

Fig.1 Prior-art. MOSFET transistor. (1) p-Si substrate; (2) heavily-doped Si layer under drain electrode (3) metal layer of drain (4) gate dielectric; (5) gate metal; (6) source metal (7) heavily-doped Si layer under source electrode.

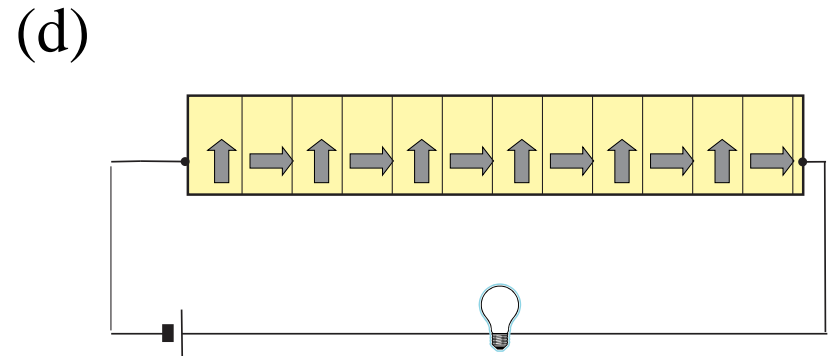
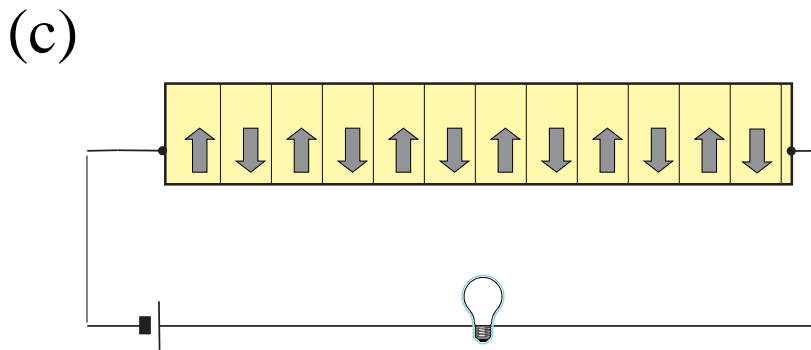
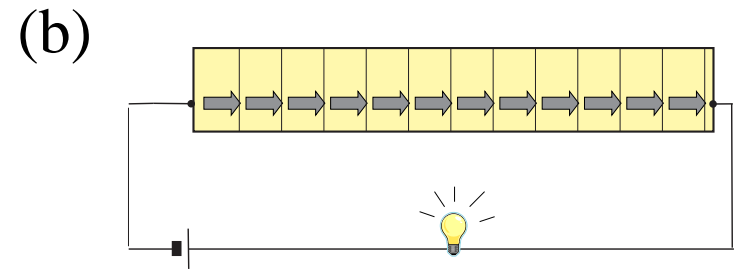
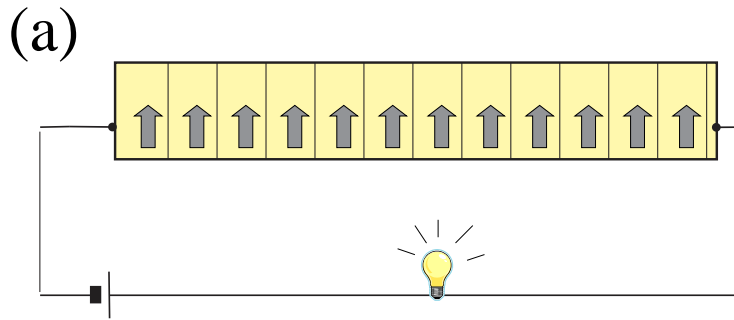
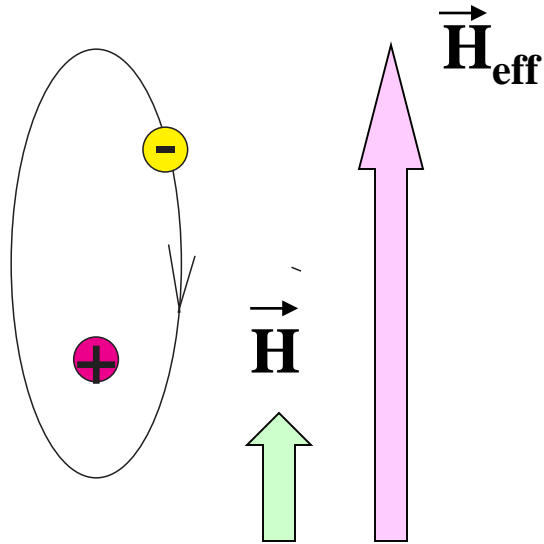


Fig.2 Prior art. Effect of magneto-resistance. The ferromagnetic wire shown in yellow. Grey arrows show magnetization directions in each domain of the ferromagnetic wire. The resistance of the ferromagnetic wire is smaller, when the magnetization of all domains is in the same direction (a)(b). The resistance is larger, when the magnetization direction is different in neighbor domains (c)(d).

(a)



(b)

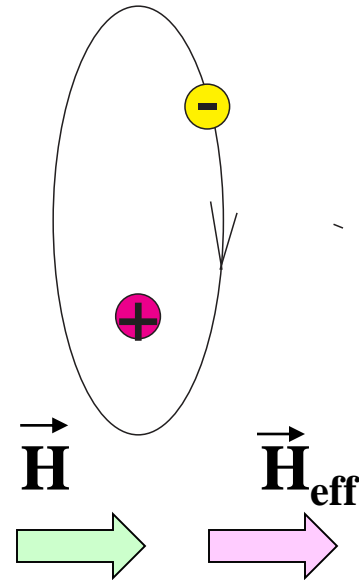


Fig.3 Prior art. Spin-orbit interaction. (a) When a magnetic field applied along deformation of the atomic orbital, the magnetic field is enhanced due to the spin-orbit interaction. The electrical field experienced significantly larger effective magnetic (pink arrow) field than the applied magnetic field (green arrow). (b) When a magnetic field applied perpendicularly to deformation of the atomic orbital, there is no enhancement of the magnetic field

