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Characteristics of diode temperature sensors which exhibit Mott conduction in low-temperature region

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Abstract. Heavily doped silicon diodes of n^{++}-p^{+} type which exhibit the Mott temperature dependence of the forward current in a certain range of bias voltages and low temperatures have studied from the point of their use as temperature sensors. In the region of hopping conduction, the operating signal of diodes U (T) (U is a voltage drop across the diode during the passage of a constant current, T is the temperature) reproduces the Mott law (with opposite sign in the exponent), and the temperature sensitivity of such sensors after passing through a minimum (as the temperature is lowered) increases again up to the values typical of room temperature.

Keywords: junction diode, temperature sensor, silicon, hopping conductivity, heavy doping, strong compensation.

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1. Introduction

In [1], we have shown that, by means of the heavy doping of the base of a silicon thermodiode, one can get rid of a sharp kink in its response curve at temperatures near 40 K connected with the freezing-out of free current carriers into impurities. Under conditions of high-level doping, the base conductivity becomes metallic and current carriers do not freeze-out at any temperatures. Herewith in [1], we observed a continuous decrease in the temperature sensitivity of such a sensor with temperature lowering connected with the domination of the tunnel component in the diode current under such conditions (heavy doping, low temperatures) (we are talking here about the so-called excess tunnel current [2] rather than the direct interband tunneling).

Continuing our investigations of the influence of a high-level doping of the diode base on its characteristics, we have manufactured the silicon diodes which exhibit (in a certain range of temperatures and forward bias voltages) the Mott temperature dependence of the diode current at a constant voltage drop across the diode [3]. This dependence has been interpreted previously as a manifestation of hopping conduction through the electron "drops" which have to arise (in correspondence with the theory [4]) in the central, strongly compensated, region of the *p-n* junction that may be likened to heavily doped and strongly compensated semiconductor.

In this paper, we represent the results of comparative analysis of the characteristics for two of such type diodes (which are distinguished lightly by doping level) including also their response curves as temperature sensors. The Mott temperature dependence of the forward current observed in both diodes is shown to be consistent with the published data on the temperature dependence of the conductivity of heavily doped and strongly compensated bulk silicon. The diodes with such properties being used as temperature sensors demonstrate (unlike the diodes studied in [1]) the presence of a minimum in their temperature sensitivity (when the temperature lowers), after which its subsequent sufficient increase is observed again. Herewith, the value of sensitivity reaches (at the liquid helium temperature) the magnitudes typical of silicon diode sensors at room temperature, *i.e.* of the order of 2 mV/K.

2. Results of measurements and their analysis

2.1. Current-voltage characteristics

In Fig. 1, we present the temperature families of the forward current-voltage characteristics (CVCs) of two silicon planar diodes of n^{++}-p^{+} type, whose bases as well as the emitters were doped up to metallic conductivity (samples N 6-6 and N 6-7). The *p-n* junctions were formed by opposite diffusion of boron and phosphorus at slightly different concentrations of the dopants. The

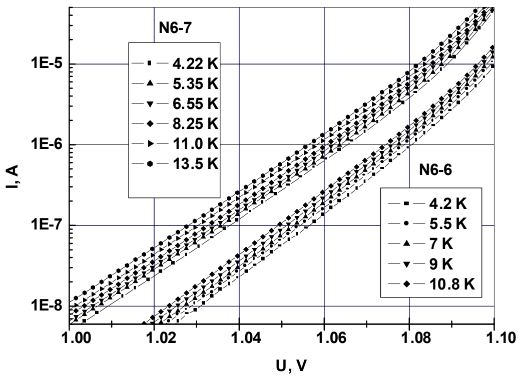


Fig. 1. Current-voltage characteristics of two silicon n^{++}-p^{+} diodes N6-6 and N6-7 in cryogenic temperature region.

CVC families are shown for the range of voltages and temperatures where the diode current is the tunnel one completely. The visual indication of this fact (as was shown by us in [1]) consists in the quasiparallel character of the CVCs at different temperatures plotted on the semilogarithmic scale; in Fig. 1, it is the range between 1 and 1.08 V. In this region, the CVCs are described by the expression [2]

$$I(U,T) = I_0(T)\exp\left(\frac{U}{U_t}\right), \tag{1}$$

where U is the applied voltage, T is the temperature, $U_t^{-1} = \frac{4}{\hbar}\sqrt{\chi\, m^* \frac{N_A + N_D}{N_A N_D}}$ is a temperature-independent constant, $\hbar$ is the Planck constant (divided by 2π), m^* is the effective mass of tunneling carriers, χ is the dielectric constant of the semiconductor, and N_D and N_A are the concentrations of donors and acceptors, respectively. Herewith [2]

