GaAs HBT Wideband and Low Power Consumption Amplifiers to 24 GHz

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ABSTRACT

This paper reports on the design and performance of a 2-24 GHz distributed matrix amplifier and a 1-20 GHz 2-stage Darlington coupled amplifier based on an advanced HBT MBE profile which increases the bandwidth response of the distributed and Darlington amplifiers by providing lower base-emitter and collector-base capacitances. The matrix amplifier has a 9.5 dB nominal gain and a 3-dB bandwidth to 24 GHz. It is the highest bandwidth reported for an HBT distributed amplifier. The input and output VSWRs are less than 1.5:1 and 2.0:1, respectively. The total power consumed is less than 60 mW. The chip size measures 2.5x2.6 mm^2. The 2-stage Darlington amplifier has 7 dB gain and 3-dB bandwidth to 20 GHz. The input and output VSWRs are less than 1.5:1 and 2.3:1, respectively. This amplifier consumes 380 mW of power and has a chip size of 1.66x1.05 mm^2.

INTRODUCTION

Wideband HBT amplifiers have been reported earlier [1],[2] based on both distributed and Darlington feedback design approaches. HBT distributed amplifiers have achieved up to 10 GHz bandwidth [2] using a 3 μm self-aligned base ohmic metal (SABM) HBT technology. Single stage Darlington feedback amplifiers have achieved up to 20 GHz bandwidth [1] using 2 μm SABM HBT technology. The performance of HBT distributed amplifiers have been limited by the high base-emitter capacitance of the transistor. Bipolar devices in general, have an inherently high input capacitance, C_π, which depends on the base transit time, τ_B, of the device [$C_\pi = C_{je} + G_m(\tau_B + \tau_C)$]. Consequently, the high input capacitance limits the bandwidth that can be achieved by HBT distributed amplifiers. Device scaling and capacitive dividers at the input have been used for reducing the device input capacitance. The use of capacitive dividers, however, is not power efficient for HBT devices since the high input capacitance of the device results in a large voltage division. Wideband bipolar feedback designs, on the other hand, are limited by the collector-base capacitance which is Miller multiplied by the voltage gain. Device scaling and cascode configurations are design techniques that enhance the circuit frequency response, however, they do not address the transistor performance limitations which are related to the device design. An optimal solution will involve the implementation of both circuit techniques and device performance improvements. In this paper, we report the results of an HBT distributed amplifier and a Darlington feedback amplifier which use an advanced HBT MBE profile[4] with an exponentially graded base doping that creates a drift field component in the base resulting in a reduced base transit time, τ_B. This reduction in τ_B reduces the input capacitance compared to our flat-doped (uniform) base profile. This reduction in input capacitance in addition to using a 2 μm SABM HBT process has extended the frequency bandwidth of the distributed amplifier from 10 GHz [2] to over 20 GHz. In addition, a wide collector profile is used to reduce the collector-base capacitance which is important for increasing the bandwidth of the Darlington amplifier. With the aid of the reduced collector-base capacitance and a scaled-size input device in the Darlington cell we have been able to implement a 2-stage Darlington amplifier that can achieve a 20 GHz bandwidth without excessive gain roll-off. Details of these results are reported in the following sections.

GaAs HBT TECHNOLOGY

The GaAs HBT wideband distributed and Darlington-coupled amplifiers were fabricated using 2 μm SABM process tehnology. This process integrates 2 μm emitter width npn HBTs, schottky diodes, thin film resistors (NiCr), metal-insulator-metal (MIM) capacitors, and spiral inductors (air-bridged) facilitating monolithically combined microwave, analog, and digital functions. This process has been reported in detail elsewhere[3]. The HBT MBE profiles used in the fabrication of these amplifiers is illustrated in fig. 1. The design of this novel profile and its measured effects on device performance has been reported earlier in detail[4]. The MBE profile incorporates an exponentially graded base doping,

MBE Epitaxial Structure Used for HBT Fabrication

Layer	Thickness (μm)	Doping (cm^{-3})	Al Composition
Cap	0.075	$7x10^{18}$	0
Emitter	0.03 0.12 0.03	$5x10^{17}$ $5x10^{17}$ $5x10^{17}$	0.3→0 0.3 0→0.3
Base	0.14	$5x10^{19} \rightarrow 5x10^{18}$	0
Collector	0.7/1.0	$7x10^{15}$	0
Subcoll.	0.6	$5x10^{18}$	0

Fig. 1 HBT Molecular Beam Epitaxy cross-section of the drift profile

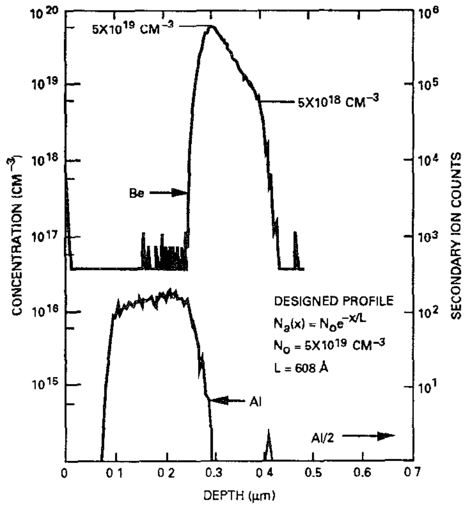

Fig. 2 SIMS of the exponentially graded base profile

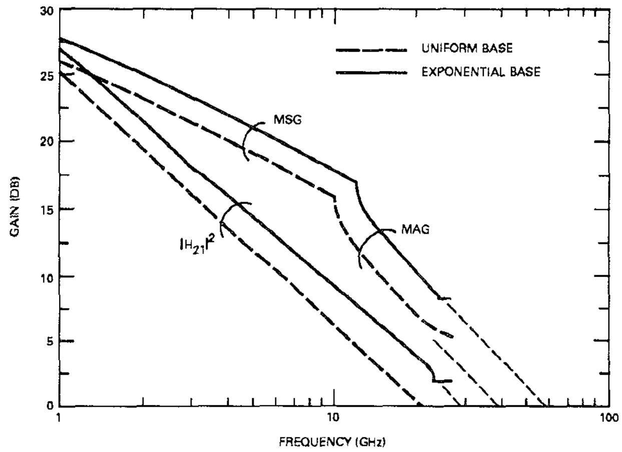

Fig. 3 Maximum stable/available gain and current gain (H21) vs.frequency for the uniform and exponentially graded base profiles

from 5×10^{18} cm^{-3} at the collector to 5×10^{19} cm^{-3} at the emitter. The collector is 1.0 µm wide. A SIMS profile of the graded structure is shown in fig. 2. The base profile follows an exponentially decaying function from the emitter to the collector side of the base region and is expressed as: $N_a(x)=N_o e^{-x/L}$ where $N_o=5 \times 10^{19}$ cm^{-3} and L=608Å. The resultant field produced by this grading, to a first order, is given by:

$$E = -\frac{d\Psi}{dx} = -\frac{kT}{q}\frac{1}{N(x)}\frac{dN(x)}{dx} = \frac{1}{L}\frac{kT}{q}$$

This field helps sweep the electrons from the emitter to the collector thus reducing the transit time through the base and increasing f_t. The effect of this graded profile on f_t and f_{max} are compared to the uniformly doped profile (for a fixed collector width of 1.0 µm) and is shown in fig. 3. This shows that the f_t has increased from 22 to 31 GHz and the f_{max} has increased from 40 to 58 GHz due to the graded profile alone. These figures of merit were taken at a current density of 20 kA/cm^2. For this example, f_{max} has increased due to a combination of higher f_t and lower R_b where the reduction in base resistance has been verified by small signal modeling of s-parameters. Table 1 lists HBT small signal model parameters based on the equivalent circuit of fig. 4, for three different MBE profiles; graded base doping with a 1 µm collector, uniform base doping with a 1 µm collector, and the uniform base doping with a 0.7 µm collector. By comparing the model parameters of the three profiles, three conclusions concerning frequency response of the graded base profile with the 1.0 µm collector can be deduced: (1) The input capacitance, $C\pi$, decreased by 25-30 % due to the drift field which reduces τ_B, (2) the collector-base capacitance significantly decreases from using a wide 1 µm collector, and (3) the base resistance has decreased because of the higher base doping (5×10^{19} cm^{-3}) on the emitter side of the graded base region. These three features are attractive for both distributed and feedback designs implemented in HBTs.

MBE PROFILE	BETA	τ (ps)	R_π (Ω)	C_π (pf)	R_{bx} (Ω)	R_{bi} (Ω)	R_e (Ω)	C_{c1} (ff)	C_{c2} (ff)	R_{ci} (Ω)	R_{cx} (Ω)	C_{be} (ff)	C_{cb} (ff)	C_{ce} (ff)
DRIFT (1)	115	2.0	450	0.6	12	6	10	1.8	7.5	3	2	65	5	23
FLAT BASE (1)	70	2.6	400	0.85	15	10	12	4.0	7.0	3	2	70	8	23
FLAT BASE (2)	56	2.95	416	0.81	12	17	13	3.6	14.0	2.2	2	60	4.5	28

(1) COLLECTOR THICKNESS 1.0 µm
(2) COLLECTOR THICKNESS 0.7 µm

INTRINSIC (C_{c1}, C_{c2}); LAYOUT PARASITICS (C_{be}, C_{cb}, C_{ce})

TABLE 1

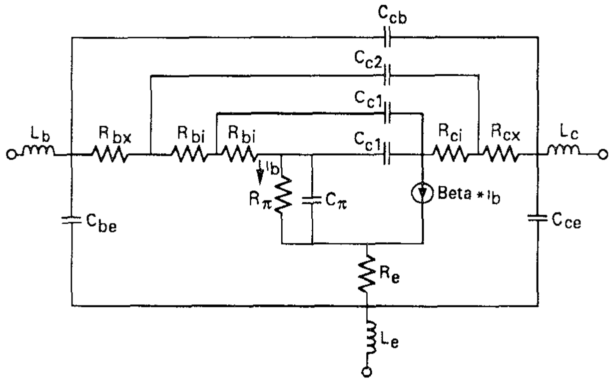

Fig 4 HBT hybrid-π small signal equivalent circuit model

CIRCUIT PEFORMANCE

The schematic of the 2x3 matrix amplifier is presented in fig. 5, which is similar to the MESFET matrix amplifiers reported earlier [5]. The first row includes three 2µm x 6µm single emitter devices which provide a suitable input capacitance required for a 20 GHz bandwidth. The second row contains 2µm x 10µm single emitter devices. The matrix amplifier is more flexible than the conventional distributed amplifier topology since the input row of devices can be scaled down to decrease the input capacitance while maintaining larger devices in the output row to obtain practical output power. This scheme avoids capacitive division in the

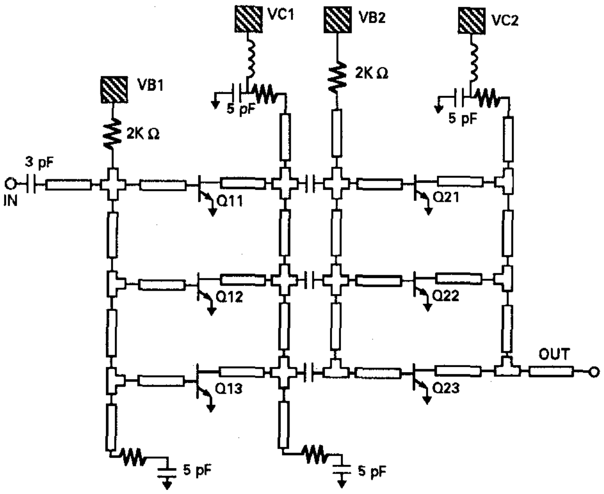

Fig. 5 Schematic diagram of the HBT distributed matrix amplifier

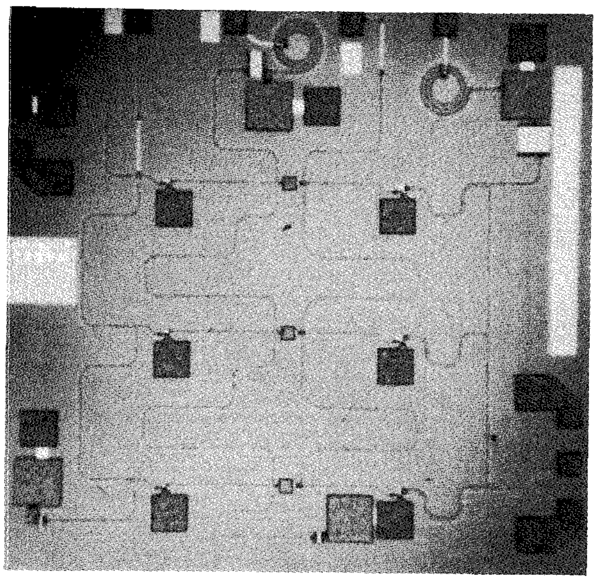

Fig. 6 Microphotograph of the HBT 2x3 matrix amplifier (chip size: 2.5x2.6mm^2)

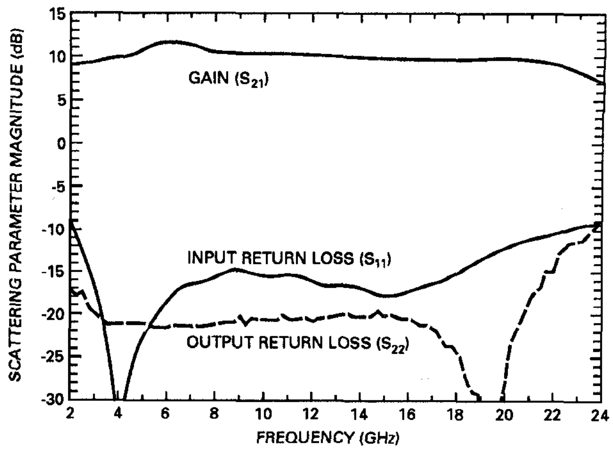

Fig. 7 Gain and input/output return-loss of the HBT matrix amplifier

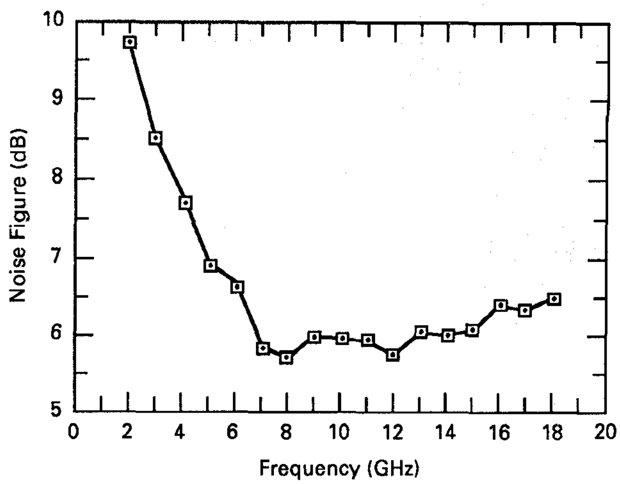

Fig. 8 Noise figure performance of the HBT matrix amplifier

input row which reduces the power efficiency. The fabricated 2x3 HBT matrix amplifier is shown in fig. 6. The chip size is 2.5x2.6 mm^2. The wideband frequency response is shown in fig. 7. The nominal gain is 9.5 dB with a 3-dB bandwidth to 24 GHz. The low-end gain response is flat down to 2 GHz where the 3 pF input coupling capacitance rolls-off the gain. The input and output VSWRs are less than 1.5:1 and 2.0:1 from 2 to 20 GHz. Fig. 8 gives the noise figure performance. The noise figure is between 5.5-6.5 dB from 7 GHz to 18 GHz. From 7 GHz down to 2 GHz the noise figure increases linearly from 6 to 9.75 dB. The chip is manually biased with separate base and collector voltages for each row of the matrix. The total power dissipation is less than 60 mW.

The schematic for a 2-stage Darlington coupled HBT amplifier is shown in Fig. 9. This 2-stage Darlington amplifier includes a 2μm x 10μm single emitter input device, followed by a 2μm x 10μm quad-emitter output device. The input device is scaled down to reduce power dissipation and collector-base capacitance. In addition, a series inductor-resistor load is used to reduce the required bias voltage at the output. A microphotograph of the chip is shown in fig. 10. Measured gain and input/output return losses of the amplifier are shown in fig. 11. The nominal gain is 7 dB with a 3-dB bandwidth greater than 20 GHz. The 1 GHz low end roll-off is due to two 5 pF coupling capacitors. The input and output VSWRs are less than 1.5:1 and 2.3:1, respectively. The noise figure performance, shown in fig. 12, measures between 8 to 9.5 dB across the band. This design is self-biased and uses a 6 Volt supply. The total power consumed is 380 mW. The chip size is 1.66x1.05 mm^2.

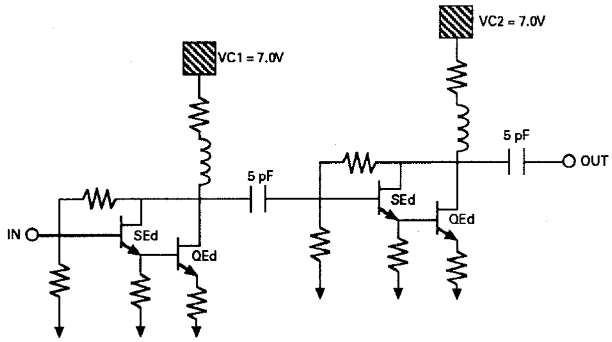

Fig. 9 Schematic diagram of the 2-stage Darlington feedback amplifier

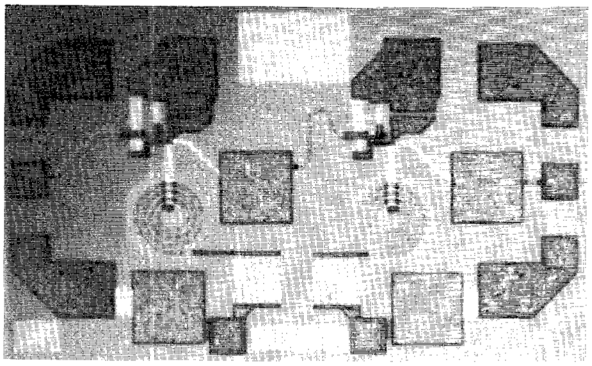

Fig. 10 Microphotograph of the fabricated 2-stage Darlington feedback amplifier (chip size: 1.66x1.05 mm^2)

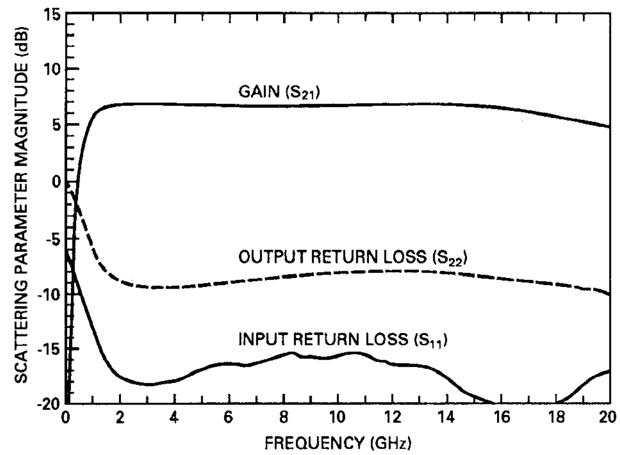

Fig. 11 Gain and input/output return-loss of the 2-stage Darlington feedback amplifier

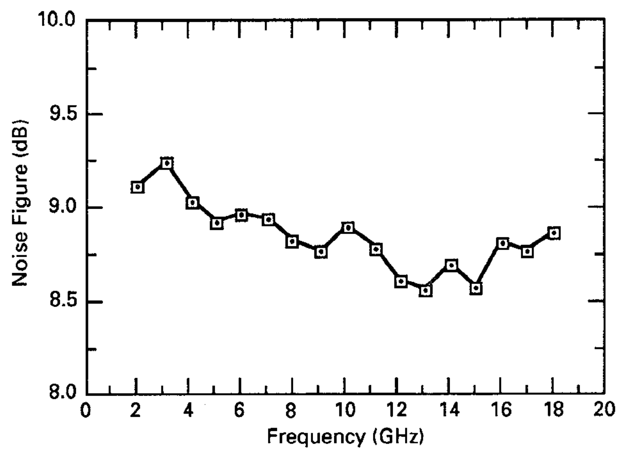

Fig. 12 Noise figure performance of the 2-stage Darlington feedback amplifier

SUMMARY

The results of two different HBT wideband amplifiers are presented, both based on an advanced exponentially graded base HBT MBE doping profile as well as device scaling techniques to achieve bandwidths greater than 20 GHz. The HBT matrix amplifier achieves the widest bandwidth so far reported for HBT distributed amplifiers and consumes less than 60 mW. The 2-stage HBT Darlington amplifier achieves a 1-20 GHz bandwidth using a scaled down input transistor and wide collector profile.

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