Semiconductor Physics, Quantum Electronics & Optoelectronics, 2017. V. 20, N 2. P. 195-198.
doi: https://doi.org/10.15407/spqeo20.02.195

PACS 72.20.Ee, 72.20.My, 85.30.Kk

New evidence of the hopping nature of the excess tunnel current in heavily doped silicon *p-n* diodes at cryogenic temperatures

V. L. Borblik [1, *], Yu. M. Shwarts[1, 2], M. M. Shwarts[1], A. B. Aleinikov[1, 2]
[1]*V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine,*
41, prospect Nauky, 03680 Kyiv, Ukraine
[2]*International Laboratory of High Magnetic Fields and Low Temperatures,*
Wroclaw, 53-421, Poland
[*]*Corresponding author e-mail: borblik@isp.kiev.ua*

Abstract. The new experimental data concerning the effect of magnetic field on electric properties of silicon diodes with high doping levels both in the emitter and base (conduction of which at low temperatures is determined by the excess tunnel current) has been analyzed. In addition to previous investigations of the influence of magnetic fields up to 9.4 T on this tunnel current at 4.2 K, now the measurements have been carried out up to 14 T at temperatures lower than the liquid helium temperature. Under these conditions, the transfer to saturation of the diode magnetoresistance was observed, which agrees with the results predicted theoretically for the hopping conduction via impurity centers in high magnetic fields.

Keywords: *p-n* diode, silicon, heavy doping, excess tunnel current, hopping conduction, magnetoresistance.

Manuscript received 23.12.16; revised version received 13.03.16; accepted for publication 14.06.17; published online 18.07.17.

1. Introduction

Traditional silicon *p-n* diodes, at low temperatures, suffer from the effect of freezing-out free carriers into the impurities in the diode base and, as consequence, from current instabilities related to their impact ionization in the electric field [1].

When the doping level of the diode base is high enough (*i.e.*, the impurity concentration exceeds the critical value for dielectric-metal transition), one can avoid this problem, as it has been shown by us in a number of papers [2-5]. In this case, any instability does not appear, the diode resistance is completely determined by resistance of the *p-n* junction, and the current voltage characteristics demonstrate predominance of the excess tunnel current (via certain localized states in the forbidden band of semiconductor, as it has been accepted to believe [6, 7]).

It has been found [3-5] that the temperature dependence of this excess tunnel current (at the constant voltage drop across the diode) is well described by the Mott's law for hopping conduction $I(T) \propto \exp\left[-(T_0/T)^{1/4}\right]$, that suggests the hopping character of the excess tunnel current at low temperatures. It has been supposed in [3] that in this case the electron hops take place via system of electron and hole "lakes" which could be formed (in accordance with the theory [8]) in heavily doped and highly compensated region of the *p-n* junction at the expense of large-scale potential. The lengthy compensation region could appear because of opposing diffusion of boron and phosphorus in the diode investigated.

Studying the influence of magnetic field on the characteristics of these diodes at 4.2 K [9], we have established that, in the region of low magnetic fields, negative magnetoresistance takes place, that is typical for the systems where conduction proceeds by carrier hopping via localized states.

With growth of the magnetic field, the negative magnetoresistance turned into positive one with the quadratic dependence on the field, which (in the fields not excee-

doi: https://doi.org/10.15407/spqeo20.02.195

ding 9.4 T) came close to a linear dependence. In this paper, we show that with further increase in the magnetic field, the above mentioned linear dependence of the diode magnetoresistance $\Delta R/R(0) \equiv \left(R(B) - R(0)\right)/R(0)$ passes to the saturation demonstrating transition to dependence $\Delta R/R(0) \propto \mathrm{const}B^{1/3}$ (B is induction of the magnetic field) predicted theoretically for the variable range hopping conduction of Mott's type in high magnetic fields [10]. Thereby, it has been proved that the excess tunnel current in heavy doped silicon diodes is determined by electron hops via local impurity centers, though this does not contradict (as it will be shown below) to the previous point of view.

