Semiconductors, Vol. 34, No. 5, 2000, pp. 550–554. Translated from Fizika i Tekhnika Poluprovodnikov, Vol. 34, No. 5, 2000, pp. 567–571.
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SEMICONDUCTOR STRUCTURES, INTERFACES, AND SURFACES

Conditions for Negative Differential Resistance and Switching in a Tunnel Diode under the Effect of an External Microwave Signal

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Submitted November 22, 1999; accepted for publication November 26, 1999

Abstract—Experimentally observed phenomenon of the origination of the mode of negative differential resistance and switching in a tunnel diode under the effect of external microwave signal is theoretically interpreted. The reasons for the existence of the ranges of bias voltages applied to the diode and the power levels of microwave signal for which the phenomenon is observed are clarified. *© 2000 MAIK "Nauka/Interperiodica".*

INTRODUCTION

A high-strength microwave field substantially affects the characteristics of charge transport in the structures based on *p–n* junctions [1–3]. In [4, 5], the phenomenon of variation in the shape of current–voltage (*I–V*) characteristics of tunnel diodes under the effect of large-amplitude microwave signals was observed experimentally and interpreted theoretically. In particular, it was found that, as a result of the appearance of a thermal current of hot charge carriers and the detector phenomenon under the effect of microwave power, the peak value of current in the forward *I–V* characteristic decreases and the portion with negative differential resistance disappears for a certain level of microwave signal. If a tunnel diode energized by a dc voltage power supply was used as an active element in a self-excited oscillator, the above resulted in the suppression of autooscillations [6].

The use of load resistances in the feed circuits of tunnel diodes or a series connection of several tunnel diodes causes the dc voltages to be redistributed between the elements of an electric circuit under the effect of the microwave signal [7]. In particular, such a process can give rise to the mode of negative differential resistance and switching in the tunnel diode under the effect of an external microwave signal in the case where the voltage applied to the diode is much lower than the peak value. Such phenomena are the objects of this study.

EXPERIMENTAL

We studied experimentally the influence of high-power microwave radiation on the shape of low-frequency *I–V* characteristics of 1I308 tunnel diodes, with a constant series resistance of 50 Ω being connected in the feed circuit of these diodes.

The tunnel diode was mounted on a holder in a resonator based on a section of a short-circuit waveguide with a cross-sectional area of 7.2×3.4 mm^2. The frequency of microwave radiation was 38 GHz.

In order to reduce the effect of thermal heating of a diode structure, we used the ac voltage power supply with a frequency of 100 Hz.

The value of the supply voltage V_d of positive polarity applied to the series connected tunnel diode and resistance was chosen so that, in the absence of a microwave signal, the bias voltage V_0 applied to tunnel diode did not exceed the peak value V_p.

Figure 1 shows the experimental *I–V* characteristics of the tunnel diode measured for various power levels of the microwave signal and within the same range of voltages V_d.

It follows from the results obtained that, as the power level of microwave radiation increases to a certain value, the bias voltage V_0 applied to the tunnel diode increases abruptly and the operating point falls first in the region of negative differential resistance and then in the diffusion portion of the *I–V* characteristic of the tunnel diode; i.e., the mode of negative differential resistance and the switching mode occur in the tunnel diode as a result of microwave irradiation.

Figure 2 shows experimental dependences of the bias voltage V_0 applied to the tunnel diode on the value of voltage V_d; they suggest that the switching voltage corresponding to an abrupt transition of the tunnel diode from the low-resistance state to the high-resistance state decreases with the increasing power of microwave radiation.

With a further substantial increase in the power of microwave radiation, the region of negative differential resistance disappeared and the *I–V* characteristic of the tunnel diode became almost linear (Fig. 1, curve *6*).

MODEL USED IN CALCULATIONS

When simulating the behavior of a tunnel diode incorporated into the microwave resonator, we used the equivalent circuit shown in Fig. 3. The elements of this equivalent circuit simulate the semiconductor diode structure in the form of parallel connection of the capacitance C and nonlinear resistance R [3]. The diode case is simulated by the elements L_c and C_c, and the waveguide section is represented by the input admittance in the plane of the diode Y_0.

It was assumed that the resistance of the diode base was independent of the current and is much less than the resistance R of the p–n junction for the bias voltages V no greater than the contact-potential difference V_{cont}. For $V > V_{cont}$, the value of R was assumed to be constant and was defined as $R = \rho\frac{l}{S}$, where ρ, l, and S are the resistivity, thickness, and area of the base of the diode structure.

