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(54) **DEVICE USING A METAL-INSULATOR TRANSITION**

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H01L 31/109 (2006.01)
H01L 31/0328 (2006.01)
H01L 31/0336 (2006.01)

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(58) **Field of Classification Search** 257/43, 257/192, 194, 295, E39.007, 310
See application file for complete search history.

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(57) **ABSTRACT**

A switching field effect transistor includes a substrate; a Mott-Brinkman-Rice insulator formed on the substrate, the Mott-Brinkman-Rice insulator undergoing abrupt metal-insulator transition when holes added therein; a dielectric layer formed on the Mott-Brinkman-Rice insulator, the dielectric layer adding holes into the Mott-Brinkman-Rice insulator when a predetermined voltage is applied thereto; a gate electrode formed on the dielectric layer, the gate electrode applying the predetermined voltage to the dielectric layer; a source electrode formed to be electrically connected to a first portion of the Mott-Brinkman-Rice insulator; and a drain electrode formed to be electrically connected to a second portion of the Mott-Brinkman-Rice insulator.

46 Claims, 4 Drawing Sheets

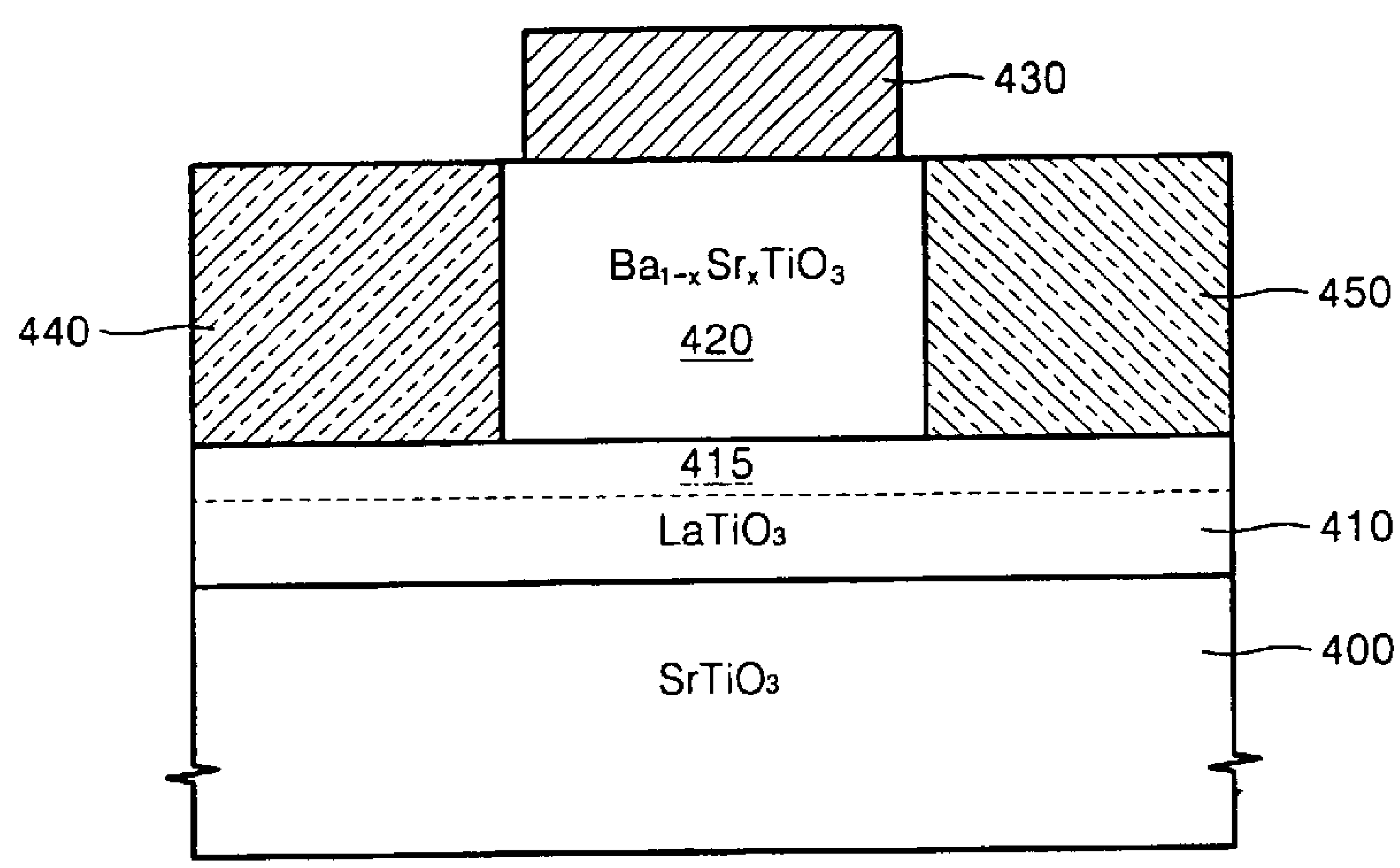


FIG. 1A

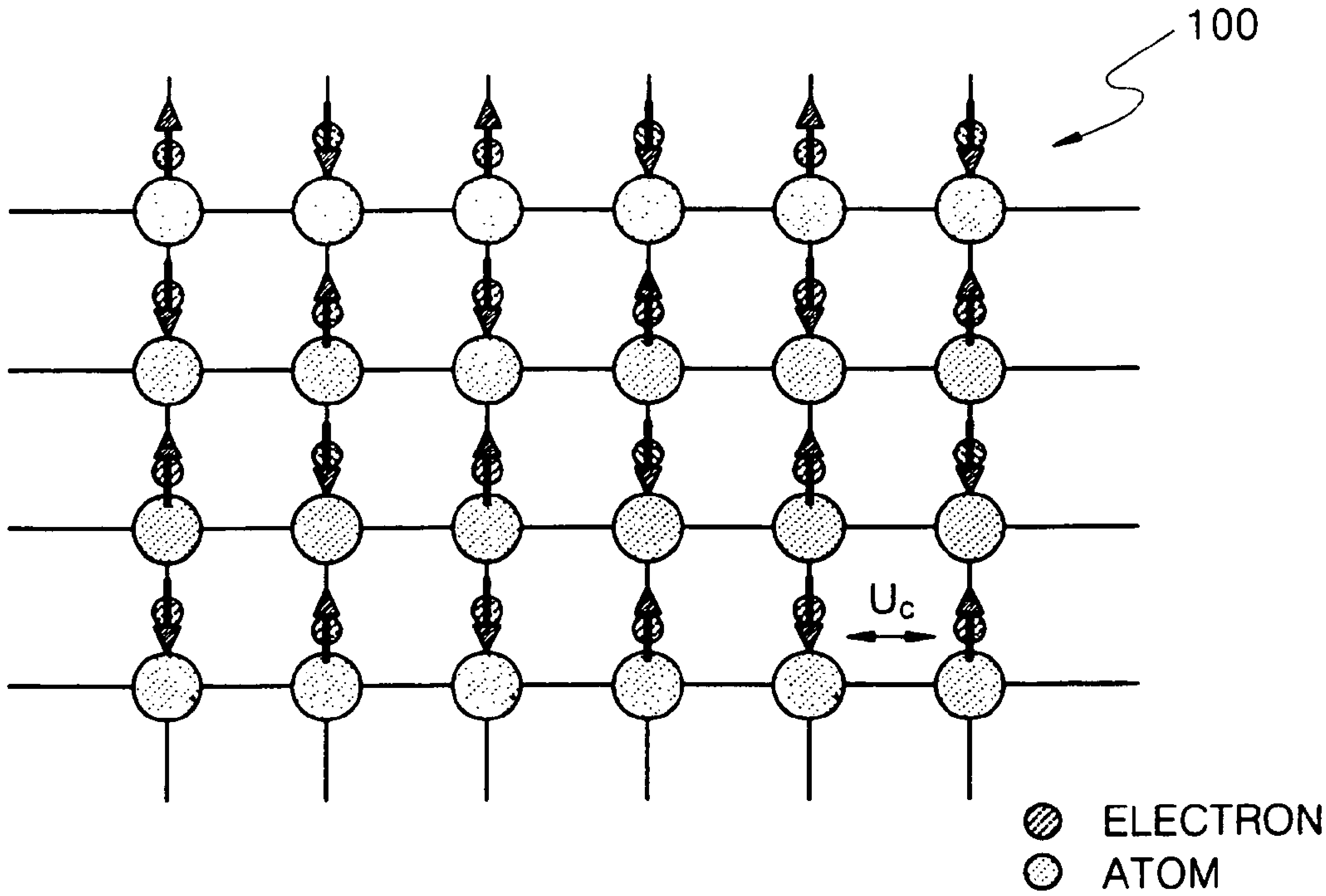


FIG. 1B

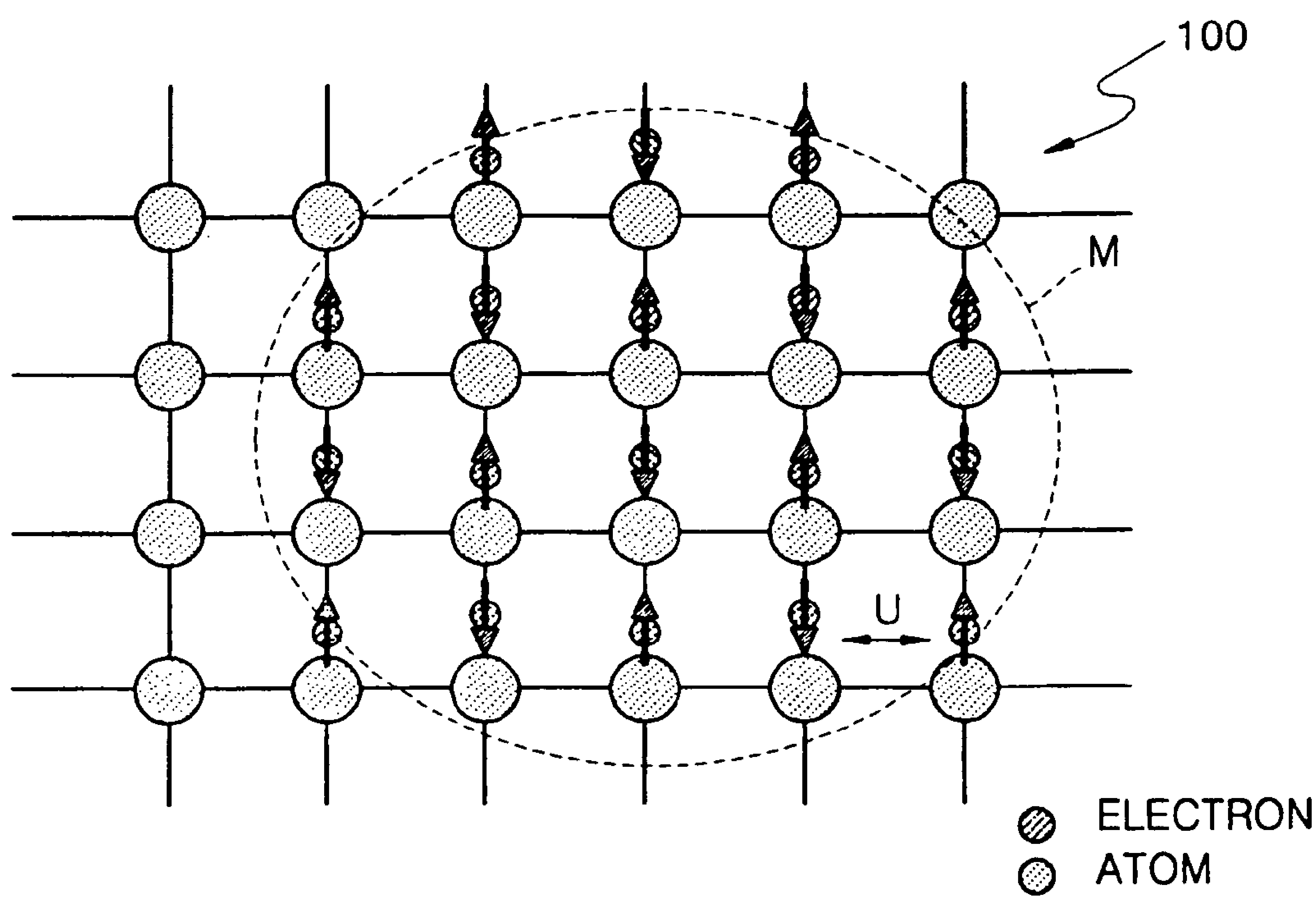


FIG. 2

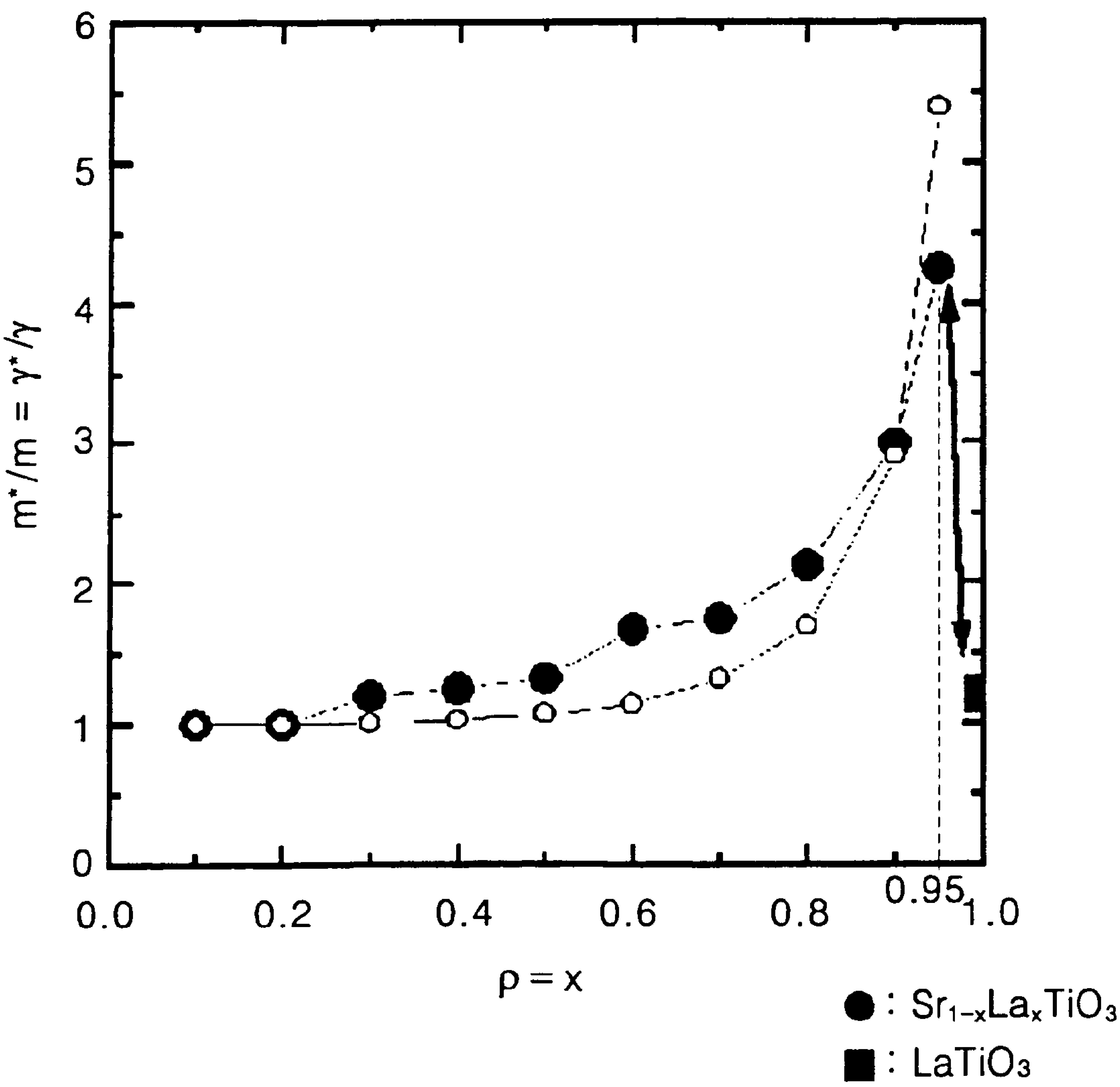


FIG. 3

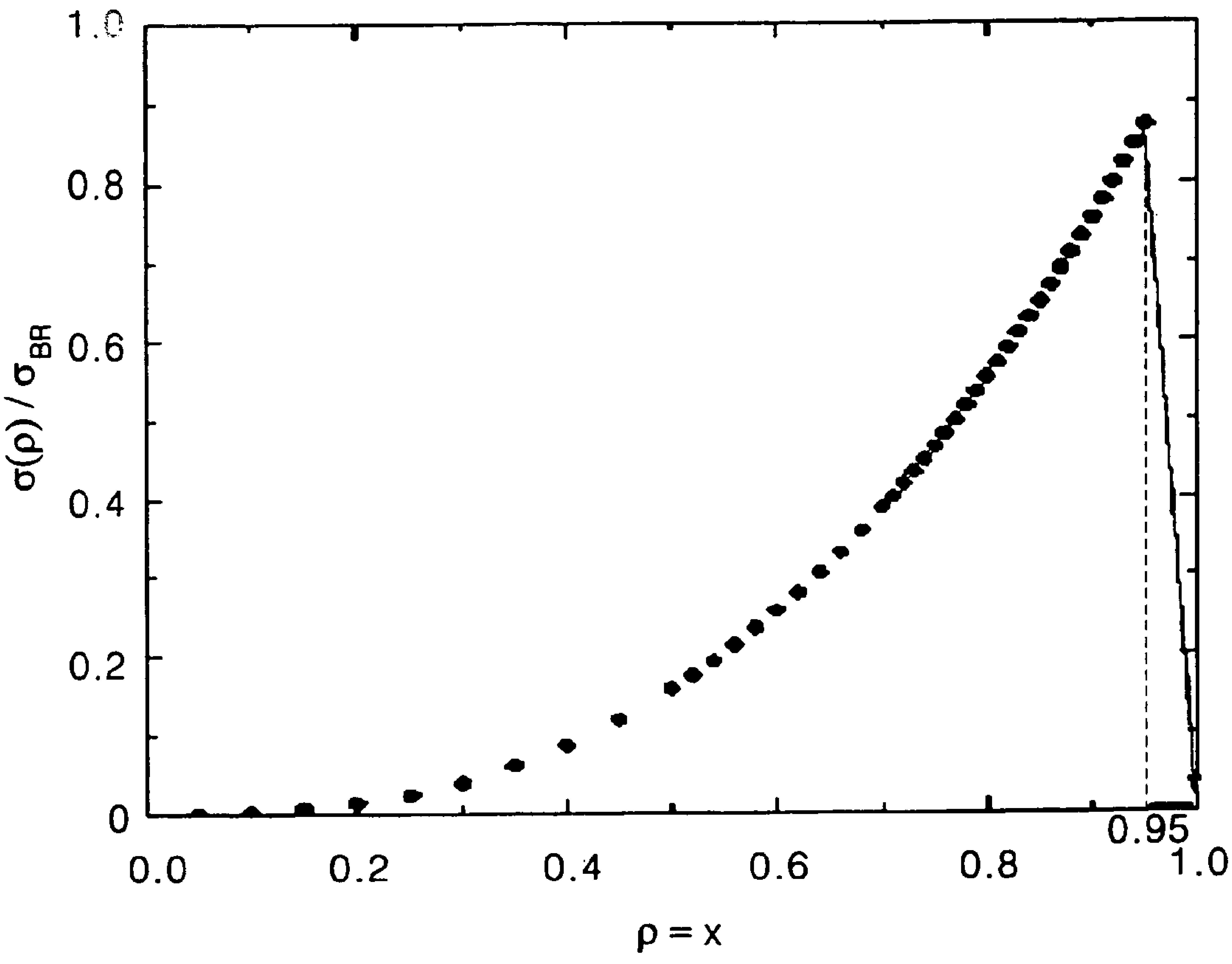
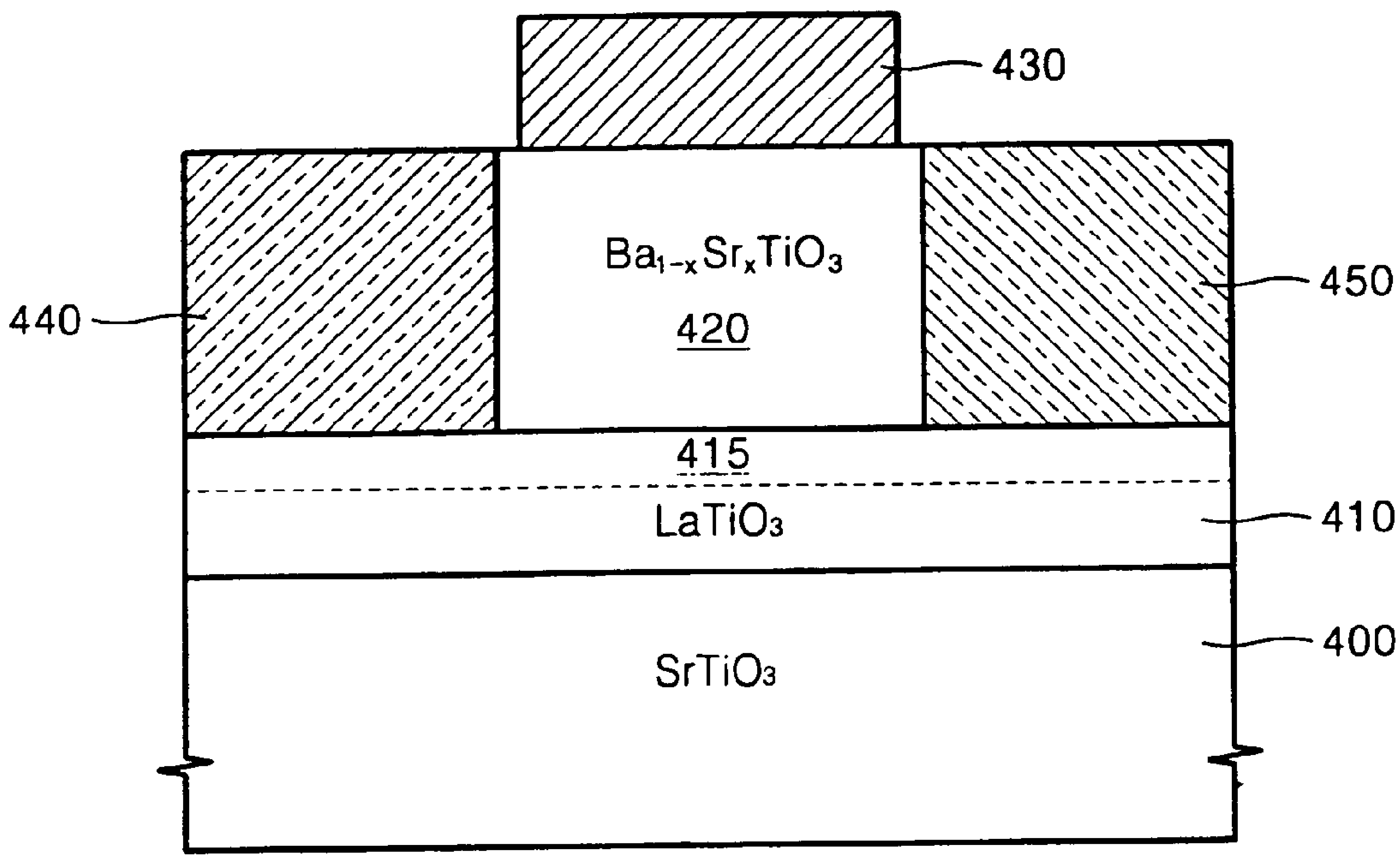


FIG. 4



DEVICE USING A METAL-INSULATOR TRANSITION

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a field effect transistor, and more particularly, to a switching field effect transistor (FET) using abrupt metal-insulator transition.

2. Description of the Related Art

Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) have been widely used as micro and super-speed switching transistors. A MOSFET has two pn junction structures showing linear characteristics at a low drain voltage as a basic structure. However, when a channel length is reduced to about 50 nm or below as the degree of integration of a device increases, an increase in a depletion layer changes the concentration of a carrier and an decrease of the depth of the gate insulator remarkably makes current flowing between a gate and a channel.

To overcome this problem, IBM institute has performed Mott FETs using the Mott-Hubbard insulator in a channel layer in reference "D. M. Newns, J. A. Misewich, C. C. Tsuei, A. Gupta, B. A. Scott, and A. Schrott, Appl. Phys. Lett. 73, 780 (1998)". The Mott-Hubbard insulator undergoes a transition from an antiferromagnetic insulator to an metal. This transition is called the Mott-Hubbard metal-insulator transition in reference "J. Hubbard, Proc. Roy. Sci. (London) A276, 238 (1963), A281, 401 (1963)". This is a continuous (or second order) phase transition. Unlike MOSFETs, Mott FETs perform an ON/OFF operation according to metal-insulator transition and do not have a depletion layer, thereby remarkably improving the degree of integration of a device and achieving a higher-speed switching characteristic than MOSFETs.

Since Mott-Hubbard FETs use continuous metal-insulator transition, charges used as carriers should be continuously added until the best metallic characteristics reach. Accordingly, the added charges must have a high concentration. Generally, charges N per unit area can be expressed by Equation (1).

$$N = \frac{\varepsilon}{ed} V_g \tag{1}$$

Here, "∈" denotes the dielectric constant of a gate insulator, "e" denotes a basic charge, "d," denotes the thickness of the gate insulator, and "V_g" denotes a gate voltage.

