HOT-CARRIER-INDUCED RADIATION EMISSION IN AlGaAs/GaAs HIGH ELECTRON MOBILITY TRANSISTORS AND GaAs MESFETs (§)

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New results are presented concerning the spectral distribution in the 1.7 - 2.9 eV range of the electromagnetic radiation emitted by 0.5 µm GaAs MESFETs and 0.3 µm AlGaAs/GaAs HEMTs biased at high drain voltages (> 4.0 V). The energy distribution of the emitted light intensity cannot be described by assuming a maxwellian electron energy distribution function. The detection of emitted radiation is markedly correlated with the presence of non-negligible gate and substrate hole currents, which are not due to breakdown of the gate-drain Schottky junction, but are due to collection of holes generated by impact ionization.

1. Introduction

Microwave and millimeter-wave communication systems widely adopt GaAs-based FET devices with submicrometer gate lengths. It is well known that, under bias conditions, very high electric fields (up to several tens of kV/cm) can be found near the drain region of submicron FETs. Consequently, the average electron energy largely exceeds the thermal one, leading to undesired "hot electron" phenomena, such as avalanche multiplication [1], increase in gate and substrate currents [2, 3], real-space transfer [4] and trapping phenomena [5].

Energy-resolved measurements of hot-electron induced radiation, coupled with measurements of device electrical characteristics, represent a powerful tool which has been applied to the characterization of GaAs MESFETs [6] and Si MOSFETs [7-10] .

In this paper we present new results concerning the spectral distribution of the radiation emitted by 0.5 µm GaAs MESFETs and 0.3 µm AlGaAs/GaAs HEMTs in the 1.7 - 2.9 eV range, and try to correlate them to microscopical processes characteristic of carrier transport in a high electric field. Our measurements indicate that:

(i) MESFET and HEMT devices emit visible light when biased at high drain voltages (>4 V in our samples);

(ii) for both MESFETs and HEMTs the energy distribution of the emitted light intensity cannot be described by simply assuming a maxwellian electron energy distribution function;

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(iii) for both MESFETs and HEMTs the detection of emitted radiation in the 1.7 - 2.9 eV range is markedly correlated with the presence of a non-negligible gate hole current which is not due to breakdown of the gate-drain Schottky junction.

2. Samples and experimental techniques

The devices used in this study were : (i) commercially available Toshiba S8901 AlGaAs/GaAs HEMTs with gate width W = 200 μm, gate length L_g = 0.3 μm, source-to-gate spacing 0.5 μm and gate-to-drain spacing 1.5 μm, as measured by Scanning Electron Microscopy (SEM) on the device cross-section schematically reported in Fig. 1; (ii) GaAs MESFETs manufactured by Telettra with 10 gates with total W = 600 μm, L_g = 0.5 μm, source-to-gate spacing 2.0 μm, gate-to-drain spacing 2.5 μm.

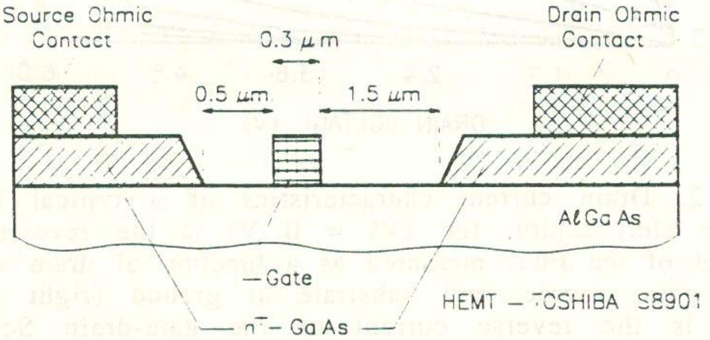

Fig. 1. Schematic cross-section of Toshiba S8901 HEMT devices, as obtained by scanning electron microscopy.

Device characteristics were measured by means of a Hewlett-Packard 4145 Semiconductor Parameter Analyzer, which was also employed for dc biasing the device during optical measurements. An upper bound was chosen for drain voltages Vds, in order to avoid both avalanche breakdown and excessive device heating due to power dissipation. The absence of drifts in the device characteristics was determined by continuously monitoring gate and drain currents and voltages. Self-oscillations of microwave devices were eliminated by adopting adequate coaxial cables and electrical filtering.

