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SEMICONDUCTOR STRUCTURES, INTERFACES, AND SURFACES

An Analysis of the Charge-Transport Mechanisms Defining the Reverse Current–Voltage Characteristics of the Metal–GaAs Barriers

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Abstract—Reverse current–voltage characteristics of metal–GaAs contacts with a Schottky barrier were measured. Linear portions of the reverse-current dependence on the squared electric-field strength in the space-charge region of diodes were obtained. Such a dependence is related to electron interaction with the lattice vibrations. The reverse current of the Mo–GaAs:Si contacts is analyzed at different temperatures. Results of the analysis showed that measured current–voltage characteristics are controlled by the phonon-assisted electron tunneling from metal into semiconductor with the involvement of a deep center attributed to the *EL2* trap. A similar mechanism governs the reverse current–voltage characteristics of the Ni–GaAs:S Schottky diodes.

1. INTRODUCTION

An increase in the speed of response and a decrease in the power consumption are still urgent problems in the development of modern circuits for computer engineering and information processing. The first problem may be resolved by choosing semiconductor materials with a high carrier mobility and the second, by reducing the operating voltages of devices. In view of these circumstances, Schottky diodes based on the III–V materials are more and more widely used in microwave (MW) engineering and optoelectronics. Therefore, the current development of semiconductor MW electronics and integrated microcircuits, in which the field-effect transistors with a Schottky gate based on GaAs are used, reflects a necessity for more detailed study of the material itself and of the electron processes which occur in the space charge region (SCR) of devices.

The objective of this study was to gain insight into the mechanism of an increase in the probability of the electron transitions from deep-level centers in the SCR of semiconductor devices and into the influence of these effects on the reverse current–voltage characteristics of the metal–semiconductor contacts.

2. EXPERIMENT: THE REVERSE CURRENT DEPENDENCES ON THE ELECTRIC FIELD

We studied two series of samples. Among the first series were Schottky diodes fabricated by the electrochemical deposition of Ni on S-doped GaAs. The sample preparation was described elsewhere [1, 2]. Among the second series were commercial MW varicaps based on the Schottky diodes. The *n*-GaAs epilayer substrates were grown by vapor-phase epitaxy. The varicap structure consisted of three consecutively grown layers with concentrations of the doping impurity (Si) equal to 0.3×10^{18}, 4.1×10^{18}, and 0.3×10^{18} cm^{-3}. The Schottky barrier was fabricated by molybdenum vacuum deposition. The contact area was about 1 mm^2. Studies of the contact characteristics [1, 3] showed that these structures are Schottky diodes. The current–voltage (I–V) characteristics of the MW varicaps were measured at a reverse bias in a voltage range from 0 to 10 V and in a temperature range of 100–370 K (Fig. 1). We measured the current–voltage characteristics of the Ni–GaAs barriers at room temperature in the voltage range of 0–2 V.

It can be seen from Fig. 1 that, in a rather wide temperature range (from 125 to 243 K), the current in the samples of the second series (varicaps) is scarcely affected by temperature, but at the same time a strong field dependence exists. Such dependence of current is typical of the tunnel mechanism of charge transport [3]. In this case, the current is given by [4]

$$I_c = I_{0c}\exp\left[-\frac{4}{3}\frac{\sqrt{2m^*}}{eF\hbar}(E_+^*)^{3/2}\right], \qquad (1)$$

where F is the electric field strength in the SCR, and E_+^* is the tunneling effective energy which depends on the energy depth of level. To verify an assumption concerning the tunnel mechanism of the charge transport, I–V characteristics were rearranged to the $I = f(1/F)$ coordinates. The reverse bias voltage applied to the sample was converted to the field strength in the SCR

