

# InGaP-Plus™: Advanced GaAs BiFET Technology and Applications

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## Abstract

The InGaP-Plus™ BiFET technology has been developed at ANADIGICS for high volume production of commercial MMICs. The vertical integration of the InGaP HBT and the pHEMT on the same 6 inch GaAs epitaxial wafer allows independent optimization of each device for a given application. This is possible since the only shared epitaxial layer among those of the HBT and pHEMT structure is a heavily n-doped layer located between the HBT and the FET structure. Otherwise, the process flow has been developed to minimize cost and maximize yield. The InGaP-Plus™ BiFET technology allows greater integration of the various dc and rf functions required in front end modules on a single chip.

## Introduction

In wireless circuit applications, the front end circuitry is generally comprised of the power amplifier, receiver, and antenna switching functions. For the power amplifier (PA), the InGaP HBT is firmly established as the technology of choice due to its excellent performance and manufacturability at low cost. Likewise, for wireless switching applications, the pseudomorphic HEMT (pHEMT) is widely accepted for its low insertion loss and broadband performance. The front end receiver circuitry relies on a low noise amplifier (LNA) which typically is achieved using pHEMT technology. These functions are typically realized on individual GaAs IC chips and bundled together into a front end module (FEM). The relentless drive to shrink board space, lower cost, increase functionality and improve yields is creating opportunities to consolidate these functions into fully integrated Front-End ICs.

Monolithic integration of HBT and pHEMT on the same chip have been reported in the literature [1-3]. However, these approaches suffer various shortcomings, such as limited FET performance where the FET structure was not separate from the HBT, or complicated and costly epi re-growth approaches. Recently, we introduced the InGaP-Plus™ technology for high volume manufacturing of hand set PAs using a low cost and high yield approach [4,5].

In this paper, we review the development of InGaP-Plus™ technology currently in production for high volume applications. The first is the High Efficiency at Low Power (HELP) PA application used in wireless handsets. The second application is the highly integrated Front-End IC (FEIC) for Wireless Local Area Network (WLAN) applications. The InGaP-Plus™ technology underlying these applications is setting the standard for state-of-the-art rf GaAs products in terms of performance, integration, and low cost manufacturing.

## InGaP-Plus™ Epi Structure

One variation of the InGaP-Plus™ is shown schematically in Figure 1. Also referred to conceptually as a BiFET technology, InGaP-Plus™ represents the vertical integration of the InGaP HBT and a high performance Field Effect Transistor (FET), grown epitaxially on a semi-insulating GaAs substrate. Importantly, each device structure may be independently optimized to achieve their best performance. In the examples reported here, the FET is a pseudomorphic High Electron Mobility Transistor (pHEMT). The pHEMT is grown below the HBT structure. The HBT and pHEMT share a single highly doped n-type GaAs layer which serves as the cap for pHEMT and as the sub-collector for HBT.

One implementation of the InGaP-Plus™ BiFET technology is illustrated schematically in Fig. 1. In this implementation the FET device utilizes a double-recess pHEMT epitaxial structure combined with a plated T-gate process. The advantage of the T-gate is low gate resistance as well as lower parasitic source resistance, resulting in a device suitable for low noise applications. This BiFET structure is used in ANADIGICS WLAN FEIC applications. Another implementation of the InGaP-Plus™ BiFET (see Ref. [5]) utilizes a single-recess pHEMT epitaxial structure, together with an evaporated gate process. That structure is used in ANADIGICS HELP PA products where the FET is used primarily as an rf switch

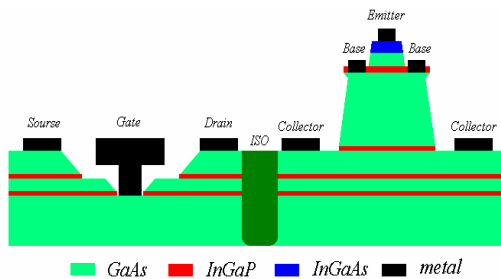


Figure 1). Schematic of ANADIGICS InGaP-Plus™ with T-gate FET option.

Both BiFETs utilize the InGaP HBT for the power amplifier function. After completion of pHEMT layers, a highly doped GaAs contact n-layer with optimum thickness is grown on top of the etch-stop layer and serves as the cap layer of pHEMT and the subcollector layer of the HBT. The rest of the InGaP HBT structure layers are grown next. An n-type collector is grown on top of the subcollector followed by a p-type GaAs base layer and an n<sup>-</sup> InGaP emitter layer. A highly doped InGaAs is grown as emitter contact layer.