The experimental apparatus for spectral analysis of emitted radiation is the same described in [7]; the light emitted by the devices was analyzed in wavelength (energy) by a suitable filter and detected by an S20 photomultiplier, capable of single-photon counting technique (EMI-9816QB). The photomultiplier was cooled in order to reduce the thermionic noise (dark current). The electric pulses not corresponding to single-photon events were rejected by means of a window discriminator (ORTEC 583), while the signals corresponding to single photons have been determined by means of a counter (ORTEC 776). An OCLI-CV 400 - 1200 interference filter monochromator was adopted to perform spectral analysis of the emitted light in the wavelength range 430 - 720 nm, corresponding to the energy range 2.9 - 1.7 eV, respectively.

The reading was corrected by subtracting the constant counts in the dark, due to residual noise; after subtraction, the corrected intensity was obtained by taking into account the filter spectral response and the photomultiplier quantum efficiency.

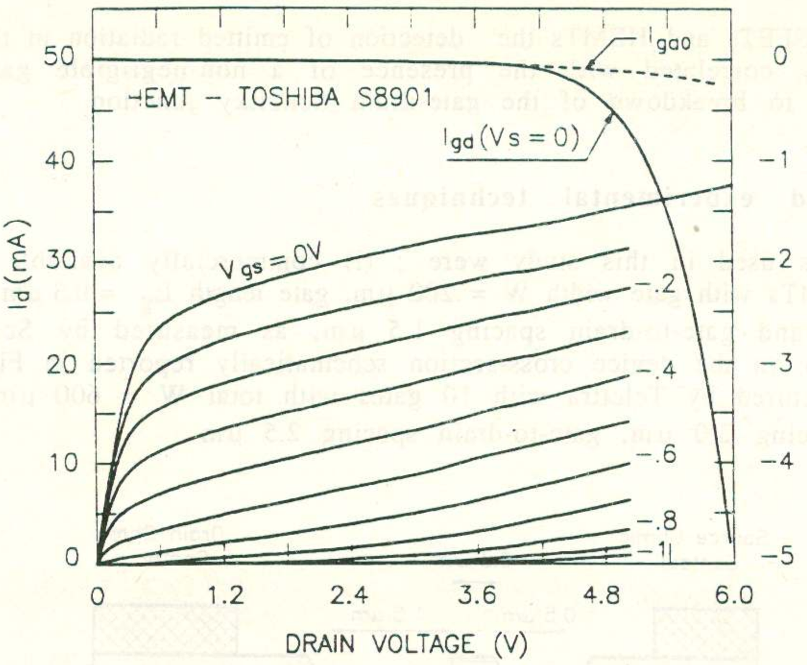

Fig. 2. Drain current characteristics of a typical HEMT device (left scale). Igd (Vs = 0 V) is the reverse gate current of the FET, measured as a function of drain voltage with gate, source, and substrate at ground (right scale). Igd0 is the reverse current of the gate-drain Schottky diode, measured with gate and substrate at ground, source floating (right scale).

3. Experimental results

Figure 2 reports the electrical characteristics of one of the analyzed Toshiba S8901 HEMTs. When biased at high drain voltages (Vds > 4.0 V), these devices emit visible light, with a spectral distribution reported in Fig. 3 for various Vds at 300 K.

Assuming the photon energy distribution to be directly related to the electron energy distribution [9], characteristics temperatures in the range 2500 - 3100 K could be estrapolated from the measurements for Vds = 5.0 - 6.0 V, respectively. This is clearly only a rough estimate of the effective electron temperature in the channel, since it requires the distribution to be maxwellian. The analysis of spectra in Figure 3 shows indeed strong deviations from a simple maxwellian behaviour, suggesting that different temperatures should be used for different ranges. Furthermore, due to the strong inhomogeneity of the electric field distribution (and consequently of the carrier heating) inside the transistor, a single temperature can be used simply as a qualitative reference.

The higher "electron temperature" found at increasing Vds corresponds to the enhancement of the carrier heating, which leads directly to the emission of more energetic photons. Accordingly, a lower temperature (about 1700 K) is derived from the emission spectrum of the MESFET device biased at Vds = 7.5 V and Vgs = -0.6 V (see Fig. 4).

The spatial distribution of the emitted light was also observed by using IR and visible light microscopes (Reichert Infrapol and Zeiss Optiphot); for all the samples, the light emission is homogeneous across the whole active area, ruling out the presence of localized breakdown points or microplasmas [11] .

