Analysis of HBT Behavior After Strong Electrothermal Stress

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Abstract—**We present two-dimensional simulations of one-finger power InGaP/GaAs Heterojunction Bipolar Transistors (HBTs) before and after both electrical and thermal stress aging. It is well known that GaAs-HBTs with InGaP emitter material can be improved with respect to reliability if the emitter material covers the complete p-doped base layer forming outside the active emitter the so-called InGaP ledge. We analyze the influence of the ledge thickness and of of the surface charges on the device performance and its impact on reliability. The possibility to explain device degradation mechanisms by means of numerical simulation is of high practical importance.**

Keywords— **Electrothermal effects, Simulation software, Stress measurement, Charge carrier density, Semiconductor device reliability.**

I. INTRODUCTION

THE two-dimensional device simulator MINIMOS-NT [1] deals with different complex materials and structures such as binary and ternary alloys with arbitrary material composition profiles. Various physical effects, like band gap narrowing, surface recombination, and self-heating, are taken into account. The efficiency of the models was proven by hydrodynamic DC-simulations with self-heating of forward, reverse and output characteristics of one-finger AlGaAs/GaAs and InGaP/GaAs-HBTs [2], furthermore, by small-signal RF-simulation [3]. Simulation results are in very good agreement with measured data at several ambient temperatures. For reliability reasons of high practical interest, a study on the particular influence of the InGaP ledge on the device performance of InGaP/GaAs-HBTs is presented.

II. IMPACT OF THE InGaP LEDGE

It is well known that GaAs-HBTs with InGaP emitter material can be improved with respect to reliability if the emitter material covers the complete p-doped base layer [4]. Outside the active emitter area remains the so-called InGaP ledge. Using MINIMOS-NT we investigate the impact of the ledge thickness d and negative surface charges, which are known to exist at the ledge/nitride interface, on the device performance. A schematic drawing of the simulated device structure is shown in Fig. 1. Because of symmetry, the simulation domain covers only a half of the real device in order to save computational effort.

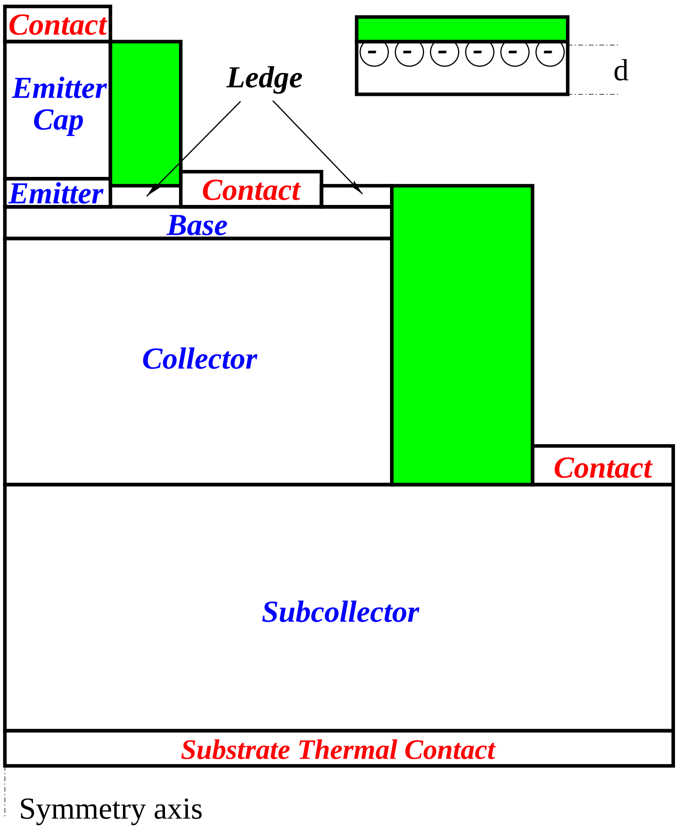

Fig. 1. A schematic drawing of the simulated device structure of InGaP/GaAs HBT with an InGaP ledge. Negative surface charges on the ledge/nitride interface exist.

