Magnetic-field-driven electron transport in SOI back-gate device

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Abstract. In this work, we studied the electronic transport properties of silicon nanowire field effect transistors with a back gate. A nontrivial magnetic field influence on the drain current at low temperature (10 K) was found. The strongest effect was observed in the majority carrier accumulation mode. In this mode magnetic field of 0.5 T increases current through the device by more than an order of magnitude. The paper describes the possible mechanisms of the magnetic field influence on the electronic transport characteristics of the structures.

1. Introduction

At present, devices based on silicon nanowire (SiNW) attract considerable attention as elements of integrated nanoscale electronics [1, 2], as well as for studying fundamental properties in small dimensions [2]. Schottky barrier source / drain field-effect transistors (FET) have a number of advantages including simple and low temperature processing, good suppression of short channel effects [4, 5] and the elimination of source / drain contact doping [6, 7]. These features are particularly suitable for SiNW devices, since they allow avoiding difficult fabrication problems, such as precise control of the doping level and the formation of reliable ohmic contacts. Using SOI as a substrate can significantly simplify the formation of nanowires and fabrication of a back gate [8].

In our work, we studied a number of SiNWFET samples made on SOI substrates with ferromagnetic drain and source (Fe). The magnetic field effect on the conductivity of the field channel of the structures at a temperature of 10 K was studied.

2. Experimental

Nanowire devices were formed on boron doped silicon on insulator (SOI) substrates with a concentration of 10^{15} cm^{-3} using e-beam lithography and wet and dry etching. Prior to this, a 15 nm thick film of iron was deposited on SOI by thermal evaporation under ultrahigh vacuum. As a result, the devices represent itself silicon nanowires with ferromagnetic metal drain and source. To create the back gate of the field-effect transistor, an ohmic contact of indium was formed on the back side of the SOI substrate. Figure 1(a) shows a schematic representation of a SiNWFET device. The obtained devices were cooled with liquid helium to a temperature of 10 K in a flow-through cryostat of EMPXHF probe station (Lake Shore cryotronics). All transport characteristics were measured with a Keithley 2634B nanovoltmeter in a zero magnetic field, as well as in a field of 0.5 T of different polarity applied in the plane of the substrate and perpendicular to the device channel (Fig. 1(b)).

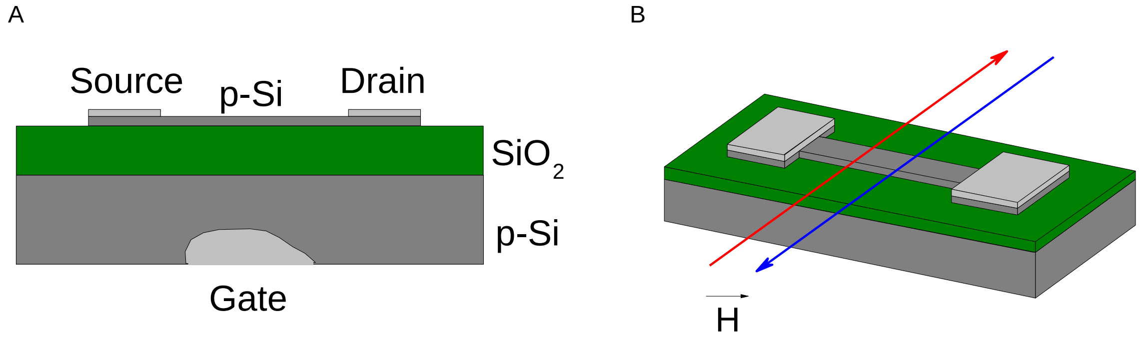

Figure 1(a, b). (a) The SiNWFET structure scheme, **(b)** experimental geometry.

Figure 2 shows the obtained experimental dependences of the transport characteristics of SiNWFET with a channel width w_c = 500 nm. The devices show ambipolar characteristics of both forward and reverse current in the channel depending on the gate bias. Voltage-current source-drain characteristics (VCC) are non-linear. This is due to the fact that the Fe/Si contact is not ohmic. At the Fe / Si interface, there is a Schottky barrier that acts as a semiconductor heterojunction of a field-effect transistor in this device. Consequently, transistor is close at zero gate bias.

