Silicon diode temperature sensor weakly sensitive to magnetic field

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Introduction

At low temperatures, usual diode temperature sensors on the base of silicon are strongly subjected to influence of magnetic fields that excludes possibility their use under these conditions [1]. The reason is a freezing-out of free carriers in the diode base that results in hopping conduction via impurities which depends strongly on magnetic field.
In the resistant thermometers such the problem takes place as well. It is overcome by means of choice of the conditions when sensor's magnetoresistance changes its sign in actual region of the fields. Then magnitude of magnetoresistance is proved as a whole to be small enough.
But if the diode base is doped up to metallic conductivity the freezing-out at low temperatures does not occur and the diode resistance is defined completely by resistance of the *p-n* junction. In the papers [2, 3], we have investigated current-voltage characteristics of such the diodes at cryogenic temperatures and have found that they demonstrate predominance of the tunnel current under these conditions (via certain localized states in the forbidden band of semiconductor). The temperature dependence of this tunnel current is well described by the Mott's law that points to hopping nature of the current flow through the *p-n* junction region in such the diodes.
In this paper we report results of the investigations concerned with influence of magnetic fields on properties of such the diodes at cryogenic temperatures. As so often is the case hopping conductivity under these conditions demonstrates the negative magnetoresistance whose magnitude is proved to be extremely small.

Current-voltage characteristics of the heavily doped silicon diodes

The typical current-voltage characteristics of the investigated silicon diodes at low temperatures are shown in fig. 1.

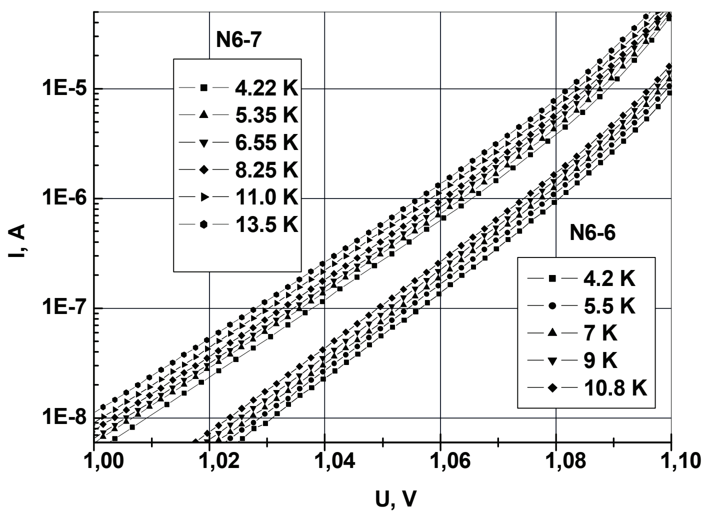

Fig. 1. Current-voltage characteristics of two heavily doped silicon diodes (N6-6 and N6-7) at cryogenic temperatures.

There are intervals of applied voltages in fig. 1 where the characteristics at different temperatures plotted in semi logarithmic scales are linear and parallel, i.e. they are described by the dependencies

$$I = I_0 \exp(U / U_t) \qquad (1)$$

where U is applied voltage and U_t is temperature-independent characteristic voltage. As is known such the dependencies point to tunnel nature of the diode current [4]. The matters is not about direct band-to-band tunneling but about tunneling through localized states in forbidden band of semiconductor – so called excess tunnel current (see fig. 2).

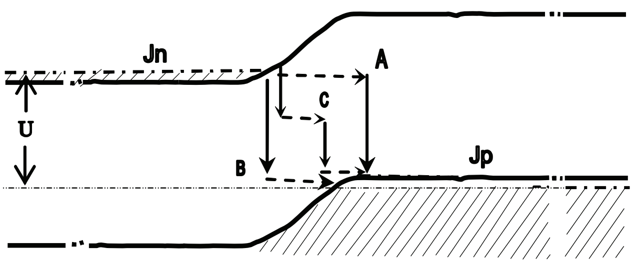

Fig. 2. Band diagram explaining mechanism of tunneling in heavily doped diodes.

Shown in fig. 3 are the temperature dependencies of the diode current at fixed applied voltage U plotted in three different manners: versus $\left(1/T\right)$, versus $\left(1/T\right)^{1/2}$, and versus $\left(1/T\right)^{1/4}$. It is seen that the best fit of measurement results is provided by Mott's temperature dependence