2. Results of measurements

In the experiment, a voltage drop U across the diode was measured under the passing given current I through it (the current-controlled regime). In this regime, variation of U reflects variation of the diode resistance R. Results of the measurements are presented in Fig. 1 for a number of low temperatures as a function of magnetic field induction for two orientations of the magnetic field relative to the diode plane – in parallel and normal to it.

As it follows from Fig. 1, in the range of low magnetic fields (for both field orientations), sections of small negative magnetoresistance take place. These sections demonstrate slight dependence of their extent in magnetic field on temperature (marked by vertical dotted lines).

The diode magnetoresistance is determined here as a ratio of the voltage change at magnetic field B to the voltage in the absence of the field: $\dfrac{\Delta R}{R(0)} = \dfrac{\Delta U}{U(0)} \equiv \dfrac{U(B) - U(0)}{U(0)}$. The corresponding data are shown in Fig. 2.

As seen from Fig. 2, in the positive range, the diode magnetoresistance depends on magnetic field at first quadratically; then the dependence comes close to the linear one and further exhibits a tendency to saturation in high magnetic fields. With decrease in temperature, this picture becomes more and more distinct.

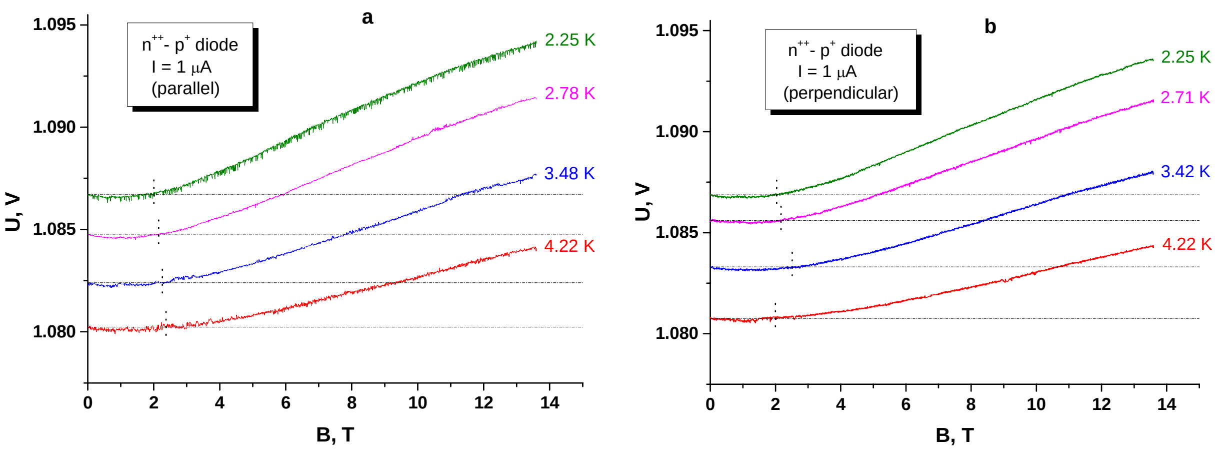

Fig. 1. Dependences of the voltage drop across the diode on the magnetic field at parallel (a) and perpendicular (b) orientations of the field relative to the diode plane at a number of temperatures.

