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Superhigh-Frequency Characteristics of Optical Modulators on the Basis of InGaAlAs Resonance-Tunnel Heterostructures

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Abstract—The impedance of InGaAlAs resonance-tunnel heterostructures used for modulation of optical radiation is experimentally studied in the frequency range from 45 to 18 MHz. The dependence of their equivalent circuit on the bias voltage is determined. The spectrum of the harmonics of the current in the resistive frequency multiplication in such structures is calculated. The results confirm that these structures are promising as applied to the frequency multiplication. The effect of frequency multiplication is demonstrated experimentally at low frequencies.

The tunnel diodes (TDs) created on the basis of two-barrier heterostructures were first proposed in [1]. They are characterized by a substantially nonlinear voltage–current characteristic (VCC) with regions of negative differential conductance (NDC). In [2], the efficiency of TDs at frequencies above 2 THz was demonstrated, which shows that these devices are promising for different microwave applications. In [3, 4], the possibility of modulation of light by TDs in the microwave band on the basis on the Franz–Keldysh effect [5] was demonstrated. The effect of the modulation of light depends on the TD microwave characteristics (impedance), which have been insufficiently studied.

In this work, we study the impedance of TDs on the basis of InGaAlAs structures used in [4]. The structures were grown on an n^+ InP substrate using molecular-beam epitaxy (Fig. 1a) and consisted of two 2-nm thick AlAs barrier layers separated by a 6-nm thick InGaAs quantum pit. These layers were placed between two 500-nm thick layers of doped (Si: 5×10^{16} cm^{-3}) $In_{0.53}Ga_{0.42}Al_{0.05}As$ which served as a core of an optical waveguide. The InP substrate and the upper strongly doped (Si: 2×10^{18} cm^{-3}) InAlAs layer served as a coating of the optical waveguide directing the light parallel to the barrier layers. The upper δ-doped InGeAs layer served for the formation of Au–Ge–Ni ohmic contacts. The rectangular profile of the optical waveguide with a width 2–6 μm and mesas on both sides was produced by chemical etching, and the ohmic contacts were formed along the upper side of the optical waveguide and mesas. The surface of the plate was coated by a SiO_2 film with windows in it that were etched to provide the electric connection between the ohmic contacts and the upper bonding areas formed by sections of the 50-Ω coplanar waveguide (Fig. 1b).

Figure 2 shows the VCCs of two TD specimens (*1* and *2*). For the TD active area equal to 200 μm^2, the current density J_p at the VCC maximum was 50 kA/cm^2, the ratio $J_p/J_v \approx 3$, the difference between the valley and the peak voltages $\Delta U \approx 0.9$ V, and the difference between the current densities of the peak and the valley $\Delta J = J_p - J_v \approx 35$ kA/cm^2. Following [6], let

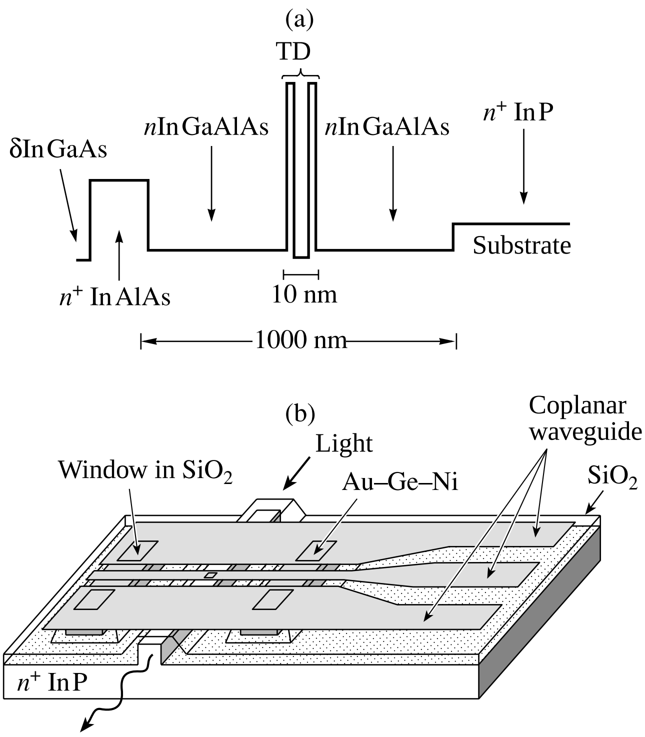

Fig. 1. (a) Scheme of the TD layers and (b) topology of the TD optical modulator.

