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Polariton-like stimulated excitations in rectifying terahertz GaAs/AlAs double barrier nanostructures driven by nonequilibrity of the resonant-tunneling proces

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Abstract. We have studied the periodical-in-voltage oscillations in the current-voltage characteristics of GaAs/AlAs double barrier resonant tunneling diode terahertz detectors. The found oscillations of the negative differential conductance are attributed to LO-phonon-branch polariton excitations stimulated by electrons tunneling through the quantum active region in the resonance nanostructure. It is argued that, due to the conduction-band profiles disposition in a manner of the inversion-like nonequilibrium cascade, the tunneling current supplies the inevitable excessive energy. The RTD serves as an internal amplifier of weak electromagnetic signals, provided by the region of negative differential conductance.

1. Introduction

The resonant tunneling diode (RTD) is a quantum-effect semiconductor device using quantum mechanical tunneling which operating principle is based on the resonant tunneling effect. Quantum effects, harmonics generation and high-frequency rectification mechanisms in high¬speed RTDs are considered traditionally as rather promising to increase the operation frequency of semiconductor nanoelectronic devices toward the terahertz and subterahertz range. Novel application possibilities develop in resonant tunneling devices exploiting the RTD property attributed to the internal amplification of weak electric signals. RTDs attract the growing interest in the development of sensors for various physical quantities, such as temperature, pressure, light, or microwaves, in the investigation of RTDs with embedded quantum dots operated as single photon detectors and photon counters, or high-gain RTD photodetectors for room temperature telecommunication wavelength light sensing (see [1] and references therein). The advances of RTD devices are resultant of the high internal amplification, low-voltage operation, and supplementary functionality, inherently provided by the region of negative differential conductance (NDC), and as in avalanche diodes, the RTD device performance is tuned by the applied bias voltage. RTD nanostructures are also rather encouraging for possible implementations of the nanoscale thermodynamic cycles [2], similar to the laser cooling [3], for example.

2. Experimental

The computed by a rigorous tunneling theory current-voltage characteristics are less or more idealized functions and comparisons are required with the measured I- V curves, as usual affected by external or internal distortions not considered in the theory. The most basic reasons of the distortions, causing the measured current-voltage characteristic to have the hysteresis, bistability, discontinuities, humps, plane and stepped sections in the NDC, are the excessive series resistance (Rs), parasitic oscillation, charge build-up and longitudinal-optical-phonon (LO) replicas of a tunneling peak [4-7]. There have been several means to extract the parameters of a test resonant tunneling diode accurately: to monitor the oscillation status by measuring the second derivative of I-V curve, to place a resistor in parallel with the RTD, which could stabilize most of test circuits, etc. [6, 7].

These means are used here to extract the reasons of experimentally found periodical-in-voltage features [7, 8] of the NDC. It is argued that, due to the conduction-band profiles disposition in a manner of the inversion-like nonequilibrium cascade (cf. Figure 5 in [7]), the tunneling current supplies the inevitable excessive energy for stimulated excitations in a resonant tunneling process [7]. The found oscillations of the NDC region are considered taking account of the LO-phonon- branch polariton excitations stimulated by tunneling. We found that an RTD serves as a detector of weak subterahertz electromagnetic signals with the internal amplification, inherently provided by the region of negative differential conductance.

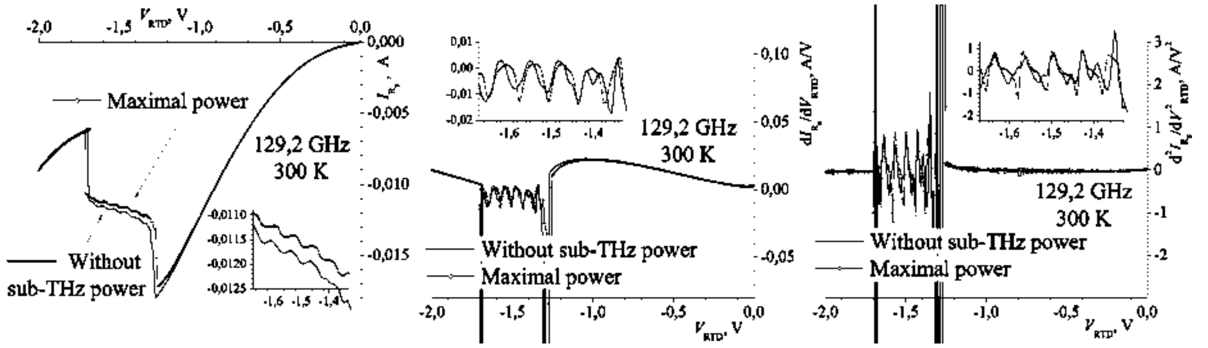

Figure 1. I-V curves (left), first (center) and second (right) derivatives of I-V curves for a double-barrier RTD with and without incident sub-THz power. Maximal incident power is order of 10 /iW [8]. Inserts show more details. T=300 K, active layers of AlAs/GaAs barriers/well 23/45/20 A.

