ANALYSIS OF THE SCALING PROPERTIES OF REAL-SPACE TRANSFER TRANSISTORS USING A MONTE CARLO APPROACH

M. B. Patil and U. Ravaioli
Beckman Institute, University of Illinois, Urbana, IL 61801

Abstract

Monte Carlo simulations of the Real-Space Transfer Transistor (RSTT) are performed for various geometries. A reduction in the collector length is found to improve the transconductance. Transient analysis of the RSTT shows that the device with a smaller collector length would exhibit higher cutoff frequencies. A reduction in the width of the collector drift region is shown to result in an increased peak-to-valley ratio in the heater current which makes the device more efficient for microwave generation.

I. INTRODUCTION

The Real-Space Transfer (RST) effect occurs when hot electrons transfer from one layer of semiconductor material into an adjacent layer across a heterointerface [1],[2]. Transistor structures based on RST have been experimentally demonstrated for various applications [3]. In the charge injection transistor structure, the overlap between the source and drain regions and the n+ collector region gives rise to parasitic capacitances which limit the microwave performance. Recently, a "collector-up" RSTT structure was demonstrated [4] in which the parasitic capacitances are significantly reduced. The RSTT showed an improved microwave performance with f_T=60 GHz. For a larger barrier height, the pseudomorphic InGaAs/AlGaAs/GaAs material system was used which makes room-temperature operation of the device possible. In this paper, we discuss the effect of scaling the device dimensions and possible improvements in device performance due to a reduction in the device size.

II. RESULTS AND DISCUSSION

In our simulations, we use a two-dimensional, self-consistent, ensemble Monte Carlo model which will be described in detail elsewhere [5]. The simulated device structure is shown in Fig. 1. We are interested in the device behavior for various values of L and W.

A. Scaling of L

The I-V characteristics for five different values of L, with V_C=1.8 V and W=0.21 μm held constant, were calculated. The I_H-V_H curves are shown in Fig. 2(a). For small values of V_H, no significant RST occurs and the channel resistance varies approximately linearly

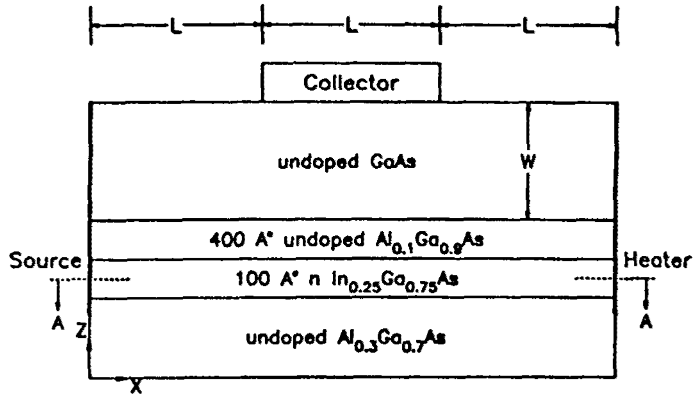

Fig. 1 Schematic diagram of real-space transfer transistor used in simulations.

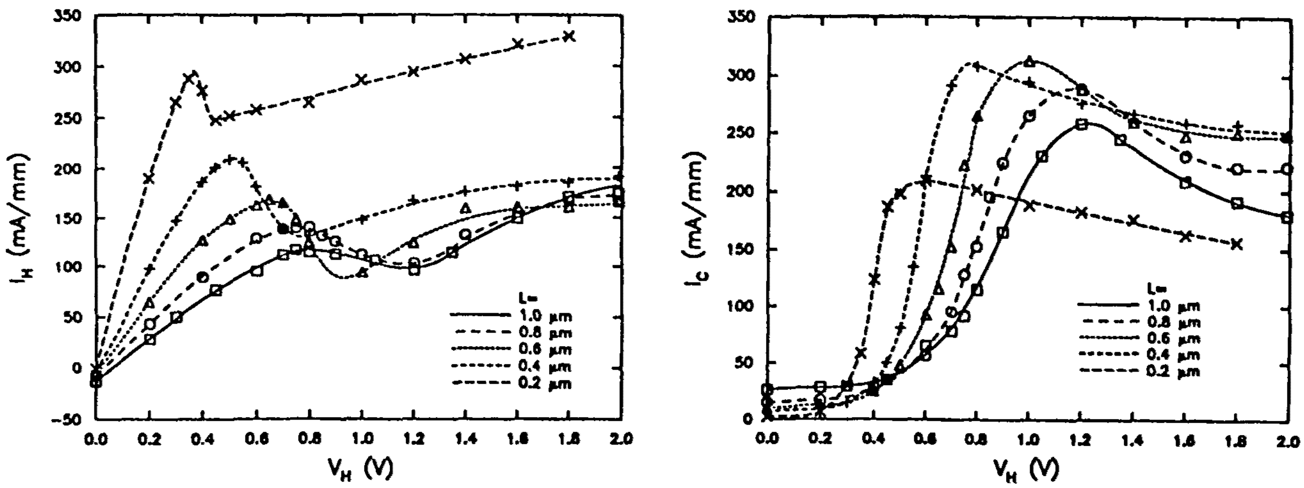

Fig. 2 Calculated terminal currents versus heater voltage for various values of L. (a) heater current and (b) collector current (V_C=1.8 V, W=0.21 μm)

