Impact Ionization and Light Emission in InAlAs/InGaAs Heterostructure Field-Effect Transistors

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***Abstract*— We present measurements on impact ionization effects, real space transfer of holes and electrons, and light emission occurring in n-channel InAlAs/InGaAs heterostructure Field-Effect Transistors based on InP operated at high electric fields and at different temperatures. The channel electrons heated by the lateral electric field give rise to impact ionization and light emission. By comparing the electrical characteristics and the integrated light intensity in different energy ranges and at different temperatures, we were able to identify two main different light emission mechanisms: conduction to conduction-band transitions for low energy photons and conduction to valence-band transitions for high energy photons. The correlation between the gate current and the light intensity allowed us to separately evaluate the electron and hole components of the gate current.**

I. Introduction

In RECENT years InAlAs/InGaAs Heterostructure Field-Effect Transistors, HFET's, based on InP have become of great interest in the field of ultra-high frequency microwave applications, owing to several advantages of this heterostructure system such as a high electron velocity and a high room-temperature mobility [1]. In addition the conduction-band discontinuity in InAlAs/InGaAs is 0.5 eV providing excellent confinement for the electrons [2]. Indeed InAlAs/InGaAs HFET's have demonstrated excellent performance [3].

However, due to the narrow bandgap InGaAs channel, impact ionization in InAlAs/InGaAs HFET's is a limiting factor for the power handling capability of these devices, even under normal operating conditions [4]–[9]. Therefore, a detailed physical understanding of impact-ionization and of the behavior of the enormous number of holes that are generated in InGaAs channels is crucial to developing guidelines for designing high-performance devices. Gate current measurements and electroluminescence spectra have been widely adopted to evaluate hot-electron effects and impact-ionization in GaAs-based MESFET's and HEMT's [10], [11], but no agreement has been found as of the origin of the different spectral components of the emitted radiation. No work has been presented, up to now, in InGaAs-based HFET's.

The aim of this paper is to show that in InAlAs/InGaAs HFET's the channel electrons heated by the lateral electric field give rise to impact ionization and light emission. We find that the gate current at room temperature is strongly influenced by Real Space Transfer (RST) of both hot holes and electrons across the InAlAs barrier. At low temperatures ($T = 173$ K) and at high drain voltages, V_{DS}, the gate current, I_G, is dominated by hot hole collection up to positive V_{GS}. By comparing the electrical characteristics and the integrated light intensity, in the 1.1–1.25 eV and 2.0–2.5 eV energy ranges, we are able to identify two different light emission processes. The main emission mechanism in the low energy range is due to conduction-conduction-band transitions, while the high energy range is due to conduction-valence band recombination. This work provides great insight to the physics of hot carriers in InAlAs/InGaAs HFET's.

II. Samples

Samples used in the present work are n-channel, normally on InAlAs/n^+-InGaAs HFET's grown on a semi-insulating InP [12], followed by a 1000 Å $In_{0.52}Al_{0.48}As$ buffer, a 75 Å $In_{0.53}Ga_{0.47}As$ subchannel, a 100 Å n^+-$In_{0.53}Ga_{0.47}As$ Si-doped channel ($N_{Si} = 6 \times 10^{18}$ cm^{-3}), a 300 Å $In_{0.41}Al_{0.59}As$ strained insulator, and a 50 Å $In_{0.53}Ga_{0.47}As$ cap layer. A schematic cross section of the device and the equilibrium energy band diagram are shown in Fig. 1. All measurements were carried out on samples having nominal gate lengths of 1 μm, widths of 30 μm, gate-source and gate-drain distances of 2 μm.

III. Electrical Characterization

Fig. 2(a) shows the typical drain current, I_D, characteristics as a function of the drain voltage up to $V_{DS} = 5$ V for positive and negative gate voltages (-0.6 V $< V_{GS} <$ 0.9 V) measured at $T = 300$ K. Well-behaved characteristics have

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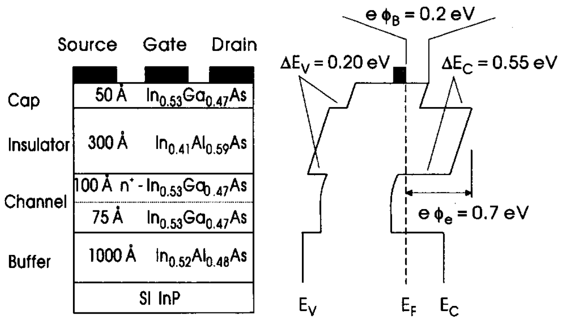

Fig. 1. Schematic cross section of InAlAs/InGaAs HFET and its equilibrium energy-band diagram.

