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High Frequency AlGaAs/GaAs HBT

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This paper presents a self-aligned and self-passivated high frequency AlGaAs/GaAs Heterojunction Bipolar Transistor technology. With this technology, a record high f_{max} of 350 GHz was extrapolated from fabricated common base HBTs. The common emitter HBTs showed f_{max} of 170 GHz and f_T of 60 GHz. The self-aligned E/B structure has significantly reduced the base collector capacitance and the base resistance, which leads to very high frequency response. The self-passivated E/B process produced depleted AlGaAs ledge to suppress the surface recombination at the emitter peripheral area and thus enhance the DC current gain. The same technology also produced HBTs with both f_T and f_{max} reaching 100 GHz.

INTRODUCTION

AlGaAs/GaAs Heterojunction Bipolar Transistors have demonstrated excellent high speed and high power performance in the microwave frequency range. For further improvement of the HBT performance, both the vertical and lateral dimensions must be optimized. Higher f_T can be obtained by shortening the collector and the base length. It also can be enhanced by using the base dopant gradients and the ballistic collection structure to allow for the electron velocity overshoot[1]. Higher f_{max} can be achieved by using the self-alignment techniques to reduce the base resistance and base collector capacitance.

Several self-alignment approaches have been reported for HBT processing[2,3] to enhance the device performance. A self-aligned, self-passivated dual lift-off process successfully developed to fabricate the high performance HBTs with excellent frequency response is described in this paper. The characteristics and performance of fabricated devices are presented and a variety of high frequency applications are demonstrated with an emphasis on its multifunctional capability.

DEVICE FABRICATION

A self-aligned and self-passivated HBT process has been developed and its device cross section is shown in Fig. 1. In this process the emitter base self-alignment and edge passivation were processed using one photolithography step. The emitter GaAs cap was selectively etched down to AlGaAs emitter layer using reactive ion etch with the proper undercut control. A thin photo-enhanced CVD Si_3N_4 was then deposited and etched away with Si_3N_4 left only on the sidewalls and undercut regions of the emitter. The remained Si_3N_4 protects the AlGaAs in the GaAs undercut region from the subsequent AlGaAs etch and was used to passivate the emitter peripheral. To expose the base layer for making the base metal contact the exposed AlGaAs was subsequently etched away anisotropically. The collector in this extrinsic base region was implanted with protons to reduce the base collector capacitance. After proton implant, the base metal and another Si_3N_4 were deposited and lifted off at the same time. This process preserves the self-aligned emitter base structure to enhance the device RF performance and leaves a depleted AlGaAs layer (0.3 μm width) to suppress the surface recombination in the emitter peripheral, thus achieving high DC current gain. The processing uniformity, device yield and the device performance reported in the previous paper[4].

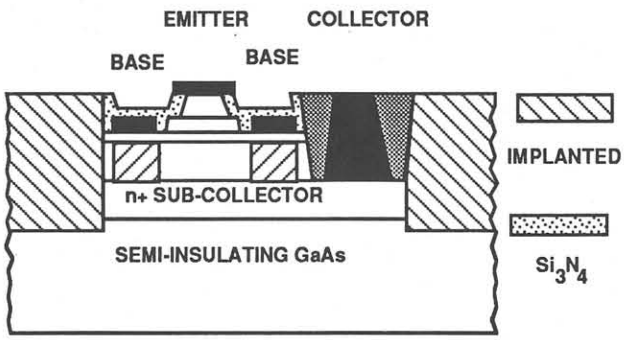

Fig. 1 Representative self-aligned, self-passivated AlGaAs/GaAs HBT device cross-section.

HBT CHARACTERISTICS

Representative Gummel plots are shown in Fig. 2 for a device with two emitter fingers of 1.8 μm x 9 μm area. For a base doping level of 5 x 10^{19} cm^{-3}, DC current gain was 31±2 across a 3-inch wafer. The current

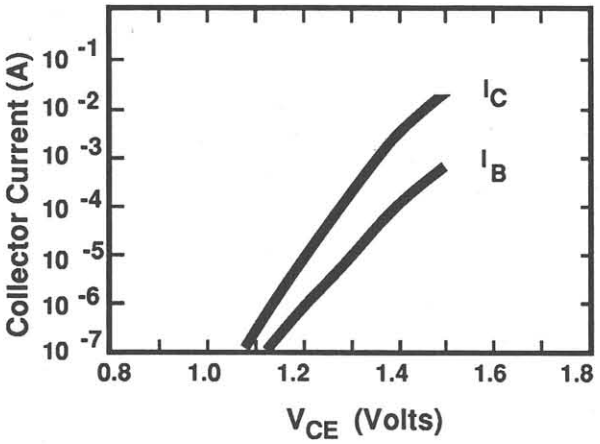

Fig. 2 Gummel plots of C-doped base HBT across a 3-inch wafer with base doping level of 5×10^{19} cm^{-3}.

gain decreased by less than 10% as the device emitter periphery over area ratio increased. This illustrates the effect of the emitter edge passivation on suppressing the surface recombination as it decreases the current gain.

