Experimental Validation of GaN HEMTs Thermal Management by Using Photocurrent Measurements

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***Abstract*—A major limitation in the performances of AlGaN/GaN high-electron mobility transistors (HEMTs) is due to self heating effects, connected to the efficiency of heat removal from the device. In this paper, we present a new experimental investigation on the thermal handling capabilities of AlGaN/GaN HEMTs, with conventional and flip-chip bonding. Efficient photocurrent measurements were performed in order to extract directly the channel temperature for all the device configurations. We were able to measure devices realized on sapphire substrate both with conventional and flip-chip bonding, and to compare them with devices on SiC substrate with conventional bonding, demonstrating that flip-chip bonding allows to achieve almost the same results that SiC substrate. Measured results are in good agreement with the presented simulation data.**

***Index Terms*—AlGaN, GaN, high-electron mobility transistors (HEMTs), photoconductivity, temperature measurements, thermal resistance.**

I. Introduction

WIDE-BANDGAP AlGaN/GaN high-electron mobility transistors (HEMTs) have been demonstrated as ideal candidates for high power microwave devices, due to the electronic properties of the AlGaN/GaN material system [1]. Although GaN HEMT devices are expected to have higher operating lifetime with respect to conventional devices, their high-temperature reliability still has to be demonstrated through long-term failure tests [2]. The thermal management of AlGaN/GaN high power devices has become a very critical aspect, requiring a detailed knowledge of self heating effects, accurate study of power dissipation, optimal geometrical layout, and proper device substrate mounting. GaN HEMTs on sapphire substrate suffer from strong self-heating, due to the sapphire low thermal conductivity (0.35 W/cm/K at 300 K [3]), which leads, in practical operating conditions, to a high channel temperature that degrades the device performances and affects their reliability. Great advantage can be achieved by using higher thermal conductivity SiC substrates (3.3 W/cm/K at 300 K [4]), and/or by flip-chip bonding technology [5], improving heat sinking and removal.

Failure rates in power HEMTs are mainly determined by the operating channel temperature; this is, therefore, the key parameter on which the experimental and simulation studies must be focused. Several techniques have been exploited to measure the thermal behavior of this kind of devices. DC measurements have been used to obtain a qualitative comparison between different heat removal approaches for AlGaN/GaN HFET [6], while Raman spectroscopy has been considered to acquire thermal maps of the device. Such technique, however, is only related to the average temperature of GaN layer, and therefore underestimates the peak channel temperature [7]. A similar problem also exists for the photoluminescence technique which has been applied to GaN devices measurements [8]. The liquid crystals method has also been considered to achieve a high spatial resolution (below 1 μm), but with the limitation of surface temperature measurement [9]. The flip-chip configuration has been proved to significantly enhance heat removal for devices realized on sapphire substrate [5], [10]; actually, the previous thermal characterization methods are not completely reliable in dealing with flip-chip bonded devices, where the front-end surface is represented by the substrate. Even optical approaches, like photoluminescence or Raman spectroscopy, which can access to the active part of the flip-chip device thanks to the transparence of the substrate layers, are not able to detect the real highest temperature of the device, namely the channel temperature: due to their intrinsic characteristics, these techniques are able to measure only the mean temperature of the GaN layer, and in the flip-chip mounted devices it can be several degrees different by the channel one. A detailed and accurate determination of channel temperature for flip-chip bonded devices is therefore a major open issue.

In this work, we apply, for the first time to GaN devices, an experimental methodology for thermal resistance evaluation based on photocurrent (PC) measurements [11], [12]. The PC approach is well suited for our measurement requirements, since it allows for direct measurement of the channel temperature in both conventional and flip-chip technology. Moreover, this method is easy to use and compact with respect to the needed setup. This enables to investigate various thermal management solutions for AlGaN/GaN HEMTs related to substrate materials (SiC and sapphire), and bonding technologies (conventional, i.e., backside, or flip-chip on AlN substrates). The achieved experimental data have been compared with simulation results, to validate the adopted thermal conductivity models.

