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8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000

Does the quasibound-state lifetime restrict the high-frequency operation of resonant-tunneling diodes?

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Abstract. We have shown that, firstly, the response time ($\tau_{\rm resp}$) of the resonant-tunneling diode (RTD) can be much smaller as well as much larger than the quasibound-state lifetime in the quantum well ($\tau_{\rm dwell}$); secondly, the real part of the RTD conductance can be negative at the frequencies higher than the reciprocal $\tau_{\rm dwell}$. The Coulomb interaction of the electrons in the quantum well with emitter and collector is responsible for the effects. A simple analytical expression for the impedance of the RTD has been derived and it is in fairly good agreement with experimental data.

1. Introduction

The resonant-tunneling diodes (RTD) on the basis of the double-barrier heterostructures are extensively studied for a long time. It was demonstrated that they work up to the frequency of several THz. The complicated numerical approaches to simulation of the dynamic response of RTD have been developed recently. They allow one to deal more or less accurately with the problem. Nevertheless, up to now there was not a simple analytical and physically clear approach, that would allow one to describe quantitatively the high frequency behavior of RTD. The problem has been solved in the present work. Also, it is widely believed that the RTD response time ($\tau_{\rm resp}$) can not be less than the quasibound-state lifetime ($\tau_{\rm dwell}$) in the quantum well (QW). We show that it is not true.

All the results of the present work are obtained in the sequential tunneling approximation and the problems were treated self-consistently. The details of derivation could be found in [1]. Here we present just the new and main results, discussion and comparison with experiment.

2. The response time and conductance of RTD

The following equations have been derived for the linear response of RTD:

$$\left[\frac{\partial}{\partial t}+\frac{1}{\tau_{\rm resp}}\right]\delta N_{\rm 2D}(t)\propto\delta E_{fc}(t), \tag{1}$$

$$\frac{1}{\tau_{\rm resp}}=\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm e}(U_w)}+\frac{e^2\rho_{\rm 2D}}{C}\left\{\frac{1}{\tau_{\rm e}(U_w)}-\left[E_{fe}-E_{fw}\right]\frac{\partial}{\partial U_w}\left(\frac{1}{\tau_{\rm e}(U_w)}\right)\right\}, \tag{2}$$

here $\tau_{\rm c}$ and $\tau_{\rm e}$ are the electron dwell times in QW due to the tunneling to collector and emitter, respectively; e is the electron charge, $\rho_{\rm 2D}$ is the 2D density of states in QW, $C=\epsilon(L+d)/4\pi Ld$ is the capacitance of QW per unit area, the effective emitter-well distance (d) is more than the emitter-barrier thickness by the Thomas–Fermi screening length and the half width of QW; L is the similar well-collector distance, that includes