### InGaP-Plus™ Fabrication Process

The major InGaP-Plus™ process steps are as follows. The process begins by formation of the emitter ohmic contact using evaporation and lift-off. Emitter mesa is defined using photoresist mask and selective wet etch of the emitter cap. Next, the base ohmic contact is formed by selective wet etch of InGaP emitter layer and evaporated metal lift-off. Base mesa is defined next by selective wet etching of the collector layer using photoresist mask. A nitride

passivation layer is deposited by PECVD on the wafer to protect the HBT device during subsequent process steps. Helium ion implantation is used to provide electrical isolation between HBTs, pHEMTs and other active and passive devices. The isolation resistance achieved in the InGaP-Plus™ process is similar to the stand-alone HBT process with no degradation. After the isolation step, the collector ohmic contact of the HBT and the source/drain ohmic contact of the pHEMT are formed in one step using standard AuGe/Ni metalization and alloy. At this point the intrinsic HBT device fabrication is completed.

Prior to the gate formation, a recess area is defined by photoresist and selective wet etching. The pHEMT gate is formed using either an evaporated gate process (switch FET) or a plating process (LNA FET). The evaporated FET is straightforward and has been described in [4]. In the T-gate case, the foot of the gate is defined in resist and a gate recess is achieved through this resist to an etch stop below the recess surface. A plating “seed” metal is sputtered on the wafer and a second photo resist is patterned to allow plating up of the T-gate. Finally, the seed metal and resists are removed in appropriate etch and strip processes. After the gate formation, the wafers are passivated with a PECVD deposited silicon nitride film.

The remaining process steps are to form the passive elements (MIM capacitors, inductors, NiCr resistors and interconnect metals) and final passivation. In one of the present applications (FEIC), we added an additional thick metal interconnect layer in order to achieve very high Q inductors. This interconnect is similar to the others (formed by plating thick air-bridge layer of metal) but the Au metal thickness is approx. 6um. Finally, upon completion of the frontside processing, the wafer goes through the standard backside via process and die separation.

### InGaP-Plus™ Device Characteristics

The current-voltage and transfer characteristics of the InGaP-Plus™ low noise amplifier pHEMT are shown in Figs. 2 and 3. The IDSS current (at Vgs=0V) is roughly 250mA/mm and Id reaches 400 mA/mm at Vgs=0.4. The pinch-off voltage (defined at 5% of IDSS) is about -0.73V. The output characteristics are relatively smooth and kink free. The transconductance (Fig. 3) is also a smooth function and reaches a peak value of roughly 400 mS/mm near Vgs=0V. For low

noise applications, a typical bias point of the FET is about 1/3  $I_{Dss}$ , corresponding to a  $V_{gs}$  of -0.4V and where  $G_m$  is still quite high (350mS/mm). The breakdown voltage (not shown) is greater than 8 V.

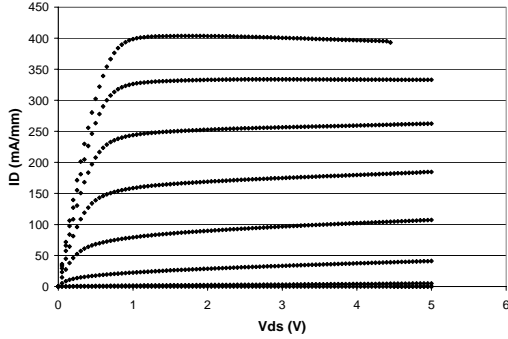


Figure 2. Current-Voltage curves of InGaP-Plus™ LNA pHEMT from  $V_{gs} = 0.4V$  to  $-1.0V$  ( $-0.2V$  steps).

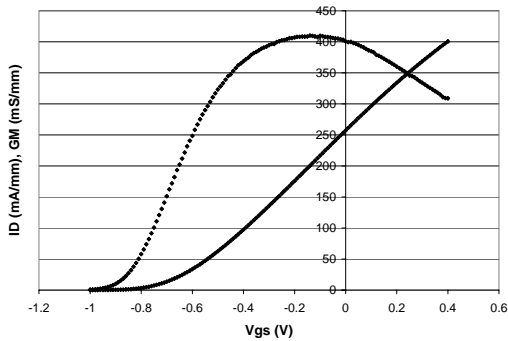


Figure 3. Transfer curves of InGaP-Plus™ LNA pHEMT at  $V_{ds} = 3V$ .

The noise and gain characteristics of the LNA FET were measured at 2.4 and 5.5 GHz and are shown in Fig. 4. At 35%  $I_{Dss}$ , the  $F_{min}$  is 0.19 dB and 0.53 dB, resp. at 2.4 and 5.5 GHz. The corresponding gains are 18.6dB and 14.8 dB.

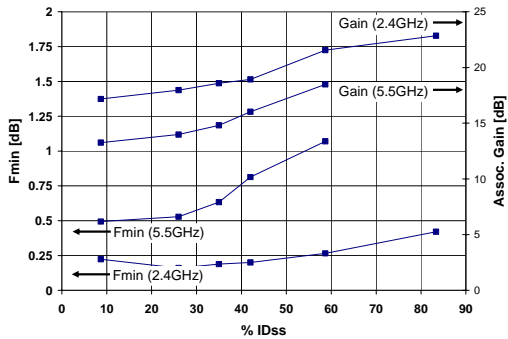


Figure 4. Noise and gain characteristics of the InGaP-Plus™ LNA pHEMT.

