# Magnetotransport phenomena and spin accumulation in MIS structures

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# Magnetotransport phenomena and spin accumulation in MIS structures

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**Abstract.** The present work is devoted to magnetic transport in Fe/$SiO_2$/*p*-Si, Mn/$SiO_2$/*p*-Si and $Fe_3Si$/*p*-Si hybrid structure. For Mn/$SiO_2$/*p*-Si diode extremely large values of magnetoresistance were observed ($10^5$ % for AC and $10^7$ % for DC) which is explained by impact ionization process that can be suppressed by the magnetic field. Lateral photovoltaic effect in Fe/$SiO_2$/*p*-Si have also shown a strong dependence on the magnetic field in low-temperature region (the relative change of photovoltage exceeded $10^3$ %). In $Fe_3Si$/*p*-Si spin accumulation was found via 3-terminal Hanle measurements. We believe that the magnetic field affects electric transport through Lorentz force and through the interface states which are localized at the insulator/semiconductor or metal/semiconductor interfaces. Such states play a decisive role in magnetotrasnport as their energy can be controlled by a magnetic field. In $Fe_3Si$/*p*-Si they also participate in spin-dependent tunneling, causing spin injection from the $Fe_3Si$ film into the silicon.

## 1. Introdiction

Structures with ferromagnetic layers have been intensively studied since the discovery of the giant magnetoresistance effect [1]. Later, the interest in ferromagnetic metal/insulator/semiconductor (MIS) hybrid structures had arisen [2]. Compatibility with CMOS and SOI technology as well as the possibility to induce and control the spin-dependent transport allowed MIS structures to find practical applications in different magnetic and spintronic devices such as magnetic field sensors, memory and logic devices [3-6]. Recent advances in the study of hybrid structures may lay in a basis of the future spin transistor.

Our investigations of the AC and DC magnetic transport in MIS structures revealed the unusual effects, which are not directly spin-dependent. We observed the AC and DC giant magnetoresistance in Fe/$SiO_2$/*p*-Si and Mn/$SiO_2$/*p*-Si diodes with the Schottky barrier [7-10]. The assumption was made that one of the mechanisms of the MR effects in our structures is related to surface states localized at the insulator/semiconductor interface. These states are involved in the recharging process and can be affected by magnetic field.

In order to study the interplay between the electricity, magnetism and optical irradiation in our structures we measured the lateral photovoltaic effect (LPE). LPE was discovered by Schottky [11] and Wallmark [12] and found its application in position detectors due to the high sensitivity to a laser

spot position [13]. Photovoltaic effect in Fe/$SiO_2$/*p*-Si showed surprisingly high sensitivity to a magnetic field.

One of the most interesting results obtained is the spin accumulation in low doped silicon in the epitaxial $Fe_3Si$/*p*-Si structure [14]. Similar results had been reported in [15-17], however the spin accumulation was observed either in structures with insulating barrier, or in structures with highly doped substrates ($6\cdot10^{19}$ $cm^{-3}$) compared to our case ($2\cdot10^{15}$ $cm^{-3}$). Main conclusion is that detected localized interface states are involved in all observed magneto- and spin-dependent effects.

## 2. Materials and methods

In present work we will consider Me/$SiO_2$/*p*-Si (where Me are Fe and Mn) and $Fe_3Si$/*p*-Si structures. Detailed description of sample fabrication can be found in [18-20] for Me/$SiO_2$/Si and in [14] for $Fe_3Si$/*p*-Si. Samples were fabricated on boron doped Si substrates. All films were deposed by thermal evaporation at ultrahigh vacuum conditions in Angara chamber [21] providing polycrystalline and epitaxial growth. Before film deposition in Me/$SiO_2$/*p*-Si, $SiO_2$ layer was formed by exposing in aqueous solution of $H_2O_2$ and $NH_4OH$. In case of $Fe_3Si$/*p*-Si structure oxide was removed by high temperature annealing at vacuum chamber. Parameters of the samples are presented in Table 1.

