Direct observation of gain collapse phenomena in multi-finger HBTs using digital cameras

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Abstract

In this paper, electroluminescence (EL) from a filp-chip mounted InGaP/GaAs-HBT power amplifier chip is investigated to characterize the thermal effects. Because the EL peak energy corresponds to the bandgap energy of the GaAs base, the EL spectrum can be used to detect the junction temperature. The EL intensity increases in proportion to the collector current. Thus the current distribution among the emitter fingers can be observed in the near-infrared image of the chip. As a practical example, non-uniform current distribution under gain collapse condition is successfully visualized. These techniques provide useful information for good thermal management of power HBTs.

Introduction

GaAs-based heterojunction bipolar transistors (HBTs) are widely used for power amplifiers (PAs) due to their high linearity and high efficiency [1]. An important issue concerning PAs is prevention of thermal runaway during high power operation. In fact, a lot of works have focused on this subject. Simulation-based studies have revealed the critical condition of current hogging and calculated current distribution among fingers [2]. Experimental verifications have been carried out with some simplified test devices, such as a pair of HBTs [3]. However, few works involve observation of the current distribution in a real PA chip. Because the number of fingers in practical PA chips exceeds several tens, it becomes almost impossible to probe each current at each finger.

In this paper, we propose a new method to characterize the thermal effects of flip-chip mounted HBT PAs by using electroluminescence (EL) from emitter-base junction as a probe of current. By analyzing the EL, we can obtain important information on PAs such as junction temperature and finger current. A very simple method using a digital still camera visualizes the current distribution in an HBT PA chip. Non-uniform current flow near critical condition of thermal runaway can be successfully detected by this method. This image will be useful for improving the thermal management of HBT-PAs.

Electroluminescence from GaAs HBTs

In this paper, we focus on a flip-chip mounted HBT-PA. Because the semi-insulating GaAs substrate is transparent to the EL from the heavily doped GaAs base ($p=4E19cm^{-3}$), we can observe the EL through the substrate.

The PA chip was designed to emit 34 dBm RF power at 900MHz. The output stage was composed of 128-finger InGaP/GaAs-HBT. The total emitter size was 15400 μm^2.

First, we investigated the EL spectrum and intensity. Figure 1 shows the EL spectra for collector currents Ic from 200mA to 500mA (@V_{CE} = 2V). The EL integrated intensity increases in proportion to the collector current (Fig.2). This indicates that the light emission intensity reflects the current flow distribution at the multi-finger HBT.

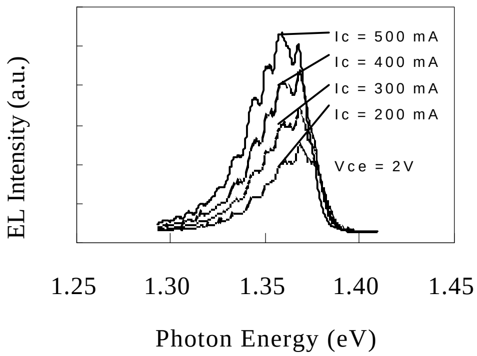

Figure 1 EL spectra for Ic from 200mA to 500mA

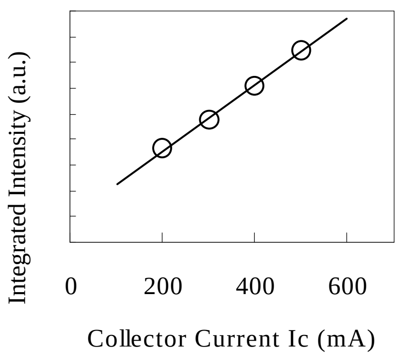

Figure 2 Collector current dependence of integrated EL intensity

The photon energy also changed as a function of Vce as shown in Fig. 3, because of the junction temperature change. Plural peaks appear in each spectrum due to multi-reflection. Here we use the energy of the spectral peak of highest energy (hí$_p$) as the representative energy of each spectrum, as indicted by arrows in Figs 3.

