 48-52 (October 1993), which is incorporated herein by reference. Memory **100** includes a memory array **105** of multiple memory cells **110**. Row decoder **115** and column decoder **120** decode addresses provided on address lines **125** to access the addressed memory cells in memory array **105**. Command and control circuitry **130** controls the operation of memory **100** in response to control signals received on control lines **135** from a processor **140** or other memory controller during read, write, refresh, and erase operations. Command and control circuitry **130** includes a refresh circuit for periodically refreshing the data stored on floating gate transistor or other floating electrode memory cells **110**. Voltage control **150** provides appropriate voltages to the memory cells during read, write, refresh, and erase operations. Memory **100**, as illustrated in **FIG. 1**, has been simplified for the purpose of illustrating the present invention and is not intended to be a complete description. Only the substantial differences between DEAPROM memory **100** and conventional DRAM and flash EEPROM memories are discussed below.

[0031] **FIG. 2** is a cross-sectional view that illustrates generally, by way of example, but not by way of limitation, one floating gate transistor embodiment of a memory cell **110**. Other structural arrangements of floating gate transistors are included within the present invention. Also included are any memory cells that incorporate a floating electrode (such as a floating electrode capacitor) having, at an interface between the floating electrode an adjacent insulator, a barrier energy that is less than the barrier energy at a polysilicon-SiO_2 interface. In the embodiment of **FIG. 2**, memory cell **110** includes a floating gate FET **200**, which is illustrated as an n-channel FET, but understood to include a p-channel FET embodiment as well.

[0032] FET **200** includes a source **205**, a drain **210**, a floating gate **215** electrode, and a control gate **220** electrode. A gate insulator **225** is interposed between floating gate **215** and substrate **230**. An intergate insulator **235** is interposed between floating gate **215** and control gate **220**. In one embodiment, substrate **230** is a bulk semiconductor, such as silicon. In another embodiment, substrate **230** includes a thin semiconductor surface layer formed on an underlying insulating portion, such as in a semiconductor-on-insulator (SOI) or other thin film transistor technology. Source **205** and drain **210** are formed by conventional complementary metal-oxide-semiconductor (CMOS) processing techniques. Source **205** and drain **210** are separated by a predetermined length for forming an inversion channel **240** therebetween.

[0033] **FIG. 3** is an energy band diagram that illustrates generally the conduction band energy levels in floating gate **215**, gate insulator **225**, and substrate **230**. Electron affinities χ_{215}, χ_{225}, and χ_{230} describe floating gate **215**, gate insulator **225**, and substrate **230**, respectively, when measured with respect to a vacuum level **300**. A barrier energy Φ_{GI}, which describes the barrier energy at the interface between floating

gate **215** and gate insulator **225**, is given by a difference in electron affinities, as illustrated in Equation 1.

$$\Phi_{GI}=\chi_{215}-\chi_{225} \quad (1)$$

A barrier energy Φ_{SG}, which describes the barrier energy at the interface between substrate **230** and gate insulator **225**, is given by a difference in electron affinities, as illustrated in Equation 2.

$$\Phi_{SG}=\chi_{230}-\chi_{225} \quad (2)$$

Silicon (monocrystalline or polycrystalline Si) has an electron affinity $\chi_{215}\approx 4.2$ eV. Silicon dioxide (SiO_2) has an electron affinity, χ_{225}, of about 0.9 eV. The resulting barrier energy at a conventional Si—SiO_2 interface between a floating gate and a gate insulator is approximately equal to 3.3 eV. One aspect of the present invention provides a barrier energy Φ_{GI} that is less than the 3.3 eV barrier energy of a conventional Si—SiO_2 interface.

[0034] According to one aspect of the invention, the interface between floating gate **215** and gate insulator **225** provides a smaller barrier energy Φ_{GI} than the 3.3 eV barrier energy at an interface between polysilicon and silicon dioxide, such as by an appropriate selection of the material composition of one or both of floating gate **215** and gate insulator **225**. In one embodiment, the smaller barrier energy Φ_{GI} is obtained by forming floating gate **215** from a material having a smaller electron affinity χ_{215} than polysilicon. In one embodiment, for example, polycrystalline or microcrystalline silicon carbide (SiC) is used as the material for forming floating gate **215**. In another embodiment, the smaller barrier energy Φ_{GI} is obtained by forming gate insulator **225** from a material having a higher electron affinity χ_{225} than SiO_2. In one embodiment, for example, amorphous SiC is used as the material for forming gate insulator **225**. In yet another embodiment, the smaller barrier energy Φ_{GI} is obtained by a combination of forming floating gate **215** from a material having a smaller electron affinity χ_{215} than polysilicon and also forming gate insulator **225** from a material having a higher electron affinity χ_{225} than SiO_2.