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II. GaN HEMT Fabrication and Thermal Considerations

GaN HEMTs have been fabricated by the SELEX Sistemi Integrati SpA on AlGaN/GaN structures (an AlGaN layer thin about 35 nm on a 2–3 μm GaN layer), epitaxially grown on sapphire or 4H-SiC wafer substrates (whose thickness is about 400 μm). This process involves ohmic contacts formation obtained by metal deposition (Ti/Al/Ni/Au) and subsequent high temperature rapid thermal processing (over 850 °C), active device isolation by ion implantation, SiN passivation for GaN surface protection, Schottky barrier metallization (Ni/Au) for gate contact formation, and passive element definition. Measured devices have 10×100 μm total gate periphery, drain-to-source distance of 5 μm, intergate spacing of 50 μm, and 1-μm gate length. The characterization of a 1-mm gate periphery device on SiC substrates, performed with an on-wafer active load-pull system, shows a maximum output power of 3.3 W with a 3-dB compression at 2 GHz for class A biasing (50% saturation current, 30-V drain-to-source voltage). The associated dissipation power ranges from 11 to 13 W. These performances are much superior to those of a similar device on sapphire substrate.

Concerning the flip-chip technology, obtained by bonding Au bumps realized on the device source pads and AuSn bumps fabricated on AlN substrates, measured results have shown a consistent improvement of dc performances (over 30%–40% on the maximum current). As an indication of the effect of the flip-chip bonding on current–voltage (I–V) characteristics, we show in Fig. 1(a) the results of I–V measurements obtained for a sapphire substrate device before flip-chip bonding under normal (60 Hz sweep), and short pulsed regime (80 μs) starting from pinch-off). A large difference in the drain current is observed, due to the different dissipation conditions; in the flip-chip bonding the differences between the dc and pulsed characteristics are significantly reduced, as shown in Fig. 1(b).

To point out the increased efficiency of devices on SiC substrates, we show in Fig. 2 the static characteristics of two devices with identical GaN/AlGaN heterostructure, the first grown on a SiC substrate, and the second on a sapphire one: the lower channel temperature of SiC substrate device causes both a higher drain current and transconductance, and a less negative slope of the I–V output characteristics versus drain voltage in saturation.

III. Thermal Resistance Evaluation by Photocurrent Measurements

Backside mounted devices are packaged in a microX suited for RF applications, with 9-mm^2 square pads, especially designed for power applications; the HEMT backside is directly bonded on the metallic support using an EPOTEK H20E conductive silver epoxy. On the other hand, flip-chip mounted devices are bonded, as described previously, on AlN substrates on which macro contacts pads are provided for device biasing.

To perform temperature measurements, the different GaN/AlGaN device packages are mounted on a thick heat sink copper support, and are provided with stabilizing circuits to avoid self-oscillation of the device. The copper support is then contacted by silicone paste to the plate of a Peltier cell,

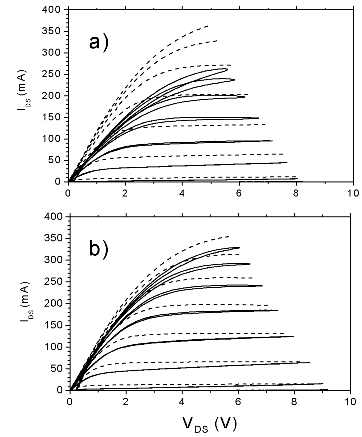

Fig. 1. Transistor output characteristics of GaN HEMT ($V_{\mathrm{GS}}^{\mathrm{Max}} = +1$ V; $\Delta V_{\mathrm{GS}} = 1.0$ V constant step): (a) before and (b) after flip-chip bonding. The device has been measured by using a Tektronix370A Curve tracer system, under standard (60 Hz I_V sweep, solid lines) and pulsed (80 μs measurement with quiescient point $V_{\mathrm{GS}} = -7$ V, dashed lines) operations.

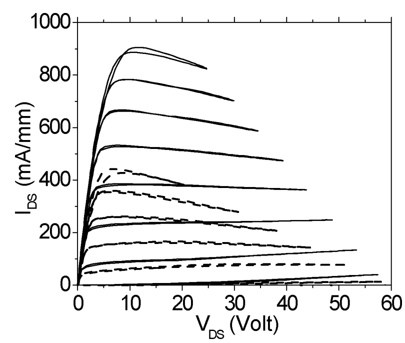

Fig. 2. Comparison between the characteristics of two GaN HEMTs ($V_{\mathrm{GS}}^{\mathrm{Max}} = +1.0$ V; $\Delta V_{\mathrm{GS}} = 1.0$ V), one with a SiC substrate (full line), the second with a sapphire substrate (dashed line).

that is able either to provide a fixed temperature source or to effectively remove heat.