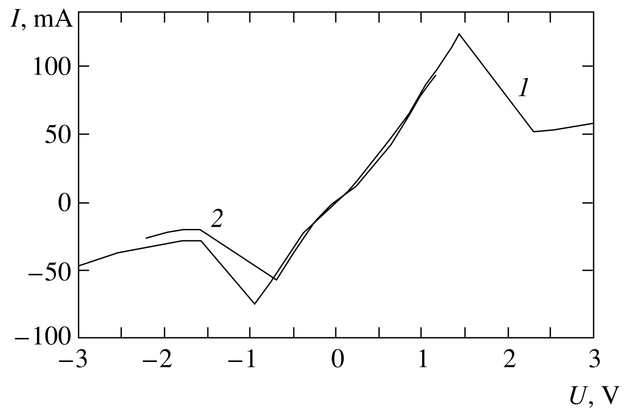

Fig. 2. VCCs of (*1*, *2*) two TD specimens.

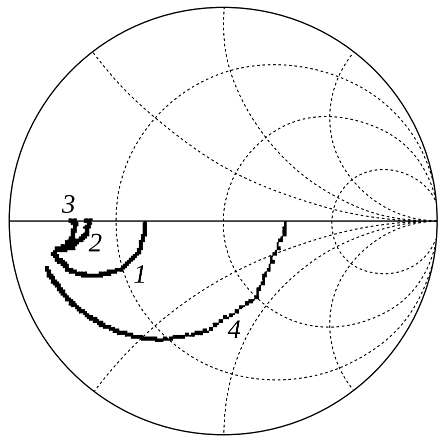

Fig. 3. Smith diagram of the TD impedance in the frequency range from 45 to 18 GHz for different bias voltages U_b = (*1*) 0.0, (*2*) –0.5, (*3*) –0.6, and (*4*) –2.0 V.

us estimate the TD switching time t_R and the critical frequency $\omega_T = 0.5/t_R$ from the static VCC. We have $t_R = 4.4(\Delta U/\Delta J)C_V$, where C_V is the capacitance at the VCC valley related to the unit area ($C_V = \varepsilon\varepsilon_0/W$, $\varepsilon = 13$ is the permittivity of the material, and $W = 0.5$ μm in the TD under study). We obtain $t_R = 6.6$ ps and $\omega_T = 76$ GHz.

Note that similar GaAs/AlAs TD structures were studied in [3]. They have noticeably worse VCC parameters: lower peak current density J_p, smaller J_p/J_v ratio, smaller ΔU and ΔJ, and greater switching time. In addition, it should be noted that InAlAs TD optical modulators can work in the range of wavelengths from 1.0 to 1.6 μm where the optical fiber has minimum loss and chromatic dispersion.

The study of the TD impedance frequency dependences for different bias voltages at the diode was carried out in the frequency range from 45 to 18 MHz by means of an HP-8510 analyzer and a meter produced by the Cascade company. The test signal power did not exceed 200 μW. For example, Fig. 3 shows the Smith diagram with the frequency dependences of the TD impedance (see Fig. 2, specimen *1*) for different bias voltages. In order to find the TD equivalent circuit, the objective function

$$G = \sum_{i=1}^{n} |Z_m(f_i) - Z_c(f_i)|^2$$

was constructed, where $Z_m(f_i)$ and $Z_c(f_i)$ are, respectively, the measured and calculated (for the sought-for equivalent circuit) TD impedances at a frequency f_i and n is the number of experimental points in the frequency range. By varying the values of the equivalent circuit elements, the minimum of objective function G was determined. It turned out that, for any bias voltage, the frequency dependence of the TD impedance corresponds to the equivalent circuit consisting of capacitor C and resistor R connected in parallel and resistor r connected in series. It should be noted that the value of the series inductance, which is usually introduced into the equivalent circuit of a diode, was negligibly small. For the TD bias voltages varying from ±0.7 to ±1.6 V, we observed an instability of the TD impedance.

Figures 4a and 4b show the curves for $R(V)$, $r(V)$, and $C(V)$. It should be noted that $R(U)$, $r(U)$, and $C(U)$ substantially depend on the bias voltage, which contradicts the results reported in [7].

On the basis of the data obtained, one can estimate the TD critical frequency ω_T at which the real part of the impedance

$$Z = r + \frac{R}{1 + j\omega RC}$$

of the diode vanishes.

We estimate negative resistance R from the gain slope (see Fig. 2) taking capacitance C equal to the capacitance of the TD under the bias voltages U_b close to the NDC region. For specimen *2*, $R \approx -15$ Ω, $C \approx 1.5$ pF, and $r \approx 3$ Ω. Then,

$$\omega_T = \frac{1}{C(-R)}\sqrt{\frac{(-R)}{r} - 1} \approx 88 \text{ GHz},$$

which is close to the value estimated above. As one can see, ω_T is too small for such diodes in the millimeter wavelength range. In fact, the diode has a large capacitance due to its large area (200 μm^2).