[0035] The smaller barrier energy Φ_{GI} provides current conduction across gate insulator **225** that is easier than for a polysilicon-SiO_2 interface. The present invention includes any mechanism of providing such easier current conduction across gate insulator **225**, including, but not limited to "hot" electron injection, thermionic emission, Schottky emission, Frenkel-Poole emission, and Fowler-Nordheim tunneling. Such techniques for transporting charge carriers across an insulator, such as gate insulator **225**, are all enhanced by providing a smaller barrier energy Φ_{GI} according to the techniques of the present invention. These techniques allow increased current conduction, current conduction at lower voltages across gate insulator **225** and lower electric fields in gate insulator **225**, shorter data write and erase times, use of a thicker and more reliable gate insulator **225**, and other advantages explained below.

[0036] **FIG. 4** is a graph illustrating generally barrier energy versus tunneling distance for a conventional polysilicon-SiO_2 interface having a 3.3 eV barrier energy. **FIG. 4** also illustrates barrier energy versus tunneling distance for an interface according to the present invention that has a barrier energy of $\Phi_{GI}\approx 1.08$ eV, which is selected as an illustrative example, and not by way of limitation. The smaller barrier energy Φ_{GI} reduces the energy to which the electrons must be excited to be stored on or removed from the floating gate **215**, such as by thermal emission over the barrier. The smaller barrier energy Φ_{GI} also reduces the distance that electrons have to traverse, such as by Fowler-Nordheim tunneling, to be stored upon or removed from floating gate **215**. In **FIG. 4**, "do" represents the tunneling distance of a conventional floating gate transistor due to the 3.3 eV barrier energy represented by the dashed line "OLD". The tunneling distance "dn" corresponds to a floating gate transistor according to the present invention and its smaller barrier energy, such as $\Phi_{GI}\approx 1.08$ eV, for example, represented by the dashed line "NEW". Even a small reduction in the tunneling distance results in a large increase in the tunneling probability, as described below, because the tunneling probability is an exponential function of the reciprocal of the tunneling distance.

[0037] The Fowler-Nordheim tunneling current density in gate insulator **225**, which is illustrated approximately by Equation 3 below, is described in a textbook by S. M. Sze, "Physics of Semiconductor Devices," John Wiley & Sons, New York (1969), p. 496.

$$J = AE^2 e^{\left(-\frac{B}{E}\right)} \quad (3)$$

In Equation 3, J is the current density in units of amperes/cm^2, E is the electric field in gate insulator **225** in units of volts/cm and A and B are constants, which are particular to the material of gate insulator **225**, that depend on the effective electron mass in the gate insulator **225** material and on the barrier energy Φ_{GI}. The constants A and B scale with the barrier energy Φ_{GI}, as illustrated approximately by Equations 4 and 5, which are disclosed in S. R. Pollack et al., "Electron Transport Through Insulating Thin Films," Applied Solid State Science, Vol. 1, Academic Press, New York, (1969), p. 354.

$$A\alpha\left(\frac{1}{\Phi_{GI}}\right) \quad (4)$$

$$B\alpha(\Phi_{GI})^{\frac{3}{2}} \quad (5)$$

For a conventional floating gate FET having a 3.3 eV barrier energy at the interface between the polysilicon floating gate and the SiO_2 gate insulator, $A=5.5\times10^{-16}$ amperes/$Volt^2$ and $B=7.07\times10^{7}$ Volts/cm, as disclosed in D. A. Baglee, "Characteristics and Reliability of 100 Å Oxides," Proc. 22nd Reliability Symposium, (1984), p. 152. One aspect of the present invention includes selecting a smaller barrier energy Φ_{GI} such as, by way of example, but not by way of limitation, $\Phi_{GI}\approx\approx 1.08$ eV. The constants A and B for $\Phi_{GI}\approx 1.08$ eV can be extrapolated from the constants A and B for the 3.3 eV polysilicon-SiO_2 barrier energy using Equations 4 and 5. The barrier energy $\Phi_{GI}\approx 1.08$ eV yields the resulting constants $A=1.76\times10^{-15}$ amperes/$Volt^2$ and $B=1.24\times10^{7}$ Volts/cm.

