Temperature distribution over a GaAs heterojunction bipolar transistor measured by fluorescent microthermal imaging

N. Boyer,[a] B. Oliver, A. Hagley, D. P. Masson, and Martine Simard-Normandin
Nortel Networks, 3500 Carling Avenue, Nepean, Ontario, Canada

Michel Meunier
Ecole Polytechnique de Montréal, Quebec, Canada

(Received 13 August 1999; accepted 10 November 1999)

Fluorescent microthermal imaging (FMI) is used to measure the temperature at the surface of a 2×2 μm^2 heterojunction bipolar transistor. The presence of an artifact at the emitter post indicates that accurate temperature measurements are limited to flat surfaces. The FMI measurements obtained for various power dissipations are compared with electrical measurements of the junction temperature. The good agreement between the two techniques suggests that the temperature drop along the emitter post of the device is within a few degrees. © *2000 American Vacuum Society.* [S0734-2101(00)06702-6]

I. INTRODUCTION

As GaAs heterojunction bipolar transistor (HBT) integrated circuit technologies mature into production, detailed characterization of the fundamental transistor lifetime and reliability is required. Conventional biased three-temperature lifetime studies[1,2] have found activation energies for thermally activated catastrophic failure of InGaP/GaAs HBTs to be in the 1.5 eV range. This is a strong temperature dependence, with lifetimes halving with an increase of operating junction temperature of only 10 °C at an ambient of 125 °C. For accurate calculation from life-study results of projected field lifetime, stress oven (ambient) temperatures require adjustment for device self heating due to the applied bias to an accuracy of a few degrees celsius.

Conventionally, device operating temperature rises are calculated from relatively simple thermal models and/or basic electrical techniques.[3] These have been accepted as sufficiently accurate for the purpose. However, recent work investigating the effect of elevated bias currents on device reliability have focused on the accuracy of self-heating corrections due in part to the known high thermal activation energy for catastrophic current gain (Beta) failure and in part to the higher junction temperature rises associated with higher bias currents during stress.

This requirement for refined junction temperature knowledge has lead to two separate investigations in an effort to ‘‘calibrate’’ a complete thermal and emitter current flux reliability model for the Nortel Networks GaAs HBT process. First, a refined electrical technique for measuring junction operating temperature has been developed. Second, physical measurements of highly localized (over the test transistor) integrated circuit surface temperatures have been undertaken by several means. Fluorescent microthermal imaging (FMI) offers the required spatial and temperature resolution to make the measurement, and yields results in agreement with more established surface temperature techniques. Furthermore, comparison with the advanced junction temperature techniques confirms the validity and usefulness of the FMI technique. In this article we report on the FMI technique and results, discuss the relationship between surface temperature and junction temperature, and present a comparison between FMI and electrical results.

II. EXPERIMENT

A. Fluorescent microthermal imaging

1. Theory

Successful fluorescent microthermal imaging was first demonstrated by Tyson and Kolodner.[4,5] FMI relies on the temperature dependent fluorescent yield of a europium chelate: EuTTA (europium thenoyltrifluoroacetonate). The EuTTA fluoresces at 612 nm when excited by UV light near 360 nm. The intensity of the fluorescence diminishes rapidly with increasing temperature. This technique was described in details by Barton *et al.*[6,7]

In a typical FMI experiment two fluorescence images are captured successively: one when the device is off (room temperature) and the other when the device is turned on. The ratio of the fluorescence of these two images depends on the temperature variation only since geometrical factors, detector efficiency, and incident UV flux cancel. It has been shown that the log of the ratio of the hot/cold images is directly proportional to the temperature rise for temperatures up to about 60 °C.[6,7]

The calibration of the EuTTA film was performed by measuring the variation in the fluorescence of a coated Si wafer sample placed on a calibrated hot plate. The temperature of the plate was varied across a range over which the response is linear.

2. Apparatus

FMI was implemented on a Zeiss laser scanning microscope (LSM). The setup is illustrated in Fig. 1. A mercury arc lamp provides UV illumination. A liquid-cooled CCD is used to detect the fluorescence. A narrow band filter centered at 612 nm is placed before the camera allowing only the EuTTA fluorescence to be captured.

---

[a] Electronic mail: nboyer@nortelnetworks.com

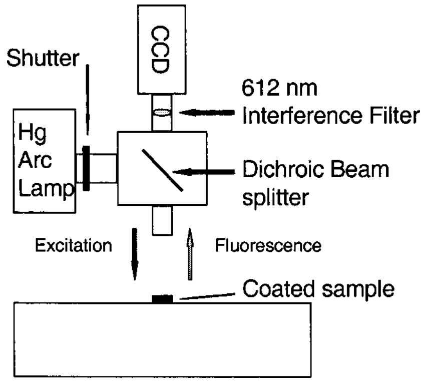

FIG. 1. Optical geometry.

