Accurate estimation of layer temperature in PHEMT MMIC by photoconductance measurements

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Abstract — **A novel technique for precise temperature measurement in MMIC high power amplifier is presented. The method based on the measurement of photogenerated current is used to estimate channel and substrate temperature of the PHEMTs. Results are presented for a 4 W wideband amplifier used in a TX/RX module.**

I. INTRODUCTION

Solid state technology is normally used in power amplifiers for Electronic Countermeasurement (ECM) systems. State-of-the-art technology for high frequency and wide bandwidth subsystems give the possibility to increase the transmitted power, reducing MMIC dimensions and costs, and allowing theirs implementation on Phase Array architectures in order to obtain the desirable ERPs.

As size is reduced, the dissipated power density increase. It becomes thus important to study the temperature profile within each component in order to evaluate the reliability of the entire system.

Predicting accurate channel temperatures for GaAs devices requires a detailed knowledge of the power dissipation, geometry of the metal layers around the channel, the method of die attach to the substrate, and the thermal boundary conditions of the substrate.

Normally, the thermal profile near the channel in complex structure like MMIC are based on numeric solutions of heat transport equations. Such simulations has been performed for a 4W wideband power amplifier 6-18GHz which is the last stage of a TX/RX module used in several applications, (naval and avionic environment etc.). Modeling operative conditions of the module a maximum temperature of 75°C for heat sink just near the power MMIC has been computed.

In order to validate the simulation models accurate measurements, are necessary. Temperature measurement by an infrared camera permits to estimate the average temperature on surfaces not less than 16x16um^2 without the possibility of evaluate the hottest spot [1]. Liquid crystals techniques affect surface temperature and are destructive as they contaminate the device. Moreover both methods only monitor the surface temperatures.

We show here that a non-invasive measurement of the temperature on the different layers forming a complex system such as a PHEMT is possible by exploiting the photoconductive effect.

By illuminating the gates region at certain wavelength it is possible to collect the photogenerated current spectrum. This spectrum is strongly related to the temperature dependent absorption characteristic of different layers forming the PHEMT. By analyzing photocurrent spectra at several operating conditions it thus possible to evaluate the temperature in the device under test.

II. THE METHOD

The last stage of the 4W wideband power amplifier is composed by four PHEMTs each channel in a balanced configuration (4.2mm of total periphery).

Figure (1) shows the hottest transistor which will be irradiated to detect temperature.

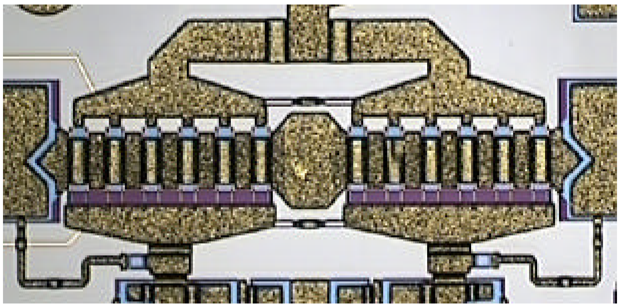

Fig. 1. Lighted area; it can be noted that the uncovered gate region is just a little percentage of total length.

By irradiating the uncovered gate regions with a monochromatic light it is possible to generate electron-hole pairs as long as the energy associated with the radiation is equal or greater than the energy gap of the constituent materials, that is GaAs for the substrate and InGaAs for the channel of PHEMTs. If a bias is applied, the photogenerated charge will be removed from the internal layer and collected at the drain and gate contacts.

By varying the wavelength of the incident radiation and detecting the photogenerated current with lock-in techniques, the photogenerated current spectrum is obtained. Current spectra are recorded at several bias conditions. The actual working temperature of the various layers is then obtained by analyzing the relative shift of specific structures associated to the GaAs and InGaAs energy gaps.

