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Monte Carlo studies of two dimensional transport in GaN/AlGaN transistors: Comparison with transport in AlGaAs/GaAs channels

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In this communication we report results on Monte Carlo transport studies in GaN/AlGaN two dimensional electron gas. In addition to steady state results we examine transit times in channels of different lengths under various bias conditions. The results are compared to those calculated for the GaAs/AlGaAs device. We find that at low electric fields, transit time in the GaN channel can be considerably longer than the time in a GaAs channel. This is attributed to the overshoot effect in the GaAs channel. However, at large electric field transport the transit times in GaN and GaAs channel are found to be comparable. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1324998]

I. INTRODUCTION

Materials in the III–V nitride family (InN, GaN, and AlN) have physical properties that are very attractive for short wavelength light emission[1–4] and for high power/high temperature electronics.[5–9] Alloys and heterostructures based on these materials are therefore being studied with great interest. Recent advances in epitaxial growth control and processing have led to excellent transistor performance using the AlGaN/GaN heterostructure. Heterostructure field effect transistors (HFETs) have shown very good high power properties. An important aspect of AlGaN/GaN structure is that due to spontaneous polarization and piezoelectric effect it is possible to have a high sheet charge without any doping. As a result the band profile of the HFET in the barrier region is quite different from what is seen in other HFETs. It is important to compare an AlGaN/GaN HFET with an AlGaAs/GaAs HFET since it is well known that the AlGaAs/GaAs has excellent high frequency performance. While the nitride system is certainly superior for high power applications it is important to examine carrier transit times in the two classes of devices.

When we compare transport in a GaN and GaAs structure several comparisons can be made:

(i) the peak velocity in GaN is higher than in GaAs by about 20%;

(ii) the saturation velocity is higher in GaN; and

(iii) when one examines the steady state velocity–field relation for the GaN system one observes that the velocity does not reach its peak value of $\sim 2.5\times 10^7$ cm/s until a field of $\sim 1.5\times 10^5$ V/cm. On the other hand in the GaAs system the velocity peaks at $\sim 2.0\times 10^7$ cm/s at only ~4 kV/cm;

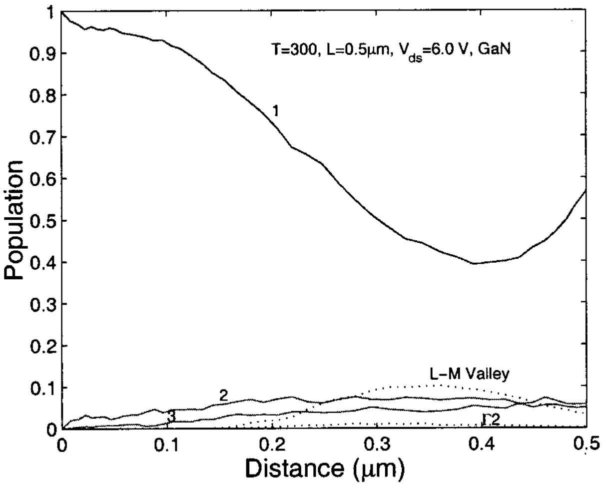
(iv) the GaAs system shows strong overshoot effect at high fields (or in short channel length devices). In the GaN case there is no overshoot effect since the scattering rates are very high.

These comparisons suggest that there may be regimes of operation where GaAs based devices are superior (in terms of transit times) and regimes where the nitride system shows superior performance. In this communication we report on results that shed light on issues dealing with such comparisons.

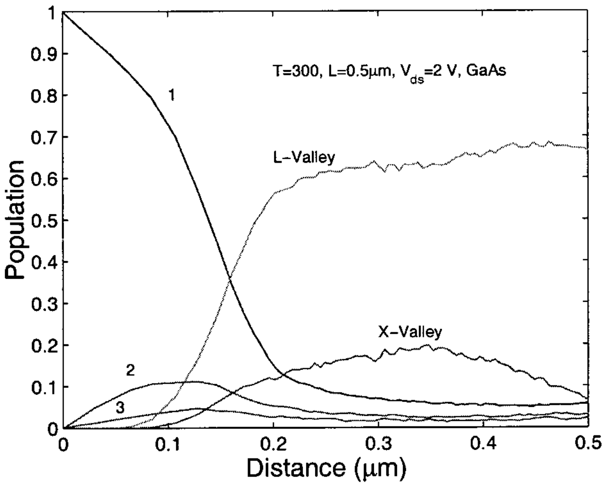
It is important to note that several device results on high frequency behavior of AlGaN/GaN transistors have been reported.[7,10–13] Reference 11 has reported f_t values of ~50 GHz for a 0.2 μm device. In GaAs technology f_t values of ~50 GHz are shown for a 0.3 μm device.[14] It is also important to note that the f_t value for GaAs devices has been observed to degrade with higher source–drain bias. For example, Ref. 7 showed that for a 0.1 μm GaAs metal–semiconductor field effect transistor (FETs) the f_t value is 18.5 GHz at a low source–drain bias of 2 V, but decreases to below 8 GHz when the drain bias is 10 V. From the published experimental results it is clear that at high source–drain bias GaN based technology is comparable or superior to GaAs technology. In this paper we carry out transport studies to shed light on the origins of these experimental observations. We carry out two dimensional ensemble Monte Carlo simulations for our transport studies.