Figure 5 reports drain current and integrated emitted light intensity of a HEMT device, biased at Vds = 5.0 V, as a function of the gate voltage. This measurement further

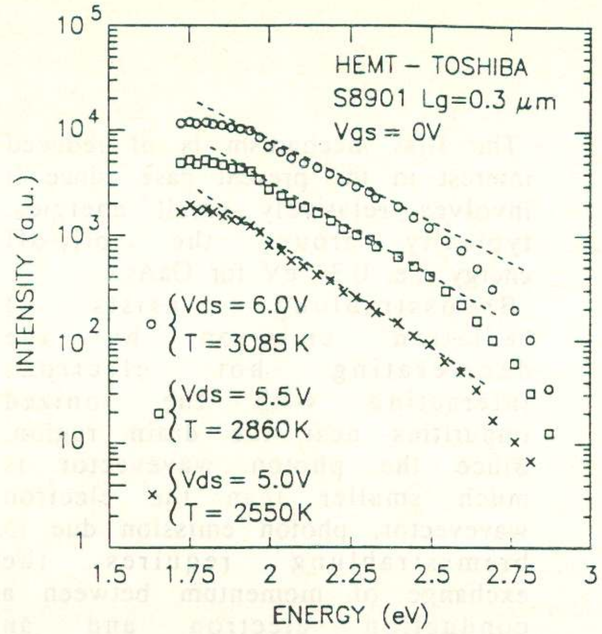

Fig. 3. Emitted light intensity as a function of energy for the same HEMT device as in Fig. 2 at 300 K, biased at Vgs = 0 V and various drain voltages. Electron temperatures extrapolated from the slope of the spectra (dashed lines) are indicated.

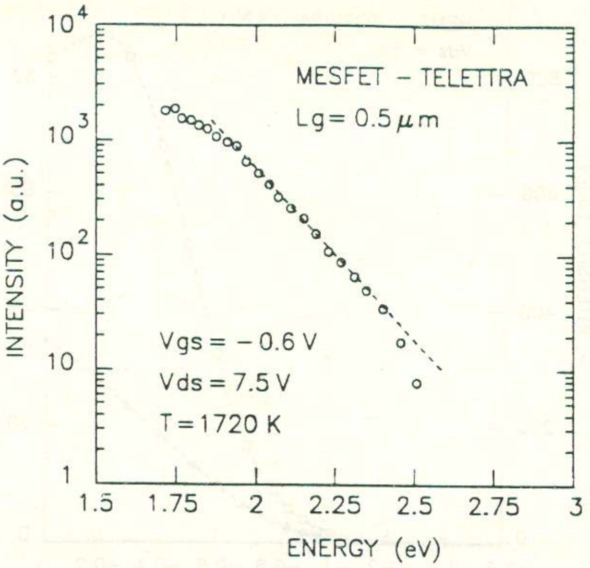

Fig. 4. Emitted light intensity as a function of energy for a typical MESFET device at 300 K, biased at Vgs = -0.6 V and Vds = 7.5 V.

confirms that the observed radiation is due to hot electrons. Accordingly, no photon emission is measured when the device is turned off (Vgs < -1.0 V), while, by increasing the gate voltage, the intensity increases as the number of high energy electrons in the channel increases. When a HEMT or a MESFET device is biased by applying a positive drain voltage (Vds > 4.0 V) with source and gate connected to ground, a marked gate reverse current Igd is observed, as shown in Fig. 2 (right scale) for a HEMT device. Such current is not due to the breakdown of the gate-drain Schottky junction. If the source is disconnected and kept floating, and the reverse characteristics of the gate-drain Schottky diode are measured, a much lower reverse current Igd0 is indeed observed at the same gate-to-drain reverse voltages (see Fig. 2). Being a reverse current flowing out of the device gate, Igd can be attributed only to holes generated through impact ionization by the high energy electrons and collected by the gate and substrate electrodes, both at ground. The increase in Igd is consequently accompanied by an increase of the device substrate current.

The appearance of gate and substrate currents is substantially correlated with the light emission, as demonstrated in Fig. 6, which reports the light intensity (integrated over the whole phototube sensitivity range, 1.55 - 6.0 eV) and reverse gate current Igd, as a function of the drain voltage at Vgs = 0 V. A similar behaviour was observed also for MESFET devices.

4. Discussion

By analyzing the visible light emission from Si MOSFETs, several authors [7-10] have suggested the following mechanisms for photon emission :

a) hole interband emission (mainly from split-off to the heavy hole band);
b) bremsstrahlung;
c) electron-hole recombination.

