Negative differential mobility in GaAs at ultrahigh fields: Comparison between an experiment and simulations

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(Received 21 January 2008; accepted 26 January 2008; published online 15 February 2008)

Direct measurement of the electron velocity v_n at an extreme electric field E is problematic due to impact ionization. The dependence $v_n(E)$ obtained by a Monte Carlo method can be verified, however, by comparing simulated and experimental data on superfast switching in a GaAs bipolar transistor structure, in which the switching transient is very sensitive to this dependence at high electric fields (up to 0.6 MV/cm). Such a comparison allows the conclusion to be made that the change from negative to positive differential mobility predicted earlier at $E \sim 0.3$ MV/cm should not happen until the electric field exceeds 0.6 MV/cm. © *2008 American Institute of Physics*.
[DOI: 10.1063/1.2870096]

The effect of electron velocity behavior at high electric fields on the maximum Gunn domain amplitude[1] and the possibility for impact ionization in Gunn domains[2,3] stimulated a study of electron transport at fields approaching the ionization threshold.[4–6] High-field electron transport is also important in small-dimension field-effect transistors,[7] thin avalanche photodiodes,[8,9] and fast switches based on bipolar structures.[10] The experimental data on the dependence of the electron velocity v_n on the electric field E have shown the presence of negative differential mobility (NDM) up to an ionization threshold of ~ 0.2 MV/cm (see Fig. 1). The dependence $v_n(E)$ in GaAs at higher fields (up to 0.5 MV/cm) was obtained from Monte Carlo simulations (see Ref. 11 and references therein) but direct experimental verification is hardly possible due to powerful impact ionization.

The recently discovered[12] phenomenon of superfast switching in a high-voltage GaAs bipolar junction transistor (BJT) was shown to be caused by a comb of powerfully avalanching domains of ultrahigh amplitude[13] (up to ~ 0.6 MV/cm), termed later as "collapsing domains."[14] One necessary condition for the formation of collapsing domains was found to be the existence of NDM at the electric fields exceeding the ionization threshold. Excellent agreement was achieved between numerical modeling and the experiment[15] when an extrapolation of the measured dependence $v_n(E)$ (Refs. 5 and 6) from $E \leqslant 0.2$ toward $E \sim 0.6$ MV/cm was used in the simulations. Proof of the collapsing domains concept would be fairly important not only for superfast switching[12] but also for a convincing interpretation of the nature of the copious terahertz and "hot" photon emission observed from a GaAs BJT structure.[14] Verification of the existence of NDM at very high electric fields is especially important in view of the contradicting predictions of Monte Carlo simulations,[11] which claim violation of NDM at $E \geqslant 0.33$ MV/cm due to population of the X_7 valley in the second conduction band.[6] In this work, we compare the experimental data on the switching transient in a GaAs BJT with the simulations using different $v_n(E)$ dependences, with the aim of clarifying the main features of the dependence $v_n(E)$ at extreme fields.

A comparison of the dependence $v_n(E)$ as measured[4] in GaAs with that obtained in Monte Carlo simulations[11] (including the effect of the X_7 valley second conduction band, see curve A), together with analytic band Monte Carlo (AMC) simulations for different doping densities performed in this work (curves 1–4), are shown in Fig. 1.

Despite of the fact that only the first conduction band (Γ_6, L_6, X_6) was taken into consideration in our AMC simulations and no special fitting of the AMC model parameters was performed here, one can see a perfect fit with the experimental data[4,5] at $100 < E < 200$ kV/cm and their extrapolation to the very high fields used in Refs. 13–15. The solid lines show the analytical fit used in GaAs BJT simulations of this work. A particularly important distinguishing feature of $v_n(E)$ dependence obtained in Ref. 11 is the sign of the differential mobility at $E \geqslant 330$ kV/cm (see curve A in Fig. 1).

A comparison of the measured collector voltage in a GaAs BJT (curve 1) with the simulated one using different $v_n(E)$ dependences is shown in Fig. 2. Excellent agreement during fast switching stage (curve 2) is achieved for the dependence $v_n(E)$ corresponding to the AMC data of this work (curves 1–4 in Fig. 1). Taking into account the prediction of positive differential mobility[11] leads to a large difference, however (compare curves A and 1 in Fig. 2). If we assume further that the differential mobility changes its sign from negative to positive at higher than 330 kV/cm fields (see curves B and C in Fig. 1), this will still not provide a good fit with the experiment (curves B and C in Fig. 2) as long as the change occurs at $E < 600$ kV/cm.