3. Film deposition

The EuTTA powder was mixed with PMMA in chlorobenzene in proportions (weight) of 1.2:1.8:97. Boyer[8] has shown that, for this concentration, a 1 μm thick film is best suited for absolute temperature measurements since it minimizes artefacts from bleaching without increasing heat diffusion responsible for loss in spatial resolution.

A uniform film was obtained by putting a drop of the EuTTA solution on the die. The drop was dried and cured in an oven at 100 °C for 1 h.

B. Heterojunction bipolar transistor

A schematic of the cross section of a HBT device is shown in Fig. 2. The active junction is buried under a 2 μm thick gold post. The two interconnection levels are also made of gold.

In this experiment the transistors were powered up in a common emitter configuration. The V_{ce} was fixed at 1.5 V while I_c was varied.

III. RESULTS AND DISCUSSION

The top view of the structure that was analyzed is shown in Fig. 3. An example of a thermal mapping image obtained by FMI is presented in Fig. 4.

The absolute temperature was determined by adding the temperature rise measured by FMI to the ambient temperature (24 °C). The uncertainty in our measurement is of the order of ±2 °C at 50 °C and it decreases with temperature.[8]

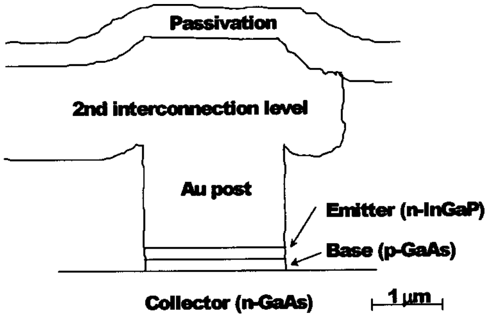

FIG. 2. Cross-section view of an heterojunction bipolar transistor. The junction has an area of about 2×2 μm^2.

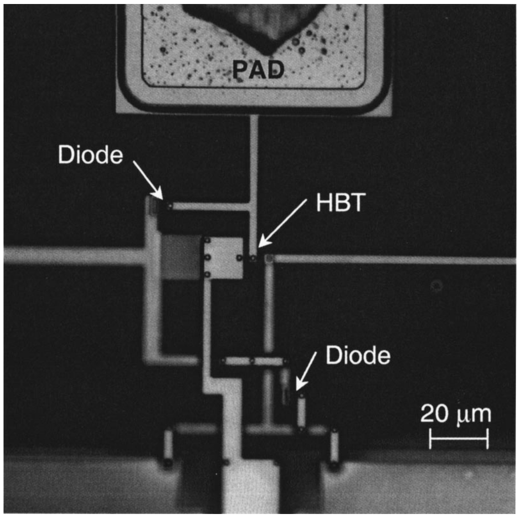

FIG. 3. Top view of the HBT structure. The arrow labeled HBT shows the location of the emitter post under which the active region is located. The junction is buried 2 μm deep under the gold post. Protective diodes and resistors are located in the HBT vicinity.

Measurements are affected by the accuracy of our calibration, possible heating from the UV and the accuracy of the measured ambient temperature. These are discussed in more details elsewhere.[8]

It is shown on Fig. 4 that the hottest region is found on the emitter metallization adjacent to the Au post location. It is surprising to see that the region above the post, shown by the arrow, is not the hottest point. The liquid crystal technique employed on the same device, suggests that this is an artifact and that the peak temperature is indeed above the post. It is tempting to associate the artifact with a local variation of the EuTTA film's thickness. This must be ruled out however because such geometrical factors cancel out in the ratio of

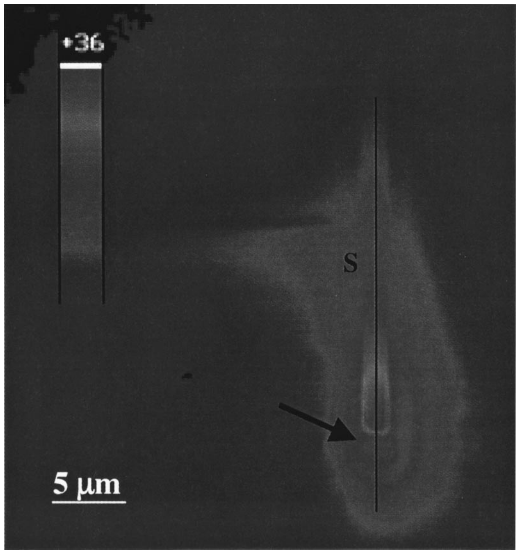

FIG. 4. Temperature mapping over the surface of the HBT. This mapping was obtained over a 2×2 μm^2 structure powered up to 19.5 mW. The arrow indicates the location of the emitter post. The temperature rise by the emitter post is 35 °C.