A. InGaP Ledge Thickness

In Fig. 2 we show the measured and simulated collector and base currents of a one-finger InGaP/GaAs HBTs with different ledge thickness operating under forward Gummel plot conditions with $V_{\mathrm{BC}} = 0$ V. Measurement refers to a device with a 40 nm thick ledge. Note the strong increase in the base current at low bias with increasing ledge thickness. As can be seen from Fig. 2 simulated and measured base currents differ significantly in the case of a 40 nm thick ledge. The reason is that insulator surface Fermi-level pinning is not accounted for if surface charges are not considered in the simulation. Therefore, a non-physical electron current path occurs in the upper ledge part as shown

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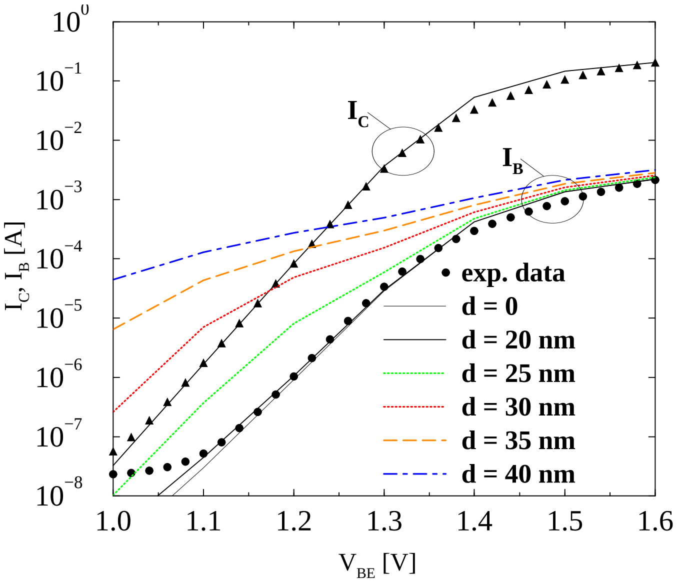

Fig. 2. Dependence of I_B on the InGaP ledge thickness compared to measurement.

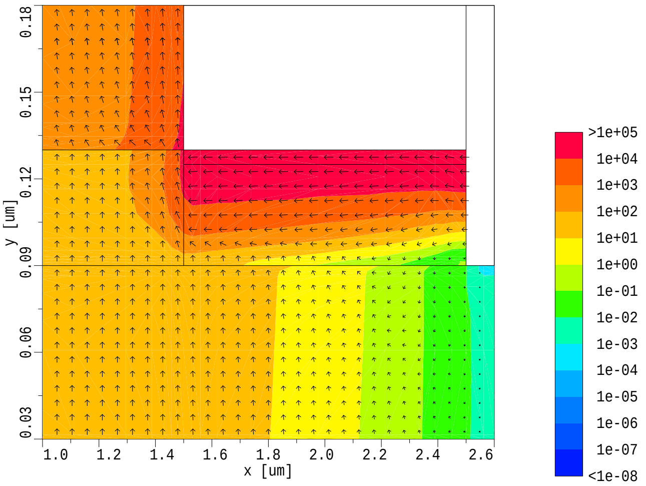

Fig. 3. Electron current density [A/cm^2] at V_{BE}=1.2V. Simulation without surface charges.

in Fig. 3. The corresponding electron distribution in the ledge using vertical cross-sections at x = 1.6 μm, 2.0μm, and 2.4μm are shown in Fig. 4. The hole distribution in the middle of the ledge (x = 2.0 μm) is also included. These concentrations shall be compared to the ones in the case of surface charges in the next subsection.

