Title:

All-metal transistor and its operational principles.

Merits:

1) *It can be made only from metal and dielectric material without usage of a semiconductor.*

A non-expensive fabrication technique like a sputtering and lift-off can be used. The expensive technique, which is used for fabrication of semiconductors(for example epitaxial growth), can be avoided.

2) It can withstand a high current and a high temperature

Electrical constants of a metal only weakly depend on temperature. In contrast, the electrical constants of a semiconductor are substantially varying with a change of temperature. The resistance of a metal is substantially smaller than the resistance of a semiconductor. As result, the metal can withstand a substantially larger current.

3) Scaling

(a) in contrast to the MOSFET transistor, the contact resistance does not limit the scaling of the all-metal transistor.
(b) The size of the transistor can be reduced by using the X-ray interferometery for the transistor fabrication instead of the use of the conventional lithography. It is possible because of a simple periodical structure of the all-metal transistor

3) Higher speed

The operational speed of MOSFET transistor is limited by the conductivity (the mobility) of Si and it is difficult to improve it. The conductivity of a metal is significantly larger; therefore the all-metal transistor may operate at a faster speed.

4) the usage of polycrystalline or amorphous materials

Only single-crystal Si can be used for MOSFET transistor in order to have required mobility. The all-metal transistor can be made from only polycrystalline or amorphous materials. Therefore, expensive growth and fabrication equipments, which are used to grow and to protect a single-crystal material, are not required for the all-metal transistor.

4) 3D integration

For the 3D-integration, a new layer of transistors should be fabricated on top of already-fabricated layer. The quality of the transistors should not degrade as a number of layers of transistors increases. It is nearly impossible to keep high-quality of MOSFET transistors fabricated on top of already-fabricated transistor layer. In MOSFET transistor, both the single-crystal and polycrystalline materials are used. It is impossible to grow a single-crystal material on top of a polycrystalline material. Only polycrystalline or amorphous materials are in the all-metal transistor. Therefore, the quality of transistors can be kept the same for any number of layers for the 3D integration.

Abstract:

A new type of all-metal spin transistor is disclosed. It consists of a thin nanowire made of a ferromagnetic metal with a periodical gate electrode on top of it. When a voltage is applied to the gate electrode, the magnetization direction in the wire under the electrode changes due to the voltage-controlled magnetic anisotropy effect. The gate voltage switches on/off the current in the nanowire, because of the magneto-resistance effect. The area of the proposed transistor is comparable with the area of present smallest Si-made MOSFET transistors. The merit of the proposed transistor is a wide range of operating currents and voltages. Another merit is that this transistor can be made from only amorphous and polycrystalline materials. By periodical deposition of transistor layers and isolation oxide layers, a dense 3D integration can be realized.

Fig. 15 (a) is the main figure.

Prior-art

The transistor is main component of any data processing circuit. At present, the metal–oxide–semiconductor field-effect transistor (MOSFET) is the most-used transistor in integrated electrical circuits. Figure 1 shows schematic diagram of the MOSFET transistor, which is fabricated on p-Si substrate. It consists of the source, the drain and the gate. The regions of Si under the gate and the source electrodes are heavily doped and they have electron-type conductivity. In contrast, under the gate the conductivity is hole-type. Because of the different types conductivities under gate and under source/drain, there is a barrier between the source and drain and without a gate voltage a current can not flow from the source to the drain. When a gate voltage is applied, a thin channel of electron-type conductivity is formed under gate and a current can flow between the source and the drain. Therefore, the gate voltage can switch on/off the current between the source and drain.

The reduction of transistor size (scaling) is important for a dense integration. At present, the size of the MOSFET transistor nearly reaches its limits. Significant problem for the scaling is a large size of source and drain electrodes. The contact resistance between a metal and a semiconductor is high. There is a fundamental limitation, which limit the metal/semiconductor contact resistance above some substantial value. Only by keeping a large size of the source and drain electrodes, the required low contact resistance of the source and the drain can be achieved.

A metal-to-metal contact resistance is very low. Therefore, the contact resistance does not limit the scaling of the disclosed all-metal transistor.

Another limitation of the MOSFET transistor is that it can be only fabricated from a single-crystal semiconductor. For the operation the MOSFET transistor, the semiconductor region under the gate should have a very high electron mobility. Only a single-crystal semiconductor has sufficiently large electron mobility. The unavoidable usage of a single-crystal semiconductor limits possibilities of a 3D integration of the MOSFET transistor. In contrast, a polycrystalline and amorphous metal can be used in the disclosed all-metal transistor. It is possible to realize the 3D integration with polycrystalline and amorphous materials.

