ELECTROTHERMAL SIMULATION OF HBT BY TLM METHOD WITH QUASI TWO DIMENSIONAL MODEL

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ABSTRACT

We presented here an improved quasi two dimensional model incorporated of depletion-layer approximation to simulate electrothermal properties of HBT. In the model the temperature profile and minority carrier distributions are numerically simulated by transmission line matrix (TLM) method. The results show that this model can conveniently simulate the electrothermal effects under the efficient reduction both in CPU time and memory space.

INTRODUCTION

Heterojunction Bipolar Transistor (HBT) is a promising candidate for microwave high power and high speed applications. But the GaAs, which is used by AlGaAs/GaAs HBT, has relatively low thermal conductivity (about one third of Si's) and thus leads to a probable problem of over heating under high power operation with large heat dissipation. For the good design of HBT , many methods have been developed to help us understand the electrothermal effects at the junctions. They fall mainly into two categories. In the first category, thermal behavior is extracted from the experimental data based on temperature's relation to base-emitter voltage or the common emitter current gain[1-3]. But the temperature extracted by this way is an average one. The detailed temperature profile within the device can be obtained by another method in which the coupling Poisson's equation, carrier (electron and hole) transport equations and heat transfer equation are numerically solved [4-6]. But to numerically solve these four equations needs lots of computer memory space and much CPU time.

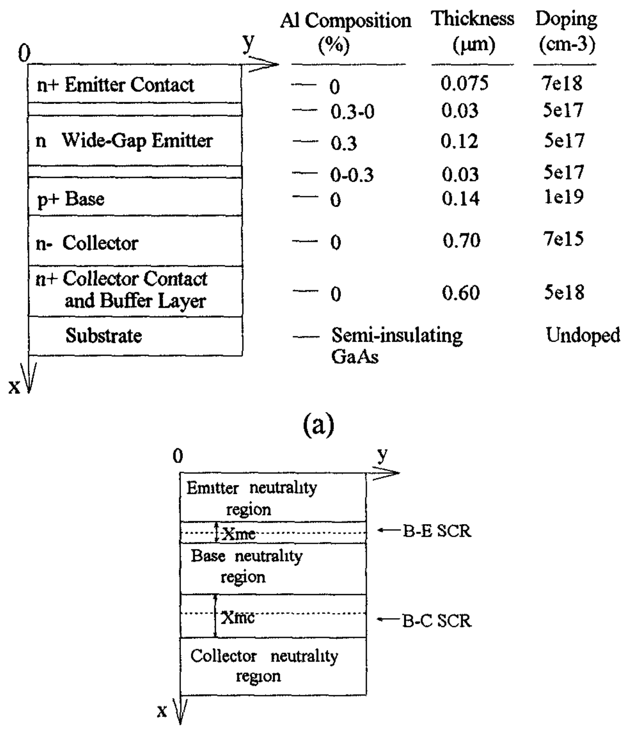

Fig.1 (a) structure of the device; (b) device in depletion-layer approximation

In this paper, we present an improved quasi-two-dimensional model by which the electrothermal characteristics of HBT can be simulated with great reduction of CPU time and memory space.

MODEL DESCRIPTION

To verify the effectiveness of the model, in our simulation a structure of HBT with the same

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parameters as [7] is used. The HBT lies on a heat sink of 300K and is shown in Fig.1(a). It can be separated into five regions, three neutrality regions (NRs) and two space charge regions (SCRs), shown in Fig.1(b), where Xme and Xmc are SCR widths at base-emitter(B-E) and base-collector(B-C) junctions. The Xme and Xmc can be analytically calculated from expressions given by [8].

In the analysis the temperature profile is evaluated in two dimensions within the cross section of entire device. The carrier distribution is calculated only in x-direction within three NRs by using boundary conditions at edges of SCRs. But the nonuniform distribution of currents in y-direction within the device caused by temperature variance is considered. Thus the device is modeled quasi-two-dimensionally in reality. It is assumed that in NRs only the minority carrier current exists. Therefore in this model only minority carrier transport equation and heat transfer equation are needed to be solved. The TLM method is used to solve these two coupling equations with a self-consistent iteration procedure. The detailed algorithms of TLM method to simulate the charge carrier transport and heat transfer problems can be found in [9,10].

The currents in the device are mainly contributed by minority carrier currents in NRs and recombination currents in SCRs, respectively. The governing equations for minority carrier transport are as follows:

$$\frac{\partial^2 n}{\partial x^2}+\frac{\mu_n}{D_n}\frac{\partial(n\cdot E)}{\partial x}-\frac{R}{D_n}=\frac{1}{D_n}\frac{\partial n}{\partial t} \qquad (1)$$

$$\frac{\partial^2 p}{\partial x^2}-\frac{\mu_p}{D_p}\frac{\partial(p\cdot E)}{\partial x}-\frac{R}{D_p}=\frac{1}{D_p}\frac{\partial p}{\partial t} \qquad (2)$$

where $n, p, \mu_n, \mu_p, D_n, D_p$ are the concentrations, mobilities and diffusion coefficients for electron and hole, respectively, R the carrier recombination rate, E the electric field, t the time.

