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Research on GaAs-based RTD performance analyses and switching time characteristics

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Abstract: The paper designed and developed GaAs-based RTD (Resonant Tunneling Diode), which can achieve a high peak-to-valley current ratio of 7.6:1 at room temperature. Then it made on-wafer measurement for S parameter of RTD, analyzed frequency characteristics of RTD and the equivalent circuit parameters are obtained by fitting in order to calculate the maximum oscillation frequency. Resonant tunneling diode AC small-signal model was established to be used for circuit simulation and the paper utilized PSPICE for analog simulation with analogue result coincidental with experimental data. Lastly it used negative resistance value to estimate switch time according to I-V characteristics and compared with other two methods, conclude that the reasonable switch time is about $0.8|R_N|Cd$.

Keywords: Resonant tunneling diode, AC small-signal model, Equivalent circuit simulation, Switching time

I. INTRODUCTION

Resonant Tunneling Diode (RTD) is a nano device with negative resistance on the two sides based on quanta tunneling phenomenon, and is the most expected device in current nano electronics. One of important development trends of next generation of integrated circuit is resonant tunneling device which has impressive advantages of quick response speed, high working frequency, low voltage, low power consumption and multifunction. With rapid development of very large scale and ultra large scale integrated circuits and increasing decrease of line width of device, the quantum effects will inevitably be placed in front of people. The Resonant tunneling oscillator (RTO) constructed with RTD as active device and slot antenna as load is a microminiature THz wave source that can operate at room temperature, and is also the only electronic device with fundamental oscillation frequency exceeding 1THz in solid electronic devices [1,2]. From 2010 till now, the fundamental oscillation frequency saw breakthroughs year after year, from 1.04 THz, 1.08 THz, 1.31THz, 1.40THz, 1.42TH, 1.46THz, 1.55 THz to 1.92 THz [1,3-9] in early 2016. The THz range can be employed in various applications, such as imaging, high speed wireless communications, search and safety inspection, biological and medical diagnosis, and radio astronomy detection [10,11]. To sum up, the key is to develop RTD with good performance. The conversion frequency between peak and valley of RTD is estimated to be up to 1.5~2.5THz [12,13]. In fact, fmax of RTD device has already been up to 2.2THz. RTD has become an important sign of development of quanta coupled device and its circuit [14].

In this paper, we designed and grew GaAs-based RTD and conducted test to get a high peak-to-valley ratio current (PVCR) of 7.6:1 at room temperature. According to RTD's current-voltage equation [15], the paper used PSPICE's voltage controlled current source to establish DC model and established RTD AC small-signal model used for circuit simulation with simulation result conforming to experimental data. We used HP8510C network analyzer to make on-wafer measurement for S parameter of RTD and then completed the test of its frequency characteristics. One port network analytical method was adopted to analyze RTD frequency characteristics. Lastly, the switching time is estimated using negative resistance value according to I-V characteristic and is very close to the result of estimation using speed-index, while the value estimated using $4R_NC_d$ is too high. Analysis shows the reasonable switching time is about $0.8|R_N|Cd$.

II. MATERIAL STRUCTURE AND TEST

RTD material structure is multilayered quantum well structure, and the commonest RTD is the double barrier structure. The molecular beam epitaxy technology is used to grow material structure of AlAs/GaAs/InGaAs/GaAs/AlAs, as shown in Table 1.

Table 1 Material structure of GaAs-based RTD

MATERIALS	THICKNESS	DOPING
GaAs	500nm	$3\times10^{18}cm^{-3}$
GaAs	10nm	$1\times10^{17}cm^{-3}$
GaAs	5nm	-
$In_{0.1}Ga_{0.9}As$	5nm	-
GaAs	0.5nm	-
AlAs	1.7nm	-
GaAs	0.5nm	-
$In_{0.1}Ga_{0.9}As$	4nm	-
GaAs	0.5nm	-
AlAs	1.7nm	-
GaAs	0.5nm	-
$In_{0.1}Ga_{0.9}As$	5nm	-
GaAs	5nm	-
GaAs	10nm	$1\times10^{17}cm^{-3}$
GaAs	1000nm	$3\times10^{18}cm^{-3}$
SI-GaAs Substrate		

Here, we not only grew an isolating layer undoped with GaAs on each side of the double barrier structure, but also grew sub-well of $In_{0.1}Ga_{0.9}As$. The mesa area is $5\times5\mu m^2$. I-V characteristic of RTD chip is tested at room temperature and the fabricated single RTD PVCR achieves 7.6:1, as shown in Fig. 1.

