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Monte Carlo simulation of impact ionization and light emission in pseudomorphic HEMTs

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Abstract

We present theoretical investigations of electrical and optical phenomena in the near breakdown regime of pseudomorphic HEMTs. The main effect of the drain current enhancement is found to be a parasitic bipolar effect due to holes, created by impact ionization, which accumulate in the substrate. Calculated electroluminescense spectra of holes, radiatively recombining with electrons in the source-sided channel, exhibit transitions which are allowed due to the bias-induced band bending of the channel. The calculated electroluminescence of the gate-source region agrees well with available experimental data. We predict that the hole accumulation in the source side of the channel region takes place on a time scale of ~150 ps, thus allowing a direct time-resolved experimental observation. © 1999 Elsevier Science B.V. All rights reserved.

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A better understanding of on-state and off-state breakdown mechanisms of HEMTs has been achieved in recent years [1–3]; in particular, experimental and theoretical analysis have shown that one mechanism leading to on-state breakdown is the accumulation of holes generated by impact ionization in the channel and in the buffer or donor layers between gate and source [1,3]. Most of these studies, however, refer to DC conditions, and only few works have considered high-frequency pulsed behavior, which could be more relevant for microwave and millimeter-wave applications of HEMTs. Vaschenko et al. [4] studied drain breakdown of GaAs MESFETs in the ns and sub-ns range and demonstrated that a portion of the holes that was generated near the drain accumulated in the SI buffer near the n + source contact, and that device burnout took place in sub-ns times. David et al. [5] estimated the time until breakdown as a function of gate-drain voltage in GaAs MESFETs; they found typical times in the 20–240 ps range. More recently, Dunn et al. [6] carried out a Monte Carlo simulation of impact ionization in 1.2 μm MESFETs and found that accumulation of holes and electrons can also be correlated to the onset of oscillations with a typical period of 5–10 ps.

Spectroscopic analysis of electroluminescence (EL) was extensively used to characterize hot

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carrier effects in MESFETs and HEMTs, starting from the works of Zanoni et al. [7], Zappe et al. [8] and Ostermeir et al. [9]. In Ref. [10] we demonstrated that the dominant contribution in the electroluminescence spectrum of AlGaAs/GaAs HEMTs around 1.4 eV was due to recombination of electrons with holes generated by impact ionization. We also observed, in the spectra of AlGaAs/GaAs and AlGaAs/InGaAs HEMTs [11,12], a peak due to the band-to-band recombination of 'cold', non-energetic, electrons and holes. This strongly suggested the presence of holes in a low electric field region of the device [13]. Recently, Shigekawa, Enoki et al. [14,15] were able to directly observe spatially resolved electroluminescence at energies corresponding to direct recombination in the $In_{0.53}Ga_{0.47}As$ channel of InP-based HEMTs. They demonstrated that the electroluminescence emission related to the recombination peak actually comes from the gate-source low electric field region.

In this paper, we report on the dynamic behavior of breakdown effects and electroluminescence related to impact ionization in 0.25 μm double heterojunction HEMTs, by means of Monte Carlo simulation. By using the distribution functions obtained by MC simulations, a recently developed tight-binding approach [16] allows us to calculate luminescence spectra of the HEMT without introducing new fitting parameters. The 2D self-consistent Monte Carlo code accounts for three conduction valleys and three valence bands. The Poisson equation is solved by applying a multi-grid technique. Impact ionization, investigated in Refs. [17–19] for lattice matched and strained InGaAs, respectively, has been described by a modified Kane model [20]. The general purpose weighted Monte Carlo procedure presented in Ref. [20] has been adopted to achieve a correct description of the physics of HEMT breakdown.

The simulated device consists of a highly doped GaAs cap layer, a 35 nm $Al_{0.2}Ga_{0.8}As$ upper barrier layer with an active Si doping concentration of $N_D = 2 \times 10^{18}\,cm^{-3}$, a 2 nm undoped $Al_{0.2}Ga_{0.8}As$ upper spacer layer, a 12 nm $In_{0.2}Ga_{0.8}As$ undoped channel layer, a 2 nm undoped $Al_{0.2}Ga_{0.8}As$ lower spacer layer, a 400 nm $Al_{0.2}Ga_{0.8}As$ lower barrier layer on a GaAs buffer. The $Al_{0.2}Ga_{0.8}As$ barrier layer below the channel contains an 8 nm thick doping layer with an active doping concentration of $N_D = 2 \times 10^{18}\,cm^{-3}$. A symmetric recess for the gate with length $L_g = 0.25\,\mu m$ has been adopted.