[0038] **FIG. 5** is a graph that illustrates generally the relationship between Fowler-Nordheim tunneling current density vs. the barrier energy Φ_{GI}, such as at various

parameterized values $E_1<E_2<E_3$ of an electric field in gate insulator **225**. The tunneling current density increases as electric field is increased. The tunneling current also increases by orders of magnitude as the barrier energy Φ_{GI} is decreased, such as by selecting the materials for floating gate **215** and gate insulator **225** or otherwise reducing the barrier energy Φ_{GI} according to the techniques of the present invention. In particular, **FIG. 5** illustrates a comparison between tunneling current densities at the 3.3 eV barrier energy of a conventional polysilicon-SiO_2 interface and at the illustrative example barrier energy $\Phi_{GI}\approx 1.08$ eV for which constants A and B were extrapolated above. Reducing the 3.3 eV barrier energy to $\Phi_{GI}\approx 1.08$ eV increases the tunneling current density by several orders of magnitude.

[**0039**] **FIG. 6** is a conceptual diagram, using rough order of magnitude estimates, that illustrates generally how the barrier energy affects the time needed to perform write and erase operations by Fowler-Nordheim tunneling for a particular voltage, such as across gate insulator **225**. **FIG. 6** also illustrates how the barrier energy affects data charge retention time, such as on floating gate **215** at a temperature of 250 degrees Celsius. Both write and erase time **600** and data charge retention time **605** are decreased by orders of magnitude as the barrier energy is decreased, according to the present invention, from the conventional polysilicon-SiO_2 interface barrier energy of 3.3 eV to the illustrative example lower barrier energy $\Phi_{GI}\approx 1.08$ eV for which constants A and B were extrapolated above.

[**0040**] The lower barrier energy Φ_{GI} and increased tunneling current advantageously provides faster write and erase times. This is particularly advantageous for "flash" EEPROMs or DEAPROMs in which many floating gate transistor memory cells must be erased simultaneously, requiring a longer time to transport the larger quantity of charge. For a flash EEPROM using a polysilicon floating gate transistor having an underlying SiO_2 gate insulator **225**, the simultaneous erasure of a block of memory cells requires a time that is on the order of milliseconds. The write and erase time of the floating gate FET **200** is illustrated approximately by Equation 6.

$$t=\int_0^t dt=\int_o^Q\left(\frac{1}{J_{225}-J_{235}}\right)dQ \tag{6}$$

In Equation 6, t is the write/erase time, J_{225} and J_{235} are the respective tunneling current densities in gate dielectric **225** and intergate dielectric **235**, Q is the charge density in Coulombs/cm^2 on floating gate **215**. Equation 6 is evaluated for a specific voltage on control gate **220** using Equations 7 and 8.

$$E_{225}=\frac{V_{220}}{\left[d_{225}+d_{235}\left(\frac{\varepsilon_{225}}{\varepsilon_{235}}\right)\right]}-\frac{Q}{\left[\varepsilon_{225}+\varepsilon_{235}\left(\frac{d_{225}}{d_{235}}\right)\right]} \tag{7}$$

-continued

$$E_{235}=\frac{V_{220}}{\left[d_{235}+d_{225}\left(\frac{\varepsilon_{235}}{\varepsilon_{225}}\right)\right]}-\frac{Q}{\left[\varepsilon_{235}+\varepsilon_{225}\left(\frac{d_{235}}{d_{225}}\right)\right]} \tag{8}$$

In Equations 7 and 8, V_{220} is the voltage on control gate **220**, E_{225} and E_{235} are the respective electric fields in gate insulator **225** and intergate insulator **235**, d_{225} and d_{235} are the respective thicknesses of gate insulator **225** and intergate insulator **235**, and ϵ_{225} and ϵ_{235} are the respective permittivities of gate insulator **225** and intergate insulator **235**.

[**0041**] **FIG. 7** is a graph that illustrates generally charge density vs. write/erase time for three different embodiments of the floating gate FET **200**, each of which have a polysilicon floating gate **215**, by way of illustrative example. Line **700** illustrates generally, by way of example, but not by way of limitation, the charge density vs. write/erase time obtained for a floating gate FET **200** having a 100 Å SiO_2 gate insulator **225** and a 150 Å SiO_2 (or thinner oxynitride equivalent capacitance) intergate insulator **235**.

[**0042**] Line **705** is similar to line **700** in all respects except that line **705** illustrates a floating gate FET **200** in which gate insulator **225** comprises a material having a higher electron affinity χ_{225} than SiO_2, thereby providing a lower barrier energy Φ_{GI} at the interface between polysilicon floating gate **215** and gate insulator **225**. The increased tunneling current results in shorter write/erase times than those illustrated by line **700**.

