SIMULATION OF LOW-TEMPERATURE CURRENT FLOW AND SENSITIVITY IN Si DIODE TEMPERATURE SENSORS

YU.M. SHWARTS, M.M. SHWARTS, O.M. IVASHCHENKO, O.V. KONDRACHUK[1], L.I. SHPINAR[1]

V. Lashkarev Institute of Semiconductor Physics, Nat. Acad. Sci. of Ukraine
(45, Nauky Prosp., Kyiv 03028, Ukraine; e-mail: shwarts@isp.kiev.ua),

[1]**Institute of Physics, Nat. Acad. Sci. of Ukraine**
(46, Nauky Prosp., Kyiv 03028, Ukraine)

UDC 621.315.592

Current-voltage characteristics and temperature response curves of silicon diode temperature sensors were investigated at low temperatures. The proposed theoretical model of the low-temperature current flow in $n^{++} - p^{+}$ diode structures takes into account the mechanism of non-Ohmic conductivity with variable-range-hopping in the range of a diode base and the tunneling current through a potential heterojunction barrier. Such a heterojunction is formed due to the asymmetric narrowing of a forbidden gap in the n^{++} and p^{+} regions, induced by the high and different doping levels of the emitter and the base of diode. The found dependences of the parameters of non-Ohmic hopping conductivity upon the temperature and the electric field, have allowed us to explain the observed features of diode sensor sensitivity in the range of helium temperatures.

Introduction

Use of the temperature dependence of voltage drop on a diode $U(T)$ during the flow of a constant direct current through it has allowed to create highly sensitive and interchangeable silicon diode temperature sensors (DTS) with a working range 4.2—500 K [1—3]. The thermometric characteristics (TMC) $U(T)$ of such sensors are well predicted in the temperature range 77—500 K, where the diffusion and/or recombination currents are responsible for the structure sensitivity ($dU/dT\sim$ -2 mV/K) [3]. In the range of cryogenic temperatures (4.2—77 K), the contributions of the diffusion and the recombination currents decrease and the role of the tunneling current increases [2], if the impurity concentration in a diode base reaches the critical values, stipulating the semiconductor/metal Mott transition [4]. At this, the sensitivity drops to values of –(0.8—1) mV/K.

In this paper, we discuss a nature of the record-breaking high sensitivity, experimentally observed in silicon DTS ($dU/dT \sim -180$ mV/K) in the region of helium temperatures. The investigation of the physical processes at low temperatures, stipulating so high dU/dT values, is very important for the understanding of the operation of semiconductor devices of low-temperature electronics as well as for the construction of cryogenic semiconductor temperature sensors and for the optimization of a design and a technology of wide-range temperature sensors.

This paper is devoted to the investigation of the features of low temperature conductivity and to the modeling of the mechanisms of low temperature current flow in heavily doped n^{++}— p^{+} silicon structures, as well as to the determination of the physical parameters responsible for the formation of DTS thermometric characteristic and sensitivity in the range of helium temperatures.

1. Samples and Experimental Methods

The DTS investigated in this paper were developed basing on the industrial planar diffusion technology of silicon diode chips. The concentration of boron in the diode base is $N_{\mathrm{B}} = 3 \cdot 10^{18}$ cm^{-3}, and the compensation level is K ≈0.03. The phosphorus concentration in the emitter is $N_{\mathrm{P}} = 5 \cdot 10^{20}$ cm^{3}.

The direct current-voltage characteristics of diodes were measured in the range of currents 10^{-11}—10^{-2} A and in the temperature range 4.2—13 K, using the automatic test bench. The error in the temperature maintaining did not exceed ±0.01 K. The sensor TMCs were measured using a metrological test bench UGT-A with stabilization of working currents not worse than ±0.1 %. The main absolute error of measurements did not exceed ±0.03 K in the temperature range 4.2—373 K.

ISSN 0503-1265. Ukr. J. Phys. 2004. V. 49, N 10

2. Model of the Heterojunction in a Diode Structure

To explain the nature of the low temperature current flow in DTS, we consider properties of a doped diode structure. For the acceptor concentration $N_{\rm B} = 3 \cdot 10^{18}$ cm^{-3} in the structures studied, $a_h N_{\rm B}^{1/3} < 1$ ($a_h \approx 23$ Å is the radius of a localized state of a hole on a boron atom). Under such conditions, boron creates an impurity zone along the diode structure, which is separated from the valence zone by the band of forbidden states. Since $N_{\rm P} = 5 \cdot 10^{20}$ cm^{-3} in the n^{++} diode region, the donor impurity leads to a Mott junction in the emitter [4].