Equation (1) and (2) can be numerically solved under the following boundary conditions:

$$p(x=\text{E - side edge of B - E SCR})=p_{0e}\exp(\frac{qV_{be}}{m_f K_b T})$$

$$p(x=\text{C - side edge of B - C SCR})=p_{0c}\exp(\frac{qV_{bc}}{m_r K_b T})$$

$$p(x=\text{emitter contact})=p_{0e}$$

$$p(x=\text{collector contact})=p_{0c}$$

$$n(x=\text{B - side edge of B - E SCR})=n_{0b}\exp(\frac{qV_{be}}{m_f K_b T})$$

$$n(x=\text{B - side edge of B - C SCR})=n_{0b}\exp(\frac{qV_{bc}}{m_r K_b T})$$

where m_f, m_r are ideality factors assumed thermal-independent, n_0, p_0 the thermal equilibrium values of minority carrier concentrations, V_{be}, V_{bc} the internal voltages across the B-E and B-C junctions and are related to the measured external voltages V_{be}', V_{bc}' [7]:

$$V_{be}=V_{be}'-(I_b+I_c)R_e-I_b R_b$$

$$V_{bc}=V_{bc}'-(I_b+I_e)R_c-I_b R_b$$

where R_e, R_b, R_c are the series resistances of emitter, base and collector.

From the solutions of equations (1) and (2), the terminal current components for an n-p-n HBT are:

$$I_{ne}=a_n S\cdot\exp(\frac{\Delta E_c}{K_b T})(qD_n\frac{\partial n_b}{\partial x}+q\mu_n n_b E_b)\Big|_{x=\text{B - side edge of B - E SCR}}$$

$$I_{nc}=a_n\cdot S(qD_n\frac{\partial n_b}{\partial x}+q\mu_n n_b E_b)\Big|_{x=\text{B - side edge of B - C SCR}}$$

$$I_{pe}=a_p\cdot S\exp(-\frac{\Delta E_v}{K_b T})(-qD_p\frac{\partial p_e}{\partial x}+q\mu_p p_e E_e)\Big|_{x=\text{E - side edge of B - E SCR}}$$

$$I_{pc}=a_p\cdot S(-qD_p\frac{\partial p_c}{\partial x}+q\mu_p p_c E_c)\Big|_{x=\text{C - side edge of B - C SCR}}$$

$$I_{re}=a_e\cdot\frac{1}{2}SqX_{me}n_i\exp(\frac{qV_{be}}{2K_b T})/\tau$$

$$I_{rc}=a_c\cdot\frac{1}{2}SqX_{mc}n_i\exp(\frac{qV_{bc}}{2K_b T})/\tau$$

where I_{ne}, I_{nc} and I_{pe}, I_{pc} are electron and hole components of emitter and collector currents, I_{re}, I_{rc} are the recombination current in B-E and B-C SCRs, n_b, p_e, p_c are the electron and hole concentrations in base, emitter and collector regions, respectively, n_i is the intrinsic carrier concentration, $\Delta E_c,, \Delta E_v$ are the conduction band and valence band discontinuities in AlGaAs/GaAs heterojunction, a_n, a_p, a_e, a_c are thermal-independent amplitude correcting factors for compensating the approximation of depletion layer widths and preset parameters, m_e, m_f are the ideality factors, E_e, E_b, E_c are the electric fields in each NR.

The HBT terminal currents are:

$$I_c=I_{nc}+I_{pc}+I_{rc}$$

$I_e = I_{ne} + I_{pe} + I_{re}$

$I_b = I_c / \beta_f + I_{re} + I_{br}$

where β_f is the forward current gain and I_{br} is the recombination current in base region. I_{br} is very small for thin base HBT and can be neglected, m, a, β_f can be extracted from the measured data by schemes of [7].

The thermal behavior within the HBT is governed by the heat transfer equation:

$$\nabla^2 T(x,y) + H = \frac{\rho C_p}{K_T} \frac{\partial T(x,y)}{\partial t}$$

where T is the temperature, ρ the density of matter, C_p the thermal capacitance, K_T the thermal conductivity, H the heat power generation rate.

RESULTS AND DISCUSSIONS

In our simulation the GaAs substrate is selected to be $100\mu m$ in x-direction and $200\mu m$ in y-direction. The device to be simulated is just located at the symmetric center of the substrate and so symmetric condition can be used. The area of HBT emitter finger is $3 \times 10\mu m^2$.

By applying the extracted m, a we first predicted the I-V properties of the device at uniform temperature distribution of 300K, as shown in Fig.2. Compared with the measured data in [7] good agreement is reached and the maximum error is less than 10%.

