Light emission spectra of commercial pseudomorphic HEMTs biased in the impact ionization regime

Paolo Cova, Elena Chioato, Paolo Conti*, Sandra Dall'Aglio, Fausto Fantini, Manfredo Manfredi, Roberto Menozzi and Riccardo Necchi.

Centro Interdipartimentale Materiali e Tecnologie dell'Informazione, Viale delle Scienze, 43100 Parma, Italy.

*CSELT S.p.A., Via G. Reiss Romoli, 10148 Torino, Italy

Abstract

The aim of this investigation is to study hot electron phenomena leading to impact ionization and light emission in commercial InGaAs-channel pseudomorphic HEMTs. Optical measurements have been performed at several temperatures by means of a single-photon counting technique in the range 1.1 eV - 3.0 eV, while biasing the devices in the impact ionization regime. The observed spectra show a sharp peak that denotes band-to-band recombinations of cold carriers and a high energy tail corresponding to hot electron transitions.

Introduction

Modern submicrometric compound semiconductor devices such as MESFETs and HEMTs, when biased at high drain voltages, experience impact ionization and light emission due to the presence of hot electrons [1]-[3]. These phenomena have recently gained a great deal of interest because of their importance in the assessment of device operating range and long-term stability.

By coupling electrical characterization with spectral analysis of the light the devices emit at high drain bias, in this work we relate the features of the measured light spectra with hot electron phenomena taking place in the InGaAs channel of commercial pseudomorphic HEMTs. Moreover, we present evidence of a band-to-band recombination peak whose position and temperature dependence are strong indications that it originates from cold electron transitions from conduction to valence band in the *InGaAs* channel.

Experimental set-up

The devices under test have been characterized in DC using a HP-4145B Semiconductor Parameter Analyzer. The HP-4145B is also used to bias the devices when they are placed in the optical measurement set-up, shown in Fig. 1. Emitted light spectra are measured biasing the HEMTs in the pre-breakdown region; the devices, whose package cap has been removed, are mounted on a socket placed into a microcooler that enables to carry out measurements down to a temperature of 20 K. The emitted light is collected by an optic fiber, through a quartz window placed perpendicularly to the channel current path at a distance that optimizes the amount of collected light; through the fiber the photons reach a phototube able to reveal a single photon in an energy range between 1.1 eV and 3 eV. A spectral analysis can be obtained by using a monochromator, i.e. a series of monochromatic interferometer filters able to continuously sweep the wavelength in the 400 nm - 1200 nm range (corresponding to photon energies between 1 eV e 3.1 eV), with a resolution of 0.05 eV. The sweep is automatically driven by a computer through an electric motor that changes the filters in the monochromator.

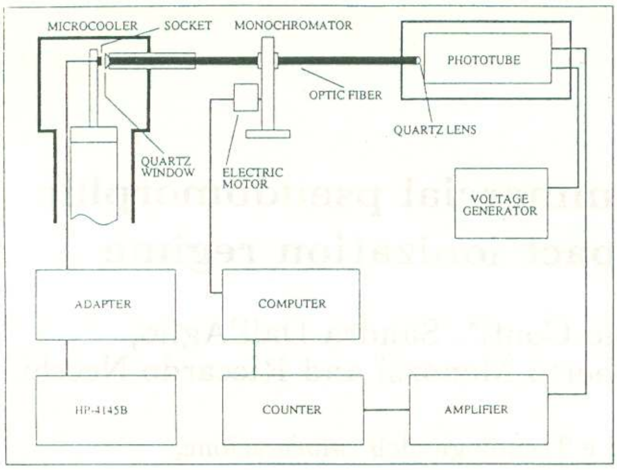

Figure 1: Measurement equipment.

The photons that get through the selected filter are then focalized by a second quartz lens on a photomultipler cathode, whose output is amplified and sent to a counter; the output of the counter is finally read by the computer. We have utilized two different phototubes, the first for energies between 1.1 eV and 1.5 eV and the second for energies between 1.5 eV and 3 eV; the phototubes are cooled down to 173 K and to 253 K, respectively, to lower their dark current.

Results and discussion

The devices under test are Fujitsu pseudomorphic *SuperHEMTs*^{TM}, with channel length < 0.25 μm and 200 μm gate width; they feature an excellent noise figure of 0.55 dB at a frequency of 12 GHz [4].

A. Electrical measurements

We have measured the $V_{DS} - I_D$ curves of the devices under test at several temperatures between 100 K and 300 K, pushing V_{DS} beyond the maximum value rated in the data-sheets and up to 4.5 V to observe hot electron phenomena. Due to short channel length, a drain bias of V_{DS} = 4 V corresponds to an average channel electric field $> 10^5$ V/cm, large enough to give rise to impact ionization. The generated electrons are collected by the drain while holes move towards the gate: therefore I_G gives an estimate