It is known [5] that high levels of a doping impurity modify the silicon band structure and lead to a narrowing of the band gap width of the semiconductor. According to [6], the main contribution to the shift value of a conduction band bottom ΔE_c and a valence band top ΔE_v is given by the exchange interaction $\Delta E_{1c(v)} = 1.83\Lambda R_{e(h)}/(N_b)^{1/3} r_s$ and the interaction between charge carriers (majority and minority) and impurity atoms $\Delta E_{2c(v)} = 1.57 R_{e(h)}/N_b r_s^{3/2}$, where N_b is the number of energy valleys in the conduction (valence) band,$r_S = r_0/a_{e(h)}$,r_0 is the average distance between the impurity atoms $\left(4\pi N_{\rm P(B)} r_0^3/3 = 1\right)$, $a_{e(h)} = \varepsilon\hbar/\pi m^*_{e(h)} q^2$ is the electron (hole) Bohr radius, $R_{e(h)} = 13.6 m^*_{e(h)}/\varepsilon^2$ is the effective Ridberg energy, ε is the permittivity, q is the elementary charge, $m^*_{e(h)}$ is the electron (hole) effective mass, $\hbar$ is the Planck's constant, Λ=1 for the conduction band and Λ=0.75 for the valence band. While determining the shift of the valence band top, a contribution of the electron-hole interaction $\Delta E_3 = 0.95 R_h/r_s^{3/4}$ is also taken into account.

The estimations carried on according to [6] give a total narrowing of the band gap in an n^{++} diode region $\Delta E_{g1} \approx$130 meV. The values obtained agree well with the published data [7].

A contact of the n^{++} region with a band gap narrowed due to a high doping level with the p^+ region with a wider band gap, can be considered as a heterojunction (Fig. 1). Closely to the junction boundary, the depletion layers with widths L_p and L_n are located. The ratio of these widths is $L_p/L_n = N_{\rm P}/N_{\rm B} \sim 10^2$. The contact potential, which determines the band bending, accords to the difference of the Fermi level energies in the n^{++} and p^+ regions prior to their contact, $U_{\rm cont} \approx F_p - F_n \approx$1 eV.

Modeling the silicon devices with $p-n$ junctions as heterojunctions with regard for the effects of high doping was discussed in [8]. However, for the analysis of the physical processes related to the current at low temperatures, such an approach was not used before.

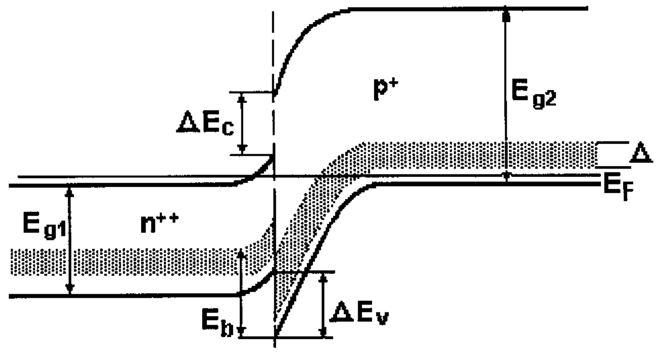

Fig. 1. Energy diagram of the $n^{++} - p^+$ diode structure under equilibrium. E_{g1}, E_{g2} are band gap values in the n^{++} and p^+ regions, respectively, ΔE_c and ΔE_v are the energetic breaks of edges of the conduction and valence bands, respectively, $E_{\rm F}$ is the Fermi level, E_b is the energy barrier, ΔD is the width of the acceptor impurity zone

3. Current Flow in Diode Structures

At low temperatures, the voltage U applied to a diode structure is redistributed between the voltage drop on the n^{++}— p^+ junction (U_d) and the voltage drop in the diode base (U_b). Then

$$U \approx U_d + U_b = U_d + I(L/S)\sigma^{-1}, \qquad (1)$$

where I is the dirrect current through the diode, L, S are the length and cross-section of the current conductive region of the diode base, respectively, and σ is the base conductivity.

