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Kink-effect related noise in short-channel InAlAs/InGaAs high electron mobility transistors

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We perform a microscopic analysis of the noise associated with the kink effect in short-channel InAlAs/InGaAs lattice-matched high electron mobility transistors (HEMTs) by using a semiclassical two-dimensional (2-D) ensemble Monte Carlo simulator. The kink effect in HEMTs has its origin in the pile up of holes (generated by impact ionization) taking place under the source side of the gate, that leads to a reduction of the gate-induced channel depletion and results in a drain current enhancement. Our results indicate that the generation of holes by impact ionization and their further recombination lead to fluctuations in the charge of the hole pile up which provoke an important increase of the drain-current noise, even when the kink effect is hardly perceptible in the output characteristics. In addition, shot noise related to the hole gate leakage current is found at the gate terminal, which can further degrade the global noise performance of HEMTs. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1745119]

I. INTRODUCTION

Although InAlAs/InGaAs High Electron Mobility Transistors (HEMTs) have revealed excellent performance in low-noise high-frequency operation,[1–3] their utility for microwave power applications is limited when the kink effect (an anomalous increase in the drain current I_D at sufficiently high drain-to-source voltages V_{DS}) emerges, since this phenomenon leads to a reduction in the gain and a large enhancement in the level of noise.[4] Impact ionization and the subsequent hole dynamics, jointly with hole recombination, are considered to be responsible for the appearance of the kink effect in HEMTs,[4–11] as we have verified in a previous work by means of Monte Carlo (MC) simulations.[12] These devices are very susceptible to suffer impact ionization processes due to the small band gap of InGaAs and the very high electric fields appearing in the gate-drain region when the device dimensions are shortened to improve the operation frequency.[1] The associated kink phenomena lead to a significant increase of the drain-current noise, which spoils the performance of the transistors even at microwave frequencies.[13] The origin of this noise enhancement is not still completely understood.

Our aim in this work is to study the noise associated with the kink effect in a 100 nm gate lattice matched $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT, whose static characteristics were analyzed and explained in Ref. 12. For this purpose, we make use of a semiclassical 2-D MC simulator[12,14–16] which incorporates all the processes involved in the kink effect. On the other hand, the MC method has been proved to be a very helpful tool in the study of noise problems in which the microscopic behavior of carriers is essential.[14,16]

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The paper is organized as follows. In Sec. II the physical model employed in the simulations is described. The main results and their discussion are provided in Sec. III. Finally, in Sec. IV the most important conclusions of this work are drawn.

II. PHYSICAL MODEL

The device under analysis is a 100 nm T-gate recessed $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT, widely described in Refs. 14–16. A schematic drawing of its topology is shown in the inset of Fig. 1. For the calculations we make use of an ensemble MC simulator self-consistently coupled with a 2-D Poisson solver which incorporates all the processes at the origin of the kink effect, particularly impact ionization and hole recombination.[12] Electron impact ionization is implemented by using the Keldysh approach,[17] with values of 0.8 eV for the ionization threshold energy E_{th} and 2×10^{12} s^{-1} for the parameter S which measures the softness or hardness of the threshold. Hole recombination is considered to take place with a characteristic time τ_{rec} (i.e., with a probability $1/\tau_{rec}$). We will perform simulations with τ_{rec} ranging between 0.01 and 0.1 ns, in order to study its influence on the kink properties. These values of τ_{rec} are slightly shorter than the real ones (about 1 ns[4,8]) to achieve affordable computation times. Indeed, the value of τ_{rec} constitutes a severe limitation for the simulation time, since hole recombination is the process with the longest characteristic time among those involved in the system under analysis. Concerning to the noise calculations, the fluctuations of the flow of carriers through the drain and gate electrodes are studied by means of the autocorrelation function. The corresponding spectral densities of drain- and gate-current fluctuations are determined by Fourier transform of the respective autocorrelation functions.