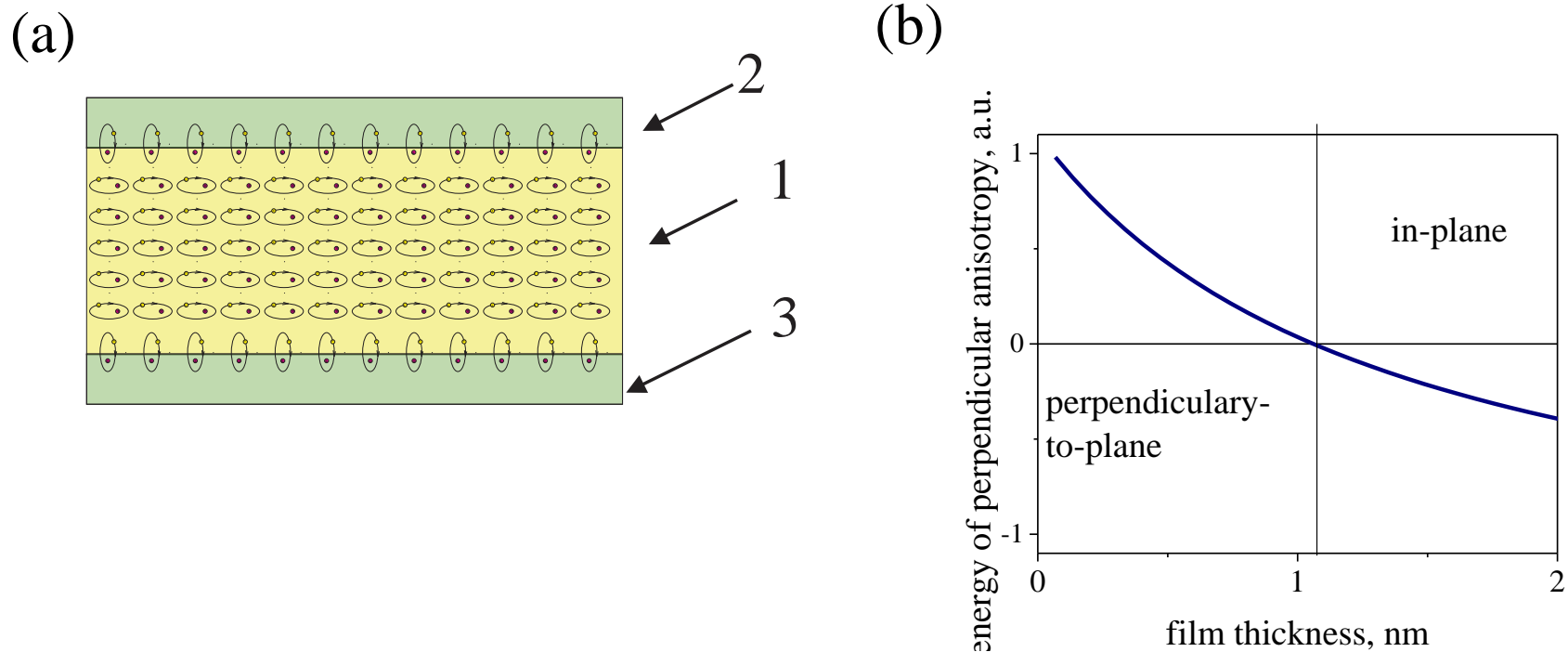
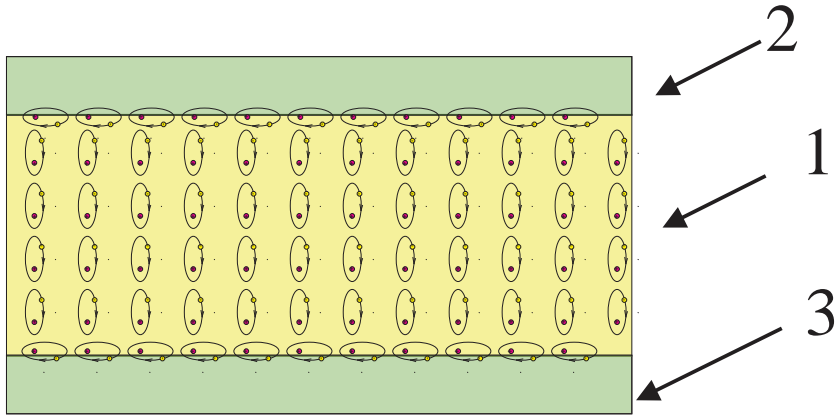


Fig. 4 Prior-art. Interface-induced perpendicular magnetic anisotropy. (a) Shape of atomic orbitals across film thickness. (1) film of ferromagnetic-metal (2) non-magnetic cover (3) non-magnetic substrate. Ellipses show the atomic orbitals in ferromagnetic metal. Only in last layer at interface the orbital are deformed along film normal due to bonding with material of cover and substrate. (b) Energy of perpendicular magnetic anisotropy (including demagnetization energy) for FeB film covered by MgO as function of film thickness. The magnetization of films thicker than 1.05 nm is in-plane. The magnetization of films thinner than 1.05 nm is perpendicular-to-plane.

(a)



(b)

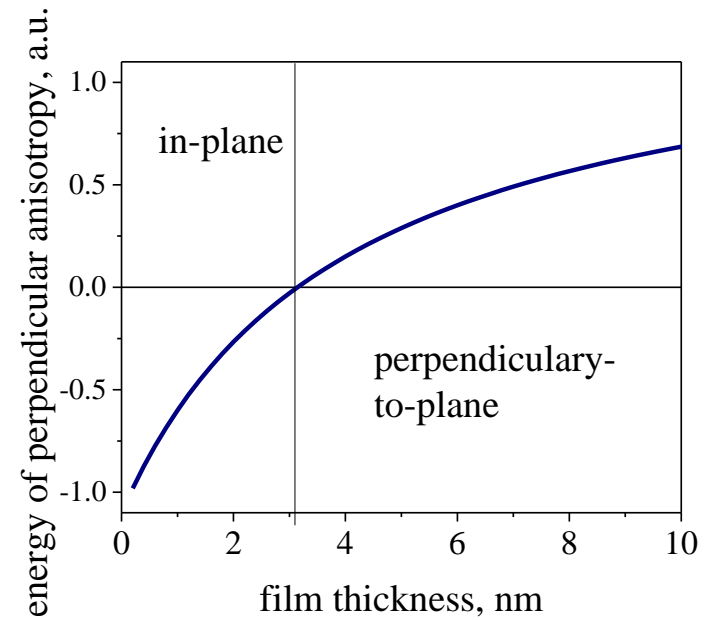


Fig. 5. Prior-art. Bulk-type perpendicular magnetic anisotropy. (a) Shape of atomic orbitals across film thickness. (1) film of ferromagnetic-metal (2) non-magnetic cover (3) non-magnetic substrate. Ellipses show the atomic orbitals in ferromagnetic metal. Except in the last layer at interface, the orbitals are deformed along film normal. (b) Energy of perpendicular magnetic anisotropy (including demagnetization energy) for FeBt film as function of film thickness. The magnetization of films thicker than 3.2 nm is perpendicular-to-plane. The magnetization of films thinner than 3.2 nm is in-plane

