Investigation of Breakdown and DC Behavior in HBTs With (Al,Ga)As Collector Layer

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***Abstract*—We report on the realization of an InGaP–GaAs-based double heterojunction bipolar transistor with high breakdown voltages of up to 85 V using an $Al_{0.2}Ga_{0.8}As$ collector. These results were achieved with devices with a 2.8 μm collector doped to 6×10^{15} cm^{-3} (with an emitter area of 60×60 μm^2). They agree well with calculated data from a semi-analytical breakdown model. A β/R_{SBI} (intrinsic base sheet resistance) ratio of more than 0.5 by introducing a 150-nm-thick graded Al-content region at the base–collector heterojunction was achieved. This layer is needed to efficiently suppress current blocking, which is otherwise caused by the conduction band offset from GaAs to $Al_{0.2}Ga_{0.8}As$. The thickness of this region was determined by two-dimensional numerical device simulations that are in good agreement with the measured device properties.**

***Index Terms*—AlGaAs, breakdown voltage, composition graded layer, double heterojunction bipolar transistor (DHBT).**

I. INTRODUCTION

GaInP–GaAs-based heterojunction bipolar transistors (HBTs) have proved to be well-suited for high-power and high-frequency applications, especially for base station amplifiers in mobile communication systems [1], [2]. To achieve high power levels, devices with sufficient breakdown stability are needed. One approach to increase the base–collector breakdown voltage is to increase the collector thickness while the collector doping concentration needs to be lowered accordingly, i.e., one gets a single heterojunction bipolar transistor (SHBT) [3]. Another approach is to use a high bandgap material in the collector, so one gets a double heterojunction bipolar transistor (DHBT). This way, one takes advantage of the higher critical electrical field at which impact ionization occurs. A challenge here is to suppress current blocking effects that usually appear due to the base–collector heterojunction. In the first part we compare both the hetero- and homojunction approach with regard to the achievable voltage stability. In the second part, we show how the formation of a conduction band barrier, which degrades the current gain, can be suppressed by adding a graded Al content region at the base–collector heterojunction.

II. EXPERIMENT AND SIMULATION

The HBT structures in our experiments were grown on 4-in semi-insulating GaAs (001) substrates using LP-MOVPE in an Aixtron AIX2400G3 planetary reactor. We used the standard group-III precursors TMGa, TMAl, and TMIn. The group-V sources were AsH_3 and PH_3. Si_2H_6 has been used for n-type doping.

The devices basically consist of a highly doped n$^+$-GaAs subcollector, a n$^-$-(Al)GaAs collector, a p$^+$-GaAs base and an n-$In_{0.48}Ga_{0.52}P$ emitter with intrinsic ballasting. The emitter is capped with a n$^+$-InGaAs contact layer to allow for nonalloyed ohmic contact formation. Devices with an emitter area of 60×60 μm^2 were processed in a two-mesa-approach using stepper lithography and air-bridge technology. Afterwards the processed devices were characterized by standard on-wafer dc measurements.

The calculation of base collector breakdown voltages was done with a semi-analytical approach. This is based on impact ionization coefficients given by [6] and a discretized one dimensional solution of Poisson's equation. Between adjacent sample points of the discretization grid constant conditions are assumed, so a parametrized analytical solution, given the steadiness and boundary conditions can be applied. This way the electrical field distribution along the base-collector-subcollector depletion region can be calculated. Together with the material specific impact ionization coefficients the well known ionization integrals for electrons and holes are then solved. This routine is iteratively performed until one of the ionization integrals equals unity. One can now for example calculate the breakdown voltage in dependence on the collector doping concentration. For simulations of HBT dc/RF operation we use a commercially available two-dimensional numerical device simulator (Silvaco ATLAS).

