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# Magnetotransport in Si⟨Sb⟩ Delta-Layer after Swift Heavy Ion-Induced Modification

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In the present paper the investigations of the influence of swift heavy ion irradiation on the magnetotransport in the antimony (Sb) $\delta$-layer in silicon are reported. Temperature and magnetic field dependences of the resistance $R(T,B)$ and the Hall coefficient $R_H(T,B)$ in the temperature range of 2 K $< T <$ 300 K and $B \leq 8$ T before and after the 167 MeV $Xe^{+26}$ ion irradiation (ion fluence of $10^8$ cm$^{-2}$) were measured. At the temperatures below 50 K there is observed the transition from the Arrhenius log $R(1/T)$ to a logarithmic $R \approx$–log$(T)$ dependence both before and after the swift heavy ion exposure which confirms the assumption that the carrier transport goes through the $\delta$-layer mainly. Moreover, the transition from the positive to negative magnetoresistance was observed with the temperature decrease that is characteristic of the two-dimensional quantum corrections to the conductivity in the case of weak localization regime. The appropriate Thouless lengths $L_{\mathrm{Th}}(T) \approx A \times T^p$ (where $p$ and $A$ are dependent on the scattering mechanism) indicated their $\approx 25-30\%$ decrease after the swift heavy ion exposure. It was shown that the exponent $p$ values were close to the theoretical one of $p = 1$, confirming the realization of 2D weak localization regime in the carrier transport.

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## 1. Introduction

Sharp and well-controlled dopant distribution profiles in semiconductors (known as $\delta$-layers) are the subject of great interest for fabricating nanoscale electronic devices as well as for the study of carrier transport in low-dimensional structures [1]. In particular, Sb $\delta$-doping of Si by molecular beam epitaxy (MBE) has received much attention in view of their application in such devices as tunnel diodes [2] and heterojunction bipolar transistors [3, 4]. The creation of sharp $n$-type dopant profiles in Si during MBE growth is challenging due to the pronounced surface segregation of the mostly used dopants like Sb, P, and As.

On the other hand, $\delta$-layers are one of the types of 2D electronic systems where it is possible to obtain electron concentrations in a rather wide range, up to the very high values of $\approx 10^{14}$–$10^{15}$ cm$^{-2}$ [5]. However, the electron mobility in the $\delta$-layers is usually very low (compared to this value in heterojunctions) due to the pronounced contribution of the elastic scattering of carriers on the impurity atoms. Meanwhile, this peculiarity creates the appropriate conditions for the observation of quantum interference effects in the $\delta$-layers (weak localization and electron–electron interaction [6–8]). The study of these phenomena, as is known, allows to extract the information about the parameters of pulse relaxation and interaction of electrons (including the case of applied external action).

Thus, the goal of the paper is to study the changes in the 2D carrier transport characteristics in the Si⟨Sb⟩$\delta$-layer due to the SHI exposure induced disordering.

## 2. Experimental procedures

The sample with the $\delta$-Sb layer in Si was fabricated on the 12 Ω cm Si(100) substrate by the solid-source MBE process using the Riber SIVA-21 machine. Epitaxial grown Si was deposited with the help of e-beam evaporator, Sb was deposited from the effusion cell. Growth temperature was controlled by a specially calibrated thermocouple and the IMPAC IS 12 IR pyrometer [9]. The $\delta$-doped layer was formed using the selective doping

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technique described in Ref. [10] and the growth procedure is briefly described below. After standard cleaning of Si substrate (prior to the epitaxial growth) a 100 nm thick Si buffer layer was deposited at 550 °C in order to obtain an atomically flat Si surface. Then the temperature was reduced to 350 °C and a certain amount of Sb (≈ 0.3 ML) was deposited and then capped by a 2 nm thick Si layer at such a low temperature. This allowed to obtain a sharp rise in the doping concentration. In order to obtain a sharp drop in the Sb bulk concentration (and thus complete the $\delta$-layer formation) the growth was interrupted, the temperature was raised up to 535 °C and a 75 nm thick Si capping layer was deposited at this temperature. Due to the very high value of segregation ratio at 535 °C [10], the Sb incorporation is negligible that allowed obtaining the sharp decrease in the Sb bulk concentration.

