Impact Ionization and Real-Space Transfer of Minority Carriers in Charge Injection Transistors

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***Abstract*—High electric fields in the channel of InGaAs/InAlAs heterostructure complementary charge injection transistor give rise to impact ionization and real-space transfer of minority holes from the channel. These phenomena are investigated by measuring light emission in the 1.1–3.1 eV energy range for different points on the electrical characteristics. The effective carrier temperature, determined from the exponential tails of electroluminescence spectra, is 2100 K in the channel and 450 K in the barrier.**

OPERATION of the charge injection transistor (CHINT) is based on real-space transfer (RST) [1], [2] of hot electrons between two conducting layers. Unipolar CHINT, employing the RST of majority carriers between layers of the same conductivity type, has been extensively investigated, see the review [3]. Recently an optoelectronic version of the device, in which RST occurs into a collector layer of complementary conductivity type, was proposed [4] and demonstrated [5], [6]. Charge injection transistors have a potential for ultrahigh speed microwave applications [7], [8] and permit the implementation of multiterminal optoelectronic logic functions [9].

In this letter, we report the study of impact ionization phenomena occurring at high electric fields and the RST of both majority (electrons) and minority (holes, generated by impact ionization) carriers in a complementary CHINT. These phenomena are accompanied by light emission which has been studied in the 1.1–3.1 eV range. Samples used are complementary n-channel CHINT implemented in lattice matched InGaAs/InAlAs heterostructure material grown by 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 $L_{CH} = 1$ μm and the channel width is $W = 40$ μm. Details of the structure and processing have been described previously [9].

In the normal operating regime the source of CHINT is grounded, while both the drain and the collector are positively biased. Channel electrons, heated by the lateral field, are injected into the collector layer over the barrier $\Delta E_C \cong$ 0.5 eV. In a complementary CHINT, the injected electrons recombine with holes in the collector active region, emitting radiation peaked at h$\nu \cong 0.75$ eV, corresponding to the bandgap of InGaAs [5], [6], [9].

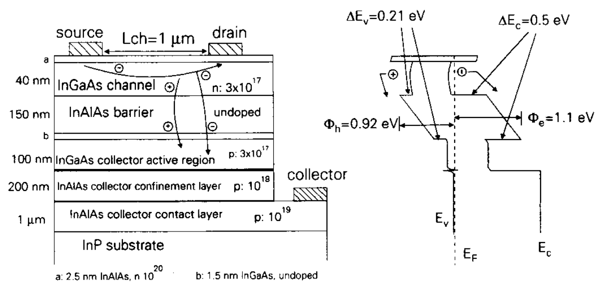

Fig. 1. Cross section of our complementary charge injection transistor structure and its equilibrium energy-band diagram. Arrows indicate the RST fluxes of both majority electrons and impact-ionized holes for a bias condition $V_D > V_C > 1$ V. The doping are in units of cm^{-3}.

In contrast, when the collector is grounded, $V_C = 0$ V, the RST of channel electrons is suppressed by the built-in electric field of the collector-to-channel pn junction, which increases the effective barrier height to $\Phi_e \cong 1.1$ eV. Therefore, for $V_C = 0$ V and indeed for $V_C < 0$ V, electrons are confined to the channel and, at sufficiently high drain-source bias, can gain sufficient energy to impact ionize. Similar potential configuration with electron confinement in the channel occurs also at the channel drain side for positive V_C, provided $V_D > V_C$. Holes, created by this process near the drain, drift toward the source, gaining energy from the channel field. The RST of hot holes over the valence-band barrier, $\Delta E_V \cong 0.2$ eV, gives rise to a negative collector current, a direct evidence of impact ionization in the channel [9].

Fig. 2 shows the typical drain, I_D, and collector, I_C, current characteristics as a function of the drain voltage, V_D, at different collector biases, both positive and negative. For negative V_C and high drain bias ($V_D > 3$ V) the electrons in the channel acquire enough energy to impact ionize. Holes created in the channel undergo RST over the barrier and are injected into the collector resulting in a negative I_C, Fig. 2(b). This current is several orders of magnitude larger than the reverse current I_{CDO} of the drain-collector junction measured with source floating, shown in Fig. 2(b) by a dashed line. At constant V_D, the RST of holes, as monitored by I_C in Fig. 2(b), decreases when we apply higher negative collector voltage. This is because the gating action of the collector layer suppresses, as shown in Fig. 2(a), the electron channel current.