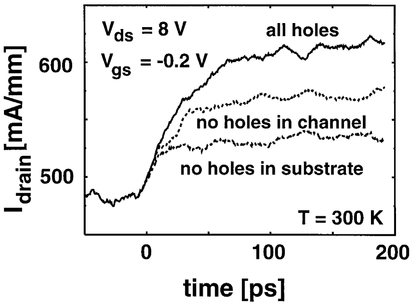

Fig. 1. Drain current versus time, calculated by taking into account various space charge contributions due to hole accumulation in the device. Solid line: total space charge (all holes); dashed line: all holes below channel removed (no holes in substrate); dashed dotted: holes in channel excluded from self-consistent solution of Poisson equation (no holes in channel). At $t = 0$, impact ionization is switched on in the simulation.

Biased at high drain voltage, the electrons in the channel become energetic enough to start impact ionization in the high-field region of the channel. Accompanied by the onset of impact ionization we find an enhanced drain current. This temporal evolution of the drain current is depicted in Fig. 1. To analyze the influence of holes on the drain current, we monitored the hole density in the device as a function of time. We find that the majority of holes, generated in the high-field region of the channel, follow three paths. Either they spill over to the barrier layers in the region where they are created, or move along the channel towards the source contact. The holes in the upper barrier layer move directly to the gate contact, where they are collected to calculate the gate current. The holes moving along the channel towards the source contact first accumulate under the gate contact (~10–20 ps). Some of them diffuse further towards the source contact and accumulate in the source sided part of the channel. The rest diffuse into the substrate. To figure out, whether the hole space charge in the source-sided channel or the one in the substrate is mainly responsible for the enhanced drain current, we removed all the holes which
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diffuse into the substrate below the channel. The corresponding drain current enhancement due to impact ionization is reduced (see dashed line in Fig. 1) by $\sim \frac{2}{3}$. This indicates that the hole space charge in the substrate region mainly causes the enhanced drain current. As a further proof of this effect, we excluded the hole charge in the source sided part of the channel from the net charge which enters into the self-consistent potential profile calculation. The corresponding temporal evolution of the drain current is dipicted in Fig. 1 (dashed dotted line). For this situation, the stationary drain current is only marginally reduced ($\sim$20%) with respect to the simulation taking into account the hole charge all over the device. This confirms that the increased drain current of this device, biased close to breakdown, originates mainly from the accumulation of holes in the source-sided layer, which in turn, gives rise to an enhanced drain current via a parasitic bipolar effect.

The presence of electrons and holes in the InGaAs channel opens the way for radiative recombination processes leading to band edge electroluminescence. As already discussed above, the holes generated in the drain-sided high-field region of the channel partially move towards the gate contact, while the rest is sweept back in the channel towards the source contact or moves towards the substrate. A considerable overlap between cold electrons and holes can be found only in the channel. As a first estimate, the emitted light intensity can be considered to be proportional to the product of electron and hole density. This suggests the following scenario. At short times (20 ps) recombination starts in the channel at the source-end of the gate region, due to the accumulation of holes in the gate-induced potential valley. On a time scale of $\sim$150 ps, however, hole accumulation takes place also in source region of the channel, which seems to be in an accessible range for direct time-resolved measurements.

By using the stationary distribution functions obtained by the MC simulation, we calculated the electroluminescence spectra of the HEMT by the previously mentioned tight binding approach. The calculated electroluminescence spectrum, for $T =$ 195 K, as a function of the emission energy is shown in Fig. 2 and compared with experimental data. Since hole and electron distribution function, as well as potential profile vary from gate to source, we have averaged the electroluminescence spectra of different cross sections along the channel. The electroluminescence is composed of a broad peak around 1.3 eV and two other minor peaks close to 1.35 eV. We observe that the bias-induced bending of the quantum well forming the channel allows radiative recombinations of electrons and holes even from levels normally forbidden under flat band condition. Indeed, the C2 → HH1 transition is forbidden for a symmetric infinite barrier quantum well, but is allowed when the well is distorted by the band bending. The symmetry breaking is much more pronounced close to the gate region, while in the source-gate region the absence of contacts reduces the asymmetric bending of the channel.

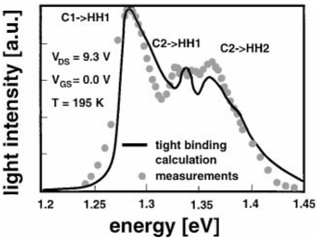

Fig. 2. Comparison of the calculated and experimental electroluminescense spectra at given bias conditions. The calculated spectra are the sum of various contributions along the channel in the region between gate and source.

In conclusion, Monte Carlo analysis of impact ionization in AlGaAs/InGaAs pseudomorphic HEMTs demonstrates that the injection and accumulation of holes in the layers below the channel have the most dramatic effect on the drain current. Due to the relatively long time scales involved, effects of impact ionization under RF drive may be significantly different from those observed in DC. The band-edge luminescence is found to originate dominantly from the source-sided channel region.

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