INFLUENCE OF SWIFT HEAVY IONS ON ELECTRIC AND MAGNETOTRANSPORT

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In the present paper we report about the influence of Swift Heavy Ions (SHI) irradiation on the electric and magnetotransport in the antimony (*Sb*) δ-layer in silicon. Temperature and magnetic field dependences of the sheet resistance *R(T, B)* in the temperature range $2 < T < 300$ K and magnetic field induction *B* up to *8 T* before and after the 167 MeV Xe^{+26} ion irradiation with ion fluences since $1{\times}10^8$ cm^{-2} to $5{\times}10^{10}$ cm^{-2} were measured. It was detected strong role of quantum corrections on low-temperature *R(T, B).*

Keywords: delta-layers; quantum corrections; silicon; antimony; swift heavy ion irradiation.

Introduction

Dopant distribution profiles in semiconductors (known as δ-layers) are the subject of interest for fabricating nanoscale electronic devices as well as for the study of low-temperature carrier transport in low-dimensional structures [1]. Sb δ-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 such dopants like Sb, P and As.

Besides, δ-layers are one of the mostly typical 2D electronic systems, where it is possible to obtain the electron concentrations in a rather wide range, up to the very high values of ~ 10^{14} – 10^{15} cm^{-2} [5]. But, the electron mobility in δ-layers is usually very low, in comparison with heterojunctions, due to the pronounced contribution of the elastic scattering of carriers on the impurity atoms. Meanwhile, this peculiarity of δ-layers creates the appropriate conditions for the observation of 2D quantum interference corrections (QIC), which take into account weak localization and electron-electron interaction effects [6-8]. These phenomena, as is known, allow to extract the information about the changes in Thouless length, pulse relaxation and electron interaction coefficient due to external influences.

So, the goal of the paper is to study the changes in 2D carrier transport characteristics in the *Si<Sb>* δ-layer due to disordering induced by SHI exposure.

Experimental procedures

The sample with δ-Sb layer two epitaxial *Si* layers was fabricated on 12 Ω·cm Si (100) substrate by solid-source MBE process on the Riber SIVA-21 machine. Epitaxial *Si* was produced using e-beam evaporator, and *Sb* was deposited from the effusion cell. Growth temperature was controlled by specially calibrated thermocouple and the IMPAC IS 12 IR pyrometer [9]. The δ-doped layer was formed using the selective doping technique described in Ref. [10] and the growth procedure is described in brief below. After standard cleaning of Si substrate (prior to epitaxial growth) a 100 nm thick Si buffer layer was deposited at 550 ºC in order to obtain an atomically flat Si surface. Then temperature was dropped down to 350 ºC 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 us to obtain a sharp rise in doping concentration. In order to obtain a sharp drop in Sb bulk concentration (and thus complete the δ-layer formation) the growth was interrupted; temperature was raised up to 535 ºC and a 75 nm thick Si capping layer was deposited at this temperature. Due to the very high value of segregation ratio at 535 ºC [10], the Sb incorporation is negligible that allowed obtaining the sharp decrease in Sb bulk concentration.

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

Two current contacts and four potential probes were prepared using lithography technique (see Insert in Fig. 1). The end, more wide areas of these contacts were covered with the metallic films for ultrasonic soldering of copper microwires by indium. The ohmic behavior of the contacts was controlled by measuring the I–V characteristics, which were strictly linear in the entire range of temperatures. To perform the electrical measurements, the structure was placed into a special measurement probe which was inserted into low-temperature measuring system (Cryogenics Ltd., UK) with superconducting solenoid based on a closed cycle refrigerator. This system allowed measuring the electrical resistance in the temperature range of 2 K < T < 310 K and in the magnetic fields B up to 8 T. GaAs diodes were used as thermometers that were calibrated with an accuracy of 0.5 mK in the temperature range of 1.5-20 K and with 0.001 K for higher temperatures. The temperature controller (Lakeshore, model 331) made it possible to stabilize the temperature with an accuracy of 0.005 K during scanning of B or sweeping-out of I–V characteristics. The electrical resistance was detected with an accuracy to 0.1%.

