

Commercial Viability of a Merged HBT-FET (BiFET) Technology for GaAs Power Amplifiers

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Abstract

This paper covers the history and recent developments of GaAs BiFETs in commercial high volume GaAs HBT manufacturing environment. Further more, the paper also goes into “merged/stacked” FET-HBT integration schemes and their impacts on cost, yield and cycle time. Various circuit applications such as stage bypassing, attenuators, advanced bias circuit controls etc., that are realized in both BiFET approaches are also reviewed to show the commercial success of BiFET process technology. The challenges in using stacked FET-HBT geometry for an integrated transmit/receive switch and an alternative approach of utilizing advanced multi-chip module (MCM) techniques to deliver the same level of functionality in the smallest possible form-factor are examined with an emphasis on functional test yield and fabrication process yield.

INTRODUCTION

The phenomenal growth and proliferation of the cellular handset market has driven unprecedented development in the area of power amplifiers (PA). Significant progress in the epitaxial material structure has led to improvements in ruggedness, linearity and efficiency of the amplifiers which has helped meet the stringent requirements in diverse modulation schemes. In recent years, the emergence of GaAs HBT process technologies along with the emphasis of on-chip integration of high Q passives, FET and HEMT devices (BiFET) has undoubtedly changed the traditional PA design approach and led to the development of advanced bias control techniques, load insensitive PA (LIPA™), high efficiency at medium power designs and WiMAX power amplifiers with build-in step attenuators.

In this paper, Skyworks’ BiFET integration approach is discussed along with the application drivers. It is not our intent to simplify the discussion and declare a winner among different BiFET integration schemes, but rather simply to present the richness in the circuit capabilities offered by the integration of FET and HBT. Finally, an attempt is made to discuss the idealistic vs. realistic goal of “all-in-one” chip with the integration of antenna switch module, Low Noise Amplifier, Power amplifiers, in a multi-mode, multi-band front-end module.

MERGED BiFET DEVICE

Several BiFET integration schemes have been proposed and demonstrated [1-4] including some of the first MMIC CDMA/WCDMA power amplifiers. Choices of integration are either placing a MESFET or pHEMT at the bottom of HBT or a MESFET integrated into the emitter of an HBT. To establish a BiFET process in our high volume GaAs HBT production line, a merged FET in the emitter of HBT is chosen for the products, and is shown in Fig. 1.

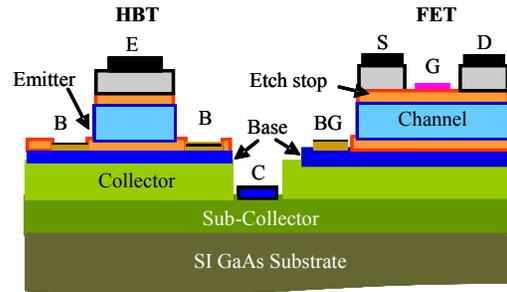


Fig 1. Cross sectional schematic of merged FET in the emitter of HBT epitaxial layer. Except for the dedicated channel and gate process steps, the rest of the processes to define the FET are common to HBT fabrication steps.

The merged/hybrid construction of the FET in the emitter of the HBT has also lead to a 4 terminal FET device, rather than a conventional 3 terminal FET when placed below the HBT collector. By tying the 4th terminal (indicated as BG in Fig.1) to either Gate (G) or to source (S), one can effectively tune the threshold and control the leakage. With an optimum connectivity, a negative pinch of voltage of 0.34V, g_m of 165 mS/mm with very low leakage ~ 10 nA/mm, were achieved with excellent repeatability. Epitaxial layers that belong to the FET were optimized so that the RF performance of the HBT is adequately maintained, and is depicted in Fig 2. The placement of FET in the emitter of HBT also allows the integration of FET in epitaxial materials with any base and collector profiles to achieve the desired functionality of the power amplifier design.