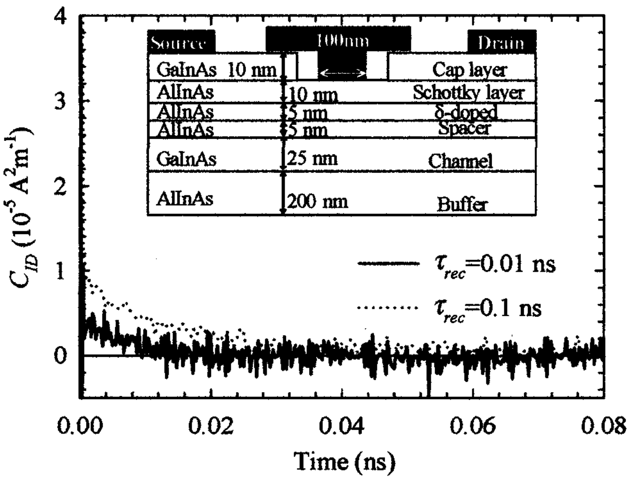

FIG. 1. Drain-current autocorrelation function $C_{ID}(t)$ for $V_{DS}=3.0$ V and $V_{GS}=-0.3$ V and different τ_{rec}. The inset presents a schematic drawing of the HEMT topology used in the simulations.

III. RESULTS

Our previous works enable the interpretation of the physical origin of the kink effect as follows.[12] For high enough V_{DS}, holes, generated by impact ionization in the gate-drain region, tend to pile up in the channel under the source side of the gate due to the attracting potential caused by the surface charge at the recess and, mostly, by the gate potential. Due to this pile-up of positive charge, the potential barrier which controls the passage of electrons through the channel is lowered, thus the channel is further opened and I_D increases, leading to the kink effect in the output characteristics.

Apart from this static effect, impact ionization and hole recombination lead to fluctuations of the hole concentration in the channel, particularly in the pile-up. Since these charge fluctuations are strongly coupled to the drain-current fluctuations by the high transconductance of the transistor, an important increase of the drain-current noise is expected to take place concurrently with the kink in the I_D-V_{DS} curves. The cutoff of this excess noise should thus be related to the relaxation time of the hole accumulation fluctuations.

Figure 1 shows the drain-current autocorrelation function, $C_{ID}(t)$, for $V_{DS}=3.0$ V, $V_{GS}=-0.3$ V and two different recombination times, $\tau_{rec}=0.01$ ns and $\tau_{rec}=0.1$ ns. In the presence of the kink, a positive long-time tail appears in $C_{ID}(t)$, associated with the charge fluctuations of the hole pile-up, which are governed by the generation–recombination of holes. Thus, the characteristic time of this contribution to the noise associated with the kink effect should be related to both the impact ionization rate and τ_{rec}. This is confirmed by Fig. 1, where the decay time of $C_{ID}(t)$ is of the order of τ_{rec}. On the other hand, the values of the correlation function are higher the longer is τ_{rec}, the more important is the hole pile-up and the more pronounced is the kink effect.[12]

Figure 2 shows the spectral density of drain-current fluctuations, $S_{ID}(f)$, for $V_{GS}=-0.3$ V and (a) $\tau_{rec}=0.01$ ns and different values of V_{DS}, and (b) $V_{DS}=3.0$ V and different values of τ_{rec}, and also in the case of absence of impact ionization (for the sake of comparison). The insets show the