For example, in the case of La_2CuO_4, which is one of the materials falling under the group Mott-Hubbard insulator, when holes are added to La_2CuO_4, the characteristics of $La_{2-x}Sr_xCuO_4$(LSCO) appear, and a metal having best hole carriers at x=0.15 (15%) is obtained. Here, the added holes become carriers. Generally, x=0.15 is a high concentration, so if the N value increases, the dielectric constant of the gate insulator increases, the thickness of the gate insulator decreases, or the gate voltage increases. However, when the dielectric constant is too great, the fatigue characteristics of a dielectric sharply worsens during a high-speed switching operation, thereby reducing the life of a transistor. Moreover, there is a limit in decreasing the thickness of the gate insulator due to limitations in fabrication processes. In addition, when the gate voltage increases, power consumption also increases, which makes it difficult to be the transistor with a low power.

SUMMARY OF THE INVENTION

To solve the above-described problems, it is an object of the present invention to provide a switching field effect transistor using abrupt metal-insulator transition so that the field effect transistor shows metallic characteristics even if holes of a low concentration are added thereto.

To achieve the above object of the invention, there is provided a field effect transistor including a substrate; a Mott-Brinkman-Rice insulator formed on the substrate, the Mott-Brinkman-Rice insulator undergoing abrupt metal-insulator transition when holes add therein; a dielectric layer formed on the Mott-Brinkman-Rice insulator, the dielectric layer adding holes into the Mott-Brinkman-Rice insulator when a predetermined voltage is applied thereto; a gate electrode formed on the dielectric layer, the gate electrode applying the predetermined voltage to the dielectric layer; a source electrode formed to be electrically connected to a first portion of the Mott-Brinkman-Rice insulator; and a drain electrode formed to be electrically connected to a second portion of the Mott-Brinkman-Rice insulator.

Preferably, the substrate is formed of $SrTiO_3$.

Preferably, the Mott-Brinkman-Rice insulator is formed of $LaTiO_3$, $YTiO_3$, Ca_2RuO_4, Ca_2IrO_4, V_2O_3, $(Cr_xV_{1-x})_2O_3$, $CaVO_3$, $SrVO_3$ and YVO_3.

Preferably, the dielectric layer is formed of $Ba_{1-x}Sr_xTiO_3$ or dielectric materials.

Preferably, the source electrode and the drain electrode are separated from each other by the dielectric layer.

BRIEF DESCRIPTION OF THE DRAWINGS

The above object and advantages of the present invention will become more apparent by describing in detail a preferred embodiment thereof with reference to the attached drawings in which:

FIGS. **1**A and **1**B are diagrams showing atomic lattices within a Mott-Brinkman-Rice insulator having abrupt metal-insulator transition under predetermined conditions;

FIG. **2** is a graph showing the effective mass of a carrier versus the band filling factor of a Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO);

FIG. **3** is a graph showing electrical conductance σ versus the band filling factor of a Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO); and

FIG. **4** is a sectional view of a switching field effect transistor according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Hereinafter, embodiments of the present invention will be described in detail with reference to the attached drawings. The present invention is not restricted to the following embodiments, and many variations are possible within the spirit and scope of the present invention.

The following description concerns the operating principle of a field effect transistor (FET) according to the present invention.

FIGS. **1**A and **1**B are diagrams showing atomic lattices within a Mott-Brinkman-Rice insulator having abrupt metal-insulator transition under predetermined conditions. The Mott-Brinkman-Rice insulator, that is, a paramagnetic insulator in reference "W. F. Brinkman, T. M. Rice, Phys. Rev. B2, 4302 (1970)", is different from an antiferromagnetic insulator of the Mott-Hubbard insulator used by IBM group.

Referring to FIG. **1**A, when an atom has two electrons and the intensity U of the repulsive Coulomb interaction between the two electrons is the same as the maximum Coulomb energy U_c between the electrons, that is, $U/U_c=k=1$, the two electrons cannot exist in the atom together, so one of them moves to a neighboring atom and is bound to the neighboring atom. An insulator having such a bound and metallic electron structure is referred to as a Mott-Brinkman-Rice insulator **100**.

If holes are added to the Mott-Brinkman-Rice insulator **100** at a very low concentration, the Mott-Brinkman-Rice insulator **100** is abruptly transformed into a metal due to a decrease in the Coulomb interaction and is thus changed into a non-uniform metallic system having both a metal phase and an insulator phase. Such abrupt transition, that is, first-order transition is well described in the reference "Hyun-Tak Kim in Physica C 341-348, 259 **[**(2000); http://xxx.lanl.gov/abs/cond-mat/0110112".**]** *(2000)."* Here, the Mott-Brinkman-Rice insulator **100** is changed into a non-uniform metal system because the number of electrons becomes less than the number of atoms due to the addition of holes.

In this case, as shown in FIG. **1**B, the intensity U of the repulsive Coulomb interaction becomes less than the maximum Coulomb energy U_c, that is, $U/U_c=k<1$. As a result, the Mott-Brinkman-Rice insulator **100** locally becomes a strong correlation metal (denoted by M in FIG. **1**B) complying with the strong correlation metal theory of Brinkman and Rice. The strong correlation metal theory is well disclosed in the reference "W. F. Brinkman, T. M. Rice, Phys. Rev. B2, 4302 (1970)". Such a strong correlation metal has an electron structure in which one atom has one electron, that is, a metallic electron structure in which an s energy band is filled with one electron.

In the metal region M of FIG. **1**B, the effective mass m*/m of a carrier is defined by Equation (2).

$$\frac{m^*}{m}=\frac{1}{1-k^2} \tag{2}$$

Here, k<1 is satisfied, and abrupt metal-insulator transition occurs at a value within a range between k=1 and a certain value close to k=1. This theoretical equation is introduced in the reference "W. F. Brinkman, T. M. Rice, Phys. Rev. B2, 4302 (1970)". The theory about a strong correlation was introduced in the reference "N. F. Mott, Metal-Insulator Transition, Chapter 3, (Taylor & Frances, 2nd edition, 1990) for the first time.

