Electroluminescence Study of "on" and "off" state breakdown in InP based HEMTs

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Abstract

We investigate the low-energy (0.7-0.9eV) electroluminescence (EL) at low temperature (30 - 100 K) of short gate lattice-matched InP based HEMTs. This study allows to observe directly impact ionization in the "on" and "off" state $In_{0.53}Ga_{0.47}As$ channel. In the on-state, the evolution of the luminescence as a function of the bias applied to the device shows that the electroluminescence intensity depends on two parameters: the gate-drain electric field and the drain current intensity. The voltage breakdown in the off-state is discussed in term of impact ionization in the InGaAs channel due to hot carriers originating from the gate leakage current.

Introduction

Lattice-matched HEMTs on InP substrate present excellent high-frequency and low noise performances [1,2]. However, InP based HEMTs have an important weakness compared with GaAs based HEMTs : the breakdown voltage V_{br} is low. This low V_{br} has been attributed to an impact ionization mechanism in the InGaAs channel [3,4]. These studies are based on electrical characterizations of the gate current. Through an electroluminescence (EL) study of short gate HEMTs on InP, we show directly the localization of impact ionization in the InGaAs channel, both in the on state (conducting channel) and in the off-state. Besides the well-known role of high electric fields in the impact ionization process and their influence on the EL intensity and the device breakdown, we point out the important role of the carrier density of the device current density in the on-state.

The InP HEMT results are compared with a previous study of pseudomorphic InGaAs HEMTs on GaAs [5].

Experimental conditions

The device structure "A" consists of a 600 Å lattice-matched $In_{0.53}Ga_{0.47}As$ channel grown on a 2500 Å $In_{0.52}Al_{0.48}As$ buffer on InP. The channel is followed by a 100 Å $In_{.52}Al_{0.48}As$ spacer, a Si planar doped layer ($5 * 10^{12}$ cm^{-2}), a 100 Å undoped $In_{0.52}Al_{0.48}As$ layer for the Schottky contact and a 100 Å undoped $In_{0.53}Ga_{0.47}As$ cap layer. The device has a single recess and the gate length is L_g = 0.4 µm. At 50 K, the transistors have a threshold voltage V_{th} = - 1 V, exhibit a maximum transconductance g_{mmax} = 420 mS/mm and a maximum extrinsic cut-off frequency of 75 GHz at I_{ds} =150 mA/mm.

The device structure "B" consists of a 600 Å lattice-matched $In_{0.53}Ga_{0.47}As$ channel grown on a 1500 Å $In_{0.52}Al_{0.48}As$ buffer on InP. The channel is followed by a 35 Å $In_{0.52}Al_{0.48}As$ spacer, a 110 Å Si doped layer ($6 * 10^{18}$ cm^{-3}), a 220 Å undoped $In_{0.52}Al_{0.48}As$ layer for the Schottky contact and a 100 Å undoped $In_{0.53}Ga_{0.47}As$ cap layer. The gate length is L_g = 0.3 µm. At 50 K the transistors have a threshold voltage V_{th} = -2.4 V and exhibit a maximum transconductance g_{mmax} = 850 mS/mm and a maximum extrinsic cut-off frequency of 120 GHz at I_{ds} = 500 mA/mm.

A chip with many transistors is placed in a specially developed cryostat designed for both electric (dc, pulsed and microwave) and optical characterization. Movable coplanar heads allow to choose the device to be electrically contacted. The luminescence emitted by the electrically driven device comes out from the cryostat through an optical window above the chip, is focused on the entrance slit of a 0.64 m monochromator and detected with a liquid nitrogen cooled germanium detector.

Photoluminescence of epitaxial layers of studied HEMTs

The photoluminescence (PL) spectra of sample A measured at 5 K is presented in Fig. 1. The excitation light is provided by an argon laser with 50 mW output power. The PL is dominated by the radiative recombination of electrons and holes in the InGaAs channel (≈ 810 meV). At higher energy (1.57 eV), one also observes the radiative recombination associated with the InAlAs layers with a lower intensity as well as PL associated with the InP substrate near 1.4 eV. In the latter case, one distinguishes both the band-to-band emission and an emission involving an acceptor center at lower energy. The peaks associated with the InAlAs layers and the InP substrate have a much weaker intensity than the peaks related to the InGaAs channel, due to carrier relaxation in the low band-gap layers.