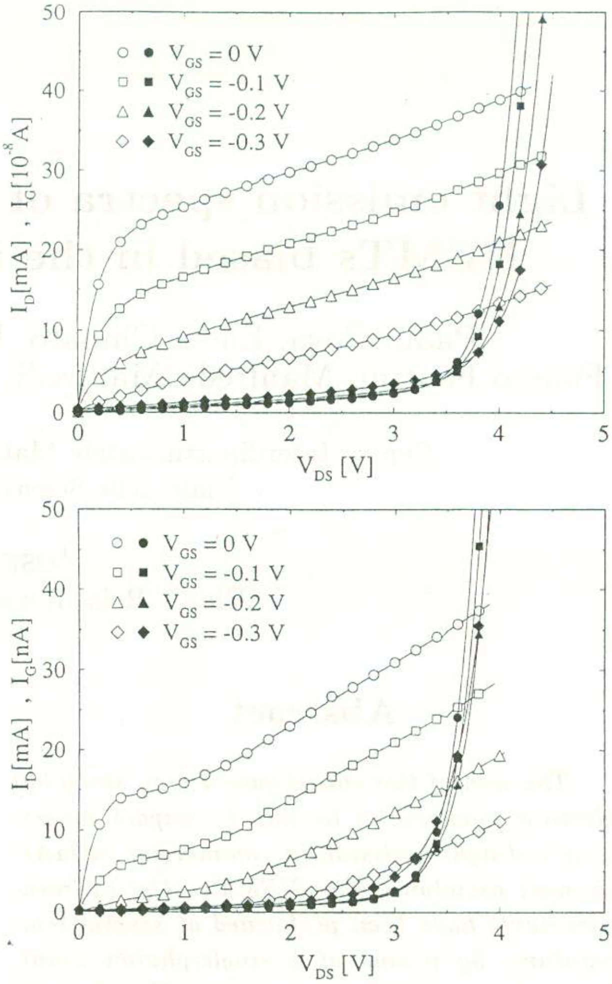

Figure 2: Drain (open symbols) and gate (full symbols) currents of a Fujitsu *SuperHEMT*^{TM} versus V_{DS} for various V_{GS}; T = 300 K (top), T = 100 K (bottom).

of the amount of generated hole-electron pairs [1]-[3]. Fig. 2 shows the drain and gate current characteristics at a temperature of 300 K and 100 K. The rapid increase of the gate current at $V_{DS} > 3.5$ V at both temperatures is thus an indicator of hot electrons giving rise to impact ionization in this bias range. The smaller currents measured at 100 K are probably due to lower electron concentration in the 2DEG overcompensating the increase of mobility and saturation velocity [5].

The room temperature dependence of I_G on V_{GS} at fixed V_{DS}, illustrated in Fig. 3, shows the well known [2, 3, 6] bell-shaped behavior, commonly observed when impact ionization phenomena take place. The maximum current oc-

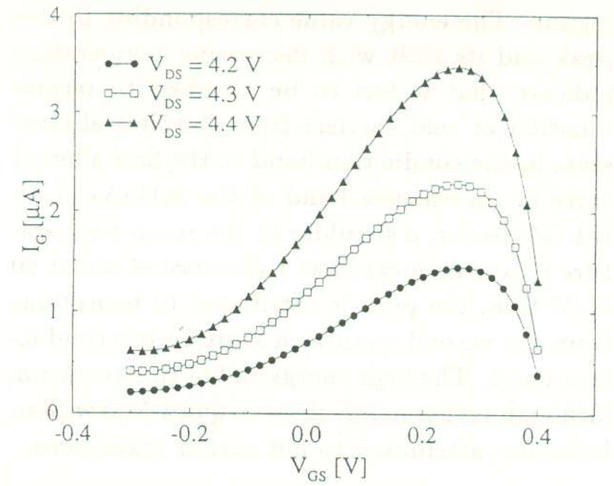

Figure 3: Gate current versus V_{GS} at different values of the drain bias; $T = 300\ K$.

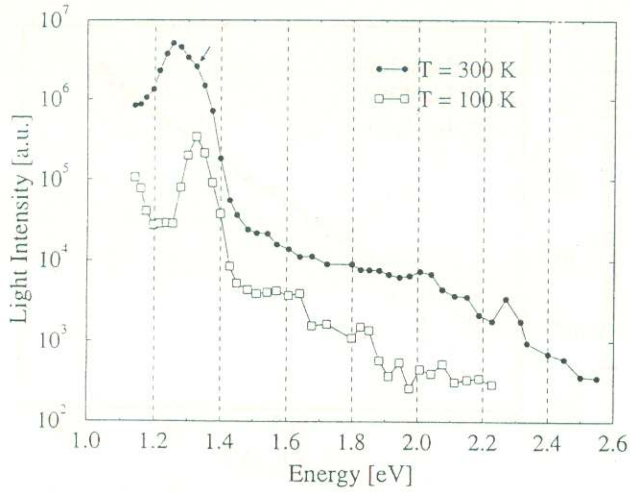

Figure 4: Emitted light spectra at $T = 300\ K$ and $T = 100\ K$; $V_{DS} = 4.4\ V$, $V_{GS} = 0\ V$. The arrow marks the position of the shoulder in the 300 K spectrum.

curs for $V_{GS} \simeq 0.2 \div 0.3\ V$.

B. Emission spectra

Fig. 4 shows the light spectra obtained at the temperatures of 300 K and 100 K with the devices biased at $V_{GS} = 0\ V$ and $V_{DS} = 4.4\ V$.