Results and Discussion

Our previous studies [11] have shown that due to the multiple layers in the studied structure $Si_{epy}/\delta/Si_{epy}/Si_{sub}$ (two lightly-doped epitaxial Si_{epy} layers, heavy-doped δ-layer and substrate Si_{sub}), the current distribution by the sample in the wide range of temperatures is rather complicated. This is reflected in the specific shape of temperature dependences of

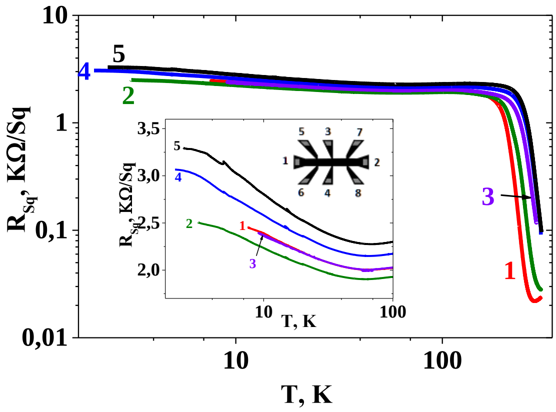

Fig. 1. Resistance $R_{Sq}(T)$ before (1) and after SHI irradiation with different fluences D: $1\cdot10^8$ (2), $1\cdot10^9$ (3), $1\cdot10^{10}$ (4) and $5\cdot10^{10}$ ion/cm^2 (5). Insert: $R_{Sq}(\mathrm{Lg}T)$ at T < 100 K and configuration of electric contacts in the structure under study

sheet resistance $R_{Sq}(T)$ shown in Fig. 1 in double logarithmic coordinates. As is seen, at T > 200 K current is flowing through Si substrate, but below 25 K, when carriers in substrate and two epy-layers are freezed-out, all the current percolates only through thin δ-layer. Note that at T > 200 K for all D values $R_{Sq}(T)$ curves are linearized in Arrhenius scale with the slopes close to energy gap for Si substrate. We can see also, that below 25 K $R_{Sq}(T)$ curves are linearized in semi-log coordinates that indicates the presence of 2D QIC contribution into Droude conductance. The tending of $R_{Sq}(lgT)$ to saturation at lowering the temperature can be attributed to minimal metallic conductivity of δ-layer.

Such complicated behaviour of carrier transport in the structure under study impedes its characterization on the basis of the only $R_{Sq}(T)$ dependences. So, to identify the main contributions into QIC just in the δ-layer before and after SHI irradiation, we have carried out the detailed analysis of the $R_{Sq}(B)$ at temperatures below 25 K in wide range of magnetic fields B.

As is seen from Fig. 1, the irradiation has led to a decrease of $R_{Sq}(T)$ at the lowest D used and then its increase with the D growth. Moreover, we observe a decrease in negative contributions to the relative magnetoresistance (MR) modulo at low temperatures, while positive contribution (due to the Lorentz MR in Si substrate/epilayers) at T > 150 K did not become prevailed. In accordance with [6-8], for 2D weak localization, magnetoresistance of δ-layer at different temperatures can be expressed by the following equation:

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

where ψ is digamma function, $B_i = \hbar/(4eD_d\cdot\tau_{Th}) = \hbar/(4eL_{Th})$, D_d - diffusion coefficient for carriers, τ_{Th} - the phase breaking time, L_{Th} - Thouless length.

