Circuit Modeling of Tunneling Real-Space Transfer Transistors: Toward Terahertz Frequency Operation

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Abstract—High frequency operation of tunneling real-space transfer transistor (TRSTT) in the negative differential resistance (NDR) regime is assessed by calculating the device common source unity current gain frequency ($f_T$) range with a small signal equivalent circuit model including tunneling. Our circuit model is based on an In$_{0.2}$Ga$_{0.8}$As and $\delta$-doped GaAs dual channel structure with various gate lengths. The calculated TRSTT $f_T$ agrees very well with experimental data, limiting factor being the resistance of the $\delta$-doped GaAs layer. By optimizing the gate dimensions and channel materials, we find $f_T$ in the NDR region approaches terahertz range, which anticipates potential use of TRSTT as terahertz sources.

Index Terms—Tunneling real-space transfer transistor (TRSTT), negative differential resistance (NDR), small signal equivalent circuit model, unity current gain frequency

I. INTRODUCTION

Tunneling real space transfer (TRST) is a quantum mechanical effect that arises between two channels of different mobilities in field effect transistors to achieve NDR controlled by the gate bias [1]. The effect was first demonstrated in pseudo-morphic AlGaAs/InGaAs MODFET [2], and investigated in several TRSTT structures in the last decades [3]–[5]. Recently, very clean TRST-induced NDRs with modulated peak to valley (P/V) ratios up to 4 at room temperature were demonstrated in pseudo-morphic GaAs/InGaAs MODFET structures (fig.1 inset) [6]. The devices however were relatively long and wide with large capacitance, so that $f_T$ was below 10 GHz. Therefore considerable room for improvement is expected with frequency operation far above 100 GHz, and hopefully up to the THz range [7].

The TRSTT operation frequency in the NDR region depends on two main factors: the tunneling time $\tau$ between the two channels, and the carrier transit time $\tau_D$ from the source to drain in the dual channel structure. Usually, the tunneling time is estimated to be less than 0.5 ps [6], so the TRSTT performances are essentially determined by $\tau_D$.

In this letter, based on devices similar to those in ref [6] we implement a small-signal equivalent circuit model accounting for tunneling between the TRSTT two channels, and for which $f_T$ in tunneling mode is calculated analytically in the common source circuit configuration. Our model predicts that $f_T$ in NDR region can reach THz range by optimizing the channel material, and shortening the gate length.

II. TRSTT STRUCTURE AND MEASUREMENT

![Fig. 1. Experimental drain current vs. drain voltage under different gate voltages in TRSTT starting from $V_{gs}=0$ V to $V_{gs}=0.6$ V with a step of 0.1 V.](image)

The device structure is schematically shown in fig.1 inset. The heterostructures consist of a 0.8-$\mu$m intrinsic GaAs buffer layer, a 90-Å undoped In$_{0.2}$Ga$_{0.8}$As channel layer, a 90-Å undoped GaAs spacer layer, followed by a silicon $\delta$-doped layer with a $4\times10^{12}$ cm$^{-2}$ sheet density, and a 300-Å undoped GaAs cap layer. The gate dimension is 2$x$60 $\mu$m$^2$, and the source-gate and gate-drain separations are 2 $\mu$m, each.

Fig. 1 displays the device output characteristics with NDR
under different gate biases. Noticeable gate leakage current is observed with the NDR onset, which is attributed to TRST [6]. The channel electron mobility is measured to be 5604 cm²/Vs by Hall test, and the sheet density of carrier in In₀.₃Ga₀.₇As channel is 9.02×10¹² cm⁻² at room temperature. In the absence of NDR i.e. TRST, \( f_T \) at bias point C (\( V_{gd} = 0.6 \) V, \( V_{gs} = 5 \) V) is measured to be 8.9 GHz.

### III. Small Signal Equivalent Circuit with Tunneling

![Equation (1)](image)

\[ I_D = g_{m1}V_1 + g_{m2}V_2 \]  
\[ I_G = j\omega (C_{gs1} + C_{gs2})V_1 + j\omega C_{gs2}V_2 + \frac{V_2}{R_g} \]  
\[ v_1 = \frac{v_g - (i_g + i_d)R_T}{1 + j\omega (C_{gs1} + C_{gs2})R_{t_1}} \]  
\[ v_2 = \frac{v_g - (i_g + i_d)R_T}{1 + \frac{R_{t_2} + \frac{R_T}{1 + j\omega R_T}}{\frac{R_{t_2} + \frac{R_T}{1 + j\omega R_T}}}} \]

with \( \omega = 2\pi f_T \), \( \tau_T = R_TC_\delta \). Owing to the strong I vs. V non-linearity, the \( f_T \) determination in the NDR region would be tedious under small signal operation. Rather, one can estimate its value by calculating it on both sides of the NDR region i.e. at points A and B shown on fig. 1(a). By ignoring the gate leakage, one obtains the following equation for drain currents in the two channels right before and after tunneling,

\[ n_{s1}qW_gv_{x1} + n_{s2}qW_gv_{x2} = I_{d1} \]  
\[ I_{d2} = (n_{s1} + n_{s2})qW_gv_{x1} \]  

