GAAS® 97 • 5th European Gallium Arsenide and related III-V compounds Applications Symposium
Bologna, Italy - September 3rd-5th, 1997

GaAs Device Technologies for Wireless Communication

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Abstract

GaAs devices have been used in the wireless communication systems such as terrestrial, space and mobile communication. New systems for more convenient life are planned to utilize continuously GaAs devices. In this paper described are device technologies of HEMT, HBT and MESFET and in addition the discrete device, hybrid IC and monolithic IC are discussed for several applications.

1. Introduction

Due to an increased demand for personal communication, a point to multi-point type wireless communication has been widely used in the world. Digital cellular system is the interactive point to multi-point system which is becoming more and more popular in Europe, North America and Japan. In the other countries the digital cellular system has been chosen as a network infrastructure instead of conventional fiber or point to point radio because of lower cost and easiness of installation.

Modern communication network is required to transport not only voice but also data and motion video. Recent development of Internet is enhancing the need for high capacity point to multi-point communication network. Two new systems are proposed to respond to the need. One is a satellite communication where millions of subscribers are able to communicate using quasi-millimeterwave frequency. Another system is LMDS, which is often called "Wireless CATV". It is a cellular type network which can realize interactive communication with lower cost than CATV. The frequency to be used is quasi-millimeterwave or millimeterwave.

The future communication network requires much higher capacity and access from anywhere, at anytime is desired. As the compatibility with optical fiber network will be necessary, the network has to have the bit rate above 100 Mbit/s. Due to an advantage of broadband the millimeterwave wireless LAN has been proposed and being developed.

2. Device performance requirements

Digital Cellular

The major system architectures employed in the world are GSM, PDC and CDMA. As GSM system employs GMSK (Gaussian-filtered Minimum Shift Keying) modulation scheme, it does not need linear amplification. Silicon MOS power transistor was chosen in GSM and analog systems because of its low cost and no negative voltage. However, other systems employing $\pi/4$-shift QPSK or CDMA requires linear amplification to avoid interference to adjacent channel. The key RF device used in the handset is a power amplifier because the linearity and power consumption of the system is mainly determined by it. Lower voltage operation is also preferable because it enable to use Lithium-ion or the reduced number of battery cells and makes phone small and light weight.

The power amplifier for the base station has to provide with high output power capability because it needs to amplify peak envelope of multi-carrier signal. As superior intermodulation performance and lower power consumption is necessary, class AB operation and the feed forward error correction or predistortion technique are usually applied.

Satellite Communication, LMDS and millimeterwave LAN

RF devices required for these applications are high power amplifier (HPA), low noise amplifier (LNA), mixer, voltage controlled oscillator (VCO), switch and phase shifter etc. In millimeterwave area, there are few devices commercially available because most of the effort had been done mainly for defense application. To realize commercial millimeterwave

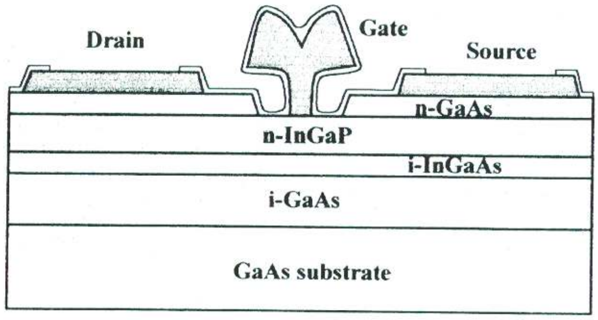

Figure 1 : InGaP/InGaAs/GaAs HEMT

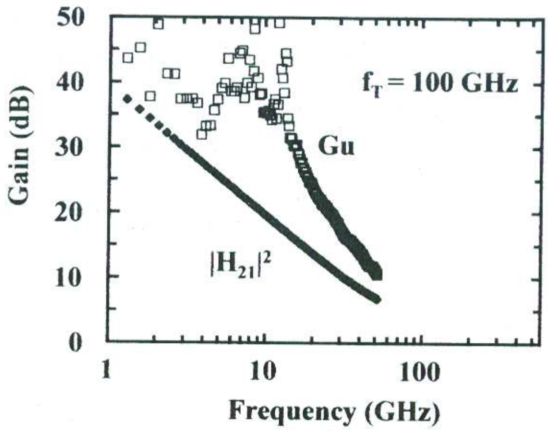

Figure 2 : Typicasl characteristics of InGaP/InGaAs/GaAs HEMT

devices is highly challenging because high performance, low cost and high volume production have to be realized simultaneously. From the performance view point, high gain and consistency are more important.