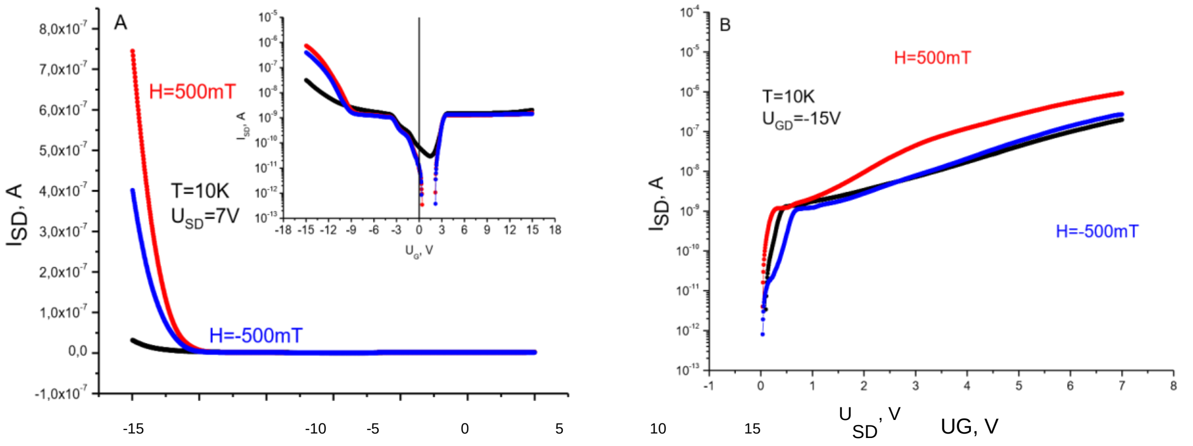

Figure 2(a, b). (a) The transfer characteristics of the structure with a channel width of 500 nm in a magnetic field of 500 mT of different polarity (the inset shows the same data plotted on a semilog scale), **(b)** VCC of the device.

3. Results and discussion

When the magnetic field directed perpendicular to the current channel is turning on, a change in the current in the device is observed. The effect is most pronounced at a negative gate voltage above 10 V. At this gate bias the device operates in accumulation mode (hole transport). Based on geometry of the experiment, the most probable mechanism of the magnetic field effect is the Lorentz force acting on the charge carriers moving in a perpendicular magnetic field. As a result, carriers should be deflected to the front or back part of the nanowire, depending on the magnetic field polarity which will lead to current reduction due to an increase free path of carriers. However, the opposite behavior is observed at high gate bias. The magnetic field-effect leads to an increase of current. Figure 3 shows the relative change of current in a magnetic field of 500 mT of different polarity, which was determined by a formula similar to magnetoresistance

$$MI = (I(H) - I(0)) / I(0). \quad (1)$$

Magnetocurrent (MI) demonstrates a non-linear dependence on the gate voltage and on the magnitude of the drain-source electrical bias. Relative change in the magnitude of the current in the channel exceeds 2000 percent.

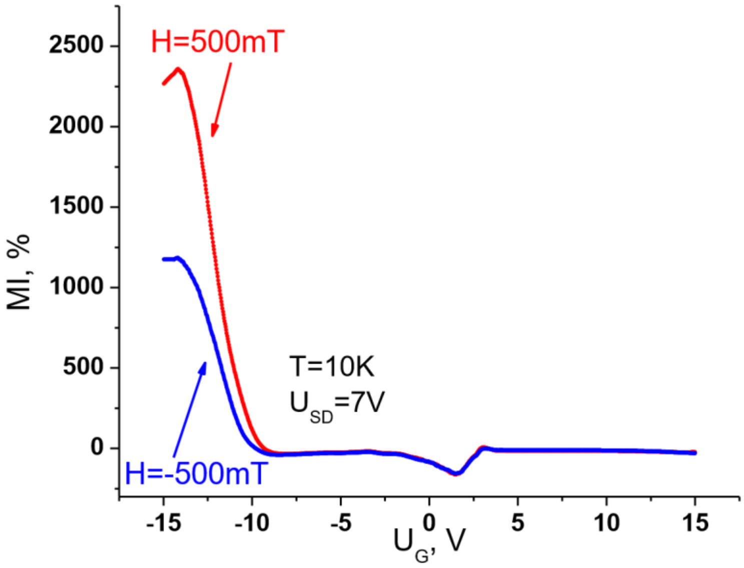

Figure 3. The magnetocurrent versus gate voltage dependence.