The reason for the reduction in the switching speed (when NDM is violated) lies in the reduction in the impact

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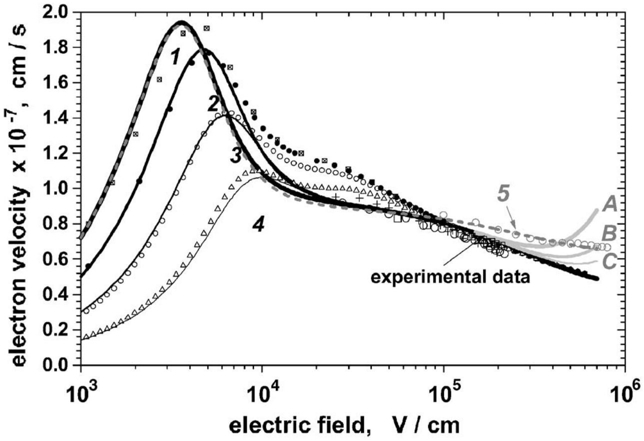

FIG. 1. Dependence of electron velocity on the electric field in GaAs. The scattered graphs 1–4 were obtained using Monte Carlo simulations for different doping levels N_D (cm^{-3}): $1-10^{15}$, $2-10^{17}$, $3-10^{18}$, $4-5\times10^{18}$. The solid lines (1–4) show the analytical dependences used in drift-diffusion simulations of the switching transient. The analytical formula was of a similar structure to that used in Ref. 13, but was modified to account for the doping dependence of the electron velocity simulated here:

$$v_n(E)=[\mu_n E+(v_0+v_1\times e^{(-E-E_0)/E_1})]\times\frac{(E/E_t)^4}{1+(E/E_t)^4}, \quad (1)$$

where the exponential decay in electron velocity at high fields is determined by the parameters: $E_0=1.8\times10^4$ V/cm; $E_1=2.9\times10^5$ V/cm; $v_0=4.4\times10^6$ cm/s; and $v_1=4.7\times10^6$ cm/s. The critical field E_t (V/cm) and mobiligy μ_n ($cm^2/V\,s$) values, which are dependent on the concentration N_d (cm^{-3}), are selected as follows: N_d (E_t,μ_n): 10^{15} (4000, 7200), 10^{17} (5200, 5000), 10^{18} (6300, 3000), and 5×10^{18} (7900, 1400). The experimental data (Refs. 4–6) for the 20–200 kV/cm range are shown for the sake of comparison (scatter graph). The gray-colored curve A presents the change from negative to positive differential mobility at $E\sim330$ kV/cm predicted in Ref. 11, and this dependence was accounted for in the corresponding GaAs transistor simulations by adding the term $v_2\times[\ln(E/E_2+1)]^5$, ($v_2=10^5$ cm/s and $E_2=10^5$ V/cm) to formula (1). Curves B ($E_2=1.4\times10^5$ V/cm) and C ($E_2=1.8\times10^5$ V/cm) represent speculative situations in which the mobility sign changes at 430 and 530 kV/cm, respectively (see corresponding transistor simulations below). A difference between the simulated electron velocity and the analytical fit at $E\sim10^4-10^5$ V/cm is of minor importance since field values in this range are not present within or between the high-field domains. The gray-colored dashed curve 5 represents the FBMC simulation results obtained here when taking account of the X_7 valley.

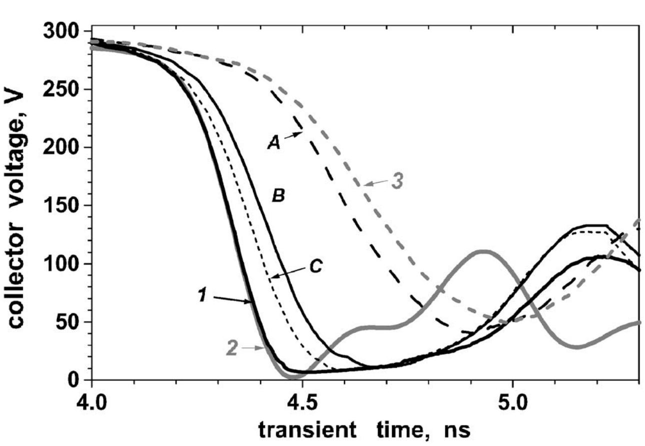

FIG. 2. Measured (curve 1) and simulated (curves 2, A, B, and C) collector voltages across a GaAs BJT during switching. The simulation results presented in curve 2 were obtained for the dependence $v_n(E)$ represented by curves 1–4 in Fig. 1. Curves A, B, and C correspond to the curves in Fig. 1 marked with the same letters. Curve 3 presents the collector voltage simulated with the dependence $v_n(E)$, as shown by curve 5 in Fig. 1 (FBMC results obtained in this work).