The nonlinear resistance R was defined as the average resistance of the p–n junction for the first harmonic of microwave current; i.e.

$$R = \frac{V^{\sim}}{I^{\sim}}, \quad \text{where } I^{\sim} = \sqrt{A^2 + B^2},$$

$$A = \frac{2}{T}\int_0^T I(V)\sin\omega t dt,$$

$$B = \frac{2}{T}\int_0^T I(V)\cos\omega t dt,$$

$$V = V_0 + V^{\sim}\sin\omega t.$$

Here, V_0 and $V^{\sim}$ are the constant bias voltage and the amplitude of alternating microwave voltage applied to the tunnel diode, I is the current through the resistance R, and $T = 2\pi/\omega$ is the period of microwave oscillations.

In the context of the model suggested, the constant bias voltage V_0 is identified with the instantaneous value of the low-frequency alternating bias voltage applied to the tunnel diode in the experiments; this low-frequency voltage may be regarded as constant compared to the microwave voltage.

When simulating the current through the tunnel diode, we used an expression for the I–V characteristic derived with allowance made for variations in the tunnel (I_T), excess (I_X), and diffusion (I_D) components of the total current I due to heating of the free charge carriers [5]; i.e., we have

$$I(V) = I_T + I_X + I_D.$$

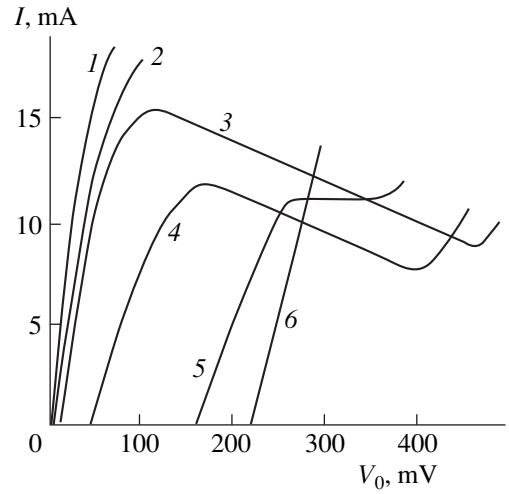

Fig. 1. Experimental I–V characteristics of the tunnel diode for the power levels of microwave radiation P_0 equal to (*1*) 0, (*2*) 50, (*3*) 100, (*4*) 400, (*5*) 800, and (*6*) 1200 mW for V_d = 900 mV.

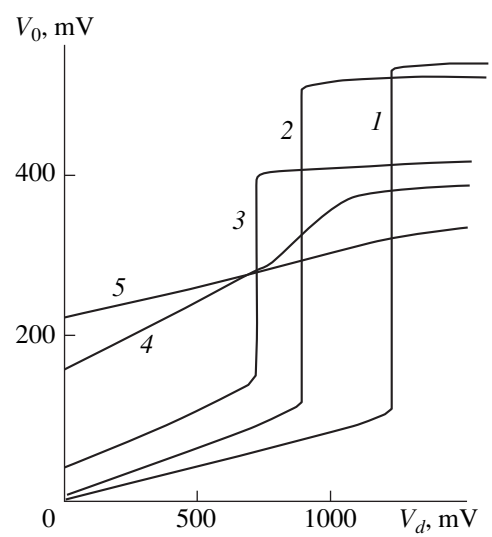

Fig. 2. Experimental dependences of the bias voltage V_0 applied to the tunnel diode on the supply voltage V_d for the power levels of microwave radiation P_0 equal to (*1*) 0, (*2*) 100, (*3*) 400, (*4*) 800, and (*5*) 1200 mW.

Here,

$$I_T = AT_T\int_{\varepsilon_c}^{\varepsilon_v}[f_{CT}(\varepsilon) - f_{VT}(\varepsilon)]g_c(\varepsilon)g_v(\varepsilon)d\varepsilon,$$

$$I_X = A_1 D_x S\exp(-a_x\varepsilon_x),$$

$$I_D = \frac{qSD_n n_{p0}}{L_n}\left\{\frac{kT_n}{\zeta_n(T_n) - \varepsilon_c}\frac{\zeta_n(T_0) - \varepsilon_c}{kT_0}\right.$$