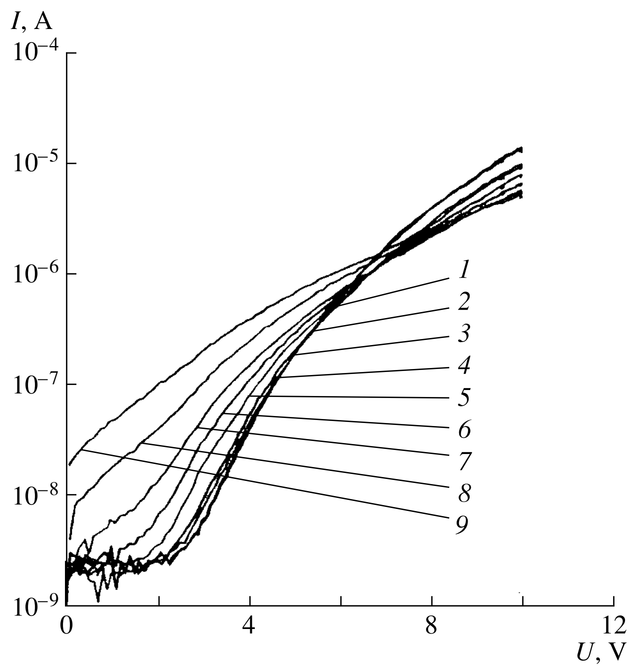

Fig. 1. Reverse current–voltage characteristics of microwave varicap at temperatures T = (*1*)125, (*2*) 168, (*3*) 209, (*4*) 243, (*5*) 275, (*6*) 307, (*7*) 338, (*8*) 351, and (*9*) 370 K.

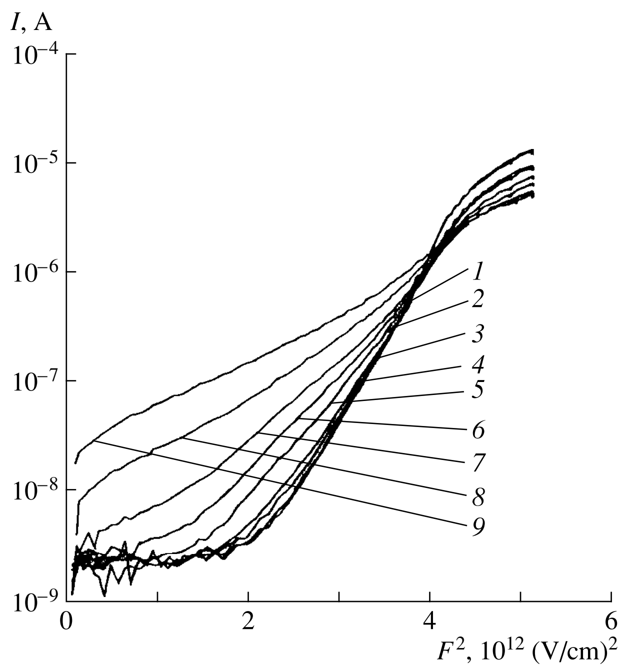

Fig. 2. Reverse current dependence of microwave varicap on the squared field strength in the space charge region at temperatures T = (*1*) 125, (*2*) 168, (*3*) 209, (*4*) 243, (*5*) 275, (*6*) 307, (*7*) 338, (*8*) 351, and (*9*) 370 K.

of the Schottky contact according to the relation [3]

$$F(U) = \frac{1}{\varepsilon\varepsilon_0 S}\int_{U-U_k}^{U} C(u)du, \tag{2}$$

where integration was performed over the experimental dependence of the SCR capacitance (C) on the voltage (U) for forward (from $u = U - U_k$ to 0) and for reverse (from 0 to $u = U$) biases and S is the barrier area. This conversion is necessary because of the complexity of the doping profile of the samples under study [5].

I–V characteristics in the $I = f(1/F)$ coordinates are well approximated in the high field region by a straight line in the entire temperature range. The effective energy obtained from the slope is equal to 0.64 eV. It is evident that experimental results are well described by the tunneling model through the deep center. The energy depth of the center E_+ was calculated from the equation [4]

$$E_+^* = E_g\left\{\frac{3}{16}\left[\frac{\pi}{2} - \arcsin\left(1 - \frac{2E_+}{E_g}\right)\right] - \frac{3}{8}\left(1 - \frac{2E_+}{E_g}\right)\sqrt{\frac{E_+}{E_g} - \left(\frac{E_+}{E_g}\right)^2}\right\}^{2/3}, \tag{3}$$

where E_g is the band gap, and was found to be 0.73 eV, which agrees well with the trap level *EL2* in GaAs.

In the low-field region, the current depends only slightly on field. Such *I–V* behavior is related to a predominance of the leakage currents in this region.