In order to evaluate the device performances with respect to the thermal behavior, it is used to introduce the static thermal resistance, that can be derived from the channel temperature as a function of the dissipated power, according to the standard definition

$$R_{\mathrm{th}} = \frac{T - T_s}{W_{\mathrm{DS}}} \tag{1}$$

where: $W_{\mathrm{DS}} = V_{\mathrm{DS}} I_{\mathrm{DS}}$ is the dc power dissipated within the channel, T is the channel temperature, and T_s is the environment temperature. In our setup, T_s is the temperature detected by a thermocouple embedded in the copper support near to the mounted device, in order to be as accurate as possible to obtain the actual environment temperature sensed by the device. Before, to perform each set of measurements, we waited until the value reported by the thermocouple stabilized, and we checked that it kept constant during the measurements.

The channel temperature T has been obtained by photocurrent measurements [11], [12]. The experimental setup implements an optical probing method, based on the detection of the

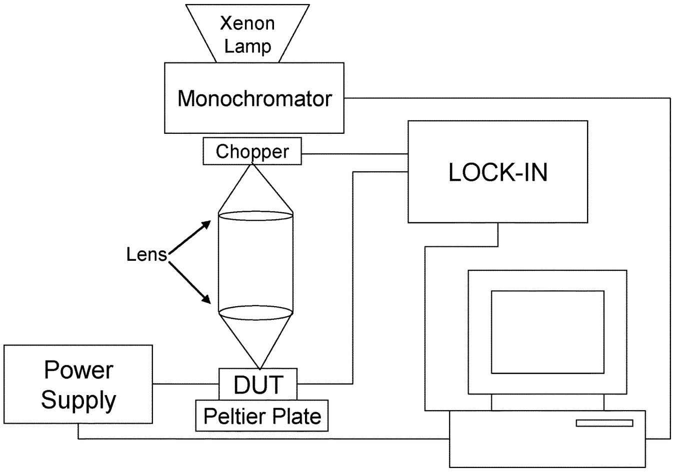

Fig. 3. Photocurrent setup. The light emitted from a Xenon lamp is dispersed by a monochromator, choppered, and focused on the device. A lock-in amplifier is then used to extract the photogenerated current, taking the reference frequence from the chopper. A voltage generator is used to polarize the device during the power dissipation measurements. A Peltier plate is used to fix the temperature of the copper support. The whole setup is remotely controlled by PC.

temperature behavior of the absorption threshold within the active channel region: the whole setup used to perform this kind of measurements is described elsewhere [12] and the used scheme is reported in Fig. 3.

The absorption is obtained by measuring the spectrally resolved photocurrent response of the device. Fig. 4 shows the shift of the absorption edge of the photocurrent spectra of a GaN/AlGaN HEMT occurring when the internal temperature changes. For increasing temperature, the semiconductor bandgap narrows, and the wavelength corresponding to the absorption threshold increases. So far, the light spot used in the measurements is covering all the fingers of the device, thus we are not able to measure spatially resolved temperatures, but only the mean temperature of all the fingers of the device. However, the main two advantages of this technique are: 1) the collection efficiency is much higher in the channel, thus the photocurrent is mainly related to the channel conditions and 2) the adsorbing edge is related to the device hot-spot, since the band-gap is lower in the higher temperature region [13].

The above points make thermal measurements through PC detection a unique technique for direct channel temperature measurement: In order to define the overall thermal performances of the device, we are quite confident that this data are absolutely relevant to discuss the behavior of the device.

Moreover, both sapphire and SiC are transparent to the wavelengths which are absorbed by GaN. In fact, the energy gap of sapphire is 6.2 eV compared to the 3.4 eV of GaN, while the absorption coefficient of SiC, even if it has an indirect band gap at 3.2 eV, is negligible up to 3.4 eV [14]. The method can therefore be applied also to flip-chip bonded devices, without any consequences due to the presence of the substrate.

The first step of PC measurements is the calibration procedure, that in our setup it is carried out in the following way. We fixed the device temperature by heating the copper support by mean of the electronically controlled Peltier cell under it. The device itself is biased at very low power to avoid self-heating: Actually, the power flowing in the devices during the calibration

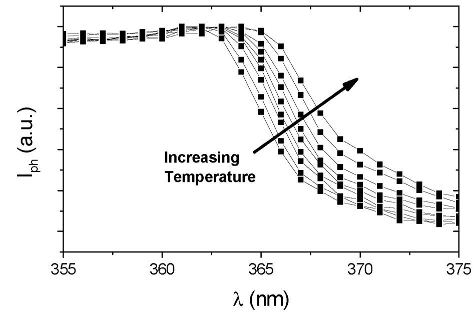

Fig. 4. Photocurrent spectra at different temperatures. The absorption wavelength moves toward higher values with increasing device temperature, indicating a narrowing of the semiconductor band gap.

