Hot electron luminescence in $In_{0.53}Ga_{0.47}As$ transistor channel

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Measurements of light emission are reported in the 1.1–2.5 eV energy range, by hot electrons in the $In_{0.53}Ga_{0.47}As$ channel of a complementary charge injection transistor. By comparing electrical characteristics and light emission, there is the ability to identify the intraconduction band transitions as the main light emission mechanism. Hot-electron effective temperatures up to 2200 K have been determined from high energy exponential tails of the electroluminescence spectra. © *1995 American Institute of Physics.*

Hot-carrier luminescence in compound semiconductor and silicon devices is a powerful technique to investigate hot-carrier effects and degradation phenomena.[1–4] To extract information on hot carriers from the luminescence spectra it is, first of all, necessary to determine the mechanism responsible for the light emission. Recent theoretical and experimental works on silicon based devices have indicated intraband transitions as the main mechanism responsible for hot-carrier luminescence.[5,6] Unfortunately, there is no consensus as to the dominant mechanism responsible for light emission in heterostructure based devices despite a considerable amount of experimental work available.[7]

In this letter, we report the measurements of light emission by hot electrons in the $In_{0.53}Ga_{0.47}As$ channel of a complementary charge injection transistor (CHINT).[8] The complementary CHINT is shown to be particularly suitable for studying the emission mechanism. The absence of a top gate in the device structure and the position of the hot-carrier light emission spot only a few hundred angstroms below the surface, avoids the problems of reabsorption of the light, allowing one to detect smaller signals unaffected by the wavelength-dependent attenuation.

Samples used are complementary n-channel CHINT implemented in lattice matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure material grown by molecular beam epitaxy (MBE) on InP substrates. A schematic cross section of the device and the equilibrium energy band diagram are shown in Fig. 1. The channel length is $L_{ch}=1\ \mu m$ and the channel width is $W_{ch}=40\ \mu m$. Details of the structure and processing have been described previously in Ref. 8. In the normal operating conditions of the CHINT, the source is grounded while both the drain and collector are positively biased. Channel electrons, heated by the drain-source bias V_{DS}, are injected over the barrier into the collector. The real space transfer (RST) of electrons, between the channel and the collector layer, manifests itself in an increase of the positive collector current and, in a complementary CHINT, in an intense light signal due to the radiative recombination with holes in the p-type collector region.[9,10]

At a sufficiently high positive collector bias, the electron energy distribution in the channel is strongly affected by the

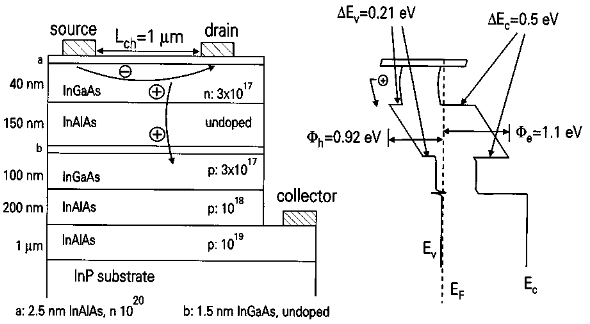

FIG. 1. Cross section of the complementary charge injection transistor structure and its equilibrium energy-band diagram. The downward arrow indicates the RST flux of holes, created by impact ionization, for a bias condition $V_{DS}>0\geqslant V_{CS}$. The doping is in units of cm^{-3}.

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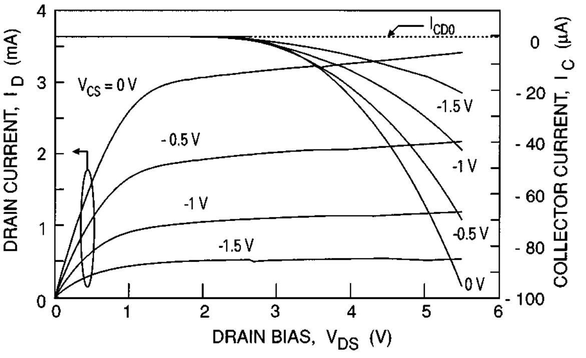

FIG. 2. Room-temperature current-voltage characteristics of the device. The heating bias V_{DS} is varied at different collector biases $V_{CS} \leqslant 0$ V. The dashed line shows the reverse current I_{CD0} of the collect-drain junction, measured with the source floating.