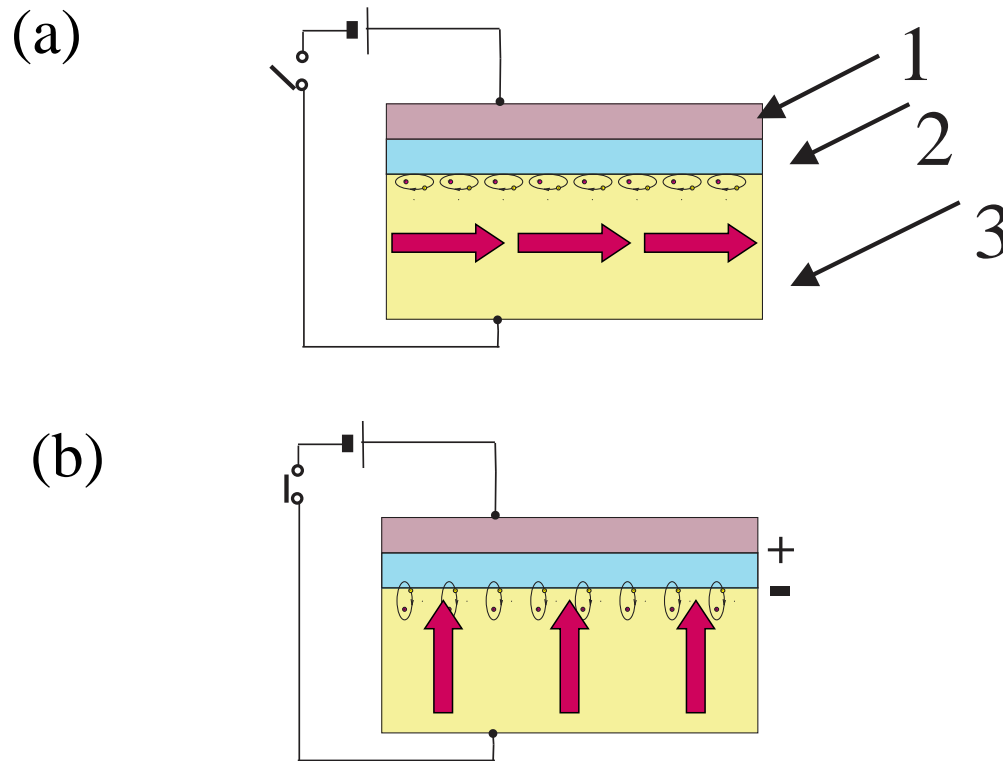
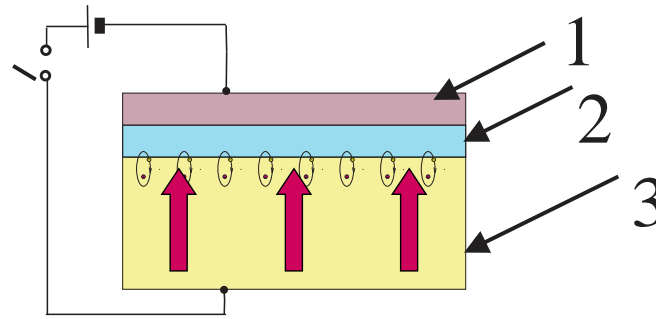


Fig. 6. Prior-art. Effect of voltage-controlled perpendicular magnetic anisotropy. The case when magnetization of ferromagnetic metal is in-plane (1) top electrode (2) non-conductive dielectric; (3) ferromagnetic metal. Ellipses show the atomic orbitals in ferromagnetic metal at boundary with dielectric. Red arrows show magnetization direction in the ferromagnetic metal. At side of the dielectric the polarity of the applied voltage is shown. (a) without applied electrical field the magnetization is in-plane. The atomic orbits are not deformed and there is no spin-orbit interaction. (b) the voltage is applied to the dielectric. The electrons at the boundary of the ferromagnetic metal are attracted to the top electrode, the electron orbital become elliptical and elongated towards top electrode (1). Because of the spin-orbit interaction, the magnetization of the ferromagnetic metal becomes perpendicular-to-plane.

(a)



(b)

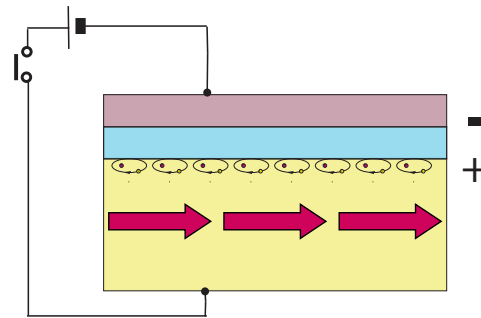


Fig. 7. Prior-art. Effect of voltage-controlled perpendicular magnetic anisotropy. The case when magnetization of ferromagnetic metal is perpendicular-to-plane (1) top electrode (2) non-conductive dielectric; (3) ferromagnetic metal. Ellipses show the atomic orbitals in ferromagnetic metal at boundary with dielectric. Red arrows show magnetization direction in ferromagnetic metal. At side of the dielectric the polarity of the applied voltage is shown. (a) without applied electrical field the magnetization is perpendicular-to-plane, because the atomic orbitals at boundary with dielectric are deformed due to the bonding with atoms of the dielectric and there is a strong spin-orbit interaction. (b) the voltage is applied to the dielectric. The electrons at the boundary of the ferromagnetic metal are repelled from the top electrode, the electron orbitals become spherical and they are no longer elongated towards dielectric. It reduces the spin-orbit-interaction and the magnetization of the ferromagnetic metal becomes in-plane.