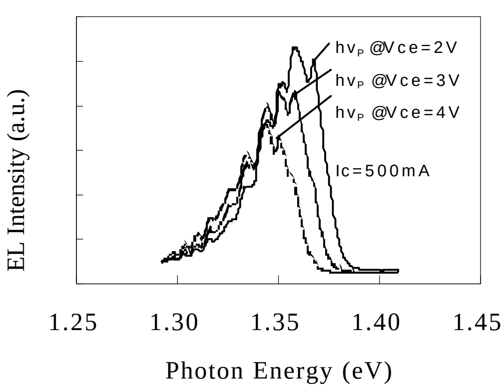

Figure 3 EL spectra for Vce from 2 V to 4 V (@ Ic= 500 mA)

Figure 4 shows the hí$_p$ as a function of dc power consumption (Pc=Ic*Vce). The hí$_p$ is almost proportional to the Pc and its slope (ö) is -1.76E-2 eV/W. As the temperature coefficient of the bang-gap of GaAs (è = dEg/dT) is about -4.6E-4 eV/K at RT, the thermal resistance Rth can be estimated to be ö/è= 38 K/W. This value agreed well with that derived from Dawson's method (36 K/W) [4]. Because we can assume that the hí$_p$ at ambient temperature should be equal to the y-axis intercept of Fig. 4, the junction temperature (Tj) is given by

$$T_j = T_{amb} + \left(h\nu_0 - h\nu_p\right)\cdot\theta^{-1} \qquad (1).$$

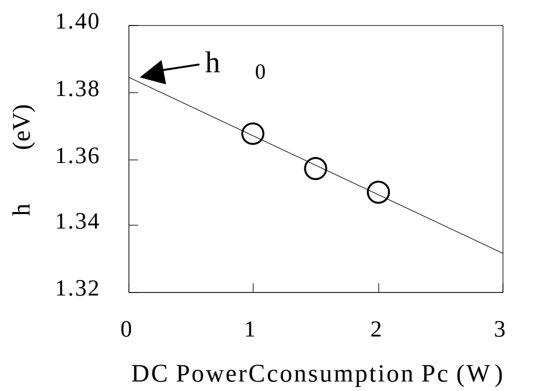

Figure 4 DC power dependence of spectral peak energy í$_P$

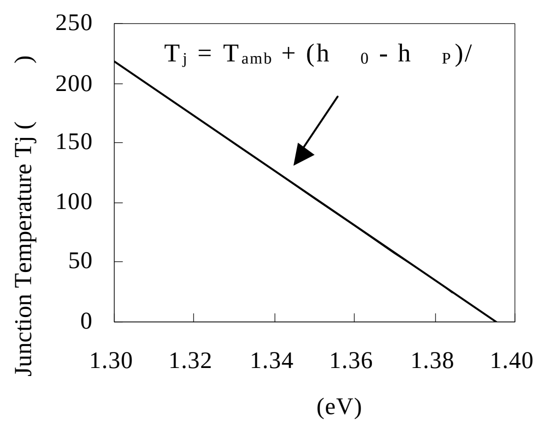

Figure 5 Junction temperature Tj as a function of hí$_p$

Then, we can estimate the junction temperature as a function of hí$_{p}$ as shown in Fig.5. In the application of the infrared thermal imaging technique to flip-chip mounted PAs, the difficulty of correction of emissivity arises. Although the IR is emitted from the heated junction, its intensity is strongly disturbed by metal pattern existing underneath the junction. The conventional black painting method is not applicable to the flip-chip mounted PAs, because the target region exists on the bottom surface of the chip. Compared with the infrared thermal imaging technique, the measurement of Tj derived from EL spectra is very effective in the case of the flip-chip method.

Electroluminescence image of multi-finger HBTs

To get the current flow image, we used a commercial digital still camera sensitive to near-infrared emission. Figure 6 shows the setup of the measurement system. In order to avoid diffused reflection, the backside of the chip was mirror polished.

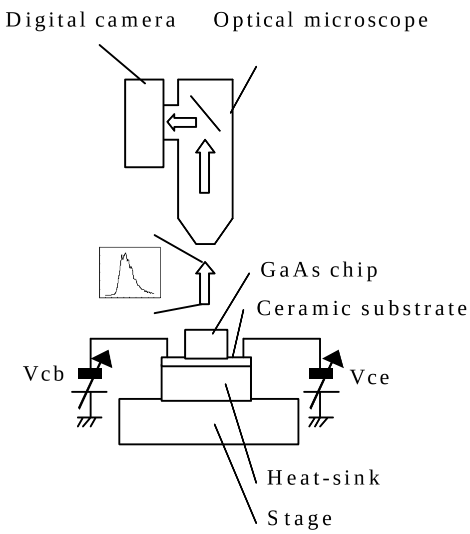

Figure 6 Setup of the measurement system

We measured two samples with different thermal bump configurations. In sample I, we intentionally introduced a defective bump with poor thermal connection. In sample II, all bumps were made under normal conditions.