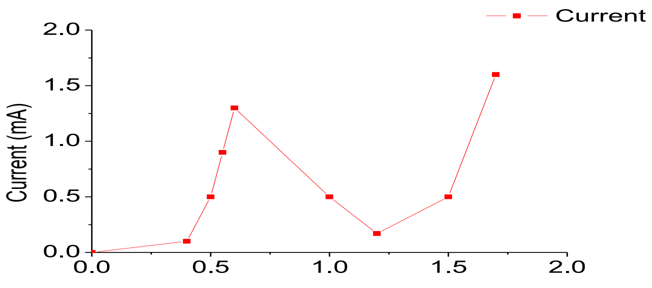

Figure 1 DC characteristic of $5\times5\mu m^2$ RTD

III. SIMULATION ANALYSES ON EQUIVALENT CIRCUIT

Combining RTD's physical mechanism, its equivalent circuit is selected as shown in Fig. 2 including RTD intrinsic differential negative resistance R_d (expressed by controlled current source), intrinsic capacitance C_d, series resistance R_S (including lead resistance, ohmic contact and spreading resistance of crystal wafer) and series inductance L_S.

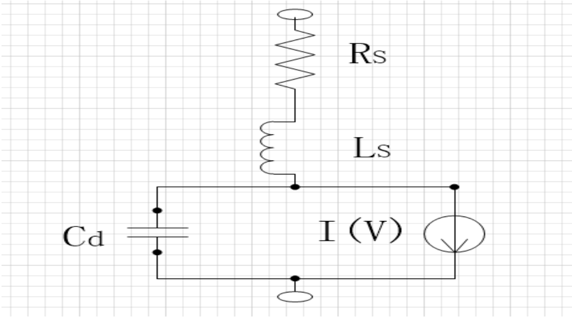

Figure 2 RTD equivalent circuit model

Current expression of controlled current source is got by adopting RTD current-voltage equation with physical significance. RTD current is mainly composed of partially mutually competing current [16]. They are respectively tunneling current (generated by direct tunneling) and excess current (similar to common diode), as shown in equation below:

$$J = J_{\mathrm{RT}} + J_{\mathrm{EX}} \tag{1}$$

J_{RT} is a part of resonant tunneling current, which just leads to negative differential resistance of I-V characteristic curve and J_{EX} is residual excess current element. Based on the physical significance of the formula, the experimental data were fitted. By fitting, the simplified current expression is as shown in equation below:

$$\begin{aligned} \mathrm{I} = {} & 4.68 \times 10^{-4} \times \ln\left[\frac{1 + \exp\left[\left(-0.1085 + 0.187 \times V\right)/0.027\right]}{1 + \exp\left[\left(-0.1085 - 0.187 \times V\right)/0.027\right]}\right] \\ & \times \left[1.57 + \tan^{-1}\left(\frac{0.1625 - 0.187 \times V}{0.014}\right)\right] \\ & \cdots + 2.75 \times 10^{-8}\left[\exp[(0.164 \times V)/0.027] - 1\right] \end{aligned} \tag{2}$$

On-wafer measurement is made for S parameter of this resonant tunneling diode using HP8510 (C) network analyzer. For one port network, reflection coefficient $S_{22} = (Z_{in}-Z_0)/(Z_{in}+Z_0)$ is output. Normalize $Z_0 = 50\Omega$, we can deduce $Z_{in}=Z_0(1+S_{22})/(1-S_{22})$. The S and Z_{in} here are all plural, and then the equivalent impedance of RTD is obtained. Generally maximum oscillating frequency of diode is cutoff frequency of resistance. According to definition of resistance cutoff frequency, it is oscillation frequency when real part of impedance is zero. RTD's S parameter is obtained by network analyzer. RTD impedance can be obtained by direct conversion of data. As the equivalent circuit diagram in Fig. 2, the expression of input impedance $\mathbf{Z_{in}}$ is as follows:

$$Z_{in} = \left[R_S + \frac{-R_d}{1 + \left(wR_dC_d\right)^2}\right] + j\left[wL_S + \frac{-wC_dR_d^{\,2}}{1 + \left(wR_dC_d\right)^2}\right] \tag{3}$$

Cutoff frequency of resistance is:

$$f = \frac{1}{2\pi R_d C_d}\sqrt{\frac{R_d}{R_s} - 1} \tag{4}$$

The equivalent circuit parameters were obtained through the calculation and fitting and we calculated that maximum oscillation frequency is up to 26.5 GHz. In order to obtain a better frequency characteristic, we changed the mesa area to carry on the optimization. Test and analysis as the above methods, and the maximum oscillation frequency can reach 54 GHz when the mesa area AE is 4×4μm^2.

To sum up, combine RTD DC part and the extracted AC small-signal parameters and use PSPICE to establish RTD equivalent circuit model. Simulate and calculate RTD equivalent impedance in the same DC bias to see whether it is coincidental with impedance result obtained by converting measured S parameter. The output result of 5×5μm^2 RTD and 4×4μm^2 RTD is as shown in Fig. 3 and Fig. 4, respectively. The simulation results are well coincidental with real data.