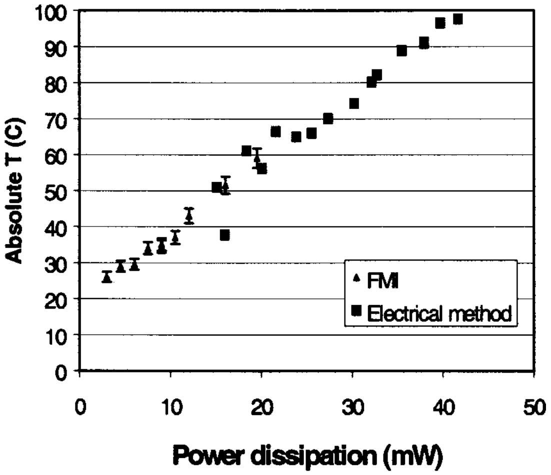

FIG. 5. Absolute temperature at the surface of the HBT structure for various power dissipations as measured by FMI and by the electrical method. The data from the electrical method are a measure of the temperature at the junction and become less accurate below 25 mW.

the hot to the cold image. Instead, the ‘‘cold’’ post artifact can be explained by reflections of the fluorescence on the edges of the dome shaped Au post (see Fig. 2). Fluorescence from the EuTTA film near but not directly above the post can be deflected off the edges of the Au post towards the CCD camera. This additional contribution to the fluorescence is not quenched when the device heats up and the post appears colder than it really is (see Ref. 8 for more details).

Because of the presence of the artifact, the absolute temperature next to the post location, on the emitter connection (second metallization level), was used to evaluate the device temperature at various power dissipations. The results are presented in Fig. 5. With no power dissipation the data extrapolate to ambient temperature ($\sim$20 °C).

In Fig. 5, the FMI results are compared with temperature measurements obtained using an electrical method developed by Hagley.[9] A detailed explanation of this method and a discussion of its precision over the temperature of interest is in preparation. As seen in Fig. 5, the noise in the electrical data increases at low power ($<$25 mW). In the overlap region however, the two sets of data agree to within a few degrees. The electrical method measures the temperature at the junction while FMI measures the temperature at the surface of the device. The difference in temperature between the junction and the top of the Au post is expected to be small because of the high thermal conductivity of Au. The evaluation of the temperature gradient along the emitter connection (line S on Fig. 4) supports this hypothesis. A 1.7 °C/μm drop was measured from the digitized image in Fig. 4 at the emitter connection. This is expected to be higher than the gradient along the post because of the difference in the thermal characteristics of the isolation layer surrounding the gold post and the emitter connection.

IV. SUMMARY

FMI was used to obtain absolute temperature maps over the surface of a commercial 2×2 μm^2 GaAs HBT structure. The spatial resolution of the FMI measurements was of the order of 1 μm and the temperature could be measured with an accuracy of about 20 °C. It was found that artifacts results from irregularities in the surface topography. Specifically, we found that the Au posts which forms tiny bumps on the surface can give rise to stray reflections of the fluorescence creating artifacts in the temperature map. Irregular topographies especially those which involve reflecting metal layers may not be appropriate for accurate absolute temperature measurements by FMI.

The FMI measurements at the surface of the device agreed to within a few degrees with the data from an electrical method which measure the temperature at the buried active junction. Comparison of the two techniques confirms that the temperature drop along the gold post is small. Work is in progress to improve and extend the data of the electrical method to lower power dissipation range.

[1] C. Beaulieu, B. Beggs, J. Bennett, J. P. D. Cook, L. Hobbs, T. Lester, B. Oliver, and R. Surridge, Proceedings of the GaAs Rel. Workshop, 1996.
[2] T. S. Low *et al.*, Proceedings of the GaAs Rel. Workshop, 1998.
[3] D. E. Dawson, A. K. Gupta, and M. L. Salib, IEEE Trans. Electron Devices **39**, 2235 (1992).
[4] P. Kolodner and J. A. Tyson, Appl. Phys. Lett. **40**, 782 (1982).
[5] P. Kolodner and J. A. Tyson, Appl. Phys. Lett. **42**, 117 (1983).
[6] D. Barton and E. I. Cole, Jr., Proceedings of the IRPS, 1997, pp. 8.1–8.26.
[7] D. L. Barton and P. Tangyunyong, Proceedings of the 23rd ISTFA, 1997, pp. 41–49.
[8] N. Boyer, M.Sc.A. thesis, Ecole Polytechnique de Montreal, 1999.
[9] A. Hagley, Ph.D. thesis (to be published).