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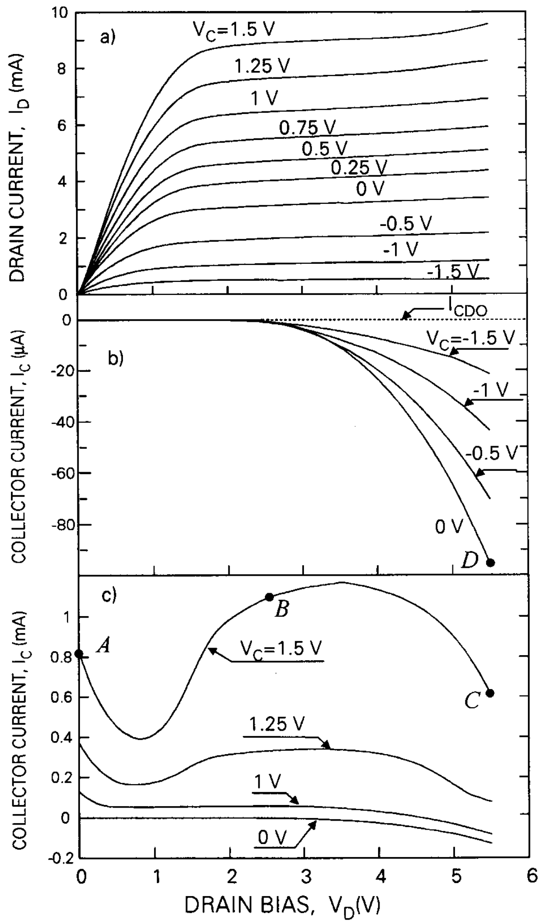

Fig. 2. Room temperature current-voltage characteristics of the device. The heating bias V_D is varied at different fixed collector biases V_C. (a) Drain current I_D. (b) Collector current I_C at negative V_C. Dashed line shows the reverse current I_{CDO} of the collector-drain junction, measured with source floating. (c) Collector current I_C at positive V_C. Points A, B, C and D indicate the bias conditions of optical measurements reported in Fig. 3.

Consequently, I_C, which is proportional to the number of holes created in the unit of time by impact ionization of the electron in the channel, decreases.

When the collector is positively biased above 1 V, top curves of Fig. 2(c), we can distinguish three regions of different behavior. At $V_D = 0$ V, the I_C is the forward current of collector-channel pn junction. With increasing V_D this current drops roughly by half, as the collector-to-drain bias decreases. For $V_D > 1$ V the RST of electrons takes over and I_C increases to a maximum value at $V_D \cong 3.5$ V. At still higher V_D, a decrease of I_C is observed, also due to negative contribution by the RST of impact-ionized holes from the channel into the collector. At $V_C = 1.5$ V the electron RST current, although clearly identifiable by the increase in I_C, is only a small fraction of I_D and no negative differential resistance (NDR) appears in the drain current characteristics. At higher values of V_C the electron RST current becomes comparable to I_D and a clear NDR shows [9].

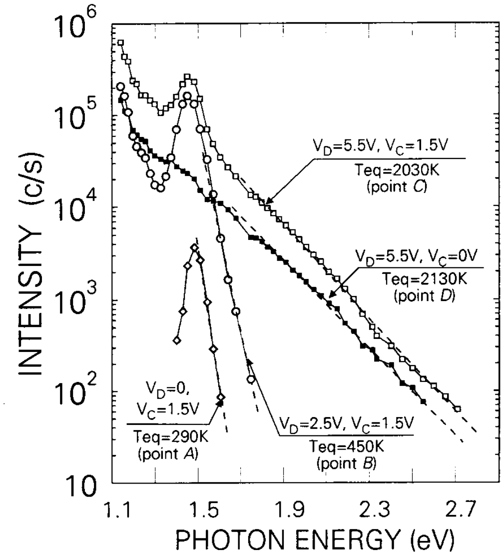

Fig. 3. Room temperature light emission spectra at different bias configurations (labeled as in Fig. 2). Equivalent temperatures T_{eq} are calculated from a linear interpolation of the high energy tails.

