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Thermoreflectance imaging of current dynamics in high power SiGe heterojunction bipolar transistors

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By generating high resolution two dimensional temperature images of electronic devices and linking heat dissipation to electrical current, the authors demonstrate that thermoreflectance measurements employing a charge-coupled device can provide a useful and nondestructive method for profiling current density in electronic devices. Here they apply this method to high power SiGe heterojunction bipolar transistors (HBTs) integrated in a commercial SiGe bipolar complementary metal-oxide-semiconductor platform, measuring the current carried by each subcell and quantifying current collapse under high-bias operation. They show that current hogging for a HBT with two emitter subcells can lead to one subcell carrying 81% of the total current. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2402947]

A main application of SiGe high power heterojunction bipolar transistors (HBTs) is power amplifiers[1] which can suffer thermal instability at high bias.[2,3] This instability often manifests itself in the collector current through either thermal runaway or current collapse. Although the base-emitter heterojunction of SiGe HBTs can maintain thermal stability up to certain bias levels, at high bias severe device heating can cause an increase in collector current, leading to an increase in power dissipation which causes further heating. This positive feedback effect can lead to thermal runaway in the collector current and eventual device burnout when the device is biased by a constant voltage source between the emitter and the base. On the other hand, if the base current is held constant, thermal instability can lead to one finger carrying a majority of the collector current and reaching a high temperature, which will increase injection of the base current into the emitter on this finger (and hence decrease its gain). This will reduce the base current into all the other fingers, dramatically reducing (collapsing) the overall collector current.

Many schemes have been developed to maintain thermal stability of power HBTs. However, implementation of these techniques has been hampered by the lack of a convenient method for accurately quantifying the temperatures of individual emitter fingers or emitter subcells. The strong tie between finger (or subcell) temperature and overall gain in a multifingered HBT suggests the potential use of high resolution thermal imaging for studying HBT operation and reliability.

Analytical models have been developed to examine current collapse and thermal runaway and to guide the design of emitter and base ballast resistors[4] which can be used to stabilize device performance by achieving a zero feedback loop gain on the total collector current. Further models have been used to study current crowding and simulate the current in each emitter finger, suggesting that the current density in one finger of a multifinger HBT under high bias can be as high as four times that of the other fingers.[5] Prior work to measure the collector current in each finger directly has used ion implantation to electrically isolate the emitter fingers from each other. Separate collector contact pads can then be used for different fingers to allow individual current measurement.[6] However, this method is impractical for measuring highly integrated circuits, requires significant extra fabrication steps, and necessitates "test" structures which may deviate in performance from the original structures. As a result, a simple and nondestructive approach is needed to measure the current carried by each subcell independently without any device modification. Such a technique would be useful to profile current density not only in HBTs but also in electronic devices generally.

Here we take advantage of the link between current density and temperature to nondestructively image current density in separate HBT fingers. Previously, nondestructive electrical methods have been used to measure an "average" HBT junction temperature; however, this provides only a single data point that is a function of all finger temperatures rather than giving individual finger temperatures.[7] In order to obtain a two dimensional temperature map of a multifingered transistor, micro-Raman spectroscopy has been applied with a resolution of 10 K on AlGaN/GaN heterostructure field-effect transistors to study how device defects and cracks affect self-heating.[8,9] However, this temperature resolution is not sufficient to allow derivation of current density in separate subcells.

In the present work, we apply the technique of thermoreflectance imaging using a charge-coupled device (CCD) camera, a method which has demonstrated temperature resolution less than 1 K.[10] In order to obtain the relatively large imaging area required to measure the left and right subcells simultaneously, a 10× objective is used, yielding a spatial resolution of approximately 2 μm. This spatial resolution can be increased to 700 nm by using a 100× objective, but the field of view does not then include both subcells. Details

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of the experimental setup have been reported before[11] and will not be repeated here. The thermoreflectance technique is based on measuring the variation in the normalized device surface optical reflection coefficient ($\Delta R/R$) and relating this to temperature variation (ΔT) by the relation $\Delta T = \kappa^{-1}(\Delta R/R)$, where κ is the thermoreflectance coefficient. Literature values or calibration using microthermocouples can be used to measure κ for the surface metal alloy of the HBT under study here, we find it to be 8.2×10^{-4} K^{-1}. Below, we will discuss only $\Delta R/R$ profiles rather than converting to temperature since we will only be comparing regions that have the same κ.