$$I(T) \propto \exp\left[-\left(\frac{T_0}{T}\right)^{1/4}\right]. \qquad (2)$$

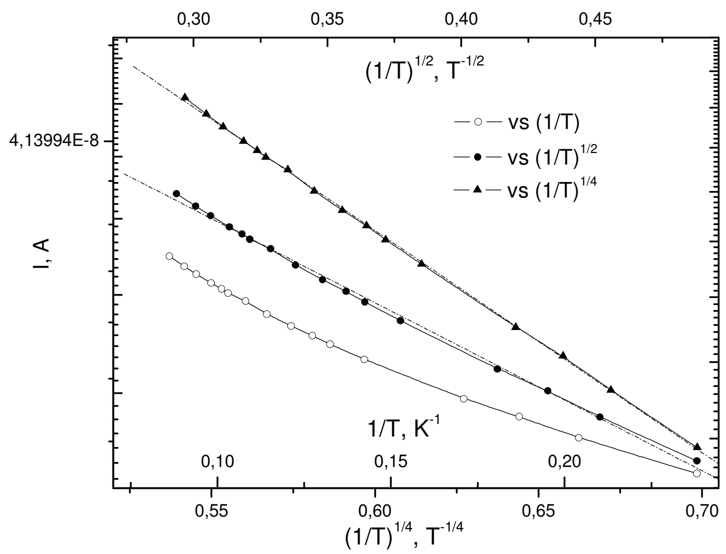

Fig. 3. Superposed in the same graph the temperature dependencies of the diode current (at U =1.02 V) versus $\left(1/T\right)$, $\left(1/T\right)^{1/2}$ and $\left(1/T\right)^{1/4}$.

This fact (along with gradual decreasing activation energy when temperature lowers) points to hopping character of the diode conduction at low temperatures. Under such conditions we can expect, in principle, existence of negative magnetoresistance and so change of its sign with magnetic field growth.

Influence of magnetic field on the resistance of heavily doped silicon diodes

We have investigated effect of magnetic fields on the diode resistance up to 9.4 T. The voltage drop U across the diode was measured under conducting through it constant forward current I of different values (it is just the temperature measuring regime). The measurement results for a number of fixed currents at temperature of 4.2 K are given in fig. 4 as a function of magnetic induction B.

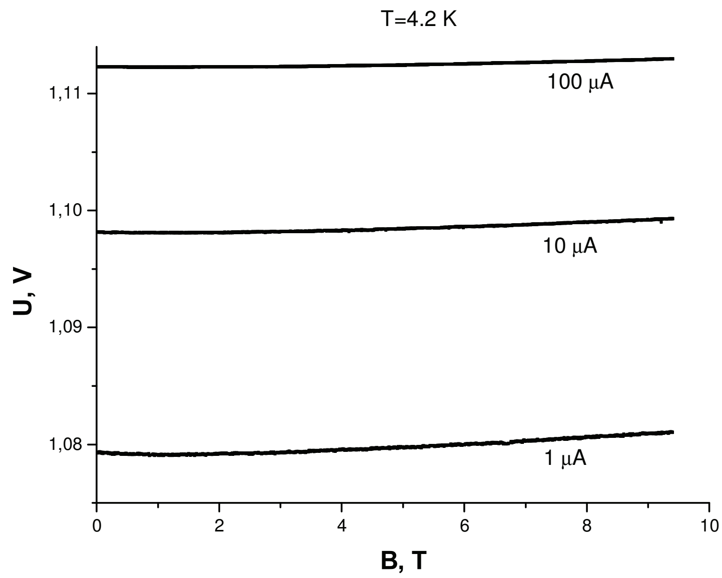

Fig. 4. Dependence of the voltage drop across the diode on magnetic induction at three values of the current through the diode (1, 10, and 100 μA); T=4.2 K.

As it can be seen from Fig. 4 magnitude of the voltage drop across the diode depends essentially on the current value being equal about 1.08 V at the current of 1 μA, about 1.10 V at the current of 10 μA and about 1.11 V at the current of 100 μA.

Further, in fig. 5, the results of the measurements have been presented as the ratio $\frac{U(B)-U(0)}{U(0)} \equiv \frac{\Delta U}{U_0}$ which coincides with relative change of the diode resistance in magnetic field. At low fields, a negative component is observed in the magnetoresistance of the diode which decreases with growth of the feeding current. After change of magnetoresistance sign from negative to positive (with growth of the field) its dependence on the magnetic field is quadratic at first but then it comes close to linear one. The smaller negative magnetoresistance value, the more extended is the square section of the curve and the shorter is the linear one.

Above mentioned peculiarities have grate academic interest because permit discrimination between different mechanisms of tunneling through the localized states.

If observed hopping conduction would be stipulated by the electron hops via certain deep isolated impurities (because all shallow impurities have been ionized in view of metallic conductivity both of the diode emitter and the base), it would be expected changing the quadratic dependence of the magnetoresistance in the high fields ($\propto B^2$) into root one ($\propto \sqrt{B}$) [5] that is not observed. It remains to suppose that the hops take place between electron „lakes“ [6] which can arise in central region of heavily doped *p-n* junction because this region may be liken to heavy doped and strongly compensated semiconductor. The fact that such the diodes have been produced by opposite diffusion of the dopants may be considered as one of arguments that this is the case.