In the disclosed design of the all-metal transistor, the Giant Magneto Resistance (GMR) effect is utilized. The GMR effect states that the resistance of two neighbor regions of ferromagnetic metal depends on mutual magnetization directions of these regions. Figure 2 explains the GMR effect. A ferromagnetic wire can be divided into the domain, where the magnetization direction can be changed independently in the neighbor domains. The resistance of the wire is lower when the magnetization direction is the same in all domains (Fig. 1(a),(b)). The wire resistance is higher when the magnetization is neighbor domains is in different directions (Fig. 1(c),(d)).

The switching operation of the disclosed all-metal transistor is based on a modulation of the effect of the Spin-Orbit Interaction. The Spin-Orbit interaction is a relativistic effect, which states that an electron experiences an effective magnetic field when it moves in an electrical field. An electron experiences a very strong electrical field when it orbits a atomic nuclear. The Spin-Orbit interaction could induce a very strong magnetic field, because the electron moves very close to the nuclear at a high speed. However, the electron moves in two opposite directions when it orbits an atomic nuclear and it experiences the opposite magnetic field for the movement in opposite directions. In the case of the spherical orbit, the opposite magnetic fields fully compensate each other and in total the electron does not experience any magnetic field. When the atomic orbital is deformed and an external magnetic field is applied, the electron may experience a strong magnetic field due the Spin-Orbit interaction. The effective magnetic field due to the Spin-Orbit interaction may be significantly stronger than the applied magnetic field. The effective magnetic field is stronger along the deformation of the atomic orbital (Fig. 3(a)) and there is near no effective magnetic field perpendicularly to the deformation direction (Fig. 3(b)).

The Spin-Orbit interaction may cause the equilibrium magnetization of a ferromagnetic film to be perpendicular to the film plane. The effect is called the perpendicular magnetic anisotropy (PMA). Without the Spin-Orbit interaction the magnetization of any ferromagnetic film would be in-plane. When the magnetization is perpendicular- to-plane, the demagnetization field forces the magnetization to turn to in-plane direction.

The Spin-Orbit (SO) interaction may induce two types of the perpendicular magnetic anisotropy (PMA): (1) interface-type and (2) bulk-type. The interface-type PMA occurs due to the deformation of atomic orbital at an interface in direction toward a cover layer or a substrate (Fig.4). In this case the orbits of only one atomic layer at interface are deformed and only electrons of this layer experience strong Spin-Orbit interaction. The orbits in the bulk of the ferromagnetic metal are not deformed or they are deformed in-plane and they do not experience any the SO interaction. The orbits at interfaces are deformed differently than orbits in the bulk of film, because at interface atoms bond with atoms of different materials of the cover and the substrate. The bonds at interface may be significantly different from bonds inside the film. As result, the orbits are deformed differently. In the case of interface-type PMA the magnetization is perpendicular-to-plane for a thinner film and the magnetization is in-plane for a thicker film. It is because only in the case of a thin film, the PMA energy of the interface may become dominated. Figure 4(b) shows the PMA energy for FeB film covered by MgO. The magnetization of a FeB film thinner than 1.05 nm is perpendicular-to-plane. The magnetization of a FeB film thicker than 1.05 nm is in-plane.

In the case of the bulk-type PMA the atomic orbitals in the bulk of the ferromagnetic metal are deformed. It can occur due to stress in the film or crystal anisotropy along growth direction. Often in the case of the bulk-type PMA the orbits at interface are not deformed and they do not experience the SO interaction (Fig. 5a). In the case of the bulk-type PMA the magnetization is perpendicular-to-plane for a thicker film and the magnetization is in-plane for a thinner film. It is because only in the case of a thick film, the PMA energy of the bulk is dominated. Figure 5(b) shows the PMA energy for FeBTb film. The magnetization of a FeBTb film thicker than 3.2 nm is perpendicular-to-plane. The magnetization of a FeBTb film thinner than 3.2 nm is in-plane.

The switching mechanism of the disclosed transistor is the voltage-control PMA effect [1,2]. Figure 6 explains the effect of the voltage-control PMA. The structure consists of ferromagnetic layer (3), which is covered by a non-conductive dielectric (2). There is a gate electrode (1) on the top of the dielectric (2). The equilibrium magnetization of the ferromagnetic layer is in-plane. A voltage is applied between the top electrode and the ferromagnetic layer. Since both the top electrode and the ferromagnetic layer are conductive, there is no electrical field inside of them. All electrical field is applied to the dielectric. In an electrical field an atomic orbit is deformed along the field, which induces the SO interaction. Only the top layer of the ferromagnetic metal, which is bond to the dielectric, experiences the electrical field. Only in this layer the orbitals are deforms and only this layer experiences a strong SO interaction. If the ferromagnetic layer is sufficiently thin (See Fig. 4), the magnetization can turn to the perpendicular-to-plane direction (Fig. 6(b).