The device RF performance can be characterized by the s-parameters measured from 0.1 GHz to 40 GHz using a cascade probe. A record high f_{max} of 350 GHz was extrapolated in Fig. 3 by assuming 6 dB/octave falloff rate from the unilateral gains (U). The device was biased at $I_c = 8 \times 10^4$ A/cm^2 and $V_{ce} = 1.8$ V in the common base mode, the device has 2 emitter fingers of 1.8 µm x 9 µm area. The epitaxial structure was grown by MOCVD with carbon doped base with doping level of 6×10^{19} cm^{-3} and thickness of 650Å. The collector thickness was 7000Å with doping level of 3×10^{16} cm^{-3}. A small signal T-equivalent model fitted from measured microwave results of fabricated HBTs has been established. The simulated MSG/MAG and U of the HBT model also reached 350 GHz of f_{max}. The device parasitics were optimized and extracted in Table I based on the T-equivalent circuit model. Significant advance in f_{max} resulted from combination of low C_{bc}, low R_b and low base transit time. For the common emitter devices the best extrapolated f_{max} was 170 GHz and f_T was 60 GHz from the same wafer. In general the common base HBT is of more a unilateral device than common emitter HBT. The low direct interaction (low negative feedback) between the emitter and collector in the CB HBT may have produced a higher small signal gain at higher frequency.

Shortening the collector thickness is effective in increasing the cutoff frequency; however, it will decrease the maximum oscillation frequency because of the high C_{bc} and also will reduce the breakdown voltage for the practical applications. An effective way to maintain the f_{max} is to use the structure with graded highly doped base. Raising the base doping level lowers R_b and grading base doping reduces the base transit time. Figure 4 shows a 100 GHz of both f_T and f_{max} extrapolated from the device biased at $I_c = 8 \times 10^4$ A/cm^2 and $V_{ce} = 1.25$ V in the common emitter mode. The epitaxial structure was grown by MBE with Be doped base graded from 8×10^{19} cm^{-3} to 1.2×10^{20} cm^{-3} and the collector was 2000Å thick.

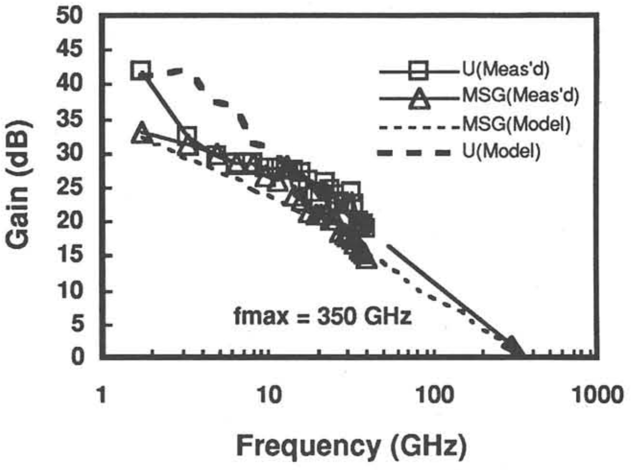

Fig. 3 Frequency dependence of maximum stable gain (MSG) and unilateral gain (U) for a common base HBT.

Table I. Extracted HBT Parameters for the Device with Extrapolated f_{max} of 350 GHz

R_b (Ω)	R_e (Ω)	R_c (Ω)	C_{be}(pF)	C_{bc}(pF)	α	τ_1 (ps)	τ_2 (ps)
5.5	2.76	2.92	0.17	.025	0.95	1.80	1.06

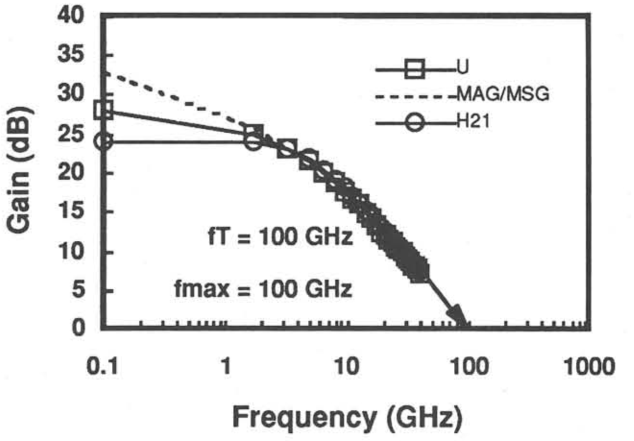

Fig. 4 Frequency dependence of MSG and U for a common emitter HBT.

HBT APPLICATIONS

HBTs are expected to have a widespread impact on both analog and digital circuit applications. This section illustrates some of the more established application areas.

a) Microwave and millimeter wave applications:

For microwave applications AlGaAs/GaAs HBT power amplifiers have demonstrated very high power-added-efficiency of 67.8% at 10 GHz with associated gain of 11.6 dB. At 18 GHz, the common emitter HBTs achieved 48.5% PAE and 6.2 dB gain. At 1.5 GHz, a

CE HBT has achieved 72% added efficiency with CW output power of 2W. The performance at 44 GHz is also significant as it demonstrates a PAE of 30% with associated gain of 8 dB linear gain and power density of 1.25 mW/μm^2. Another demonstration for the high frequency operation is the fabrication of 35 GHz quasi-optical grid oscillators, which potentially will be a more efficient way to combine the power in free-space for applications at high frequencies. The frequency operation as shown in Fig. 5 is 34.75 GHz with frequency span of 100 MHz at 22 dBm equivalent radiated power.

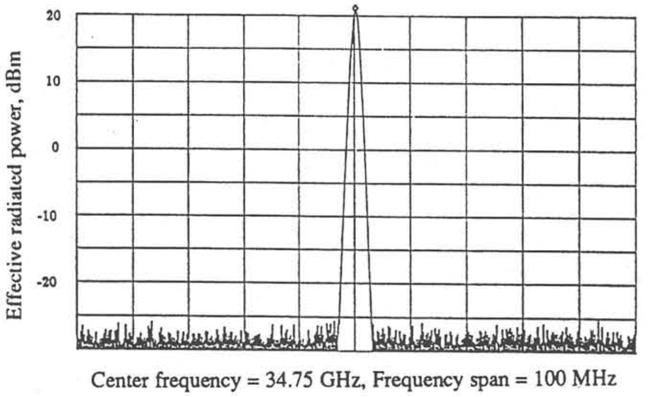

Fig. 5 Frequency spectrum of HBT grid oscillator displaying the oscillation at 34.75 GHz.

The demonstration for the MMIC applications is shown in a high power broadband amplifier. The amplifier has demonstrated a peak performance of 5.9 W at 34.5% power added efficiency and 12 dB gain. Over 7.5 to 9.5 GHz range, power above 4 W with 28% or better PAE is achieved. The chip dimensions are 3 mm x 3mm which is very compact for a MMIC at this power level. Excellent linearity is also demonstrated in a linear 7.5-14 GHz power amplifier which shows a better than -20 dBc of third intermodulation ratio (IM3) at 1 dB compression point and provides 1W saturated power in class AB operation.

b) Digital circuits:

Excellent high speed digital circuits have also been demonstrated successfully. Performance of HBT 2:1 MUX at 30 Gbits/s and 1:2 DEMUX at 27 Gbits/s has been achieved using the non-self-aligned baseline process. The phase detector is a key circuit for clock recovery in receivers of lightwave communication systems. The outputs of the phase detector operated at 5 GHz clock rate Output signal rise and fall times are in the range of 40-60 ps, and power consumption was 750 mW.

RELIABILITY

Carbon-doped base HBT could be very reliable if the device layout and processing were carefully designed. At Rockwell Science Center a small size (1.4 μm x 3 μm) of carbon base HBT was stressed at 5 x 10^4 A/cm^2 current density for 600 hours at 260°C. Only 12% change in current gain was measured.

FUTURE DIRECTIONS

To enhance the high frequency response, further reduction of C_{bc} is essential. This can be done by implanting the subcollector in the extrinsic base region. The collector up configuration is also very attractive because its base collector capacitance C_{bc} is lower than that of an emitter up configuration. This characteristic is advantageous to increase f_{max}, and is especially useful for power transistors.

For high power microwave amplifiers, thermal management to decrease maximum device temperature and avoid thermal runaway is a key issue. Several effective methods such as novel thermal shunt and thermal lens techniques[5)] and partial vias and peeled films concept to place heatsinking materials close to the device area are being evaluated.

Other alternatives to the AlGaAs/GaAs HBT for the high frequency applications are to use InGaAs/InP or InGaAs/InAlAs HBTs grown on the InP substrates[6)]. The recent developments in the InGaP emitters and collectors could also benefit device performance especially in the 1/f noise characteristics and improved temperature sensitivity[7)].

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