Then by considering the device self-heating we plotted Fig.3-Fig.6 for a single-emitter-finger HBT. Fig.3 displays the temperature distribution in x-direction. It shows that the highest temperature is at B-C SCR and this agrees with the fact that the main heat source of HBT is in B-C SCR. From Fig.4 and Fig.5 we can see that the highest junction temperature and collector current increase with V_{be} and V_{ce} and there exists a turn point of V_{be} for a given V_{ce}. When V_{be} is higher than the turn point, the junction temperature will rise rapidly and the device enters a state of runaway. So a critical value of V_{be}, which is named as V_{be_cr} in this paper, can be defined for given V_{ce}. The curve of $V_{be\_cr} - V_{ce}$ is shown in Fig.6 and it separates $V_{be} - V_{ce}$ plane into a safe operation region and an over-heating region. When the device operates in the over-heating region, it will probably go into a runaway state.

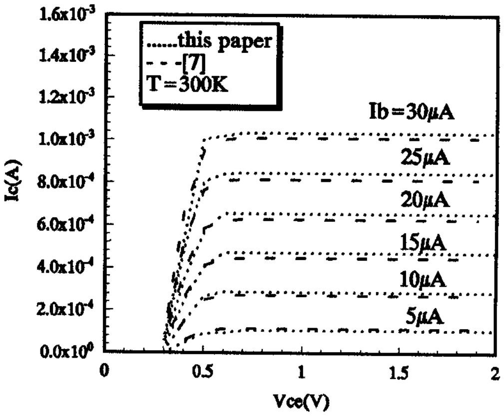

Fig.2 I-V characteristics at uniform temperature distribution of 300K

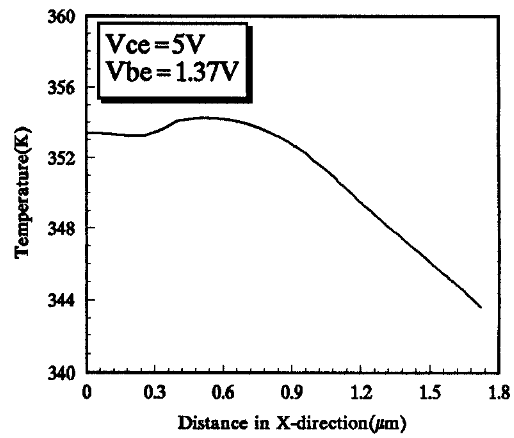

Fig.3 Temperature distribution in x-direction

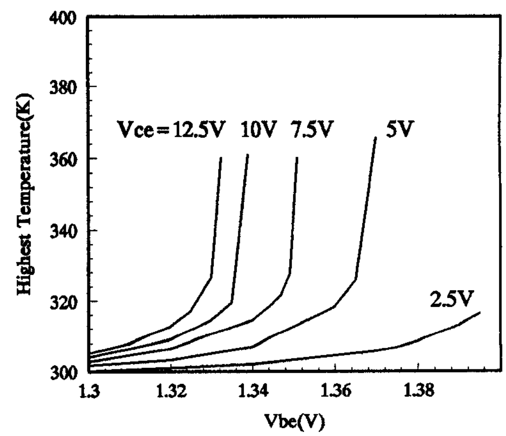

Fig.4 Highest temperature within device at different voltage bias

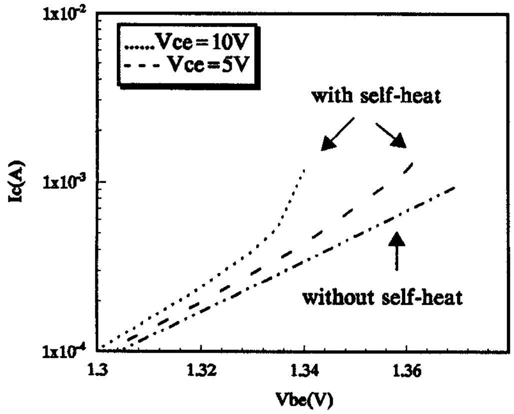

Fig.5 Collector current as a function of V_{be} and V_{ce} with thermal and no thermal consideration

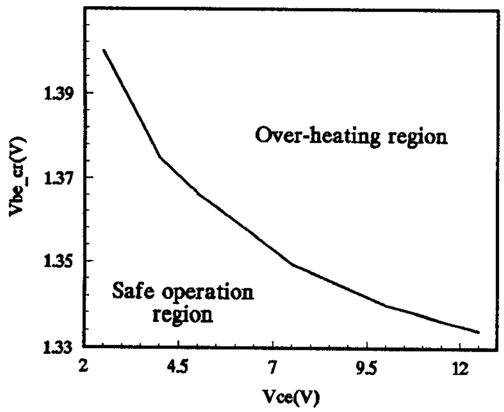

Fig.6 The critical voltage of V_{be} vs. V_{ce}.

CONCLUSION

A model to describe the electrothermal behavior of HBT with much smaller consumption of computer memory space and CPU time has been developed based on the depletion-layer approximation. The numerical results show that the model is feasible. And the TLM method is a very good numerical algorithm to simulate the carrier transport and heat transfer phenomena. It is easy to extend the model from quasi-two-dimension to two or three-dimension.

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