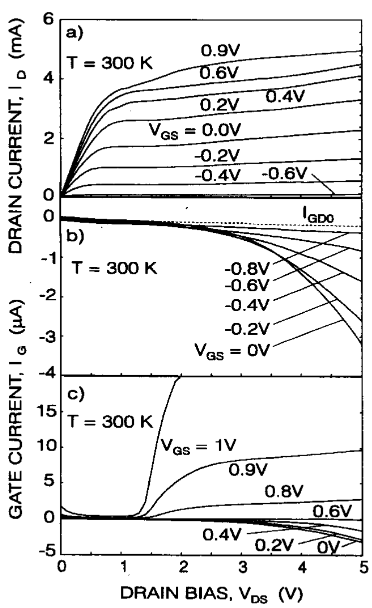

Fig. 2. (a) Device output characteristics as a function of V_{DS} for positive and negative V_{GS} measured at $T = 300$ K. (b) I_G as a function of V_{DS} for negative gate voltages measured at $T = 300$ K. (c) For positive gate voltages measured at $T = 300$ K. Fig. 2(b) also shows as dashed line the leakage current of gate-drain junction I_{GD0}.

been obtained. For negative gate voltages changing from -0.8 V to 0 V, a strong increase in the negative gate current with V_{GS} and V_{DS} is observed at $V_{DS} > 2.5$ V, corresponding to high electric field conditions in the channel, as shown in Fig. 2(b). Furthermore, the negative gate current reaches a maximum when $V_{GS} = 0$ V and then decreases by increasing the gate voltage toward negative values. This increase in the negative gate current is due to the Real Space Transfer (RST) and collection of holes generated by impact ionization at the drain end of the channel, where the maximum electric field occurs. Fig. 2(b) also shows the leakage current of the gate-drain Schottky junction, I_{GD0}, measured by keeping the source floating, which results to be negligible in comparison with I_G.

At high drain voltages with $T = 300$ K and when the gate voltage is increased over $V_{GS} = 0$ V, the absolute value of I_G decreases, I_G changes its polarity and becomes positive for $V_{GS} > 0.6$ V, as shown in Fig. 2(c). For $V_{GS} > 0.6$ V and drain voltages higher than a certain onset voltage, $V_{DS} = 1.3$ V, a dramatic increase in the positive gate current is observed, followed by a saturation at about $V_{DS} = 2.4$ V. This has been explained in terms of the RST of electrons from the source end of the channel to the gate, as already reported by Bahl *et al.* [12].

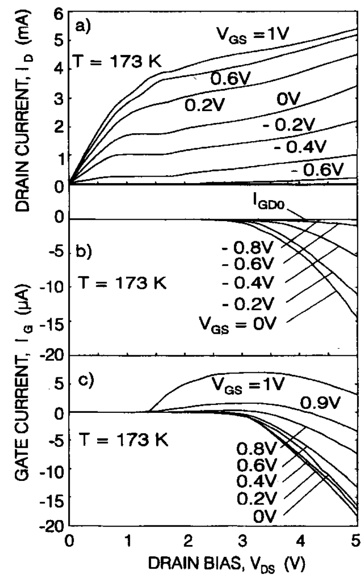

Fig. 3. (a) Device output characteristics as a function of V_{DS} for positive and negative V_{GS} measured at $T = 173$ K. (b) I_G as a function of V_{DS} for negative V_{GS} measured at $T = 173$ K. (c) For positive V_{GS} measured at $T = 173$ K. In Fig. 2(a) the curve I_{GD0} and I_G for $V_{GS} = -0.8$ V are superimposed.

Fig. 3(a) shows similar characteristics to those of Fig. 2 at $T = 173$ K. By comparing the electrical characteristics measured at low and at room temperature, respectively, we notice in the linear regime a smaller slope in the I_D versus V_{DS} characteristics. This indicates an increased linear resistance R_{ON} between the drain and source for low temperatures. For $V_{GS} = 0$ V, the resistance R_{ON} increases from 166 Ω to 193 Ω by lowering the temperature from $T = 300$ K to 173 K. Moreover, at low temperature a slightly larger output conductance is evident with respect to the high temperature data.