B. *Negative Surface Charges*

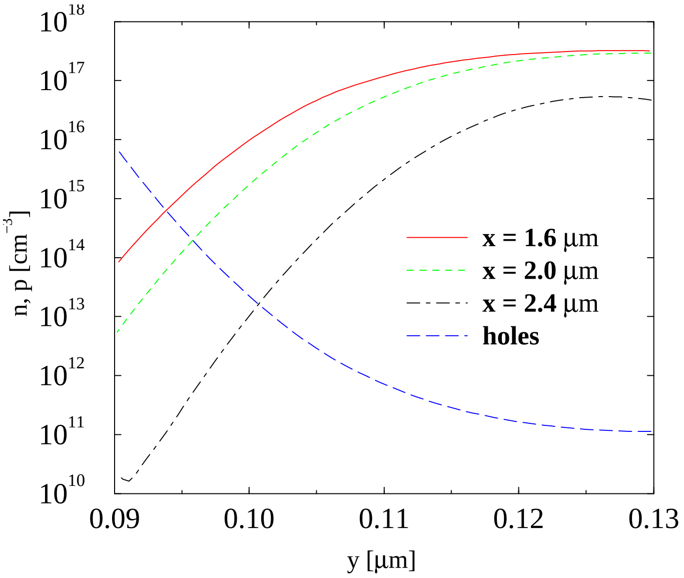

Fig. 4. Electron and hole distribution in the ledge. Simulation without surface charges.

The influence of fixed negative surface charges which are homogeneously distributed along the interface between ledge and passivation was investigated. As can be seen from Fig. 5, where simulation refers to a device with 40 nm ledge, the base current is reduced if more negative surface charges are introduced. The upper part of the ledge is also depleted [5] and the leakage is reduced (Fig. 6). In Fig. 7 we present the corresponding electron distribution in the ledge at x = 1.6 μm, 2.0μm, and 2.4μm, and the hole distribution at x = 2.0 μm. Note that even in this case the ledge is not completely depleted. However, the electron concentrations near the InGaP/SiN interface are significantly lower in comparison to the ones shown in Fig. 4. Thus, with a surface charge density of 10^{12} cm^{-2} the measured base current can be simulated very well. We have to note that in the case of negative surface charges the hole concentration in the ledge increases and at higher values gives the opportunity a hole current path to occur.

III. Device Reliability

Based on these investigations it is possible to explain the base current degradation of an InGaP/GaAs HBT which was strongly stressed under conditions far from normal operating conditions. In this case the base current degradation in the middle voltage range can be explained by a decreasing surface charge density along the interface between ledge and passivation from 10^{12} cm^{-2} to 4.10^{11} cm^{-2}. This might be due to compensation of the negative surface charges by H+ ions which are known to be present in the device due to the epitaxial manufacturing processes [6], [7]. In Fig. 8 a comparison of measured and simulated forward Gummel plots at V_{CB} = 0 V is shown. Filled and open symbols denote measured characteristics of the non-degraded and degraded device, respectively. The corresponding simulation results are shown with lines. The good agreement also for stressed devices demonstrates the applicability of physics-based device simulation to device

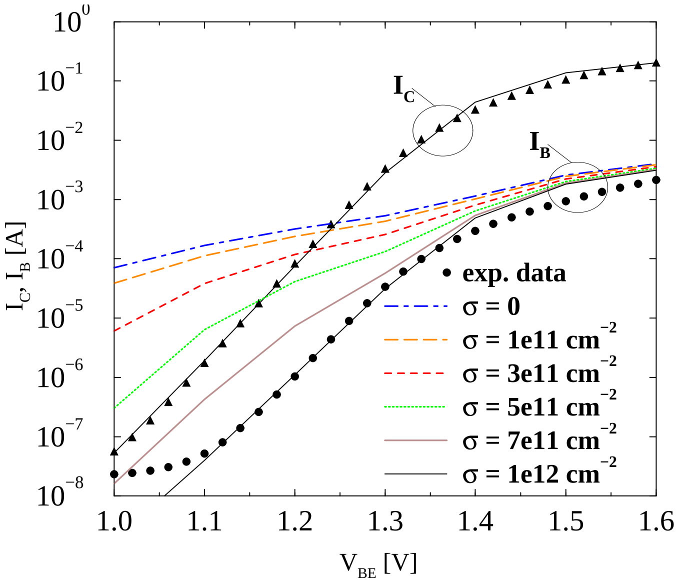

Fig. 5. Dependence of I_B on the charge density at the ledge/nitride interface. Charge density of 10^{12} cm^{-2} is sufficient to get agreement with the measurements.