3. CALCULATION OF PARAMETERS OF THE PHONON-ASSISTED TUNNELING MODEL

Multiphonon processes are of considerable importance in nonradiative transitions [2, 6–8]. Electron–phonon interaction results in the temperature dependences of the capture coefficients and in an increase of the thermal emission rate in high electric fields. The vibration states of the impurity centers cause a similar effect which may explain the observed current increase with temperature. It is experimentally [2, 9] and theoretically [10–18] shown that the probability of these transitions in high electric fields increases exponentially with the squared electric-field strength. A similar strong increase in electric current (considering that $U \propto F^2$ for an abrupt *p–n* junction) can be seen in Fig. 2. According to Fig. 2, the electric field strength F exceeds 2×10^6 V/cm, which corresponds to high electric fields, in the SCR of the MW varicap. As can be seen from Fig. 2, a linear dependence of the logarithm of the current on F^2 is observed in the range from 10^{12} to 4×10^{12}(V/cm)^2 (abscissa axis).

If only one level exists in the band gap of a semiconductor, then the reverse current through the SCR with the involvement of this level (irrespective of the charge transport mechanism) can be expressed as

$$I = Se\int_0^l \frac{W_1 W_2}{W_1 + W_2}dx \approx Se\frac{W_1 W_2}{W_1 + W_2}l, \qquad (4)$$

where l is the SCR width, and W_1 and W_2 are the probabilities of the electron transition from metal to the deep level and from this level to the conduction band. The probability of one of the transitions is usually higher. Assuming that the energy distance between the deep level and the bottom of the conduction band is $E_t > \varphi_b - E_t$, where φ_b is the barrier height, we obtain $W_2 \gg W_1$. In this case, formula (4) may be rewritten as $I \approx SeW_1 l$. Therefore, to an accuracy of the field dependence of the SCR width, we have $I(F, T) = \text{const}\,W_1(F, T)$.

In recent papers devoted to the study of multiphonon generation–recombination processes involving deep impurity centers based on the studies of Perel and Yassievich [15–19], the probability of tunnel multiphonon ionization as a function of the electric field is given by the relation [19]

$$W(F, T) = W(0, T)\exp(F^2/F_0^2), \qquad (5)$$

where

$$\frac{1}{F_0^2} = \frac{\tau_2^3 e^2}{3m^*\hbar}, \text{ but } \tau_2 = \frac{\hbar}{2kT} - \frac{\hbar}{2\hbar\omega}\ln\left(\frac{S\hbar\omega}{E_0}\right). \qquad (6)$$

Here S is a coefficient. Approximating the linear portions of the curve $\log I(F^2)$ (Fig. 2) by straight lines, we obtained the slopes of these portions $\frac{d\ln I}{d(F^2)}$. Then, after plotting the $\sqrt[3]{\frac{d\ln I}{d(F^2)}} = f\left(\frac{10^3}{T}\right)$ dependence, we analyzed the applicability of formulas (5) and (6) to describe the experimental curves (Fig. 3). Initially (at high temperatures) this dependence is well approximated by the straight line

$$y = (\tan\alpha_{\text{exp}})\frac{10^3}{T} - y_0.$$

The slope of this line is $\tan\alpha_{\text{exp}} = 3.24 \times 10^{-5}$. This result is in good agreement with the theoretical value obtained from (6):

$$\tan\alpha_{\text{theor}} = \frac{\hbar}{2k}\sqrt[3]{\frac{e^2}{3m^*\hbar}}\frac{1}{10^3} = 1.83\times 10^{-5}.$$

It should be noted that so far we have not made any assumptions about the character of the deep center that is involved in this transition. We now assume that trap *EL2* is involved in this process. According to the above, we assume that the energy of the *EL2* level is E_0 = 0.73 eV. We used the local phonon energy as well as the Huang and Rhys factor as adjustable parameters. The cutoff value $y_0 = -1.51 \times 10^{-5}$ obtained from approximation by a straight line is in good agreement with the theoretical value calculated from the relation (6) for $\hbar\omega$ = 28 meV and S = 7. This result differs only slightly from the data reported, for example, in [20] where