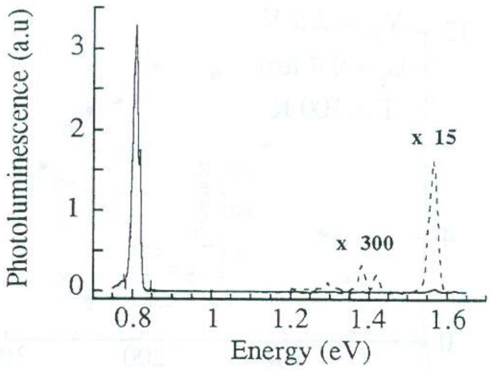

Fig. .1 : 5 K photoluminescence spectra of device A before process

Electroluminescence of HEMTs with a conducting channel

Localization of impact ionization

Fig. 2 shows the EL spectra at 30 K and 100 K of sample A biased at V_{ds} = 3 V and V_{gs} = -0.4 V which corresponds to the maximum transconductance $g_{m,max}$. The spectra present an emission peaked near 0.8 eV, which corresponds to the radiative recombination in the $In_{0.53}Ga_{0.47}As$ channel at these temperatures. This value of 0.8 eV is sufficiently far from the Ge detector cut-off energy to follow "accurately" the peak intensity variations versus applied HEMT biases. This low energy emission is related to radiative recombination in the InGaAs quantum well between cold electrons thermalized at the bottom of E_1 level in the quantum well and holes located on the HH_1 level created by impact ionization. As there is no p-type material in the investigated structures, the holes which are involved in the recombination process are created by impact ionization.

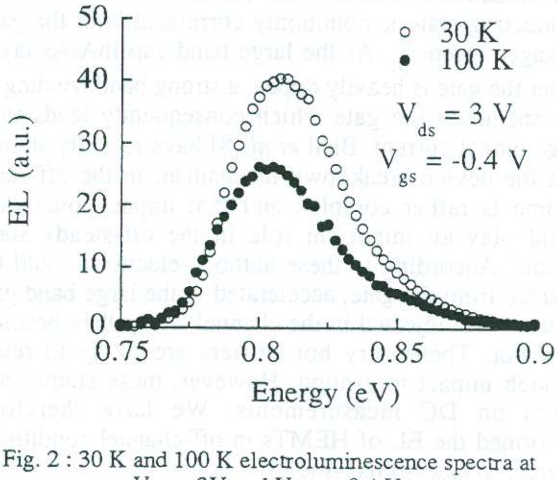

Fig. 2 : 30 K and 100 K electroluminescence spectra at V_{ds} = 3V and V_{gs} = -0.4 V. device A.

The occurence of impact ionization exclusively in the large band gap doped InAlAs layer and the subsequent recombination of the carriers in the channel are unlikely. In such a case, the majority of holes created in InAlAs layers would shift toward the gate whereas a few of them could drift towards the channel. The luminescence of the channel layer would be very weak while a luminescence peak associated to the band-to-band recombination in the InAlAs layer should be observed. This EL peak was not observed in our experiments. We therefore suggest that impact ionization mainly occurs in the channel. it is due to its low band gap energy, to the strong energy that electrons may acquire under these bias conditions and to the large concentration of carriers as compared to other layers. This is the case as long as the gate bias is lower than the voltage corresponding to the Schottky effective barrier height (≈ 0.8 eV).

As the InGaAs channel is relatively thick (60 nm), one observes a single luminescence peak which corresponds to the lowest sub-levels. There is no visible shift with temperature but since the EL emission is rather broad, a small variation is difficult to detect. This situation differs from the PM-HEMTs on GaAs with narrower well which showed luminescence from the first two sublevels [5]. In this case, at low temperatures changes in the respective intensity of the two peaks as well as a variation of their energy spacing have been observed due to Fermi occupation changes, the associated band-bending and the shifts in position of the sublevels with bias.