The device under test is a commercial SiGe HBT with eight emitter fingers (0.9×20.3 μm^2 each) grouped in two emitter subcells. No ballast resistor is connected to any of the emitter fingers. The collector doping has been optimized for carrying a high breakdown voltage ($BV_{CEO}=6-7$ V). The HBT is placed on a heat sink with a temperature of 20 °C and is biased in a common emitter configuration, with V_{CE} varied from 1 to 5 V. The heat source power in each finger is therefore given by $I_C\times V_{CE}$. The measured change in collector current with increasing V_{CE} is plotted in Fig. 1(a).

Thermoreflectance images of the device at different bias points are shown in Fig. 2. These images are taken while modulating V_{BE} with a square-wave signal of amplitude 1.52 V and frequency 10 Hz, capturing $\lambda=472$ nm light-emitting diode reflected off of the device surface with a CCD camera. The measured difference in each pixel's brightness when V_{BE} is 1.52 V versus when it is 0 V is the thermoreflectance signal ΔR which is related to surface temperature. At low collector-emitter bias (low V_{CE}), no significant heating is observed in the device, and the normalized thermoreflectance signals ($\Delta R/R$) within each emitter subcell are nearly the same. At $V_{CE}=4$ V, it can be observed that the thermoreflectance signal (i.e., temperature) is roughly the same for both emitter subcells (averaging over each subcell,

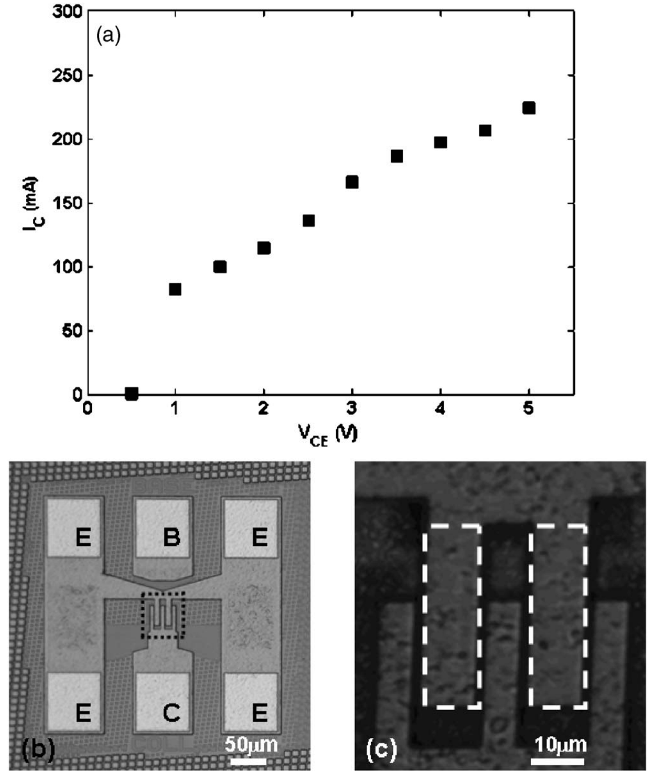

FIG. 1. (a) Total collector current (I_C) for different values of collector-emitter bias (V_{CE}) with a base-emitter voltage (V_{BE}) of 1.52 V. A high V_{BE} is used to intentionally induce thermal instability within the device. (b) Optical image of the device under test: E is the emitter contact pad, B is the base contact pad, and C is the collector contact pad. (c) Magnified image of the dotted square in (b). There are two emitter subcells, as highlighted by dashed lines. Each subcell contains four emitter fingers with an area of 0.9×20.3 μm^2 each.