[**0043**] Line **710** is similar to line **705** in all respects except that line **710** illustrates a floating gate FET **200** in which gate insulator **225** has a lower barrier energy Φ_{GI} than for line **705**, or intergate insulator **235** has a higher permittivity ϵ_{235} than for line **705**, or control gate **220** has a larger area than floating gate **215**, such as illustrated by way of example by the floating gate FET **800** in the cross-sectional view of **FIG. 8**. As seen in **FIG. 8**, the area of a capacitor formed by the control gate **220**, the floating gate **215**, and the intergate insulator **235** is larger than the area of a capacitor formed by the floating gate **215**, the gate insulator **225**, and the inversion channel **240** underlying gate insulator **225**. Alternatively, or in combination with the techniques illustrated in **FIG. 8**, the intergate insulator **235** can have a higher permittivity than the permittivity of silicon dioxide.

[**0044**] As illustrated in **FIG. 7**, the barrier energy Φ_{GI} can be selected to reduce the write/erase time. In one embodiment, by way of example, but not by way of limitation, the barrier energy Φ_{GI} is selected to obtain a write/erase time of less than or equal to 1 second, as illustrated in **FIG. 7**. In another embodiment, by way of example, but not by way of limitation, the barrier energy Φ_{GI} is selected to obtain a write/erase time of less than or equal to 1 millisecond, as illustrated in **FIG. 7**. Other values of write/erase time can also be obtained by selecting the appropriate value of the barrier energy Φ_{GI}.

[**0045**] The lower barrier energy Φ_{GI} and increased tunneling current also advantageously reduces the voltage required for writing and erasing the floating gate transistor memory cells **110**. For example, conventional polysilicon

floating gate transistors typically require complicated and noisy on-chip charge pump circuits to generate the large erasure voltage, which typically far exceeds other voltages required on the integrated circuit. The present invention allows the use of lower erasure voltages that are more easily provided by simpler on-chip circuits. Reducing the erasure voltage also lowers the electric fields, minimizing reliability problems that can lead to device failure, and better accommodating downward scaling of device dimensions. In one embodiment, the barrier energy Φ_{GI} is selected, as described above, to obtain an erase voltage of less than the 12 Volts required by typical EEPROM memory cells.

[0046] Alternatively, the thickness of the gate insulator **225** can be increased from the typical thickness of a silicon dioxide gate insulator to improve reliability or simplify processing, since the lower barrier energy Φ_{GI} allows easier transport of charge across the gate insulator **225** by Fowler-Nordheim tunneling.

[0047] The lower barrier energy Φ_{GI} also decreases the data charge retention time of the charge stored on the floating gate **215**, such as from increased thermal excitation of stored charge over the lower barrier Φ_{GI}. However, conventional polysilicon floating gates and adjacent SiO_2 insulators (e.g., 90 Å thick) have a data charge retention time estimated in the millions of years at a temperature of 85 degrees C., and estimated in the 1000 hour range even at extremely high temperatures such as 250 degrees C. Since such long data charge retention times are longer than what is realistically needed, a shorter data charge retention time can be accommodated in order to obtain the benefits of the smaller barrier energy Φ_{GI}. In one embodiment of the present invention, by way of example, but not by way of limitation, the barrier energy Φ_{GI} is lowered to $\Phi_{GI} \approx 1.08$ eV by appropriately selecting the composition of the materials of floating gate **215** and gate insulator **225**, as described below. As a result, an estimated data charge retention time of approximately 40 seconds at a high temperature, such as 250 degrees C., is obtained.

[0048] According to one aspect of the present invention, the data stored on the DEAPROM floating gate memory cell **110** is periodically refreshed at an interval that is shorter than the data charge retention time. In one embodiment, for example, the data is refreshed every few seconds, such as for an embodiment having a high temperature retention time of approximately 40 seconds for $\Phi_{GI} \approx 1.08$ eV. The exact refresh rate can be experimentally determined and tailored to a particular process of fabricating the DEAPROM. By decreasing the data charge retention time and periodically refreshing the data, the write and erase operations can be several orders of magnitude faster, as described above with respect to **FIG. 7**.

[0049] **FIGS. 9A and 9B** are schematic diagrams that respectively illustrate generally a conventional DRAM memory cell and the present invention's floating gate FET **200** embodiment of memory cell **110**. In **FIG. 9A**, the DRAM memory cell includes an access FET **900** and stacked or trench storage capacitor **905**. Data is stored as charge on storage capacitor **905** by providing a control voltage on control line **910** to activate FET **900** for conducting charge. Data line **915** provides a write voltage to conduct charge across FET **900** for storage on storage capacitor **905**. Data is read by providing a control voltage on control line **910** to activate FET **900** for conducting charge from storage capacitor **905**, thereby incrementally changing a preinitialized voltage on data line **915**. The resulting small change in voltage on data line **915** must be amplified by a sense amplifier for detection. Thus, the DRAM memory cell of **FIG. 9A** inherently provides only a small data signal. The small data signal is difficult to detect.

