Comparison and Analysis of Two Microwave Equivalent-Circuit Models for Resonant Tunneling Diode*

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Abstract: The distinction between two microwave equivalent-circuit models, quasi Esaki tunneling model (QETM) and quantum well injection transit model (QWITM), for the resonant tunneling diode (RTD) is discussed in details, and two groups of circuit parameters are extracted from experiment data by the least square fit method. Both theory analysis and the comparison of fit results demonstrate that QWITM is much more precise than QETM. In addition, the rationality of QWITM circuit's parameters confirms it too. On this basis, the resistive frequency is calculated, whose influence factors and improvement method are simply discussed as well.

Key words: resonant tunneling diode; microwave equivalent-circuit; quantum well injection transit; resistive frequency

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1 Introduction

Resonant tunneling diode(RTD), a two-terminal negative resistance device based on quantum resonant tunneling, is one of those devices with highest operation frequency and fastest response speed. The most interesting characters of RTD are high speed and special folded I-V characteristics, which has made RTD useful for the implementation of ultra-fast logic gates, latches, quantizers, and static random memory element.

For its high speed, RTD also has great application prospect in the fields of microwave, because of which a precise equivalent circuit model needs to be established to get the performance parameters, on the basis of all-around theory analysis. Until now there are two kinds of primary microwave equivalent-circuit models, quasi Esaki tunneling model(QETM)[1] and quantum well injection transit model(QWITM)[2], whose difference will be discussed below by means of the circuits parameters extracted from the experiment data. Then the resistive frequency (f_R) of each model will be calculated and the influence factors of f_R will be discussed.

2 Experiment

The RTD used in this paper was prepared by molecular beam epitaxy (MBE) for double barrier-single well structure and then was fabricated by traditional Ⅲ-Ⅴ compound semiconductor technology to gain the investigated device. In the material structure design, an $In_{0.25}Ga_{0.75}As$ sub-well has been put into GaAs quantum well to reduce the en-

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ergy level and decrease the set-on voltage. Figures 1 and 2 show the material structure and *I*-*V* characteristic of RTD, 5μm×5μm, respectively[3].

n^+-GaAs	500nm	$1\times10^{18}cm^{-3}$
n-GaAs	50nm	$2\times10^{17}cm^{-3}$
n-GaAs	50nm	$2\times10^{16}cm^{-3}$
GaAs	3nm	Undoped(UD)
AlAs	2nm	UD
GaAs	1.5nm	UD
$In_{0.25}Ga_{0.75}As$	2.5nm	UD
GaAs	1.5nm	UD
AlAs	2nm	UD
GaAs	3nm	UD
n-GaAs	50nm	$2\times10^{16}cm^{-3}$
n-GaAs	50nm	$2\times10^{17}cm^{-3}$
n^+-GaAs	1000nm	$1\times10^{18}cm^{-3}$
SI-GaAs	Substrate	

Fig.1　Material structure of RTD

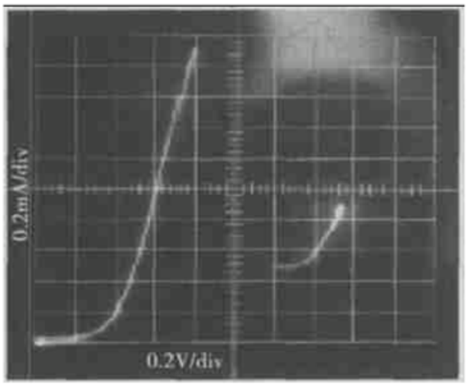

Fig.2　*I*-*V* characteristic of RTD

In experiment, RTD could be considered as a network of two terminals, and its microwave performance was assessed by bias-dependent scattering parameters measurement on chip from 45MHz to 26.5GHz with network analyzer HP8510(C)[4]. In the four *S*-parameters of RTD obtained, S_{22} can be expressed as a function of Z_{in}: $S_{22} = (Z_{in} - Z_0)/(Z_{in} + Z_0)$. In this equation, $Z_0 = 50\Omega$, is the matching load of transmission line terminal, and S_{22} and Z_{in} are both complex numbers. In the measurement frequency range, 201 frequency points were set under the bias of 0.7V in the negative resistance region and S_{22} of each point could be transformed to Z_{in} from above equation. With so many points of frequency, we can determine the optimal values of these parameters through a least square fit method to get the real and imaginary part of Z_{in}.