The regular oscillations of the NDC region in the I- V characteristics of an RTD have been detected at room temperature and below [7, 8]. To extract the reasons of these regular features we used here the means discussed in [6,7]: to monitor the oscillation status of the resonant tunneling diode by measuring the second derivative of I- V curve. Information on experimental techniques and RTD working principles, including schematic conduction-band profiles under an applied bias voltage V is shown in Figure 5 in [7] and may be found in [8] and [5, 9], respectively.

The regular oscillations of NDC in the I- V curve are shown in the Figure 1 (left) for a double-barrier RTD with and without an incident sub-THz (0.1292 THz) power at room temperature. First and second derivatives of the I-V curves, obtained from the data points of Figure 1 (left) by machine-routine computations, are presented in the Figure 1 (center, right). Inserts in the figures show more details of the I- V curves and derivatives. From comparisons of the date shown in the figures and those presented in [6, 7] one can conclude the absence of parasitic external oscillations in a circuit with our test RTD. The second derivative curve should show a sharp valley immediately followed by a sharp peak at the lower-voltage point where circuit oscillations would begin. The typical measured derivative curves with diode-curcuit oscillations are shown in Fig. 2(c) in [6]. This feature corresponds to a derivative of the smoothed delta-function in the first derivative of I-V curve, which in turn is a derivative of a step — a negative step of the smoothed theta-function in the I- V curve. This triplet of features may be considered as a classical continuous-media-electrodynamics illustration of a creation-annihilation operator. At the second point corresponding to a higher voltage, as the NDC is smaller negative, oscillations are quenched. The same characteristic of a sharp valley immediately followed by a sharp peak should appear in the second derivative curve at this point also. This pair of the oscillatory features in the second derivative curve can be used to monitor the circuit-oscillation status in the measurement circuit and determine the bias voltage range in which circuit oscillations occur. Such pairs of the oscillatory features in the second derivative curve, monitoring the oscillation status in the measurement circuit, can be found, being periodically repeated, in the insert of Figure 1 (right) for a double-barrier RTD with an incident sub-THz power and, contrary, are practically indistinguishable for an RTD without an incident power.

So the observed NDC regular-in-voltage oscillations in the I-V curves are of the intrinsic nature not dependent on the oscillations in an RTD's test circuit. The observed in the Figure 1.

