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Theory of unipolar ballistic and quasiballistic transit-time oscillators for a terahertz range

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Abstract

We are the first to consider DC characteristics and a linear admittance of a very short undoped transit space (T-space) in the case of a ballistic transport of electrons injected into this space from a heavily doped cathode contact. We have considered both a classic case of a unipolar space-charge-limited injection current and a case of a unipolar tunnel injection through a rectangular or triangular heterostructure barrier. In both cases, the effective injection occurs in not very strong electric fields ($\leqslant (1-3)\times 10^5$ V/cm). To reach a high-energy ballistic electron transport, we have assumed highly positioned noncentral electron valleys over the bottom of a central Γ-valley and have selected the appropriate semiconductors for the T-space.

For all the considered examples, we have obtained frequency windows of a negative conductance in a deep terahertz range. This means that such unipolar devices are perspective as terahertz oscillators. Numerical estimates are completed for the InP-T-space with the length of 70 nm.

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1. Introduction

Among ultra-high-frequency (UHF) electromagnetic oscillators, a group of transit-time electron devices plays a very important role both in the case of vacuum technology (see, for example, [1]) and in the semiconductor technology case. In the latter, IMPATT-diodes head the list. These diodes are substantially based on impact ionization phenomena and an avalanche formation. De-facto, IMPATT-diodes are pn-diodes, in which inertia of the impact ionization together with inertia of an electron transit across a depletion layer of a reverse-biased pn-junction is used. The main disadvantage of this oscillation mechanism is caused by the same inertia of an avalanche multiplication and also by a length of the so-called dead space that is too long, which should be overcome to develop the necessary multiplication. Note that IMPATT-diodes are dissipative transport devices in principle and cannot exist in a ballistic version. Despite these disadvantages, IMPATT-diodes are currently champions both on an oscillation frequency (up to 400 GHz, see [2]) and on efficiency among the transit-time diodes.

A long time ago, the so-called TUNNETT-diodes [3–5] were proposed as higher-frequency

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competitors of IMPATT-diodes. In these oscillators, an electron supplier is not impact ionization but a tunneling through a semiconductor bandgap (that is, a Zener tunneling). This means that such a device contains a reverse-biased pn-junction, and the same depletion layer of such a junction is used as a drift (or transit) space. This space cannot be very short because to develop an effective Zener emission, a reverse bias, which is not very small, is necessary. Therefore, hopes to obtain the record-breaking oscillation frequencies on the basis of TUNNETT-diodes are futile for the present.

In our recent article [6], we propose a new version of a transit-time heterostructure oscillator device that is characterized by the following features:

(1) The device is unipolar. Its active transit space (T-space) is embedded between two n^+-contacts, cathode (C-contact) and anode (A-contact; see Fig. 1). We do not foresee any hole generation in oscillatory regimes.
(2) As a result of a sufficiently large positive biasing of the A-contact, the C-contact injects electrons in the T-space. The injected electrons are speeded up by an electric field in the T-space ballistically (that is, without any scattering). It is possible if the T-space is very short. A length of the T-space should not exceed an electron mean free path for energies gained by electrons in this T-space and in these electric fields. The condition of ballisticity dictates a requirement of sufficiently high positions of L- and X-valley bottoms over Γ-valley bottom in the T-space in order to avoid an electron scattering from a Γ-valley to L- and X-valleys. To meet this requirement, we should eliminate from the list of T-space materials not only such multi-valley semiconductors as electron Si, Ge, SiC, diamond, GaP, AlAs, etc. but GaSb and possibly also GaAs, in which the L-valleys position is too low. A low position of these valleys decreases DC voltages and powers, which could be applied in such devices. A sufficiently high position of L-valleys (and a higher position of X-valleys) takes place in $A_{III}B_V$-semiconductors (and in their alloys) containing In as a dominating A_{III}-component. They are InP, $In_{0.53}Ga_{0.47}As$, InAs, $InP_{0.69}Sb_{0.31}$, and InSb; InAs and especially InSb have a very narrow bandgap, but we deal with very short ballistically penetrable T-spaces with lengths, which are obviously shorter than lengths of dead spaces for the impact ionization. In Ref. [6], we have considered InP T-space with n^+-InGaAs C-contact as a certain optimal version.