[0050] In **FIG. 9B**, the DEAPROM memory cell **110** according to the present invention includes floating gate FET **200**, having source **205** coupled to a ground voltage or other reference potential. Data is stored as charge on floating gate **215** by providing a control voltage on control line **920** and a write voltage on data line **925** for hot electron injection or Fowler-Nordheim tunneling. This is similar to conventional EEPROM techniques, but advantageously uses the reduced voltages and/or a shorter write time of the present invention.

[0051] The DEAPROM memory cell **110** can be smaller than the DRAM memory cell of **FIG. 9A**, allowing higher density data storage. The leakage of charge from floating gate **215** can be made less than the reverse-bias junction leakage from storage capacitor **905** of the DRAM memory cell by tailoring the barrier energy Φ_{GI} according to the techniques of the present invention. Also, the DEAPROM memory cell advantageously uses the large transconductance gain of the floating gate FET **200**. The conventional DRAM memory cell of **FIG. 9A** provides no such gain; it is read by directly transferring the data charge from storage capacitor **905**. By contrast, the DEAPROM memory cell **110** is read by placing a read voltage on control line **920**, and detecting the current conducted through FET **200**, such as at data line **925**. The current conducted through FET **200** changes significantly in the presence or absence of charge stored on floating gate **215**. Thus, the present invention advantageously provides an large data signal that is easy to detect, unlike the small data signal provided by the conventional DRAM memory cell of **FIG. 9A**.

[0052] For example, the current for floating gate FET **200** operating in the saturation region can be approximated by Equation 9.

$$I_{DS} = \frac{1}{2}\mu C_0\left(\frac{W}{L}\right)(V_G - V_T)^2 \tag{9}$$

In Equation 9, I_{DS} is the current between drain **210** and source **205**, C_o is the capacitance per unit area of the gate insulator **225**, W/L is the width/length aspect ratio of FET **200**, V_G is the gate voltage applied to control gate **220**, and V_T is the turn-on threshold voltage of FET **200**.

[0053] For an illustrative example, but not by way of limitation, a minimum-sized FET having W/L=1, can yield a transconductance gain of approximately 71 μA/Volt for a typical process. In this illustrative example, sufficient charge is stored on floating gate **215** to change the effective threshold voltage V_T by approximately 1.4 Volts, thereby changing the current I_{DS} by approximately 100 microamperes. This significant change in current can easily be detected, such as by sampling or integrating over a time period of approximately 10 nanoseconds, for example, to obtain a detected data charge signal of 1000 fC. Thus, the DEAPROM

memory cell **110** is capable of yielding a detected data charge signal that is approximately an order of magnitude larger than the typical 30 fC to 100 fC data charges typically stored on DRAM stacked or trench capacitors. Since DEAPROM memory cell **110** requires a smaller capacitance value than a conventional DRAM memory cell, DEAPROM memory cell **110** can be made smaller than a conventional DRAM memory cell. Moreover, because the CMOS-compatible DEAPROM storage capacitor is integrally formed as part of the transistor, rather than requiring complex and costly non-CMOS stacked and trench capacitor process steps, the DEAPROM memory of the present invention should be cheaper to fabricate than DRAM memory cells, and should more easily scale downward as CMOS technology advances.

Amorphous SiC Gate Insulator Embodiment

[**0054**] In one embodiment, the present invention provides a DEAPROM having a storage element including a gate insulator **225** that includes an amorphous silicon carbide (a-SiC). For example, one embodiment of a memory storage element having an a-SiC gate insulator **225** is described in Forbes et al. U.S. patent application Ser. No. 08/903,453 entitled CARBURIZED SILICON GATE INSULATORS FOR INTEGRATED CIRCUITS, filed on the same day as the present patent application, and which disclosure is herein incorporated by reference. The a-SiC inclusive gate insulator **225** provides a higher electron affinity χ_{225} than the approximately 0.9 eV electron affinity of SiO_2. For example, but not by way of limitation, the a-SiC inclusive gate insulator **225** can provide an electron affinity $\chi_{225} \approx 3.24$ eV.