If we assume that the behavior of the carriers, when a magnetic field is applied perpendicular to the current channel, is determined only by the action of the Lorentz force, it is unclear why the magnetic current increases, both in the positive direction of the magnetic field and in the negative direction. Nevertheless, we propose a possible mechanism for the observed positive MI effect.

Figure 4 shows the charge carriers accumulation behavior in the device channel in magnetic fields of different polarity. Taking into account the fact that the device is made on SOI, the carriers deflected by the magnetic field in the direction of the substrate will not go deep into the structure, as would be the case when using a conventional substrate. They will begin to accumulate near the boundary of the insulator, changing the shape of the conduction channel. This will effectively contribute to the field effect and will lead to an increase of the magnetocurrent (Fig. 4 (b)). With an oppositely applied magnetic field, carriers will accumulate near the surface of the nanowire, which will also affect the channel shape. As a result, the electric field created by the back gate effectively increases, but weaker than in previous case due to the fact that some of the carriers deflected in this way will recombine on the surface structural defects and surface states and will not participate in the formation of the channel front (Fig. 4 (c)). At the moment it is difficult to make more detailed conclusions about the mechanisms responsible for the observed phenomena. This question requires further researches.

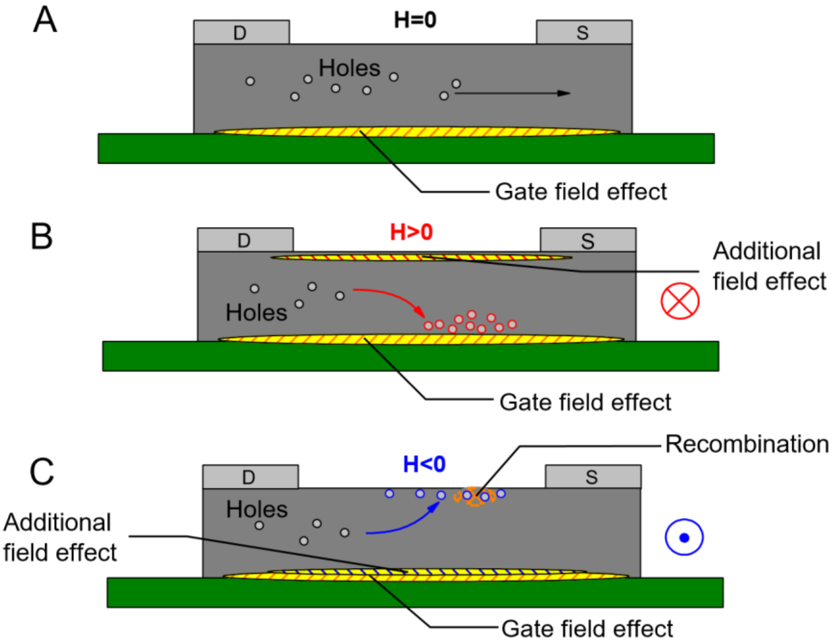

Figure 4(a, b, c). The charge carriers accumulation mode in the channel of the device: **(a)** in a zero magnetic field, **(b)** when turning on a positive magnetic field (holes are curved in the magnetic field towards the SOI dielectric, accumulating there and thus creating an additional electric field) and **(c)** when turning on a negative magnetic field (Holes are curved in the magnetic field towards the nanowire surface. Accumulated near the top of the surface, holes create an additional electric field, but lower than in previous case since some of them recombine.)

4. Acknowledgments

The reported study was funded by Russian Foundation for Basic Research, Government of Krasnoyarsk Territory, Krasnoyarsk Region Science and Technology Support Fund by project № 1842-243022 and supported in part by the Russian Foundation for Basic Research by project no. 18-32- 00035. The work was partially supported by the Ministry of Education and Science of the Russian Federation and by Siberian Branch of the Russian Academy of Sciences (Project II.8.70) and Fundamental research program of the Presidium of the RAS no. 32 «Nanostructures: physics, chemistry, biology, basics of technologies».

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