III. RESULTS

Measured breakdown voltages of fabricated SHBT devices denoted by symbols, where collector doping concentration N_C as well as collector thickness X_C was varied are shown in Fig. 1. Also shown in Fig. 1 is the calculation of the base-collector breakdown voltage BV_{CBO} in dependence of N_C for GaAs and $Al_{0.2}Ga_{0.8}As$. The calculations were done as described in the previous section. The calculated dependencies fit the measured values well especially with respect to different collector thicknesses. This proves the suitability of the model to be used for this purpose.

When N_C decreases, BV_{CBO} increases until the depleted region reaches the subcollector. In that case, the potential drop across the collector cannot significantly increase any further and BV_{CBO} is thus limited by X_C. But, on the other hand, the collector transit time and the critical current density J_C at which base push out starts decreases, and thus a thicker and lower doped collector leads to deteriorated RF properties. Therefore, to realize high-power microwave amplifiers with an SHBT operating at 2 GHz we found a 2.8 μm thick collector doped to $N_C = 6 \times 10^{15}$ cm^{-3} a sufficient trade-off [2].

In a first attempt we exchanged the collector material leaving X_C and N_C untouched to see how BV_{CBO} changes. The use of

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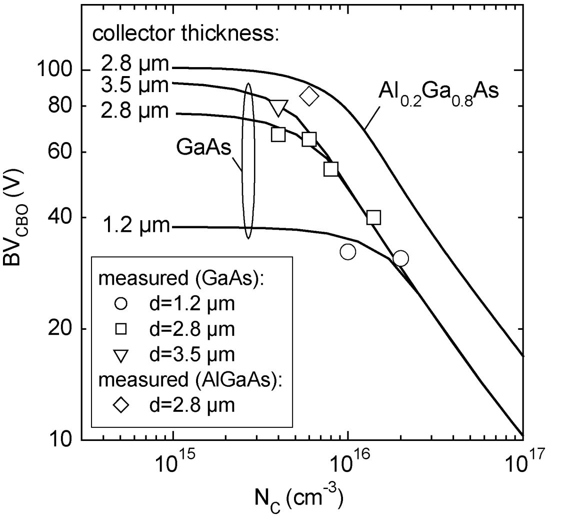

Fig. 1. Calculated (lines) and measured (symbols) breakdown voltages for different collector doping concentrations (N_C) and thicknesses for p-GaAs/n-GaAs homojunctions (SHBT) and p$-$GaAs/n $-$ Al$_{0.2}$Ga$_{0.8}$As heterojunctions (DHBT).

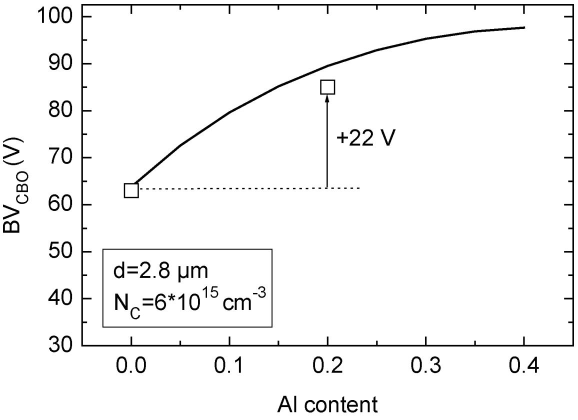

Fig. 2. Calculated and measured increase of BV$_{\rm CBO}$ for the p^{++} $-$ GaAs/ n$^-$ $-$ Al$_x$Ga$_{1-x}$As heterojunction in dependence on the Al content.

Al$_x$Ga$_{1-x}$As offers two advantages 1) it shows a higher (composition dependent) critical electrical field than GaAs, and 2) it is easily grown on GaAs due to almost perfect lattice matching for all composition fractions which makes it preferable over other wider band gap materials.