For these on-state bias conditions, EL involves holes created by impact ionization and electrons which are present in the channel.. Besides, the observation of local heating effects in these short gate InP HEMTs at low temperature is unlikely due to the weak dependence of band gap energy with temperature at 30 K.

The intensity reduction of the EL peak at rising temperatures (cf Fig. 2) reflects the increase of the non radiative relaxation rate respective to the radiative recombination rate as well as the reduction of impact ionization.

Influence of electric field intensity and of carrier density on impact ionization

Fig. 3 shows the variation of the EL peak intensity versus drain-source voltage V_{ds} with V_{gs} as a parameter for a device as in Fig. 2. The EL peak and subsequently impact ionization are detected in the V_{ds} = 2-2.5 V range. The impact ionization threshold may occur at lower voltages, however the created hole current remains small and the detection of the emission is difficult. The above V_{ds} = 2-2.5 V voltage range is somewhat lower than the one corresponding to InGaAs PM-HEMTs on GaAs [6]. It is explained by the smaller band gap energy (0.8 eV) of $In_{0.53}Ga_{0.47}As$ channel (InP HEMT) compared to the 1.2 eV for the strained $In_{0.2}Ga_{0.8}As$ channel of GaAs PM-HEMT.

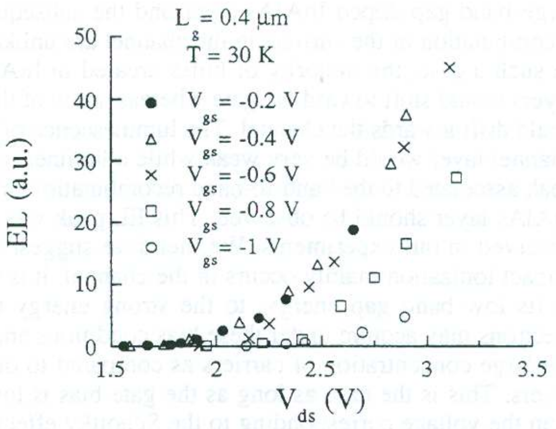

Fig. 3 : 30 K electroluminescence intensity measured at peak maximum versus drain voltage at different gate voltages. Device A.

Fig. 4 shows that the EL peak intensity depends both on V_{gs} and V_{ds}. For V_{gs} near the threshold voltage V_{th} (V_{gs} =- 1 to -0.8 V) and $V_{ds} \leq 2.5$ V, the detected signal has a very weak intensity. At drain voltages $V_{ds} \geq 2.5$ V, the fast rise of the EL intensity at large V_{ds} is accompanied by a noticeable increase of the HEMT output conductance commonly observed in submicron gatelength HEMTs.

Under open channel conditions(-0.6 V< V_{gs}< 0.0 V), Fig. 3 shows a saturation of EL intensity versus V_{gs} for each value of V_{ds}. This trend suggests that opposed mechanisms determine the evolution of the impact ionization rate versus gate bias. It may be mentioned here for comparison that Woodhead *et al* [6] have observed at room temperature in 0.7 µm gatelength HEMTs on InP ($V_{th} \approx$ -1 V) and at moderate current density (I_{dss} = 180 mA/mm) a stronger EL intensity at the larger V_{gs}. The investigated range of V_{gs} biases is larger in our case which explains that we may observe saturation of the EL intensity versus V_{gs}. In order to understand the complex evolution of the EL peak intensity versus V_{gs} seen on Fig. 3, we have reported on Fig. 4 the variation of the EL peak intensity versus I_{ds} at a fixed V_{ds} = 2.5 V. The inset shows the corresponding I_{ds}= f(V_{gs}) characteristic. The EL spectrum presents a maximum versus V_{gs} interpreted as follows. The electric field between gate and drain associated with the applied V_{gd} becomes smaller as V_{gs} is increased. As long as an increase of V_{gs} is followed by an increase of carrier density in the channel with an energy above the impact ionization threshold, the EL peak intensity increases. But when the number of carriers having this threshold energy becomes too small due to lateral field decrease above $V_{gs} \approx$ -0.3 V, impact ionization decreases. This phenomenon is amplified by the saturation of drain source current I_{ds} for V_{gs} reaching positive values. The reduction of impact ionization is further decreased due to the loss of carriers in the channel. Starting from the more negative V_{gs} values, it is the reduction of the carrier density in the channel which is at the origin of the reduction of the impact ionization process.