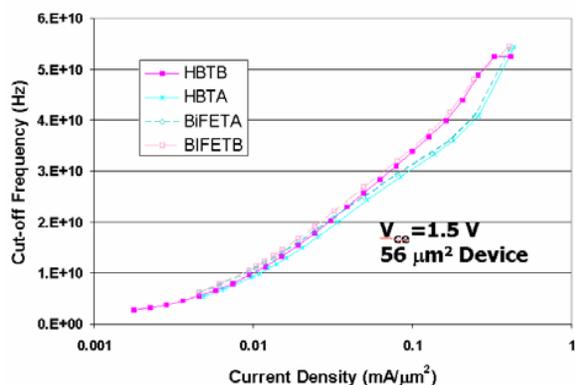


Fig 2. f_t vs. collector current density of conventional HBT and merged FET+HBT. A and B denote two epitaxial materials with different collector profiles.

APPLICATION DRIVERS

a) PA Bias Control:

Traditionally GSM/EDGE PAs use a silicon bias controller while the CDMA/WCDMA PAs use an on-chip bias controller. Typical bias circuits in HBT for CDMA/WCDMA are based on simple current mirror circuitry, and often the design emphasis is placed to compromise between linearity performance, temperature compensation and noise. There are several limitations in the conventional current mirror based bias circuits, such as: large V_{be} and h_{fe} variations with temperature and inability to lower the reference voltage of a PA due to $2 \cdot V_{be}$ stack up [5]. Current sensing feedback resistor topologies can improve the performance against temperature variations but often lead to higher standby current consumption. Combination of a HBT and a FET in the current mirror (shown in Fig 3) leads to a stable RF performance over a wide range of V_{ref} , even down to 1.8V. BiFET technology also enables “No V_{ref} ” as well as temperature insensitive bias circuit designs. For example, Fig 4 compares the output current as a function of control voltage of a HBT and BiFET based complex bias circuits designed for CMOS interfaced analog bias control.

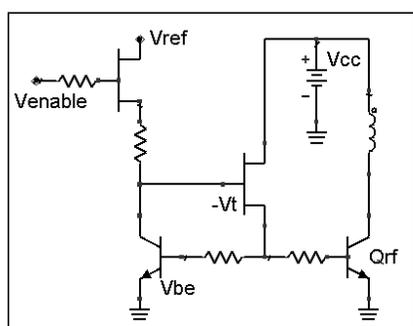


Fig 3. Schematic of a BiFET based bias circuit with an enable FET.

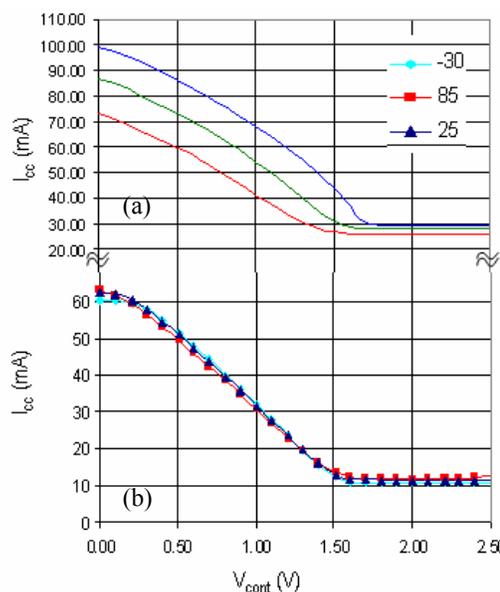


Fig 4. Output current as a function of control voltage at different operating temperatures (shown in the inset) of: a) HBT based and b) BiFET based complex bias circuits.

b) Attenuators for WiMAX PAs

Emergence of WiMAX technology with complex modulation scheme such as Orthogonal Frequency Division Multiple (OFDM) and the use of multiple-input multiple-output (MIMO) allow higher transmission efficiency. In addition, efficient power control algorithms are used to improve the overall performance of the system. The control of the transmit power level by the base station in the NLOS (non line of sight) coverage in WiMAX demands an attenuator switch integrated in the amplifier design. To achieve the power control, a FET switch is added to the input section of low gain amplifier, as shown in Fig. 5. Using this approach, a 12 dB gain step was achieved without degrading linearity and noise [6].