Our optical measurement set-up is described in Ref. [10]. The 1.1–3.1 eV photon energy range of the present study does not include the region of intense emission around the InGaAs band gap energy 0.75 eV, arising from the radiative recombination of RST electrons in the collector active region [5], [6], [9]. Fig. 3 shows the room temperature emission spectra, obtained with the device biased in four different conditions, indicated in Fig. 2 by points A, B, C and D.

At point A ($V_D = 0$ V and $V_C = 1.5$ V) the pn junction, formed by the collector and channel layers, is under forward bias. Radiative recombination of thermalized carriers in either of these layers, produces a luminescence signal at 0.75 eV, out of our range. The observed peak at 1.47 eV is due to the recombination of holes and electrons *in-flight* over the barrier. Because of the band alignment in InGaAs/InAlAs, the forward diode current is mostly due to holes [5] injected from the collector with a small contribution of electrons injected from the channel. The recombination signal is thus limited by the availability of electrons. When the drain bias is increased, keeping the source grounded and the collector fixed at 1.5 V (which corresponds to moving along the characteristic shown by the top curve in Fig. 2(c)), the intensity of the electroluminescence peak at 1.47 eV first decreases, roughly by half, as the forward bias current is quenched under the drain contact. Then, as the electrons are heated by the lateral field, point B, the intensity of the peak is enhanced by two orders of magnitude, as the number of electrons over the barrier increases due to RST. From point B to C, the RST of electrons slightly increases further, and so does the peak intensity, although the collector current decreases, also due to a negative contribution from the RST of holes into the collector. In contrast, no peak is detected when the device is biased at point D ($V_D = 5.5$ V, $V_C = 0$ V), since at this point *only* the RST of holes takes place, the barrier for electrons being too high.

High energy tails of the emission spectra in Fig. 3 are nearly exponential. The equivalent temperature, T_{eq}, obtained from the slope of these spectra, is representative of the temperature of carriers involved in the mechanism of light emission [11]. The spectrum at point A shows a $T_{eq} \cong 290$ K, indicating that the electron-hole plasma in flight over the barrier is in equilibrium with the lattice. For the spectrum at point B, the T_{eq} rises up to 450 K, indicating that the plasma in the barrier layer is overheated by hot electrons participating in RST.

Much higher equivalent temperatures, $T_{eq} \cong 2100$ K, are observed in the two spectra obtained at points C and D, where the heating bias is high, $V_D = 5.5$ V, and impact ionization takes place in the channel. We emphasize that the signal in this region of the spectrum, h$\nu > 1.9$ eV, is not related to electron-hole recombination in the collector. The latter is peaked at 0.75 eV and has a much steeper tail. It is possible to recognize a trace of this tail in the lower energy part of the spectra, corresponding to points B and C in Fig. 3. The signal with equivalent temperature $T_{eq} = 2100$ K reflects the properties of a Maxwellian ensemble of electrons and holes created by impact ionization in the channel of a complementary CHINT.

We found a tight correlation between the light intensity P (integrated over energies higher than 1.1 eV) and the collector current I_C. In the collector grounded configuration, the dependences $P(V_D)$ and $I_C(V_D)$ are proportional to one another (while varying over three orders of magnitude) to within the sensitivity of our optical measurement set-up (> 100 counts per second). Inasmuch as I_C is proportional to the number of holes generated by impact ionization, this correlation lends further support to our interpretation.

In conclusion, we have studied the RST of minority carriers, generated by impact ionization in the channel of a complementary CHINT at high electric fields. Visible light emission has been analyzed in the 1.1–3.1 eV range. Hot electron luminescence spectra indicate that the effective temperature of carriers in the channel is as high as 2100 K.

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