3. Device Technologies

In this section, the development of our device technology is described. Topics are HEMT for millimeterwave applications, HBT and enhancement mode-MESFET(E-FET) for high power amplifiers for cellular telephone handsets.

HEMT

HEMTs have been used in low noise amplifiers of telecommunication systems and direct broadcasting satellite systems(DBS) at X-band. The n-AlGaAs/i-GaAs heterostructure was used most of the pioneering work on HEMTs [1]. The latest target is in Ka to W-band, such as space communication, millimeter wave LAN and collision avoidance system. Pseudomorphic HEMTs (P-HEMTs) are increasingly gaining importance in the domain of high frequency applications. InGaAs is used as an alternative to GaAs channel. The electron mobility and saturation velocity are improved with increasing indium mole fraction in the channel. InGaAs is not lattice matched to GaAs but the channel layer thinner than a critical thickness can be accommodated by coherent layer strain. Common P-HEMT structures are AlGaAs/InGaAs/GaAs where In mole fraction is 15%.

Device size scaling is another way to improve HEMT characteristics sufficient for these applications. Figure 1 shows our P-HEMT structure with T-shaped gate. The gate was patterned by electron beam lithography. The n-GaAs/n-InGaP/i-InGaAs/i-GaAs epitaxial layers were grown by MOCVD. Thanks to the high doping in the InGaP layer, the distance between channel and gate can be reduced comparing to the conventional AlGaAs/ InGaAs/GaAs P-HEMT [2]. This structure, thus, suppressed the short channel effect even for fine gate lengths. Our P-HEMT with gate length of 0.15 μm has a cut-off frequency of 100GHz and a maximum oscillation frequency of 200GHz. Figure 2 shows the typical characteristics, which is sufficient even for the applications at millimeter wave domain.

HBT

Heterojunction bipolar transistors (HBTs) are one of the most promising devices for high-power microwave amplifiers in future mobile communication systems due to their superior power features, such as high-efficiency and low-distortion characteristics even at low-bias voltage with only single supply [3]. Moreover, InGaP/GaAs HBTs have several advantages over the conventional AlGaAs/GaAs HBTs such as their smaller knee voltage due to their smaller collector-emitter offset voltage of less than 0.1 V and higher reliability even at a high current density. The large current handling capability enables high output power with a low supply voltage at a low cost [4-5]. InGaP/GaAs HBT is a suitable device for high power amplifiers in

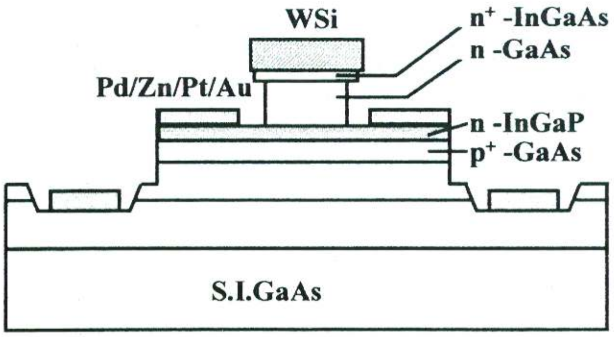

Figure 3 :Cross-sectional Structure of InGaP/GaAs HBT

future digital mobile communication systems.

The InGaP/GaAs HBT structure grown by MOCVD consists of an n^+-InGaAs cap layer, an n-InGaP emitter layer doped with silicon to carrier density of 3 $\times 10^{17}$ cm^{-3}, a p^+-GaAs base layer doped with carbon to carrier density of 3 $\times$ 10^{19} cm^{-3}, an n/i-GaAs collector layer and an n^+-GaAs sub-collector layer (Figure 3). As an emitter electrode WSi was sputtered on the n^+-InGaAs cap layer. Pd/Zn/Pt/Au base metal was evaporated on the InGaP emitter layer. The base ohmic contact was formed through the thin emitter layer by annealing. This specific device structure where the emitter-base heterojunction is fully covered with the emitter layer proves the high reliability. A ballasting resistance of 2.5 ohms ia used in each 2 μm × 20 μm emitter area of the HBT to provide thermal stability [6]. All emitters are connected through via holes to a plated Au layer on the backside of the substrate thinned to 28 μm.

The DC and RF measurements were performed on a fabricated HBT with an emitter area of 2 μm × 20 μm. The collector emitter offset voltage is 80 mV which is 0.1 -0.3 V lower than that of the AlGaAs/GaAs HBT. The breakdown voltage at an open base BV_{ceo} is 14 V. The f_T and f_{max} of the InGaP/GaAs HBT are 40 and 110 GHz respectively at a collector current of 16 mA and a collector bias of 3.5 V.