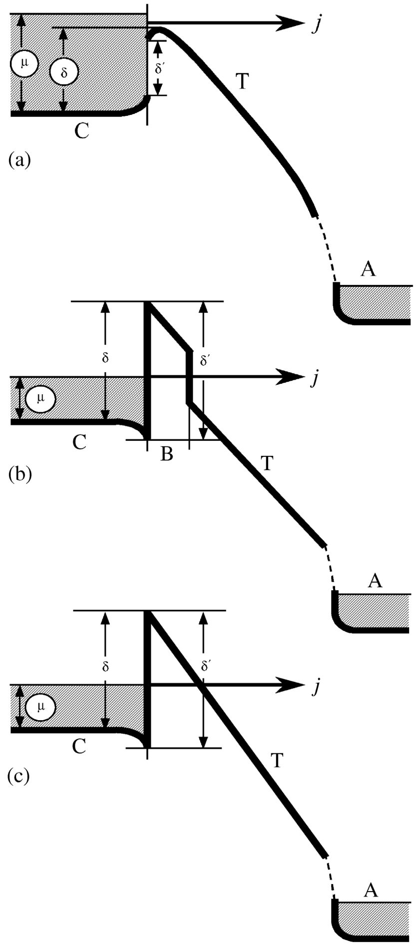

Fig. 1. Spatial distributions of an electric potential near a heterostructural boundary C-contact/T-space. Here μ is a Fermi-level in a depth of the C-contact, δ is the effective height of a heterobarrier, δ' is a conduction band discontinuity, C is the C-contact, B is an intermediate tunnel barrier (the B-barrier), T is the T-space, and A is the A-contact. A case of (a) a space-charge-limited injection, (b) tunnel-barrier-limited injection with the intermediate B-barrier, and (c) tunnel-barrier-limited injection without an intermediate barrier.

Nitrides InN, GaN, and AlN and their alloys are also characterized by high positions of noncentral valleys (both in zinc blende and especially in wurtzite versions). Some disadvantage of these materials is associated with a very strong polar phonon scattering of electrons. Therefore, we need T-spaces, which are too short to implement ballistic or quasiballistic electron transport across them. If a 70-nm length of the InP T-space is satisfactory [6], in the GaN T-space case we need to consider 20–30-nm lengths and accordingly increased electric fields.

2. Two variants of an electron injection

There are two different possible variants of electron injection from the C-contact into the T-space: (A) an injection over a barrier (Fig. 1(a) and (B) an injection under a barrier (Figs. 1 b and c). The injection over a barrier is limited usually by a spatial charge of injected electrons (space-charge-limited injection). This charge controls the height of a potential barrier, which should be overcome by injected electrons. A classic example of an injection over a barrier is a thermionic electron emission in vacuum tubes. It has been known for years [7,8] that in a vacuum diode with a space-charge-limited current, frequency windows of a negative conductance appear as a result of the transit-time effects considered here. These windows lead to oscillatory regimes. Analogous effects can be predicted for a ballistic electron transport across the short T-spaces. For a T-space length $l_T \leqslant 100$ nm and an average electron velocity $V_S \cong 10^8$ cm/s, an oscillation frequency reaches 5–10 THz and higher. Note that these oscillatory effects are maximal if in the total T-space the ballistic electrons accelerated by an electric field have a parabolic dispersion relation $\varepsilon_p = p^2/2m$. Transfer into a nonparabolic region decreases oscillatory effects, and they disappear entirely for a linear dispersion $\varepsilon_p = V_S p$ with $V_S = \text{const}$. For the realistic nonparabolic dispersion relation for InP Γ-electrons at $\varepsilon_p < 0.6$–0.7 eV, this effect of oscillation suppression rarely takes place.