Based on experimentally determined data for the ionization coefficients that can be found in [4]–[7], we first calculated BV$_{\rm CBO}$ in the same manner as we did for the SHBT, except that the composition is additionally taken into account. The coefficients given in [6] offer a functional description in dependence on the AlGaAs composition ($0 \leq x \leq 0.45$). The calculation of BV$_{\rm CBO}$ as a function of the aluminum content with $X_C = 2.8$ μm and $N_C = 6 \times 10^{15}$ cm^{-3} is plotted in Fig. 2. Apparently there is a nonlinear dependence on the aluminum content that flattens toward the direct-to-indirect bandgap transition of Al$_x$Ga$_{1-x}$As ($x = 0.45$). Thus, most of the expected increase of breakdown voltage appears at lower aluminum content. Furthermore, for aluminum contents higher than approximately 0.2 the formation of DX-centers acting as carrier traps in lowly doped n-AlGaAs is a well-known problem [8]. Thus, for the experimental verification, we chose an aluminum content of $x = 0.2$ expecting an improvement for BV$_{\rm CBO}$ of approximately 25 V without potential complications from DX-centers.

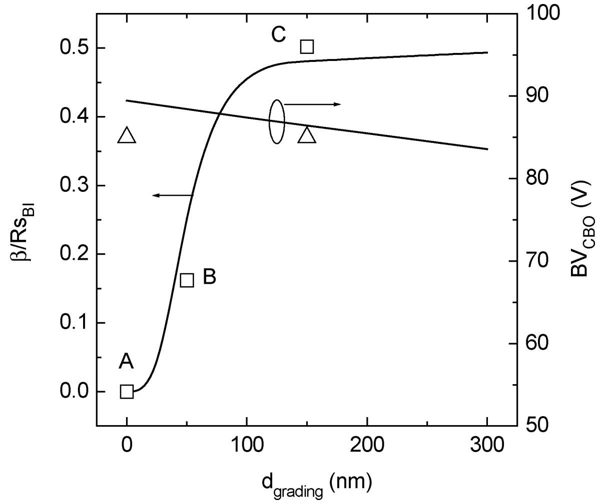

Fig. 3. Calculated (lines) and measured (symbols) maximum dc current gain β and base-collector breakdown voltage depending on the thickness of the graded-composition intermediate layer.

In fact, we obtained a breakdown voltage of 85 V, a noticeable improvement of 22 V compared to the SHBT (see Fig. 2). The agreement between measured and calculated voltages is quite good and proves the validity of the impact ionization coefficients used for the calculation.

Besides the achieved higher voltage stability the dc device operation is expected to suffer from the base-collector heterojunction without additional modifications.

Accordingly, one finds that D-HBTs with the GaAs-base directly grown on the Al$_{0.2}$Ga$_{0.8}$As-collector show no current gain at all (see point A in Fig. 3). The conduction band offset at the p-GaAs/n-Al$_{0.2}$Ga$_{0.8}$As hetero interface prevents electrons, that move through the base region by diffusive transport, from entering the collector region, i.e. full current blocking takes place. We were able to show that this blocking effect, that reduces the current gain, can be minimized by the use of a composition-graded intermediate layer with a certain thickness. The graded layer leads to a separation of the pn- and heterojunction and kind of expands the heterojunction into the depleted collector region, respectively. This was done using a two-dimensional numerical device simulations. Fig. 3 compares calculated and measured ratios of current gain to base sheet resistance as a function of graded layer thickness. Apparently the agreement between measured and calculated values for $\beta/R_{\rm SBI}$ is quite good. One finds that a thickness of 150 nm is sufficient to restore the maximum dc current gain β to the value obtained for a GaAs collector layer. This DHBT is, thus, very much comparable to the SHBT.

On the other hand, the use of a graded intermediate layer is only of interest as long as the gained breakdown voltage becomes not significantly influenced (lowered) by it. Therefore, Fig. 3 (right axis) also shows the breakdown voltages calculated for different thicknesses of the graded intermediate layer. While the calculation shows a slightly decreasing dependence, the measured values do not. In principle, one would expect a slightly decreasing dependence due to the fact that with increasing graded layer thickness, the mean AlGaAs composition becomes lower and, thus, BV$_{\rm CBO}$ is being lowered, too (see Fig. 2). Here, the measurement is not sensitive enough to detect this slight decrease. That means that a graded layer of up to 150 nm is sufficient to restore the maximum current gain (point C in Fig. 3), and does not affect the overall breakdown voltage significantly.