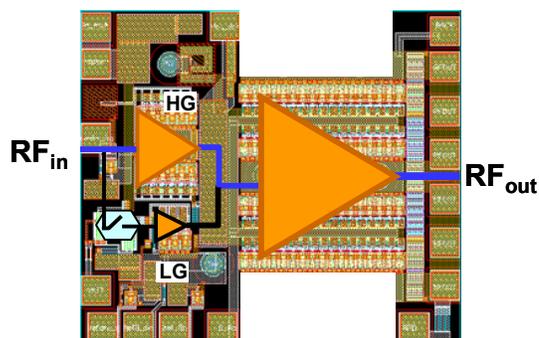


Fig 5. Layout and functional blocks of a WiMAX PA with an integrated step attenuator built in Skyworks’ BiFET process. LG and HG are low and high gain amplifiers respectively.

c) PAs with high efficiency at mid power

Reducing the average power dissipated by the power amplifier over different power levels can significantly increase the efficiency of the amplifier and thereby improve the handset talk time. Several circuit schemes were demonstrated in recent years which can be classified broadly into two categories: i) amplifier stages with integrated switches to bypass a section of the amplifier and ii) switch-free amplifier designs. In the case of switch-free amplifiers, the design either uses an external DC-DC converter [7] by which the output supply is varied in accordance with the input power level, or analog bias control to lower the quiescent bias as a function of RF drive, or with complex impedance matched main and auxiliary HBT stages [8]. In the case of designs with switches, a section of the HBT stage is bypassed either shutting off the RF path or shutting off the bias to the PA with effective power combining circuit topologies, as shown in Fig. 6. In the topology of Fig 6a, the switches have to be low loss in the ON state and high RF isolation in the OFF state, the performance which can be only achieved when the FET is placed on the Semi Insulating GaAs, underneath the HBT. In the case of merged BiFET (shown in Fig. 1), the presence of P+ base layer of the HBT prevents the device to completely shut off in the OFF state, leading to poor RF isolation. However, instead of placing the FET in the RF path, it is used to switch the bias voltage for a section of the PA in a balanced amplifier configuration (Skyworks switched LIPA™ technology). Fig. 7 shows the integrated HBT and FET cells of the switched LIPA™ output section.

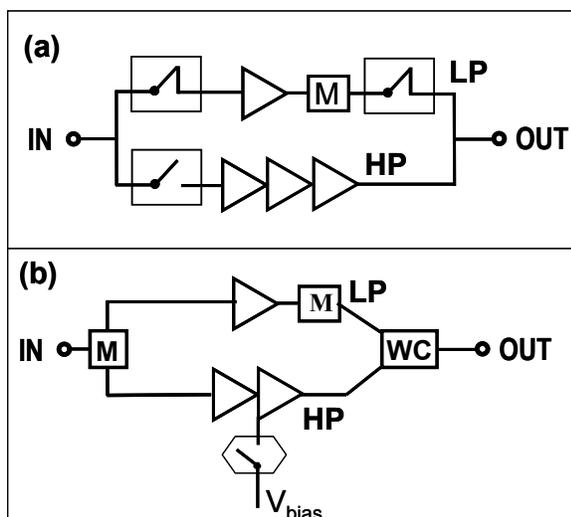


Fig 6. Bypass circuit topologies with integrated FET switch in HBT PA: a) switch in the RF path, b) switch in the DC path. M denotes appropriate matching

components and WC denotes power combiner circuitry. HP and LP are the high and low power path respectively.

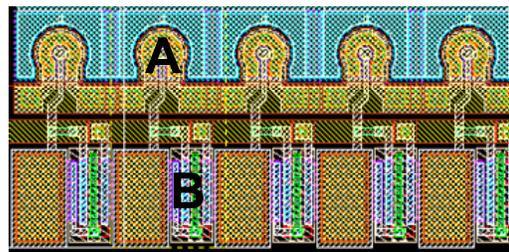


Fig 7. A portion of the circuit layout shown in Fig. 6(b), with an integrated FET in the bias path. 'A' denotes the HBT cell and 'B' is the FET.