If electrons over a barrier are practically absent (for example because of a heterobarrier which is too high embedded between the C-contact and the T-space), the injection current is limited not only (and not so much) by an electron spatial charge. It is limited mainly by the heterobarrier itself since electrons should tunnel through this barrier. In the simplest case, a tunnel injection is described by the Fowler–Nordheim formula [9] justified for a triangular barrier formed in a strong homogeneous electric field E near a sharp heteroboundary (Fig. 1c):

$$j/j_N = (E/E_N)^2 \exp(-E_N/E). \tag{1}$$

Parameters E_N and j_N in Eq. (1) depend on electron effective masses m_1 and m_2 on the different sides of the heteroboundary, the height of the heterobarrier, δ, and the position of a Fermi-level, μ, in the C-contact ($0 < \mu < \delta$). If $\mu \geqslant \delta$, a space-charge injection limitation takes place. The same occurs if $\mu \leqslant \delta$ but $\delta - \mu \leqslant T$, where T is an electron temperature in the C-contact.

3. Selected results of calculations

If an injection is space-charge-limited and a parabolic dispersion relation occurs, an admittance of the device, Y, is defined only by parameters of the T-space (an electron effective mass $m = m_2$, a dielectric constant κ_D, a T-space length l_T), a DC current density, j, and a frequency, $\omega = 2\pi f$:

$$Y = R_0^{-1} \frac{A + iB}{A^2 + B^2}, \tag{2}$$

where $R_0 = ej/\kappa_D^2 m\omega^4$, $A = 2(1 - \cos\chi_l) - \chi_l \sin\chi_l$, $B = \chi_l(1 - \cos\chi_l) - 2\sin\chi_l + \chi_l^3/6$, and $\chi_l = \omega(6m\kappa_D l/ej)^{1/3}$. It is seen that the above-mentioned frequency windows of a negative conductance exist in the χ_l-intervals $(2\pi, 3\pi), (4\pi, 5\pi)$ and so on. Maximums of the negative conductance are reached at $\chi_l \cong 2.5\pi, 4.5\pi, \ldots$. Such windows tend to narrow and finally close as a result of taking into account a nonparabolic electron dispersion and deepening into a nonparabolic region. An acceleration of electrons with an increase in their momentum is a necessary condition for the existence of the negative conductance windows in the case of a space-charge-limited injection.

A transfer to a tunnel injection changes the above-described picture. In this case, an electric field in the T-space and an electron concentration tend to level, and particularities of an electron dispersion relation become not very important.

A conductance and a susceptance of a ballistic diode with a tunnel injector are presented in Figs. 2 and 3 in dependence on a frequency. For these figures, we have selected the diode with $l_T = 70$ nm and with material