The theory of magnetoresistance under such conditions is absent for 3-dimensional case. However, negative magnetoresistance for such type conductivity has been predicted in 2-dimensional case [7]. Furthermore, negative magnetoresistance has been observed experimentally in the similar conditions in heavily doped and highly compensated Ge where conductivity also obeyed the Mott's law [8]. Unfortunately, magnetic fields did not exceed of 0.5 T in this experiment, i.e. covered only region of the negative magnetoresistance.

At such interpretation weakening the effect of negative magnetoresistance with growth of the feeding current in our case can be explained by increase in the joule heating the sample emptying the electron "lakes".

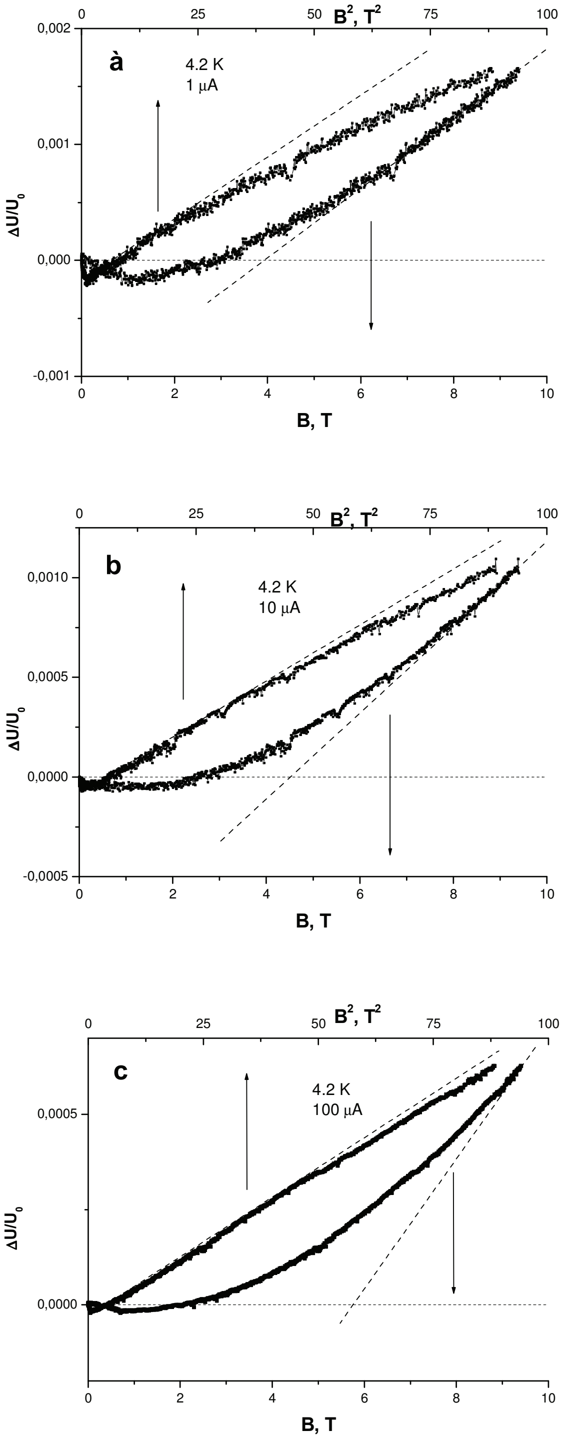

Fig. 5. Relative value of the diode magnetoresistance as a function of B (bottom curves) and B^2 (top curves) at the feeding currents of 1 μA (a), 10 μA (b), and 100 μA (c).

Sensor properties of the investigated diode in magnetic field

In connection with passing of the diode magnetoresistance through zero its value (as it was expected) is proved, as a whole, to be extremely low. In the Table, the calculated relative measurement error (if temperature of 4.2 K is measured by means of the investigated diode) is presented as a function of magnetic induction (the first line). For comparison, the analogous data for silicon temperature sensor and the sensor made of GaAlAs produced by Lake Shore Cryotronics, Inc. (USA) are quoted from the firm catalog [1] (the second and the third lines). Excitation current is 10 μA in all cases. It is obvious that our thermo-diode is appreciably less sensitive to the influence of magnetic field. Only at 5 T it yields to GaAlAs sensors which, however, have not such repeatability as silicon ones and are more expensive.

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

B, T	1	2	3	4	5
For the diode developed in ISP (Kiev, Ukraine) (ΔT/T, %)	1	1	-1	-3	-5
For diode temperature sensors produced by LakeShore Cryotronics, Inc. (USA)					
For Si diode in the most favorable orientation (ΔT/T, %)	-8	-9	-11	-15	-20
For GaAlAs diode (ΔT/T, %)	2.9	3.8	3.7	2.8	1

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