Two characteristic slopes can be distinguished in the experimental current-voltage characteristics measured in the temperature range 4.2—13 K (Fig. 2). For the voltages 1—1.06 V, the current through a diode weakly depends on the temperature with activation energy $\sim$ 1 meV (Fig. 3) and sharply increases under small voltage change. Such dependences are typical of the tunneling mechanism of current flow.

Let us analyze the influence of a heterojunction on the current flow in a diode. At low temperatures, when the applied direct offset U is smaller than the contact voltage between the n^{++} and p^+ regions, the current is absent through the diode, since the potential barrier $U_{\rm cont}$ is too high for free carriers in the conduction band of the n^{++} region, as well as for localized carriers in the acceptor impurity zone. Out of the space charge region

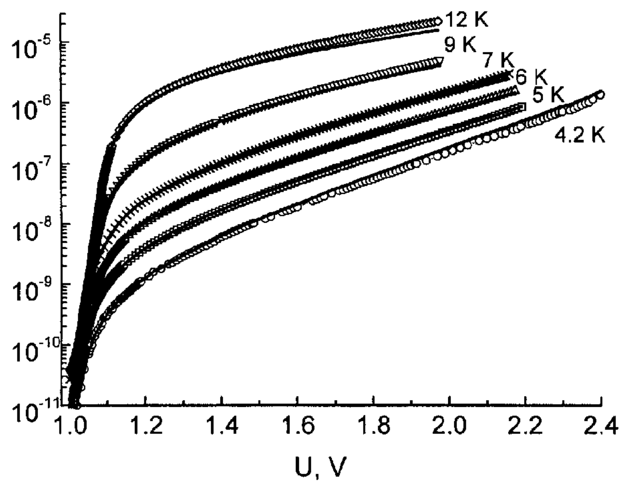

Fig. 2. Current-voltage characteristics of a diode structure at different temperatures. Dots are experiment, solid lines are the result of calculations

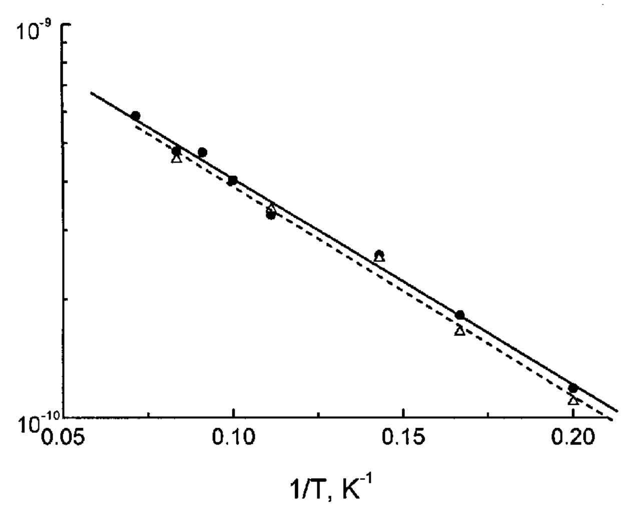

Fig. 3. Dependence of the current on $1/T$ in the temperature range 4.2—13 K at U=1.04 V. • – experiment, Δ — calculation

of a junction, the boron impurity zone in the n^{++} region is filled with electrons completely, while empty states are present in the impurity zone of the p^+ region due to the compensation degree $K \approx 10^{-3}$.

At raising the direct voltage offset, when the lower edge of the impurity zone in the p^+ region descends below the impurity zone (the top of the modified valence band) in the n^{++} region, electrons can pass from the n^{++} region into the p^+ one. At this, a current flows through a diode. The passing rate of electrons from the n^{++} region is determined by the tunneling probability through a