**Table 1.** Parameters of the Me/$SiO_2$/p-Si and $Fe_3Si$/p-Si structures

| | Substrate resistivity | Substrate orientation | Doping density $N_A$ | Oxide thickness | Film thicknesses |
|---|---|---|---|---|---|
| Me/$SiO_2$/*p*-Si | 5 Ω cm | (100) | $2\cdot10^{15}$ $cm^{-3}$ | 1.5 nm | 10 nm |
| $Fe_3Si$/*p*-Si | 7.5Ω·cm | (111) | | N/A | 21 nm |

The measurements were performed using different experimental schemes (figure 1). In order to study AC and DC electric transport, Me/$SiO_2$/*p*-Si MIS Shottky diodes were fabricated (figure 1*a*). Indium ohmic contacts were attached to the substrate backside. Lateral device for measuring LPE is shown on figure 1*b*. The sample was irradiated by a laser diode with λ = 1 μm. The light was focused into a narrow strip of 0.5 mm in width on the structure surface. Spin accumulation in $Fe_3Si$/*p*-Si was measured using 3-terminal planar microstructure (figure 1*c*) fabricated by conventional photolithography and wet chemical etching [22]. To perform electrical transport measurements samples were placed to helium cryostat with quartz window that is a part of a home-built facility [22] equipped with an electromagnet, Keithley 2634b SourceMeter, Keithley 2182a nanovoltmeter and Agilent E4980A LCR-meter. During the experiments, temperature varied from 4.2 K to 300 K and magnetic field swept up to 1 T.

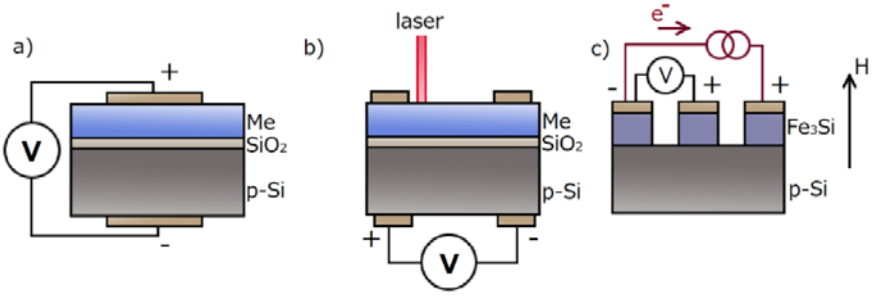


**Figure 1.** Experimental schemes: *a* — Schottky diode for AC and DC transport measurements; *b* — lateral device for measuring lateral photovoltaic effect; *c* — 3-terminal device for measuring spin accumulation.

## 3. Results

### 3.1. Mangetoresistance

Firstly, we will consider AC transport in Mn/$SiO_2$/*p*-Si structure [18,19]. Figure 2 shows magnetic field dependence of $R_{ac}$ (the real part of the impedance) at $V_b$ = 0 and 5 V where $V_b$ is the bias voltage. At zero bias, we observe a giant magnetoresistance effect of about 200% which is typical for MIS structures. However, applying the forward bias drastically change $R_{ac}(H)$ behavior, and magnetoresistance (MR) value reaches $10^5$ %. The results obtained at reverse bias are similar to those for Fe/$SiO_2$/*p*-Si which are presented in [8-10].