Temperature and magnetic field dependences of the electrical resistance $R(T,B)$ and the Hall coefficient $R_H(T,B)$ in the temperature range of 2 K $< T <$ 300 K and the magnetic induction $B \leq 8$ T before and after the SHI irradiation were determined. After the initial electric characterization, the samples were irradiated by 167 MeV $Xe^{26+}$ ions with the fluence $D = 10^8$ ion/cm$^2$ at room temperature at the IC-100 cyclotron of FLNR JINR, Dubna (Russia). The ion beam homogeneity of 5% on the irradiating specimen surface was obtained using the beam scanning in horizontal and vertical directions. The average Xe ion flux was about $5 \times 10^7$ cm$^{-2}$ s$^{-1}$ thus excluding any target heating.

Two current contacts (1-2), two Hall contacts (3-4), and four potential probes (5-8) were prepared using the lithography technique as shown in the inset 1 in Fig. 1. The end areas of these contacts were covered by the metallic films for ultrasonic soldering of copper microwires by indium. The ohmic behaviour of the contacts was controlled by measurements of the current–voltage ($I$–$V$) characteristics. The $I$–$V$ characteristics were strictly linear in the entire range of temperatures under study. In order to perform the electrical measurements, the sample was placed into a special CHNF system (Cryogenics Ltd., UK) based on a closed cycle refrigerator using a special measurement probe. The CHNF system made it possible to measure the $I$–$V$ characteristics, electrical resistance, and Hall effect in the temperature range of 1.8 K $< T <$ 310 K and in the magnetic fields up to 8 T. Gallium-arsenide diodes were used as thermometers that were calibrated to an accuracy of 0.5 mK in the temperature range of 1.5–20 K and 0.001 K for higher temperatures. The used temperature controller (Lakeshore, model 331) made it possible to stabilize the temperature with an accuracy of 0.005 K during the course of the magnetic field scanning or during measurements of the $I$–$V$ characteristics. The used devices for voltage/current measurements made it possible to determine the electrical resistance and measure the Hall effect with an accuracy up to 0.1%.

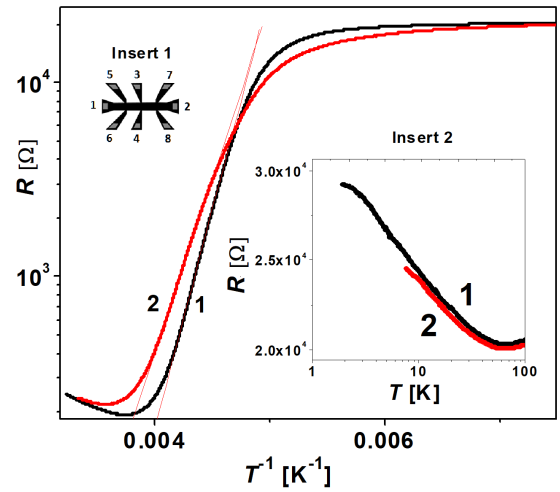


Fig. 1. Arrhenius plot of the resistance $R$ before (1) and after (2) SHI irradiation. Inset 1: photo of top view of the sample with ohmic probes. Inset 2: $R(T)$ with $T$ in the logarithmic scale.

## 3. Results and discussion

Our studies have shown that due to the multiple layers of the sample (substrate, two lightly-doped epitaxial layers, heavy-doped $\delta$-layer), the current distribution in the sample is rather complicated. This impedes the characterization of carrier transport in the investigated sample on the basis of the $R(T)$ dependences.

In order to identify the mechanisms of carrier transport through the $\delta$-layer before and after the SHI irradiation we have carried out the detailed analysis of the magnetotransport properties of the sample at temperatures below 25 K, when the electrons in the silicon substrate and in the lightly doped epitaxial Si layers are frozen. The selected temperature range can be easily detected representing the $R(T)$ dependences in different scales, namely, the Arrhenius $\log R(1/T)$, the Mott $\log R((1/T)^n)$ (with $n < 1$), logarithmic $R \approx \pm \log(T)$, etc.

The linearization of the high-temperature part of the Arrhenius plot $\log R(1/T)$ (Fig. 1) indicates that the carrier transport at 200 K predominantly goes through the lightly doped silicon (substrate and epilayers). Thus, as can be seen from Table I, in this temperature range the conductivity activation energy $E_\delta$ is reduced after irradiation due to the introduction of lattice defects into the substrate (which may lead to the appearance of localized tail states on the edges of the allowed bands).