(1) M. Weisheit *et al*. *Science* **315**, 349 (2007). (2) T. Nozaki *et al. Nature Phys.* **8**, 491 (2012).

In case of a ferromagnetic layer with an interface-type PMA, an applied voltage may turn the magnetization in-plane (Fig.7). In this case without applied voltage, the orbitals at interface are deformed. It induces the PMA. The applied voltage makes these orbital more spherical. It reduces the PMA and the magnetization turns to in-plane direction.

It should be noticed that the voltage-induced PMA strongly depends on the materials of the dielectric and the ferromagnetic metal and the type of bonding between them at the interface. For example, experimentally-measured [1] the voltage-induced PMA for Fe:MgO film has opposite polarity to the polarity of the voltage-induced PMA shown in Figs.6 and 7. The polarity of the voltage-induced PMA depends on the ferromagnetic-metal/dielectric interface, its materials and type of bonding between them.

[1] T. Nozaki, A. Kozioł-Rachwał, W. Skowroński, V. Zayets, Y.Shiota, S. Tamaru, H. Kubota, A. Fukushima, S. Yuasa, and Y.Suzuki, " Large Voltage-Induced Changes in the Perpendicular Magnetic Anisotropy of an MgO-Based Tunnel Junction with an Ultrathin Fe Layer" , Phys. Rev. Applied 5, 044006 (2016);

additional information on features of the spin-orbit interaction can be found here
https://staff.aist.go.jp/v.zayets/spin3_32_SpinOrbit.html

Main part

Figure 8 shows the cross sectional-view of disclosed all-metal transistor. It consists of a ferromagnetic wire (3), which is covered by a non-conductive dielectric (2). On the top of the dielectric there is a periodic gate electrode (1). The source voltage is applied between sides of the ferromagnetic wire (3). The gate voltage is applied between the ferromagnetic wire (3) and the periodic gate electrode (1). Due to the voltage-induced PMA, a gate voltage turns the magnetization direction of the ferromagnetic wire under the top electrode. In the gap between electrodes the magnetization is not affected by the gate voltage. Therefore, mutual directions of magnetization under electrode and in the gap can be change by the gate voltage. As result, the resistance of the ferromagnetic wire can be controlled by the gate voltage and the source current can be switched on and off by the gate voltage.

Figure 8 shows the top view of disclosed all-metal transistor. The ferromagnetic wire has a snake-like shape. The periodical top electrodes are crossing the ferromagnetic wire. The merits of this design are a large number of electrodes per a wire, a small area of transistor and a simple easy-to-fabricate design.

The magneto-resistance effect per an electrode is not large. In order to achieve a required on/off ratio, the number of electrodes in the disclosed transistor should be large. At same time, the area of disclosed transistor should be small. Using electrode design shown in Fig. 9, it could be achieved. For example, for a wire of 10-nm wide and 10-um long, 10 nm-period of electrodes and 1 % MR per a period, the total MR will be 1000 % and the transistor area will be only 0.1 μm^2. It is sufficient to provide a sufficiently high off-state resistance and a high integration density. The area of this all-metal transistor is smaller or comparable to the area of the present MOSFET transistor shown in Fig.1.

The size of disclosed all-metal transistor can be reduced even more, if instead of the conventional lithography the X-Ray interferometery can be used as a fabrication technique. Using the X-Ray interferometery, it is possible to fabricate lines with width smaller than 1 nm. However, by the X-Ray interferometery it is only possible to fabricate periodical lines. Therefore, the fabrication of the MOSFET transistor (Fig.1) is impossible by the X-Ray interferometery. In contrast, the design of all-metal transistor is periodical and it is possible to fabricate it by the X-Ray interferometery.

Figure 10 shows operation principle of the disclosed all-metal transistor when the equilibrium magnetization of the ferromagnetic metal is in-plane. Without a bias voltage the magnetization is in-plane in all regions under gate electrodes and in the gap between electrodes. The resistance of the ferromagnetic wire is low. When a gate voltage is applied, the magnetization under the gate electrode turns to the perpendicular-to-plane direction. The magnetization in the gap region remains in-plane. Because of different magnetization directions in neighbor domains, the resistance of the ferromagnetic wire becomes large.

Figure 11 shows operation principle of the disclosed all-metal transistor when the equilibrium magnetization of the ferromagnetic metal is perpendicular-to-plane. Without a bias voltage the magnetization is perpendicular-to-plane in all regions under the gate electrodes and in the gap between electrodes. The resistance of the ferromagnetic wire is low. When a gate voltage is applied, the magnetization under the gate electrode turns to the in-plane direction. The magnetization in the gap region remains perpendicular-to-plane. Because of different magnetization directions in neighbor domains, the resistance of the ferromagnetic wire becomes large.

