BREAKDOWN SIMULATION OF SEMICONDUCTOR DEVICES INCLUDING ENERGY BALANCE AND LATTICE HEATING

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Abstract

A self-consistent nonisothermal energy balance model has been incorporated into a general purpose device simulator, ATLAS. The breakdown characteristics of submicron BJT and SOI transistors have been investigated and compared with the results predicted by simpler models.

I. INTRODUCTION

Most semiconductor device simulation uses the drift-diffusion and isothermal (constant lattice temperature) approximations. These can lead to poor accuracy in predicting the electrical characteristics of modern semiconductor devices. 'Energy balance' models can account for non-local transport effects; and 'nonisothermal' models can account for lattice heating. Most advanced simulation has focused on isothermal energy balance models and on nonisothermal drift-diffusion models. However, models that include both energy balance and nonisothermal effects have started to appear [1-5].

The implementation and use of a nonisothermal energy balance model is described here. The breakdown characteristics of deep submicron BJT and SOI devices are calculated using four different models: isothermal drift-diffusion (DD), nonisothermal drift-diffusion (NDD), isothermal energy balance (EB), and nonisothermal energy balance (NEB). Direct comparisons are made, and interesting physical effects are identified.

II. PHYSICAL MODEL AND NUMERICAL TECHNIQUES

The NEB model is a set of six partial differential equations for electrostatic potential, electron and hole concentrations, electron and hole carrier temperatures, and lattice temperature. The dependencies of all transport parameters on both carrier temperature and lattice temperature are included. The NEB model is an extension of Stratton's energy balance model [6,7], and is similar to the models used in [1] and [5].

A general 2D implementation of the NEB model is now available in the ATLAS device simulator. Numerical solutions are obtained using box integration on a general triangular grid, and Sharfetter-Gummel type discretizations for carrier current and energy flux densities. The implementation of the NEB supports realistic heat-sinks and very general thermal boundary conditions [8]. The fully coupled Newton algorithm, and several decoupled block schemes [9,10], can be used to solve the discretized nonlinear algebraic systems.

III. BJT EXAMPLE

The BJT structure has doping concentrations in the emitter, base, n^- collector, and n^+ collector of 5 10^{19}, 5 10^{18}, 4 10^{17} and 10^{19} cm^{-3} respectively. The emitter, base, n^- collector, and n^+ collector region widths are 50, 50, 100, and 50 nm respectively. The heat flux is set equal to zero at boundaries, except at the bottom of the device where different values of a thermal resistor are connected to a 300 K source. The collector is connected to the collector supply voltage V_{cc} through an external resistance. V_{cc} is ramped with the emitter-base voltage held at -0.7V.

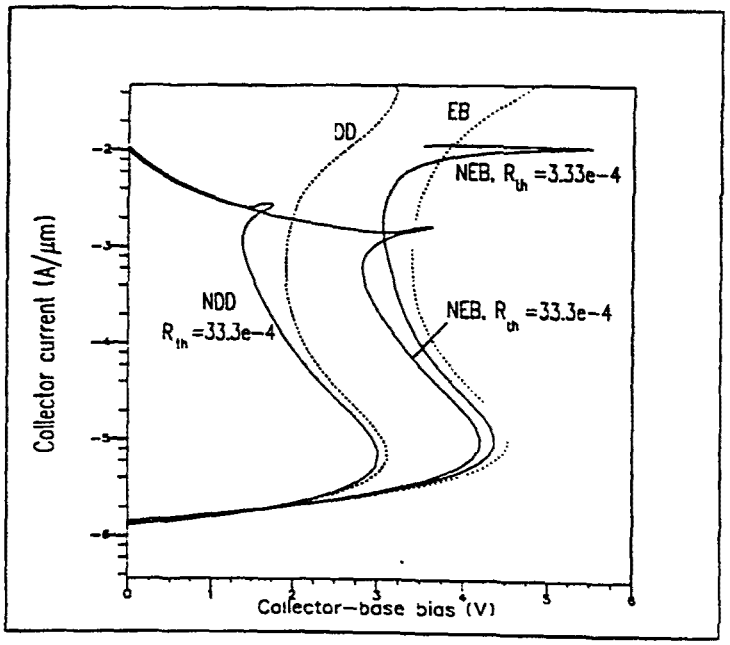

Figure 1. Log collector current versus collector-base voltage for the DD, NDD, EB and NEB models. V_{eb}=-0.7V.