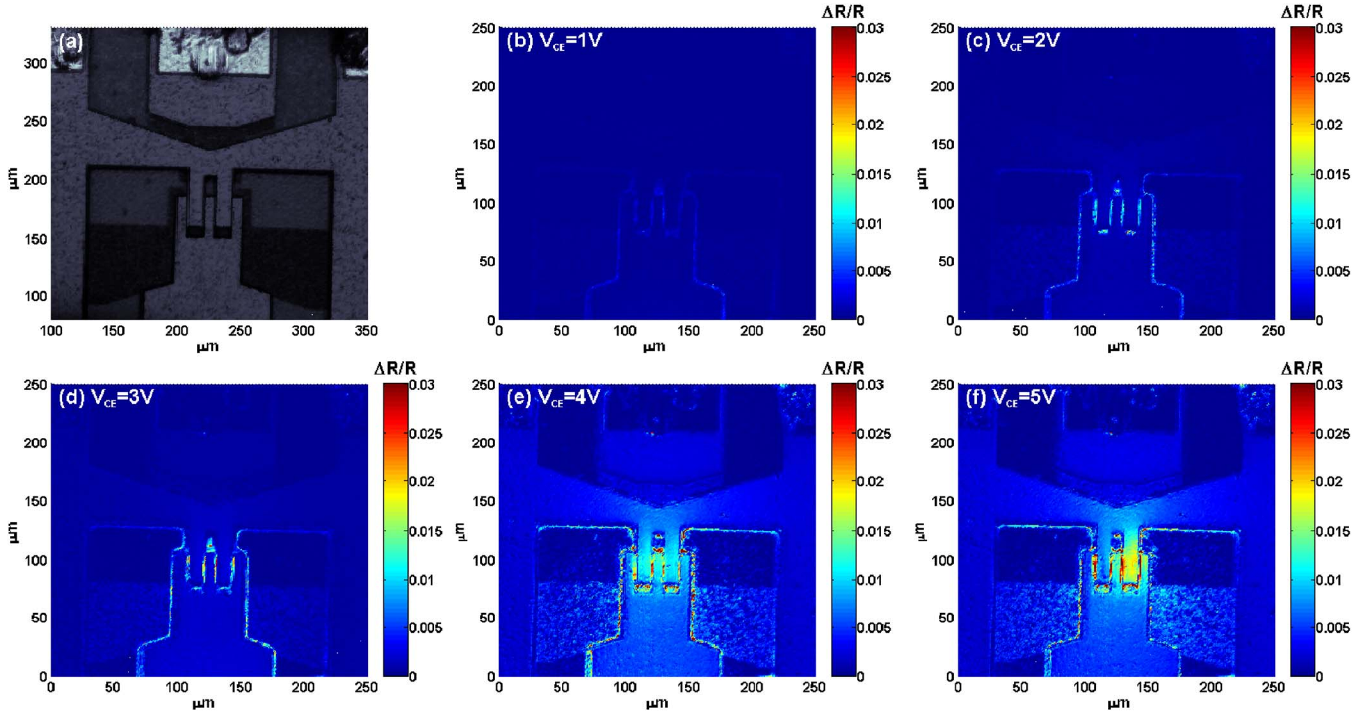

FIG. 2. (Color online) (a) Optical image (R). [(b)–(f)] Normalized thermoreflectance images ($\Delta R/R$) of the SiGe HBT at different V_{CE} biases for $V_{BE}=1.52$ V.