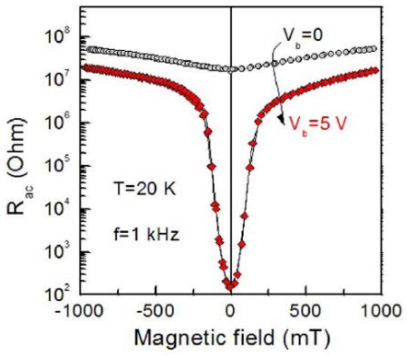


**Figure 2.** Field dependences of $R_{ac}$ of the Mn/$SiO_2$/*p*-Si at $V_b$ = 0 and 5 V, $T$ = 20 K and $f$ = 1 kHz.

DC resistance shows similar behavior, which can be seen from its temperature dependence (figure 3*a*) at $V_b$ = 3.5 V. The MR value is even higher than for ac, and reaches the value of $10^7$ % (figure 3*b*). It can be seen from both ac and dc measurements, that the sharpest increase of MR appears in relatively low magnetic fields ($H$ < 250 mT) at low temperatures below 40 K.

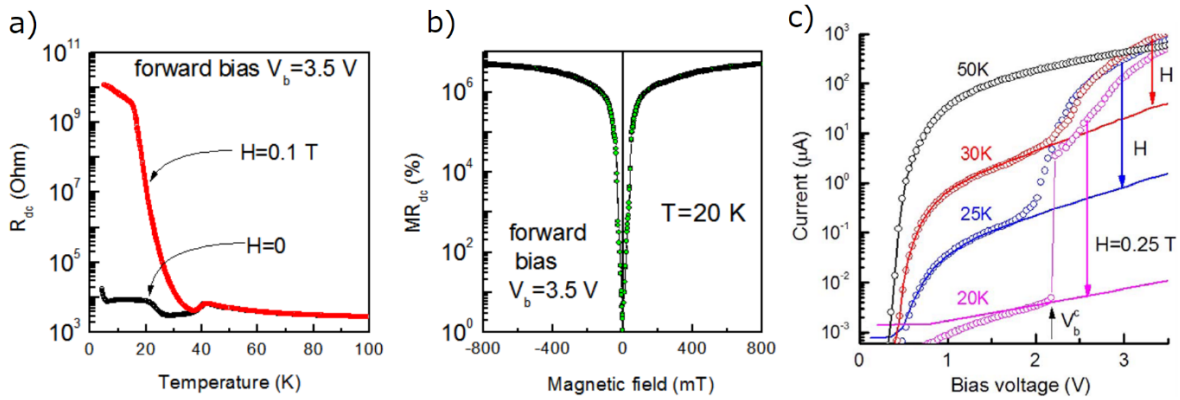


**Figure 3.** Temperature dependence of $R_{dc}$ of the Mn/$SiO_2$/*p*-Si at $V_b$ = 3.5 V, at $H$ = 0 and 0.1 T (*a*) and $MR_{dc}$ as a function of magnetic field at $T$ = 20 K (*b*); *c* — *I*-*V* curves at $H$ = 0 (open circles) and $H$ = 250 mT (solid lines) at different temperatures.

The form of *I*-*V* characteristics has typical form for MIS Shottky diode (figure 3*c*) above 40 K. In low temperature region, current increases drastically when certain threshold $V_b$ is applied. This means that the process of impact ionization takes place, which will be described in the discussion section. Magnetic field suppresses impact ionization as can be seen from the figure 3*c*. It explains the extremely large MR values in this temperature region.

### 3.2. Lateral photovoltaic effect

Lateral photovoltage in Fe/$SiO_2$/*p*-Si showed high sensitivity to a magnetic field [18,19]. Figure 4 shows temperature dependences of lateral photovoltage measured from the substrate as shown in

figure 1*b* at different values of *H*. We defined a relative change of photovoltage in a magnetic field as MV = (PV(*H*)–PV(0))/PV(0). At $T > 30$ K the value of *MV* does not exceed 10-20%. However, at $T < 30$ K much more complicated magnetic field dependence of LPV is observed. Below 30 K *PV* decreases and changes sign near 12 K. The highest MV is observed below 10 K and can exceed $10^3$ % in a field of 700 mT.