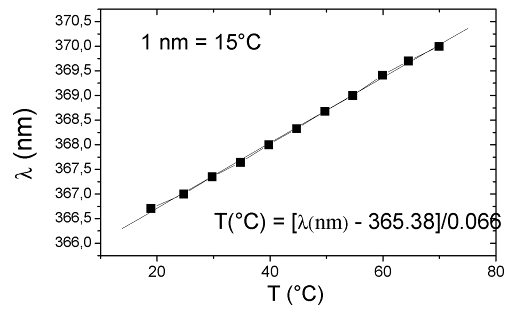

Fig. 5. Linear relation between absorption wavelength and device temperature, obtained by calibration measurements.

steps has always been under 20 mW, which means *a posteriori* a temperature increase of less than 1 °C, well below the error level. For any different value of the so externally controlled temperature of the device we measured the photocurrent spectra: the differential photocurrent shows a pronounced peak which is related to the onset of the absorption of the GaN (around 365 nm at room temperature). By changing the temperature of the Peltier cell, we can monitor the temperature dependence of this absorption edge and correlate its value with the temperature of the channel. Therefore a direct relationship between the device channel temperature and the absorption edge wavelength, as shown in Fig. 5, is obtained. One expression for the temperature dependence of the bandgap of semiconductors has been proposed [15] for silicon and germanium studying the effect of thermal lattice vibrations on bandgap energy and it has been successfully applied to GaN [16]

$$E_g = E(0) - \frac{\kappa}{\exp\left(\frac{\vartheta_E}{T}\right) - 1}$$

where $E(0)$ is the bandgap at 0 K, θ_E is the Einstein temperature, and κ is a constant. In the range between 300 and 400 K this dependence is linearly decreasing: being the wavelength inversely proportional to the bandgap, the obtained behavior follows the expected one. Moreover, the linear fit performed on the calibration line allows to connect the change in wavelength with the temperature increase, namely 15 °C for each nanometer. By evaluation of the achievable wavelength resolution (0.3 nm), we can estimate a temperature error of about 5 °C.

After the calibration step, it is possible to measure the self-heating effect of the device: in this case we fixed the temperature of the Peltier cell to a given temperature (20 °C) and then changed the power dissipated in the channel by changing

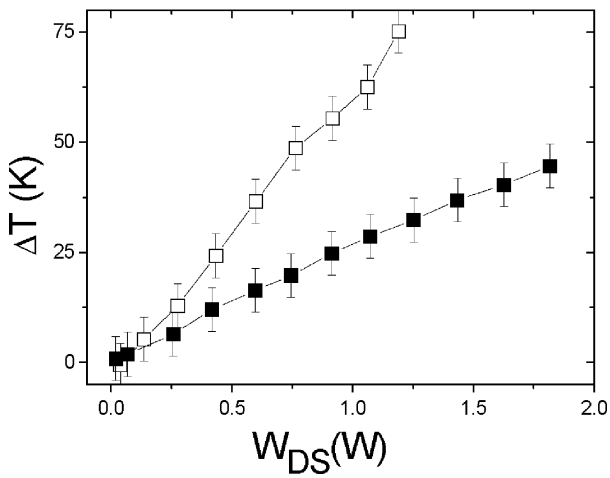

Fig. 6. Comparison of the temperature increase as a function of the electrical dissipated power, for GaN HEMTs on sapphire with (open dots) conventional bonding, and (full dots) flip-chip bonding.

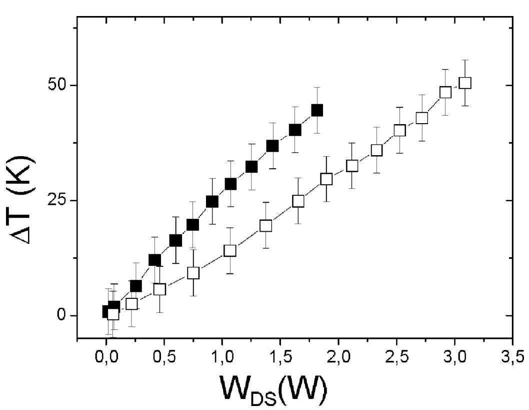

Fig. 7. Comparison of the temperature increase as a function of the electrical dissipated power, for GaN HEMTs. (Full dots) GaN on sapphire flip-chip bonded. (Open dots) GaN on SiC with conventional bonding.

the polarization of the device. All measurements provided high photogenerated signals, allowing for the accurate determination of the absorption threshold, which is then univocally related, through the calibration curve, to the channel temperature. Using this technique, we compared the self heating of GaN HEMTs on a sapphire substrate with conventional and flip-chip bonding.