Furthermore, as shown in Figs. 2(b) and 3(b), at $T = 173$ K for negative V_{GS}, a remarkable increase by approximately a factor of 5 in the negative gate current, which is dominated by the RST of holes, is observed with respect to the one measured at $T = 300$ K. This effect is mainly explained by the reduction in electron-phonon scattering resulting in an increased ionization rate and hole generation at low temperatures, as commonly observed in many semiconductors [13], [14]. The leakage due to the gate channel Schottky junction is negligible, $I_{GD0} \approx 10$ nA, as well as the gate current in pinch-off conditions.

Fig. 3(c) shows the corresponding gate current for positive V_{GS} at $T = 173$ K. A much larger negative gate current (due to collection of holes) is observed in comparison with room temperature characteristics (see Fig. 2(c)). The maximum I_G now occurs at $V_{GS} = 0.2$ V instead of 0 V at room temperature. On the contrary, RST of electrons decreases. At $V_{GS} = 0.9$ V the positive I_G is 3–4 times lower than that at room temperature. At high $V_{DS} > 3$ V, even with V_{GS} larger than 0.8 V, the contribution of impact-ionized holes is relevant and I_G decreases instead of saturating as it occured at room temperature (see Fig. 2(c)).

At low temperature, one would expect an increase of the electron RST due to the increase of the mean-free path and energy gain, respectively, of the electrons [13], [14], which is in contradiction to our experimental result. A similar decrease of electron RST was also observed by Mastrapasqua *et al.* [15] in CHarge INjection Transistors (CHINT) and was explained by an increase of the barrier height due to an increased contact resistance at low temperature. As mentioned above, the R_{ON} resistance in our devices increases at low temperature suggesting an increase of the resistance of source contact and of the part of the channel between the source and the gate. This causes at low temperature a larger voltage drop occuring at the source contact and in the part of the channel between the source and the gate. This voltage drop gives rise to an increase in the positive potential and as a consequence to a higher effective (InAlAs) energy barrier for the electrons in the channel region where RST of electrons takes place. Therefore, the RST of electrons decreases at low temperature with respect to room temperature as shown in Figs. 2(c) and 3(c).

The effect of an increased voltage drop in the source contact region on the RST of electrons was studied at $T = 300$ K by adding in series with the source an external resistance $R_{ext} = 10\ \Omega$, comparable with the increase of R_{ON} from $T = 300$ K to 173 K. The maximal voltage drop on the external resistance is 80 mV. As a result we notice that the positive gate current due to RST of electrons drops dramatically by a factor of roughly 3 with respect to the condition with $R_{ext} = 0\ \Omega$, as shown in Fig. 4. This strongly suggests that the decrease of electron RST observed at low temperatures is in fact due to the increase of the R_{ON} resistance. The voltage drop of 80 mV also influences slightly the impact ionization current. As it can be seen in Fig. 2(b) that a change of 80 mV in the source drain voltage induces a negligible decrease of the negative gate current induced by the RST of holes.

To show more clearly the contribution of holes and electrons to the gate current I_G in the high electric field regime, we have plotted in Fig. 5 the value of the gate current taken at $V_{DS} = 4.5$ V as a function of V_{GS} and the corresponding gate diode characteristics, I_{GDS}, measured with source and drain short circuited and grounded. For both temperatures, the gate current I_G shows a bell-shape behavior with a maximum at $V_{GS} = -0.1$ V for $T = 300$ K and at $V_{GS} = 0.3$ V for $T = 173$ K, respectively. The bell-shape behavior of I_G was already reported for GaAs-based MESFET's, HEMT's, and PM-HEMT [16], [17]. The qualitative model proposed in [18] explains the bell shape behavior as a superimposition of two effects; as V_{GS} is increased from threshold toward positive values, the number of electrons (I_D) drifting from the drain to the source increases; thus an increasing number of holes is

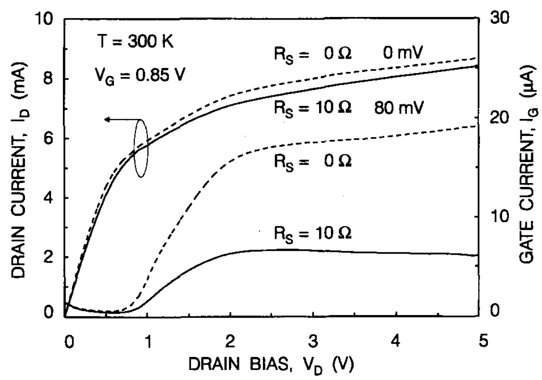

Fig. 4. I_D and I_G characteristics. Dashed line: no external resistance. Continuous line: with a 10 Ω external resistance in series with the source electrode.