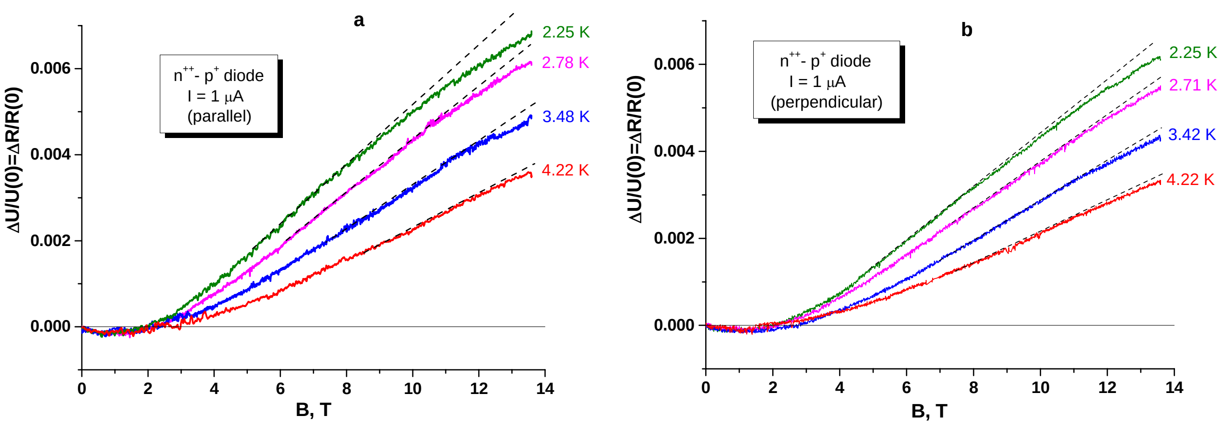

Fig. 2. Magnetic field dependences of the diode magnetoresistance at parallel (a) and perpendicular (b) orientations of the field at different temperatures.

3. Analysis and discussion of results

The theory of the variable range hopping conduction of Mott's type via impurity centers predicts, in the high field limit, a magnetic field dependence of the resistance in the form [10]

$$R(T,B) = R_0 \exp\left(\chi (B/T)^{1/3}\right), \quad (1)$$

where $\chi \approx \left[2.1e/c\hbar k_B g(E_F)a\right]^{1/3}$, e is the electron charge, c – light velocity, $\hbar$ – the Plank's constant, k_B – Boltzmann constant, $g(E_F)$ – density of states at the Fermi level, a – Bohr radius of the impurities (the localization radius). In Fig. 3, the high-field sections of the measurement results (for parallel field orientation) are presented in semilogarithmic scale as a function of $(B/T)^{1/3}$ and indeed demonstrate going into linear dependencies at high fields. At T = 4.22 K this going takes place just after B = 9.4 T, where the measurements in the paper [9] were finished. The lower temperature, the lower is the magnetic field in which this going to the linear dependencies occurs. The slope of the straight lines (χ value) exhibits a slight temperature dependence. Completely analogous results take place under perpendicular field orientation including values of the slope.

The obtained results imply that the mechanism of excess tunnel current in the investigated diode is hopping conduction via local impurity centers. However, this fact by no means excludes the picture based on the system of electron and hole "lakes" assumed in Ref. 3 (see Fig. 4). Indeed, the tunnel transitions through the potential barriers from one "lake" to another one occur via the same local impurity states within the barriers. This statement is obviously true also for the case of low-temperature conduction via the system of electron "lakes" in macroscopically homogeneous heavily doped and strongly compensated semiconductors (as in Ref. 11).

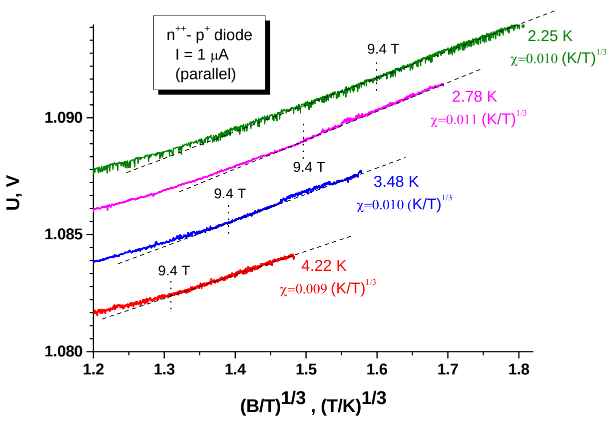

Fig. 3. High-field sections of the measurement results (in semilogarithmic scale) as a function of $(B/T)^{1/3}$ at parallel field orientation; the fields equal to 9.4 T are marked by dotted lines.