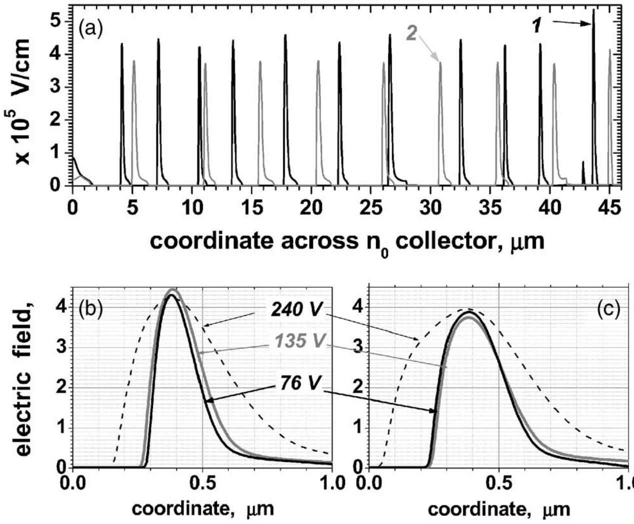

FIG. 3. (a) Electric field profiles across the n_0-collector layer, simulated using two dependences $v_n(E)$: curve 1 corresponds to the NDM dependences 1–4 in Fig. 1 and curve 2 to an approximation with positive differential mobility (PDM) shown by curve A in Fig. 1. The profiles 1 and 2 correspond to instants ($t_1\approx4.33$ ns, $t_2\approx4.62$ ns in Fig. 2) when the collector voltage $U_c\approx135$ V. Profiles with higher spatial resolution typical of a single domain are shown in (b) and (c) under the following conditions: the domains shown in (b) are simulated with NDM approximation (curves 1–4 in Fig. 1) and three domains correspond to instants when the collector voltages are 240, 135, and 76 V, respectively; the domains shown in (c) are simulated with PDM approximation (curve A in Fig. 1).

generation rate due to saturation in the amplitude of the field domains. One can see from a comparison of the profiles 1 and 2 in Fig. 3(a) that the domain amplitudes are higher in the case of NDM, the collector voltage being the same. Despite the fact that individual domains can deviate from each other in amplitude and width, typical domain characteristics at different transient instants can be compared, as shown in Figs. 3(b) and 3(c). A reduction in the domain amplitude, e.g., from ~446 to ~375 kV/cm [compare (b) and (c) at $U_c\approx135$ V] causes a reduction by a factor of ~5 in the electron ionization rate and this slows down the switching transient significantly (compare curves 2 and A in Fig. 2). Note that the differential mobility changes its sign in the field range of ~300–390 kV/cm (curve A in Fig. 1), which is comparable to the maximum (saturated) domain amplitude in Fig. 3(c). Less understandable in this context is the difference between curves 2 and C in Fig. 2, as the change in the mobility sign occurs at ~510–610 kV/cm (curve C in Fig. 1), while the domains of that high amplitude are not typical [see Fig. 3(b)]. The difference between curves 2 and C in Fig. 2 is caused, however, by the occasional appearance of domains of up to ~600 kV/cm at the right-hand side of the n_0 layer [profile 1 in Fig. 3(a)].