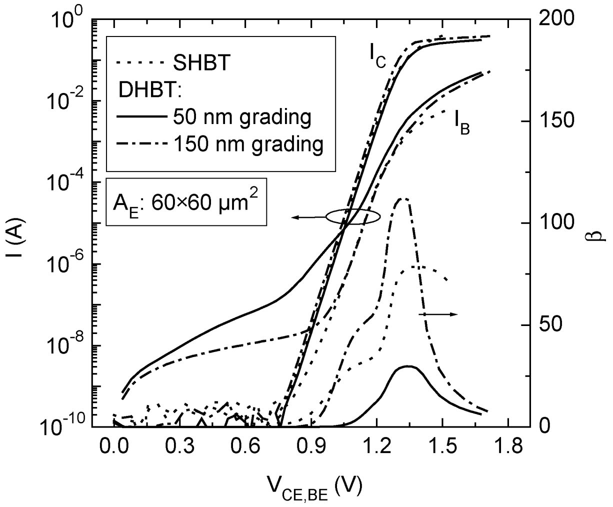

Fig. 4. Comparison of typical gummel-plots for 50- and 150-nm graded intermediate layer thickness with a standard SHBT. Note that the devices are not passivated here, i.e., increased base leakage currents occur.

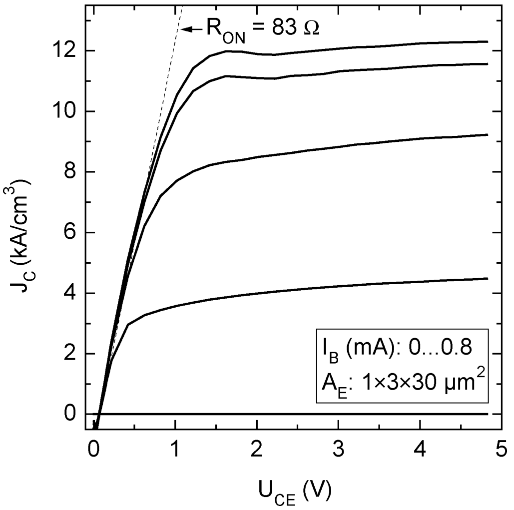

Fig. 5. Output characteristics of the DHBT with 150-nm graded intermediate layer.

Fig. 4 shows corresponding gummel-plots of devices with $d_{\text{grading}} = 50\text{nm}$ and $d_{\text{grading}} = 150$ nm and a standard SHBT. The DHBT with 150-nm grading thickness exhibits a higher maximum current gain than the SHBT of about $\beta = 110$. Although these large devices are almost insensitive to high current density effects, it seems that the D-HBTs suffer from some kind of an early onset of the Kirk effect, causing an earlier drop in current gain than the SHBT shows.

The critical current density J_C is mainly affected by N_C and v_D (electron drift velocity). The use of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ implies a reduced v_D compared to GaAs and, thus, a lowered J_C is expected. According to this, Fig. 5 shows output characteristics measured on a $1 \times 3 \times 30$ μm^2 device. Unfortunately, these devices suffer from noticeably lower dc current gain β compared to the large area devices. This is believed not to be an intrinsic device problem, but rather is being caused by extrinsic leakage currents. These came to light in the open-emitter base-collector breakdown voltage measurements. But the main thing to notice in Fig. 5 is the rather low critical current density $J_C = 1.2 \times 10^4$ A/cm^2. However, the lowered J_C is supposed to not only be caused by a lowered v_D, but may partially be an outcome of the BC heterojunction, e.g., current-induced barrier formation as is reported in [9]. While the latter can be addressed using a pulsed doped n-layer near the heterojunction (see [10]), the reduced drift velocity can easily be compensated by increasing N_C with respect to J_C. According to Fig. 1, choosing $N_C = 1 \times 10^{16}$ cm^{-3} could be sufficient without a significant loss in breakdown voltage. Also, a lower on resistance R_{ON} is expected too when increasing N_C. As also denoted in Fig. 5 the presented DHBT devices with a grading layer thickness of 150 nm show $R_{\text{ON}} = 83$ Ω. The corresponding SHBT devices show $R_{\text{ON}} = 44$ Ω, which is only half of the DHBT value.