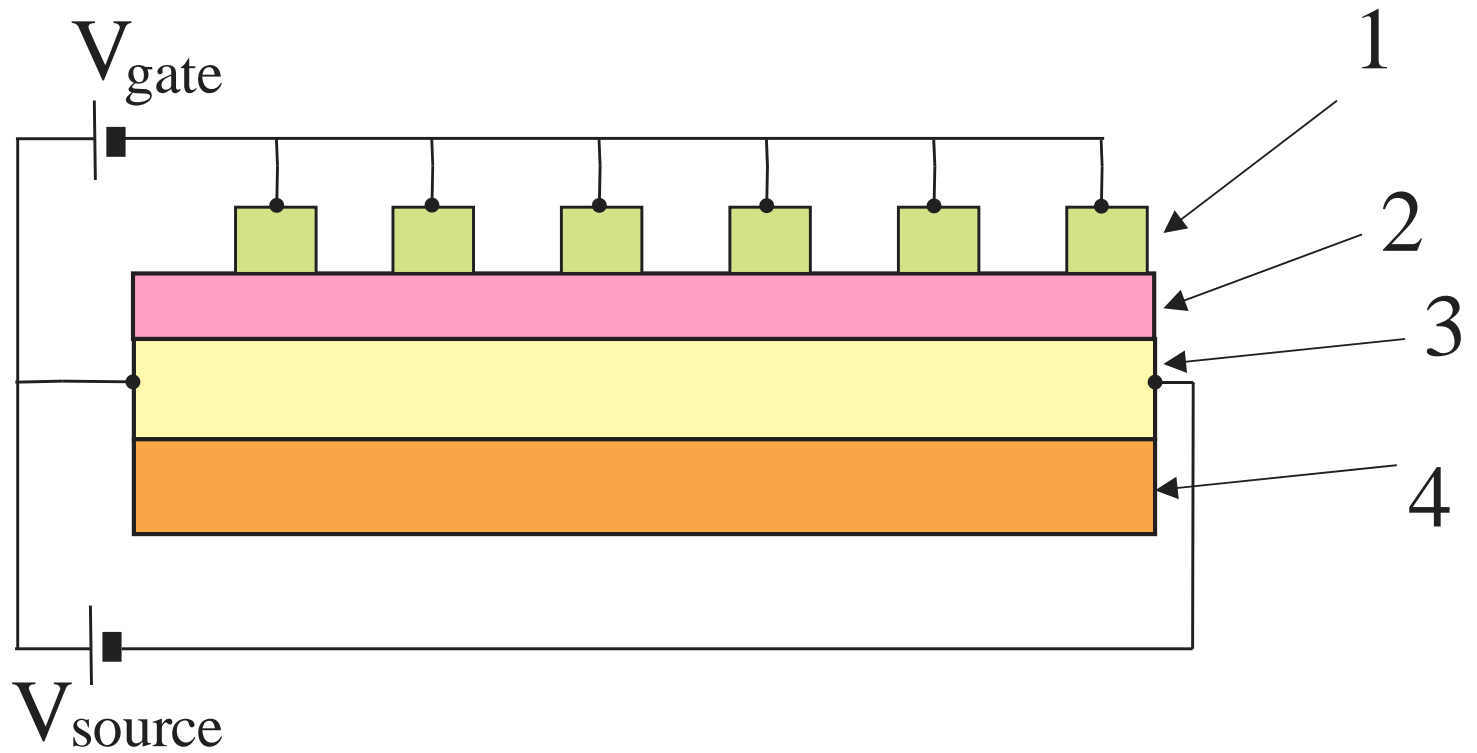


Fig. 8 All-metal transistor of disclosed invention. Cross-sectional view. (1) metal of gate electrode. (2) gate dielectric (3) wire of ferromagnetic metal (4) substrate



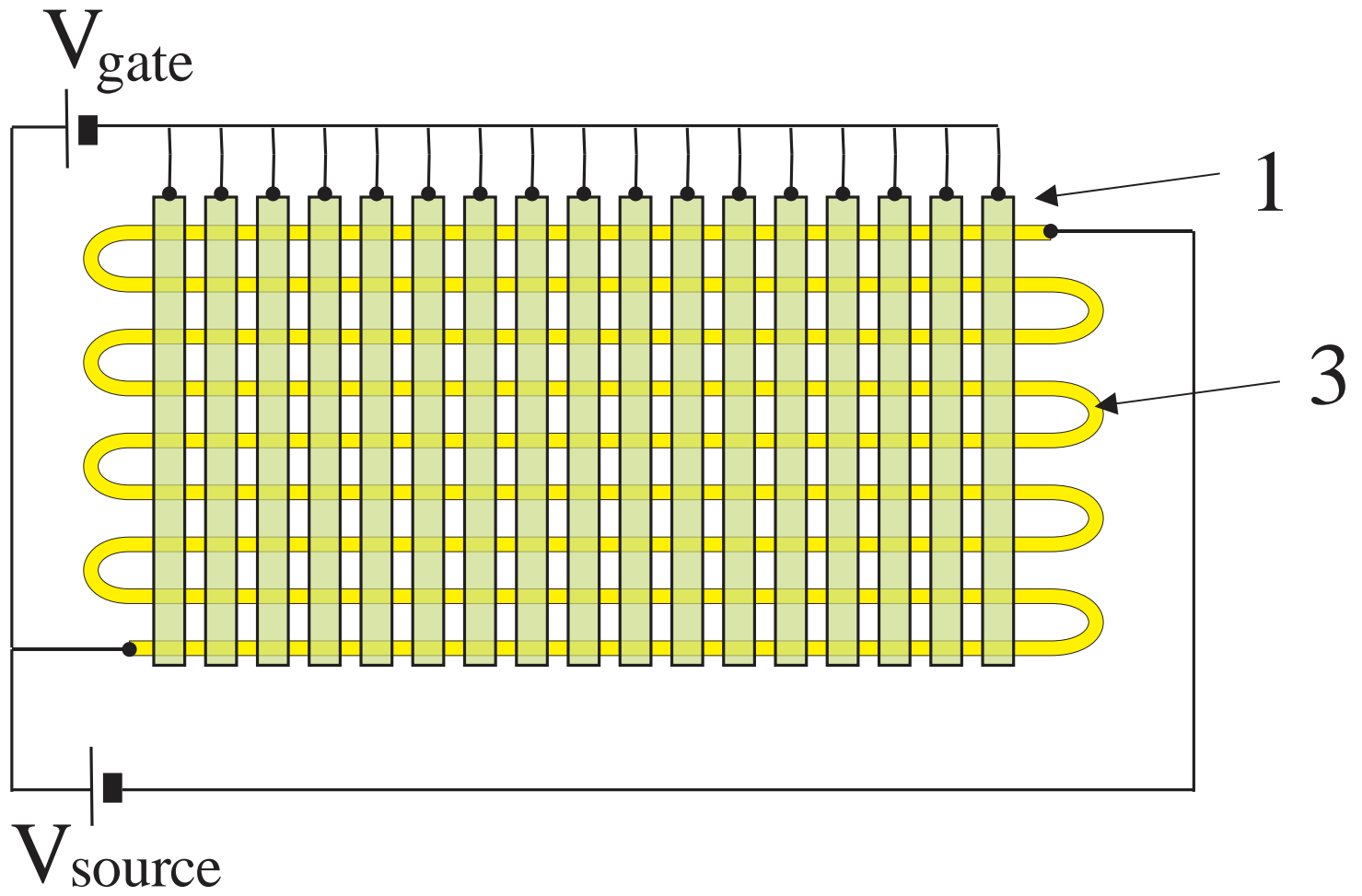


Fig. 9 All-metal transistor of disclosed invention. Top view. (1) metal of gate electrode. (3) wire of ferromagnetic metal