II. FORMALISM

To understand the transport in AlGaAs/GaAs and AlGaN/GaN devices, we have developed a formalism based on the following three components: (i) A charge control model: A self-consistent solution of Poisson equation and Schrödinger equation is carried out. In the case of the nitride system we include the effects of the polarization charges at the AlGaN/GaN interface as discussed in Ref. 15. (ii) A scattering theory: We include two dimensional scattering rates for carriers in the two dimensional electron gas channel.[16–20] At the high fields we are interested in the dominant scattering due to the optical phonons. (iii) Monte Carlo method for transport: Both steady state and transient Monte Carlo simulation have been performed to examine transport properties. For the AlGaN/GaN system, the ten lowest subbands in the Γ are included together with the $L-M$ and Γ_2 band structures. Material parameters are given in Refs. 15 and 20. The Γ

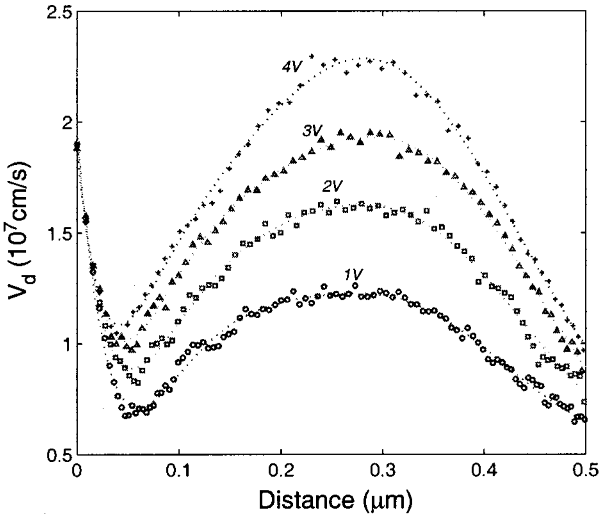


(a) AlGaN/GaN

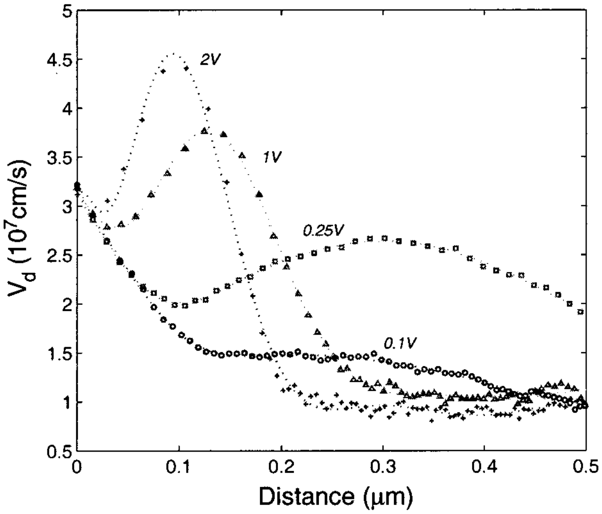


(b) AlGaAs/GaAs

FIG. 1. Occupation of electrons in various subbands in the 0.5 μm: (a) GaN and (b) GaAs two-dimensional channels.



(a) AlGaN/GaN



(b) AlGaAs/GaAs

FIG. 2. Drift velocity of electrons as a function of channel distance from transistor source for a 0.5 μm device.

valley electrons are treated as two dimensional and the scattering rates are evaluated numerically. For the upper valleys ($L-M$, Γ_2) we treat the scattering as three dimensional scattering events.

In the case of the steady state simulation, one-electron motion is traced for a long period of time to obtain the steady state transport properties including the drift velocity and population of each subband and each valley. For the case of transient transport, an ensemble Monte Carlo scheme is used. As many as 20 000 electrons are simulated at the same time. The initial distribution of electrons is assumed to be Maxwellian in each subband based on the equilibrium state population obtained in the charge control model.

The three dimensional scattering in the $L-M$ and Γ_2 valleys are the same as those reported by Fawcett.[21] The transitions from the subbands of the Γ valley to the higher valleys or vice versa are calculated using the approach by Yokoyama and Hess.[20]

In order to shed light on the comparison of transit time effects in the GaN and GaAs channels we must use an electric field profile, which realistically represents fields encountered in FET channels. We know that in FETs the field is very small at the source, then grows and becomes large near the drain side of the gate. In our simulations we assume that the electric field in the FET channel of length L rises linearly with distance between the source and $0.6L$. It is constant between $0.6L$ and $0.9L$. Then it falls to zero at the drain. Thus the field peaks on the drain side of the gate. In the model we assumed that the peak field is 1.65 times the average field in the channel. We have used other qualitatively similar field profiles and obtained similar results.