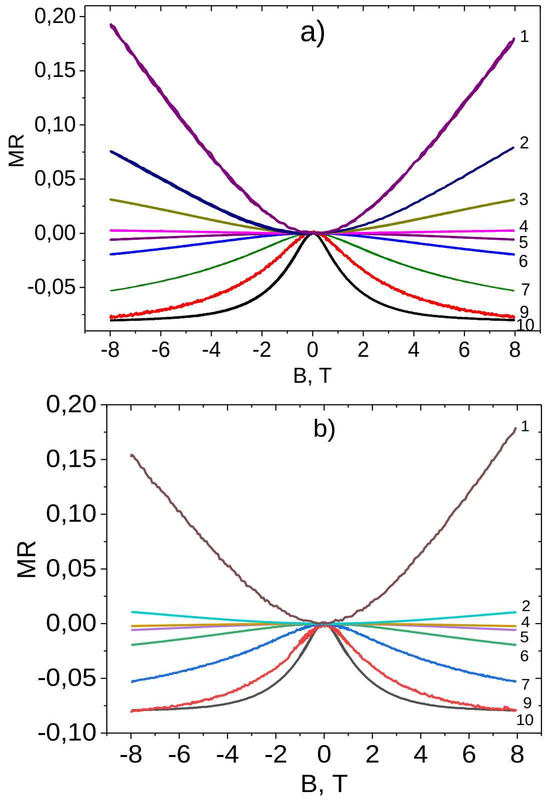

Fig. 2. The examples of $MR(B)$ curves of the studied structure at some temperatures before (a) and after SHI irradiation with fluence $D = 5\cdot10^{10}$ ion/cm^2 (b): 1 – 300 K; 2 – 200 K; 3 – 150 K; 4 - 100K; 5 – 50 K; 6 - 25 K; 7 – 10 K; 8 - 8 K; 9 – 5 K; 10 - 2K

Fitting $MR(B)$ curves was carried out with the only adjustable parameter B_i in the temperature range of 2 - 25 K and at low magnetic fields up to 1 T where negative magnetoresistance was observed. The result of calculations is presented in Table 1.

Table 1. Some characteristics of the δ-layer before and after SHI exposure

D, ion/cm^2	$L_{Th}(T = 10\ K)$, nm	p
0	10.3	0.8
$1\cdot10^8$	14.1	0.9
$1\cdot10^{10}$	8.5	1.0
$5\cdot10^{10}$	5.2	1.4

We can see that the values of Thouless length for T = 10 K and their selves curves $L_{Th}(D)$ come through the maximum.

According to the theory [8-10], the $L_{Th}(T)$ has the form of a power function:

$$L_{Th} \approx A \cdot T^{-p/2} \quad (1)$$

where A and p are constants that depend on the scattering mechanism.

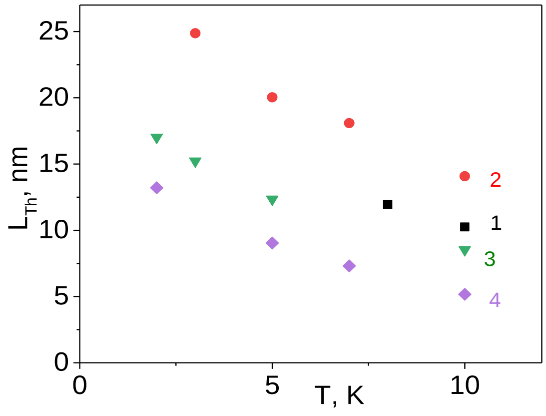

Fig. 3. Temperature dependences of the Thouless length $L_{Th}(T)$ before (1) and after SHI irradiation with fluences D: $1 \cdot 10^8$ (2), $1 \cdot 10^8$ (3) and $5 \cdot 10^{10}$ ion/cm^2 (5)

The obtained values were close to the theoretical value of $p = 1$, which was explained in [6-8] by 2D QIC to Droude conductivity for the case of weak localization where phonon breaking phase of interfering electrons was predominant.

Conclusions

Electron transport in *Si<Sb>* δ-layer grown by MBE process was studied in detail at temperatures lower than 15 *K* and in magnetic fields *B* up to 8 *T* before and after SHI irradiation by 167 MeV Xe^{+26} ions with ion fluences between 1×10^8 cm^{-2} and 5×10^{10} cm^{-2}. It was shown that the low temperature carrier transport through δ-layer is described by the model of two-dimensional quantum corrections to Droude conductivity for the case of weak localization when phonon mechanism of phase breaking of interfering electrons is prevailed. In so doing, SHI irradiation as a whole result in decrease of Thouless length from 14.08 to 5.17 nm and increase of the parameter p in Eq. (1) from 0.78 to 1.4.

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