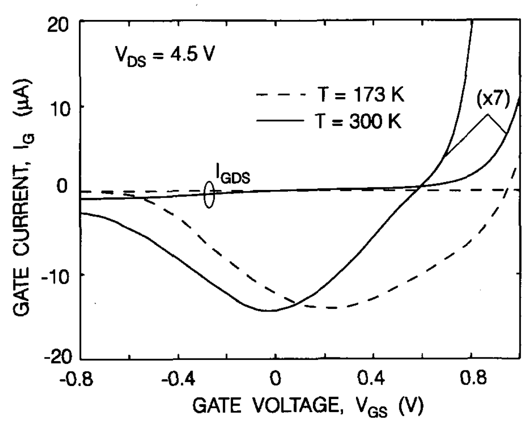

Fig. 5. I_G as a function of V_{GS} measured at constant $V_{DS} = 4.5$ V and at $T = 300$ K (dashed line) and $T = 173$ K (solid line). The gate current I_{GDS} measured with $V_{DS} = 0$ V is included to show that the gate diode forward current does not contribute to positive I_G in the examined V_{GS} range for both temperatures.

generated by impact ionization. These holes exhibit RST over the barrier layer and are collected at the gate; in this regime, I_G is proportional to I_D and therefore increases in absolute value. When V_{GS} is further increased, the longitudinal electric field at the drain-gate gap drops due to the opening of the channel, causing a decrease of electron heating. As the impact ionization rate is exponentially dependent on the electric field, the net result is a strong decrease of holes generated and of the hole contribution to the gate current.

However, in InAlAs/InGaAs HFET the additional presence of RST of electrons must be taken into account to explain the behavior of I_G. In fact when V_{DS} is increased toward positive voltages the RST of electrons remarkably affects I_G adding a positive current component to the negative one due to RST of holes. As a consequence I_G decreases and eventually changes its polarity and becomes positive when, for further increase of V_{GS}, is completely dominated by electron RST. Therefore, the qualitative model proposed to explain the bell-shape behavior of I_G in InAlAs/InGaAs devices is mainly based on the superimposition of two components of I_G: the first one negative, induced by hole RST, and prevailing at negative V_{GS}; the second one positive, induced by electron RST and prevailing for V_{GS} positive and larger than a critical value. The decrease of the longitudinal electric field, which occurs when V_{GS} is increased towards positive values, seems to play a less relevant role with respect to the electron RST to explain the I_G behavior in InAlAs/InGaAs devices, even if it may affect the shape of the gate current and in particular its negative component.

In particular, as can be seen in Fig. 5, at room temperature I_G remains negative (i.e., dominated by holes) for $V_{GS} < 0.6$ V, while for $V_{GS} > 0.6$ V the gate current I_G becomes positive due to RST of electrons. On the contrary, at $T = 173$ K and for $V_{GS} < 0.9$ V the current I_G is negative and much larger than at room temperature due to an increased impact-ionization and to a decreased RST of electrons. As a consequence the maximum of the bell-shape is shifted towards positive V_{GS} values and I_G changes its sign at $V_{GS} = 0.9$ V. At both temperatures the forward gate-source current is always negligible with respect to the gate current as shown in Fig. 5. This clearly demonstrates that the strong increase of the positive gate current is due to the RST of electrons and not due to the forward current of the gate-channel diode at both temperatures.

Summarizing the electrical data, we have demonstrated that under high electric field conditions the gate current in InGaAs/InAlAs HFET's has as its two main contributions RST of holes and electrons. Furthermore, at positive V_{GS} holes contribute to the gate current. The ratio between the electron (I_{Ge}) and hole (I_{Gh}) components of the gate current I_G is strongly dependent on the temperature. By decreasing the temperature, the RST of holes is increased due to increased impact-ionization, while the RST of electrons is reduced due to an increase in the open channel resistance with a consequent increase in the effective barrier height. As a consequence I_{Gh} dominates I_G in a wider V_{GS} range at low T. In the following we demonstrate that a detailed study of light emission can be used to separate quantitatively the electron and hole contribution to the gate current.