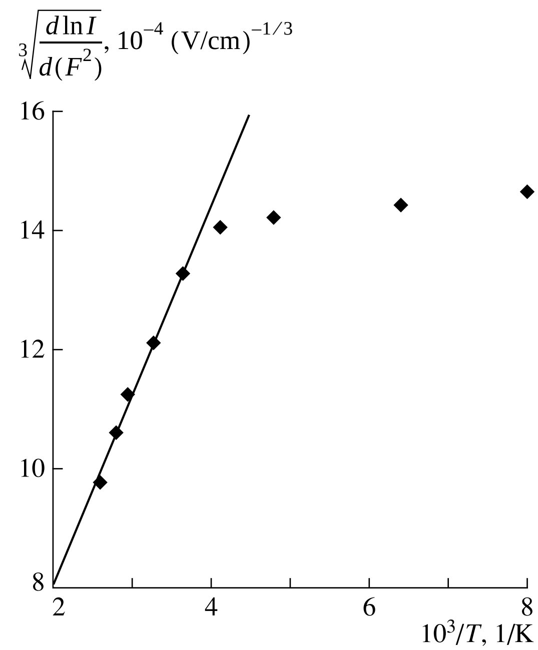

Fig. 3. Dependence of $[d\ln I/d(F^2)]^{1/3}$ on $10^3/T$.

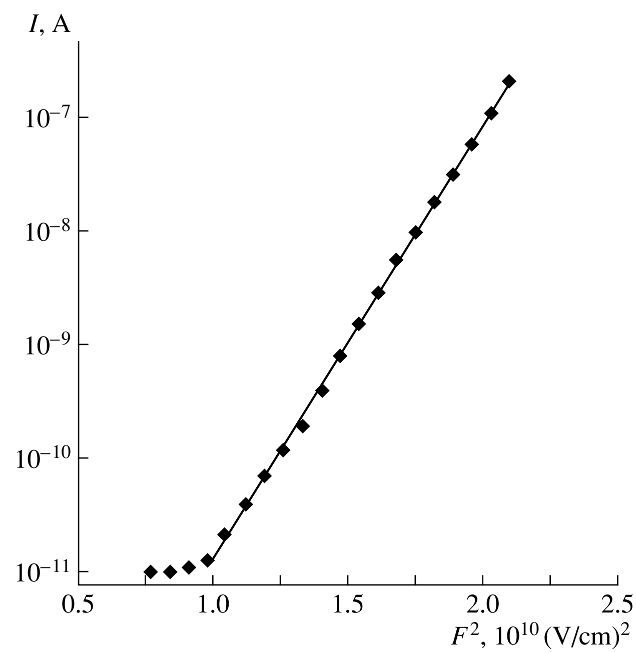

Fig. 4. Reverse current–voltage characteristic of the Ni–GaAs:S diode at T = 295 K.

$\hbar\omega = 20 \pm 5$ meV and $S\hbar\omega = 115 \pm 50$ meV. It should be noted that the deep center of the $V_{Ga}S_{As}$ complex, which we previously studied [2], either is not involved at all in the charge transport in the SCR of the reverse-biased diode or its contribution is negligible. This follows from the fact that the energy depth of this center is larger than the potential-barrier height of the Ni–GaAs contact.

A plot of the reverse current as a function of the squared field strength in the SCR of the Ni–GaAs:S diode is shown in Fig. 4. It can be seen that, in the squared-field range from 10^{10} to 2.5×10^{10} (V/cm)^2, the dependence of log$I$ on F^2 is linear. The slope in this portion of the curve is $d\ln I/d(F^2) = 8.81 \times 10^{-10}$, which agrees with the theoretical value

$$\frac{d\ln I}{d(F^2)} = 1/F_0^2$$

for parameters $\hbar\omega = 19.5$ meV and $S = 7$ (the calculation was performed on the assumption that *EL2* traps with the energy depth $E_0 = 0.73$ eV are involved in the process). This result agrees better with the data of [20], although due to the absence of the temperature-related measurements we cannot state that *EL2* traps exist. Nevertheless, an obvious linear current dependence on the squared field strength observed in all the samples studied enables us to state that a mechanism for phonon-assisted tunnel transport of charge carriers exists.

4. CONCLUSION

Thus, we measured the reverse current–voltage characteristics of the Ni–GaAs:S Schottky diodes, fabricated in the laboratory, and of commercial MW varicaps based on the Mo–GaAs:Si Schottky diodes. In both types of samples, linear portions of the reverse current dependences on the squared electric-field strength in the space charge region of diodes were observed. It is shown that such dependence is related to the interaction of electrons with the lattice vibrations. The reverse current of the MW varicaps is analyzed at different temperatures. Results of analysis showed that the current–voltage (*I*–*V*) characteristics are controlled by the phonon-assisted electron tunneling from metal into semiconductor with the involvent of a deep center attributed to the *EL2* trap. It is shown that a similar mechanism also governs reverse *I*–*V* characteristics of the Ni–GaAs:S Schottky diodes.

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