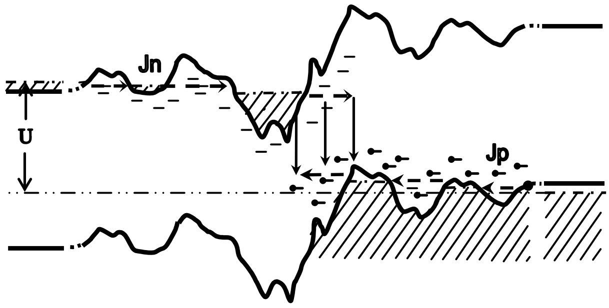

Fig. 4. The presumable picture for excess tunnel current in heavily doped *p-n* diode with the lengthy compensated region at low temperature. Here, the sinuous lines are bottom of the conductivity band and top of the valence band with taking into account the large-scale potential, the horizontal dashes indicate empty donor states, the black points imply occupied acceptor states, the dash-dotted lines show the Fermi levels, occupied states in the bands are shaded, J_n and J_p are flows of electrons and holes, respectively, and the vertical arrows mean electron-hole recombination.

4. Conclusions

Thus, all taken together, namely –

1) the Mott law for the low-temperature dependence of the diode conductivity,

2) availability of the negative magnetoresistance in small magnetic fields,

3) transition (with increase in magnetic field) to the positive magnetoresistance with quadratic dependence on the field and then to its cube-root dependence, as well as

4) practical independence of the diode magnetoresistance on mutual orientation magnetic field and the diode plane –

allows us to state that the excess tunnel current in silicon heavily doped *p-n* diodes is determined by the electron hops via the impurities centers irrespective of whether the system of electron and hole "lakes" are generated in the compensation region of the *p-n* junction or not.

References

1. Aleinikov A.B., Berezovets V.A., Borblik V.L., Shwarts M.M., and Shwarts Yu.M. Effect of magnetic field on hysteretic characteristics of silicon diodes under conditions of low-temperature impurity breakdown. *Semiconductor Physics, Quantum Electronics & Optoelectronics*. 2012. **15**, No. 3. P. 288–293.
2. Shwarts Yu.M., Borblik V.L., Kulish N.R., Sokolov V.N., Shwarts M.M., and Venger E.F. Silicon diode temperature sensor without a kink of the response curve in cryogenic temperature region. *Sensors and Actuators*. 1999. **76**, No. 1-3. P. 107–111.

doi: https://doi.org/10.15407/spqeo20.02.195

3. Borblik V.L., Shwarts Yu.M., and Shwarts M.M. Revealing the hopping mechanism of conduction in heavily doped silicon diodes. *Semiconductor Physics, Quantum Electronics & Optoelectronics.* 2005. **8**, No.2. P. 41–44.
4. Borblik V.L., Shwarts Yu.M., and Shwarts M.M. Manifestation of disorder effects in excess tunnel current of heavily doped silicon diodes. *Bull. Russian Acad. Sci.: Physics.* 2007. **71**, No. 8. P. 1073–1075.
5. Borblik V.L., Shwarts Yu.M., and Shwarts M.M. Characteristics of diode temperature sensors which exhibit Mott conduction in low-temperature region. *Semiconductor Physics, Quantum Electronics & Optoelectronics.* 2007. **10**, No. 3. P. 44–47.
6. Sze S.M. *Physics of Semiconductor Devices.* 2nd ed., John Wiley & Sons, New York, 1981.
7. Del Alamo J.A. and Swanson R.M. Forward-bias tunneling: a limitation to bipolar device scaling. *IEEE Electron. Device Lett.* 1986. ***EDL*-7**(11). P. 629–631.
8. Shklovskii B.I. Hopping conduction of heavily doped semiconductors. *Sov. Phys.-Semicond.* 1973. **7**, No. 1. P. 77–83 (in Russian).
9. Borblik V.L., Rudnev I.A., Shwarts Yu.M., and Shwarts M.M. Negative magnetoresistance of heavily doped silicon *p-n* junction. *Semiconductor Physics, Quantum Electronics & Optoelectronics.* 2010. **14**, No. 1. P. 88–90.
10. Shkovskii B.I. and Efros A.L. *Electronic Properties of Doped Semiconductors.* Berlin, Springer, 1984.
11. Ionov A.N., Rentzsch R., and Shlimak I. Role of electron “lakes” in the effect of negative magnetoresistance in the region of Mott hopping conductivity. *JETP Lett.* 1996. **63**, No. 3. P. 199–203.