3　Equivalent circuits

3.1　Quasi Esaki tunneling model

This model quotes the Esaki tunneling diode theory to explain the high frequency performance of RTD. The circuit model is shown in Fig.3, in which R_S is the series resistance, containing the contact and bulk resistance; L_S is the series inductance; R_W stands for the intrinsic negative resistance of quantum well whose value approximately equals to the differential resistance under the bias of 0.7V; and C_W represents the total capacitance of device, including the parallel-plate capacitances of each layer, the active capacitance in the quantum well, and the depleted region capacitance owing to depletion of charge. This model has been used to estimate f_R and used in the research for large signal response in microwave operation[5].

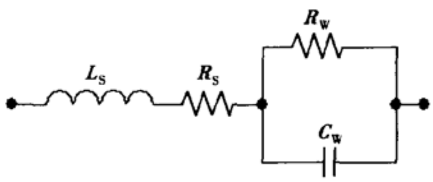

Fig.3　Equivalent circuit of QETM for RTD

But the limitation of this model is obvious. Because it integrates the capacitances in and out of the quantum well, we apply this model only for the situation when demand of calculation precision is not very strict.

The expression of Z_{in} of this model is shown below, where ω is the angle frequency, $\omega = 2\pi f$.

$$Z_{in} = \left[R_S + \frac{R_W}{1 + (\omega R_W C_W)^2}\right] + j\left[\omega L_S - \frac{\omega R_W^2 C_W}{1 + (\omega R_W C_W)^2}\right] \quad (1)$$

3.2 Quantum well injection transit model

Although above-mentioned QETM is widely applied, it is still a relatively approximate method. In fact, in most of RTDs' structures, the collector layer of RTD is usually designed not too heavy doping and there is an intrinsic spacer layer between well and collector which is inevitable to improve the quantum transmitting efficiency[6]. On this condition, a wide depleted region will emerge in the collector side of quantum well, so the electrons should traverse the space charge region before reaching the collector electrode. On the other hand, the quantum well is designed to be very thin to improve the quantum effect, which makes the transit time in the quantum well less than that in the depleted region sometimes. So a more precise model is necessary for calculating the performance parameters more exactly. And the impedances in the depleted region and quantum well should be separated too, that is to apply the quantum well injection transit model. Former studies in other transit time devices[7~9] have indicated that impedance has a form similar to the quantum well. The total impedance could be expressed like $Z = Z_W + Z_D$, and equivalent circuit is shown in Fig. 4.

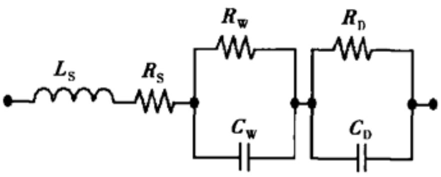

Fig. 4 Equivalent circuit of QWITM for RTD

In Fig. 4, R_S and L_S have same meaning with Fig. 3, while C_W represents the intrinsic capacitance in the quantum well only; C_D is the depleted region capacitance that comes out of the delay of electrons in depleted region, and R_W and R_D are the negative resistances of the quantum well and space charge region, respectively. In terms of the physics meaning, this model expresses, more close to reality, the operation status on the condition of high frequency and a given bias more exactly. The expression of Z_{in} of QWITM is shown below.

$$Z_{in} = \left[R_S + \frac{R_W}{1 + (\omega R_W C_W)^2} + \frac{R_D}{1 + (\omega R_D C_D)^2} \right] + j\left[\omega L_S - \frac{\omega R_W^2 C_W}{1 + (\omega R_W C_W)^2} - \frac{\omega R_D^2 C_D}{1 + (\omega R_D C_D)^2} \right] \quad (2)$$

The following discussion is concerned with the difference of two models in terms of data fitting and parameters extraction.