The channel temperature, corresponding to different power dissipation levels, is shown in Fig. 6, where ΔT indicates the difference $T - T_S$. As expected, the flip-chip bonding has greatly improved the thermal dissipation of the device; in fact, $R_{\rm th}$ decreases from (65 ± 4) K/W for the device with conventional bonding to (25 ± 2) K/W for the flip-chip bonded device. To realize how significant is the improvement achieved, we can compare this last value with the one of a GaN HEMT on 4H-SiC-substrate with the same interdigitated structure (Fig. 7) that provides similar results: $R_{\rm th} = (17 \pm 1)$ K/W.

IV. Comparison With Thermal Simulations

Thermal simulations were performed on the measured devices through the three-dimensional finite-element thermal solver COMSOL multiphysics (former FEMLAB) [17]. For each device we simulated a quarter of the die considering its fourfold symmetry. Physics-based simulations confirm that the device heat source is approximately located in the two–dimensional electron gas (2DEG) channel, close to the gate edge toward the drain; thus, the photocurrent method actually is able to provide information on the part of the device that is most critical from the thermal standpoint. In all simulations the room temperature was assumed as 300 K. In order to compare simulations with experimental data (see Fig. 9), the computed temperature was averaged on the heat source regions.

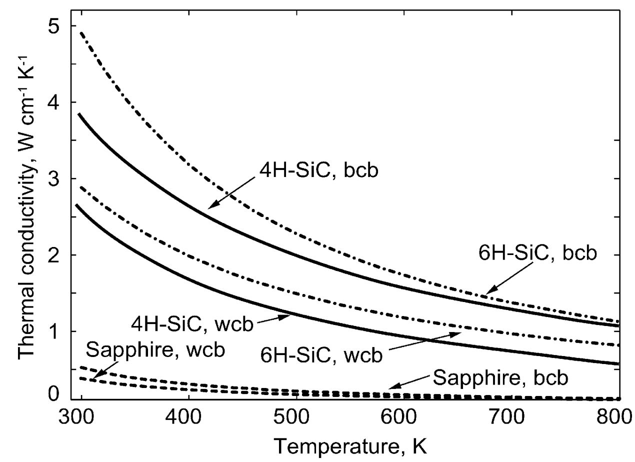

Fig. 8. Temperature behavior of BCB and WCB models of (4H and 6H) SiC and sapphire.

Owing to the remarkable spread of thermal conductivity values found in the literature, the sapphire and SiC conductivities were modeled as a function of the temperature according to a best-case and worst-case bound (BCB and WCB, respectively) approach, see Fig. 8.

For 4H-SiC, the WCB and BCB models were taken from [18] and [19], respectively, as

$$K_{\text{4H-SiC,WCB}}(T) = 2.6 \times \left(\frac{T}{300}\right)^{-1.49} \frac{W}{\frac{\rm cm}{\rm K}} \tag{2}$$

$$K_{\text{4H-SiC,BCB}}(T) = 3.95 \times \left(\frac{T}{300}\right)^{-1.29} \frac{W}{\frac{\rm cm}{\rm K}} \tag{3}$$

while, for sapphire, the WCB and BCB models were taken from [3], [20], and [21], respectively; the room temperature conductivity ranges from 0.35 (WCB) to 0.52 (BCB) W/cm/K and the temperature behavior follows the law $(T - T_r) - 1, T_r = 159$ K. For GaN, a constant conductivity of 1.49 W/cm/K was adopted ([22], [23]), while for AlN the conductivity was modeled according to [24]. Thermal boundary resistance effects [25] at the GaN/SiC (GaN/sapphire) and substrate/mounting interfaces were apparently not significant in the devices considered, i.e., the simulated bulk thermal resistance yielded results compatible with experimental data.