TABLE I

Some characteristics of the sample before and after SHI exposure.

| $D$ [ion/cm$^2$] | $E_\sigma$ [eV] | $L_{\mathrm{Th}}(T = 25$ K) [nm] | $p$ in Eq. (2) |
|---|---|---|---|
| 0 | 0.45 | 9.0 | 0.78 |
| $10^8$ | 0.36 | 6.2 | 1.12 |

Cooling the sample below 150 K causes freezing of charge carriers in a lightly-doped silicon so that the increase of electrical resistance in Fig. 1 slows down sharply ($E_\sigma$ values sharply decrease, see Table I) with the temperature lowering. In the literature, the presence of a variable conductivity activation energy is often attributed to the hopping mechanism of carrier transport [11], but an attempt of the linearization of $R(T)$ curves in the Mott scale did not lead to success. At the same time, the representation of $R(T)$ curve in a logarithmic scale $R \approx -\log(T)$ indicates the close-to-linear dependence at low temperatures (curves 1 and 2 in inset 2 in Fig. 1). This linear dependence in a range of 3 K $< T <$ 12 K and the presence of the minimum on the $R \approx -\log(T)$ curve at 15–16 K indicates the prevailing of carrier transport through the $\delta$-layer below 25 K with the features of the 2D weak localization regime. Note that the transition from the positive (above 100 K) to the negative (below 50 K) magnetoresistance (MR) effect with the decreasing temperature (Fig. 2) also evidences the realization of the 2D quantum corrections to the conductivity mechanism of carrier transport going through the $\delta$-layer.

As can be seen from Figs. 1 and 2, the irradiation has led to an increase of $R$ as well as a decrease in negative contributions to the MR modulus at low temperatures while positive contribution (due to the Lorentz MR in the Si substrate/epilayers) at $T >$ 150 K remains unchanged.

In addition, it was found that the saturation of $R(T)$ curves in inset 2 (Fig. 1) at the lowest temperatures indicates the possibility of approaching the so-called minimum metallic conductivity limit, or simply transition to the residual resistance of the metallic-like $\delta$-layer.

As is well known [6–8], in the case of 2D weak localization, magnetoresistance of the $\delta$-layer at different temperatures can be expressed by the following equation:

$$MR = \frac{\Delta R_{sqr}(B,T)}{R_{sqr}(0,T)} = -R_{sqr}(0,T)\frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{B_i}{B}\right)+\ln\left(\frac{B_i}{B}\right)\right], \quad (1)$$

where $R_{sqr}$ is the sheet resistance, $B$ — magnetic induction, $\psi$ — digamma function, $B_i = \hbar/(4eD_d\tau_{\mathrm{Th}}) = \hbar/(4eL_{\mathrm{Th}})$, $D_d$ is the diffusion coefficient of carriers, $\tau_{\mathrm{Th}}$ — the time period over which a state looses the information about its phase, $L_{\mathrm{Th}}$ is the Thouless length.

The fitting procedure using this formula requires the transition from the sample resistance $R(T)$ to the sheet resistance $R_{sqr}(T) = R(T)W/L$, where $W$ is the conductive channel width and $L$ is the distance between the potential probes. In our sample the $W/L$ ratio is $\approx 0.32$.

The approximation of the experimental $R(T,B)$ dependence in Figs. 1 and 2 by the relation (1) has allowed to determine the temperature dependence of the Thouless length $L_{\mathrm{Th}}(T)$ in the $\delta$-layer before and after the irradiation (Fig. 3). Fitting was carried out in the temperature range of 2–25 K and the magnetic fields up to 1 T with only one adjustable parameter $B_i$. According to the theory [8-10], the $L_{\mathrm{Th}}(T)$ has a form of the power