III. RESULTS

In Fig. 1 we show the occupation of electrons in various subbands in the 0.5 μm GaN [Fig. 1(a)] and GaAs [Fig. 1(b)] two-dimensional channels. We find that in the nitride case

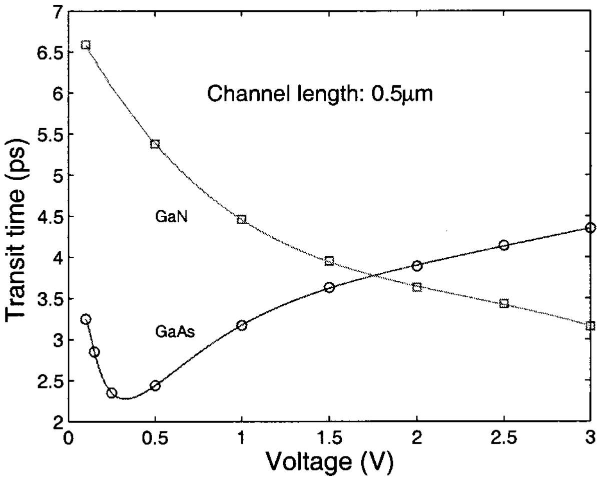


FIG. 3. Transit time across a 0.5 μm channel in GaN and GaAs devices.

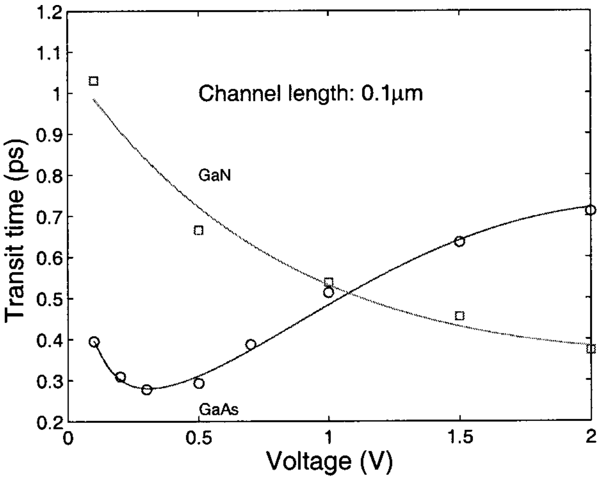


FIG. 4. Transit time across a 0.1 μm channel in GaN and GaAs devices.

the electrons remain in the first subband even at a high drain bias of 6 V. This reflects the large scattering rates encountered by electrons in GaN. This prevents the carriers from gaining high energies from the field. Also as noted above the second subband is quite removed in energy. In the GaAs channel we see that even at smaller drain bias values of 2.0 V the electrons are in upper valleys. At a comparable voltage value, in GaN all of the electrons are found to be in the first subband.

In Fig. 2 we show the drift velocity of electrons as they go from the source to the drain in the two dimensional channels. In Fig. 2(a) we show results for the GaN channel. The electrons are injected initially with thermal velocity. The electrons initially slow down as a result of entering a region of low field and high scattering rate. However, as the field increases the carrier velocity increases. The electrons essentially remain in steady state showing no overshoot effect even at high applied bias values. In contrast, in the GaAs channel the carriers show strong overshoot effects as can be seen in Fig. 2(b). However, as can be seen from this figure once the initial overshoot effect is over, the electrons spend a considerable distance in the device traveling at the saturation velocity of 10^7 cm/s.

In Fig. 3 we show the results for transit time across a 0.5 μm channel in the nitride and GaAs case. We see that when the applied bias is small, the GaAs channel shows a transit time that is much smaller than that in the GaN channel. However, as the bias increases, the transit time in GaN decreases since the velocity in the channel rapidly increases with field. On the other hand in GaAs the transit time initially decreases and then increases. The increase is because at very high fields, once the initial overshoot effect is finished, electrons in GaAs travel at a rather low saturation velocity.

In Fig. 4 we show transit time results in 0.1 μm channels. The overall time decreases when we compare the results with those of Fig. 3. Once again we see that at low bias values the GaAs channel has shorter transit times. At high bias values the GaN channel shows superior performance. Thus once again, in spite of overshoot effects, at high bias values the superior velocity in GaN ensures faster transport. Other qualitative field profiles are also used and the transit times obtained are within 10% of the results given above.

IV. CONCLUSIONS

In summary, in this paper we have examined two dimensional transport in AlGaN/GaN and AlGaAs/GaAs FETs. An ensemble Monte Carlo approach has been used in this study and two dimensional scattering rates have been calculated in the channel numerically. We find that for small bias conditions, GaAs based devices show a shorter transit time. For example, when the peak electric field in a 0.5 μm channel is 3.3×10^4 V/cm, the transit time in the GaN and GaAs channels is 4.5 and 2.0 ps, respectively. However, when the field is increased the GaN channel has a shorter transit time. This difference can be traced to the velocity field relations in the two materials. It is interesting to note that in spite of the velocity overshoot effects in GaAs, at high bias values GaN shows superior results. Our studies show that for low power applications, GaAs based devices should have superior high frequency performance. However, at large bias values we can expect AlGaN/GaN HFETs to have superior performance. As noted in the introduction, experimental studies on GaAs and GaN based devices do show this trend.

ACKNOWLEDGMENTS

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