Magnetic-field-driven electron transport in ferromagnetic/ insulator/semiconductor hybrid structures

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Abstract. Extremely large magnetotransport phenomena were found in the simple devices fabricated on base of the Me/SiO_2/p-Si hybrid structures (where Me are Mn and Fe). These effects include gigantic magnetoimpedance (MI), dc magnetoresistance (MR) and the lateral magneto-photo-voltaic effect (LMPE). The MI and MR values exceed 10^6 % in magnetic field about 0.2 T for Mn/SiO_2/p-Si Schottky diode. LMPE observed in Fe/SiO_2/p-Si lateral device reaches the value of 10^4 % in a field of 1 T. We believe that in case with the Schottky diode MR and MI effects are originate from magnetic field influence on impact ionization process by two different ways. First, the trajectory of the electron is deflected by a magnetic field, which suppresses acquisition of kinetic energy and therefore impact ionization. Second, the magnetic field gives rise to shift of the acceptor energy levels in silicon to a higher energy. As a result, the activation energy for impact ionization significantly increases and consequently threshold voltage rises. Moreover, the second mechanism (acceptor level energy shifting in magnetic field) can be responsible for giant LMPE.

keywords: hybrid structures, magnetoresistance, magnetoimpedance; photovoltage

1. Introduction

Magnetotransport phenomena in hybrid structures, which are compatible with CMOS technology, are an attractive field of investigation because of the interesting physical phenomena and promising application in memory devices, sensors, magnetic field-controlled logic, etc[1,2,3,4]. Semiconductor structures and devices are of special interest for fundamental research[5], because any developed magnetoelectronic or spintronic devices need to be compatible with modern semiconductor electronics. Semiconductor-based MR elements and devices can be easily integrated in semiconductor chips. In this way, semiconductor electronics acquires new functional possibilities.

At the present time, in hybrid structures the authors of [6,7,8] demonstrated spin injection, spin detection, and carrier transport manipulation via electron spin states in semiconductor structures with ferromagnetic electrodes of special topology; i.e., the transport properties of such structures can be controlled by a magnetic field. Moreover, it was established that semiconductor structures without ferromagnetic elements and simply bulk semiconductor can also exhibit the giant MR effect. Such effects are related to the occurrence of inhomogeneous states in semiconductors. In particular, the MR effect in the bulk of silicon can be caused by space charge inhomogeneity[9]. The other group of MR effects in semiconductors and semiconductor devices is related to the autocatalytic process of impact ionization, which can be suppress by magnetic field[10,11].

The giant ac and dc MR effects were observed in the on metal/insulator/semiconductor(MIS) diodes with the Schottky barrier[12,13]. Unfortunately, it remains unanswered whether the MR effect originates from the bulk of silicon or from interface. Our studies on lateral devices and Schottky diodes based on the Fe/SiO_2/*p*(*n*)-Si hybrid structures showed that interface states localized near the SiO_2/*p*(*n*)-Si boundary significantly contribute to magnetotransport[14,15,16,17].These surface states are involved in recharging processes and their energy structure is rearranged by a magnetic field. However, this is apparently not the only possible mechanism and it cannot explain the variety of MR effects observed in the MIS-structure-based devices.

Another one transport effect that was observed in the superlattices[18], heterostructures[19], two-dimensional electron systems[20], Schottky barrier structures[21] is the lateral photovoltaic effect (LPE). LPE discovered by Walter Schottky in 1930[22] continues attracting the considerable interest due to its application potential as small displacements sensor. However LPE's sensitivity to magnetic field was found only last decade in some systems[23,24] which can provide an enhancement of the functionality for the LPE-based devices. Until today, in fact, nobody has discussed the LMPE origin and carried out detailed fundamental investigation.

Thus in this paper we present results of systematically study of Mn/SiO_2/*p*-Si structure magnetotransport properties and LPE in external magnetic field for the hybrid metal-insulator-semiconductor (MIS) structure with Schottky barrier Fe/SiO_2/p-Si.

2. Experiments

The Mn/SiO_2/*p*-Si and Fe/SiO_2/p-Si structures were fabricated using the technique developed for fabricating structures with a Fe layer[17]. A *p*-Si(100) wafer with a resistivity of 5 Ω·cm (a doping density (N_A) of 2×10^{15} cm^{-3}) was used as a substrate. Metal films with thicknesses 10 nm were deposited by thermal evaporation at room temperature. The residual pressure in a vacuum chamber was 6.5×10^{-8}Torr and the sputtering rate was 0.25 nm/min. Before deposition 1.5 nm thickness SiO_2 layer was grown by exposing in the aqueous solution of H_2O_2 and NH_4OH in the ratio 1:1:1 for 30 min at 60°C. The layers thickness was *in situ* controlled with an LEF-751 high-speed laser ellipsometer.