Figure 1 shows the calculated collector current vs base-collector voltage as predicted by the DD, NDD, EB and NEB models. Figure 2 shows the maximum lattice temperature in the device vs collector voltage for the NEB model with Rth=3.33 10^{-4} Kcm^2/W and Rth=33.3 10^{-4} Kcm^2/W, and for the NDD model with Rth=33.3 10^{-4} Kcm^2/W. These results display several interesting features. In the limit of low collector voltage and low current the results are, as anticipated, very close. The shift of breakdown voltage predicted by the EB model, as compared to the DD model, is due to the well-known overestimation of impact ionization in the DD model. If the thermal resistance is set to zero the NEB and NDD produce virtually the same results as the EB and DD, respectively. This is because the active region of the device is very small, and specifying an isothermal boundary condition provides effective "cooling". The situation changes dramatically when a realistic thermal resistance is added to the bottom of the device. For Rth=3.33 10^{-4} Kcm^2/W the NEB predicts almost the same breakdown voltage (first snap back) as the EB. However, the predicted behaviour in the high current region is very different. The NEB predicts second (thermal) breakdown, which is not predicted by the EB. Increasing the value of Rth to a value of 33.3 10^{-4} Kcm^2/W leads to a decrease in the first and second breakdown voltages.

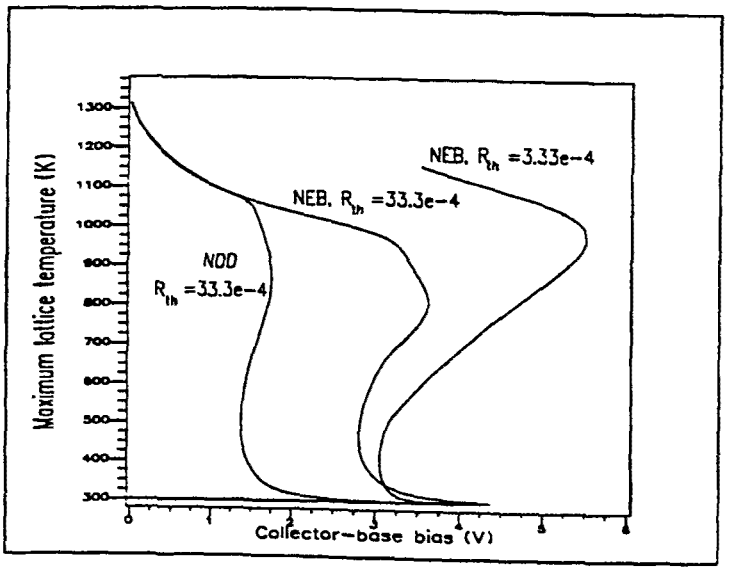

Figure 2. Maximum lattice temperature versus collector-base voltage for the NDD and NEB models. V_{eb}=-0.7V.

The NDD and NEB models predict behavior that is qualitatively similar. For currents around 10^{-2} A/μm the results of the NEB and NDD are quantitaively similar. This is an initially surprising result. The explanation is that carrier temperatures are close to the lattice temperature, and the drift diffusion approximation becomes reasonable for such conditions.