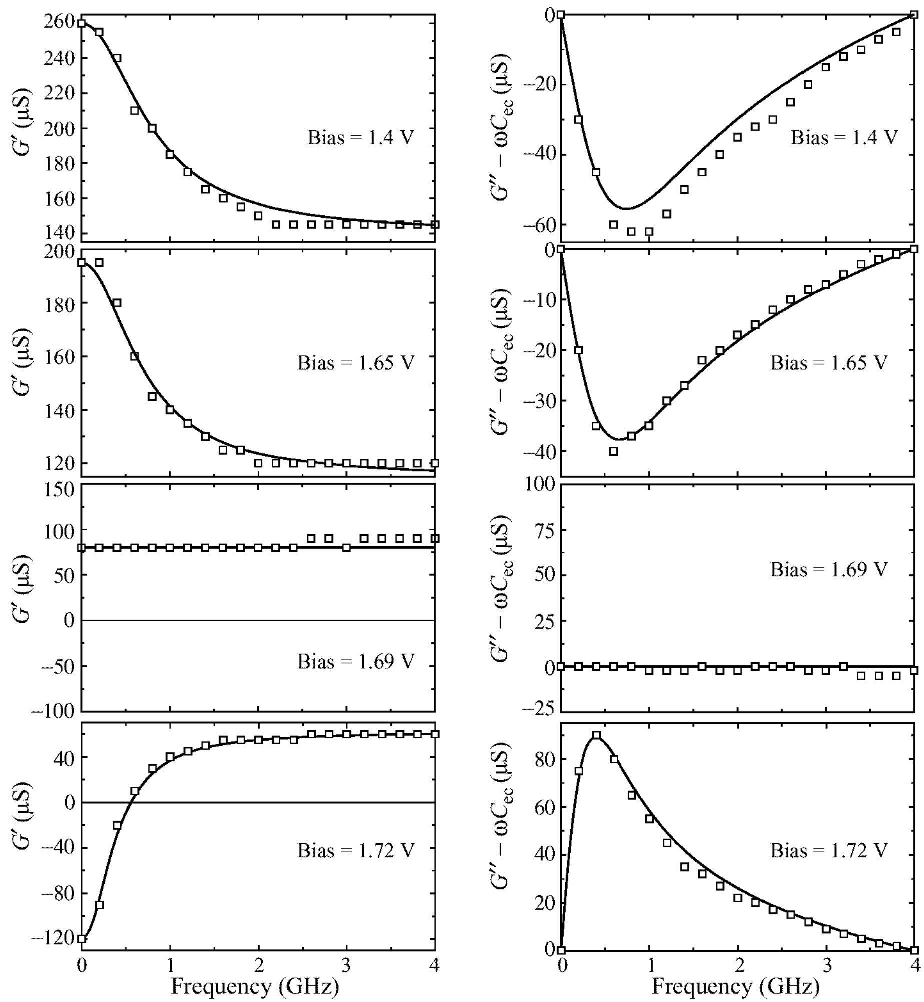

Fig. 1. On the left are the plots of $G' \equiv \mathrm{Re}(G)$ for different bias voltages (the upper 3 are for biases in PDC region and the lower one in NDC region) and on the right are the corresponding plots of $G'' - \omega C_{\mathrm{ec}}$, where $G'' \equiv \mathrm{Im}(G)$. The experimental points are taken from [2]. C_{ec} was calculated in [2] by averaging G'' between 3.9 and 4.0 GHz. Continues lines in the figures are $G'(\omega)$ and $G''(\omega)$ calculated with the help of (4). The necessary parameters were extracted as follows. The value of G_{nonres} was extracted from the plots with bias 1.69 V: G is independent on frequency in the case, i.e. $G^0_{\mathrm{RT}} \approx 0$. G^0_{RT} is known for all biases from the experimental points, G' at large frequencies gives the ratio of $\tau_c d/(L+d)$ and τ_{resp} (6). As it follows from (4), $G'(\omega) = (G'(0) + G'(\infty))/2$ at $\omega = 1/\tau_{\mathrm{resp}}$. It should be noted that the negative sign of $G'' - \omega C_{\mathrm{ec}}$ at low frequencies and biases 1.4 V and 1.65 V corresponds to $\tilde{C} < C_{\mathrm{ec}}$; and positive sign at 1.72 V corresponds to $\tilde{C} > C_{\mathrm{ec}}$.

also the thickness of the depletion region; N_{2D} is the electron concentration in the QW, by δ we denote small variations, E_{fc} is the collector Fermi level, emitter is supposed to be grounded ($\delta E_{fe} = 0$). $\tau_{\rm resp}$ has the sense of the tunnel relaxation time of the fluctuation of N_{2D}. The first and the second terms in (2) describe the relaxation due to the electron tunneling to collector and emitter, respectively, and they give the electron dwell time in QW: $1/\tau_{\rm dwell} \equiv 1/\tau_{\rm c} + 1/\tau_{\rm e}(U_w)$. As the Fermi level in QW (E_{fw}) changes, the energy of the bottom of the 2D subband in the QW (U_w) also shifts due to the Coulomb interaction of the electrons in the QW with emitter and collector. As a result, firstly, an additional contribution in emitter-well current appears due to the change of the number of the free states in QW available for tunneling (third term). Secondly, the current changes owing to the variation of $\tau_{\rm e}(U_w)$ with the shift of the bottoms of the 2D subband in QW, that is described by the fourth term in (2). Variation of $\tau_{\rm e}(U_w)$ is significant, $\tau_{\rm e} \to \infty$ when U_w becomes lower then the bottom of the conduction band in the emitter; the variation of $\tau_{\rm c}$ is supposed to be negligibly small. The factor before the figure brackets in (2) equals to $\delta U_w/\delta E_{fw}$ and its typical value is 5–10. Due to the factor the third term in (2) is always much larger than the second one. The last term in (2) can increase as well as diminish $\tau_{\rm resp}$. If the Coulomb effects are omitted ($C \to \infty$), then $\tau_{\rm resp} = \tau_{\rm dwell}$. The Coulomb interaction significantly changes $\tau_{\rm resp}$.

Next the following equation has been derived, it relates $\tau_{\rm resp}$ to the static differential conductance due to the resonant current ($G^0_{\rm RT}$):

$$G^0_{\rm RT} = \left[1 - \frac{\tau_{\rm resp}}{\tau_{\rm dwell}}\right]\frac{C_{wc}}{\tau_{\rm c}}, \tag{3}$$

where $C_{wc} = \epsilon/4\pi L$ is the well-collector capacitance. Eq. (3) gives possibility to get $\tau_{\rm resp}$ in the static measurement of the I–V curve.