IV. Light Emission

When devices are operated at high electric fields infrared and visible light is emitted. Electroluminescence spectra in the 1.1–2.5 eV energy range and integrated light intensity, in the 1.1–1.25 eV and 2.0–2.5 eV energy ranges, were measured using the optical experimental set-up described in detail in [16].

Fig. 6 shows the emission spectra measured at $T = 300$ K and 173 K with the device biased at $V_{GS} = 0$ V and for different V_{DS}. All spectra show several distinctive features in different energy ranges, which are listed below:

i) in the low energy range, $E < 1.25$ eV, all spectra exhibit a nearly flat behavior;

ii) in the intermediate energy range two main features can be observed. First, a remarkable step in the emitted light intensity, is observed at about $E \approx 1.3$ eV. The energy position of this drop exhibits a negative temperature coefficient while it appears to be independent of V_{DS}. Secondly, in the energy range around 1.47 eV, corresponding to the energy gap of the InAlAs insulating barrier, we do not observe the presence of any peak suggesting that direct electron-hole recombination does not occur in this barrier layer;

iii) in the high energy range, $E > 1.8$ eV, all spectra exhibit an exponential behavior in good agreement with a Maxwellian distribution whereas the slopes are different. The effective temperatures, T_{eff}, of these distributions can be evaluated from the slope of the energy spectra and lie in the 1170 K–1360 K temperature range. T_{eff} increases at increasing drain voltages and at decreasing temperatures; and

iv) the intensity of the emitted light, as well as in the low energy and in the high energy range of the spectra, increases remarkably with increasing the drain voltage at constant T, or with decreasing the temperature at constant V_{DS}.

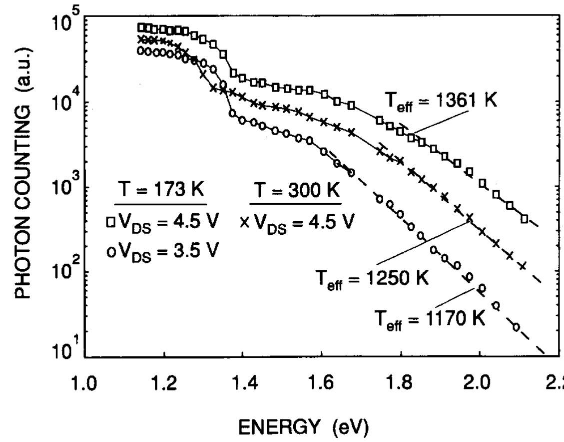

Fig. 6. Spectra of the emitted light for $V_{GS} = 0$ V and for $V_{DS} = 4.5$ V at $T = 173$ K (square) and at $T = 300$ K (cross) and for $V_{DS} = 3.5$ V at $T = 173$ K (circle).

In general there are two important types of light emission processes in semiconductors: radiative transitions which involve only one type of carrier; and radiative recombination involving both carrier types [19]. In the former case, the light intensity is expected to be proportional to the concentration (current) of only one type of carrier, electrons or holes. While in the latter, the intensity is expected to be proportional to the product of the electron and hole concentrations (currents).

To investigate the physics of the light emission mechanisms we have analyzed at different temperatures the correlation between the light intensity I_{INT}, the gate (I_G), the drain (I_D), and the product of these currents ($I_G \times I_D$) as a function of gate voltage. In particular light intensity was integrated in two energy, E, ranges: i) a low energy range 1.1 eV $< E <$ 1.25 eV and ii) a high energy range 2.0 eV $< E <$ 2.5 eV. The correlations taken at $T = 173$ K are shown in Figs. 7 and 8, respectively, while for $T = 300$ K in Fig. 9.