4 Fitting and analysis

Depending on the real and imaginary parts of Z_{in} in Eqs. (1) and (2), the experiment data have been fitted with program Origin, after being transformed from S-parameters to Z-parameters. Figure 5 shows the fitting results of QETM and equivalent parameters: $R_S = -5.54\Omega$, $L_S = -1.05 \times 10^{-11}$ H, $R_W = -358.27\Omega$, $C_W = 1.21 \times 10^{-13}$F, the best-

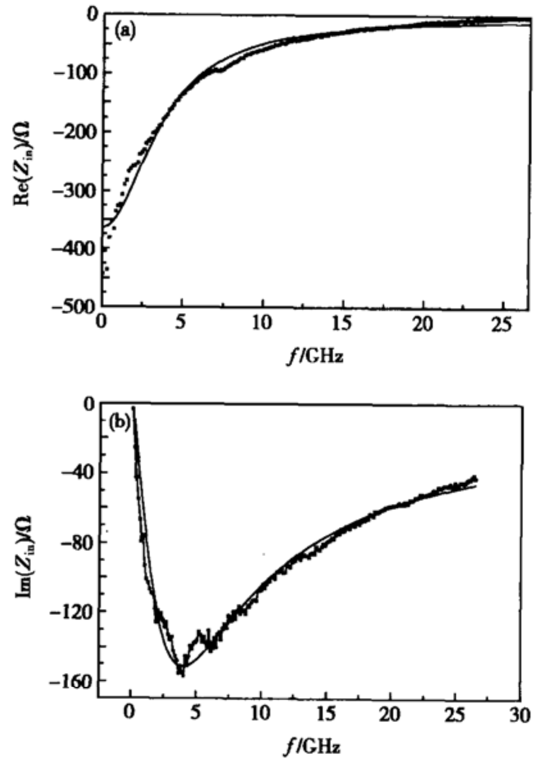

Fig. 5 (a) Curve fit result of real part impedance of QETM; (b) Curve fit result of imaginary part impedance of QETM ——fit data; ······experimental data fit root mean square error is 160.57 of real part, and 38.57 of imaginary part. Figure 6 shows the fitting results of QWITM and equivalent parameters: $R_S = 4.60\Omega$, $L_S = 3.61\times10^{-11}$ H, $R_W = -171.11\Omega$, $C_W = 1.01\times10^{-12}$F, $R_D = -258.21\Omega$, $C_D = 1.14\times10^{-13}$F, the best-fit root mean square error is 19.06 of real part, and 9.65 of imaginary part.

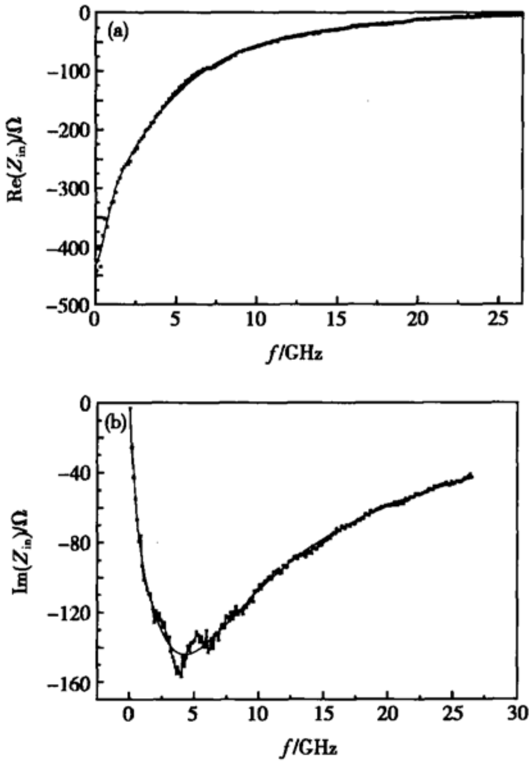

Fig. 6 (a) Curve fit result of real part impedance of QWITM; (b) Curve fit result of imaginary part impedance of QWITM ——fit data; ……experimental data

Judging from the fit results, QWITM excels QETM in two sides: First, the best-fit root mean square error of each part of QWITM is much smaller than QETM, that is to say, the impedance expression of QWITM matches the experiment curve better than QETM through the optimization procedure and is closer to reality. Second, during the optimization procedure, R_S and L_S are negative numbers in QETM, while positive in QWITM. But according to the definition of these two parameters, both they should be positive; it is obvious that QWITM embodies more precise physical mechanism. In former calculation in order to get positive R_S and L_S in QETM, consequently calculate f_R, we had to initiate them with positive numbers by estimate, which apparently is not scientific and exact.