Here \( q \) is the electron charge, \( I_{d1} \) and \( I_{d2} \) are the drain currents at bias points A and B, \( v_{x1}, v_{x2} \) are the saturation velocity of electrons in both channels, \( W_g \) is the gate width, and \( n_{s1} \) and \( n_{s2} \) are the carrier density in the 2-DEG channel and \( \delta \)-doped channel under the gate after tunneling. Based on the definition \( g_{mn} \) and \( g_{m2} \), one gets

\[ g_{m1} = \frac{\gamma_p - \gamma_V}{\gamma_p (1 - \gamma_y)} g_m, \quad g_{m2} = \frac{\gamma_V (1 - \gamma_p)}{\gamma_p (1 - \gamma_y)} g_m \]  

\[^{1} \text{In ref. [6], the mentioned } f_T = 9 \text{ GHz is taken from the 6 } \mu \text{m channel length sample used in our modeling and its accurate value is 8.9 GHz.}\]
where we call $\gamma_p = I_{dd}/I_{dd}$ and $\gamma_V = v_{ce}/v_{ce}$ the tunneling peak ratio and velocity difference ratio.

Usually, the gate-source capacitance $C_gs$ is defined as the net increase of positive charge in the depletion area by an incremental increase in gate-source voltage [8]. However for $\delta$-doped TRSTT, the only positive charge is in the $\delta$-doped layer. Instead, we obtain $C_gs$ indirectly by calculating the variation of the carrier densities $Q_1$ and $Q_2$ in the two channels under the gate. In the tunneling mode, the total gate-source capacitance can be written as

$$C_gs = \frac{\partial Q_1}{\partial Vgs} + \frac{\partial Q_2}{\partial Vgs} = g_{d1}Wg_1 \frac{\partial n_{s1}}{\partial Vgs} + g_{d2}Wg_2 \frac{\partial n_{s2}}{\partial Vgs}$$

(7)

The drain currents in the two channels read

$$I_{d1} = qWg_v\nu_{s1}n_{s1} = g_{d1}V_{ds}, I_{d2} = qWg_v\nu_{s2}n_{s2} = g_{d2}V_{ds}$$

(8)

where $g_{d1}$, $g_{d2}$ are the drain conductance of the 2-DEG and $\delta$-doped channels, respectively. Combining (7), (8), one can get

$$C_gs = \frac{g_{d1}}{v_{ce}}g_{m1} + \frac{g_{d2}}{v_{ce}}g_{m2}$$

(9)

One determines $f_T$ in the tunneling mode by solving (1)–(4), (6) and (9). In a first order approximation one can neglect $R_i$, $R_2$, $R_d$, $C_{gs}$, and $\pi$ compared to other circuit elements to obtain a closed form for $f_T$ at point B as shown in (10)

$$f_{T,B} = \frac{\gamma_p(1 - \gamma_V)}{2\pi L_{g1}(\gamma_p - \gamma_V) + L_{g2}(1 - \gamma_p)}$$

(10)

When no tunneling occurs, $\gamma_p = 1$ and $\gamma_V = 0$. The $f_T$ at point A can be derived from that of $f_{T,B}$ as shown in (11)

$$f_{T,A} = \frac{\nu_{ce}}{2\pi L_{g}}$$

(11)

V. RESULTS AND DISCUSSION

Based on the measured channel mobility, one can estimate the saturation velocity $v_{ce}$ of the sample to be $1 \times 10^7$ cm/s. Inserting this value into (11), we get $f_T = 7.96$ GHz, which agrees well with the experimental value $8.9$ GHz obtained for the device in saturation, in the absence of TRST.

In Fig. 3, we show the calculated $f_T$ as a function of gate length around the NDR region for different tunneling positions along the 2-DEG channel. The best $f_T$ can be achieved by shrinking the gate length to 40 nm with a tunneling position close to the drain. If we optimize the saturation velocity to $2 \times 10^7$ cm/s by using higher indium composition InGaAs material and maintain the values of other parameters in (10) and (11), $f_T$ in the NDR region can reach a range between $620$ GHz and $800$ GHz for $L_d/L_g = 0.7$, which indicates that high frequency response is obtained for tunneling closer to the drain than the source, in order to reduce the $\delta$-doped channel resistance. This range of $f_T$ is shown in Fig. 3 between the black solid line with solid circles and the red solid line.

VI. CONCLUSION

Our small signal equivalent circuit model for TRSTT shows that THz frequency operation in the NDR region of the devices is possible by shrinking the gate length, but also improving the mobility or saturation velocity in the 2DEG channel. As expected the critical factor is the $\delta$-doped channel resistance that should remain significant compared to the 2DEG channel resistance if large NDR peak-to-valley ratios are required. In this context, it may be worth exploring other material systems offering optimum mobility/saturation velocity difference with large and abrupt NRDRs. Finally, let us mention that a key assumption in our analysis was the TRST occurrence along the channel. For this purpose a physical model of quantum tunneling between channels under bias conditions is desirable.

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