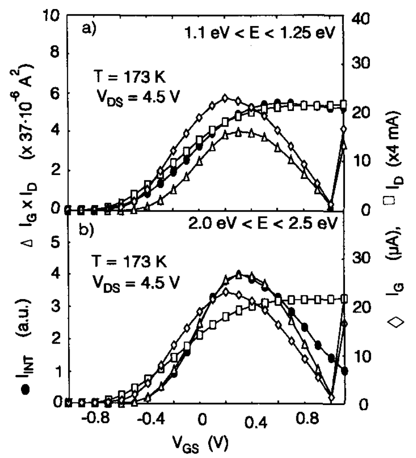

Fig. 7. The integrated light intensity, I_{INT}, in the (a) 1.1–1.25 eV and in the (b) 2.0–2.5 eV energy range and I_D, I_G and $I_G \times I_D$ product measured at constant $V_{\mathrm{DS}} = 4.5$ V as a function of V_{GS} at $T = 173$ K. Normalizing constants have been used for graphical reasons.

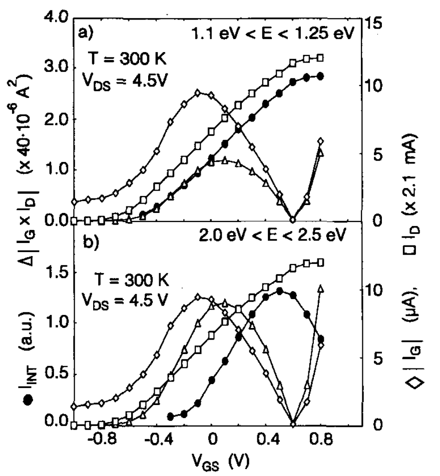

Fig. 9. The integrated light intensity, I_{INT}, in the (a) 1.1–1.25 eV and (b) 2.0–2.5 eV energy range and I_D, I_G and $I_G \times I_D$ product measured at constant $V_{\mathrm{DS}} = 4.5$ V as a function of V_{GS} at $T = 300$ K. Nomalizing constants have been used for graphical reasons.

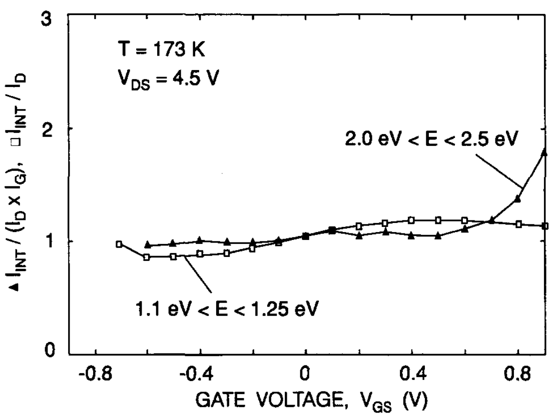

Fig. 8. The ratio I_{INT}/I_D for the 1.1 eV $< E <$ 1.25 eV energy range and $I_{\mathrm{INT}}/(I_G \times I_D)$ for the 2.0 eV $< E <$ 2.5 eV energy rangeas a function of V_{GS} with constant $V_{\mathrm{DS}} = 4.5$ V and $T = 173$ K.

At $T = 173$ K the light intensity I_{INT} integrated in the low energy range (1.1 eV $< E <$ 1.25 eV) shows a tight proportionality with the drain current I_D for all gate voltages applied, as shown in Fig. 7(a). If the integration is carried out in the high energy range (2.0 eV $< E <$ 2.5 eV), the light intensity I_{INT} is proportional to the product $I_G \times I_D$ for $V_{\mathrm{GS}} <$ 0.6 V, while above 0.6 V the correlation is lost, as shown in Fig. 7(b). The linear relationship is evident in Fig. 8, where the ratios I_{INT}/I_D and $I_{\mathrm{INT}}/(I_G \times I_D)$ are plotted for the low and high energy ranges, respectively. For graphical reasons the ratios are normalized at $V_{\mathrm{GS}} = 0$ V.

The tight correlation observed at $T = 173$ K between the light intensity integrated in the low energy range and I_D (see Figs. 7(a) and 8) suggests conduction-to-conduction band transitions as the dominant emission mechanism for low energy photons. Since, as argued before, for this type of emission mechanism we should expect the integrated light intensity to be proportional to the concentration of hot electrons in the channel which can be estimated by measuring the electron current I_D.