The magnetic properties of the grown films were examined using SQUID magnetometry (MPMS-5, Quantum Design) and the magnetooptical Kerr effect (NanoMOKE-2, Quantum Design). According to the data obtained, there is no magnetic order and the manganese film remains paramagnetic even at the lowest temperatures (2 K). Whereas iron film is ferromagnetic up to highest measuring temperatures (400 K).

To study the electrical properties of the Mn/SiO_2/*p*-Si structure, we fabricated MIS Schottky diodes. The transport properties of the MIS diode in the ac and dc modes were studied in the two-probe configuration (Fig. 1(a)). Bottom contact to the substrate backside was attached via an Indium ohmic contact for all samples. To investigate LPE and LMPE lateral device pictured in Fig. 1(b) was made. The samples (see Fig. 1(b)) were irradiated from metal film side by a laser diode with wavelength of 668 nm. The light was focused into a narrow strip (0.5 mm in width) on the structure surface. A position of a narrow beam of light was fixed on the surface asymmetrically relative to contacts. Photovoltage *V* was controlled by a KEITHLEY 2182A nanovoltmeter. MIS Schottky diodes transport properties was measured using a KEITHLEY 2400 current/voltage source meter (dc) and an Agilent E4980A analyzer (frequency range from 20 Hz to 1MHz).

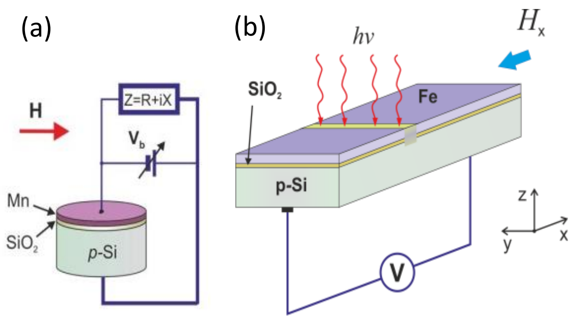

Figure 1. Experimental setup for (a) Mn/SiO_2/*p*-Si diode and (b) Fe/SiO_2/p-Si LPV device.

3. Results and discussion

3.1. *Magnetoimpedance*

We started studying the Schottky diodes with the Mn electrode with impedance ($Z = R_{ac}+iX$, where R_{ac} and X are the real and imaginary parts of the impedance, respectively) and magnetoimpedance measurements. At reverse and low forward bias V_b ($V_b < V_b^c \approx 2$ V), we obtained the results similar to those reported in[15,17] for the structures with Fe. At the forward bias above the critical value of V_b^c, which, in our case, is about 2 V (this value changes insignificantly in temperature range from 5 K to 40 K), the behavior of the $R_{ac}(H)$ and $R_{ac}(V_b)$ dependences and the effect of the magnetic field on the impedance drastically change. Figure 2(a) shows the behavior of R_{ac} as a function of H at fixed temperature for the cases V_b = 0 and V_b = 5 V. The response to the magnetic field strongly changes under the bias; the magnetoresistance ratio increases from 200 to 10^5%; the largest changes in R_{ac} are observed in relatively low fields(H < 250 mT). It can be seen in Fig.2(b) that the magnetoresistance ratio sharply increases only at forward biases above V_b^c. All the data presented in Fig. 4 were obtained at a measuring voltage frequency of 1 kHz.

Figure 2(c) presents frequency dependences of MR_{ac}. In contrast to the case $V_b < V_b^c$, at a high bias about 1 MHz the device exhibits a fairly high positive MR ($MR_{ac} > 10^3$ %), which rapidly grows with a decrease in frequency to about 5 kHz. Then, the growth slows down, but, in contrast to the low-bias case, where MR_{ac} tends to 0