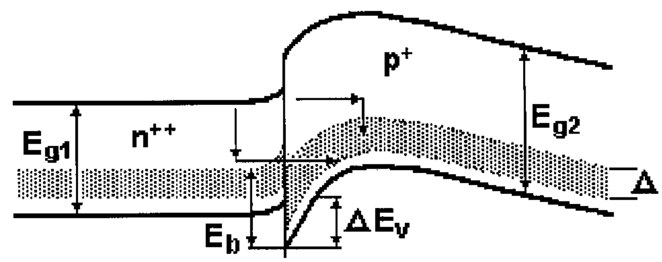

Fig. 4. Model of tunneling in a $n^{++} - p^+$ diode structure at direct offset. The arrows show possible ways for tunneling

barrier. Since the impurity acceptor zone in the emitter region of a diode is fully filled with electrons, it cannot be conductive. This means that an increase of the number of electrons tunneling into the p^+ region of the impurity zone which can conduct current should occur through the conduction band of the emitter by a recombination transition of electrons into the impurity zone close to the heterojunction. This mechanism is similar to that proposed in [9], where the recombination occurs through surface states on the interface.

The following possible tunneling ways can be considered. Electrons from the emitter conduction band can pass into states in the conduction band and then tunnel into the impurity zone of the p^+ region, or electrons can pass into free states in the impurity zone of the n^+ region close to the junction, and then tunnel into the impurity zone of the p^+ region. The tunneling model in the $n^{++} - p^+$ diode structure under consideration under direct voltage offset is shown in Fig. 4.

Using the results of [9] for the tunneling through a potential barrier of a heterojunction, the following expression can be written for the tunneling current I_T:

$$I_T = A \exp\left\{ \frac{-4(m^*\varepsilon)^{1/2} E_b}{3q\hbar (N_{\mathrm{B}})^{1/2}} \right\}, \tag{2}$$

where

$$E_b = (U_{\mathrm{cont}} - U_d)q, \tag{3}$$

$$U_{\mathrm{cont}} = (E_{g1} + \Delta E_v - \delta p)/q, \tag{4}$$

E_b is the barrier height, E_{g1} is the band gap width in the n^{++} region, $\Delta\ E_v$ is the energy break between the edges of the valence bands, δp is the distance of the Fermi level from the valence band top in the p^+ region, A is the quantity weakly dependent on the voltage and temperature, m^* is the effective mass of carriers in the impurity zone.

In the framework of the model chosen, the slope of the current-voltage characteristics under the tunneling mechanism of current flow is determined by the parameter U_T which is not dependent on the temperature and voltage:

$$U_T = 3\hbar(N_{\rm B}/m^*\varepsilon)^{1/2}/4. \quad (5)$$

Since the exact data on the effective mass in an impurity zone, and the permittivity of silicon with concentrations interesting for us are absent, we use $\varepsilon = 11.47$ and $m^* = 0.3m_0$ [10] for estimations, which results in $U_T \approx 0.015$. According to the experimental data, $U_T = 0.014 \div 3.9 \cdot 10^{-4}T$. A weak dependence of the U_T on temperature can be stipulated by the sensitivity of this parameter to details of the potential profile of an impurity zone in the p^+ region of a heterojunction, and to the distribution of energy levels in the impurity zone. To find the potential distribution in a region close to the heterojunction, the distribution of states in the impurity zone should be known, but any information is lacking at present.

Thus, under the direct voltage offsets $U \sim U_{\rm cont}$, the main voltage part drops on the heterojunction, and the tunneling mechanism of current flow dominates in the diode structure. At U exceeding $U_{\rm cont}$, a part of the voltage $U_b \approx U - U_{\rm cont}$ drops on the diode base.

We have shown in [11] that at low temperatures the current flow occurs through the impurity zone in testing structures which are basic for DTS. Such an impurity zone arises due to the casual heterogeneity at considerable doping levels and consists of a huge number of localized states occasionally distributed in both the energy space (in a certain energy band) and semiconductor bulk. The electric conductivity in the impurity zone is realized by electron hopping from one localized state into another due to the finite overlap of electron wave functions on these states. Such a hopping is possible only if some of these localized states have no electrons, i.e., when the impurity compensation takes place.