On the other hand, the strong correlation observed at $T =$ 173 K between the light intensity integrated in the high energy range and the $I_G \times I_D$ product (see Figs. 7(b) and 8) suggests conduction to valence-band recombination as the dominant emission mechanism for high energy photons. In fact, for this emission mechanism we should expect the integrated light intensity to be proportional to the product of hole and electron concentrations in the channel. As mentioned above the electron concentration is directly represented by I_D, while the hole concentration correlates tightly with I_G when the gate current is mainly dominated by hole collection. As discussed above, at $T = 173$ K, I_G is mainly dominated by hole collection up to $V_{\mathrm{GS}} \approx 0.6$ V. Therefore, we can assume that for $V_{\mathrm{GS}} < 0.6$ V the hole concentration generated by impact ionization is directly proportional to the gate current, which means $I_G \approx I_{Gh}$. Consequently, recombination-induced light emitted is expected to be proportional to the product $I_G \times I_D$, as indeed verified for the high energy part of the emitted light as shown in Figs. 7(b) and 8.

According to these arguments, we only expect these correlations if the current I_G is composed only by holes. This conditions is lost at $T = 300$ K, where, at $V_{\mathrm{GS}} = 0$ V the gate current I_G is due to superimposition of three contribution: RST of holes, RST of electrons and a more pronounced leakage of the gate-drain diode. The correlation is therefore lost as shown in Figs. 9(a) and 9(b). In fact, even at $T = 173$ K when the RST of electrons becomes again comparable with the RST of holes for $V_{\mathrm{GS}} > 0.6$ V at $V_{\mathrm{DS}} = 4.5$ V, the gate current I_G is no longer representative of the hole current and the correlation is lost, as shown in Figs. 7(b) and 8. Even in the low energy range the correlation between the integrated light intensity and the drain current is evident, but less pronounced than at low temperature, as shown in Fig. 7(a).

We emphasize that the light signal in the high energy part of the spectrum is related to electron-hole recombination; therefore, the effective temperature, T_{eff}, reflects the properties of a Maxwellian ensemble of hot electrons and holes created by impact ionization in the high electric field region of the channel of an InGaAs/InAlAs HFET.

The drop in the observed light intensity spectra at E = 1.3 eV, shown in Fig. 6, exhibits a negative temperature dependence similar to the one of an energy gap and could be explained by any of the following mechanisms: a) a scattering mechanism which becomes effective at an electron energy around 1.3 eV for this material system, such as impact-ionization, which has a threshold energy of roughly 1.2 eV [13]; b) a reduction in the density of allowed states for electron energies larger than that value [20]; and c) absorption in the channel or upper layers possibly enhanced by resonance between quantized levels. An unambiguous identification of the physical origin of this step would require further experimental and theoretical work.

V. Gate Current Components

The strong proportionality at T = 173 K and at high V_{DS} between the intensity I_{INT} of high energy light emitted and the product $I_G \times I_D$ for $V_{\text{GS}} < 0.6$ V allow us for the first time to determine quantitatively the contribution of RST of holes, I_{Gh}, and electrons, I_{Ge} to the gate current I_G as a function of gate voltage. The gate current I_G itself at low temperature is given only by the sum of RST of electrons and RST of holes and is expressed as $I_G \approx I_{\text{Ge}} + I_{\text{Gh}}$. In fact the contribution of the leakage current and the forward current of the channel-gate diode can be neglected at T = 173 K for all gate voltages applied. Furthermore at low temperature (T = 173 K) the light emitted by the high energy photons is due to recombination processes. Therefore, the light intensity can be expressed as

$$I_{\text{INT}} \approx k(I_{\text{Gh}} \times I_D) \tag{1}$$

where the proportionality constant k can be determined in the V_{GS} range on which I_G is completely determined by the hole contribution, $I_G \approx I_{\text{Gh}}$. The correlation between I_{INT} and $I_G \times I_D$ product is nearly perfect, i.e., for $V_{\text{GS}} < 0.6$ V as shown in Figs. 7(b) and 8. When I_G is also due to electron RST, i.e., for $V_{\text{GS}} > 0.6$ V, the knowledge of k allows us by using (1) to evaluate I_{Gh} from I_{INT} and I_D values. Consequently the electron component I_{Ge} is then given by the difference of $I_G - I_{\text{Gh}}$.