An empirical formula [2,3] is used to relate energy gap with temperature (T) and alloy concentration (x) of a $In_{1-x}Ga_xAs$ layer:

$$E(x,T) = 0.42 + 0.625 \cdot x - \left(\frac{5.8}{T+300} - \frac{4.19}{T+273}\right) \cdot 10^{-4} \cdot T^2 \cdot x + \\ - \frac{4.19 \cdot 10^{-4}}{T+271} \cdot T^2 + 0.475 \cdot x^2 \tag{1}$$

We should point out that this equation is strictly valid for non-strained materials. However, we expect that the relative variation of the gap with temperature will not be significantly modified by strain in our measurament range. On the other hand, one can precisely obtain the temperature dependence of the energy gap of the semiconductors forming the PHEMT by recording the photogenerated current when the device is externally heated at a well defined temperature. In this way one can calibrate with high accuracy the measurement for a given technology.

III. MEASUREMENT SET-UP

The white light of a 30W tungsten lamp is first choppered and then dispersed by a ½meter CHROMEX monochromator. The monochromatic light emerging from the monochromator is then focalized on the biased DUT which is mounted on a piezo-controlled XYZ micropositioner. A little part of the drain or gate current is sent to a lock-in amplifier (with a reference signal given by the chopper) and the photogenerated current is than extracted. The entire set-up is PC controlled via GPIB. The diameter of the focalized light spot could be easily reduced down to 10 µm. In the present case we have not optimized the light spot diameter which is of the order of 100 µm.

The PHEMT MMIC is contained in a test jig in order to avoid self-oscillations on the device itself.

IV. RESULTS

Figure (2) shows typical spectra obtained performing a photoconductance measurement on the considered MMIC focusing the irradiated spot on the gate region of the final stage. Three peaks can be identified: around 725 nm for the AlGaAs buffer, 875 nm for the GaAs substrate and around 900 nm for the InGaAs channel. Peaks relative to GaAs and InGaAs are very near each other and, with temperature changes, can overlap as can be seen below.

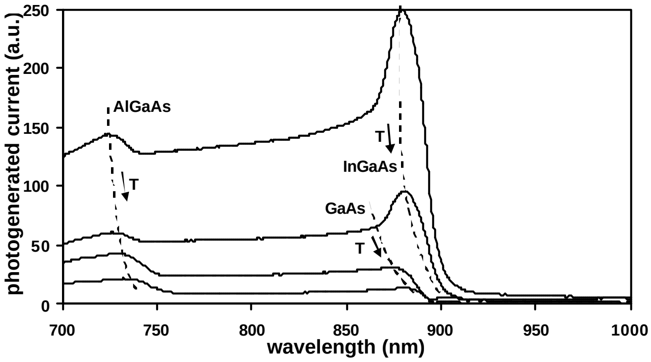

Fig.2. Typical drain photogenerated current as a function of the light wavelength for different bias

A first drain photocurrent spectrum is performed with a very low DC drain current to avoid the heating of the device. Figure (3) shows the photogenerated current spectrum obtained for this low-power biasing condition (Vgs=-0.6V, Vds=0.06V). This measure is associated with the room temperature T_{room} indicated by a termocouple sensor fixed inside the test jig (24 °C in this case).

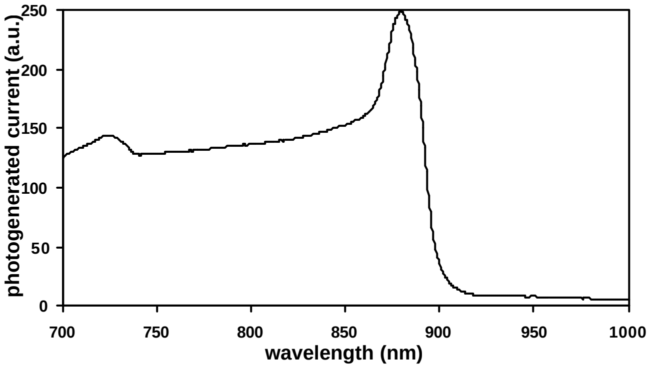

Fig. 3. Drain photogenerated current as a function of the light wavelength for a low-power (room temperature) measurement.

Figure (3) shows two well distinct regions: one around 725 nm, which corresponds to the absorption of the AlGaAs buffer and the other that extends up to 900 nm marking the presence of a $In_{1-x}Ga_xAs$ strained channel. We should point out, however, that solving Eq.(1) for the peaks of the photocurrent (which marks the energy gap) one find a slight different temperature (T_1) with respect to the measured room temperature. Such difference can be caused for example by tail states in the gap due to impurities, defects etc.