with the source-to-heater distance. Consequently, the slope of the I_H-V_H curves in the linear regime increases as L is reduced. The critical heater voltage V_{HC} corresponding to the peak heater current (i.e., the onset of NDR) is seen to decrease as L becomes smaller. This can be understood if we realize that NDR occurs when the parallel electric field exceeds a critical value. The parallel field, in turn, varies approximately as V_H/L, since at the onset of NDR, most of the potential drop along the channel occurs between source and collector [5] and if we assume $E_{\|}$ to be approximately constant, then $V_H = E_{\|}L$. Thus, as L is reduced, a smaller V_H is sufficient to give rise to the same value of $E_{\|}$. Therefore, V_{HC} scales roughly as $1/L$. As L is reduced, the peak-to-valley ratio in the I_H-V_H characteristics increases at first and then decreases as seen in Fig. 2(a). As L is reduced, the collector current rises more sharply with respect to the heater voltage (see Fig. 2(b)). The maximum collector current increases at first and then decreases as L is reduced. The decrease in the maximum I_C at small L occurs because the collector cannot efficiently collect the electrons undergoing RST.

B. Scaling of W

We calculate the I-V characteristics for two values of W, with V_C=1.8 V and L=0.4 μm. The heater and collector currents are plotted in Figs. 3(a) and 3(b) for W=2100 Åand W=900 Å. Before the onset of NDR, no significant RST occurs and there is virtually no difference in the I-V curves for the two W-values. Beyond the onset of NDR, however, very different behavior is observed in the two cases. For the smaller value of W (900 Å), the transverse electric field, which sweeps the electrons towards the collector, is larger and this makes the collector a more effective sink for the electrons undergoing RST. This gives rise to a larger peak-to-valley ratio in the heater circuit and a sharper rise of I_C.

C. Implications for Microwave Performance

The RSTT is useful for microwave amplification and generation. When it is used for amplification, the heater voltage is the *input* and the collector current is the *output*. The best microwave amplification performance is achieved when the heater terminal is biased at $V_H \approx V_{HC}$ which corresponds to the peak heater current [6]. Therefore, in the following discussion, we will concentrate on the I-V characteristics in the region $V_H \approx V_{HC}$.

We first consider the effect of reducing L. The low-frequency current gain of the RSTT is proportional to $(\Delta I_C/\Delta I_H)$. As L is reduced, the increase in the collector current with respect to V_H (at $V_H \approx V_{HC}$) becomes sharper. Due to the sharper rise, we expect the low-frequency current gain to improve as L is reduced. However, this improvement will be limited because, as L is reduced, ΔI_H increases as well (see especially the L=0.2 μm curve in Fig. 2(a)). Thus, we can conclude that reduction in L beyond a certain point is not beneficial as far as the low-frequency current gain is concerned.

Another important consideration for microwave amplification performance is the transient response of the device. We must examine how the collector current responds to a sudden change (step) in the input voltage V_H. For this purpose, we have performed transient simulation of the RSTT for L=1.0 μm and L=0.2 μm with V_C=1.8 V and W=0.21 μm. We start with a steady state solution corresponding to V_H slightly less than V_{HC} and compute the transient currents due to a sudden increase ΔV_H=50 mV. Figure 4 shows the collector transient current for the two values of L. A substantial reduction in the duration of the