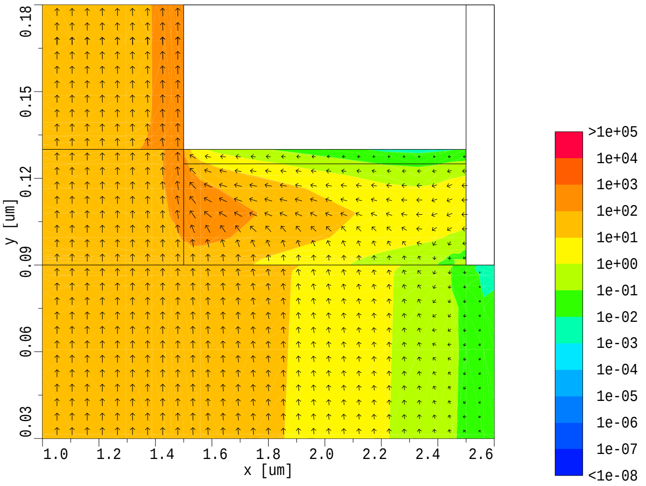

Fig. 6. Electron current density [A/cm^2] at V_{BE}=1.2V. Simulation with a surface charge density of 10^{12} cm^{-2}.

reliability issues. In Fig. 9 we present the electron current density corresponding to 4.10^{11} cm^{-2} surface charge density. In Fig. 10 we present the corresponding electron distribution in the ledge at x = 1.6 μm, 2.0μm, and 2.4μm, and the hole distribution at x = 2.0 μm. Note that the upper part of the ledge is now not completely depleted, thus again allowing a base leakage current.

Several other effects supposed to lead to strong increase in the base leakage current, e.g. spreading out of the base contact at the metal/GaAs interface, increased recombination/generation in the InGaP layer, degradation of the SiN/GaAs interface (see e.g. [8], [9] and references therein) were also analyzed. The simulation results show such effects cannot be the dominant reason for beta-degradation. The decrease in the collector current at high level injection is suggested to be due to increased emitter resistance which could occur due to emitter contact detachment, indium segregation in the metal layer, or dislocations at the InGaAs/GaAs interface (see e.g. [9]). Our simulations show that in the case of contact detachment there is an electron current crowding in the remaining contact area which leads to insignificant changes. Only a slightly probable emitter contact detachment of more than 80% can explain the measured values (see Fig. 11). We find indium segregation in the metal can be the reason by increasing the emitter contact resistance while the decrease of the indium content in the cap has no significant influence on the emitter resistance.

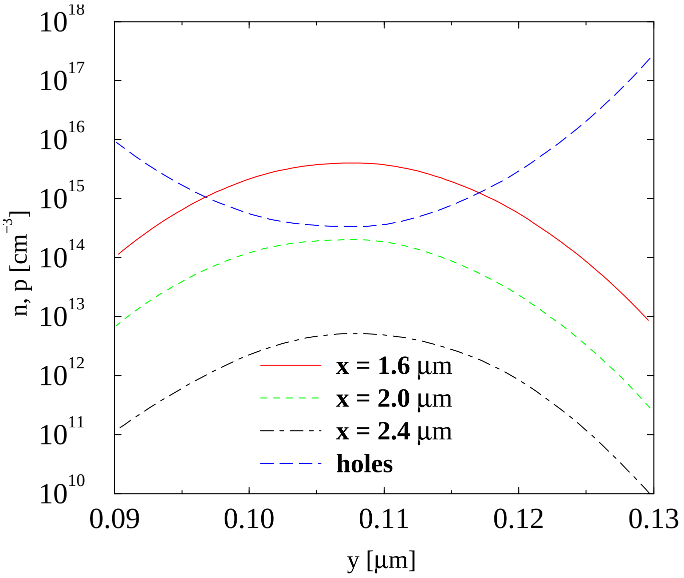

Fig. 7. Electron and hole distribution in the ledge. Simulation with a surface charge density of 10^{12} cm^{-2}.

IV. Conclusions

We present two-dimensional simulations of InGaP/GaAs HBTs before and after electrothermal stress aging. The influence of the ledge thickness and the surface charges on the device performance are analyzed. The effect of vanishing negative surface charges on the ledge/SiN interface is proposed as a reason which could explain the beta-degradation of InGaP/GaAs HBTs.