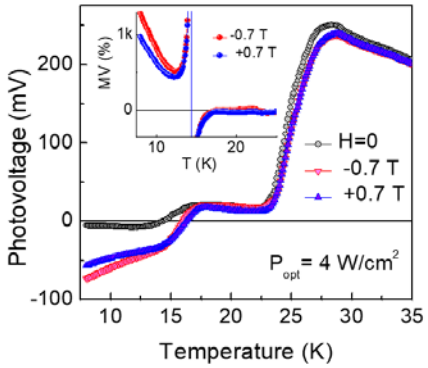


**Figure 4.** LPV as function of temperature at $H = 0$, 0.7 T, –0.7 T and $P = 4$ W/cm$^2$. Inset: *MV* as function of temperature at positive and negative fields.

3.3. Spin accumulation

In order to study the spin-dependent transport, we used the epitaxial $Fe_3Si$/*p*-Si structure as a sample [14]. Firstly, we checked the necessary electrical properties such as film resistivity and Schottky barrier parameters. $Fe_3Si$ shows metallic type of conductivity from 4 to 300 K. The resistivity values in this temperature region vary from 55 μOhm·cm to 120 μOhm·cm which is typical for $Fe_3Si$ films [23,24]. Parameters of the Schottky barrier were extracted from the *I*-*V* characteristic of the prepared diode (figure 5). Ohmic contact on substrate backside was made by indium alloying (right inset on figure 5). The diode shows typical rectifying behavior. By analyzing the direct branch of the *I*-*V* curve via Cheung's method [25], we calculated the barrier height which is $\phi_{Bp} = 0.57$ eV. It is an adequate value for M/S diode based on *p*-Si substrate and can provide spin injection from $Fe_3Si$ to *p*-Si.

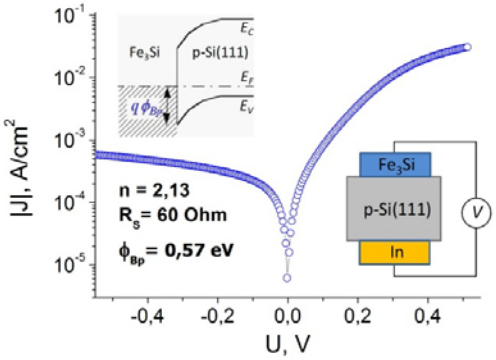


**Figure 5.** *I*-*V* characteristic of the $Fe_3Si$/*p*-Si diode at $T = 295$ K. The right and left insets show schematic illustrations of the experimental scheme for $Fe_3Si$/Si(111) diode and an energy diagram of the Schottky barrier for $Fe_3Si$/*p*-Si(111) structure respectively

Measurements of the spin accumulation were performed by three-terminal Hanle technique [26]. The experimental scheme is shown on figure 1*c*. If the spin injection into a semiconductor is realized, then the external magnetic field perpendicular to a sample plane will cause spin precession and the spin accumulation will be reduced as it distributes deep into the semiconductor. As a result, Δμ(*H*) curve will have the Lorentzian shape. According to [2,27,28] accumulation is correlated with 3-terminal voltage signal as $\Delta V = A_{sp}\Delta\mu/2$, where $A_{sp}$ is efficiency coefficient of spin injection from ferromagnetic metal into semiconductor.

$\Delta V(H_z)$ curves for our structure are presented in figure 6 where $\Delta V$ is 3-terminal voltage signal and $H_z$ is magnetic field oriented perpendicular to the sample plane. Experimental results are in good agreement with Lorentz fitted curves (solid lines) which indicates spin accumulation in silicon.