Meanwhile, the effective mass m*/m of a carrier in the entire metal system of FIG. **1**B can be expressed by Equation (3).

$$\frac{m^*}{m}=\frac{1}{1-k^2\rho^4} \tag{3}$$

Here, ρ is a band filling factor and can be expressed by a ratio of the number of electrons (or carriers) to the number of atoms. In this case, when k=1, there occurs a abrupt transition from a value close to ρ=1 to ρ=1. This theory is well described in the reference "Hyun-Tak Kim in Physica C 341-348, 259 **[**(2000); http://xxx.lanl.gov/abs/cond-mat/0110112".**]** *(2000)."*

For example, in the case of a material of $Sr_{1-x}La_xTiO_3$ (SLTO), La^{+3} is substituted for Sr^{+2} in an insulator of $SrTiO_3$ (STO) when the material is doped with electrons, and in contrast, Sr^{+2} is substituted for La^{+3} in a Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO) when the material is doped with holes.

FIG. **2** is a graph showing the effective mass of a carrier versus the ratio of Sr^{+2} holes added to a Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO), that is, a band filling factor ρ. As shown in FIG. **2**, when k=1, there occurs abrupt transition from a metal having a maximum effective mass of a carrier to a Mott-Brinkman-Rice insulator (represented by an arrow in the graph) in a section from ρ=1 to ρ=0.95, that is, until the percentage of the Sr^{+2} holes added to the Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO) becomes 5%. Here, it was observed in a test that the quantity N_c of electrons corresponding to ρ=0.95 was about 1.7×10^{22} cm^{-3}. The result of the test is disclosed in references "Y. Tokura, Y, Taguchi, Y. Okada, Y. Fujishima, T. Arima, K. Kumagi, and Y. Iye, Phys. Rev. Lett. 70, 2126 (1993)" and "K. Kumagai, T. Suzuki, Y. Taguchi, Y. Okada, Y. Fumjishima, and Y. Tokura, Phys. Rev. B48, 7636 (1993)". When p<0.95, that is, when the quantity of added La^{+3} electrons decreases or when the quantity of added Sr^{+2} holes does not increase to at least 5%, continuous metal-insulator transition occurs due to a decrease in the number of carriers.

FIG. **3** is a graph showing electrical conductance σ versus the ratio of Sr^{+2} holes added to a Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO), that is, a band filling factor ρ. In FIG. **3**, σ_{HK} denotes the threshold electrical conductance of a metal.

As shown in FIG. **3**, it was observed in a test that the electrical conductance sharply increases to a maximum value at ρ=0.95 in a section from ρ=1 to ρ=0.95, that is, until the percentage of the Sr^{+2} holes added to the Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO) becomes 5%. The result of the test is disclosed in references "Y. Tokura, Y, Taguchi, Y. Okada, Y. Fujishima, T. Arima, K. Kumagi, and Y. Iye, Phys. Rev. Lett. 70. 2126 (1993)" and "K. Kumagai, T. Suzuki, Y. Taguchi, Y. Okada, Y. Fumjishima, and Y. Tokura, Phys. Rev. B48, 7636 (1993)".

It can be concluded from the results of the tests shown in FIGS. **2** and **3** that adding holes to a Mott-Brinkman-Rice insulator of $LaTiO_3$(LTO) is more effective than adding electrons to an insulator of $SrTiO_3$(STO) in obtaining the maximum electrical conductance.

FIG. **4** is a sectional view of a FET using abrupt metal-insulator transition according to the present invention. Referring to FIG. **4**, a Mott-Brinkman-Rice insulator **410** of $LaTiO_3$(LTO) is disposed on a substrate **400** of $SrTiO_3$ (STO). The Mott-Brinkman-Rice insulator **410** may be formed of $LaTiO_3$, $YTiO_3$, h-$BaTiO_3$, Ca_2RuO_4, Ca_2IrO_4, V_2O_3, $(Cr_xV_{1-x})_2O_3$, $CaVO_3$, $SrVO_3$ and YVO_3. A dielectric (or ferroelectric) layer **420** having a dielectric constant of at least 200, for example, $Ba_{1-x}Sr_xTiO_3$(BSTO), is partially formed as a gate insulation layer on the surface of the Mott-Brinkman-Rice insulator **410**. When a predetermined voltage is applied, the dielectric (or ferroelectric) layer **420** of $Ba_{1-x}Sr_xTiO_3$(BSTO) makes holes to add into the Mott-Brinkman-Rice insulator **410** so that abrupt metal-insulator transition can occur in the Mott-Brinkman-Rice insulator **410**, thereby forming a conductive channel **415**.

A gate electrode **430** is formed on the dielectric layer **420** to apply a predetermined voltage to the dielectric layer **420**. A source electrode **440** is formed on a first portion of the Mott-Brinkman-Rice insulator **410**, and a drain electrode **450** is formed on a second portion of the Mott-Brinkman-Rice insulator **410**. The source electrode **440** and the drain electrode **450** are separated by the dielectric layer **420**.

The following description concerns the operations of the FET. A predetermined voltage is applied to the source electrode **440** and the drain electrode **450**, thereby generating a predetermined potential on the surface of the Mott-Brinkman-Rice insulator **410** of $LaTiO_3$(LTO). Next, a gate voltage is applied to the gate electrode **430** so that Sr^{+2} holes can flow from the dielectric layer **420** of $Ba_{1-x}Sr_xTiO_3$ (BSTO) into a Mott-Brinkman-Rice insulator **410** at low concentration. Then, the Mott-Brinkman-Rice insulator **410** undergoes abrupt metal-insulator transition, and the conductive channel **415** is formed. As a result, current flows between the source electrode **440** and the drain electrode **450** through the conductive channel **415**.

When the concentration of holes is 5%, that is, ρ=0.95, the number of electrons in a metal region formed due to the abrupt metal-insulator transition is about $4\times10^{14}/cm^2$. This number of electrons is about at least 100 times of the number of electrons (about $10^{12}/cm^2$) in a channel of a usual Metal Oxide Semiconductor Field Effect Transistor (MOSFET), so a high current amplification can be achieved.

According to circumstances, electrons can be added to the Mott-Brinkman-Rice insulator **410**. However, the addition of electrons increases power consumption more than the addition of holes. In other words, when a gate voltage V_g is 0.12 volts, the dielectric constant $\in$ of the dielectric layer **420** is 200, and the thickness "d" of the dielectric layer **420** is 50 nm, then the number N_{charge} of static hole charges corresponding to a low concentration ρ=0.95 is about $4\times10^{14}/cm^2$ ($N_{charge}=V_g\in/ed$). Accordingly, if a hole concentration N_{hole} is set to about $4\times10^{14}/cm^2$, and other variables, i.e., the dielectric constant $\in$ and the thickness "d" of the dielectric layer **420** are adjusted to the conditions of transistor fabrication, the gate voltage V_g can be significantly decreased, so power consumption can be decreased.