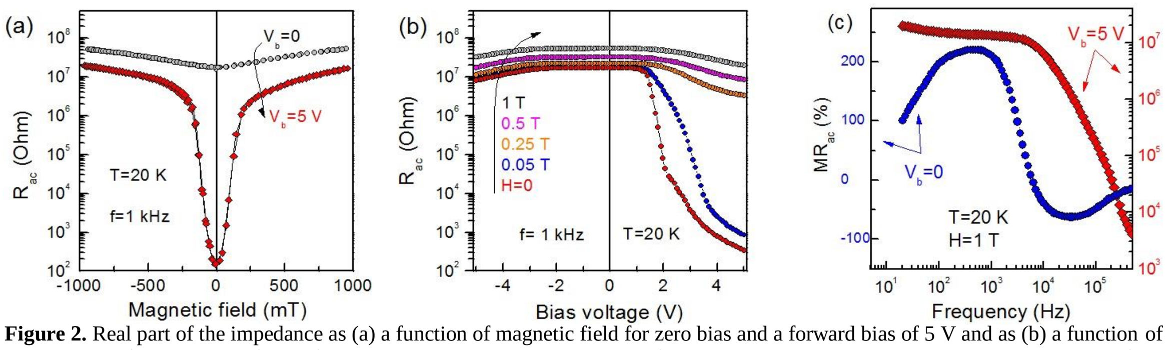

Figure 2. Real part of the impedance as (a) a function of magnetic field for zero bias and a forward bias of 5 V and as (b) a function of bias voltage for magnetic fields from zero to 1T at T= 20 K. The frequency is 1 kHz. (c) Frequency dependences of ac magnetoresistance in a magnetic field of 1 T. The forward biases are 5 V and zero.

when f moves to 0, continues up to the lowest frequencies and the values $MR_{ac} > 10^7$ % are attained. At reverse and low forward bias the effect of the magnetic field can be understood assuming that it shifts the energy levels of interface states (and acceptor levels as a whole) relative to the semiconductor band edges, that changes R_{ac} value[15,17]. To explain huge MR_{ac} at $V_b > V_b^c$ we must involve another mechanisms.

3.2. The dc magnetoresistive effect

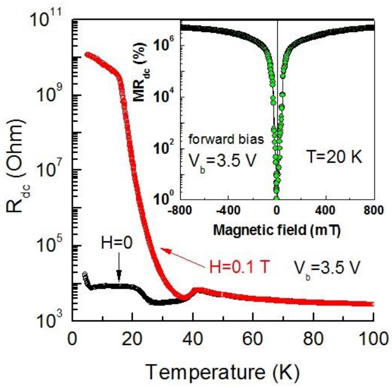

Figure 3. Temperature dependences of dc resistance at a forward bias of 3.5 V without magnetic field and in a field of 0.1 T. Inset: dc magnetoresistance ratio as a function of magnetic field at a temperature of 20 K and a forward bias of 3.5 V.

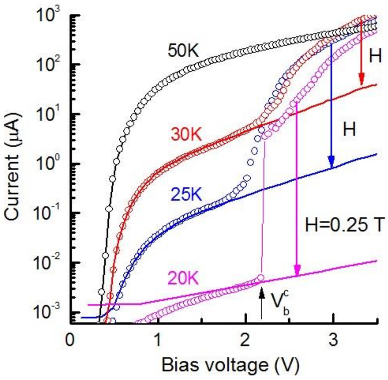

Figure 4. I-V curves at $H=0$ (open circles) and $H=0.25$ T (solid lines) at different temperatures.

Since at $V_b > V_b^c$ we observe the largest MR_{ac} values at the lowest frequencies, it is reasonable to investigate the MR effect in the dc mode and its dependence on V_b. In the Mn/SiO_2/p-Si structure the MR effect is insignificant at $V_b < V_b^c$, but, as can be seen in Fig. 3, at $V_b > V_b^c$ in the low-temperature region, the MR_{dc} value can be more than 10^7%. The strongest changes in the R_{dc} value are observed even in weaker fields (H < 100 mT) than in the ac mode (Fig. 2(a)).