The analysis of the experimental current-voltage characteristics of testing structures has shown [11] that, at electric fields $E \leq 10^2$ V/cm, the conductivity of base structures in the temperature interval under study, is described well by the Mott law [4]. Mott conductivity in Si:B with a concentration of $3.5 \cdot 10^{18}$ cm^{-3} was also observed experimentally by authors of [12] in the range 1—7 K. The peculiarity of a current flow in the testing base structures is the non-Ohmicity of hopping conductivity with variable hopping length (Mott conductivity) which is observed in the region of moderate electric fields $kT/qa_h > E > kT/qR (20T^{5/4} < E < 370T$ V/cm). It is stipulated by the increase of the electron energy by an electric field on the hopping length R. The dependence of conductivity on the electric field and temperature has the following form [11]:

$$\sigma(E,T) = \sigma_0 \exp\Big\{ Cq(a_h/2)(T_0/T)^{1/4} \times$$
$$\times (kT)^{-1}E - (T_0/T)^{1/4} \Big\} \sim \exp\alpha(T)E, \quad (6)$$

where $\alpha(T) = (C/kT)(a_h q/2)(T_0/T)^{1/4} = \alpha_0 T^{-5/4}$, $T_0 = 16/g(\mu)a_h^3$, $g(\mu)$ is the state density at the Fermi level μ (in the framework of the model chosen, g is constant), C is a constant.

The voltage drop in a diode structure with hopping conductivity in the base, in the region of moderate electric fields looks as

$$U = U_d + U_b \approx U_d +$$
$$+ I\left\{\frac{S}{L}\sigma_0 \exp\left[\alpha_1 T^{-5/4}(U - U_d) - \left(\frac{T_0}{T}\right)^{1/4}\right]\right\}^{-1}, \quad (7)$$

where $\alpha_1 = \alpha_0/L$.

Using (1), (2) and (7), the current-voltage characteristics have been calculated taking into account the theoretical dependence $\sigma_0(T)$ [13], the experimental dependence $U_T(T)$, the values of the parameters $\alpha_1 \approx 26$ cm·K$^{5/4}$/V, $(T_0)^{1/4} = 39$ K$^{1/4}$, which were found from the experimental current-voltage characteristics of the testing base structures [11], and using the fitting parameter $A = 6 \cdot 10^{-12}$A. As can be seen from Figs. 2 and 3, the model proposed describes the principal features of the current-voltage characteristics of the diode structure studied.

4. Thermometric Characteristics and DTS Sensitivity

Using the model of the low-temperature current flow in a diode structure, one may calculate the sensor TMC. For this, Eq. (7) should be considered as a dependence $U(T)$ at a constant current value. To find $U(T)$, we used the non-linear least-square Newton—Gauss method. The calculation has been carried out using the Optimisation Toolbox extension package of the MatLab software. The results of numerical modeling as well as the experimental TMC for different values of the working current are presented in Fig. 5.

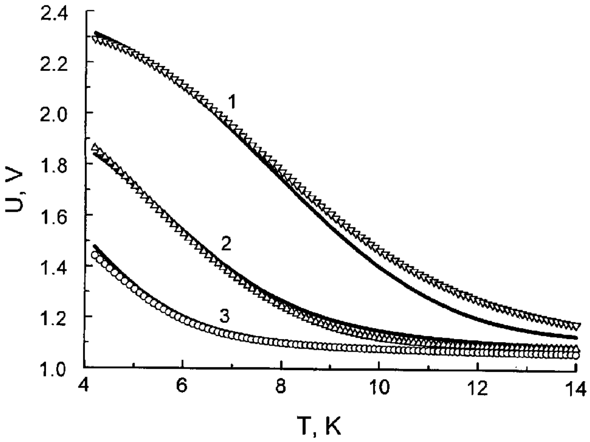

Fig. 5. Thermometric characteristics of DTS for the working currents, I, μA: *1* — 1; *2* — 0.1; *3* — 0.01. Lines are experiment, dots are the result of calculations

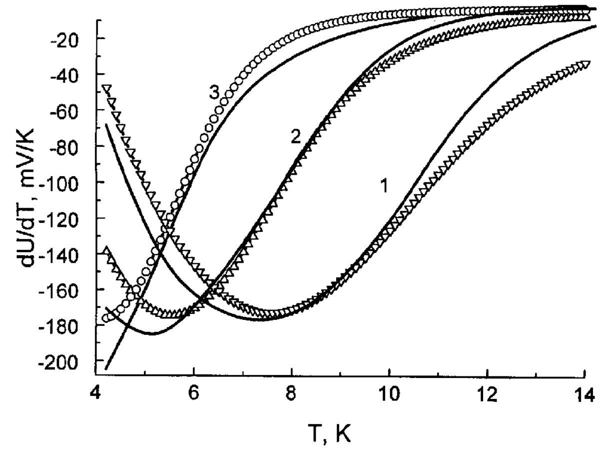

Fig. 6. Temperature dependence of DTS sensitivity for the working currents, I, μA: *1* — 1; *2* — 0.1; *3* — 0.01. Lines are experiment, dots are the result of calculations