$$I_0(T) = I_{00}(T)\exp\left[-qV_{bi}(T)/U_t\right], \tag{2}$$

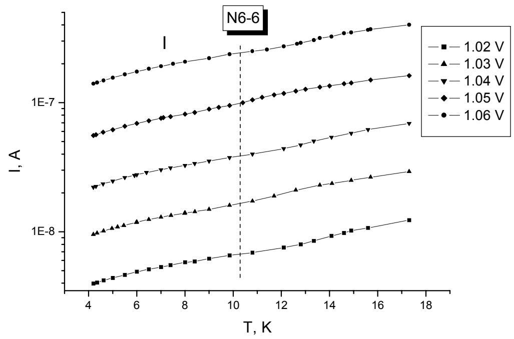
where q is the electron charge, $V_{bi}(T)$ is the built-in potential of a *p-n* junction. Under the degeneration conditions, $qV_{bi}(T) = E_g(T) + \varepsilon_{Fn} + \varepsilon_{Fp}$ [5], where $E_g(T)$ is the temperature-dependent semiconductor gap, ε_{Fn} and ε_{Fp} are the degeneracy degrees for the conduction and valence bands, respectively. So, the temperature dependence of V_{bi} is determined, mainly, by the temperature dependence of the gap. Because $E_g(T) = E_g(0) - aT^2/(b+T)$ [5] where a and b are constants, then $E_g(T) \approx E_g(0) = \text{const}$ at low temperatures, and one can expect to observe the temperature dependence of the excess tunnel current not obscured by the temperature dependence of the *p-n* junction barrier.

From Fig. 1, we obtain the ratio of CVCs' slopes for two diodes $\frac{U_t^{-1}\big|_{6-7}}{U_t^{-1}\big|_{6-6}} = \frac{80\,B^{-1}}{88\,B^{-1}} = 0.91$. This is in agreement with the value of 0.93 following from the expression for U_t^{-1} with substitution of the corresponding doping levels.

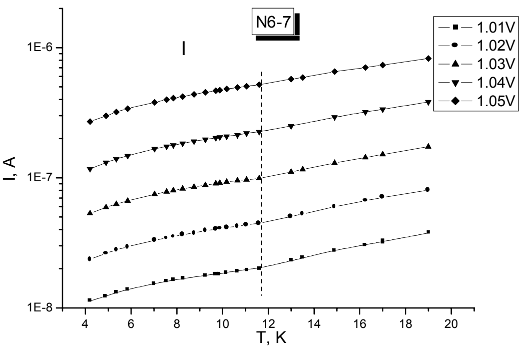
2.2. Temperature dependence of the forward current at fixed bias voltages

In Fig. 2 a, b, we display the temperature dependences of both diode currents at a number of fixed values for the bias voltage. To clarify the mechanism of the current flow, Fig. 3a, b shows the same temperature dependences at a bias voltage of 1.02 V (at the rest voltages, the picture is similar) in three different forms: versus $1/T$, $(1/T)^{1/2}$, and $(1/T)^{1/4}$. Herewith, because the current interval where hopping conduction is anticipated is rather small, Fig. 3 depicts the product of I and $\sqrt{T}$ as a function of $(1/T)^{1/4}$ and the product of I and T as a function of $(1/T)^{1/2}$; these procedures take the pre-exponential factors in the Mott [6] and Efros-Shklovskii [7] formulas, respectively, into account.

In the region of lowest temperatures (region I), the current as a function of temperature is described well just by the Mott law

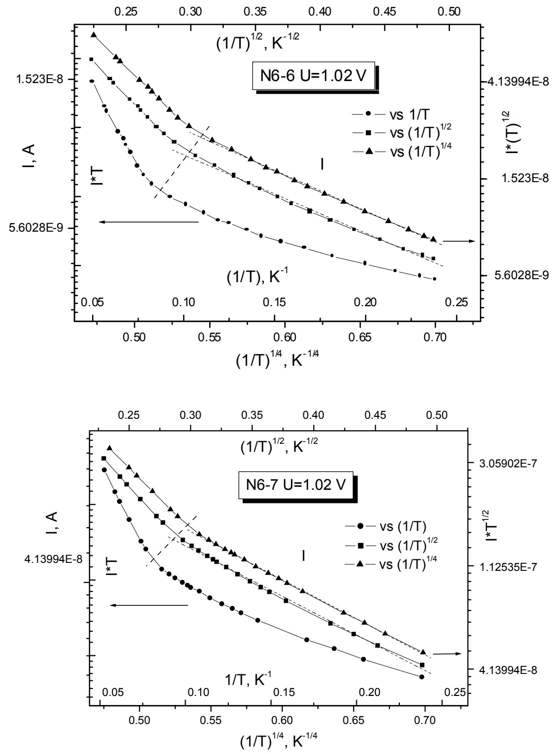


a



b

Fig. 2. Temperature dependences of the forward current for the diodes N6-6 (*a*) and N6-7 (*b*) at a number of bias voltages U.