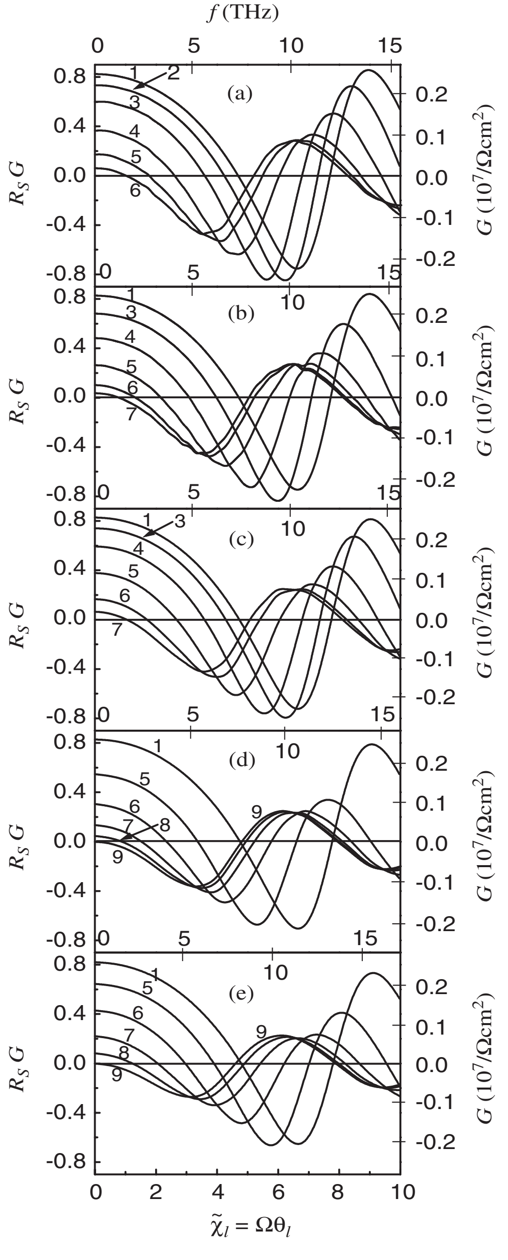

Fig. 2. Conductance, G, plotted against frequency, f, and normalized frequency, $\tilde{\chi}_l = \omega\tau_S\theta_l$, for different values of $\Omega_0[\Omega_0 = \infty$ (1), 300 (2), 100 (3), 30 (4), 10 (5), 3 (6), 1 (7), 0.3 (8), and 0 (9)] at the current density $j = 10^3$ A/cm^2 (a), 3×10^3 A/cm^2 (b), 10^4 A/cm^2 (c), 5×10^4 A/cm^2 (d), and 2×10^5 A/cm^2 (e); $\tau_S = (\kappa_D m V_S/2ej)^{1/2}$, $\omega = 2\pi f$, and $R_S = l^2/V_S\kappa_D$.

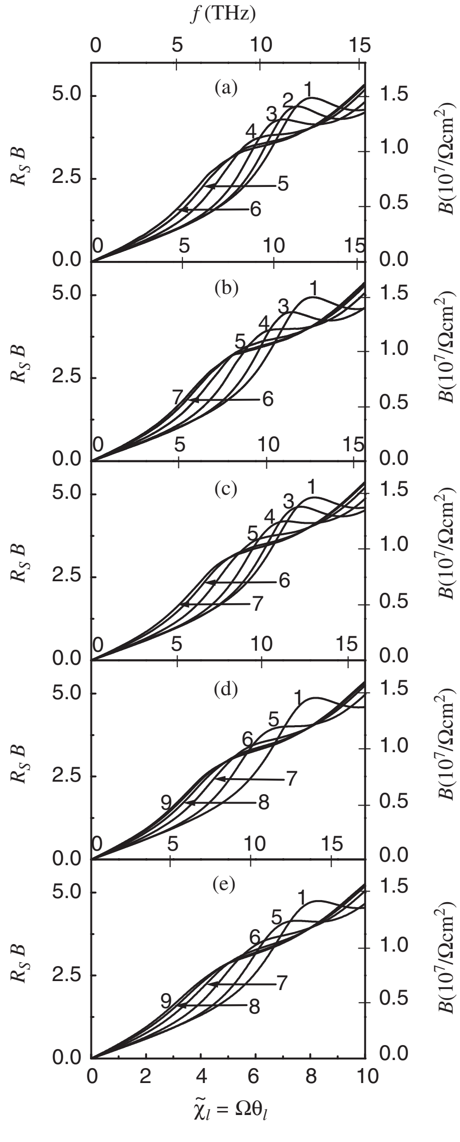

Fig. 3. Conductance, G, plotted against frequency, f, and normalized frequency, $\chi_l = \omega\tau_S\theta_l$, for different values of Ω_0 and the current density j. All the designations are the same as in Fig. 2.