The multi-finger power HBTs offer high-efficiency and low-distortion power characteristics at low operation voltage. Measured output power of the HBT with an emitter size of 2 μm × 20 μm x 64 fingers is 34.3 dBm with a power added efficiency (PAE) of 57.7% at 1.5 GHz and at a collector bias of 3.5 V. Even at lower bias voltage of 2.5 V, the HBT

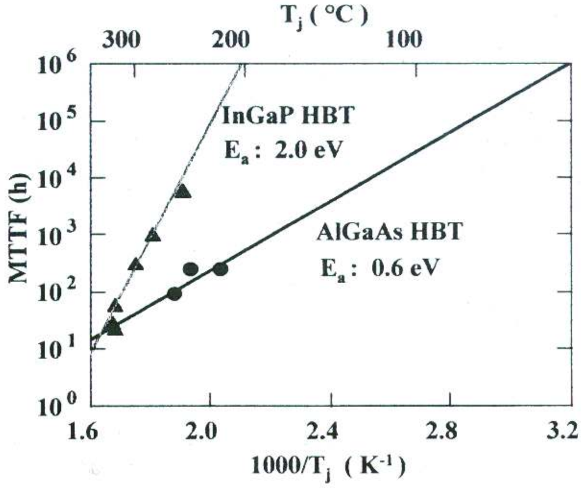

Figure 4 : Dependence of the time to failure on the junction temperature of InGaP/GaAs and AlGaAs/GaAs HEMT

indicates an output power of over 31 dBm [5]. For 1.5 GHz π/4-shift QPSK modulated signal, an ACP at a 50 kHz offset frequency is -49 dBc with a high PAE of 56% and an output power of 31 dBm under a supply voltage of 3.5 V [6].

The InGaP/GaAs HBTs have much higher reliability than AlGaAs/GaAs HBTs (Figure 4). In the case of our AlGaAs/GaAs HBTs, their current gain, β, gradually decreased, then catastrophically degraded (i.e., after 200 hours at 150°C) [4]. After degradation, the device exhibits an increase in base current which has an ideal factor n∼2 in the Gummel plot. The activation energy, E_a, for the degradation was estimated to be 0.6±0.1 eV. On the other hand in InGaP/GaAs HBTs comparatively longer mean time to failure (MTTF) than in AlGaAs/GaAs HBTs was obtained. No significant reduction in β was observed under a bias stress of more than 1,000 hours at an ambient temperature of 150°C. The estimated MTTF was 10^6 hours at a current density of 6 × 10^4 A/cm^2 and a junction temperature of 200°C with higher E_a of 2.0±0.2 eV. The InGaP/GaAs HBTs show sufficient reliability for actual system application.

E-FET

The trends of cellular telephone handset to higher frequencies, to lower voltages and to digital systems which require highly efficient and linear amplifiers. Obstacles for GaAs is negative voltage supply. The

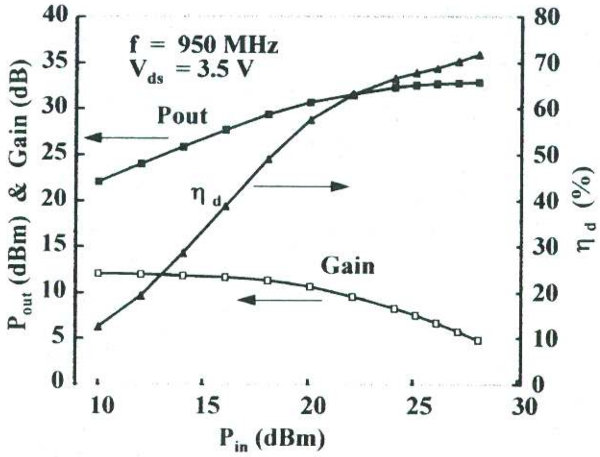

Figure 5 : P_{out} vs. P_{in} performance of E-FET

negative voltage supply requires additional circuits such as DC-DC converter and drain current switch which further increases product cost, weight and current drain.

We had already developed E/D HEMT technology for digital circuit applications. We combined E-HEMT technology and HFET technology and developed E-FET which reduced its Schottky leakage current improving linearity and power added efficiency with high dynamic range.