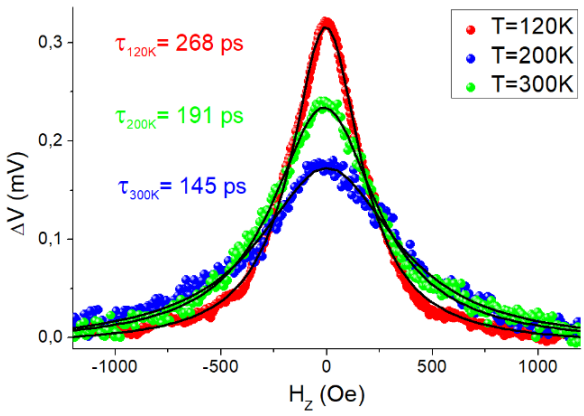


**Figure 6.** Experimental Hanle curves of the $Fe_3Si$/*p*-Si structure at $T$ = 120, 200 and 300 K (circles) and Lorentzian fits (solid lines).

By the analysis of Lorentzian curve, spin lifetime values were calculated form the expression $\tau_s = 1/\omega_L = h/2\pi g_h \mu_B \Delta B$ where $\Delta B$ is half-width of the curve in its half-max, $g_h$ is Lande $g$-factor of holes ($g_h$ = 2). The calculated values are $\tau_{300K}$ = 145 ps, $\tau_{200K}$ = 191 ps and $\tau_{120K}$ = 268 ps. These are typical for silicon.

It is interesting that the spin injection is realized in $Fe_3Si$/*p*-Si despite the absence of an insulating tunnel barrier or narrow Shottky barrier contact, like in other works [15,17]. We believe that the spin dependent tunneling is realized through the interface states which will be discussed in the next section.

## 4. Discussiaon

In the following section we will discuss the possible mechanisms of the magnetic field effect on the transport properties as well as the role, played by the interface states. As was shown in figure 3*c*, the *I-V* curves of the MIS diode below 50 K demonstrate the rapid increase of current when the bias voltage exceeds certain threshold value. It is caused by the shallow acceptor boron states in the bulk of the semiconductor. When the high enough bias voltage is applied, carriers acquire the kinetic energies which exceed the ionization energy of acceptor impurities. It leads to the autocatalytic process of impact ionization [29]. Magnetic field affects impact ionization process via two mechanisms. Firstly, it increases the energy of acceptor levels [8], therefore higher kinetic energy is required to initiate impact ionization and the threshold voltage increases. The second mechanism is Lorenz force. It deflects carriers' trajectories, increasing the probability of inelastic scattering and decreasing kinetic energy, suppressing impact ionization. In order to restore it, the higher bias voltage is required, which also leads to the increase of the threshold voltage.

The same mechanisms are responsible for the magnetic field influence on LPE (figure 4). At $T > 27$ K, Lorenz force deflects trajectories of photoinduced carriers which drift in lateral direction under the action of the space-charge region field $\varepsilon(z)$. It increases the recombination probability and the decrease of LPV is observed. At $T < 27$ K, magnetic field increases the energies of acceptor states $E_a$ including the surface states which are localized at the $SiO_2$/Si interface. $E_a$ levels become higher than the Fermi level for an increasing number of interface states, resulting in the decreasing of acceptor density and consequently decreasing of $\varepsilon(z)$. The relative contribution of the electrons diffusion into the semiconductor increases and the LPV caused by nonequilibrium carriers increases.

As for the spin-dependent transport in the $Fe_3Si$/*p*-Si structure, magnetic field decreases spin accumulation inside the semiconductor via Hanle effect. Considering the fact that our structure doesn't have an insulating tunnel barrier or narrow Shottky barrier contact, we believe that the spin injection is realized by the spin-dependent tunneling through interface states [30]. It is confirmed by the fact that the efficiency of the spin-dependent tunneling depends weakly on temperature and changing the carriers' mobility can increase spin lifetime only by 30-50% [30]. And in our case, it can be increased almost twice (figure 6) [31,32].

## 5. Conclusion

In summary, it is clear that the decisive role in magnetotransport and spin-dependent effects is played by the interface states, which energy can be controlled by a magnetic field in order to manipulate the electric transport. Such states can be also used to replace insulating barriers or Shottky contacts and provide the spin dependent tunneling into a semiconductor.

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