A significant nonlinearity of the VCC and potentially high critical frequencies make the TDs very promising as resistive frequency multipliers. Theoretically, a 100% transformation of the fundamental frequency into the nth harmonic can be carried out if the nonlinear element has a VCC in the form of the n-order Chebyshev polynomial [8]. An asymmetric VCC of the TD means that the fundamental frequency can be most

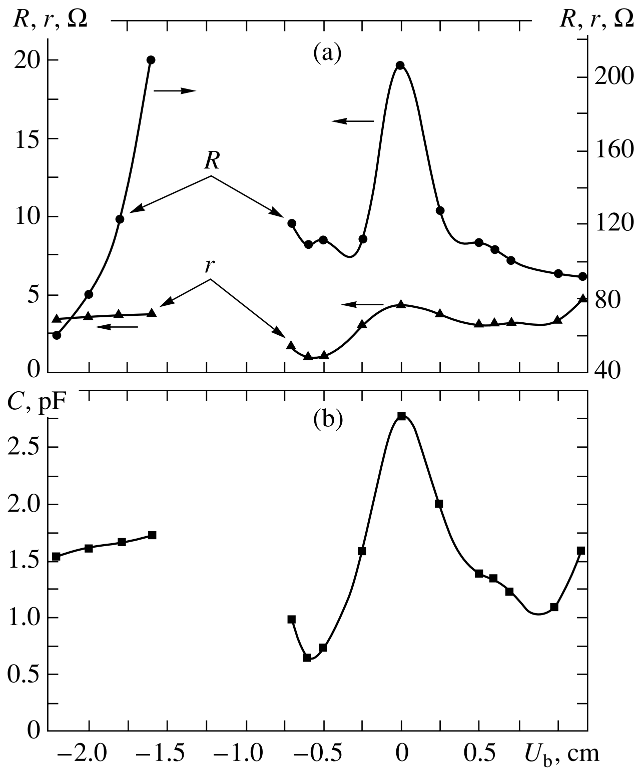

Fig. 4. (a) Resistances *R* and *r* and (b) capacitance *C* of the equivalent circuit vs. bias voltage.

efficiently transformed into odd harmonics and especially into the fifth harmonic (at a sufficiently high level of the input signal). In the earlier studies [9, 10], the frequency multiplication was provided by TDs with a small J_p/J_V ratio; hence, the efficiency $\eta = P_n/P_1$ of the frequency transformation was about 1%. Here, P_n is the power of the *n*th harmonic released in the load and P_1 is the power supplied to the multiplier from the pumping oscillator.

Calculated and experimental amplitudes of the harmonics of the current

U_{in}, V	Experiment/Calculation, μA						
	1	*2*	*3*	*4*	*5*	*6*	*7*
0.15	3.16/4.5	–	–	–	–	–	–
0.45	10.9/13	–	–	–	–	–	–
0.75	23.1/26	–	0.39/0.33	–	0.15/0.12	–	–
1.5	46.6/41	5.4/–	4.3/2.3	3.5/–	3.9/2.5	2.7/2.7	2.3/2.3
2.25	49/51	5.0/12	12.5/10.5	7.0/2.8	3.9/3.0	6.2/6.1	3.5/4.7
3	65.1/69	2.7/–	6.6/27	3.5/14.7	7.8/7.6	5.8/3.9	–/4.8

Note: Figures *1–7* denote the number of the specimen.

In order to demonstrate the TD performance acting as a resistive frequency multiplier with the zero bias voltage, we calculated theoretically and observed experimentally the spectrum of the current flowing through the TD (specimen *2*) generated by a sinusoidal voltage with the frequency of 50 MHz. In our opinion, the spectrum of the current through the diode uniquely characterizes the TD as a frequency multiplier, because the transformation efficiency η depends on the circuits that match the device with the pumping oscillator and the load; in the known works, these circuits were different and the choice was not always optimal.

It should be noted that, in the installation for detecting the current in the TD, the voltage of the pumping oscillator was supplied to the TD through a transformer with $n = 2$ and 3 in order to avoid instabilities produced by the resistance of the pumping oscillator.

The spectrum of the current through the diode was registered by means of the Micro-Cap V program. To this end, we performed the input of the diode VCC (Fig. 2) and simulated the performance of the circuit of the experimental installation. The amplitudes of the harmonics of the current through the diode observed and calculated for different values of voltage U_{in} of the pumping oscillator are presented in the table.

As follows from the data presented in the table, the calculated and experimental values are in good agreement. The results obtained also demonstrate a high efficiency of the transformation of the oscillator power into higher harmonics of the current. According to the table, for $U_{in} = 3$ V, the ratio of the amplitudes of the fifth and first harmonics of the current is $G_5/G_1 \approx 12\%$. This fact confirms that TDs can be applied as resistive frequency multipliers with the zero shift. However, for application in the millimeter wavelength range, which is of practical interest, it is necessary to use specimens with a smaller cross-sectional area and without buffer layers, because the latter cause additional losses. In this case, the contribution of the capacitance as a function of voltage will be essential. It is also important to prevent the mutual compensation of the varistor and varactor effects.

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