The 300 K spectra can be divided in three regions, one corresponding to energies $< 1.3\ eV$ (region 1), one for energies between 1.3 eV and 1.4 eV (region 2) and finally one that covers energies $> 1.4\ eV$ (region 3). In the lowest temperature (100 K) spectrum these regions are shifted to slightly higher energies.

Region 1. At $T = 300\ K$ the low-energy region ($E < 1.3\ eV$) is characterized by a peak at 1.26 eV. When the temperature is decreased to 100 K the peak's position shifts to 1.33 eV. Both the position and the temperature dependence of the peak indicate that it can be attributed to transitions from the lowest energy state in the conduction band of the *InGaAs* channel layer (E_1) to the first allowed state of the valence band, i.e. to band-to-band recombination of cold electrons. As a comparative figure, if we assume that the Indium mole fraction in the channel is 15%, calculations using material parameters given in [7] result in a bandgap of 1.27 eV at 300 K and 1.34 eV at 100 K. It has to be stressed, however, that these figures must be taken with some caution for a twofold reason: i) due to possible energy quantization in the channel, the peak energy is expected to be somewhat higher than the bandgap of bulk InGaAs, hence a larger Indium molar fraction could be present in the device channel; ii) moreover, due to device self-heating, the channel temperature is higher than the ambient temperature. It can finally be noticed in Fig. 4 that for energies $< 1.1\ eV$ measurements indicate that light intensity does not drop to negligible values; such low-energy photons are in general attributed to Bremsstrahlung [8].

Region 2. In the second region ($1.3\ eV < E < 1.4\ eV$) we note, at 300 K, a shoulder placed at about 1.32 eV. A similar feature is reported in [3], where it is attributed to electron transitions from the second quantized state (E_2) in the conduction band: in our low temperature (100 K) measurement, possibly due to negligible occupation of E_2, the shoulder disappears and a sharper peak is observed. The distance between the 300 K peak and shoulder is approximately 60 meV, a reasonable value for quantized level splitting in a quantum well channel.

Region 3. The high-energy emission ($E > 1.4\ eV$) shows a rather noisy, nearly Maxwellian distribution, which is generally attributed to hot electron recombinations.

C. Integrated light measurements

In order to clarify the emission mechanisms of high-energy photons, integrated light inten-

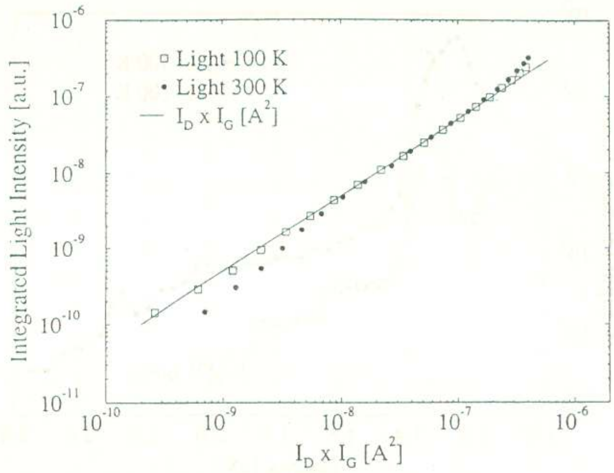

Figure 5: High-energy ($E > 1.5\ eV$) integrated light versus $I_D \times I_G$ product at 300 K (full circles) and 100 K (open squares); $V_{DS} = 4.4\ V$. A solid line corresponding to linear dependence is shown for comparison.

sity has been measured for $E > 1.5\ eV$ as a function of V_{GS}. Previously published measurements [2] carried out on MESFETs and $AlGaAs/GaAs$ HEMTs showed a linear dependence of the integrated light intensity on the $I_D \times I_G$ product, i.e. on the product of electron and hole concentrations; this was claimed to prove that recombination of hot electrons was the main cause of light emission. To investigate this point, in Fig. 5 we plot the dependence of the integrated light intensity at 300 K and 100 K on the product $I_D \times I_G$. A line corresponding to linear dependence is drawn for comparison. A reasonably linear dependence is shown in the central part of th graph, corresponding to gate voltages between -0.3 V and 0.1 V. A marked deviation from linearity is seen outside this range at 300 K. Non-linearities, however, can be expeted both at low V_{GS}, when the gate bias approaches the pinch-off voltage, and at high V_{GS}, due to reduction of the electric field that drives the holes towards the gate.

Conclusions

We report on the observation of a sharp peak in the emitted light spectrum of pseudomorphic HEMTs biased into the impact ionization regime. The energy value corresponding to this peak and its shift with decreasing temperature indicate that it has to be ascribed to recombination of cold carriers from the first allowed state in the conduction band to the first allowed state in the valence band of the InGaAs channel. Moreover, a shoulder in the room temperature spectrum located at a distance of about 60 meV from the peak is attributed to transitions from the second quantized state in the conduction band. The high energy tail of the spectrum, although rather noisy, shows a quasi-Maxwellian behavior, attributed to hot carrier transitions.

Acknowledgments

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