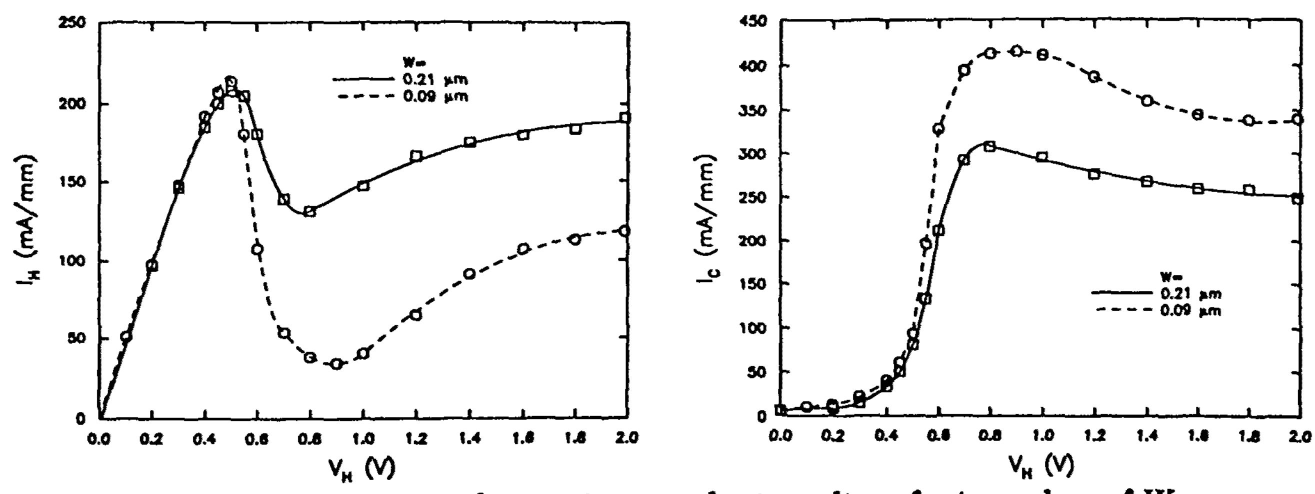

Fig. 3 Calculated terminal currents versus heater voltage for two values of W. (a) Heater current and (b) Collector current (V_C=1.8 V, L=0.4 μm)

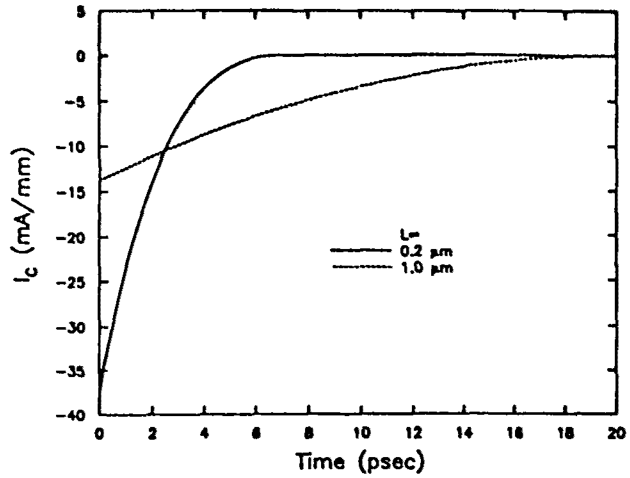

Fig. 4 Collector current versus time due to a step change ΔV_H=50 mV for two different values of L. The steady state current is taken as a reference.

transient current can be clearly seen for the smaller collector length. Thus, higher cutoff frequencies can be expected from a device with a smaller L.

Next, we consider the effect of reducing W. For microwave amplification, the slope $\delta I_G/\delta V_H$ (transconductance) is an important parameter. At a first glance, it appears that the device with a smaller W would be better for amplification since it exhibits a larger transconductance. However, the increase in the transconductance occurs for V_H *larger* than V_{HC}, i. e. in the NDR regime and, for amplification, the device cannot be biased in the NDR regime. The transconductance at $V_H \approx V_{HC}$ is approximately the same in the two cases. Therefore, we expect the microwave amplification performance to be more or less the same for the two values of W. The larger peak-to-valley ratio in the device with smaller W is certainly advantageous for microwave *generation*. Thus, for oscillator applications, it is better to have a device with a small W.

III. CONCLUSIONS

The effect of reducing the device dimensions on the I-V characteristics of the RSTT is discussed. It is observed that a reduction in collector length results in a sharper rise of the collector current with respect to the heater voltage. Transient analysis shows that the cutoff frequency of the RSTT can be improved substantially by reducing the collector length. A smaller length of the collector drift region is found to increase the peak-to-valley ratio in the heater current, which makes the device more efficient for microwave generation.

References

[1] K. Hess, H. Morkoç, H. Shichijo, and B. G. Streetman, *Appl. Phys. Lett.*, **35**, 469 (1979)
[2] Z. S. Gribnikov, *Sov. Phys.-Semicond.*, **6**, 1204 (1973)
[3] For a review, see S. Luryi, *Superlattices and Microstructures*, **8**, 395 (1990)
[4] M. R. Hueschen, N. Moll, and A. Fischer-Colbrie, *Appl. Phys. Lett.*, **57**, 386 (1990)
[5] M. B. Patil, U. Ravaioli, and M. R. Hueschen, submitted to *IEEE Trans. Electron Devices*
[6] A. Kastalsky et al, *Appl. Phys. Lett.*, **48**, 71 (1986)