LOW TEMPERATURE MAGNETORESISTANCE IN SILICON DOPED BY ANTIMONY

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I. INTRODUCTION

Magnetoresistance and magnetotransport in silicon and silicon-based nanostructures has great impact on the development of silicon spintronics and quantum information processing [1,2]. This is due to the importance of silicon technology and by the non-triviality of spin-dependent processes in silicon doped with various impurities. Within this framework, the investigations of the non-linear electrical effects are also relevant. Their implementation along with the spin dependent processes can pave the way to a novel energy efficient information processing devices based on silicon technology. In Refs. [3,4] authors investigated low temperatures non-linear I-V curves in silicon doped by antimony. It was shown that, with the temperatures decrease, the crossover from spin-dependent electron hopping (T = 5-20 K) to the activation mechanism (T = 1.9-4 K) occurs. During this, with an increase in the current density, a region of negative differential resistance arises [3,4].

In this contribution, the magnetoresistance (MR) of Si doped by Sb with the concentration of $N_d=10^{18}$ cm^{-3} and temperature T = 2 K within the current range 0.015 – 0.048 A/cm^2 in magnetic field up to 8 T is considered. Samples were grown by Czochralski method.

II. RESULTS AND DISCUSSION

The MR was determined from measured I-V curves at T = 2 K and *B* in the range of 0 – 8 T. Such a procedure allows determining the MR and various bias currents. It was obtained that, at $0.0015<j<0.034$ A/cm^2 the MR is positive (PMR), whereas at $j>0.041$ A/cm^2 the MR is negative (NMR). In the intermediate current region, $0.034<j<0.041$ A/cm^2 we obtained a series of crossovers from PMR to NMR with the *B* increase. In the latter case, with an increase in the current density, the magnitude of the magnetic field induction at which the transition to the NMR occurs decreases.

System under consideration is characterized by the processes of localization of the injected electrons on the neutral states D^0 of Sb and by the nucleation of negatively charged D^- states in the region of relatively small currents [3,4]. The concentration of D^- states is up to (1-3)10^{17} cm^{-3} [4]. In addition, this region is characterized by the drop of the differential resistance (DR) from 300 to 10-20 Ω cm and small time of momentum relaxation, 3-5 fs. With the increase of the current density the delocalization of the D^- states occurs. This process is accompanied by further decrease of the DR down to a few of Ω cm and increase of the momentum relaxation time up to 10-15 fs and greater.

Taking into account the general trend of transition from PMR to NMR with an increase in current density, we associate the results obtained with the manifestation of weak localization (WL), the action of a magnetic field on it, which is accompanied by competing spin-dependent processes. The dephasing in WL is determined by inelastic processes of scattering of conduction electrons on phonons, D^- states, as well as on paramagnetic antimony impurities with a mutual spin reversal. Inelastic scattering on D^- states is associated with the process of their ionization. The energy of the conduction electrons is about 1.3-5 meV, depending on their concentration, and the binding energy of the D^- state is 1.48 meV. This leads to the process of ionization of D^- states due to an electron impact. Estimates of the dephasing time of the conduction electrons are carried out. As the results showed, the main contribution in this case is made by the processes of ionization of D^- states and scattering on neutral impurities with a mutual spin reversal. The dephasing time varies in a wide range (τ_φ =4 10^{-14}-10^{-11} s) depending on the energy of the conduction electrons.

The MR related to WL in the presence of the spin orbit interaction (SOI) demonstrates peculiar properties. The interference additive to WL remaining after the spin flip increases the conductivity. The final sign of the correction depends on which spin state gives the greater contribution, singlet or triplet. The intensity of spin-orbit scattering strongly depends on the atomic weight of the impurity. The effect of the spin-orbit interaction is stronger in materials containing heavy elements. In the case of the Si:Sb system, Sb atoms induce SOI in silicon with a constant equal to 0.3 meV.

In the case of spin-orbit scattering on impurity atoms, the dependence of conductivity on the magnetic field is significantly different for singlet and triplet spin states. In a weak magnetic field, the main role is played by the singlet contribution, which has the opposite sign compared to WL in a magnetic field, which gives PMR. As the magnetic field increases and the saturation of the field dependence of the singlet component, the role of the triplet contribution increases, which leads to the appearance of a maximum in the PMR first, and then the NMR.