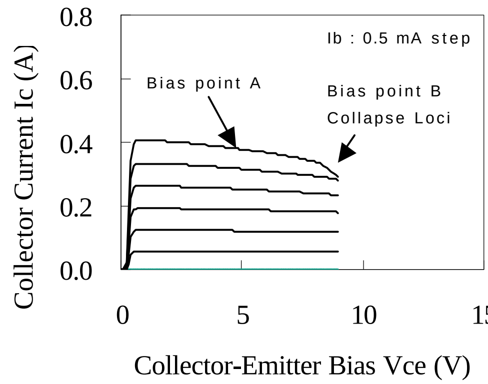

Figure 7-a Ic-Vce characteristics of sample I

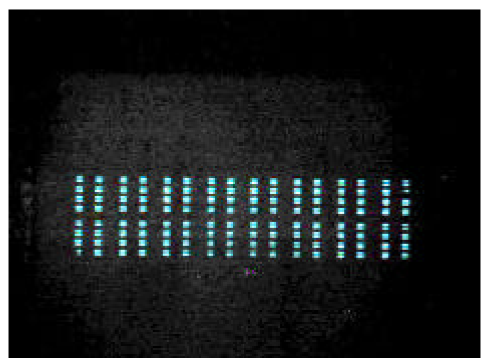

Figure 7-b Light emission image at point A

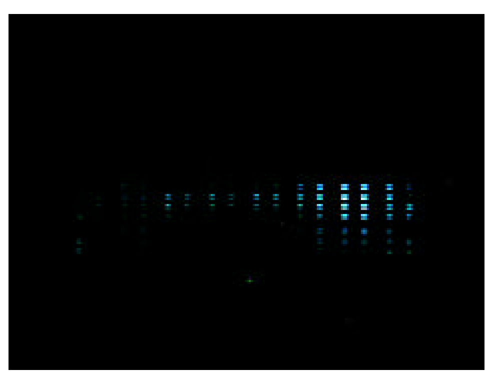

Figure 7-c Light emission image at point B

Figure 7-a shows the Ic-Vce characteristics of sample I. The bias point A corresponds to the normal operating condition. The bias point B corresponds to the gain collapse condition. Figures 7-b and 7-c are the light emission images of the points A and B taken by the digital camera, respectively. The light emission intensity reflects the collector current (see Fig. 2). So, we can observe the current distribution in these photographs. At point A, all of the 128-emitter fingers operated uniformly. At point B, only the right hand portion of the chip drained currents. This photograph suggests that a hot spot breaks out in this area. In fact, this area corresponds to the intentionally introduced defective bump. As shown here, this method enables us to detect thermally problematic areas.

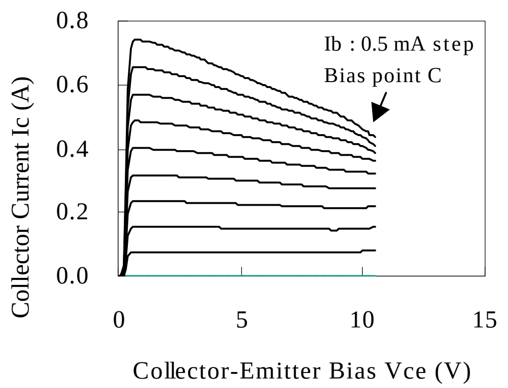

Figure 8-a Ic-Vce characteristics of sample II

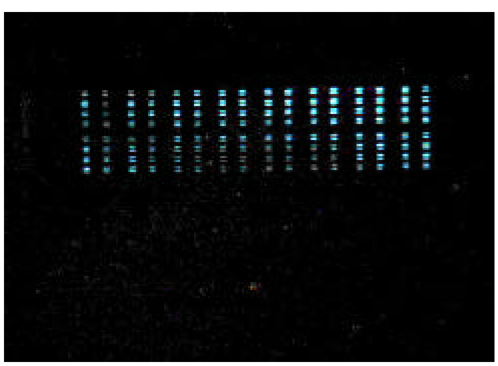

Figure 8-b Light emission image at point C

Figure 8-a shows the Ic-Vce characteristics of sample II. Figure 8-b shows the light emission images at the bias point. The uniformity of the current distribution was kept during high power operation, so that the safe operating area (SOA) limited by the thermal runaway was extended from the case of sample I.

Conclusion

We have demonstrated that the electroluminescence from InGaP/GaAs-HBT PAs can be used for both evaluations of junction temperature and current distribution. The EL spectrum peak energy reflects the band-gap energy of the base and becomes a good indicator of the junction temperature. The image of the EL is easily obtained with a commercially available digital still camera. Using this method, we successfully observed current crowding at a hot spot in a PA chip. These techniques provide useful information to achieve good thermal management of power HBTs.

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