RST, which efficiently removes electrons with energy above the conduction band discontinuity between channel and barrier, $\Delta E_C \approx 0.5$ eV. In contrast, if the collector is grounded, the RST of electrons from the channel is suppressed by the built-in electric field of the collector-to-channel pn junction, which increases the effective barrier height to $\Phi_e \approx 1.1$ eV, as shown in Fig. 1. Therefore, for $V_{CS}=0$ V and indeed for $V_{CS}<0$ V, electrons are confined in the channel and, heated by the drain field, can gain energy far above ΔE_C. The RST process, therefore, no longer prevents impact ionization and generation of holes in the pinch-off region near the drain. These holes drift towards the source, and, heated by the same electric field that is responsible for the impact ionization, undergo RST over the valence-band barrier, $\Delta E_V \approx 0.2$ eV. The built-in electric field of the pn junction, that suppresses the RST of electrons, also helps the RST of holes. The resulting negative collector current I_C, is proportional to the concentration of impact generated holes.[9,11]

With $V_{CS} \leqslant 0$ V the complementary CHINT behaves like a depletion-mode field effect transistor FET, with the collector layer playing the role of a gate. Figure 2 shows the typical drain I_D and collector current characteristics as a function of the drain voltage V_{DS} at different negative collector biases. For a high drain bias ($V_{DS} \geqslant 3$ V) the RST of holes created by impact ionization in the channel results in a negative I_C. This current increases with increasing V_{DS} and becomes several orders of magnitude larger than the reverse current I_{CD0} of the drain-collector junction measured with the source floating (shown in Fig. 2 by a dashed line). The impact ionization current, as monitored by I_C, decreases for higher negative collector voltages since the channel electron density is reduced by the field effect.

For the purpose of studying the hot-carrier luminescence, the complementary CHINT, due to its inverted layered structure with the "gate" (collector) below the channel, has a clear advantage over standard heterostructure field-effect transistor (FETs). The down-gate disposition avoids the problems of light absorption in the gate, allowing us to detect smaller signals. Even more importantly, the down-gate disposition allows the measurement of luminescence spectra unaffected by the wavelength-dependent attenuation due to the gate absorption. Finally, if compared with a unipolar structure, the complementary nature of the collector layer suppresses the drain-collector leakage, permitting to apply higher drain bias.

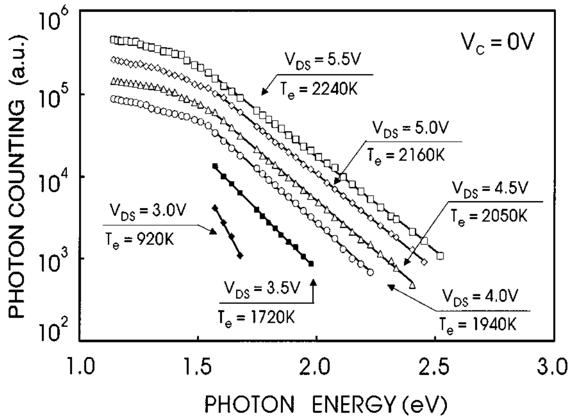

FIG. 3. Room-temperature photon counting of the emitted light as a function of energy at various V_{DS} for $V_{CS}=0$ V. The effective electron temperatures T_e extrapolated from the slope of the spectra (continuous lines) are shown.

The optical setup used in the present work is described in Ref. 1. Figure 3 shows the room-temperature emission spectra with the device biased at $V_{CS}=0$ V and different drain bias.[12] The intensity of the emitted light increases with increasing drain voltage. At energies higher than 1.5 eV all spectra exhibit an exponential tail whose slope decreases with increasing drain voltage. At low photon energy, the slope of the spectra decreases. Similar results were also obtained for $V_{CS} \leqslant 0$ V.

In order to correlate the luminescence spectra with the hot-carrier energy distribution it is necessary to ascertain the mechanism responsible for the light emission. The two relevant candidates are: radiative recombination between the conduction and the valence band and intraband radiative transitions which involve only one type of carrier. In the former case the light intensity is expected to be proportional to the product of the electrons and holes concentration, while in the latter the intensity is expected to be proportional to the concentration of either electrons or holes. In either of these two cases, to generate photons with energy well above the forbidden gap of $In_{0.53}Ga_{0.47}As$, the emission must occur in the high field region of the channel.