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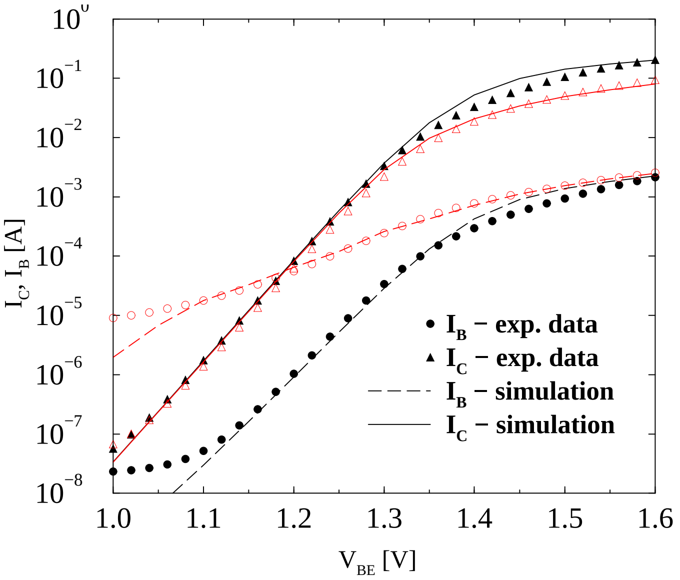

Fig. 8. Forward Gummel plots at $V_{CB} = 0$ V. Comparison of measurement (symbols) and simulation (lines) before (filled) and after (open) HBT aging.

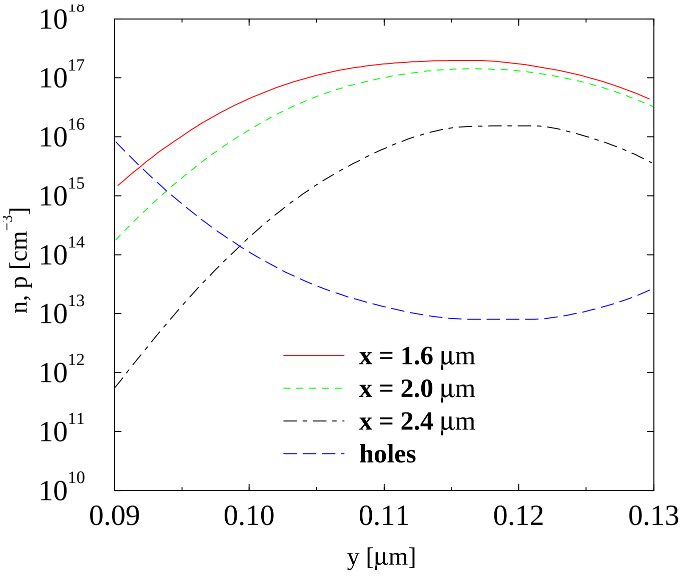

Fig. 10. Electron and hole distribution in the ledge. Simulation with a surface charge density of 4.10^{11} cm^{-2}.

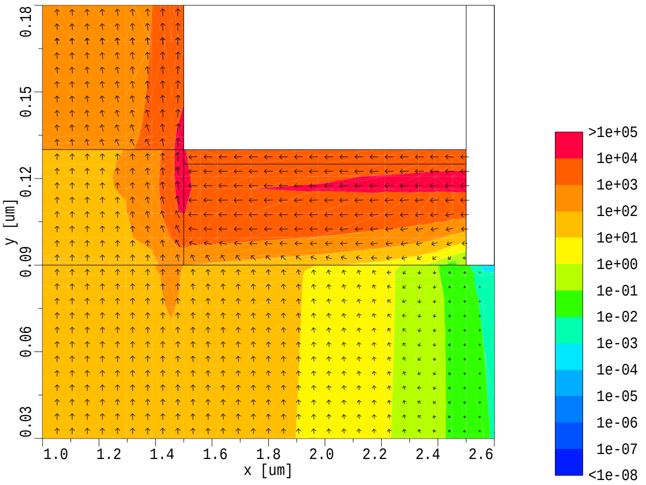

Fig. 9. Electron current density [A/cm^2] at V_{BE}=1.2V. Simulation with a surface charge density of 4.10^{11} cm^{-2}.