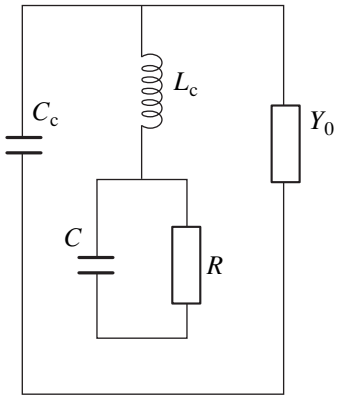

Fig. 3. Equivalent microwave circuit of a tunnel diode mounted in a microwave resonator.

$$\times \exp\left(\frac{qV_{\text{cont}}}{kT_0} - \frac{\zeta_n(T_0) - \varepsilon_c}{kT_0}\right)$$

$$\times \ln\left[1 + \exp\left(\frac{\zeta_n(T_n) - \varepsilon_c}{kT_n} - \frac{qV_{\text{cont}}}{kT_n} + \frac{qV}{kT_n}\right)\right] - 1\Bigg\}$$

$$+ \frac{qSD_p p_{n0}}{L_p}\Bigg\{\frac{kT_p}{\varepsilon_v - \zeta_p(T_p)}\frac{\varepsilon_v - \zeta_p(T_0)}{kT_0}$$

$$\times \exp\left(\frac{qV_{\text{cont}}}{kT_0} - \frac{\varepsilon_v - \zeta_p(T_0)}{kT_0}\right)$$

$$\times \ln\left[1 + \exp\left(\frac{\varepsilon_v - \zeta_p(T_p)}{kT_p} - \frac{qV_{\text{cont}}}{kT_p} + \frac{qV}{kT_p}\right)\right] - 1\Bigg\},$$

where $f_{CT}(\varepsilon)$ and $f_{VT}(\varepsilon)$ are the Fermi–Dirac distribution functions for electrons in the conduction and valence bands for the electron temperature T_n; T_p is the hole temperature; T_0 is the lattice temperature; A, A_1, and a_x are constants; T_T is the probability of tunneling transit through the potential barrier between the p-region and the n-region; $g_c(\varepsilon)$ and $g_v(\varepsilon)$ are the densities of energy states in the conduction and valence bands; ε_c and ε_v are the energies corresponding to the bottom of the conduction band and to the top of the valence band; ε_g is the bandgap; ζ_n and ζ_p are the quasi-Fermi levels in the n- and p-type semiconductors; D_x is the density of occupied states located in the forbidden band above the top of the valence band by the energy ε_x defined as

$$\varepsilon_x \approx \varepsilon_g - qV + (\zeta_n(T_n) - \varepsilon_c) + (\varepsilon_v - \zeta_p(T_p));$$

D_n and D_p are the diffusion coefficients for electrons and holes; S is the cross-sectional area of the p–n junction; and V is the voltage applied to the diode.

We calculated the I–V characteristic of the diode taking into account the detector effect and using the relationship

$$I_c = \frac{1}{T}\int_0^T I(V)dt.$$

It was taken into account in calculations that the constant resistance R_l connected in series with the tunnel diode was included in the feed circuit. The current–voltage characteristic $I_c(V_0)$ was determined by solving the equation

$$V_d = V_0 + I_c R_l,$$

where V_d is the supply voltage applied to the series-connected tunnel diode and the resistance.

The amplitude of microwave voltage $V^{\sim}$ was determined from the value of microwave power P absorbed by the diode; i.e.,

$$P = \frac{(V^{\sim})^2}{2R}.$$

In order to calculate the power absorbed by the diode mounted in the resonator, we used the expression [8]

$$P = P_0(1 - |N|^2),$$

where P_0 is the power of microwave radiation incident on the diode, $N = \dfrac{Y - Y_0}{Y + Y_0}$ is the coefficient of the reflection of microwave radiation from the diode, and $Y = j\omega C_c + \left[\dfrac{R}{1 + j\omega RC} + j\omega L_c\right]^{-1}$ is the admittance of the tunnel diode.

RESULTS OF CALCULATIONS

The calculations showed that, if the microwave signal was absent and a small-amplitude forward voltage was applied, most of the applied voltage dropped across a 50-Ω resistor connected in series with the tunnel diode. As the forward voltage V_d increases, a steady increase in the bias voltages across the tunnel diode V_0 and across the series resistor V_l occurs, with the ratio between these voltages equal to the ratio of the corresponding resistances under the dc conditions (Fig. 4, curve *1*). If the voltage V_0 reaches the peak value V_p (in the case under consideration, $V_p \approx 110$ mV), an abrupt redistribution of voltages between the tunnel diode and the resistor occurs: as V_d increases from 1220 to 1240 mV, the voltage V_0 increases from 110 to 420 mV; i.e., the tunnel diode switches from the low-resistance state to the high-resistance one, in which case the operating point is abruptly transferred along the load line from one ascending portion of the I–V characteristic to another ascending portion of this characteristic.