The E-FET technology was applied to PA modules for PDC and GSM MMICs. The threshold voltage and turn on voltage are +0.25 V and 1.6 V. These allow RF swing of 1.1 V before gate leakage occurs. The I_{fmax} is 180 mA/mm. The leakage current at V_{ds} of 3.5 V and V_g of 0 V is less than 0.1 mA/mm. Figure 5 shows the resultant RF performance at 950 MHz. These performance of this single voltage device well exceed the state of the art Si MOS FETs.

4.Device Configuration

Microwave device configuration is classified into three categories, i.e. discrete packaged device, hybrid IC or module and monolithic IC. These three types of devices are suitably adopted depending on their applications. The final decision is made in terms of their cost. The features of these forms are summarized in the Table 1. The frequency range is considered in UHF through Ku-band. In millimeter-wave region monolithic IC is preferable. In this section, the latest technologies are presented for the each device form.

Discrete Device

The most reasonable application area of the discrete FET is a high power amplifier at L-band (base station of mobile communication) and C-band (terrestrial communication and satellite communication). A good example of this area is a push-pull FET technology. The most difficult problem on the high-power amplifier is to make impedance matching maintaining the desired frequency band, because the FET impedance becomes very low compared to 50 Ω. Push-pull circuit has been well known circuit form to overcome the problem especially for MOSFET at VHF and UHF bands. A twin FET for push-pull

Device Form	Advantage	Disadvantage
Discrete	• High power and low noise (device selection could be possible) • Basically standard device: wide range of application	• Customers need to design the circuits considering reliability issues (thermal and mechanical) • Size of circuits is large
Hybrid IC	• Performance is optimized for specific application (drop-in mounting) • Small size and light weight • Short development cycle time • Differently processed chips can be used (MCM)	• Not possible to tune • Need to care about technologies of many components (reliability, cost etc.)
Monolithic IC	• Smallest size lightest weight • Functions and performance are optimized for specific application	• Long development cycle time and large NRE cost • Performance is compromized for better yield.

Table 1 : Comparison of device form

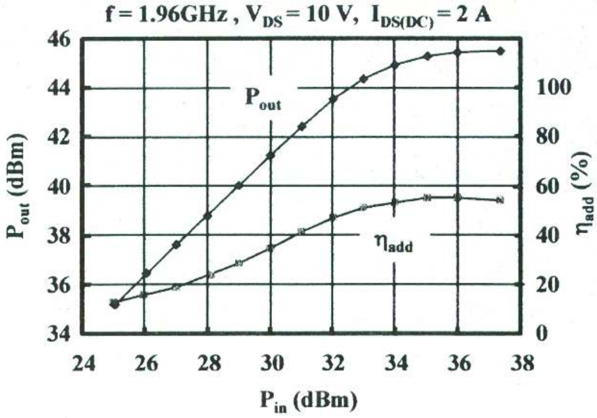

Figure 6 : Pout vs. Pin characteristics of push-pull FET

amplifier operating at 2 GHz band was developed. The impedance at the input and output ports of each FET are transformed to 25 ohms by balun, making the impedance matching easy. The Pout vs. Pin performance is shown in Figure 6. The device achieves 1dB-compression output power of 44.5 dBm and gain of 10 dB at 1.96 GHz. It is an advantage of discrete approach to combine/divide microwave power using simple component such as balun, coupler etc.

Hybrid IC

Power Amplifier (PA) modules using hybrid IC technologies have been used in handyphone. A very small and light PA module was developed for PDC. The package has multi-layer PCB based LCC structure and its weight and volume are 0.5 gr and 0.2 cc (10 mm × 10 mm × 2 mm) as shown in Figure 7. The module contains two-stage FET amplifier including matching circuits. The impedance matching elements are small chip capacitors and resistors. The interconnections and inductive elements are fabricated in the inter-layer of the PCB, reducing the area. Two FETs are mounted on one PCB utilizing MCM technology. E-FET technology is applied the FETs used. The module shows 53% of efficiency under V_{DD} = 3.5 V at 940-958MHz. This PA module has a very complicated structure and costly but its characteristics are well defined then users of the device do not need to care about the performance and assembly and tuning cost are minimized. Figure 8 shows the ACP characteristics of a two stage PA

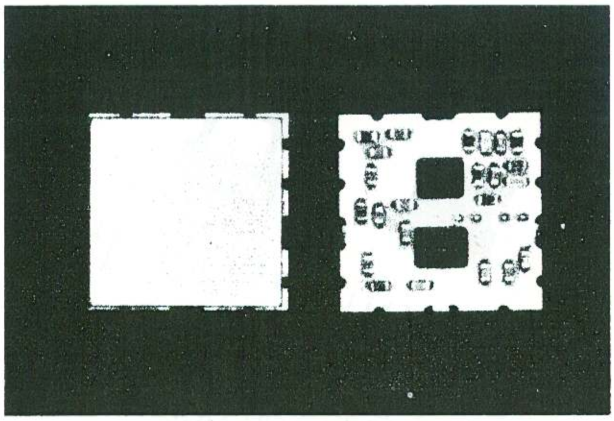

Figure 7 : Outline of 0.2 cc PA

module for PDC system handsets at 1429 MHz. The device exhibit PAE of 52% and ACP less tan -50 dBc at 30.5 dBm output.