A comparison of measured and simulated data on the average channel device temperature as a function of dissipated power is presented in Fig. 9 for three cases: (top) backside bonding on sapphire, (middle) flip-chip bonding on sapphire, and (bottom) backside bonding on SiC. Simulations are carried out with BCB and WCB models, (top and middle) for sapphire and (bottom)

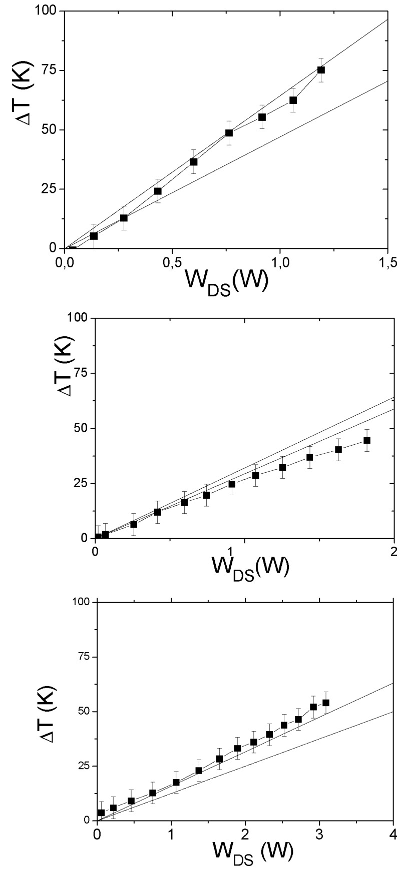

Fig. 9. Comparison of experimental data with simulations results obtained with different models of 4H-SiC and sapphire thermal conductivity: the straight lines represent the results obtained respectively with the WCB (upper straight line), and the BCB (lower straight line). From the upper graph, GaN HEMT on sapphire substrate with conventional bonding; GaN HEMT on sapphire substrate flip-chip bonded; GaN HEMT on SiC substrate with conventional bonding.

SiC thermal conductivities. For the dissipated power range considered, the thermal conductivity is almost constant and therefore the temperature linearly increases with the dissipated power. In all cases considered, WCB models actually provide closer agreement to measured data.

V. Conclusion

We have shown that thermal measurements via photocurrent detection technique can be effectively used to monitor the channel temperature for both backside and flip-chip GaN-based HEMTs. This allowed us to experimentally validate different kinds of packaging and bonding methodologies, thus providing a powerful tool to assess the thermal management of GaN HEMTs. The thermal characterization were found to be in good agreement with three-dimensional simulations. As a final result, we confirmed that devices grown on sapphire substrate with flip-chip bonding have a considerable heat dissipation properties, close to that of GaN HEMTs on SiC substrate with conventional bonding using silver epoxy and not thinned backside (400 μm), confirming that such low cost mounting and connection technique could also be an effective solution for thermal management of GaN HEMTs, particularly if the devices has been fabricated starting from substrates with higher thermal resistivity with respect SiC such as sapphire or silicon, offering additional cost advantages.

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Marco Peroni is with SELEX Sistemi Integrati, Rome, Italy (formerly AMS) as a Process Engineer at the GaAs Foundry. He has been involved in the process development, characterization, and reliability issues study, as well as the modeling of III-V microwave devices, and in these topics he has contributed numerous papers and presentations for international technical magazines and conferences. At the moment, he is primarily involved in GaN HEMT devices development, and responsible for AMS activity in several national and European research programs.

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He was Assistant Professor in Electromagnetic fields since 1983, Associate Professor in Circuit Theory with Politecnico di Milano, Milano, Italy, since 1987, and finally Full Professor in Electronics since 1990, first with University of Catania, then again with Politecnico di Torino, II Faculty of Engineering. His research activity is mainly concerned with high-frequency electronics, with particular interest in the physics-based and thermal modeling of semiconductor devices on compound semiconductors and in the modeling of passive microwave elements, in particular coplanar components. More recently, this activity was extended to innovative widegap semiconductors such as GaN and related alloys and SiC, and to power electron devices for power switching applications (both SiC and Si). He has been actively engaged since 1985 in research on optoelectronic devices, with application to fast photodetector and to electrooptic and electroabsorption modulator modeling. He has authored or coauthored more than 200 research papers on the above subjects and four books. He has been engaged in several European research projects (ESPRIT 255, COSMIC, MANPOWER, ELEN, NOE TARGET, NOE NEWCOM, KorriGaN), Italian research projects and industrial projects. Since 1998, he has been the President of the Library System of the Unviersity of Politecnico.

Dr. Ghione has been a member of the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES since 1991, and was a member (1998–1999) of the IEEE-Electron Devices Subcommitee on Compound Semiconductors and Quantum Electronics. He is aa AEI member. He has repeatedly acted as a scientific referee for several research agencies in European countries (Sweden, Ireland). He was Chairman of GAAS2002 (European Microwave Week 2002). He was a member of the IEEE Electronic Library Advisory Council from 2003 to 2004.