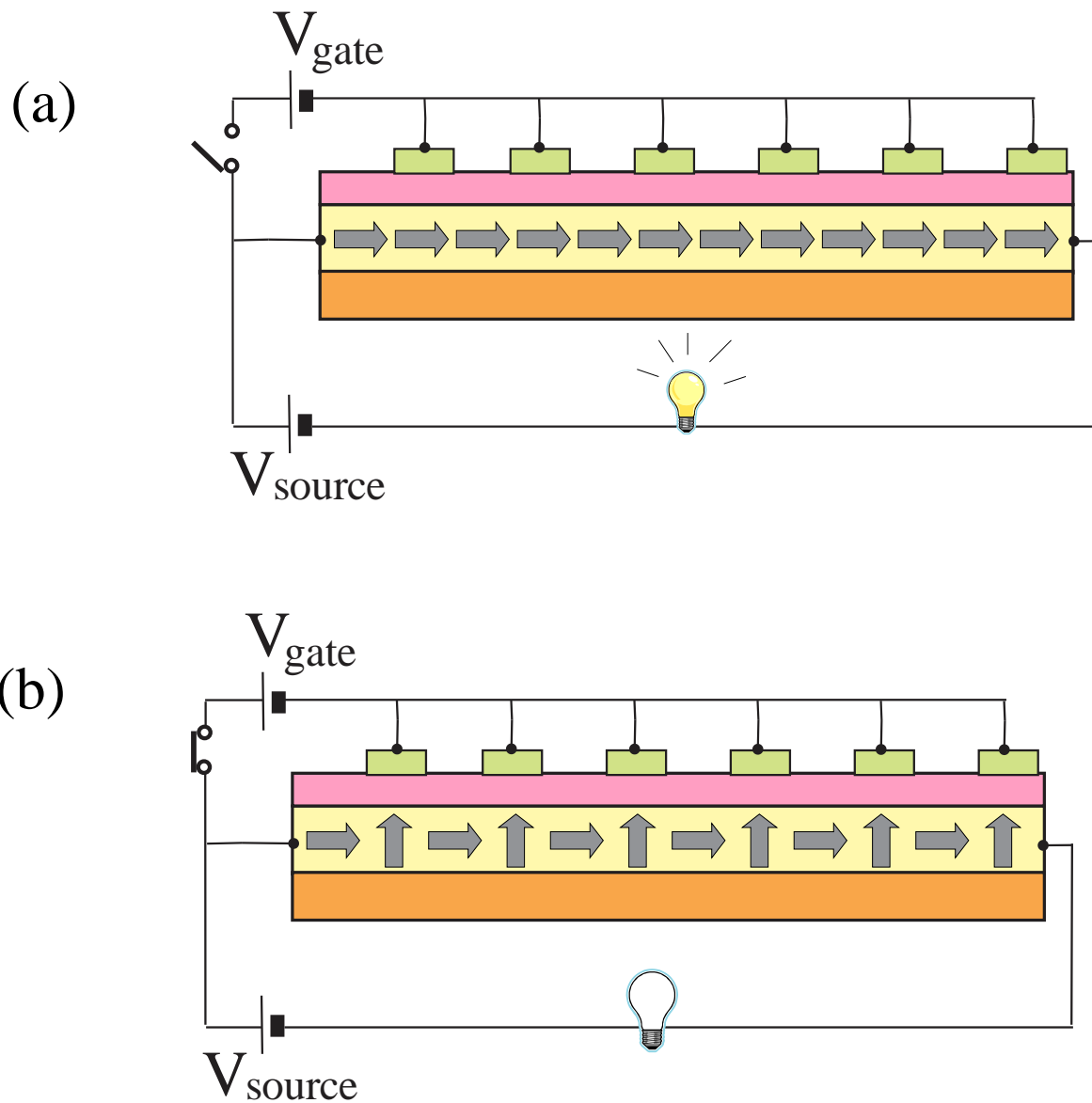


Fig. 10. Operational principle of disclosed all-metal transistor, when equilibrium magnetization of ferromagnetic wire is in-plane. Grey arrows show magnetization directions of the ferromagnetic metal. Under the gate voltage, the magnetization in regions under the gate electrodes turn to perpendicular-to-plane direction.

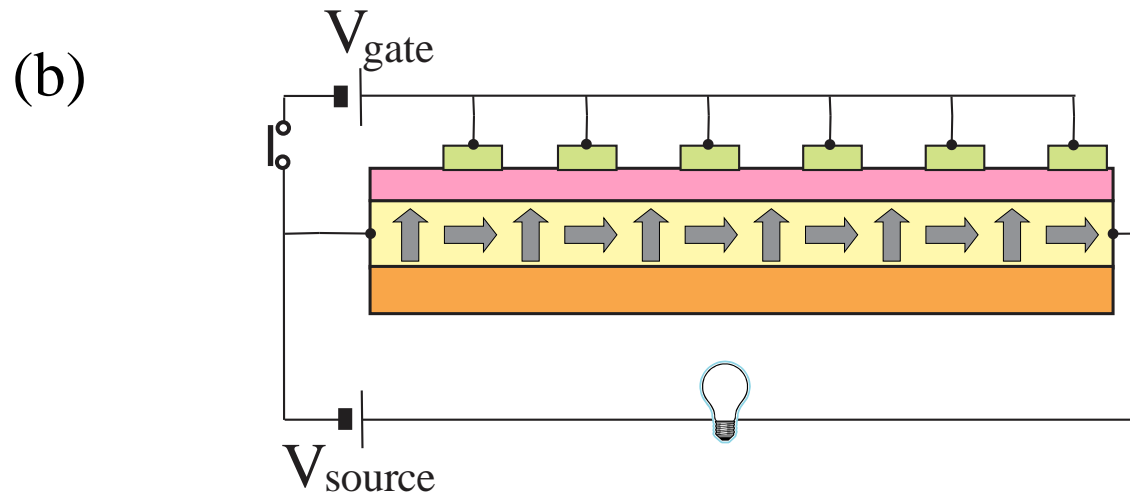
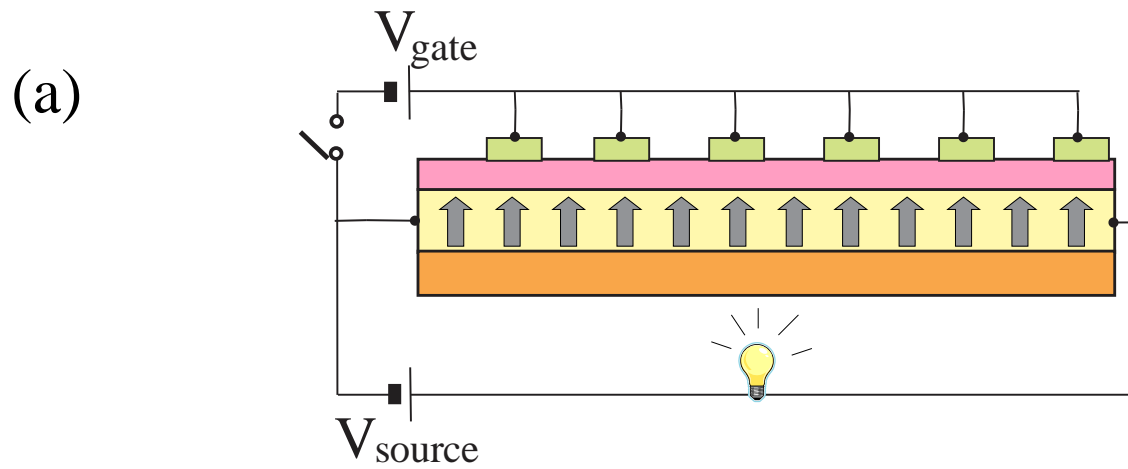