However, when static electrons corresponding to a high concentration ρ=0.95 are added to the Mott-Brinkman-Rice insulator **410**, the number $N_{electron}$ of electrons is more than the number N_{hole} of holes. Accordingly, even if the dielectric constant $\in$ and the thickness "d" of the dielectric layer **420** are properly adjusted, the gate voltage V_g becomes greater than in the case of adding holes. As a result, power consumption increases compared to the case of adding holes at a low concentration. In this specification, a transistor according to the present invention is referred to as a Mott-Gutzwiller-Brinkman-Rice-Kim (MGBRK) transistor in order to discriminate it from a Mott or Mott-Hubbard (MH) FET.

As described above, a FET according to the present invention provides the following effects. First, since a depletion layer does not exist, there is no limit in the length of a channel. Therefore, the degree of integration of a device and a switching speed can be greatly increased. Second, since a dielectric layer having a properly high dielectric constant is used as a gate insulator, an appropriate concentration of holes for doping can be obtained with a low voltage without greatly reducing the thickness of the dielectric layer. Third, when holes are added to a Mott-Brinkman-Rice insulator at a low concentration to provoke abrupt metal-insulator transition, a high current gain and a low power consumption can be achieved.

What is claimed is:

[1. A switching field effect transistor comprising:

a substrate;

a Mott-Brinkman-Rice insulator formed on the substrate, the Mott-Brinkman-Rice insulator undergoing abrupt metal-insulator transition when holes add therein;

a dielectric layer formed on the Mott-Brinkman-Rice insulator, the dielectric layer adds holes into the Mott-Brinkman-Rice insulator when a predetermined voltage is applied thereto;

a gate electrode formed on the dielectric layer, the gate electrode applying the predetermined voltage to the dielectric layer;

a source electrode formed to be electrically connected to a first portion of the Mott-Brinkman-Rice insulator; and

a drain electrode formed to be electrically connected to a second portion of the Mott-Brinkman-Rice insulator.**]**

[2. The switching field effect transistor of claim **1**, wherein the substrate is formed of a material selected from the group consisting of $SrTiO_3$, Oxide materials, Silicon on Insulator (SOI), and Silicon.**]**

[3. The switching filed effect transistor of claim **1**, wherein the Mott-Brinkman-Rice insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3$ ($0\leqq x\leqq 0.1$), where R is a cation with trivalent rare-earch ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr).**]**

[4. The switching filed effect transistor of claim **1**, wherein the Mott-Brinkman-Rice insulator is formed of a material, h-$BaTiO_3$.**]**

[5. The switching field effect transistor of claim **1**, wherein the Mott-Brinkman-Rice insulator is formed of a material selected from the group consisting of Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$($0\leqq x\leqq 0.05$), Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4$ ($0\leqq x\leqq 0.05$).**]**

[6. The switching field effect transistor of claim **1**, wherein the Mott-Brinkman-Rice insulator is formed of a material selected from the group consisting of V_2O_3, $(Cr_xV_{1-x})_2O_3$ ($0\leqq\times0.05$), $CaVO_3$, $Ca_{1-x}Sr_xVO_3$($0\leqq x\leqq 0.05$), and YVO_3.**]**

[7. The switching field effect transistor of claim **1**, wherein the dielectric layer is formed of $Ba_{1-x}Sr_xTiO_3$($0\leqq x\leqq 0.05$), $Pb(Zr_{1-x}Ti_x)O_3$($0\leqq x\leqq 0.05$), and $SrBi_2Ta_2O_9$.**]**

[8. The switching field effect transistor of claim **1**, wherein the dielectric layer is formed of a material selected from the group consisting of SiO_2, Si_3N_4, Al_2O_3, Y_2O_3, La_2O_3, Ta_2O_5, TiO_2, HfO_2, ZrO_2.**]**

[9. The switching field effect transistor of claim **1**, wherein the source electrode and the drain electrode are separated from each other by the dielectric layer.**]**

10. A device using metal-insulator transition, wherein a paramagnetic insulator is abruptly phase-transited to metal due to an energy change between electrons to form a conductive channel, wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1 - k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

11. The device using metal-insulator transition of claim 10, wherein the paramagnetic insulator has a bound and metallic electron structure.

12. The device using metal-insulator transition of claim 10, wherein the carriers generated due to the metal-insulator transition are electrons.

13. The device using metal-insulator transition of claim 10, wherein the energy change is caused by implantation of holes.

14. The device using metal-insulator transition of claim 10, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

15. A device using metal-insulator transition, wherein a paramagnetic insulator is abruptly phase-transited to metal due to implantation of holes to form a conductive channel, wherein the effective mass, m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

16. The device using metal-insulator transition of claim 15, wherein the paramagnetic insulator has a bound and metallic electron structure.

17. The device using metal-insulator transition of claim 15, wherein the carriers generated due to the metal-insulator transition are electrons.

18. The device using metal-insulator transition of claim 15, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

19. A device using metal-insulator transition, wherein holes are implanted into a paramagnetic insulator having a bound and metallic electron structure to form a conductive channel, wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

20. The device using metal-insulator transition of claim 19, wherein the carriers generated due to the metal-insulator transition are electrons.

21. The device using metal-insulator transition of claim 19, wherein the conductive channel is formed by abruptly transiting the phase of the paramagnetic insulator to metal.

22. The device using metal-insulator transition of claim 19, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

23. A device using metal-insulator transition, wherein a paramagnetic insulator having a bound and metallic electron structure undergoes abrupt transition to metal due to an energy change between electrons caused by implantation of holes to form a conductive channel, wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

24. The device using metal-insulator transition of claim 23, wherein the carriers generated due to the metal-insulator transition are electrons.

25. The device using metal-insulator transition of claim 23, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

26. A device using metal-insulator transition comprising:

a paramagnetic insulator forming a conductive channel by abruptly transiting the phase of the paramagnetic insulator to metal due to an energy change between electrons; and

an electrode making the energy change occur in the insulator,

wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

27. The device using metal-insulator transition of claim 26, wherein the paramagnetic insulator has a bound and metallic electron structure.

28. The device using metal-insulator transition of claim 26, wherein the carriers generated due to the metal-insulator transition are electrons.

29. The device using metal-insulator transition of claim 26, wherein the energy change is caused by implantation of holes.

30. The device using metal-insulator transition of claim 26, further comprising at least one electrode formed on the paramagnetic insulator, the electrode applying a predetermined voltage to the conductive channel.