Future work will deal with further optimizations of these DHBT devices especially concerning high current density operation and a lower R_{ON}.

IV. SUMMARY

We have shown that the use of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ as a collector material in D-HBTs offers a good way to increase the breakdown voltage compared to the SHBT without further increasing the collector thickness or otherwise allows for a reduction in collector thickness with unchanged breakdown voltage.

To avoid current-blocking for electrons entering the collector from the base side we successfully applied a composition graded intermediate layer. In conjunction with and based on device simulation we obtained $\beta/R_{\text{SBI}} \sim 0.5$.

Further investigations need to address the problem of a possibly existent current induced barrier formation, i.e. early Kirk effect, in conjunction with further lowering R_{ON}.

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REFERENCES

[1] P. Kurpas, F. Brunner, W. Doser, A. Maaßdorf, R. Doerner, M. Rudolph, H. Blanck, W. Heinrich, and J. Wuerfl, "Development and characterization of GaInP/GaAs HBTs for high voltage operation," in *Proc. GaAs Mantech Conf.*, 2001, pp. 23–25.

[2] D. Hill and T. S. Kim, "28-V low thermal-impedance HBT with 20-W cw output power," *IEEE Trans. Microwave Theory Techniques*, vol. 45, p. 2224, Dec. 1997.

[3] A. G. Baca, P. C. Chang, J. F. Klem, C. I. H. Ashby, and D. C. Martin, "Vertical AlGaAs/GaAs heterojunction bipolar transistors with 106 V breakdown," *Solid State Electron.*, vol. 45, pp. 721–725, 2001.

[4] G. E. Bulman, V. M. Robbins, and G. E. Stillman, "The determination of impact ionization coefficients in (100) gallium arsenide using avalanche noise and photocurrent multiplication measurements," *IEEE Trans. Electron Devices*, vol. ED-32, pp. 2454–2466, Nov. 1985.

[5] J. H. Hur, C. W. Myles, and M. A. Gunderson, "Avalanche breakdown in p-n AlGaAs/GaAs heterojunctions," *J. Appl. Phys.*, vol. 67, no. 11, pp. 6917–6923, 1990.

[6] H. F. Chau and D. Pavlidis, "A physics-based fitting and extrapolation method for measured impact ionization coefficients in III-V semiconductors," *J. Appl. Phys.*, vol. 72, no. 2, p. 531, 1992.

[7] S. A. Plimmer, J. P. R. David, G. J. Rees, R. Grey, D. C. Herbert, D. R. Wight, and A. W. Higgs, "Impact ionization in thin $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x = 0.15$ and $x = 0.30$) p-i-n diodes," *J. Appl. Phys.*, vol. 82, no. 3, p. 1231, 1997.

[8] T. Fujisawa, J. Yoshino, and H. Kukimoto, "DX centers in III-V compound and alloy semiconductors as studied by hydrostatic pressure experiments," *J. Cryst. Growth*, vol. 98, pp. 243–248, 1989.

[9] B. Mazhari and H. Morkoc, "Effect of collector-base valence-band discontinuity on Kirk effect in double-heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 59, no. 17, pp. 2162–2165, 1991.

[10] A. Maaßdorf, P. Kurpas, W. Doser, F. Brunner, T. Bergunde, H. Blanck, J. Wuerfl, M. Weyers, and G. Traenkle, "Layer design for GaAs-based DHBTs enabling 28 V high-power microwave applications," in *IEDM Tech. Dig.*, 2003, pp. 571–574.