For ferromagnetic wire with in-plane magnetization following ferromagnetic metals can be used: Fe, Co, Ni, FeB, FeCo, FeCoB, CoNi, FeNi,

For ferromagnetic wire with perpendicular-to-plane magnetization following ferromagnetic metals can be used: CoPt, CoPd, FeTb, FeBTb, GdFeCo, GdFe, FePt; and ferromagnetic metal with thickness less than 1 nm: Fe, FeB , FeCo, FeCoB and multilayers: Co/Pt; Co/Pd; Fe/Pt.

For non-conductive dielectric following materials can be used: MgO, Al2O3, SiO2, Ti2O3, HfO2, StTiO3, ZnSe, ZnS. MgSe, MgS.

Figure 12 shows the second design of the disclosed all-metal transistor. The design is the similar to the design of Fig.8, but the gaps between periodical gate electrodes are etched deeply into the ferromagnetic metal. The etched region is filled by a dielectric material (5). The dielectric material (5) can be the same material as gate dielectric (2) or it could be another dielectric. As result, the thickness of the ferromagnetic layer is thicker under gate electrodes and it is thinner in the gap between electrodes.

Merits of design of Fig.12 comparing to design of Fig. 8:

merit 1) the domain wall between the regions under the gate electrodes and the gap is strongly pinned. Therefore, the magnetization in each region can be changed independently. In design of Fig.8, under gate voltage a domain wall should be created (nucleated) between regions under the gate electrodes and under the gap. Otherwise, the magnetization in both regions turns simultaneously and the transistor is not switched off. There is no such problem in design of Fig.12.

merit 2) the PMA is different in the regions under the gate electrodes and the gap due to the different thicknesses of regions (See Figs. 4 and 5). It pins the magnetization of the region under the gap and prevents the change of the magnetization direction in this region.

Figure 13 shows the third design of the disclosed all-metal transistor. The design is the similar to the design of Fig.12, but a thin metal (6) is deposited in the gap between gate electrodes before deposition of dielectric (5). A metal, which enhances interface-type PMA, is used. Such metals are Pt, Pd. Because of high PMA energy in the region under gap, the magnetization in this region is pinned very strongly in perpendicular-to-plane direction.

Figure 14 shows the forth design of the disclosed all-metal transistor. The design is the similar to the design of Fig.12, but a thin non-magnetic metal (6) is deposited between the ferromagnetic metal (3) and the gate dielectric (2). The purpose of the thin non-magnetic metal (6) is to enhance the voltage-induced PMA effect. Non-magnetic metals, which enhance the voltage-induced PMA effect, are Ir, Cr, W, Ur, Tb, Gd.

Figure 15 shows operation principle of the disclosed all-metal transistor of Figs. 12,13,14, , when the PMA of the ferromagnetic wire is interface-type (See Fig.4). Without a bias voltage the magnetization is in-plane in regions under gate electrodes and the magnetization is perpendicular-to-plane in the gap between electrodes. It is because of different thicknesses of the ferromagnetic layer in these regions (See Fig.4(b)) The resistance of the ferromagnetic wire is high. When a gate voltage is applied, the magnetization under the gate electrode turns to the perpendicular-to-plane direction. The magnetization in the gap region is pinned to remain perpendicular-to-plane. Because of the same magnetization directions in neighbor domains, the resistance of the ferromagnetic wire becomes small and the transistor is switched on. In this case the following ferromagnetic metal with the interface-type PMA (Fig.4) should be used : Fe, Co, Ni, FeB, FeCo, FeCoB, CoNi, FeNi,

Figure 16 shows operation principle of the disclosed all-metal transistor of Figs. 12 and 14, when the PMA of the ferromagnetic wire is bulk-type (See Fig.5). Without a bias voltage the magnetization is perpendicular-to-plane in regions under gate electrodes and the magnetization is in-plane in the gap between electrodes. It is because of different thickness of ferromagnetic layer in these regions (See Fig.5(b)) The resistance of the ferromagnetic wire is high. When a gate voltage is applied, the magnetization under the gate electrode turns to in-plane direction. The magnetization in the gap region is pinned to remain in-plane. Because of the same magnetization directions in neighbor domains, the resistance of the ferromagnetic wire becomes small and the transistor is switched on. In this case the following ferromagnetic metal with bulk-type PMA (Fig.5) should be used : FeBTb, CoPt, FePt, FeCoCd, FeCoTb, and Co/Pt maultilayers.