31. A device using metal-insulator transition comprising:

a paramagnetic insulator forming a conductive channel by abruptly transiting the phase of the paramagnetic insulator to metal due to an energy change between electrons;

a first electrode making the energy change occur in the paramagnetic insulator; and

a second electrode formed on the paramagnetic insulator, the second electrode applying a predetermined voltage to the conductive channel,

wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

32. The device using metal-insulator transition of claim 31, wherein the paramagnetic insulator has a bound and metallic electron structure.

33. The device using metal-insulator transition of claim 31, wherein the carriers generated due to the metal-insulator transition are electrons.

34. The device using metal-insulator transition of claim 31, wherein the energy change is caused by implantation of holes.

35. The device using metal-insulator transition of claim 31, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

36. A device using metal-insulator transition comprising:

a paramagnetic insulator forming a conductive channel by abruptly transiting the phase of the paramagnetic insulator to metal due to an energy change between electrons;

a first electrode making the energy change occur in the paramagnetic insulator; and

two second electrodes insulated from the first electrode and electrically connected to each other by the conductive channel,

wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

37. The device using metal-insulator transition of claim 36, wherein the paramagnetic insulator has a bound and metallic electron structure.

38. The device using metal-insulator transition of claim 36, wherein the carriers generated due to the metal-insulator transition are electrons.

39. The device using metal-insulator transition of claim 36, wherein the energy change is caused by implantation of holes.

40. The device using metal-insulator transition of claim 36, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

41. A device using metal-insulator transition comprising:

a paramagnetic insulator forming a conductive channel by abruptly transiting the phase of the paramagnetic insulator to metal due to an energy change between electrons; and

a compound adding holes into the paramagnetic insulator when a predetermined voltage is applied to the compound,

wherein the holes are generated when a first element of the compound is substituted with a second element having a different atomic structure from the first element, and the holes are added to the paramagnetic insulator,

wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1-k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

42. The device using metal-insulator transition of claim 41, wherein the paramagnetic insulator has a bound and metallic electron structure.

43. The device using metal-insulator transition of claim 41, wherein the carriers generated due to the metal-insulator transition are electrons.

44. The device using metal-insulator transition of claim 41, wherein the paramagnetic insulator is formed of a material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4$ $(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3$ $(0\leqq x\leqq 0.05)$, and YVO_3.

45. The device using metal-insulator transition of claim 41, wherein the compound is formed of at least one material selected from the group consisting of $Ba_{1-x}Sr_xTiO_3$ $(0\leqq x\leqq 0.05)$, $Pb(Zr_{1-x}Ti_x)O_3(0\leqq x\leqq 0.05)$, and $SrBi_2Ta_2O_9$.

46. A device using metal-insulator transition, comprising:

a paramagnetic insulator formed of at least one material selected from the group consisting of $LaTiO_3$, $YTiO_3$, and $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ (where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with a divalent alkali-earth ions (Ca, Sr)), h-$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4(0\leqq x\leqq 0.05)$, Ca_2IrO_4, and $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3$ $(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3(0\leqq x\leqq 0.05)$, and YVO_3; and

a compound formed of at least one material selected from the group consisting of $Ba_{1-x}Sr_xTiO_3(0\leqq x\leqq 0.05)$, $Pb(Zr_{1-x}Ti_x)O_3(0\leqq x\leqq 0.05)$, and $SrBi_2Ta_2O_9$, wherein holes included in the compound are added to the insulator, wherein the effective mass m/m of carriers gen* *erated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1 - k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

47. A field effect transistor using metal-insulator transition, comprising:

a paramagnetic insulator forming a conductive channel by abruptly transiting the phase of the paramagnetic insulator to metal due to an energy change between electrons;

a gate electrode formed on one side of the insulator, the gate electrode applying a predetermined voltage to the paramagnetic insulator to induce the energy change; and

a source electrode and a drain electrode formed to be electrically connected to each other by the conductive channel, wherein the effective mass m/m of carriers generated due to the metal-insulator transition can be expressed by:*

$$\frac{m^*}{m} = \frac{1}{1 - k^2\rho^4}$$

wherein k denotes a ratio between a Coulomb energy exerted between electrons and the maximum Coulomb energy, and ρ is a band filling factor, and the band filling factor is equal to or greater than 0.95 and less than 1.

48. The field effect transistor using metal-insulator transition of claim 47, wherein the paramagnetic insulator has a bound and metallic electron structure.

49. The field effect transistor using metal-insulator transition of claim 47, wherein the carriers generated due to the metal-insulator transition are electrons.

50. The field effect transistor using metal-insulator transition of claim 47, wherein the energy change is caused by implantation of holes.

51. The field effect transistor using metal-insulator transition of claim 50, wherein a voltage is applied to the gate electrode to form a low concentration of holes causing the abrupt metal-insulator transition.

52. The field effect transistor using metal-insulator transition of claim 47, wherein the paramagnetic insulator is formed of a material selected from the group consisting a $LaTiO_3$, $YTiO_3$, *and* $R_{1-x}A_xTiO_3(0\leqq x\leqq 0.1)$ *(where R is a cation with trivalent rare-earth ions (Y, La) and A is a cation with divalent alkali-earth ions (Ca, Sr)), h-*$BaTiO_3$, Ca_2RuO_4, $Ca_{2-x}Sr_xRuO_4(0\leqq x\leqq 0.05)$, Ca_2IrO_4, *and* $Ca_{2-x}Sr_xIrO_4(0\leqq x\leqq 0.05)$, V_2O_3, $(Cr_xV_{1-x})_2O_3(0\leqq x\leqq 0.05)$, $CaVO_3$, $Ca_{1-x}Sr_xVO_3(0\leqq x\leqq 0.05)$, *and* YVO_3.

53. The field effect transistor using metal-insulator transition of claim 47, further comprising a gate insulation layer formed between the paramagnetic insulator and the gate electrode.

54. The field effect transistor using metal-insulator transition of claim 53, wherein the gate insulation layer is formed of at least one material selected from the group consisting of $Ba_{1-x}Sr_xTiO_3(0\leqq x\leqq 0.05)$, $Pb(Zr_{1-x}Ti_x)O_3(0\leqq x\leqq 0.05)$, *and* $SrBi_2Ta_2O_9$.

55. The field effect transistor using metal-insulator transition of claim 53, wherein the gate insulation layer is formed of at least one material selected from the group consisting of SiO_2, Si_3N_4, Al_2O_3, Y_2O_3, La_2O_3, Ta_2O_5, HfO_2, *and* ZrO_2.

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