[**0055**] An a-SiC inclusive gate insulator **225** can also be formed using other techniques. For example, in one embodiment gate insulator **225** includes a hydrogenated a-SiC material synthesized by ion-implantation of C_2H_2 into a silicon substrate **230**. For example, see G. Comapagnini et al. "Spectroscopic Characterization of Annealed $Si_{1-x}C_x$ Films Synthesized by Ion Implantation,"*J. of Materials Research*, Vol. 11, No. 9, pp. 2269-73, (1996). In another embodiment, gate insulator **225** includes an a-SiC film that is deposited by laser ablation at room temperature using a pulsed laser in an ultrahigh vacuum or nitrogen environment. For example, see A. L. Yee et al. "The Effect of Nitrogen on Pulsed Laser Deposition of Amorphous Silicon Carbide Films: Properties and Structure,"*J. Of Materials Research*, Vol. 11, No. 8, pp. 1979-86 (1996). In another embodiment, gate insulator **225** includes an a-SiC film that is formed by low-energy ion-beam assisted deposition to minimize structural defects and provide better electrical characteristics in the semiconductor substrate **230**. For example, see C. D. Tucker et al. "Ion-beam Assisted Deposition of Nonhydrogenated a-Si:C films,"*Canadian J. Of Physics*, Vol. 74, No. 3-4, pp. 97-101 (1996). The ion beam can be generated by electron cyclotron resonance from an ultra high purity argon (Ar) plasma.

[**0056**] In another embodiment, gate insulator **225** includes an a-SiC film that is synthesized at low temperature by ion beam sputtering in a reactive gas environment with concurrent ion irradiation. For example, see H. Zhang et al., "Ion-beam Assisted Deposition of Si-Carbide Films,"*Thin Solid Films*, Vol. 260, No. 1, pp. 32-37 (1995). According to one technique, more than one ion beam, such as an Ar ion beam, are used. A first Ar ion beam is directed at a Si target material to provide a Si flux for forming SiC gate insulator **225**. A second Ar ion beam is directed at a graphite target to provide a C flux for forming SiC gate insulator **225**. The resulting a-SiC gate insulator **225** is formed by sputtering on substrate **230**. In another embodiment, gate insulator **225** includes an SiC film that is deposited on substrate **230** by DC magnetron sputtering at room temperature using a conductive, dense ceramic target. For example, see S. P. Baker et al. "D-C Magnetron Sputtered Silicon Carbide, "*Thin Films, Stresses and Mechanical Properties V. Symposium*, pp. Xix+901, 227-32 (1995). In another embodiment, gate insulator **225** includes a thin a-$Si_{1-x}C_x$:H film that is formed by HF plasma ion sputtering of a fused SiC target in an Ar—H atmosphere. For example, see N. N. Svirkova et al. "Deposition Conditions and Density-of-States Spectrum of a-$Si_{1-x}C_x$:H Films Obtained by Sputtering,"*Semiconductors*, Vol. 28, No. 12, pp. 1164-9 (1994). In another embodiment, radio frequency (RF) sputtering is used to produce a-SiC films. For example, see Y. Suzaki et al. "Quantum Size Effects of a-Si(:H)/a-SiC(:H) Multilayer Films Prepared by RF Sputtering,"*J. Of Japan Soc. Of Precision Engineering*, Vol. 60, No. 3, pp. 110-18 (1996). Bandgaps of a-Si, a-SiC, a-Si:H, and a-SiC:H have been found to be 1.22 eV, 1.52 eV, 1.87 eV, and 2.2 eV respectively.

[**0057**] In another embodiment, gate insulator **225** is formed by chemical vapor deposition (CVD) and includes an a-SiC material. According to one technique, gate insulator **225** includes a-$Si_{1-x}C_x$:H deposited by plasma enhanced chemical vapor deposition (PECVD). For example, see I. Pereyra et al. "Wide Gap a-$Si_{1-x}C_x$:H Thin Films Obtained Under Starving Plasma Deposition Conditions,"*J. Of Non-crystalline Solids*, Vol. 201, No. 1-2, pp. 110-118 (1995). According to another technique, mixed gases of silane and methane can be used to form a-$Si_{1-x}C_x$:H gate insulator **225**. For example, the source gas can include silane in methane with additional dilution in hydrogen. In another embodiment, gate insulator **225** includes a clean a-$Si_{1-x}C_x$ material formed by hot-filament assisted CVD. For example, see A. S. Kumbhar et al. "Growth of Clean Amorphous Silicon Carbon Alloy Films By Hot-Filament Assisted Chemical Vapor Deposition Technique,"*Appl. Phys. Letters*, Vol. 66, No. 14, pp. 1741-3 (1995). In another embodiment, gate insulator **225** includes a-SiC formed on a crystalline Si substrate **230** by inductively coupled plasma CVD, such as at 450 degrees Celsius, which can yield a-SiC rather than epitaxially grown polycrystalline or microcrystalline SiC. The resulting a-SiC inclusive gate insulator **225** can provide an electron affinity $\chi_{225} \approx 3.24$ eV, which is significantly larger than the 0.9 eV electron affinity obtainable from a conventional SiO_2 gate insulator. For example, see J. H. Thomas et al. "Plasma Etching and Surface Analysis of a-SiC:H Films Deposited by Low Temperature Plasma Enhanced Vapor Deposition,"*Gas-phase and Surface Chemistry in Electronic Materials Processing Symposium, Materials Research Soc.*, pp. Xv+556, 445-50 (1994).