As expected, the I-V characteristics are nonlinear. In the temperature range 40 – 300 K they are typical of a MIS diode with the Schottky barrier and similar with dependence for 50 K shown on Fig. 4. This confirms that in this temperature range the physical mechanisms of carrier transport remain invariable. Below 40 K the current through the diode at the forward bias attaining the threshold value $V_b^c \approx 2$ V increases by a few orders of magnitude. Such behavior means that at $V_b^c \approx 2$ V the autocatalytic process of impact ionization of the shallow acceptor boron in the bulk of the semiconductor take place[25]. When the high bias voltage is applied, carriers acquire the kinetic energy, which exceeds the energy of ionization of acceptor impurities; i.e., impact ionization occurs. In case of boron doped silicon acceptor energy E_A is 40 meV and impact ionization starts at low electric field. From impedance measurements using approach proposed in[26] we found that acceptor levels energy became 42 meV in magnetic field of 1 T. Therefore, to initiate the impact ionization process charge carriers must have higher kinetic energy and consequently threshold bias voltage V_b^c is rises. Despite V_b^c depends on E_A exponentially[25] it's insufficiently to provide observed MR_{dc} value. Second magnetic field effect mechanism can be the Lorentz force. In an applied magnetic field, the Lorentz force deflects carrier trajectories, which increases the probability of inelastic scattering, decreases the kinetic energy of carriers, and, as result, suppresses impact ionization. To restore the impact ionization process, a greater electric field is required; in other words, the magnetic field increases the threshold voltage of the current breakdown[27]. Furthermore significant contribution of Lorentz force to MR effect is supported by anisotropy of the effect. The transport properties change mostly in a magnetic field perpendicular to the current.

3.3. Lateral magneto-photo-voltaic effect

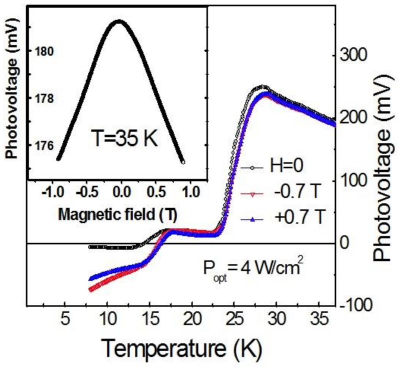

Figure 5. LPV as a function of temperature at magnetic fields of H=0, ±-7 T. Inset: LPV versus magnetic field at temperature of 35 K.

During the study of photogenerated voltage (PV) known as LPE in Fe/SiO_2/p-Si device (Fig. 1(b)) was found nontrivial dependence on temperature and sensitivity to magnetic field (Fig. 5). With the decreasing of temperature, the LPV, measured from the Si substrate side monotonically rises, reaching the maximum near 30 K. At the narrow temperature range of 27-24 K, LPV value rapidly drops, after that a step is observed on the $PV(T)$ dependence. Below 17 K LPV value changes again and the sign of the effect switches near 14 K at zero magnetic field. After the sign switch, the absolute value of LPV remains small until the lowest temperatures. Magnetic field influence on LPV was found at all measuring temperature region (5 – 273 K) but significant change of photovoltage was observed only below 27 K. As an additional parameter that indicates the magnetic field influence we will use LMPE ratio – the relative value defined as $MV=(PV(H)-PV(0))/PV(0)$, where $PV(H)$ and $PV(0)$ are LPV in magnetic field of H and in zero magnetic field, respectively. At the range of 27-24 K MV rapidly grows, reaching the value of 40 %. Sensitivity to the magnetic field polarity appears below 24K. At the lowest temperatures (5 – 12 K) the *MV* value can exceed 10^3 %.

At this stage of research it is difficult to speak about specific mechanisms of the magnetic field influence on the photogenerated carriers transport in our MIS structure. But considering other observed MR effects in Schottky barrier-based devices we can suggest that aforementioned interface states and it's shifting in magnetic field may play important role in LMPE.

4. Conclusions

It was shown that transport properties of Me/SiO_2/p-Si hybrid structures (where Me are Mn and Fe) are highly sensitive to the external magnetic field at low temperatures. The MI, MR and LMPE of extremely large values were observed. For both the dc resistance and the impedance of Mn/SiO_2/p-Si MIS diode we can distinguish several regimes of the response to the magnetic field. The giant MR effect originates from impact ionization initiated in the bulk of the Si substrate when the bias voltage attains a threshold value. Impact ionization is suppressed via the two mechanisms. The first mechanism is related to the Lorentz force: deflection of carrier trajectories in a magnetic field suppresses acquisition of the kinetic energy between scattering events; therefore, impact ionization starts at higher bias voltages. The second mechanism is displacement of the acceptor levels toward higher energies relative to the top of the valence band of the semiconductor, which requires higher voltages to initiate impact ionization. This scenario can be applied to MI since highest MI effect is observed only at the voltages of impact ionization in the bulk of the semiconductor. Concerning LMPE mechanisms, at present step of study, we can only suggest that aforementioned interface states may participate in LMPE.

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