When the microwave signal is applied to the tunnel diode, a decrease in the total-current tunnel component, a sharp increase in the diffusion component, and an insignificant increase in the excess component of the total current through the tunnel diode are observed [5]. This causes the peak current I_p in the forward portion of the tunnel-diode *I–V* characteristic to decrease as the bias voltage V_p corresponding to this peak current is increased somewhat. Consequently, the effect of the microwave signal on the tunnel diode consists in an increase of the tunnel-diode dc resistance in the range of predominance of the tunnel component of the total current and in a decrease of this resistance in the range of predominance of the diffusion component of the total current.

Such changes in the *I–V* characteristic of the tunnel diode cause the voltage V_0 across the tunnel diode to increase with increasing microwave power and with V_d kept constant in the range of positive slope of the *I–V* characteristic in the vicinity of zero bias. As the microwave power increases to a certain value P_p, the voltage V_0 reaches the value corresponding to the starting point of the descending portion in the *I–V* characteristic of the tunnel diode, and an abrupt redistribution of dc voltages between the tunnel diode and the series resistance occurs (Fig. 5, curves *3*, *4*); as a result, the operating point is transferred along the load line through the region of negative differential resistance to a point located at the ascending portion of the tunnel-diode *I–V* characteristic. It is this effect that was observed in the experiment outlined above.

As was mentioned above, a further increase in the microwave power causes the tunnel-diode resistance to decrease in the region of predominance of the diffusion component of the total current (i.e., at the second ascending portion of the tunnel-diode *I–V* characteristic). This leads to a slight decrease in the bias voltage V_0 applied to the tunnel diode for a fixed value of V_d.

Figure 6 shows the tunnel-diode *I–V* characteristics calculated for various power levels of microwave radiation and for the same range of voltages V_d.

It is noteworthy that the changes in the *I–V* characteristic of the tunnel diode caused by microwave irradiation with increasing power result in a shift of the region of abrupt increase in V_0 in the dependence $V_0(V_d)$ to smaller values of V_d (Fig. 4, curves *2–4*).

Since, as follows from the results of calculations illustrated in Fig. 5, the value of P_p for which V_0 reaches the value corresponding to the starting point of the descending portion of the *I–V* characteristic is defined by the voltage V_d and increases with decreasing V_d, the effect of abrupt redistribution of voltages is bound to be observed at higher levels of microwave power for small values of V_d. On the other hand, an appreciable increase in the microwave power causes the current to decrease in the maximum of the tunnel-diode *I–V* characteristic and to increase in the minimum of this characteristic to such an extent that the *I–V* characteristic ceases to have an *N*-shape and becomes similar to the forward *I–V* characteristic of an inversed diode. For a still larger magnitude of the microwave signal, the *I–V* characteristic of the diode becomes almost linear.

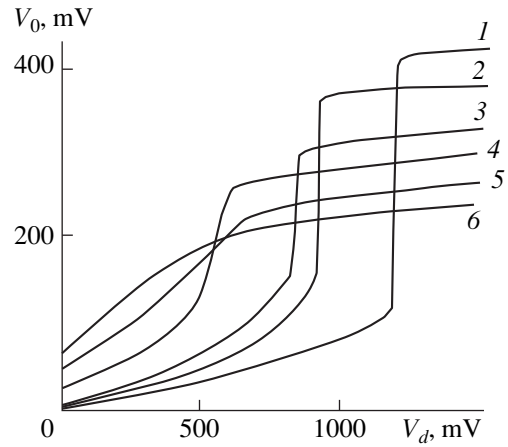

Fig. 4. Calculated dependences of bias voltage V_0 applied to the tunnel diode on the supply voltage V_d for the power levels P_0 of microwave radiation equal to (*1*) 0, (*2*) 50, (*3*) 100, (*4*) 400, (*5*) 800, and (*6*) 1200 mW.