An expression for the linear conductance (G) of RTD has been derived also:

$$G(\omega) \equiv \frac{e\delta J_{\rm RTD}}{\delta E_{fc}} = i\omega C_{\rm ec} + G^0_{\rm RT}\frac{1 + i\omega\tau_{\rm c} d/(L+d)}{1 + i\omega\tau_{\rm resp}} + G_{\rm nonres}. \tag{4}$$

$C_{\rm ec} = \epsilon/4\pi(L+d)$ is the emitter-collector capacitance, $J_{\rm RTD}$ is the RTD current, $G_{\rm nonres}$ is the conductance due to nonresonant component of current, e.g., thermionic emission. The contact resistance should be connected in series with G (4), if it is significant one.

3. Discussion

It follows from (3) that $\tau_{\rm resp}$ is always less than $\tau_{\rm dwell}$ in the positive differential conductance (PDC) region of the I–V curve. In the case of RTD with 3D emitter just the first three terms are left in (2) ($\tau_{\rm e}(U_w) \approx$ const in the PDC region) and $\tau_{\rm dwell}/\tau_{\rm resp} \approx 5-10$ due to the third one, if $\tau_{\rm e} \lesssim \tau_{\rm c}$. $\tau_{\rm resp}$ is always more than $\tau_{\rm dwell}$ in the negative differential conductance (NDC) region, as it follows from (3), and $\tau_{\rm resp}$ grows up with NDC ($\tau_{\rm resp} \to \infty$ when $G^0_{\rm RT} \to -\infty$).

The comparison of the frequency dependence of the RTD conductance (4) and the experimental data from [2] is shown in Fig. 1. The theory and experiment are in excellent agreement with each other, as it follows from the figure.

From (4) follows that RTD conductance can be approximated by RC-circuit in the low frequency limit, when $\omega\tau_{\rm c} d/(L+d) \ll 1$ and $\omega\tau_{\rm resp} \ll 1$:

$$G(\omega) \approx i\omega\tilde{C} + G^0_{\rm RT} + G_{\rm nonres}, \qquad \tilde{C} = C_{\rm ec} + G^0_{\rm RT}\left[\tau_{\rm c}\frac{d}{L+d} - \tau_{\rm resp}\right]. \tag{5}$$

The analysis of (5) and (3) shows that $\tilde{C} > 0$, although it can be essentially less than C_{ec}. The low frequency C–V characteristic has specific features in the PDC and NDC regions. In the PDC region $\tilde{C}$ can have an increase (if $\tau_c d/(L+d) > \tau_{resp}$) or dip (if $\tau_c d/(L+d) < \tau_{resp}$). Both cases are real and they are observed in plenty of experiments, e.g., the increase was observed in [3] and dip in [2] (see Fig. 1 and subscript there), the experimental data are in very good quantitative agreement with (5). As a rule, $\tilde{C}$ has peak in the NDC region and it is also in good quantitative agreement with (5).

RTD conductance can be approximated by a different RC-circuit in the high frequency region ($\omega\tau_c d/(L+d) \gg 1$ and $\omega\tau_{resp} \gg 1$):

$$G(\omega) \approx i\omega C_{ec} + G^0_{RT} \frac{d}{L+d} \frac{\tau_c}{\tau_{resp}} + G_{nonres}. \tag{6}$$

$G' \equiv \mathrm{Re}(G) \approx -dC_{wc}/(L+d)\tau_{dwell}$, if G_{nonres} is sufficiently small and $-G^0_{RTD} \gg C_{wc}/\tau_c$. In the case, G' does not depend on static differential conductance and is substantiated by τ_{dwell} and the geometry of RTD only. At low frequencies the variation of bias (δE_{fc}) leads to a significant variation of N_{2D} and J_{RTD} changes in result. At the high frequencies the situation is different. δN_{2D} is very small and its phase is shifted by $\pi/2$ with respect to δE_{fc} (see Eq. (1)), but it leads to variation of the electric field distribution in RTD and, as a consequence, to variation of the charges in emitter and collector. The variation of the charges, in its turn, leads to variation of J_{RTD} with the phase shift of $\pi/2$. The negative G' appears precisely due to the two phase shifts. So, G' can be finite and negative when $\omega\tau_{resp} \gg 1$ and it should be possible to use RTD as generator at such frequencies.

RTD conductance (4) has formally the form coinciding with RLC-circuit [4] in the intermediate frequency range ($\omega\tau_{resp} \lesssim 1$ and $\omega\tau_c d/(L+d) \ll 1$):

$$G(\omega) \approx i\omega C_{ec} + \frac{G^0_{RT}}{1 + i\omega\tau_{resp}} + G_{nonres}. \tag{7}$$

The “inductance” describes the delay of current with respect to bias [4] and the delay is τ_{resp} (“inductance” $l = \tau_{resp}/G^0_{RT}$) rather than τ_{dwell} ($l_{[4]} = \tau_{dwell}/G^0_{RT}$).

Acknowledgements

The work was supported by INTAS (97-11475), RFBR (99-02-17592), Programs FTNS (99-1124) and PAS (3.1.99). The author is grateful to V. Popov and V. A. Volkov for useful discussion.

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