Fig. 11. Operational principle of disclosed all-metal transistor, when equilibrium magnetization of ferromagnetic wire is perpendicular-to-plane. Grey arrows show magnetization directions of the ferromagnetic metal. Under the gate voltage, the magnetization in regions under the gate electrodes turn to the in-plane direction.

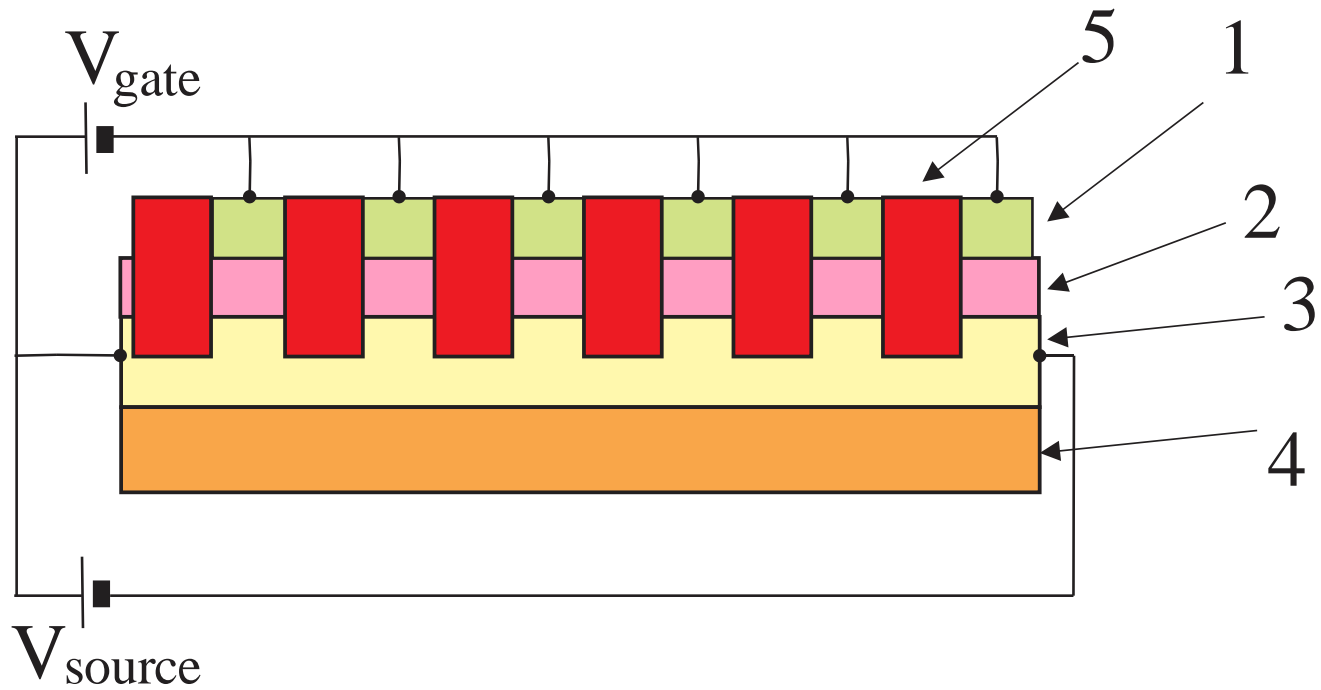


Fig. 12 All-metal transistor of disclosed invention. Cross-sectional view. (1) metal of gate electrode. (2) dielectric 1 (3) ferromagnetic metal (4) non-conductive substrate (5) dielectric 2