[**0058**] Gate insulator **225** can be etched by RF plasma etching using CF_4O_2 in SF_6O_2. Self-aligned source **205** and drain **210** can then be formed using conventional techniques for forming a FET **200** having a floating (electrically isolated) gate **215**, or in an alternate embodiment, an electrically interconnected (driven) gate.

CONCLUSION

[0059] The present invention provides a DEAPROM cell. The memory cell has a floating electrode, such as a floating gate electrode in a floating gate field-effect transistor. According to one aspect of the invention, a barrier energy between the floating electrode and the insulator is lower than the barrier energy between polysilicon and SiO_2, which is approximately 3.3 eV, by using an amorphous silicon carbide (a-SiC) gate insulator adjacent to the floating gate. The memory cell also provides large transconductance gain, which provides a more easily detected signal and reduces the required data storage capacitance value.

[0060] According to another aspect of the invention, the shorter retention time of data charges on the floating electrode, resulting from the smaller barrier energy, is accommodated by refreshing the data charges on the floating electrode. By decreasing the data charge retention time and periodically refreshing the data, the write and erase operations can be several orders of magnitude faster. In this respect, the memory operates similar to a memory cell in DRAM, but avoids the process complexity, additional space needed, and other limitations of forming stacked or trench DRAM capacitors.

[0061] Although specific embodiments have been illustrated and described herein, those of ordinary skill in the art will appreciate that the above-described embodiments can be used in combination, and any arrangement which is calculated to achieve the same purpose may be substituted for the specific embodiment shown. This application is intended to cover any adaptations or variations of the present invention. Therefore, it is manifestly intended that this invention be limited only by the claims and the equivalents thereof.

What is claimed is:

1. A method of forming a memory cell comprising:

forming a source region in a substrate;

forming a drain region in the substrate, a channel region being between the source region and the drain region in the substrate;

forming a floating gate; and

forming an amorphous silicon carbide (a-SiC) insulator between the floating gate and the channel region in the substrate, the amorphous silicon carbide (a-SiC) insulator being in contact with both the floating gate and the substrate.

2. The method of claim 1 wherein forming a floating gate and forming an amorphous silicon carbide (a-SiC) insulator further comprises forming at least one of the floating gate and the a-SiC insulator to have an electron affinity such that a barrier energy, defined as a difference between an electron affinity of the floating gate and an electron affinity of the a-SiC insulator, is less than approximately 3.3 eV.

3. The method of claim 2 wherein forming at least one of the floating gate and the a-SiC insulator further comprises forming the floating gate and the a-SiC insulator such that the barrier energy facilitates a data charge retention time on the floating gate of less than or equal to approximately 40 seconds at 250 degrees Celsius.

4. The method of claim 2 wherein forming at least one of the floating gate and the a-SiC insulator further comprises forming the floating gate and the a-SiC insulator such that the barrier energy facilitates a floating gate erase time of less than or equal to approximately 1 second.

5. The method of claim 2 wherein forming at least one of the floating gate and the a-SiC insulator further comprises forming the floating gate and the a-SiC insulator such that the barrier energy facilitates a floating gate erase voltage of less than approximately 12 Volts.

6. The method of claim 1 wherein forming an amorphous silicon carbide (a-SiC) insulator further comprises forming the a-SiC insulator to have an electron affinity that is less than an electron affinity of silicon dioxide (SiO2).

7. The method of claim 1 wherein forming a floating gate further comprises forming the floating gate to have a smaller electron affinity than polycrystalline silicon.

8. The method of claim 1 wherein forming a floating gate and forming an amorphous silicon carbide (a-SiC) insulator further comprises forming at least one of the floating gate and the a-SiC insulator to have an electron affinity such that a barrier energy, defined as a difference between an electron affinity of the floating gate and an electron affinity of the a-SiC insulator, is less than approximately 2.0 eV.