In Fig. 6, the experimental and theoretical dependences of sensitivity upon the temperature are presented, which were obtained by spline interpolation for different values of the working current. Note that the model proposed describes the characteristic features of the dU/dT behavior that are observed experimentally, namely: (i) its absolute value growth with decrease in temperature, (ii) the curve maximum and its shift with decrease in the working current. The maximum DTS sensitivity is ~ -180 mV/K. For the current 1 μA, it is observed at T=7.6 K, for 0.1 μA — at T=5.6 K. The maximum becomes less expressed when the current decreases. For a current of 0.01 μA, it is absent at all in the temperature range under investigation.

The increase of the DTS sensitivity with the temperature drop from 14 to 4.2 K occurs under the increase of the contribution of conductivity of the diode base region to the current flow. The non-Ohmicity of the current-voltage characteristics in the region of Mott hopping conductivity is determined by the relation between the first and second terms in the exponent in Eq. (7). This relation depends on the impurity zone parameters (T_0, α), the current (electric field) value, and the temperature. The maximum of the temperature dependence of sensitivity (Fig. 6) is stipulated by the non-Ohmic character of Mott conductivity in the DTS base. At low current (field) values, the role of the non-Ohmicity decreases, and the maximum disappears.

Therefore, choosing the base length and the working current value (or the field region), one may influence the TMC form as well as the value of sensitivity, by changing the contribution of non-Ohmicity to the Mott conductivity.

Conclusion

1. High doping levels of the n^{++} region of a diode structure lead to the asymmetric narrowing of the band gap by $\sim$ 130 meV, and the formation of an $n^{++} - p^{+}$ heterojunction potential barrier. The proposed model of the current flow in the $n^{++} - p^{+}$ structure with the account of non-Ohmic Mott conductivity along the acceptor impurity zone in the diode base and the tunnel current through the heterojunction potential barrier between the n^{++} and p^{+} parts of the impurity zone describes quite well experimental current-voltage diode characteristics.

2. The considered combined model allowed us to calculate the TMC and the temperature dependence of DTS sensitivity and to explain the peculiarities observed experimentally, namely: (i) the non-monotonous sensitivity in the temperature range 4.2—13 K, (ii) the maximum of dU/dT, whose value reaches ~ -180 mV/K, (iii) the influence of the value of current on the TMC and the sensitivity forms. The theoretical dependences agree well with the experimental data and can be used for the optimization of the cryogenic DTS parameters.

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Received 03.11.03.
Translated from Ukrainian by A.V. Sarikov

МОДЕЛЮВАННЯ НИЗЬКОТЕМПЕРАТУРНОГО СТРУМОПЕРЕНЕСЕННЯ І ЧУТЛИВІСТЬ В КРЕМНІЄВИХ ДІОДНИХ СЕНСОРАХ ТЕМПЕРАТУРИ

Ю.М. Шварц, М.М. Шварц, О.М. Іващенко, О.В. Кондрачук, Л.І. Шпинар

Р е з ю м е

Вольт-амперні і термометричні характеристики кремнієвих діодних сенсорів температури (ДСТ) досліджено при низьких температурах. Запропонована модель низькотемпературного струмоперенесення $n^{++} - p^{+}$ в діодній структурі враховує механізм неомічної стрибкової провідності зі змінною довжиною стрибка в базовій області діода і тунельний струм крізь потенціальний бар'єр гетеропереходу. Такий гетероперехід утворюється внаслідок асиметричного звуження ширини забороненої зони в n^{++}- і p^{+}-областях, зумовлене високими і різними рівнями легування емітера та бази діода. Знайдені залежності параметрів неомічної стрибкової провідності від температури і електричного поля дозволили з'ясувати характерні особливості чутливості діодних сенсорів, які спостерігаються в області гелієвих температур.