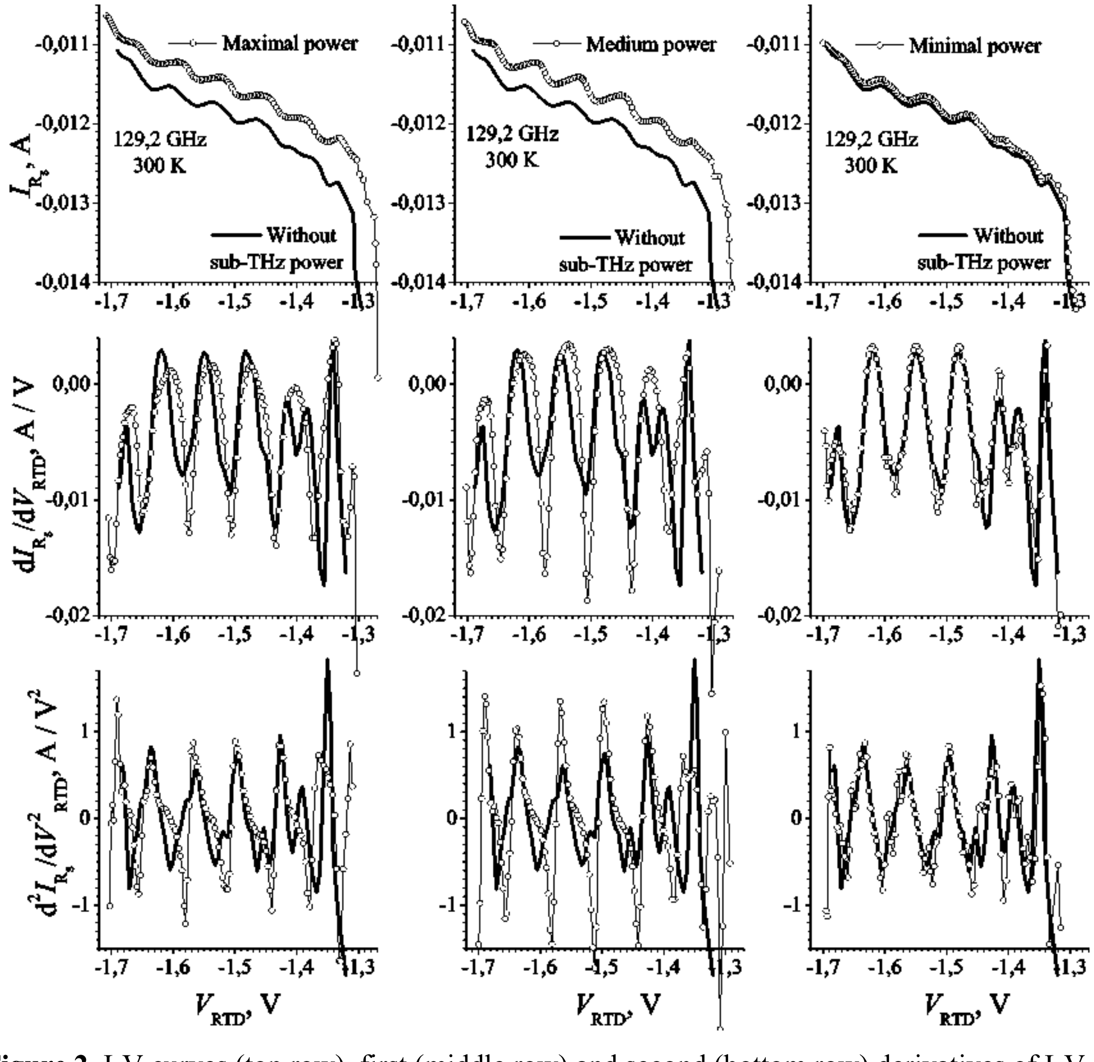

Figure 2. I-V curves (top row), first (middle row) and second (bottom row) derivatives of I-V curves for a double-barrier RTD with and without incident sub-THz power. Maximal incident power is order of 10 /j,W [8]. Data for different levels of incident sub-THz power: maximal (left column), medium (center column) and minimal (right column) are compared with curves in the absence of any incident radiation. T=300 K, active layers of AlAs/GaAs barriers/well 23/45/20 A.

(Left) low averaged value of the oscillatory NDC order of 1/300 fi-1, period of NDC oscillations order of 72 mV corresponding to the energy 72 meV of two LO-phonons under conditions of the slight asymmetry of barriers, number of these periods (7 periods in Figures 1 or 4 periods in [9]) depending on the barrier width (asymmetric of 20 and 23 A in our RTD or symmetric of 12 and 14 A in two RTDs in [9]), and excessive energy of the discussed above cascade inversion [7] provide evidences in support of the resonant tunneling process assisted by a stimulated excitation of LO-phonon-branch polariton replicas. The stimulated LO-phonon-branch polariton excitations in an RTD are provided by the effects of the boundary-dependent local fields in conducting media [7].

3. Experimental results and discussion

These conclusions are supported by comparisons with the demonstrated in Figure 2 data for different values of incident sub-THz power. The triplets of oscillatory features in the I-V curves, first and second derivative curves, monitoring the oscillation status in the measurement circuit, can be found, being periodically repeated for all investigated levels of the weak incident sub-THz power in the Figure 2. These features for the minimal power data are clearly distinct at least for the second derivative curves in the Figure 2 (bottom). Found NDC features cannot be explained by only the ordinary mechanism of the quadrature rectification proportional to a second derivative of the I-V curve d2I/dV2. Contrary, the Ampere/Watt conversion efficiency characteristic of a detector in the form (d2I/dV2)/(dI/dV) [10] allows to conclude that the RTD serves as an internal amplifier of weak electromagnetic signals, provided by the region of negative differential conductance.

4. Conclusion

In conclusions, the found oscillations are considered taking account of the LO-phonon emission stimulated by tunneling of electrons through the quantum active region in the resonance nanostructure. The RTD serves as an internal amplifier of weak electromagnetic signals, provided by the region of negative differential conductance.

Acknowledgments

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