Technical Physics Letters, 2025, Vol. 51, No. 4

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AC magnetoresistive effect in a device based on a silicon-on-insulator structure

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Received October 25, 2024
Revised December 10, 2024
Accepted December 12, 2024

The results of studies of the silicon on insulator (SOI) structure Fe/Si/SiO$_2$/p-Si and the simplest device based on it in the form of a dual Schottky diode are presented. The influence of an external magnetic field is detected. The obtained values of magnetoresistance MR on alternating current are up to 500% at a field of 1.5 T and up to 3500% in a field of 9 T. This effect is explained by the presence of impurity states at the dielectric/semiconductor interface and the process of their recharging. The energies of these states have been determined.

Keywords: magnetoresistance, SOI-structures, Schottky-diode, magnetic field, impurity states.

DOI: 10.61011/TPL.2025.04.61003.20166

Semiconductor structures are one of the main components of modern electronics. They are used widely in the production of various microelectronic devices, such as diodes [1] or transistors [2]. Advances in silicon technology have led to the development of silicon-on-insulator (SOI) structures, which are now used in a wide variety of fields. In addition to microelectronics, they find application in silicon photonics [3] and in the production of biosensors [4]. One important research trend is the study of magnetoresistive effects for SOI structures, which provide opportunities for the production of, e.g., magnetic field sensors [5]. These topics are in the focus of the present study.

An SOI structure and a device in the form of a dual Schottky diode were manufactured for experiments. With this end in view, a substrate with a boron-doped p-Si(100) layer with a resistivity of $18\,\Omega\cdot$cm was cleaned chemically [6] and annealed in ultra-high vacuum (the residual pressure was 10^{-8} Pa) at a temperature of 400 °C for 30 min to remove the natural oxide from the Si surface. The sample was then introduced into a growth chamber for deposition of a polycrystalline Fe film by thermal evaporation. Figure 1, *a* shows the cross section of the structure imaged with a transmission electron microscope (TEM). The final structure consists of a p-Si substrate with a thickness of $350\,\mu$m, a 200-nm-thick buried oxide layer (SiO$_2$), a 100-nm-thick SOI layer, and a 14-nm-thick iron film. It can be seen that the structural layers are fairly smooth and have sharp boundaries with no interdiffusion.

The two-contact method and a Quantum Design Physical Property Measurement System (PPMS-9) were used in experiments. Contacts were deposited onto the Fe film on a sample 3×5 mm in size. The metal film was etched in the center to form two metal contacts on the Si layer surface. The distance between Fe contacts was 3 mm. The area of contact pads was 1 mm^2. The schematic diagram of the device is shown in the inset of Fig. 1, *b*. AC measurements were performed at temperatures of 5–270 K in an external magnetic field up to 9 T using an Agilent E4980A LCR meter within the frequency range extending from 20 Hz to 2 MHz. The magnetic field was perpendicular to the sample plane.

Temperature dependences $R(T)$ of the real part of impedance $Z = R + iX$ revealed a feature in the form of a high-intensity peak below 40 K (Fig. 1, *b*). Under the influence of magnetic field H, this peak shifts toward higher temperatures. The shift is close to 3 K in a magnetic field of 1.5 T.

This feature of impedance or admittance is well known and associated with the delay in recharging of impurity states localized at the dielectric/semiconductor interface [7]. At a certain temperature, Fermi level E_F starts to cross the energy levels of surface states E_s, and AC voltage V_{ac} through the structure modulates the position of E_s relative to E_F, initiating the capture/emission of electrons from interface centers into allowed band E_v (Fig. 2, *a*). A maximum in temperature dependence $R(T)$ forms under the $\omega\langle\tau_0\rangle = 1$ condition, where $\omega = 2\pi f$ is the angular frequency of AC voltage V_{ac} and $\langle\tau_0\rangle$ is the average relaxation time of the process of recharging of interface states. Under the influence of external magnetic field H, the peak shifts toward higher temperatures, since the field affects the energy spectrum of localized states at the interface. The magnetic field shifts the energy levels of interface states toward higher energies (towards the center of the band gap) relative to the edges of semiconductor bands. In this case, the Fermi level crosses the energy levels of interface states at temperatures higher than those determined in zero field [8].