a

b

Fig. 3. Presentation of the temperature dependences of the forward current for the diodes N6-6 (*a*) and N6-7 (*b*) in three different forms: versus $1/T$, $(1/T)^{1/2}$, and $(1/T)^{1/4}$.

$$I(T) \sim \exp\left[-(T_0/T)^{\frac{1}{4}}\right] \Big/ \sqrt{T} . \quad (3)$$

So, conductivity has here hopping character, and the hopping length increases with decrease in temperature; simultaneously, the conductivity activation energy decreases. Defining the varying activation energy by the derivative $-\frac{d\ln I}{d(kT)^{-1}}$ (k is the Boltzmann constant), we obtain its values from 0.56 to 0.27 meV (the same for both diodes).

But the characteristic temperatures, T_0, for two diodes are different. For diode N 6-7 with lower doping level in the *n*-region, the averaged value of T_0 is 2700 K; but, for diode N 6-6, $T_0 \approx$ 2200 K. Therefore, their ratio is equal to 1.2. Because $T_0 = \frac{\text{const}}{k g(E_F) a_0^3}$ [6], where $g(E_F)$ is the density of states near the Fermi level, a_0 is the localization radius of the states through which the electron hops take place, then the ratio of characteristic temperatures may be equated to the reciprocal ratio of the densities of states if the localization radii are believed to be the same. Then the ratio of the densities of states reduces to the ratio of the doping levels that gives approximately the same value:

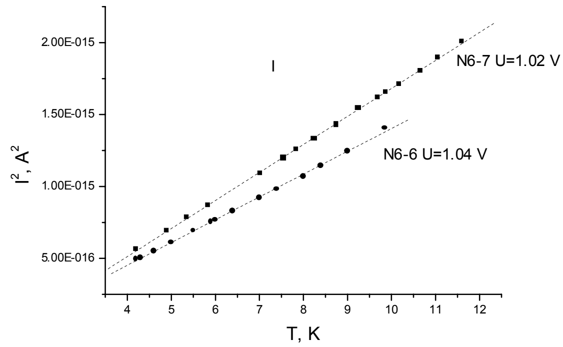


Fig. 4. Temperature dependences of the current squared for both diodes in the Mott law region.

$$\frac{T_0\big|_{6-7}}{T_0\big|_{6-6}} = \frac{2.1\,\Omega/\lozenge}{1.6\,\Omega/\lozenge} \approx 1.3 .$$

So, the results of comparative analysis of the diode characteristics do not contradict the idea of the hopping nature of their conductivity at low temperatures.

The fact of the existence of Mott conductivity in a heavily doped diode is consistent completely with the long ago noticed analogy between heavily doped, strongly compensated crystalline semiconductors and amorphous materials [8]. There are large differences, however, between magnitudes of the parameter T_0. According to [9, 10], $T_0 \approx 10^7$ K in amorphous Ge and Si. But, in our case, $T_0 \approx (2\text{–}3)10^3$ K. This fact gives evidence, in our opinion, of a larger density of localized states in a heavily doped *p-n* junction in comparison with amorphous materials. It indicates also that hopping conductivity is connected here with current carriers localized in electron drops rather than at impurities or defect states.

It is worth to note also that, in the region of Mott law action, the temperature dependence of the diode current squared is very close to a linear one (see Fig. 4, where different bias voltages are taken for different diodes in order to get comparable current magnitudes). Therefore, if no special carefulness is required, one can estimate approximately the dependence $I(T)$ as that proportional to $\sqrt{T}$. This is made, apparently, in [11] while studying the low-temperature conductivity of heavily doped and strongly compensated bulk silicon.

2.3. The response curves of the diodes

The response curve of a diode, $U(T)$, is the variation of the voltage drop across the diode with temperature when a fixed operation current, I_{oper}, is passed through it. According to Fig. 2, the conductivity of diodes decreases as the temperature decreases. Therefore, for keeping the operation current as constant (in the temperature measurement regime), the voltage drop across the diode has to increase. Just such a behavior is demonstrated by the measurement results for both diodes (at an operating current of 1 μA) presented in Fig. 5.

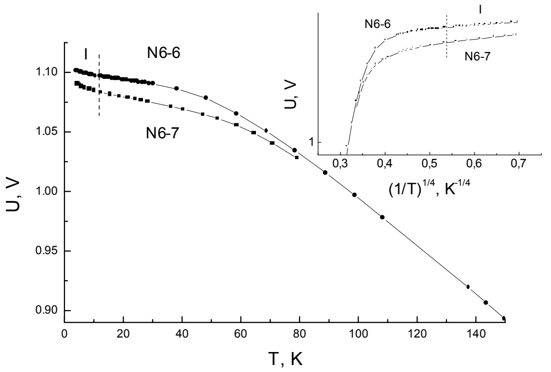


Fig. 5. Temperature response curves for both diodes; the insert – the same versus $(1/T)^{1/4}$.

