An InGaP/GaAs Collector-up Tunneling-collector HBT and Sub-transistor Via-hole Structure for Small and Highly Efficient Power Amplifiers

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Abstract — **A novel structure of InGaP/GaAs collector-up tunneling-collector heterojunction bipolar transistors (C-up TC-HBTs) with sub-transistor via-holes, for use in small power amplifier, is presented. Having the via-holes directly under the C-up HBTs is convenient in terms of thermal conduction; power amplifiers composed of multi-finger HBTs in this configuration take up dramatically less area than those with devices in the conventional configuration. The result was the demonstration of thermally stable operation for a 4-finger C-up TC-HBT at up to 0.9 mW/μm^2, in spite of the low finger pitch of only 15 μm. Moreover, a small 32-finger C-up TC-HBT, with a total area of 0.25 x 0.31 mm, was capable of delivering a power-added efficiency of 52% at 24.4 dBm in wide-band CDMA operation. These results show the strong potential for microwave application of high-efficiency power amplifiers composed of C-up TC-HBTs.**

I. Introduction

A high-power amplifier (HPA) is very useful as a component of the handsets of commercial microwave-based communications systems. The HPA usually provides control of the levels of transmitted power, and for a hand-held terminal we require the smallest device, highest levels of reliability, and most efficient use of power. Heterojunction bipolar transistors (HBTs) are promising for use as the active components of such the HPAs, due to their power characteristics at low bias voltage and their relatively high power-handling capability. Moreover, to further expand the application of HPAs composed of HBT, we need smaller devices and circuits. The miniaturization of a HPA module depends on thermal management in HBTs.

So far, the high-power application of conventional HBTs, where the emitter layer is on the surface, i.e., in an "emitter-up" (E-up) configuration, has been limited by thermal effects. Poor thermal conduction by these devices has required special thermal design measures, such as ballast resistors [1], thermal shunts [2], and wide finger spacing. However, using HBTs with such special thermal-design measures as the transistors of a high-power amplifier (HPA) module makes it difficult to design a small enough MMIC.

On the other hand, the structure of the "collector-up" (C-up) HBT [3] eases the handling of thermal dissipation. We can fabricate the emitter electrode of a C-up HBT for common–emitter-mode operation as part of a via-hole structure directly beneath the HBT. Also relevant is Mochizuki *et al.*'s development of the C-up tunneling-collector (C-up TC-) HBT, in which the tunneling-barrier layer at the base-collector junction is thin enough for electrons to tunnel through but blocks holes, providing high levels of efficiency at low levels of power consumption [4].

In this paper, we report on a InGaP/GaAs C-up TC-HBT for use in small power amplifiers, where a via-hole structure is placed directly beneath the transistor. The emitter electrode is constructed as part of this via-hole structure, producing good thermal conduction. The demonstration of thermally stable operation at up to 0.9 mW/μm^2 by a C-up TC-HBT with four 4.5 x 30-μm-collector fingers is described in this paper, along with the excellent power performance obtained with a 32-finger configuration of 4.5 x 30-μm collectors.

II. Experiments

The structure of the C-up TC-HBT on a GaAs substrate is given in Fig. 1. The process of fabricating the HBT

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Layer	Material	Thickness	Doping (cm^{-3})
Cap	InGaAs	100 nm	Si: $1.0x10^{19}$
Collector	GaAs	850 nm	Si: $3.0x10^{16}$
Tunneling-barrier	InGaP	5 nm	Si: $5.0x10^{17}$
Spacer	GaAs	20 nm	Si: $<1.0x10^{16}$
Base	GaAs	30 nm	C: $3.0x10^{19}$
Spacer	GaAs	5 nm	Si: $<1.0x10^{16}$
Emitter	InGaP	200 nm	Si: $5.0x10^{17}$
Sub-emitter	GaAs	1 μm	Si: $3.0x10^{18}$
Etch-stop	InGaP	60 nm	Si: $1.8x10^{18}$
GaAs substrate			

Fig. 1. Layered structure of the C-up TC-HBT.

consists of the following steps. Firstly, a non-alloyed metal, WSi, is laid down to provide the collector electrode and etching mask. The collector area is then formed by reactive-ion etching. A small emitter is realized by implanting B ions (at 50 keV; dose: 2 x 10^{12} cm^{-2}) through the InGaP tunneling-barrier and external GaAs-base contact area. After removing the InGaP tunneling-barrier, a Mo/Au/Pt/Ti/Mo/Ti/Pt base electrode is formed by a non-self-aligned process and the base layer is formed by wet chemical etching [4].

Fabrication of the backside emitter-electrode structure under the HBT is described with the aid of Fig. 2. Firstly, the GaAs substrate is ground down to a thickness of 50 μm. A via-hole structure which reaches the sub-emitter layer is formed underneath the HBT by wet chemical etching. Subsequently a Au/Ge/Ni emitter electrode is deposited, after which a thicker plating Au is applied. Then the electrode is heated to 370°C for 30 min to form an ohmic contact with the sub-emitter.