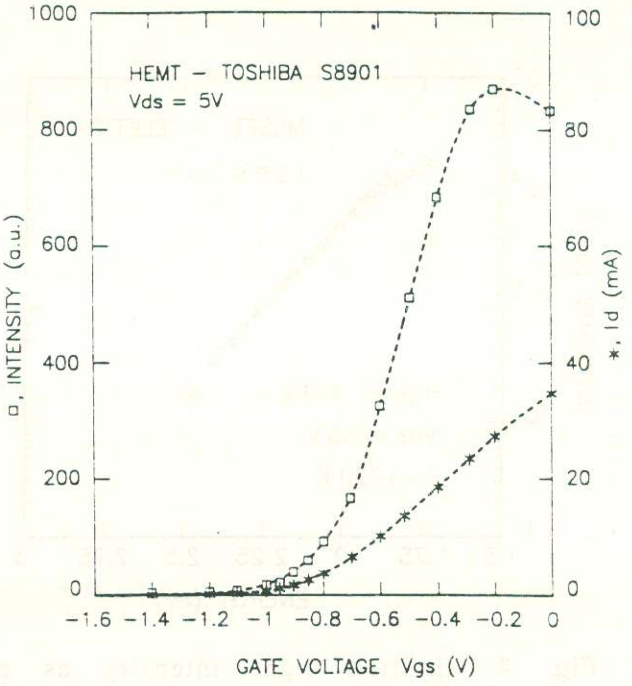

Fig. 5. Emitted light intensity (integrated over the 1.55 - 6.0 eV range) and drain current Id of the same HEMT device as in Fig. 2, as a function of gate voltage, with source and substrate at ground, and drain at 5.0 V.

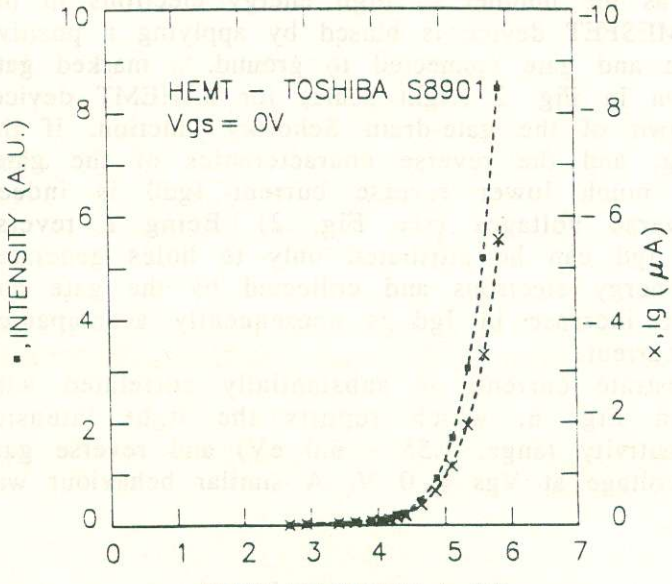

Fig. 6. Emitted light intensity (integrated over the 1.55 - 6.0 eV range) and reverse gate current Ig of the same HEMT device as in Fig. 2, as a function of drain voltage, with gate, source, and substrate at ground.

The first mechanism is of reduced interest in the present case, since it involves relatively small energies, typically around the split-off energy, i.e. 0.34 eV for GaAs.

Bremsstrahlung consists of radiation emission by the decelerating hot electrons interacting with the ionized impurities near the drain region. Since the photon wavevector is much smaller than the electron wavevector, photon emission due to bremsstrahlung requires the exchange of momentum between a conduction electron and an impurity or a phonon.

When conidering electron-hole recombination, we should distinguish between silicon and III-V compounds: in the first case photon emission is still a second-order process, due to the indirect gap of Si, while in GaAs and similar compounds a vertical transition takes place. Therefore, bremsstrahlung and recombination give comparable contributions in Si, as indicated by the experimental results of Herzog and Koch [8]; on the contrary, we expect that in direct gap materials the recombination efficiency should be much higher than bremsstrahlung. In our measurements in the 1.7-2.9 eV range, the observed light emission coincides with the presence of currents exiting from gate and substrate, i.e. due to holes. The physical mechanism we can envisage is therefore the production of hole-electron pairs due to impact ionization in the high electric fields between the gate and drain edges. Part of the generated holes are collected at the gate and substrate electrodes; part of them recombine with incoming channel electrons and lead to the observed radiation.

5. Conclusions

Light emission in the 1.7 - 2.9 eV energy range has been observed for both 0.5 µm GaAs MESFETs and 0.3 µm AlGaAs/GaAs HEMTs. As demonstrated by the gate and substrate current measurements, and by the IR and visible light microscopy observations, the emitted radiation is not due to breakdown phenomena or microplasmas, but appears to be directly correlated to hot electron phenomena in MESFETs and HEMTs, including generation of hole-electron pairs by impact ionization, followed by recombination. Strong deviations from a simple maxwellian behaviour are observed in energy-resolved spectra.

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