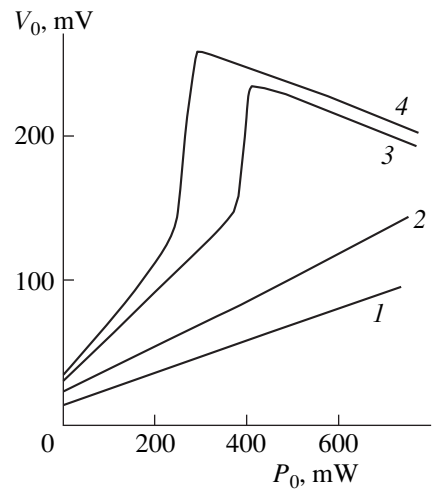

Fig. 5. The bias voltage V_0 applied to the tunnel diode as a function of the power level P_0 of microwave signal for the supply voltages V_d equal to (*1*) 250, (*2*) 350, (*3*) 500, and (*4*) 550 mV.

Such a change in the *I–V* characteristic causes the effect of abrupt switching of the tunnel diode from the low-resistance state to the high-resistance state to disappear and the region of negative differential resistance to cease to exist. In this case, abrupt changes in V_0 in the dependences $V_0(P)$ (Fig. 5, curves *1*, *2*) and $V_0(V_d)$ (Fig. 4, curves *5*, *6*) are no longer observed.

Consequently, for a given type of tunnel diode and a chosen value of series resistance, there exist a minimal

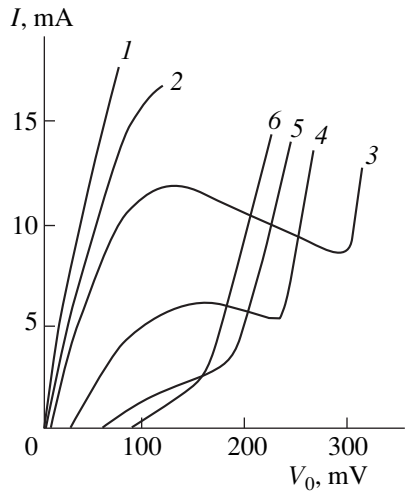

Fig. 6. The tunnel-diode *I–V* characteristics calculated for the microwave-radiation power levels P_0 = (*1*) 0, (*2*) 50, (*3*) 100, (*4*) 400, (*5*) 800, and (*6*) 1200 mW.

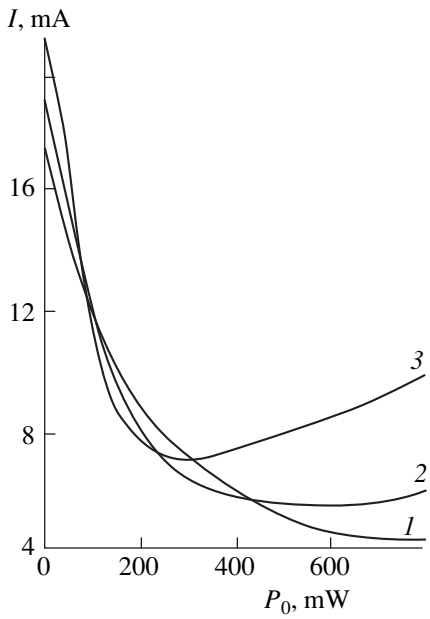

Fig. 7. The direct current of tunnel diode as a function of the power level of microwave radiation for V_d = (*1*) 250, (*2*) 270, and (*3*) 300 mV.

value V_{dm} of the voltage and a corresponding value V_{0m} of the bias voltage for which the phenomenon of negative differential resistance and switching under the effect of external microwave signal becomes possible. In the absence of a microwave signal, the value of current I_{0m} for a 1I308 diode is equal to $0.5I_p$ for $V_0 = V_{0m}$ and $R_l = 50\ \Omega$.

It is worth noting that, choosing the bias voltage at the positive-slope portion of the *I–V* characteristic $V_{0m} < V_0 < V_p$ and connecting a resistance of $R_l = 50\ \Omega$ in series with the diode (so that R_l is much larger than the tunnel-diode resistance R_0 in the vicinity of zero bias), we can use the external microwave signal to switch the tunnel diode over the region of negative differential resistance with respect to voltage (Fig. 4, curves *2*, *3*, *4*); if the resistor with $R_l = 10\ \Omega$ comparable to R_0 is employed, one can use the microwave signal to switch the tunnel diode over the region of negative differential resistance with respect to current (Fig. 7).

The results of the calculations are in good qualitative and quantitative agreement with the experimental data obtained.

CONCLUSION

Thus, we demonstrated experimentally and substantiated theoretically the possibility of initiating the mode of negative differential resistance and switching in a tunnel diode exposed to microwave radiation for supply voltages lower than the peak value.

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Translated by A. Spitsyn