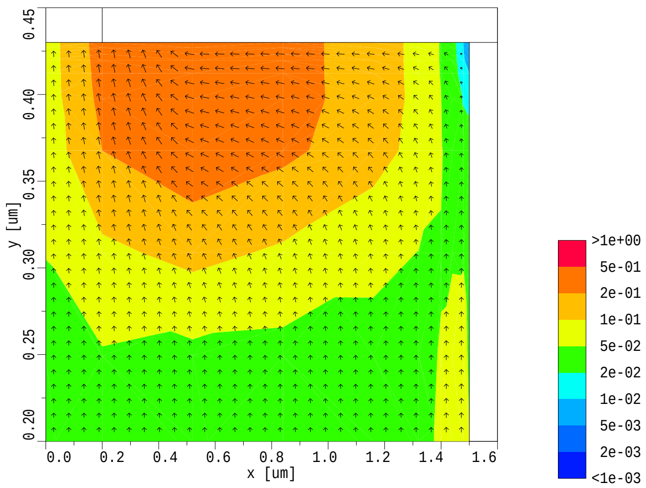

Fig. 11. Electron current density [A/cm^2]. Simulation of emitter contact detachment.

REFERENCES

[1] T. Binder, K. Dragosits, T. Grasser, R. Klima, M. Knaipp, H. Kosina, R. Mlekus, V. Palankovski, M. Rottinger, G. Schrom, S. Selberherr, and M. Stockinger, *MINIMOS-NT User's Guide*, Institut für Mikroelektronik, 1998.

[2] V. Palankovski, S. Selberherr, and R. Schultheis, "Simulation of heterojunction bipolar transistors on gallium-arsenide," in *Simulation of Semiconductor Processes and Devices*, Kyoto, Japan, Sept. 1999, pp. 227–230.

[3] V. Palankovski, R. Quay, S. Selberherr, and R. Schultheis, "S-parameter simulation of HBTs on gallium-arsenide. in *Proc. High Performance Electron Devices for Microwave and Optoelectronic Applications EDMO*, pp. 15–19, London, UK, Nov. 1999.

[4] T. Low, C. Hutchison, P. Canfield, T. Shirley, R. Yeats, J. Chang, G. Essilfie, W. Whiteley, D. D'Avanzo, N. Pan, J. Elliot, C. Lutz, Migration from an AlGaAs to an InGaP emitter HBT IC process for improved reliability, in *Digest GaAs IC Symp.*, pp. 153–157, Atlanta, Georgia, Nov. 1998.

[5] P. Ma, P. Zampardi, L. Zhang, and M.F. Chang, "Determining the effectiveness of HBT emitter ledge passivation by using an on-ledge Schottky diode potentiometer," *IEEE Electron Device Lett.*, vol. 20, no. 9, pp. 460–462, 1999.

[6] N. Bovolon, R. Schultheis, J.-E. Müller, P. Zwicknagl, and E. Zanoni, "A short-term high-current-density reliability investigation of AlGaAs/GaAs heterojunction bipolar transistors," *Electron.Lett.*, vol. 19, no. 12, pp. 469–471, 1998.

[7] M. Borgarino, R. Plana, S.L. Delage, F. Fantini, and J. Graffeuil, "Influence of surface recombination on the burn-in effect in microwave GaInP/GaAs HBT's," *IEEE Trans.Electron Devices*, vol. 46, no. 1, pp. 10–16, 1999.

[8] K.A. Christianson, "Reliability of III–V based heterojunction bipolar transistors," *Microelectron.Reliab.*, vol. 38, no. 1, pp. 153–161, 1997.

[9] K. Mochizuki, T. Oka, K. Ouchi, and T. Tanoue, "Reliability investigation of heavily C-doped InGaP/GaAs HBTs operated under a very high current-density condition," *Solid-State Electron.*, vol. 43, pp. 1425–1428, 1999.