A slight inflection, which indicates the presence of another peak, is also seen at a temperature of approximately 20 K in the peak recorded in the magnetic field. This is attributable to the fact that different localized states

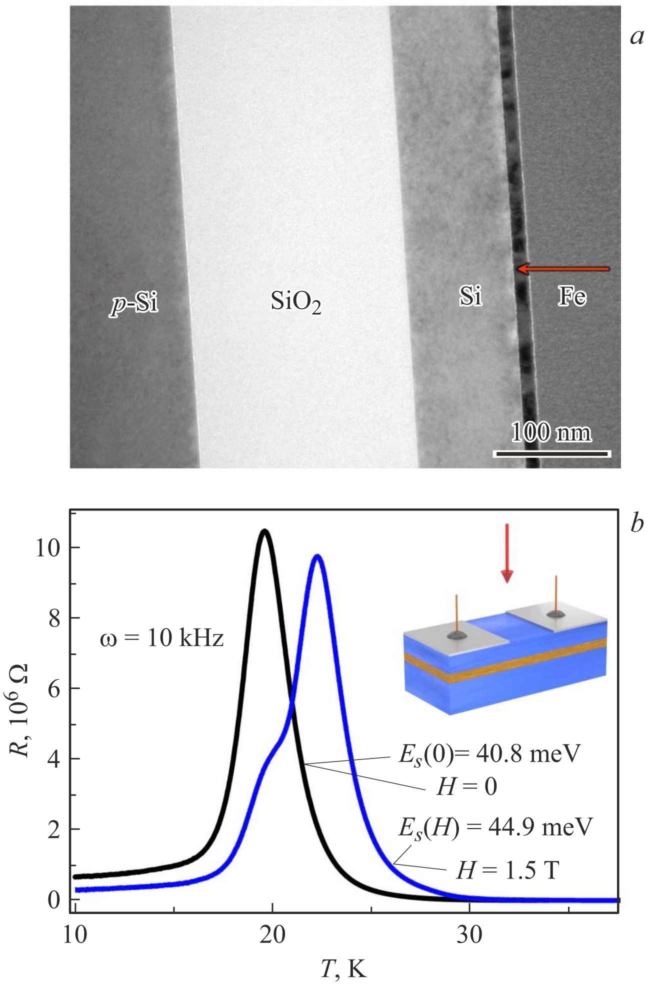

Figure 1. *a* — TEM image of the obtained Fe/Si/SiO_2/*p*-Si structure; *b* — temperature dependence $R(T)$ of the real part of impedance at an alternating current frequency of 10 kHz with zero field and in a field of 1.5 T. The schematic diagram of the device in the form of a dual Schottky diode is shown in the inset.

with different energies and concentrations may exist at the interface. A small difference in level energies may indicate that these levels are of the same nature, but have somewhat different local environments. The emergence of several levels in the magnetic field may also be attributed to Zeeman splitting and/or splitting into lower and upper Hubbard subbands [9].

The energies of impurity states were estimated using the following equation [10]:

$$\ln\omega = \ln(1/\langle\tau_0\rangle) - E_s/(k_B T_p), \qquad (1)$$

where T_p is the temperature of the $R(T)$ peak maximum at frequency ω, $\langle\tau_0\rangle$ is the average relaxation time, and k_B is the Boltzmann constant. The energy was estimated with a linear fit of the experimental dependence of $\ln\omega$ on $1/T_p$ by determining the slope of the fitting line (Fig. 2, *b*).