IDEALISTIC Vs. REALISTIC VIEW ON A SINGLE CHIP FEM SOLUTION

To date, FETs in the BiFET technology are used primarily in the less RF performance demanding path of an integrated attenuator or bypass switch architecture. Modern multimode FEM architectures require complex multiple pole, multiple throw switches with stringent demand in inter modulation performance and low noise amplifiers with very low noise figures at operating frequency bands. Such diverse functional blocks, though currently fabricated in pHEMT technology, often demand optimized epitaxial materials schemes and device topologies to achieve best-in-class performance at the module level. Though a functional integration of FET/pHEMT in HBT in a single chip can lead to reduced form-factor at the module level, fabricating all of the functional blocks using a single process and material could result in sub-optimal performance. On the other hand, MCM technology provides a better solution to the problem of incorporating various functions, when advanced packaging solutions are readily available at low cost. State-of-the-art, internal assembly manufacturing facilities can offer MCM performance with high yields and a cost effective manufacturing solution. An example of a WCDMA PA and a pHEMT based switch to achieve the stage-bypass in a 4x4 form-factor without sacrificing performance or size, is shown in Fig. 8.

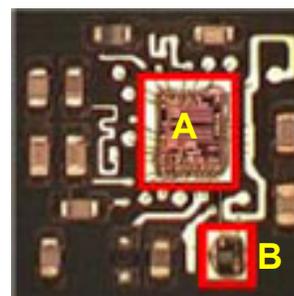


Fig 8. Open Panel of a WCDMA MCM with a pHEMT switch (B) and BiFET based PA (A) where the FETs are used only in the bias control.

Another compelling reason against complex single chip integration is yield and subsequent cost. In general, GaAs fabrication line defect densities are an order of magnitude higher than that of advanced silicon fabrication, including the particle density of the starting epitaxial material. Complex antenna switch modules and low noise amplifiers built using the pHEMT devices require on-wafer RF tests and yield loss is associated with both process defects as well as parts outside the performance window. In addition, very poor correlation exists between the limited DC PCM tests and die level RF test. On the other hand, amplifiers built using InGaP HBT devices require on-wafer DC tests for die sort and yield loss is, more often associated with metal bridging, leakage and only an extremely low percentage of failures are due to functional performance deviations. With the added complexity in characterizing the integrated FET and HBT epitaxial layers independently, overall yield of the BiFET technology based products is a product of functional test yield, which is proportional to the integration complexity, and random process yield which depends on the critical die area, and will be lower as the device/process integration complexity increases. Fig. 9 is the contour plot of normalized percentage cost increase of a discrete 4mm x 4mm CDMA PA with 8, 0201 form factor components, and illustrates the importance of functional test yield and die sort yield in achieving the lowest fabrication cost.

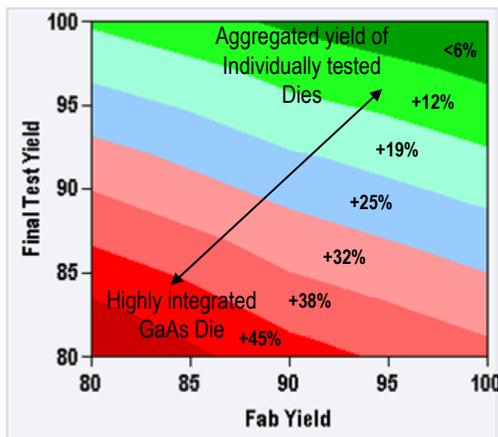


Fig 9. Contour plot of normalized cost of a 4x4 mm CDMA PA with higher mid power efficiency. The insets show the percentage increase in cost with reduction in final test yield and fab yield.

CONCLUSION

BiFET technology using a merged HBT and FET approach is shown to adequately support the PA products with complex bias functions, as evident by the

release in the past year of several PA and FEM products such as WiMAX FEM with integrated step attenuators, Switched load insensitive power amplifier (LIPA™) for improved mid power efficiency, WLAN PAs with integrated bias controls.. With in-house assembly manufacturing capabilities and an independent package development roadmap, a MCM based approach is chosen where integration of other complex switch functions and/or high performance LNA integration are deemed necessary to achieve a desired module functionality and performance.

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ACRONYMS

PA: Power Amplifier

HBT: Heterojunction Bipolar Transistor

FET: Field Effect Transistor

FEM: Front End Module

BiFET: Monolithically Integrated Bipolar HBT and FET

MCM: Multichip Module