At electric fields, high enough to cause impact ionization, the drift velocities of both electrons and holes are saturated and I_D is proportional to $(nv_s^e+pv_s^h)$,where n and p are, respectively, the electrons and holes concentration in the high field region of the channel, v_s^e is the electron saturation velocity, and v_s^h is the hole saturation velocity. At our operating biases, the contribution of impact generated holes to I_D can be neglected.[13] In fact, the transistor is still far from breakdown as is evidenced by the absence of an exponential increase of I_D in Fig. 2.

In Fig. 4 we compare the light intensity P, integrated over the 1.1–2.5 eV energy range, with I_D, I_C, and $I_C \times I_D$, as a function of V_{CS} at a fixed $V_{DS}=4.5$ V. Similar correlations were obtained for all V_{DS} values ranging from

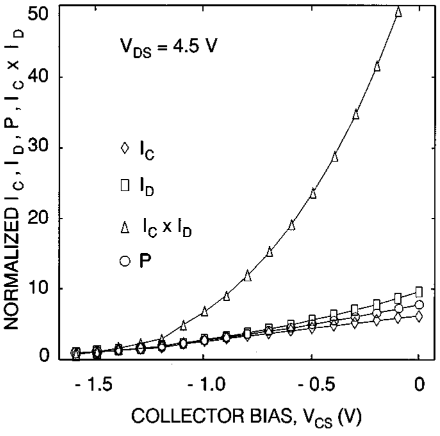

FIG. 4. Collector bias (V_{CS})dependence of: light intensity P (integrated over 1.1–2.5 eV energy range), collector current I_C, drain current I_D, and the product $I_D \times I_C$. All the quantities are normalized to their respective values at $V_{CS} = -1.5$ V.

3.0 to 5.5 V. As the collector bias increases I_D also increases due to the field effect. The bias condition of Fig. 4 corresponds, in first approximation, to a constant electric field in the pinch-off region. The impact ionization current, represented by I_C, is therefore expected to be proportional to I_D. The small discrepancy shown in Fig. 4 is due to the fact that, when V_{CS} increases the drain saturation bias also increases and therefore the electric field in the pinch-off region slightly decreases. This explains why I_C increases less than I_D.

The light intensity is seen in Fig. 4 to follow both I_C and I_D. This indicates that the light emission mechanism is caused by a single carrier transition, either hot electron or hot hole, and not by the bipolar recombination between the conduction and the valence band. In the latter case, we would expect P to scale with $I_C \times I_D$. We can be certain that electrons are the carriers responsible for the light emission, because the density of hot electrons in the high field of the channel is far greater than the density of holes (by more than an order of magnitude as indicated by the ratio of the drain and the collector currents). We remark, moreover, that hot holes with energy above the valence barrier $\Delta E_V \approx 0.2$ eV would hardly remain in the channel, since their RST is very efficient.

Thus, we identify the transition of hot electrons within the conduction band, as the cause of high energy photons in the luminescence spectra. These transitions may be either direct or assisted by phonons or impurities. Our experimental data alone do not allow us to discriminate among these processes. Only by comparing the experimental result with a simulation of the electron distribution function, including a realistic band structure for $In_{0.53}Ga_{0.47}As$ material and the proper matrix elements for each transition, we may be able to identify the prevalent light emission mechanism and to determine the exact correlation between the photon spectra and the electron distribution function.[5] However, assuming that, for energy greater than 1.5 eV, the electron density of states is constant and the matrix elements for the radiative transition are energy independent, the electron energy distribution is directly related to the photon spectra.[3] With these assumptions, an effective electron temperature T_e, that increases with V_{DS} from $T_e = 900$ to 2200 K, can be extracted from the high energy exponential tails of the light spectra in Fig. 3.

In conclusion, we have studied the light emission of hot electrons in the $In_{0.53}Ga_{0.47}As$ transistor channel of a complementary CHINT in the condition of impact ionization. Transitions of hot electrons within the conduction bands are identified as the mechanism responsible for the light emission. The slope of the tail of the luminescence spectra indicates an effective electron temperature as high as 2200 K.

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[12] Since the luminescence signal for the two lowest drain bias, $V_{DS} = 3.0$ and 3.5 V, is below the noise level of the infrared detector, the spectra at these biases are reported only for photon energy greater than 1.6 eV.

[13] The onset of a pronounced minority-carrier RST occurs at much lower fields than that required to produce enough impact ionization to be manifested in the drain characteristics. This can be seen with particular clarity from Fig. 8 of Ref. 9 where the phenomenon of minority RST was reported for the first time.