parameters of the T-space, which are appropriate to InP. They are: $m = m_2 = 0.75 \times 10^{-28}$ g, $\kappa_D = 12.4/4\pi \cong 1$, $V_S = 1.3 \times 10^8$ cm/s (see [10]; the dispersion relation is selected in the form $\varepsilon(p) = V_S[(p_S^2 + p^2)^{1/2} - p_S]$, $p_S = mV_S$), and $U_l = U(l_T) = 0.6$ V (this voltage is determined by the energy position of L-valleys). These parameters determine an average electric field in the T-space $\bar{E} = 0.86 \times 10^5$ V/cm, and if $j < j_S = \kappa_D m V_S^3 / 2el^2 = 1.14 \times 10^6$ A/cm^2 we have $E(x) \approx \bar{E}$. Besides the above-mentioned parameters, the conductance and susceptance depend on three functions of a current density j:

$$A_0(j) \cong e\bar{E}(\kappa_D/2ejmV_S)^{1/2}, \quad (3)$$

$$\theta_l(j) = 2\{[u_l^{1/2}(u_l+2)^{1/2} + A_0^2]^{1/2} - A_0\}, \quad (4)$$

$$\Omega_0(j) = (\mathrm{d}j/\mathrm{d}E)|_{x=0}(mV_S/2ej\kappa_D)^{1/2}, \quad (5)$$

where $u_l = eU_l/mV_S^2$.

The curves presented in Figs. 2 and 3 are obtained for five values of a current density $j(=10^3, 3 \times 10^3, 10^4, 5 \times 10^4, 2 \times 10^5$ A/cm^2). Since all of these five values are assumed for the single value of $\bar{E} = 0.86 \times 10^5$ V/cm, this means that each increase in the current density (from 10^3 to 2×10^5 A/cm^2) can be reached only as a result of the appropriate increase in the tunnel transparence of the tunnel barrier. Therefore, the sets of characteristics depicted in Figs. 2 and 3 cannot be related to the same device, but they relate to the diodes with different tunnel barriers. Each of the five presented sets in Figs. 2 and 3 consists of 6 curves, related to different values of the parameter $\Omega_0(j)$. The latter depends on the differential transparence of a tunnel emitter $(\mathrm{d}j/\mathrm{d}E)|_{x=0}$, which can be substantially different for different tunnel emitters at the same values of both j and E simultaneously. Therefore, 30 curves in Figs. 2 and 3 relate in fact to 30 different tunnel emitters but to the same value of the average electric field in the T-space (and to only five values of the current density).

We see that both susceptance and conductance behaviors in Figs. 2 and 3 are generally close to each other despite the 2-order difference in the DC current density. The greatest difference takes place for the low-frequency conductance ($\tilde{\chi}_l < 4-5$) at small values of $\Omega_0(j)(\leqslant 1)$. A decrease in the differential tunnel transparence shifts always the negative conductance windows to the low-frequency side with some decrease in value.

Note that the relation $(-G)/B$ (negative conductance/susceptance) for medium frequencies ($\leqslant 8$ THz) can be quite acceptable (up to 0.3).

4. Conclusion

In this paper, we have considered a new version of a semiconductor transit-time oscillator, which supposes several advantages in comparison with the existing versions:

(1) It is assumed there is a ballistic or quasiballistic electron transport across the very short (< 100 nm) T-space where electrons interact with electromagnetic radiation. Due to such a small length of the T-space and a very high electron velocity ($> 10^8$ cm/s), an oscillator can generate oscillations in a deep terahertz range.
(2) Comparatively low heterostructure barriers are used as tunnel electron injectors into the T-space (up to the space-charge-limited injection instead of the tunnel injection).
(3) Neither pn-junctions with p^+-contacts nor a Zener tunneling through a bandgap, etc. are used in the suggested version. Therefore, a sufficiently simple cascading is possible to increase efficiency and output power.
(4) Our numerical examples are based on the assumed InP T-space. We believe that similar structures can be implemented on the basis of the InN/GaN/AlN material system.

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