The obtained energies of impurity states are $E_s(0) = 40.8$ meV for zero magnetic field and $E_s(H) = 44.9$ meV for $H = 1.5$ T. These values agree closely with the boron impurity energy for a *p*-type substrate [11]. The level splitting (ΔE) calculated based on the experimental data is close to 4 meV, while the standard Zeeman splitting is on the order of 0.1 meV for $s = 1/2$ and $H = 1.5$ T. The Zeeman energy was estimated as

$$\Delta E_Z = g\mu_B H J, \qquad (2)$$

where μ_B is the Bohr magneton, g is the Landé factor, and J is the total angular momentum of an electron. The pronounced splitting of the peak in the magnetic field (Fig. 1, *b*) verifies the validity of the mechanism of influence of the magnetic field on the energy spectrum of localized states (anomalous Zeeman effect) that was proposed in our earlier study [12]. The increase in ΔE is probably due to

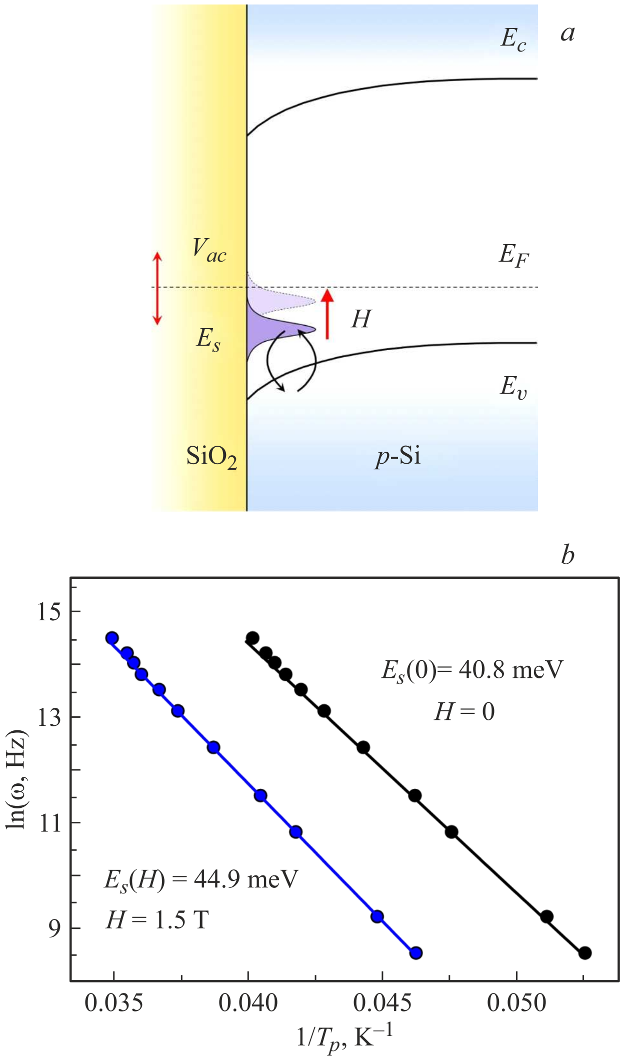

Figure 2. *a* — Schematic representation of the band diagram of the sample. E_F — Fermi level, E_s — level of impurity states, and V_{ac} — applied AC voltage. *b* — Dependences of $\ln\omega$ on reciprocal temperature of the peak maximum $(1/T_p)$ plotted to determine the energy levels of impurity states with zero field and in field $H = 1.5$ T.