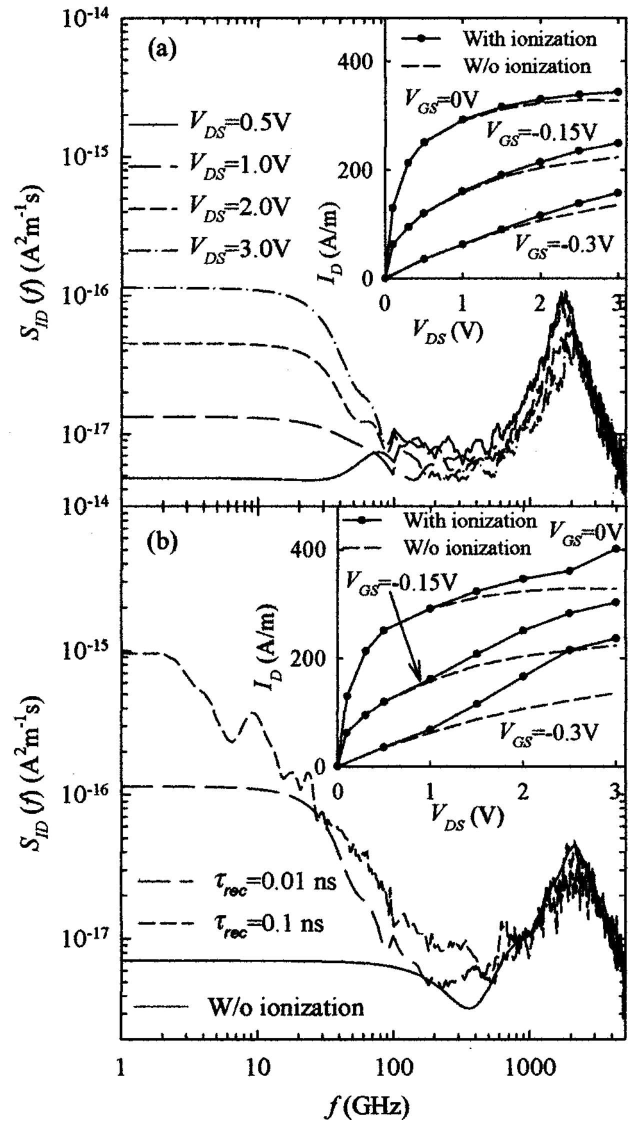

FIG. 2. Spectral density of drain-current fluctuations $S_{ID}(f)$ for $V_{GS}=-0.3$ V and (a) $\tau_{rec}=0.01$ ns and different V_{DS}, and (b) $V_{DS}=3.0$ V and different τ_{rec}, and also in the absence of impact ionization. The insets shows the output characteristics (a) for $\tau_{rec}=0.01$ ns and (b) for $\tau_{rec}=0.1$ ns.

output characteristics (I_D vs V_{DS} for different V_{GS}) for (a) $\tau_{rec}=0.01$ ns and (b) $\tau_{rec}=0.1$ ns, compared with the case of absence of impact ionization. For the applied voltages for which impact ionization events take place ($V_{DS}\geqslant 1.0$ V), the positive long-time contribution of $C_{ID}(t)$ originates a significant increase of the low-frequency plateau in $S_{ID}(f)$, which is not present when impact ionization is removed from the simulations. At higher V_{DS} the level of the plateau increases, since the effect of impact ionization is more pronounced and the increment of I_D [the inset of Fig. 2(a)] is larger. The characteristic cutoff frequency of the plateau in $S_{ID}(f)$, like the long-time tail in $C_{ID}(t)$, is linked to the impact ionization rate and the hole recombination time, thus being of the order of $1/\tau_{rec}$. This is confirmed in Fig. 2(b), where the spectral densities obtained as the Fourier transforms of the correlations functions of Fig. 1 are shown. As indicated previously, the longer is τ_{rec}, the higher is the noise level. At frequencies beyond the cutoff, the noise remains practically independent of both V_{DS} and τ_{rec}, exhibiting the typical peak related to plasma oscillations in the highly doped regions of the structure. Note that in the case of absence of impact ionization the low-frequency plateau shows no cutoff before the noise increase related to plasma oscillations.

Values of the cutoff frequency in the microwave range comparable to those found here have been observed experimentally by Rouquette *et al.*[13] in the drain-current noise of a 0.3 μm InAlAs/InGaAs HEMT in the presence of kink. Furthermore, a similar behavior has been measured by Arai *et al.*[11] in the frequency dispersion exhibited by the drain conductance $g_d(f)$ of a 0.13 μm InAlAs/InGaAs HEMT. These experimental facts support our explanation of the kink origin and dynamics, since the frequency dependence of the kink-related increase of both $g_d(f)$ and $S_{ID}(f)$ is governed by the time necessary for the setting up of the hole pile-up. However, as stated in Ref. 12, the increase of $S_{ID}(f)$ in the presence of kink is not only related to a higher g_d, but also to an increased noise temperature due to the appearance of an excess noise. The mechanism underlying this excess noise, following the results of our simulations, is the fluctuation of the hole pile-up concentration (which strongly affect the values of I_D).