9. The method of claim 1 wherein forming a floating gate further comprises forming the floating gate such that the floating gate is isolated from conductors and semiconductors.

10. The method of claim 1 wherein:

forming a floating gate further comprises forming the floating gate such that the floating gate is transconductively capacitively coupled to the channel region; and

forming a source region further comprises forming the source region in a silicon substrate.

11. A method for forming a transistor comprising:

forming a source region in a silicon substrate;

forming a drain region in the substrate;

forming a channel region in the substrate between the source region and the drain region; and

forming a floating gate separated from the channel region by an amorphous silicon carbide (a-SiC) insulator, the amorphous silicon carbide (a-SiC) insulator being in contact with both the substrate and the floating gate.

12. The method of claim 11 wherein forming a floating gate further comprises forming at least one of the floating gate and the a-SiC insulator to have an electron affinity such that a barrier energy, defined as a difference between an electron affinity of the floating gate and an electron affinity of the a-SiC insulator, is less than approximately 3.3 eV.

13. The method of claim 11 wherein forming a floating gate further comprises forming at least one of the floating gate and the a-SiC insulator to have an electron affinity such that the barrier energy provides a data charge retention time of the transistor that is adapted for dynamic refreshing of charge stored on the floating gate.

14. The method of claim 11, further comprising forming a control electrode opposite from the floating gate and separated from the floating gate by an intergate insulator.

15. The method of claim 14 wherein forming a control electrode further comprises forming the control electrode with a shape such that an area of a capacitor formed by the control electrode, the floating gate, and the intergate insu-

lator is larger than an area of a capacitor formed by the floating gate, the a-SiC insulator, and the channel region.

16. The method of claim 14 wherein forming a control electrode further comprises forming the intergate insulator to have a permittivity that is higher than a permittivity of silicon dioxide.

17. A method of forming a floating gate transistor, comprising:

forming source and drain regions in a silicon substrate;

forming an amorphous silicon carbide (a-SiC) gate insulator on the substrate over a channel region located between the source and drain regions in the substrate; and

forming a floating gate on the a-SiC gate insulator, wherein forming an amorphous silicon carbide (a-SiC) gate insulator and forming a floating gate further comprises forming the a-SiC gate insulator and forming the floating gate such that a barrier energy, defined as a difference between an electron affinity of the floating gate and an electron affinity of the a-SiC gate insulator, is less than approximately 3.3 eV.

18. The method of claim 17 wherein forming an amorphous silicon carbide (a-SiC) gate insulator further comprises forming an amorphous silicon carbide (a-SiC) gate insulator by ion-implantation of C2H2 into a silicon substrate.

19. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by laser ablation at room temperature using a pulsed laser in an ultrahigh vacuum or nitrogen environment.

20. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by low-energy ion-beam assisted deposition in order to minimize structural defects and provide better electrical characteristics in the substrate.

21. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by ion beam sputtering in a reactive gas environment with concurrent ion irradiation.

22. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by DC magnetron sputtering at room temperature using a conductive, dense ceramic target.

23. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by HF plasma ion sputtering of a fused SiC target in an Ar—H atmosphere.

24. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by radio frequency (RF) sputtering.

25. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by chemical vapor deposition (CVD).

26. The method of claim 17, wherein forming an amorphous silicon carbide (a-SiC) gate insulator includes forming an amorphous silicon carbide (a-SiC) gate insulator by inductively coupled plasma CVD, such as at 450 degrees Celsius, which can yield a-SiC rather than epitaxially grown polycrystalline or microcrystalline SiC.

27. A method of forming a floating gate transistor comprising:

forming an n-type source region and an n-type drain region in a silicon substrate;

forming an amorphous silicon carbide (a-SiC) gate insulator on the substrate over a channel region in the substrate, the channel region being located between the source region and the drain region; and

forming a polysilicon floating gate on the a-SiC gate insulator.

28. The method of claim 27 wherein:

forming an n-type source region comprises forming an n+-type source region and an n+-type drain region in a silicon substrate;

forming an amorphous silicon carbide (a-SiC) gate insulator further comprises forming the a-SiC gate insulator by ion-implantation of C2H2 into the substrate to have an electron affinity that is less than an electron affinity of silicon dioxide (SiO2);

forming a polysilicon floating gate further comprises forming the a-SiC gate insulator and forming the polysilicon floating gate such that a barrier energy, defined as a difference between an electron affinity of the polysilicon floating gate and an electron affinity of the a-SiC gate insulator, is less than approximately 3.3 eV; and

further comprising:

forming an intergate insulator on the polysilicon floating gate; and

forming a control electrode on the intergate insulator.

* * * * *