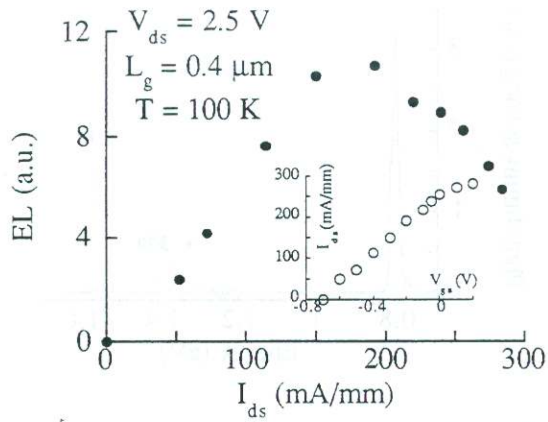

Fig. 4 :Electroluminescence intensity measured at peak maximum versus drain-source current,V_{ds} = 2.5 V, T = 100 K for device A.
Inset : Drain-source current versus gate voltage, V_{ds} = 2.5 V, T = 100 K.

We have shown that impact ionization takes place in the InGaAs channel, and that the importance of the phenomenon depends both on the applied electric field and on the carrier density in the InGaAs channel. It must be emphasized that the impact ionization process is mainly determined by the high energy of the carriers which implies that they do not loose too much energy in their interactions with the lattice when the electric field is too high.
A way to decrease the impact ionization process in a HEMT in the on-state is to increase the spatial extent of the high field region at the drain end of the gate. This is obtained in HEMTs with undoped cap layers. FETs with undoped cap layers have been originally developed in order to reduce the feedback capacitance C_{gd} [7].

Electroluminescence of HEMTs in the off-state

The breakdown voltage of InP based HEMTs in the non-conducting state is commonly correlated with the gate leakage current I_g. As the large band gap InAlAs layer under the gate is heavily doped, a strong band bending is present under the gate which consequently leads to a large tunnel current. Bahl *et al* [8] have recently shown that the device breakdown mechanism in the off-state regime is rather complex and that impact ionization could play an important role in the off-steady state regime. According to these authors, electrons could be injected from the gate, accelerated in the large band gap material and injected in the channel where they become very hot. These very hot carriers are likely to relax through impact ionization. However, these studies are based on DC measurements. We have therefore performed the EL of HEMTs in off-channel conditions in order to assess this issue.

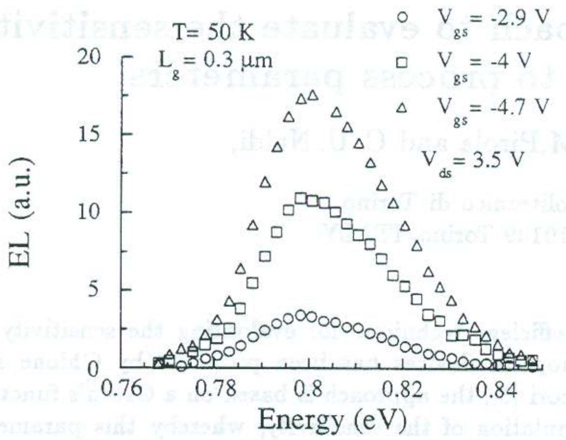

Fig. 5 : Electroluminescence spectrum at $T = 50$ K and $L_g = 0.3$ μm for device B.