We believe that the excellent agreement between curves 1 and 2 in Fig. 2 cannot be accidental and that avalanche switching in a GaAs BJT can be used to verify the dependence $v_n(E)$. Indeed, the switching includes fairly complex processes: a variation in the number of domains during the transient, a variation in domain amplitude and width, and a variation in the ionization rates within the domains and in the e-h plasma density between them. All these impose a fingerprint on the dependence of the collector voltage on time. Moreover, the same excellent fit is achieved for structures with different doping and layer thicknesses[14] and for the same structure but with a smaller emitter area.[15] (In the experiment presented here, we used a chip geometry that was properly optimized for effective switching, the details of which will be discussed elsewhere.) The model does not contain any other adjustable parameter than $v_n(E)$, and, thus, we consider this method of $v_n(E)$ verification to be as reliable as the drift-diffusion approach can be applied to the problem in principle. The drift-diffusion model, in turn, should be valid until $t \approx 4.5$ ns (curves 1 and 2 in Fig. 2), as the domain width [$\geqslant 0.22$ μm, see Fig. 3(b)] remains considerably larger than the electron ionization pass length (<0.1 μm) (Ref. 9) and much larger than the ballistic free-flight length (<0.03 μm).[8] (The applicability of the model should cease at $t \geqslant 4.5$ ns, when the width of the domains becomes comparable with the ionization dead space[9] and the simulations no longer agree well with the experiment in this range.)

Thus, the experimental and simulated switching transients in a GaAs bipolar transistor will fit well only when NDM takes place in the GaAs up to an electric field of at least ~600 kV/cm. This feature, which is intrinsic to simplified AMC simulations when only the first conduction band (Γ_6, L_6, X_6) is considered, contradicts AMC simulations[11,16] that additionally consider the X_7 valley from the second conduction band. In an attempt to resolve this contradiction, we performed full band Monte Carlo (FBMC) simulations with the X_7 valley included (the parameters of the FBMC model used here, arguments for their selection, and the main simulation results will be discussed elsewhere). The most notable finding was the possibility for obtaining NDM up to $E = 800$ kV/cm (see curve 5 in Fig. 1) within a realistic range of FBMC model parameters. The change in the sign of the differential mobility to a positive one at $E > 300$ kV/cm (Ref. 11) or at $E > 400$ kV/cm (Ref. 16) in the AMC simulations is associated with the assumption that is popular in the literature of a relatively small effective mass in the X_7 valley. This results in a growth in electron mobility at sufficiently high electric fields, when the population of the X_7 valley increases remarkably. In the FBMC simulations performed here, the population of the X_7 valley was found to be significantly lower than in earlier simulations (23% in the second band at 800 kV/cm against 60% at 800 kV/cm in Ref. 16 and against 30% at 500 kV/cm in Ref. 11).

Simulations of GaAs BJT switching using the dependence $v_n(E)$ predicted by the FBMC model (curve 5 in Fig. 1) did not fit the experimental data, however (compare curves 3 and 1 in Fig. 2), despite the fact that NDM manifests itself up to ~0.8 MV/cm. The reason lies in the small slope of the $v_n(E)$ dependence at high fields. One may interpret this result as an effect of the relatively large relaxation time τ associated with a low absolute value of NDM at a high field: $\tau_- \sim \varepsilon\varepsilon_0 / qn\mu_-$, where $\varepsilon\varepsilon_0$ is the dielectric constant, q is the electron charge, n is a characteristic plasma density between the collapsing domains, and μ_- is a characteristic absolute value of NDM at the maximum electric field achieved in the switching (~0.5–0.6 MV/cm). Namely, as the characteristic time τ_- of collapsing domain evolution grows and is no longer negligibly small relative to the switching time, the transient may slow down.

In conclusion, a verification of the electron transport in GaAs at extreme electric fields was performed using experimental data and drift-diffusion modeling of superfast switching in a GaAs BJT. The comparison showed that NDM should take place in GaAs up to an electric field of ~600 kV/cm, which disavows earlier predictions obtained with MC models considering the second conduction band. Moreover, a good fit between the experiment and simulations of a GaAs BJT requires the absolute value of the NDM to be sufficiently large ($\mu_- \geqslant 3$ cm^2/V s at 500 kV/cm), while $\mu_- < 2$ cm^2/V s already causes a noticeable difference between the measured and simulated voltage waveforms. A satisfactory dependence $v_n(E)$ at high electric fields has been predicted only by MC simulations that ignore the effect of the X_7 valley. The question remains open so far as to whether the currently available MC models overestimate the population of the X_7 valley at high electric fields, or whether the assumption of a relatively low effective mass in the X_7 valley, which is popular nowadays, is incorrect.

This work was generally supported by the Academy of Finland, while Vassil Palankovski received support from the Austrian Science Funds (FWF) START Project Y247-N13.

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