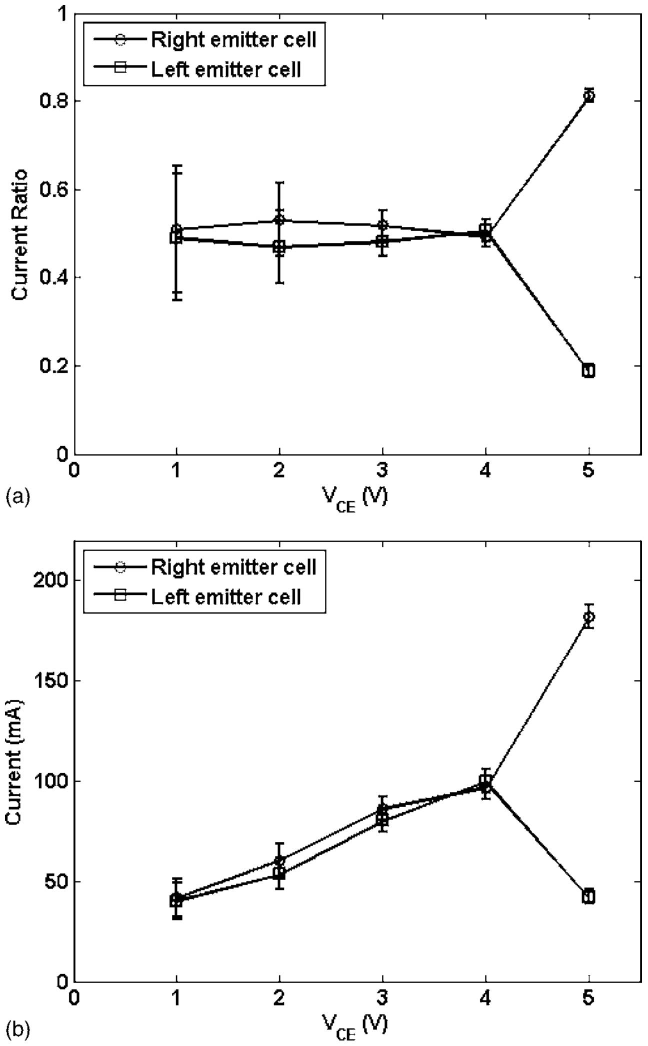

FIG. 3. (a) Current ratios and (b) total currents for the left and right emitter cells, derived by thermoreflectance imaging.

the left one has $\Delta R/R=0.0103$ and the right one has $\Delta R/R=0.0108$). This even distribution suggests the current density is also even distributed among the subcells. However, at $V_{\text{CE}}=5$ V, the thermoreflectance signals of the left and right subcells deviate, with the right one having $\Delta R/R=0.0167$ and the left one having $\Delta R/R=0.0069$. This suggests that right emitter subcell is 2.5 times hotter than the left subcell. It is important to note that the left subcell has a lower temperature at $V_{\text{CE}}=5$ V than at $V_{\text{CE}}=4$ V, even though the total collector current has increased. This is direct evidence that current is being pulled from the left subcell into the right subcell (which gets much hotter).

Since the power dissipated in each emitter subcell at a given V_{CE} is proportional to the current I_C, the subcell temperatures ($\Delta R/R$) can be used to derive the current ratio. However, in determining this ratio we must also account for temperature change due to lateral heat conduction between the subcells. It has previously been shown for typical HBTs that the ratio of the thermal resistance coupling between fingers ($R_{\text{th,couple}}$) (here we refer them to subcells) to the thermal resistance between the fingers and a heat sink (R_{th}) can be approximated by[12]

$$\frac{R_{\text{th,couple}}}{R_{\text{th}}} = \delta\left(\frac{10}{D_f}\right)^{1.5},$$

where $\delta \approx 0.25$ and D_f is the spacing distance between the heating sources (subcells) in micrometers. For the device under test, the space between subcells is 11.3 μm, so the thermal resistance ratio is 0.2. Taking this intersubcell heat flow into account, we plot the current ratio relative to the total collector current for each subcell in Fig. 3(a). The total current through each subcell is shown in Fig. 3(b). It can be observed that the current is almost evenly distributed between the two emitter cells up to $V_{\text{CE}}=4$ V. At $V_{\text{CE}}=5$ V, current crowding causes 81% (182.1 mA) of the total collector current to flow through the right subcell, while the left subcell carries only 19% (42.3 mA) of the total current. This hogging effect is indicative of nonidentical characteristics (always a practical issue in fabrication) for the two subcells which trigger thermal runaway at high bias.[13]

In conclusion, we have demonstrated that CCD-based thermoreflectance can be used as a nondestructive measurement tool for profiling current density in an electronic device. Here we show the method applied to a high power SiGe HBT; after considering the intersubcell heat transfer, we can observe and quantify current hogging within the HBT subcells.

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