## ANADIGICS' HELP™ PA

One very successful application of InGaP-Plus™ is in the HELP™ (High-Efficiency-at-Low-Power) family of CDMA and WCDMA power amplifiers. These power amplifiers are noteworthy because of their high power added efficiency at moderate output power levels - >20% as compared to <9% at  $P_O = 16dBm$  for typical HBT PAs. In a HELP™ PA, RF switches on the die are used to switch between the high power and low power paths as illustrated schematically in Figure 5.

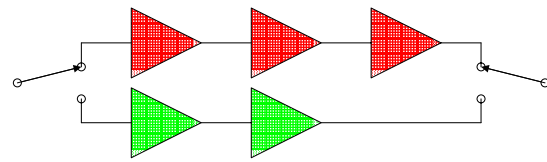


Figure 5. A schematic showing the concept utilized in ANADIGICS' HELP™ PAs. RF switches fabricated using pHEMTs are used to switch the input signal to either the high power path (with good efficiency at high power levels) or the low power path (optimized for good efficiency at low powers) depending on the demands placed on the PA.

Depending on the demands placed on the PA for a given power, the path with the higher efficiency is selected. Figure-6 illustrates the substantial current saving for urban power distribution profile through use of the various generations of HELP™ power amplifiers.

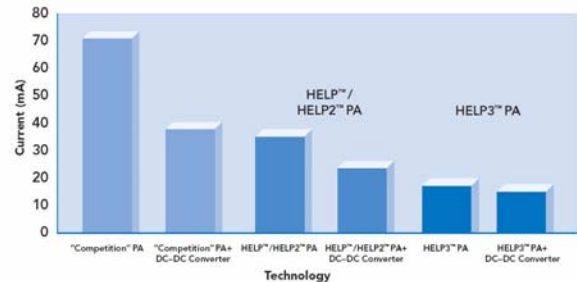


Figure 6. Simulated data showing the reduction in PA current consumption through use of ANADIGICS' HELP™ PA (the four bars on the right) compared to conventional CDMA PA and the PA module with DC-DC converter.

## InGaP-Plus™ Front End IC for WLAN Applications

The InGaP-Plus™ process allows several creative new circuit functions to be implemented. These lead to improved efficiency and better linearity, both of which are critical to handheld or portable electronic products with high data rates. Combining circuit functions onto a single die allows for much tighter control of the RF impedances, which is critical for the source matching of LNAs or load matching of PAs. An example of a product implemented in this technology is the AWL6254, shown in the block diagram of Figure 6.

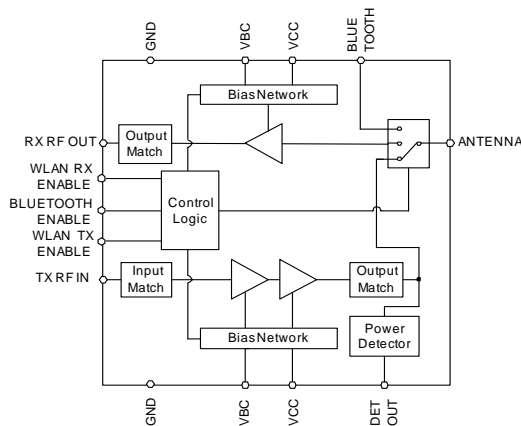


Figure 7: The AWL6254 includes PA, LNA, Switch, Detector functions, and control logic which interfaces directly with CMOS logic levels.

The AWL6254 operates from a single 3.6 V supply, and requires only a single off-chip bypass capacitor. The AWL6254 is a single band product in volume production operating from 2.4 to 2.5 GHz. The EVM and current vs power characteristics are shown in Fig. 8. Dual-band devices which support the 802.11 a/b/g/n standards are in development and have been demonstrated in the laboratory with no significant issues.

### Conclusion

InGaP-Plus™ is a high performance 6 inch GaAs BiFET technology in which both the FET and the HBT can be independently optimized for specific applications including high efficiency power amplifiers and highly integrated front end ICs for WLAN applications. The advantages of

InGaP-Plus™ include greater integration of active and passive devices on a single chip.

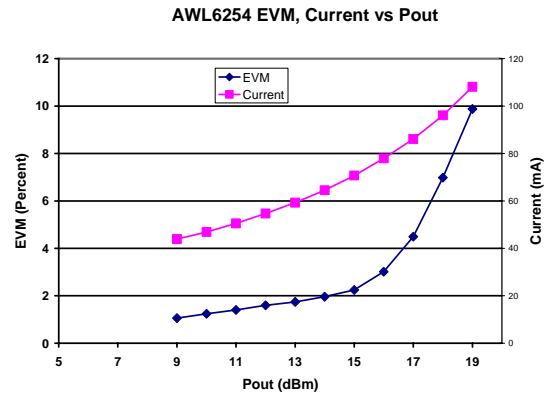


Figure 8: Error Vector Magnitude (EVM) and current vs outout power for the AWL6254.

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