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Negative magnetoresistance of heavily doped silicon *p-n* junction

V.L. Borblik[1*], I.A. Rudnev[2,3], Yu.M. Shwarts[1], M.M. Shwarts[1]
[1]*V. Lashkaryov Institute of Semiconductor Physics, 41, prospect Nauky, 03028 Kyiv, Ukraine*
Phone: +38(044)5256292, fax: +38(044)5257463
[2]*National Research Nuclear University "MEPI", Moscow, Russia*
[3]*International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw, Poland*
[*]*Corresponding author e-mail: borblik@isp.kiev.ua*

Abstract. At the liquid helium temperature and under application of magnetic fields up to 9.4 T, a voltage drop across a silicon diode with metallic conductivity of the emitter and base has been measured under passing a constant forward current through the diode. Observed magnetoresistance of the diode is proved as a whole to be extremely small, negative at low fields and changing its sign when the field increases. In the positive region of the diode magnetoresistance, its field dependence is quadratic at first and then becomes close to the linear one. With increase in the current through the diode, the negative component of the diode magnetoresistance decreases, and the smaller its value, the more extended is the quadratic section and the shorter is the linear one. The results are interpreted as caused by hopping conduction over a system of electron "lakes" in the region of *p-n* junction.

Keywords: junction diode, silicon, low temperatures, hopping conduction, magnetoresistance.

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1. Introduction

Investigation of negative magnetoresistance (NMR) of semiconductors doped with nonmagnetic impurities has already a half-century history. It is observed at low temperatures in a large number of semiconductor materials at both sides of metal-insulator transition and realized in semiconductors of both *n*- and *p*-type. In all these cases, localization effects are responsible for NMR – magnetic field moderates them increasing thereby conductivity of the system.

As for particularly silicon, experimental results for it are distinguished by sufficient variety. In the vicinity of metal-insulator transition, the magnetoresistance of *p*-Si is always positive both in the metallic region [1, 2] and dielectric one [3]. In *n*-Si, the magnetoresistance is positive in the region of hopping conduction and negative in the metallic one where, however, it becomes positive again with growth of the magnetic field [1, 3-7]. Deep into insulator region, the giant NMR (of the order of 100%) [8] is observed both in *n*-type and *p*-type silicon (at weak compensation).

Because the magnetoresistance in the metallic region is always much lower than that in the dielectric one, we have investigated (in attempt to reduce the sensitivity of the diodes used for measuring at low temperatures to magnetic field) the influence of magnetic field on the resistance of silicon diodes, both the emitter and base of which were doped up to metallic conductivity. The resistance of these diodes is defined completely by the resistance of *p-n* junction. Their current-voltage characteristics measured by us previously in absence of magnetic field [9, 10] demonstrate predominance of the tunnel current at low temperatures (over certain localized states). Its temperature dependence is well described by the Mott law, which is indicative of hopping nature inherent to the current transfer through the *p-n* junction region. This agrees with the commonly accepted viewpoint on nature of the excess tunnel current in the heavily doped diodes.

However, it was not quite clearly what hops one has to have in view: the hops via the impurity atoms or the hops via the electron "lakes". The point is that the investigated diodes have been produced by opposing diffusion of boron and phosphorus and, consequently, they have a sufficient compensation region. Furthermore, these phenomena are observed at the applied voltages of the order of E_g / e (where E_g is the

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band gap and e is the electron charge) i.e. when the diode is in the state of almost flat band. Since all shallow impurities are ionized in this case, it has been supposed in papers [9, 10] that electron hops take place just via the system of electron "lakes" which are formed (in accordance with [11]) in heavily doped and highly compensated semiconductors. So, investigation of the influence of magnetic field on such a diode means investigation of the influence of magnetic field on this specific hopping current, which allows us to define its nature more exactly.

The results of measurements (at $T = 4.2$ K) of the voltage drop U across the diode under passing through it of a number of fixed currents I are shown in Fig. 1 as a function of magnetic induction B. The measurements have been made for the fields up to 9.4 T. As seen from Fig. 1, the magnitude of the voltage drop across the diode depends on the current value and is equal approximately to 1.08 V at the current of 1 μA, to 1.10 V at the current of 10 μA, and to 1.11 V at the current of 100 μA. Note that the band gap of silicon at $T = 4.2$ K (and, consequently, the barrier height of the *p-n* junction) constitutes 1.17 eV (but with allowance for heavily doping, it is even smaller). So, the diode is really in the almost flat band state.

In Fig. 2, the results of these measurements have been presented as the ratio $\frac{U(B)-U(0)}{U(0)} \equiv \frac{\Delta U}{U_0}$ that coincides with a relative change of the diode resistance in magnetic field. At low fields, a negative component is observed in the magnetoresistance of the diode, and it decreases with growth of the feeding current. After changing the magnetoresistance sign from negative to positive (with growth of the field), its dependence on the magnetic field is quadratic at first but then it becomes close to the linear one. The smaller NMR value, the more extended is the square section of the curve and the shorter is the linear one.