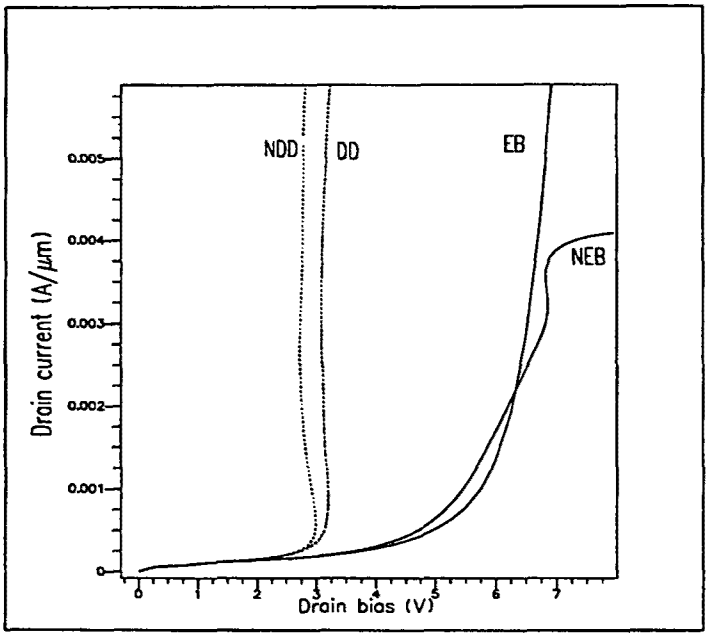

Figure 3. Drain current versus drain voltage for the DD, NDD, EB and NEB models. V_g=1.5V.

IV. SOI EXAMPLE

The SOI device has gate oxide, body, and substrate oxide thicknesses of 0.017, 0.16, and 0.5 μm respectively. The channel length is 0.5μm and the doping concentration in the channel is 10^{17} cm^{-3}. The lattice temperature is set equal to 300 K on the gate and along the bottom of the device, and the normal component of the heat flux is set equal to zero on the other part of the boundary.

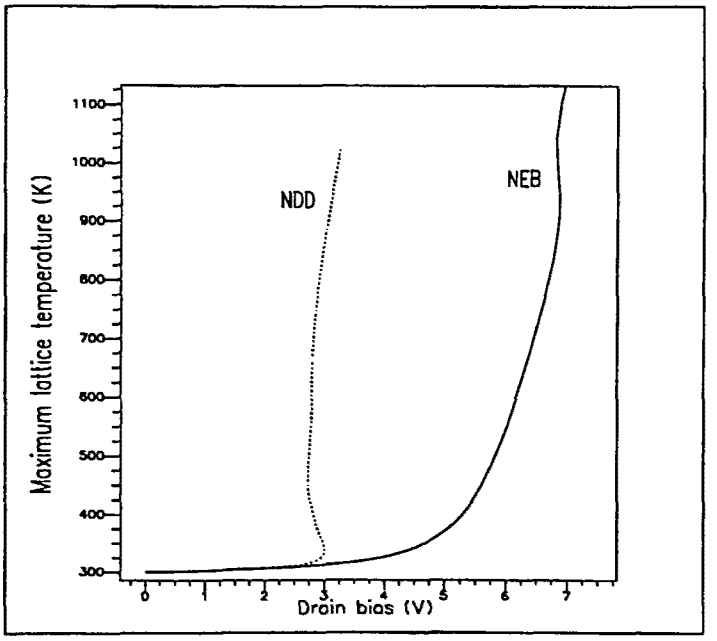

Figure 4. Maximum lattice temperature versus drain voltage for the NDD and NEB models. V_g=1.5V.

Figure 3 shows the predicted drain current as a function of drain voltage, for a gate voltage of 1.5 V, calculated using the DD, EB, NDD and NEB models. Figure 4 shows the maximum lattice temperature in the device, as a function of drain voltage, calculated using the NDD and NEB models. The significant shift of the breakdown voltage between the DD and EB models is again observed. The NEB and the NDD models show a slight decrease in breakdown voltage compared with the EB and DD models. The predicted behavior in the high current/high temperature region is very different, even qualitatively, between the EB and NEB models. The large difference between the results predicted by the EB and NEB models is due to decreased impact ionization rates at higher lattice temperatures. This indicates that the NEB model is required for accurate simulation in the strong breakdown region.

V. CONCLUSIONS

A self-consistent nonisothermal energy balance model has been incorporated into a general purpose 2-D device simulator. The breakdown characteristics of submicron BJT and SOI devices have been investigated for the first time with a model of this generality, and have been compared with the results predicted by simpler models. The results demonstrate clearly the influence of both nonisothermal and energy balance effects on the device characteristics in the strong breakdown region, and the magnitude and nature of the discrepancies associated with the use of less general models.

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