It is interesting that, in the region where conductivity varies with temperature by the Mott law (2), the voltage drops across the diodes vary by the opposite law (the plus sign in the exponent) and with another values of characteristic temperatures:

$$U(T) \sim \exp\left[\left(T_0^*/T\right)^{\frac{1}{4}}\right] \quad (4)$$

(see the insert in Fig. 5). Let us note also that we are faced here with that rare case where the response curve in the low-temperature region can be expressed analytically. This circumstance facilitates the task of obtaining the thermodiode calibration characteristic in this temperature range.

Temperature sensitivity, $dU/dT\big|_{I=I_{\rm oper}}$, of the diodes studied is presented in Fig. 6. It is characterized by the presence of a minimum near T = 20 K, after which the sensitivity increases again with decrease in temperature down to the values of the order of 1-1.5 mV/K and continues to increase farther (as shown by the previous measurements at somewhat lower temperatures).

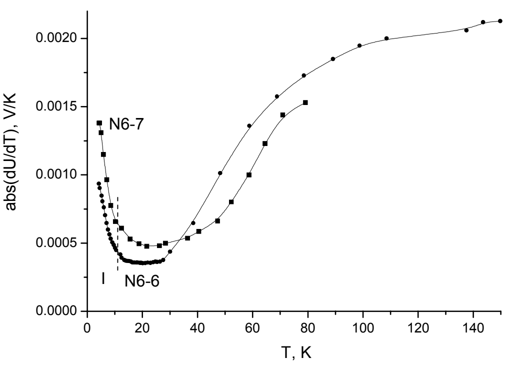


Fig. 6. Temperature sensitivity of both diodes as temperature sensors in cryogenic temperature region.

3. Conclusion

Thus, the idea of the utterly weak temperature dependence of a tunnel current proves to be valid not always. In heavily doped silicon diodes manufactured by opposite diffusion, a potential pattern resulting in the Mott hopping conduction can be produced. In such a case, one can obtain such temperature sensitivity of the diode sensors in the low-temperature region which is not worse than that at room temperature under conditions of dominating diffusion current.

References

1. Yu.M. Shwarts, V.L. Borblik, N.R. Kulish, V.N. Sokolov, M.M. Shwarts, E.F. Venger, Silicon diode temperature sensor without a kink of the response curve in cryogenic temperature region // *Sensors and Actuators, A* **76**(1–3), p. 107-111 (1999).
2. J.A. Del Alamo and R.M. Swanson, Forward-bias tunneling: a limitation to bipolar device scaling // *IEEE Electron Device Lett. EDL*-**7** (11), p. 629-631 (1986).
3. V.L. Borblik, Yu.M. Shwarts, and M.M. Shwarts, Revealing the hopping mechanism of conduction in heavily doped silicon diodes // *Semiconductor Physics, Quantum Electronics & Optoelectronics* **8**(2), p. 41-44 (2005).
4. B.I. Shklovskii, Hopping conduction of heavily doped semiconductors // *Sov. Phys.-Semicond.* 7 (1), p. 77-83 (1973) [*Fiz. Tekh. Poluprov*. 7(1), p. 112-118 (1973) (in Russian)].
5. S.M. Sze, *Physics of Semiconductor Devices.* Wiley, New York, 1981.
6. N.F. Mott, E.A. Davis, *Electron Processes in Non-Crystalline Materials.* Clarendon Press, Oxford, 1979.
7. D.N. Tsigankov and A.L. Efros, Variable range hopping in two-dimensional systems of interacting electrons // *Phys. Rev. Lett.* **88** (17), p. 176602/1-4 (2002).
8. B.I. Shklovskii and A.L. Efros, Completely compensated crystalline semiconductor as a model of an amorphous semiconductor // *Sov. Phys.-JETP* **35**(3), p. 610-618 (1972) [*Zh. Eksp. Teor. Fiz.* **62**(3), p. 1156-1165 (1972) (in Russian)].
9. M. Pollak and J.J. Hauser, Note on the anisotropy of the conductivity in thin amorphous films // *Phys. Rev. Lett.* **31**(21), p. 1304-1307 (1973).
10. R. Meservey, P.M. Tedrow, and J.S. Brooks, Tunneling characteristics of amorphous Si barriers // *J. Appl. Phys*. **53**(3), p. 1563-1570 (1982).
11. A.K. Raychaudhuri, S. Kar, and A. Ghosh, Suppression of universal conductance fluctuations by an electric field in doped Si(P,B) near the metal-insulator transition // *Physica E* **18**(1-3), p. 284-285 (2003).