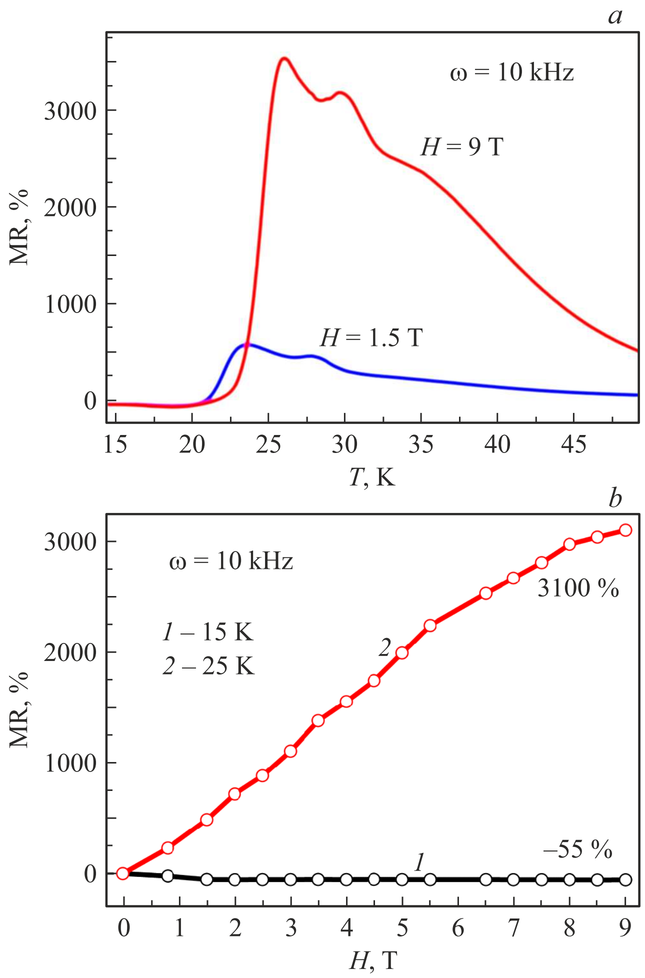

Figure 3. *a* — Temperature dependences of magnetoresistance (MR) at an alternating current frequency of 10 kHz in a field of 1.5 and 9 T; *b* — field dependences of magnetoresistance at temperatures of 15 and 25 K.

the exchange interaction with *d* electrons of iron and the electric field in the fully depleted silicon-on-insulator layer.

Since the magnetic field affects the recharging process, different resistance values are observed in the $R(T)$ dependence at a fixed temperature in an external magnetic field. This provides an opportunity to estimate the values of magnetoresistance (MR):

$$\mathrm{MR} = 100 \cdot \big((R(H) - R(0))/R(0)\big), \qquad (3)$$

where $R(H)$ is the resistance in the magnetic field and $R(0)$ is the resistance in zero field.

The magnetoresistance reaches 500 % in a magnetic field of 1.5 T at an alternating current frequency of 10 kHz. However, if magnetic field $H = 9\,\mathrm{T}$ is applied, the MR increases to 3500 % (Fig. 3, *a*). The relatively high MR values at temperatures above 40 K (i.e., outside the peak region) are likely attributable to the influence of the Lorentz force on the current component perpendicular to the magnetic field. The field dependence of magnetoresistance reveals changes in the curves for 15 and 25 K before and after the peak, respectively (Fig. 3, *b*). At 25 K, MR increases almost linearly with a maximum value of 3100 %, while negative magnetoresistance (as large as 55 %) is observed at 15 K. This is explained by the shift of the peak toward higher temperatures in stronger magnetic fields. Owing to this, the values of resistance *R* in the left wing of the peak decrease (although this reduction is limited to a certain level), and the resistance in the right wind increases linearly.

Thus, a Fe/Si/SiO_2/*p*-Si SOI structure was synthesized, and a simple device in the form of a dual Schottky diode was fabricated based on it. Features in the form of peaks in temperature dependences $R(T)$ of the real part of impedance and their shift toward higher temperatures under the influence of external magnetic field *H* were observed. The emergence of such features and their behavior were attributed to the presence of impurity states at the dielectric/semiconductor interface and the process of their recharging. The energies of impurity states $E_s(0) = 40.8\,\mathrm{meV}$ (in zero magnetic field) and $E_s(H) = 44.9\,\mathrm{meV}$ (in field $H = 1.5\,\mathrm{T}$) were determined. This enables the observation of magnetoresistance values up to 3500 % in field $H = 9\,\mathrm{T}$.

Acknowledgments

The authors wish to thank the Krasnoyarsk Regional Research Equipment Sharing Center of the Federal Research Center „Krasnoyarsk Science Center of the Siberian Branch of the Russian Academy of Sciences“ for providing the equipment for electron microscopy and the investigation of magnetic properties.

Funding

This study was carried out as part of the state research assignment of the Kirensky Institute of Physics.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin