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GaAlAs/GaAs Heterojunction Bipolar Transistors: Issues and Prospects for Application

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HBT technology has benefitted recently from improved epitaxial growth techniques, particularly for the p+ base. The technology has reached pilot production at various companies; demonstrations of producibility and reliability have been made. Advanced circuit demonstrations include high efficiency (>45%) amplifiers with 1W output at 7-11GHz; digital data multiplexers operating above 20GHz; and broadband feedback amplifiers with 30GHz bandwidth. Prospects are also good for ultralow power microwave circuits and HBT-based optoelectronic ICs.

1. Introduction

The HBT structure is known to provide numerous advantages for ultrahigh speed circuits [1-3], including ultrahigh ft and fmax with convenient optical lithography; high output current driving capability and controllable breakdown voltage; excellent voltage gain and high output resistance; low 1/f noise and freedom from backgating, hysteresis, etc. This combination of characteristics is important for use in microwave amplifiers, at high power and efficiency; broadband microwave circuits, including linear amplifiers and nonlinear circuits such as oscillators and mixers; ultrahigh speed digital circuits; and A/D converters. Recently, maturing technology has led to a thrust towards applications, as well as a continued trend towards improving performance. This paper describes developments in HBT structure and process, manufacturing status, and milestones in circuit performance for III-V HBTs.

2. Epitaxial Structure:

While the wide bandgap emitter suppresses hole injection into the quasi-neutral emitter, control over the base dopant at doping concentrations above 10^{19}cm-3 has proved to be a major challenge. Much work has been devoted to specialized approaches to avoid excessive diffusion of Be using MBE. Carbon has been demonstrated to be an efficient acceptor in GaAs, has been shown to have low diffusion coefficient, and has recently been used in HBTs at concentrations of 2-8x10^{19}cm-3. The use of carbon has allowed 1) elimination of spacers, and lower base thickness; 2) greater freedom in temperature of growth and subsequent processing. With carbon-doping, high performance MOCVD-grown wafers are available. Fig.1 illustrates microwave gain resulting from such a wafer [4].

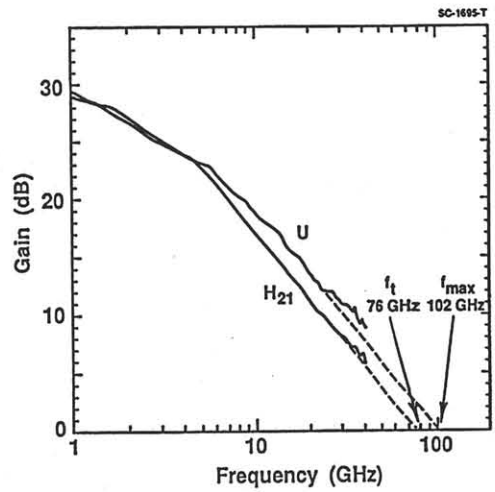

Fig. 1: Microwave current gain h21 and unilateral power gain U vs frequency for carbon-doped non-self-aligned HBT (pB=4e19cm-3).

Tailoring the electric field profile with doping spikes has produced structures with ultrahigh speed (Ballistic Collection Transistor of Ishibashi et al. [5]) as well as controllable conduction band steps.

Pseudomorphic base regions have been produced with the addition of In, or more recently, Sb to the base layer. This can lead to graded composition base without the complication of Al alloys.

3. Device Process:

Manufacturing approaches are now based on non-self-aligned structures, using emitter widths down to 1.4 um. On a laboratory basis, numerous fully-self-aligned structures have been developed. Advanced structures are being explored for reduction of device parasitics, the most important of which is extrinsic base-collector capacitance. Particularly with the use of carbon-doped bases, aggressive reduction of capacitance through use of implants is expected, as shown in fig. 2. The use of collector-up structures is an alternative to minimize Cbc, demonstrated in several papers.

4. Reliability:

Key demonstrations have been provided by Hafizi et al.[6], showing lifetime (extrapolated to 125C from higher temperature studies) of $>10^7$ hours. Degradation processes include increase of Vbe vs time and drop of current gain vs time. Lifetime of carbon-doped material exceeds that of Be-doped material, although both are compatible with high IC reliability.

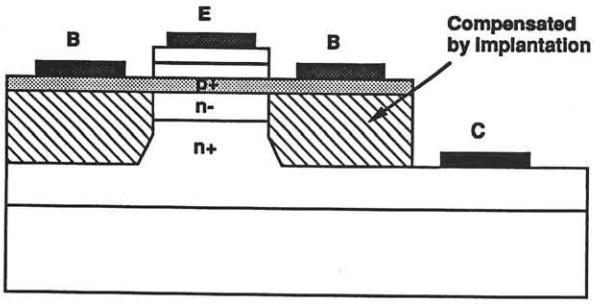

Fig. 2: HBT structure to minimize extrinsic base-collector capacitance

5. Applications:

Ultrahigh speed digital circuits based on ECL or CML include a 15GHz gate array[7], and digital data multiplexers (4:1) operating above 20Gb/s. Frequency dividers reaching 35GHz operation have been reported [8].

Analog feedback amplifiers utilize the exceptionally high voltage gain (stemming from high transconductance and high output resistance) of HBTs. Fig. 3 illustrates the gain of a feedback amplifier with response from dc to 30GHz (based on Darlington-connected HBTs with resistive feedback)[9]. Feedback can be used to attain high linearity in the microwave regime.

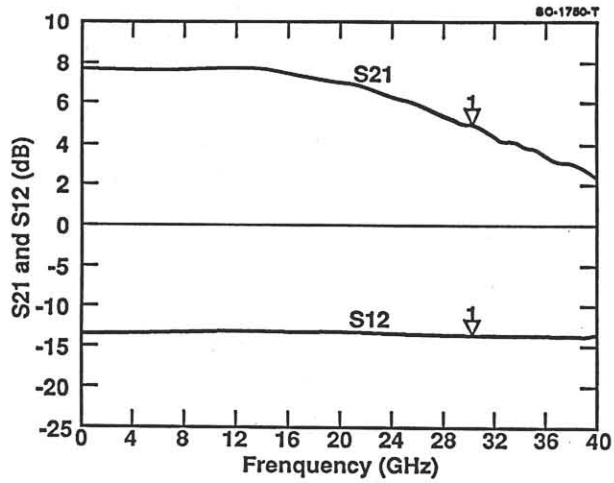

Fig. 3: Measured S parameters for HBT feedback amplifier, illustrating 30GHz bandwidth.

High power and efficiency have been demonstrated in HBT devices and amplifiers throughout the microwave regime[10,11]. Fig. 4 shows the layout of a 1W 7-11GHz amplifier based on cascode-connected HBTs. The amplifier attains power-added efficiency of 45% [11].

Increasing attention is being given to circuit operation at ultralow power dissipation, for potential use in microwave mobile communications systems. Fig. 5 illustrates ft and fmax for a device with reduced emitter dimensions, showing high microwave gain at <100uA current. Device scaling reduces parasitic capacitances that are particularly important at low current.

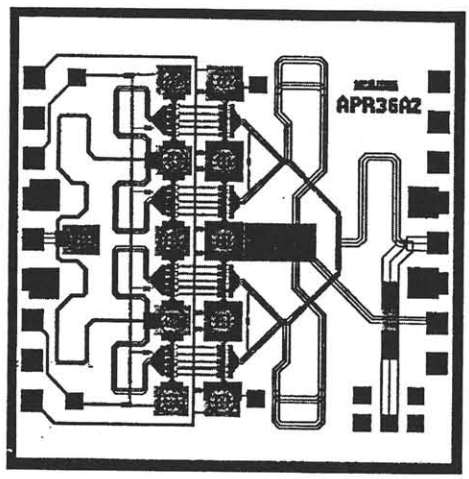

Fig. 4: Power amplifier using cascoded HBTs for 1W output in 7-11GHz band.

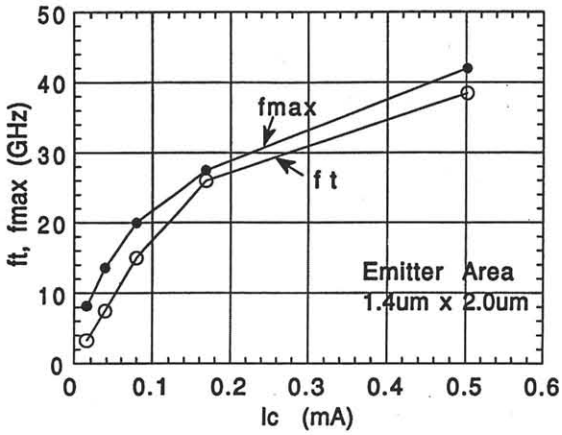

Fig. 5: Measured ft and fmax vs collector current for a small area HBT, illustrating high gain at low power.

The combination of characteristics of HBTs described above, together with low 1/f noise, makes them attractive candidates for numerous communication systems, including optical fiber systems, and microwave satellite and terrestrial systems [12].

Analog-to-digital converters based on HBTs with 6 bit resolution have operated above 3GSps. Efforts are being made to utilize architectures beyond the straightforward flash-encoding.

For high accuracy analog circuits and for microwave power performance, thermal interactions and heatsinking represent an important issue.

6. Future Prospects:

Efforts are on-going to integrate npn and pnp devices for microwave power push-pull amplifiers, for analog circuits and for complementary logic. Integration of HBTs with pin detectors have been reported with good success. Standard HBT process without modification has yielded a 9Gb/s receiver with -17.5dBm sensitivity, pictured in fig. 6 [13](although with the AlGaAs/GaAs the optical sensitivity is limited to wavelengths shorter than 0.85um). HBTs based on InGaAs/InP have demonstrated excellent performance [14], and are promising for 1.3-1.55um optoelectronics.

7. References:

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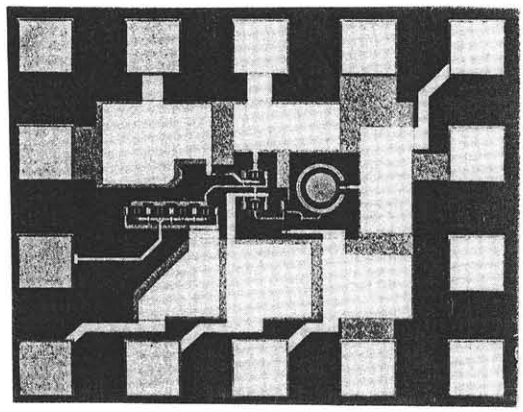

Fig. 6: Fabricated optoelectronic IC combining HBT amplifier with pin detector.