Fig. 5 shows the EL spectra at 50 K of a $L_g = 0.3$ μm HEMT, with threshold voltage $V_{th} = -2.4$ V(determined at $V_{ds} = 1.5$ V). The device is biased beyond pinch-off in a regime of strong electric field created by both a very negative gate voltage $V_{gs} << V_{th}$ and a high drain voltage V_{ds}. The EL spectra are shown at different gate biases. The first evidence is that under such bias conditions, the device exhibits EL which implies that impact ionization takes place in the device. Similarly as in conducting channel conditions, the EL peak is centered at 0.8 eV which corresponds to band-edge radiative recombination of carriers in the InGaAs channel. However, since the channel is depleted, the radiative recombination involves either electrons created by impact ionization or electrons injected from the gate. This suggests that in this case, EL is localized between gate and drain. Another difference between impact ionization in channel "on" and impact ionization in channel "off" is that in on-state electrons are accelerated in the plane of the layers while in the off-state electrons are accelerated in the transverse direction.

Conclusion

In summary, we have performed electroluminescence spectroscopy of HEMTs on InP substrates with short gate lengths. E_1-HH_1 recombination around 0.8 eV in the InGaAs channel of a HEMT biased in on-state was observed at cryogenic temperature. The evolution of the luminescence as a function of biases applied on the gate and the drain shows that impact ionization depends on two competing parameters : the electric field between gate and drain and the drain current intensity. We have also shown that impact ionization occurs when the channel is "off" due to hot carriers injected from the gate. This phenomenon contributes to the breakdown of the device when the channel is in off-state.

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References

[1] P.Ho, M. Y.Kao, P. C.Chao, K.H.G.Duh, J.M.Ballingall *et al*, "Extremely high gain 0.15 μm gate-length InAlAs/InGaAs/InP HEMTs", Electronics Lett., Vol.27, no.4, pp. 325-327, Feb.1991

[2] L.D.Nguyen, A.S.Brown, M.A.Thompson, L.M.Jelloian, L.E.Larson *et al*, "650 Å self-aligned-gate pseudomorphic $Al_{0.48}In_{0.52}As/Ga_{0.20}In_{0.80}As$ high electron mobility transistors", IEEE Electron Devices Lett., Vol.13, no.3, pp.143-145, March 1992

[3] J.Dickmann, S.Schildberg, A.Geyer, B.E.Maile, A.Schurr *et al*, "Breakdown mechanisms in the on-state mode of operation of $InAlAs/In_xGa_{1-x}As$ pseudomorphic HEMTs", 6th IPRM, pp.335-338, Santa-Barbara (USA), 1994

[4] C.Heedt, F.Buchali, W.Prost, W.Brockerhoff, D.Fritzsche *et al*, "Drastic reduction of gate leakage in InAlAs/InGaAs HEMT's using a pseudomorphic InAlAs hole barrier layer", IEEE Trans. on Electron devices, Vol.41, no.10, pp. 1685-1689, Oct.1994

[5] F. Aniel, P. Boucaud, A. Sylvestre, P. Crozat, F.H. Julien *et al*, "Electroluminescence spectroscopy of AlGaAs/InGaAs and AlGaAs/GaAs high electron mobility transistors",J.Appl. Phys. 77, pp.2184-2189, March 1995.

[6] J. Woodhead, M. Reddy, J. P. R. David, "Electroluminescence from InGaAs/InAlAs HEMTs", Electronics Lett., Vol.30, pp.1181-1183, July 1994.

[7] Y. C. Pao, C. K. Nishimito, R. Majidi-Ahi, J. Archer, N. G. Bechtel *et al*, "Characterization of surface-undoped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ high electron mobility transistors", IEEE Trans. Electron Devices, Vol.37, pp.2165-2170, Oct. 1990.

[8] S.R. Bahl, J.A.del Alamo, J. Dickmann, S. Schildberg, "Off-state breakdown in InAlAs/InGaAs MODFETs", IEEE Trans. Electron Devices, Vol.42, pp.15-42, Jan.1995