The low-frequency value of the spectral-density of drain-current fluctuations, $S_{ID}(0)$, is presented in Fig. 3 as a function of V_{DS} for (a) $V_{GS}=-0.3$ V and different values of τ_{rec}, and (b) $\tau_{\mathrm{rec}}=0.01$ ns and different values of V_{GS}. The inset of Fig. 3(a) shows the output characteristics for $V_{GS}=-0.3$ V when $\tau_{\mathrm{rec}}=0.01$ ns, $\tau_{\mathrm{rec}}=0.1$ ns and without impact ionization. $S_{ID}(0)$ is found to increase with V_{DS} due to the higher number of impact ionization events taking place at larger gate-drain potential difference. $S_{ID}(0)$ also increases with τ_{rec}, but now due to the longer time holes remain inside the device before recombination. In the two cases the charge fluctuations in the hole pile-up are enhanced; in the former mainly due to the increase in the hole density, and in the latter due to both the increased hole density and the longer characteristic time of hole density relaxation. Since these fluctuations are strongly coupled to the drain current fluctuations by the self-consistent potential (due to the strategic position of the pile-up),[12] they lead to a higher value of $S_{ID}(0)$. As observed in Figs. 3(a) and 3(b), $S_{ID}(0)$ depends on V_{DS} and V_{GS} in a similar way to that shown by the kink-related increase of I_D (more pronounced for higher V_{DS} and lower V_{GS}). However, the relative increase of $S_{ID}(0)$ with respect to its value when impact ionization is not considered in the simulations is much higher than that of I_D. Thus, although the kink effect in the I_D-V_{DS} curves is hardly detectable for $V_{\mathrm{DS}}=1.0$ V [the inset of Fig. 3(a)], $S_{ID}(0)$ already exhibits a significant increase with respect to its value in the absence of impact ionization [Fig. 3(a)]. This indicates that when HEMTs are biased in the vicinity of the kink onset, even if the static behavior of the transistors is not perturbed, their noise performance can be severely degraded, since drain noise is extremely sensitive to the dynamics of holes generated by impact ionization. This fact confirms that the increase of S_{ID} associated with the kink effect is not due to a higher g_d, but mainly to the appearance of an excess noise connected with the strong drain current fluctuations initiated by the variations of the hole concentration in the channel.

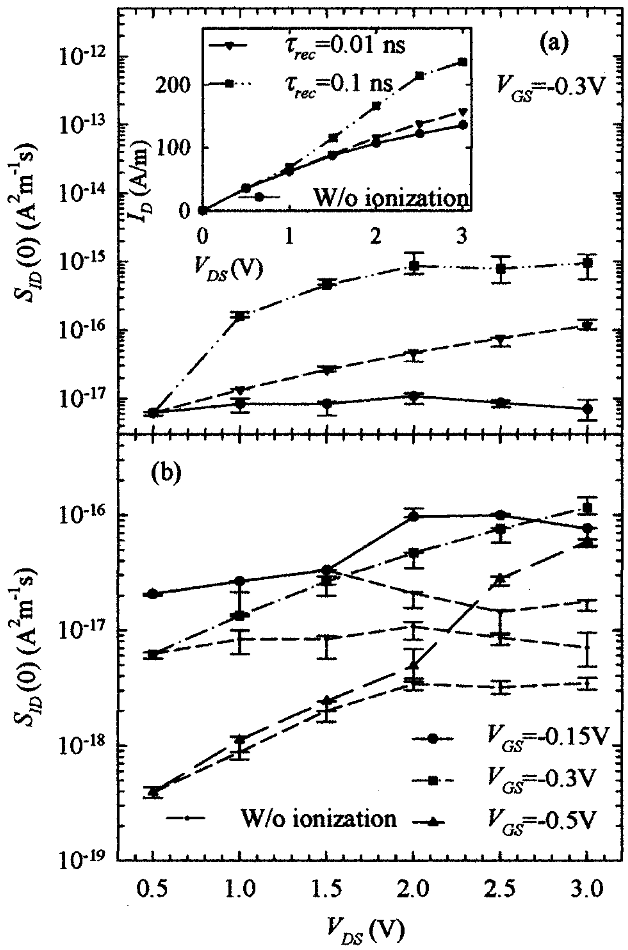

FIG. 3. Low-frequency spectral density of drain-current fluctuations $S_{ID}(0)$ vs V_{DS} for (a) $V_{GS}=-0.3$ V and different values of τ_{rec} (inset, the corresponding output characteristics); and (b) $\tau_{\mathrm{rec}}=0.01$ ns and different values of V_{GS}, compared with the case when impact ionization is not considered.