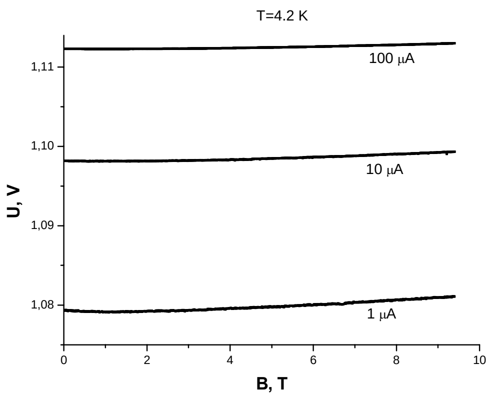

Fig. 1. Dependence of the voltage drop across the diode on magnetic induction at three values of the current through the diode; $T = 4.2$ K.

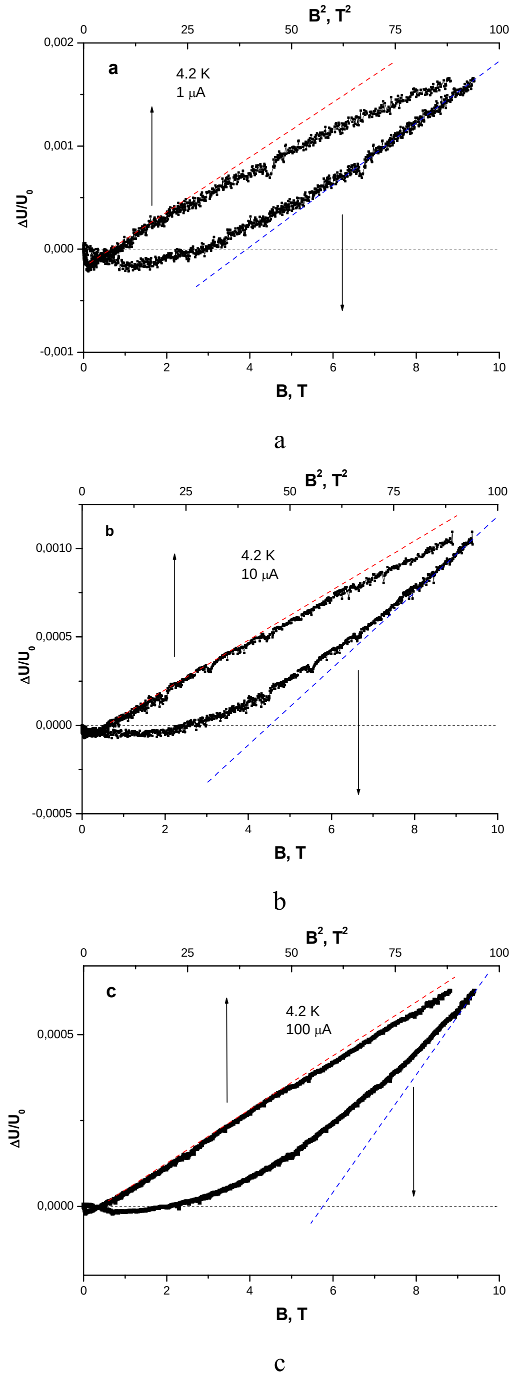

Fig. 2. Relative value of the diode magnetoresistance as a function of B (bottom curves) and B^2 (top curves) at the feeding currents of 1 (a), 10 (b), and 100 μA (c).

If observed hopping conduction were stipulated by the hops via certain deep isolated impurities (all the shallow impurities have been ionized!), it would be expected changing the quadratic dependence of the magnetoresistance into the root one ($\propto \sqrt{B}$) in the high fields [12], which is not observed. It remains only to suppose that the hops take place still and all between

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electron "lakes". Any theory of magnetoresistance for 3-dimensional case under these conditions is absent up to date. However, NMR for such type conductivity has been predicted in the 2-dimensional case [13]. NMR has been observed experimentally in the similar conditions in heavily doped and highly compensated Ge where conductivity also obeyed the Mott law [14]. Unfortunately, the fields did not exceed 0.5 T in this experiment, i.e. covered is only the region of negative magnetoresistance.

Weakening the effect of NMR with growth of the feeding current in our case may be explained completely by increase in the Joule heating the sample when emptying the electron "lakes".

Table. Relative error of measuring temperature of 4.2 K by means of silicon diodes produced in the Institute of Semiconductor Physics (ISP) (Kyiv, Ukraine) and by Lake Shore Cryotronics, Inc. (USA) as a function of magnetic induction. Excitation current for both diodes is equal to 10 μA.

B, T	1	2	3	4	5
For the diode developed in ISP (Ukraine) (Δ*T*/*T*, %)	1	1	–1	–3	–5
For the diode temperature sensor of LakeShore Cryotronics, Inc. (USA) in the most favorable orientation (Δ*T*/*T*, %)	–8	–9	–11	–15	–20

In conclusion, we dwell on applied aspect of the problem. In the Table, the calculated relative measurement error when temperature of 4.2 K is measured by means of investigated silicon diode is presented as a function of magnetic induction (up to 5 T). For comparison, the analogous data for silicon temperature sensor produced by Lake Shore Cryotronics, Inc. (USA) were quoted from the firm catalog [15]. The excitation current was 10 μA in both cases. It is seen that our thermo-diode is appreciably less sensitive to the influence of magnetic field. For example, the absolute value of the temperature error at $B = 5$ T is equal to 0.21 K (for our thermo-diode) and to 0.84 K – for the sensor of Lake Shore Cryotronics, Inc.

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