Monolithic IC

Ten years ago microwave device engineers might almost think that discrete FET and hybrid IC were to be replaced by MMICs. But it was not true. The key item for deciding the device has become only cost not performance. Discrete FET, hybrid IC and MMIC have each share from the cost point of view. The discrete HEMTs are still used in DBS LNB and any low noise MMIC cannot replace them because of the reason. In handyphone PA market there is a struggle between hybrid IC and MMIC. The hybrid approach is mentioned above. An MMIC for GSM was developed [7]. The MMIC consists of three E-mode FETs and interstage circuits. Final stage circuit is put out due to cost and performance point of view. MMIC itself is small, one-third of area

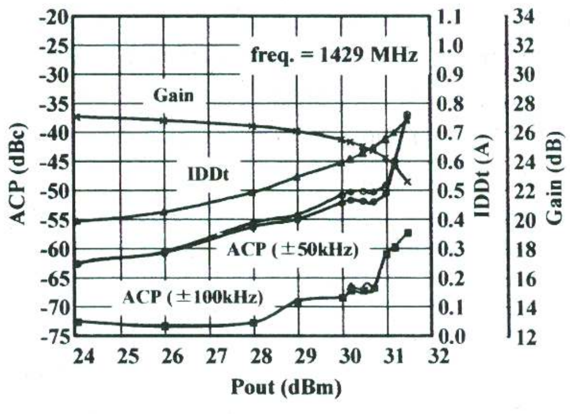

Figure 8 : ACP characteristics of 0.2cc PA

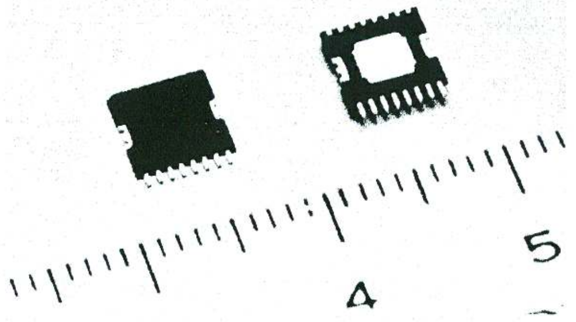

Figure 9 : Outline of PA MMIC

compared to hybrid IC shown in Figure 9. The package has SSOP-16 compatible outline and naked base metal for ground and heat path.

The last example is 60 GHz receiver MMIC. MMIC is only one solution at mm-wave frequencies. External or off-chip impedance matching does not work at this region. Figure 10 shows 60 GHz one-chip receiver MMIC for LAN [8]. The MMIC utilizes InGaP/InGaAs /GaAs pseudomorphic HEMT and achieves noise figure of 4.9 dB and conversion gain of 17 dB at 60 GHz. The MMIC is mounted on metal chip carrier with alumina I/O substrate. Tiling the MMICs on the base, a receiver system is formed.

5. Summary

The GaAs devices are getting more and more important in wireless communication systems. MESFET performance has been improved and the enhancement mode MESFET enables to be operated with single bias supply. HBT showed good RF performance and reliability data it will play an important role in a cellular telephone handset. In millimeterwave system P-HEMT is key device because of its high gain characteristics. Discrete device, hybrid IC and MMIC will keep their own positions for minimum cost depending on the usage.

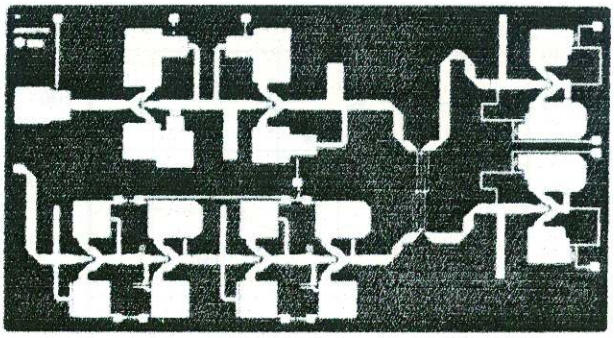

Figure 10 : 60 GHz one-chip receiver MMIC

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