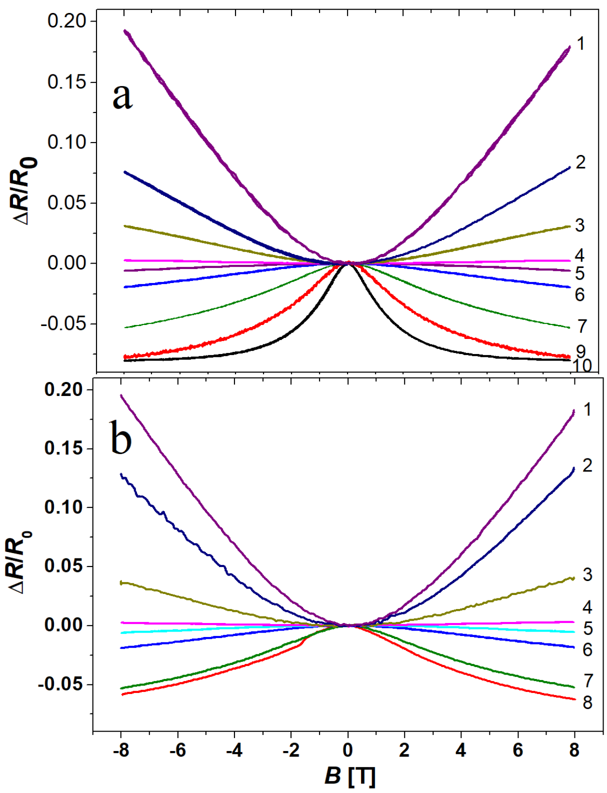


Fig. 2. Magnetoresistance of the sample at different temperatures before (a) and after (b) SHI exposure at different temperatures: 1 — 300 K, 2 — 200 K, 3 — 150 K, 4 — 100 K, 5 — 50 K, 6 — 25 K, 7 — 10 K, 8 — 8 K, 9 — 5 K, 10 — 2 K.

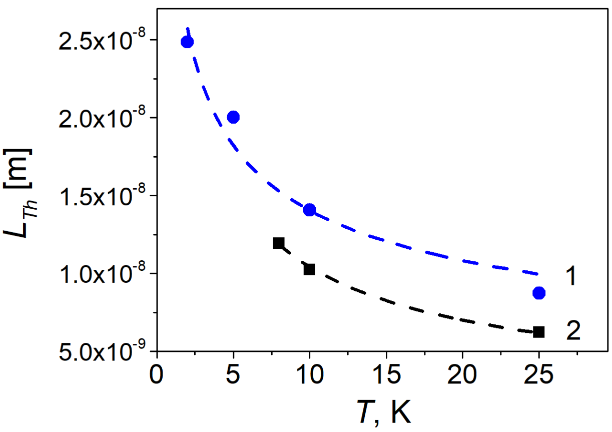


Fig. 3. Temperature dependence of the Thouless length before (1) and after (2) SHI exposure.

function

$$L_{\mathrm{Th}} \approx AT^{-p/2}, \quad (2)$$

where $A$ and $p$ are the constants that depend on the scattering mechanism. As can be seen from the dotted lines in Fig. 3 and also from Table I, the best agreement with the experimental $L_{\mathrm{Th}}(T)$ dependences was obtained for

$p \approx 0.78$ for a virgin sample and for $p \approx 1.12$ after the SHI irradiation. These values are close to the theoretical value of $p = 1$ which was obtained in [6–8] for 2D quantum corrections to conductivity in the case of weak localization excluding electron–electron interaction.

The latter is also evidenced by the values of the parameter $k = (\Delta R_H(B)/R_H(0))/(\Delta R/R_0)$ which characterizes the relative changes of the Hall coefficient and MR due to the impact of temperature and magnetic field. The obtained $k$ ratios were between 1.3 and 2.1 at the temperatures below 10 K, being close to the theoretical value of $k$, which equals two [6–8]. Deviation of $k$ from the theoretical value is probably indicative of the need for taking into account the electron–electron interaction in the 2D quantum corrections regime to the conductivity of the Si⟨Sb⟩$\delta$-layer.

## 4. Conclusions

Electron transport in the Si⟨Sb⟩$\delta$-layer grown by MBE was studied in detail at the temperatures lower than 25 K and in the magnetic fields $B$ up to 8 T before and after SHI (Xe, 167 MeV) irradiation to the fluence $10^8$ ion/cm$^2$. It was shown that the low temperature conductivity in the $\delta$-layer is described by the theory of 2D quantum corrections to conductivity in the case of weak localization excluding electron–electron interaction. In so doing, SHI irradiation results in a decrease of the Thouless length from 90 to 62 nm and an increase of the parameter $p$ from 0.78 to 1.12.

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