Estimations of the time of spin orbit scattering $\tau_{so} = \tau\,(g/\delta g)^2$ depending on the momentum relaxation time τ have been performed. Here g is the g -factor of a conduction electron, δg is the variation of g-factor due to SOI. According to the known results for Si:Sb in the nearest range of the metal to insulator crossover $\delta g \approx 3\ 10^{-2}$ [5]. The value of τ varies in a wide range, 2-10 fs [4]. Accordingly, the time of spin orbit scattering is $\tau_{so} = 2\ 10^{-12} - 10^{-11}$ s.

Calculations of the MR were performed within the model of WL for 3D samples considering different scattering mechanisms. Theory of WL was developed by many authors. The main results for 3D case were obtained by Kawabata [6]. He deduced the main equation for the 3D case. In the present work we apply the model [7] in which WL includes mechanisms of scattering on magnetic impurities, spin-flip scattering due to SOI, inelastic scattering.

As a result, the following patterns of MR manifestation in Si:Sb were established. In the region of small currents, the singlet contribution, which has the opposite sign compared to WL in a magnetic field, plays the main role. In this case, the interference contribution to the conductivity is positive. Sometimes this is called anti-localization. This leads to a positive magnetoresistance. In this region of currents, PMR occurs when the spin-orbit scattering time is less than the dephasing time, i.e., $\tau_{so} << \tau_\varphi$. In the region of intermediate current densities, the spin - orbit scattering time increases, and as the magnetic field induction increases and the field dependence of the singlet contribution saturates, the role of the triplet contribution increases, which leads to the appearance of a maximum in the PMR first, and then the NMR. In its pure form, NMR occurs at large spin-orbit scattering times, when this process is suppressed by other scattering mechanisms. Since WL is dominated by MR, which occurs due to a dephasing of coherent backscattering, the magnetic field gives an additional phase difference in the interference of electrons. Its appearance destroys coherence and leads to an increase in conductivity. Experimentally, this phenomenon was observed in the form of an NMR. In other words, the magnetic field destroys the interference additive to the conductivity and thus suppresses WL. This is due to the destruction of the coherence of the conjugated electron waves, since the magnetic field introduces a phase difference into the scattering amplitude and thereby reduces the probability of localization. As a result, the NMR manifests.

III. CONCLUSIONS

The MR of antimony-doped silicon was studied at an impurity concentration of 10^{18} cm^{-3} and a temperature of 2 K. It was shown that at low current densities, the manifestation of positive MR is due to the prevailing contribution of spin-orbit scattering. At increased current densities, the manifestation of negative MR is associated with the suppression of a weak localization by a magnetic field. At intermediate current densities, the manifestation of crossovers from positive to negative MR is associated with the competition of spin-orbit scattering and inelastic scattering, which causes a dephasing of interfering electrons.

REFERENCES

[1] R. Jansen, "Silicon spintronics" Nature Mater., Vol. 11, pp. 400–408, 2012.

[2] T. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, J.L. O'Brien "Quantum computers" Nature, Vol. 464, pp.45–53, 2010.

[3] A.L. Danilyuk, A.G. Trafimenko, A.K. Fedotov, I.A. Svito, and S.L. Prischepa, "Negative Differential Resistance in n-Type Noncompensated Silicon at Low Temperature" Appl. Phys. Letters, Vol. 109, p.222104, 2016.

[4] A.L. Danilyuk, S.L. Prischepa, A.G Trafimenko, A.K. Fedotov, I.A. Svito, N. Kargin, "Low temperature injected-caused charge carrier instability in n-type silicon below insulator-to-metal transition" *J. Phys.: Condens. Matter,* Vol.32, p. 225702, 2020.

[5] V. Zarifis, T.G. Castner, "ESR linewidth behavior for barely metallic n-type silicon" Phys. Rev. B, Vol. 35, pp. 6198-6201, 1987.

[6] A. Kawabata, "Theory of Negative magnetoresistance in three-dimensional systems" Solid State Communications, Vol. 34, pp.431-432, 1980.

[7] D.V. Baxter, R. Richter, M. L. Trudeau, R.W. Cochrane, J.O. Strom-Olsen, "Fitting to magnetoresistance under weak localization in three dimensions" Journal de Physique, Vol. 50, pp. 1673-1688, 1989.