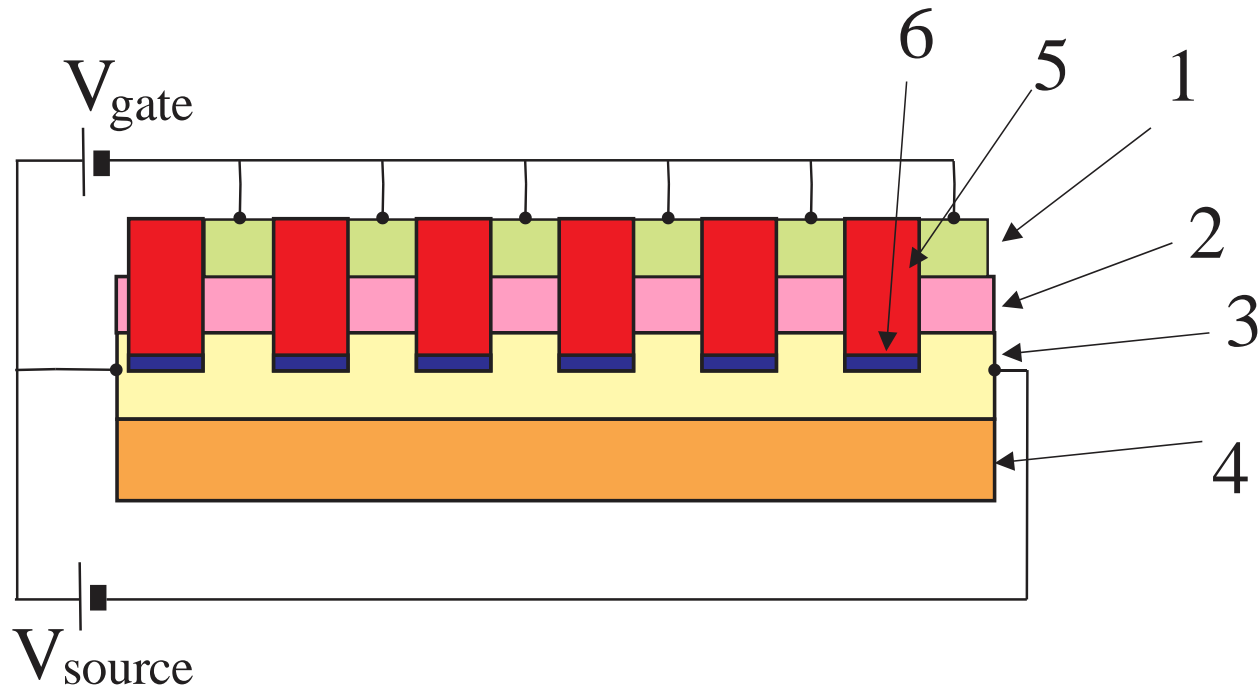


Fig. 13 All-metal transistor of disclosed invention. Cross-sectional view. (1) metal of gate electrode. (2) dielectric 1 (3) ferromagnetic metal (4) non-conductive substrate (5) dielectric 2 (6) thin metal in the gap region to enhance the perpendicular magnetic anisotropy (PMA) and to pin the magnetization in the gap regions in perpendicular-to-plane direction.

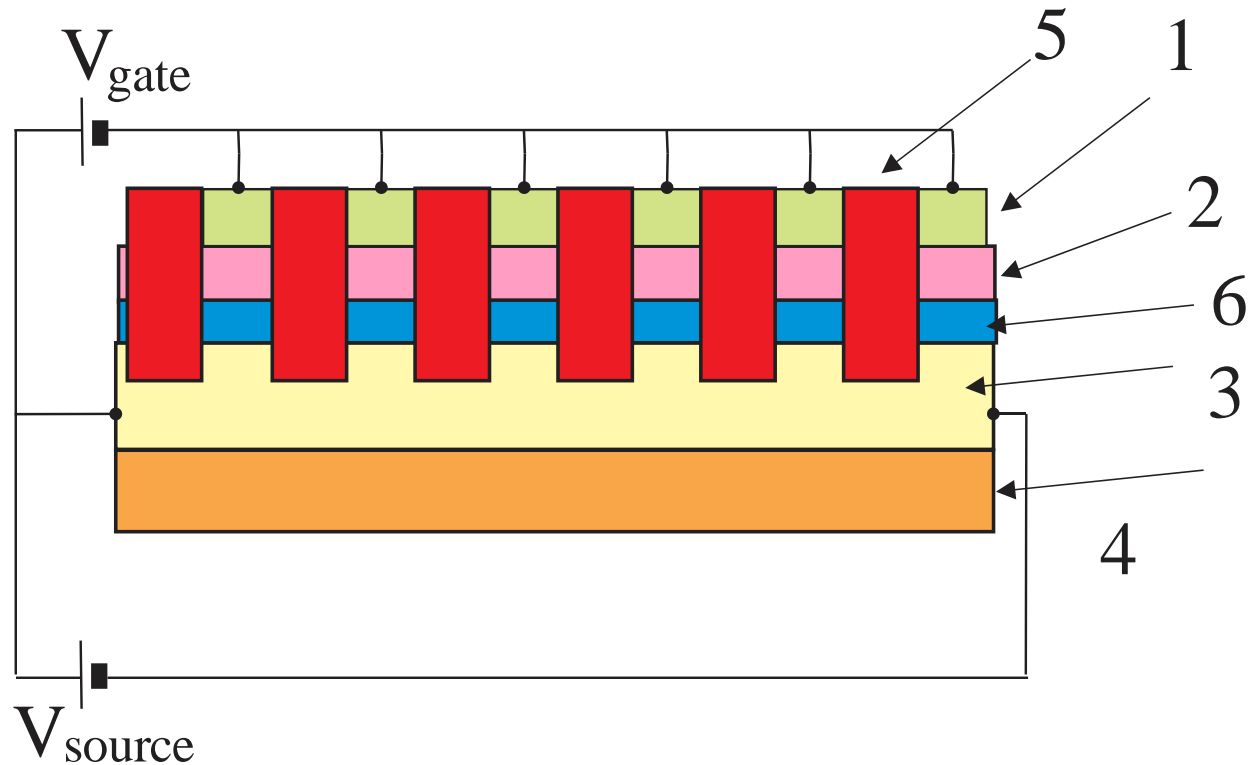


Fig. 14 All-metal transistor of disclosed invention. Cross-sectional view. (1) metal of gate electrode. (2) dielectric 1 (3) ferromagnetic metal (4) non-conductive substrate (5) dielectric 2 (6) a thin non-magnetic metal film between the gate dielectric and ferromagnetic film to enhance the voltage - induced perpendicular magnetic anisotropy (voltage - induced PMA)