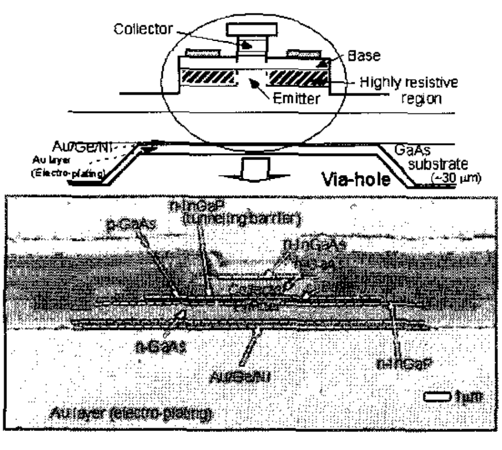

Fig. 2. Scanning-electron micrograph and schematic cross-sectional view of a C-up TC-HBT fabricated with the sub-transistor via-hole structure.

DC characteristics of the finished C-up TC-HBTs were measured by using a semiconductor parameter analyzer. RF small-signal characteristics of the devices were evaluated through S-parameter measurement. Power performance was characterized by load-pull measurements using a Wide-band- (W-) CDMA signal.

III. DC AND RF CHARACTERISTICS

Devices with 4.5 x 30 μm collectors were used in measuring the DC and small-signal characteristics of the C-up TC-HBTs

Figure 3 shows the common-emitter current-density (J_C)-voltage (V_{CE}) characteristics of a 1-finger C-up TC-HBT with the via-hole structure we have described. These characteristics confirm a V_{CE}-offset of zero, as is the case with C-up TC-HBTs that don't have the via-hole structure. This property is essential for high-efficiency in high-power amplifications [4]. The figure shows one characteristics that is improved by the new structure; the negative differential slope in the J_C-V_{CE} characteristic of the conventional GaAs HBT [5] has been eliminated,

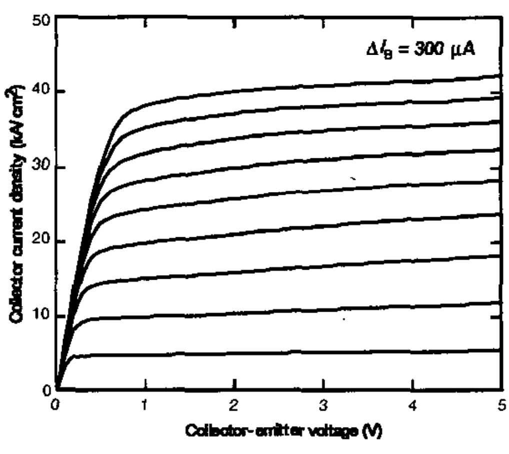

Fig. 3. *J-V* characteristics of a single-collector-finger C-up TC-HBT (4.5 x 30 μm), with base current I_B as a parameter.

even in case of high-power injection (J_C = 40 kA/cm^2, V_{CE} = 1 - 5 V). From the J_C-V_{CE} characteristics, we are able to evaluate the thermal resistance of the 1-finger C-up TC-HBT as 220°C/W; this is 60°C/W lower than the thermal resistance of the C-up TC-HBT without sub-transistor via-holes. Figure 4 shows the dependence of collector current on base-emitter voltage at different collector-emitter voltages; results are given for 1- and 4-finger C-up TC-HBTs. Here, we took the low thermal resistance into consideration in designing the 4-finger HBT with a finger pitch of 15 μm. Although a ballast resistor was not applied, no regression in the characteristic is seen at levels of power density up to 0.9 mW/μm^2. This degree of thermal stability is in agreement with the J_C-V_{CE} characteristics of Fig. 3. However, the relatively large base resistance of this device, 90 Ω (see Table I) caused by B ion implantation, may contribute to its thermal stability. Note that a conventional HBT with a comparable feature size will show current-gain collapse; that is, it will exhibit regression characteristics due to thermal instability, even at levels of power density below 0.03 mW/μm^2. The structure of our C-up TC-HBT is convenient in terms of thermal management, because heat in the HBT is directly transferred through the relatively thin emitter layer to the via-hole structure directly

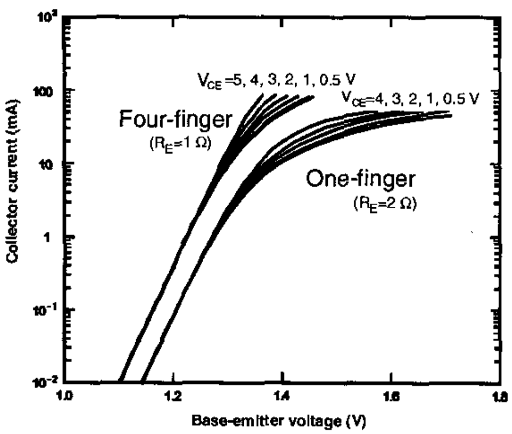

Fig. 4. Dependence of collector current on base-emitter voltage in two fabricated C-up TC-HBT with different number of fingers and collector-emitter voltages. Each finger is in 4.5 x 30 μm area.

underneath the transistor, and then to the electro-plating of Au. Therefore, this allows us to design unprecedently small high-power-amplifier modules based on C-up TC-HBTs.