5 Resistive frequency

Equation(3) is obtained from Eq.(1) on the base of the definition of f_R, the corresponding frequency when the real part of Z_{in} equals to zero.

$$f_{R1} = \frac{1}{2\pi R_W C_W}\sqrt{-\frac{R_W}{R_S} - 1} \tag{3}$$

But for negative R_S in QETM, the initiated value of R_S is 4.596Ω in QWITM to compute f_R. And the result is $f_{R1} = 35.57$GHz. It could be concluded from Eq.(3) that the decrease of R_S, R_W, and C_W would increase f_R. So in the design and fabrication of RTD, following methods have been applied to improve f_R: sufficiently alloyed and heavily doping in E region to minish R_S, thinning barrier´s width and using high mobility materials to minish R_W, reducing area of E region, and adopting atmosphere bridge structure to minish C_W.

As far as the resistive frequency, it is more complex to analyze. When Re(Z_{in}) equals zero, we can get a quadratic equation (4) versus ω^2 from which three coefficients could be obtained according to the circuit parameters as following.

$$(R_W C_W R_D C_D)^2\omega^4 + \left[\left(1 + \frac{R_W}{R_S}\right)(R_D C_D)^2 + \left(1 + \frac{R_D}{R_S}\right)(R_W C_W)^2\right]\omega^2 + 1 + \frac{R_W}{R_S} + \frac{R_D}{R_S} = 0 \tag{4}$$

$$\begin{aligned} a &= (R_W C_W R_D C_D)^2 = 2.748\times10^{-41}S^4 \\ b &= \left(1 + \frac{R_W}{R_S}\right)(R_D C_D)^2 + \left(1 + \frac{R_D}{R_S}\right)(R_W C_W)^2 \\ &= -1.778\times10^{-18}S^2 \\ c &= 1 + \frac{R_W}{R_S} + \frac{R_D}{R_S} = -93.475 \end{aligned} \tag{5}$$

The positive root is $\omega^2 = 6.474\times10^{22}S^{-2}$, and $f_{R2} = \frac{1}{2\pi}\sqrt{6.474\times10^{22}} = 40.49$GHz. The relation of

f_{R2} and the circuit parameters comes from the relation of f_{R2} and ω^2. In the expression $\omega^2 = \frac{-b+\sqrt{b^2-4ac}}{2a}$, and $b^2 = 3.160\times10^{-36} \gg 4ac = -1.027\times10^{-38}$, so $4ac$ could be ignored and a simple expression is obtained:

$$\omega^2 = -\frac{b}{a} = \left(-\frac{R_W}{R_S}-1\right)/(R_WC_W)^2 + \left(-\frac{R_D}{R_S}-1\right)/(R_DC_D)^2 \quad (6)$$

From above equation, it could be observed that f_{R2} and f_{R1} have similar forms with the only difference that QWITM has an extra RC oscillation circuit comparing with QETM. In order to increase f_{R2}, all of R_S, R_W, C_W, R_D, and C_D should be minished. So besides those methods mentioned above, the doping concentration of collector should be increased to thin the width of depleted region to increase C_D. But for that it will increase R_S, the limit of both sides in structure design should be considered.

6 Conclusion

This paper has analyzed the similarities and differences of QETM and QWITM in both physics theory and fitting results of data. And it is believed that QWITM suits to high frequency performance of RTD better than QETM because of the existence of depleted region, which is inevitable with the spacer layer and light doping in collector side. So QETM could be used as an approximate model only. While considering the important role that depleted region plays in performance, QWITM should be adopted for its greater precision.

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谐振隧穿二极管的两种高频小信号模型比较与分析*

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摘要: 讨论了谐振隧穿二极管(RTD)的两种微波等效电路模型:类江崎隧道模型(QETM)和量子阱注入传输模型(QWITM)之间的差异,并用最小二乘法拟合实验数据,提取了两种模型的电路参数.理论分析和对拟合结果的比较都说明QWITM比QETM更加精确,而提取到的QWITM的电路参数的合理性也证明了这一点.在此基础上计算了阻性频率f_R,并简单介绍f_R的影响因素及其提高方法.

关键词: RTD; 微波等效电路; 量子阱注入传输; 阻性频率

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