Fig. 10 shows the gate current I_G, I_{Ge} and I_{Gh} as a function of V_{GS}. For $V_{\text{GS}} < 0.6$ V, where the correlation between the light and the product $I_G \times I_D$ is almost perfect, the magnitude I_{Ge} is zero and the gate current is dominated by holes, $I_G = I_{\text{Gh}}$. In this regime the bell-shape behavior of I_G and its maximum may be explained, as reported for GaAs-based MESFET's and HEMT's [18], by the superimposition of the increase of I_D and of the reduction of the longitudinal electric field at the increasing gate voltage. Above $V_{\text{GS}} = 0.6$ V the component of I_{Ge} enlarges, becomes comparable with the hole component, I_{Gh}, and eventually dominates I_G for $V_{\text{GS}} > 0.9$ V.

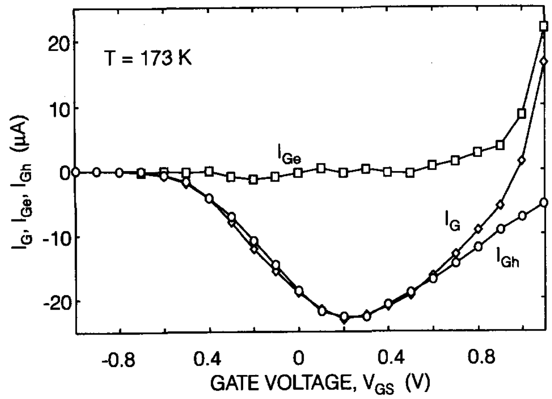

Fig. 10. I_G, I_{Gh} and I_{Ge} as a function of V_{GS}. I_{Gh} is the component of I_G due to collection of holes. I_{Ge} is the component due to RST of electrons, which causes the discrepancy of the correlation between I_{INT} and $I_G \times I_D$ for $V_{\text{GS}} > 0.6$ V, Fig. 7(b).

Note, that this procedure of evaluating the gate current components cannot be applied at room temperature. This is mainly due to the fact that, we cannot find a range of V_{GS} where at the same time the integrated light intensity, I_{INT}, is detectable and the gate current is completely due to I_{Gh}, which would allow us to define the constant k in (1).

VI. Conclusion

In conclusion, we have studied impact ionization, electron and hole real space transfer, and light emission occurring in InAlAs/InGaAs heterostructure Field-Effect Transistors based on InP and operated at high electric fields. When these devices are biased at high V_{DS} (> 3 V), significant impact-ionization takes place in the channel. A detailed study of the gate current reveals that, for negative V_{GS}, I_G is dominated by the collection of impact-ionized holes, while for positive V_{GS}, I_G is dominated by electron real space transfer at low V_{DS} and by hole collection at high V_{DS}.

Light emission both in the infrared and visible region takes place at high V_{DS}. The intensity of the emitted light increases remarkably by increasing V_{DS} or by decreasing T. For energies higher than 1.8 eV all spectra exhibit nearly Maxwellian distributions, with effective temperatures T_{eff} in the 1170 K–1360 K range. T_{eff} increases on increasing V_{DS} and at decreasing T. The intensity of the light integrated in the 1.1 ev–1.25 eV range is found to be proportional to I_D, thus suggesting conduction band-to-conduction band transitions as the dominant light emission mechanism in the infrared range. This mechanism, although predicted by simulation on GaAs MESFET's, has never been demonstrated experimentally [13]. In the 2.0 eV–2.5 eV range, the integrated light correlates well with the $I_G \times I_D$ product, suggesting conduction-to-valence band recombination as the emission mechanism. This correlation allows us to separate for the first time the electron (I_{Ge}) and hole (I_{Gh}) contributions to the gate current. At high temperatures, the quality of the correlation degrades, revealing the increasing relevance of electron real space transfer in I_G.

Finally, the emission mechanisms of light induced by hot electrons in InGaAs/InAlAs HFET's have been identified and electroluminescence intensity has been correlated with electrical characteristics. These methods can now be used by device designers to quantitatively evaluate impact-ionization phenomena and real-space-transfer effects in these devices and by applying the same methodology in other FET structures.

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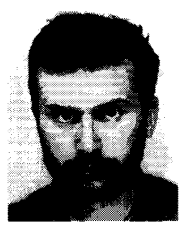

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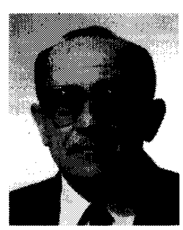

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