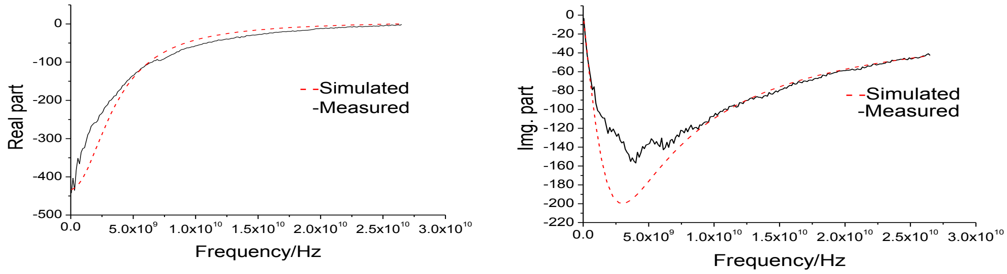

Figure 3 Comparison of simulated output impedance and actually measured impedance of 5×5μm^2 RTD Left) Impedance real part data points fit with the model ; right) lImpedance imaginary part data points fit with the model

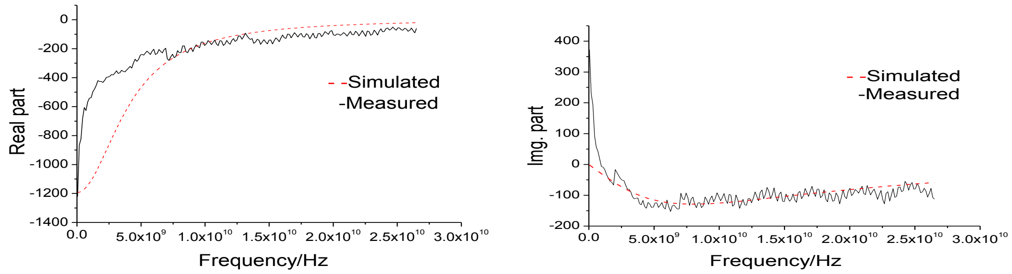

Figure 4 Comparison of simulated output impedance and actually measured impedance of 4×4μm^2 RTD Left) Impedance real part data points fit with the model ; right) lImpedance imaginary part data points fit with the model

Fig. 3 and Fig. 4 show that the two curves are well coincidental. Failure to be coincidental precisely is not because of inaccurate model, and mainly due to the fact that the bias voltage used in measurement is not calibrated precisely. So the bias voltages set in measurement and simulation are not necessarily identical, while small bias can lead to great change of differential negative resistance. It should be noted that due to influence of some interference factors, some bias points cannot keep stable, under which there may be greater maximum oscillating frequency. According to definition of the maximum resistance cutoff frequency given by E.R.Brown et al in foreign Lincoln laboratory, with change of bias voltage, differential negative resistance has a minimal value in the negative impedance region. When this value is the smallest, f_R is the largest and this minimum negative resistance is about twice of R_S. This estimated maximum resistance cutoff frequency of 5×5μm^2 RTD and 4×4μm^2 RTD are 98.5 GHz and 346.8 GHz, respectively.

IV. ANALYSIS ON SWITCHING TIME

When RTD in ultra-speed pulse digital circuit works in conversion between peak point and valley point, it must be characterized by switching time or rise time t_r. Compared with electro-optic sampling technique [17] which is difficult for measurement, usually estimate method is used to estimate t_r. By analyzing inverter composed of RTD and load resistance, deduce following expression of minimum limit of switching time:

$$t_r \ge \frac{0.8(V_V - V_P)C_d}{I_P - I_V} = 0.8R_N C_d \tag{5}$$

Use RTD I-V characteristic to estimate t_r, combine developed RTD's some measurement results and substitute into above equation to get t_r = 36 ps. Lastly, adopt $4R_NC_d$ to estimate t_r [18] and speed-index to estimate t_r [19], substitute RTD's measurement data result to get switching time of $t_r \approx 171.6$ps and tr = 36.3 ps, respectively. It is obvious that the results of estimation using speed-index and RTD I-V characteristic are very close according to above estimation result, while estimated value using $4R_NC_d$ is too high. After comparative analysis, $0.8|R_N|C_d$ is reasonable. Thereinto, R_N is absolute value of negative resistance, which can be extracted by measuring scattering parameter(S), or be obtained by from average negative resistance of DC I-V characteristic. The equation is as shown in equation (6):

$$\left| \mathrm{R}_{\mathrm{N}} \right| = \frac{V_V - V_P}{I_V - I_P} \tag{6}$$

C_d is intrinsic capacitance connected in parallel with R_n in RTD equivalent circuit, generally extracted by optimizing and fitting measured scattering parameter (S).

V. CONCLUSION

Based on advantages of resonant tunneling device RTD, the paper tested and analyzed RTD characteristics. The developed RTD has a high peak-to-valley ratio current (PVCR) of 7.6:1 at room temperature. The equivalent circuit model of resonant tunneling device is established and frequency characteristic is analyzed to lay a good foundation for next development work, delivering some practical significance. Lastly, the three methods of estimating RTD switching time tr are compared to conclude that $t_r \approx 0.8|R_N|C_d$ is reasonable.

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