Figure 4 presents the low-frequency spectral density of gate-current fluctuations, $S_{IG}(0)$, as a function of V_{GS} for $V_{\mathrm{DS}}=3.0$ and (a) $\tau_{\mathrm{rec}}=0.1$ ns and (b) $\tau_{\mathrm{rec}}=0.01$ ns. $2qI_G$ is also shown for comparison, with I_G obtained by using the Ramo–Shockley theorem[18,19] (and not by the less accurate technique of counting the number of holes reaching the gate electrode). Within our model, which does not include gate tunneling, $S_{IG}(0)$ is null in the absence of impact ionization. In contrast, in the presence of the kink $S_{IG}(0)$ is found to exhibit the expected shot noise behavior within the uncertainty of the MC calculation, which is rather large since $S_{IG}(0)$ takes very low values and makes very difficult its exact determination. Thus, $S_{IG}(0)$ is close to $2qI_G$, being maximum when the device is near pinch-off.

IV. CONCLUSIONS

We have presented a study of the noise linked to the kink effect in short-channel lattice matched $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMTs based on MC simulations. An important increase of the drain-current noise at low frequency takes place in the presence of the kink due to the strong coupling between the fluctuations of hole density in the

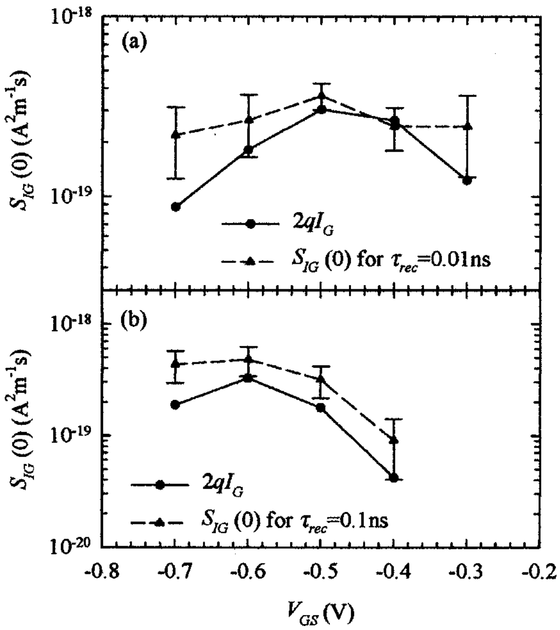

FIG. 4. Low-frequency spectral density of gate-current fluctuations $S_{IG}(0)$ vs V_{GS} for $V_{DS}=3.0$ V and (a) $\tau_{rec}=0.1$ ns, and (b) $\tau_{rec}=0.01$ ns. $2qI_G$ is also plotted for comparison.

pile-up and the drain current. The characteristic cutoff frequency of the kink-effect-related noise is associated with the two different time constants involved in the fluctuations of the global charge at the hole pile-up, i.e., the impact ionization rate and the hole recombination time. The dependence of $S_{ID}(0)$ on V_{DS}, V_{GS} and τ_{rec} is similar to that of I_D, but the relative increase of $S_{ID}(0)$ in the presence of the kink with respect to the case of absence of impact ionization mechanisms is much more pronounced than that of I_D. $S_{IG}(0)$ is found to exhibit shot noise related to the hole gate-leakage current, thus taking the highest values near pinch-off, close to the optimum biasing conditions for low noise operation. We conclude that the kink effect strongly degrades the noise performance of HEMTs, even at microwave frequencies, due to the increase of both $S_{ID}(0)$ and $S_{IG}(0)$.

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