Next, we investigated the small-signal RF characteristics of the 1-finger C-up TC HBT. Table I lists the device parameters. The f_T value is 30.7 GHz for J_C of 26.7 kA/cm^2 and V_{CE} of 1.0 V and f_{max} is 35.6 GHz for J_C of 45.7 kA/cm^2 and V_{CE} of 2.0 V. The RF characteristics of the 1-finger C-up HBT also reveal a low value of 56 fF for collector capacitance, only about one-third of the value for an equivalent conventional emitter-up HBT. So low a value is useful in terms of obtaining higher levels of performance in the high-frequency range.

Table I. Device parameters of a C-up TC-HBT fabricated with the sub-transistor via-hole structure.

h_{FE} (I_C = 24 mA)	38
Emitter resistance	2 Ω
Base resistance	90 Ω
Collector resistance	3 Ω
Collector capacitance (V_{CB} = 0 V)	56 fF
f_T (V_{CE} = 1.0 V, I_C = 36 mA)	35.6 GHz
f_{max} (V_{CE} = 2.0 V, I_C = 48 mA)	30.7 GHz

IV. Performance of a Power Amplifier

Advanced wireless handsets, and particularly those for W-CDMA cellular phone systems, represent one promising area of application for small high-power amplifiers based on the C-up TC-HBT. We thus demonstrated characteristics of a C-up TC-HBT with 32 collector fingers, each 4.5 x 30-μm as a power-stage amplifier for a W-CDMA RF signal. This application requires power transistors with a high power-added efficiency (PAE) and a low adjacent-channel-leakage power ratio (ACPR) over a wide range of output power levels (Pout). Figure 5 shows the results for PAE, gain, and ACPR against Pout, with the ACPR result obtained at a 5-MHz offset frequency. A high PAE of 52% was achieved with Pout of 24.4 dBm at the operating voltage of 3.1 V, where the gain was 11.9 dB, the quiescent current (I_q) was 38 mA, and the ACPR was –38 dBc. These are sufficiently comparable to the conventional power-stage amplifiers [6].

As well as providing a high PAE, the power amplifier's power stage, consisting of 32 4.5 x 30-μm fingers, is very small, occupying an area of only 0.25 x 0.31 mm. This is one-third smaller than an equivalent power stage implemented with conventional E-up HBTs. Hence, the C-up TC-HBT shows promise as the basis of the small power amplifiers of next-generation hand-held telephones, etc.

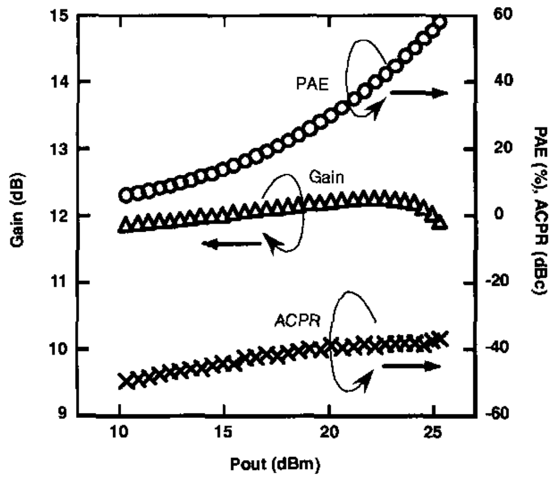

Fig. 5. Dependence on Pout of gain, PAE, and ACPR for a 32-finger C-up TC-HBT with 4.5 x 30-μm collectors; here, V_{CE} is 3.1 V and I_q is 38 mA.

V. Conclusions

We have fabricated C-up TC-HBTs that allows us to make smaller high-power amplifications; this is achieved by placing a via-hole structure directly underneath and in contact with the emitter of each transistor. The devices displayed excellent characteristics in terms of thermal management; that is, the thermal resistance of a 1-finger C-up TC-HBT was estimated as only 220°C/W and the 4-finger C-up TC-HBT demonstrated thermally stable operation at levels of power density up to 0.9 mW/μm^2, without the case of a ballast resistor. Moreover, in W-CDMA operation, a 32-finger C-up TC-HBT achieved a PAE of 52% at a Pout of 24.4 dBm. This shows that the C-up TC-HBT has a strong potential for microwave applications.

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