Other measurements are performed biasing the MMIC in the operative conditions and the resulting current spectra are shown in Fig. (4) for the InGaAs and in Fig. (5) for the GaAs, with relative peaks marked. Such interpretations of the peaks are supported by also gate photocurrent measurements where channel contribution is dominant.

We notice a clear shift of the GaAs and InGaAs related photocurrents between the room temperature measurement and that under operative condition. The entity of the shifts in the photogenerated drain current is related to the variation of temperature for each layer. In order to improve the accuracy for the InGaAs channel temperature, we calculate T_{bias} inverting (1), and consequently $\Delta T = T_{bias} - T_1$ and $T_{InGaAs} = T_{room} + \Delta T$.

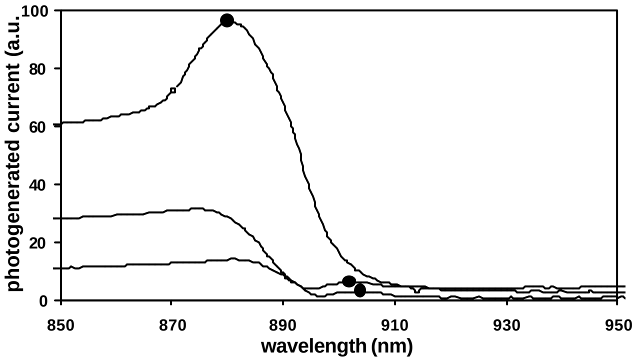

Fig. 4. InGaAs related drain photogenerated current as a function of the light wavelength for different operative conditions.

For the GaAs substrate we do not find a well defined peak for the room temperature spectrum. This does not allow us to perform the relative calculation of the substrate temperature as we have done for the channel. However, directly inverting Eq. (1) with x=1, we found realistic values of the substrate temperatures when the power increase.

The temperature values for the channel and substrate obtained at several power dissipation by means of a test jig non optimized for thermal performances, is reported in Tab.1. The heat sink temperature for each operative condition is also indicated.

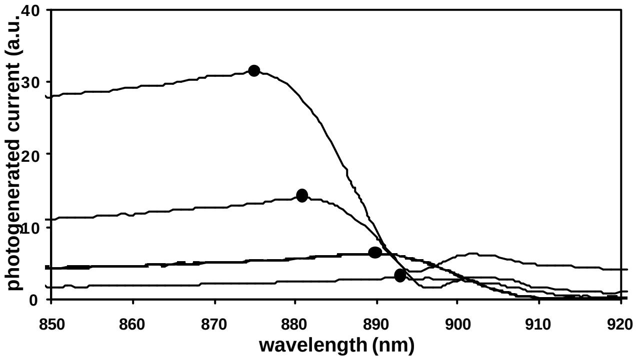

Fig. 5. GaAs related photogenerated current as a function of the light wavelength for different operative conditions.

Power [W]	T_{InGaAs} [°C]	T_{GaAs} [°C]	$T_{HeatSink}$ [°C]
~ 0	24	24	24
0.365	26.5	--	26
2.32	104	75	41
4.02	107	95	53
5.8	--	126	70
7.65	--	137	80

Tab. 1 Measured temperature in GaAs and InGaAs layers at different power.

V. CONCLUSION

We have shown how photogenerated currents can be used to monitor temperature in a PHEMT MMIC. The advantage of this method consists in the capability to measure the temperature of different layers inside the device in operative conditions with a spatial resolution that can be easily reduced up to 10-1 µm.

ACKNOWLEDGMENTS

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REFERENCES

[1] J. Wilson, K. Decker, “GaAs MMIC thermal modeling for channel temperatures in accelerated life test fixtures and microwave modules” *Tenth SemiTherm, Proceedings of 1994 IEEE/CPMT 10th* , 1994 , pp. 121-128

[2] S. Paul, J. B. Roy, P. K. Basu, "Empirical expression for the alloy composition and temperature dependence of the band gap and intrinsic carrier density in GaInAs", J. Appl. Phys. 69, 82 (1991)

[3] S. Adachi, *Physical Properties of III-V Semiconductor Compounds*, New York, Wiley, 1992