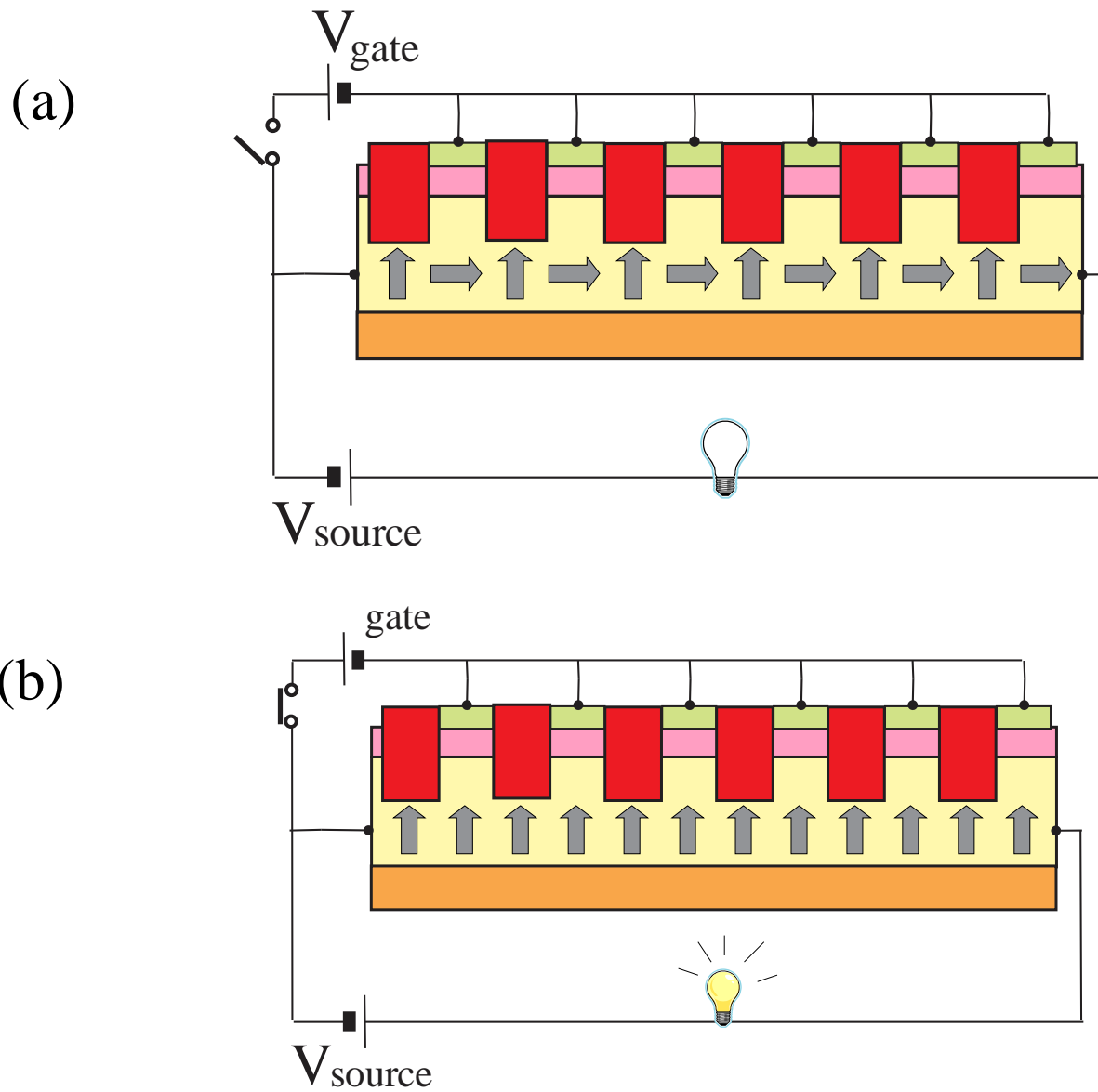


Fig. 15 Operational principle of disclosed all metal transistor, when the PMA of ferromagnetic wire is interface-type (See Fig.4). Grey arrows show magnetization directions of the ferromagnetic metal

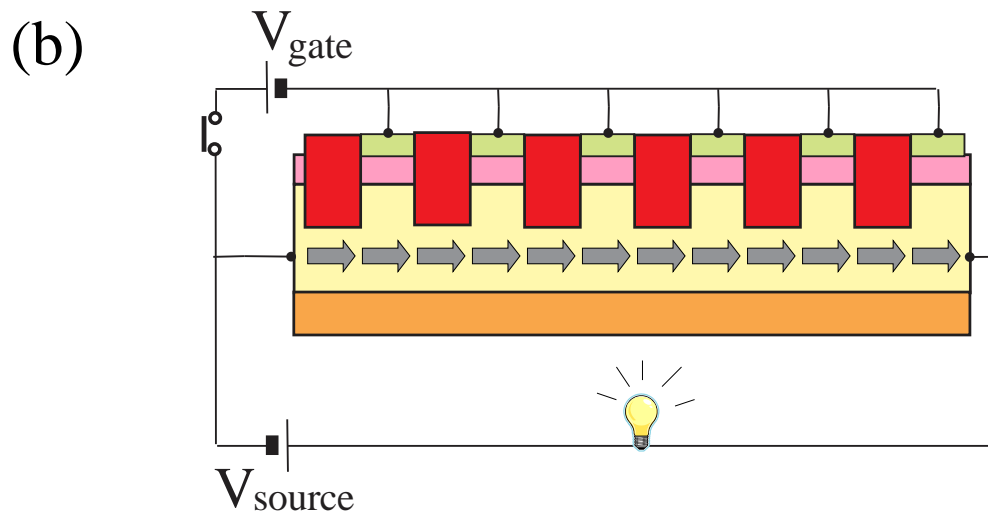
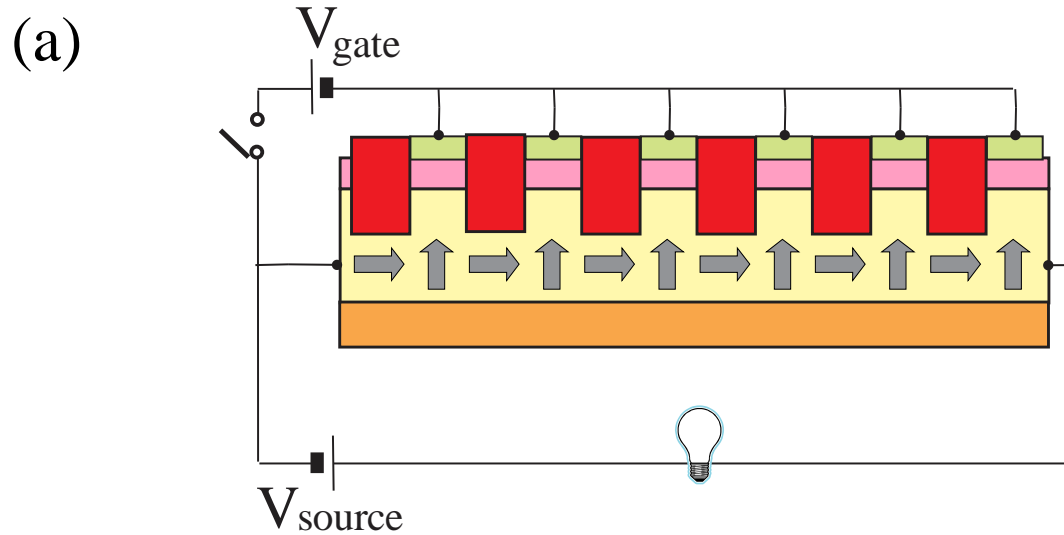


Fig. 16 Operational principle of disclosed all metal transistor, when the PMA of ferromagnetic wire is bulk-type (See Fig.5). Grey arrows show magnetization directions of the ferromagnetic metal.