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High Field Effects of GaN HEMTs

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ABSTRACT

This report represents the completion of a Laboratory-Directed Research and Development (LDRD) program to develop and fabricate geometric test structures for the measurement of transport properties in bulk GaN and AlGaN/GaN heterostructures. A large part of this study was spent examining fabrication issues related to the test structures used in these measurements, due to the fact that GaN processing is still in its infancy. One such issue had to do with surface passivation. Test samples without a surface passivation, often failed at electric fields below 50 kV/cm, due to surface breakdown. A silicon nitride passivation layer of approximately 200 nm was used to reduce the effects of surface states and premature surface breakdown. Another issue was finding quality contacts for the material, especially in the case of the AlGaN/GaN heterostructure samples. Poor contact performance in the heterostructures plagued the test structures with lower than expected velocities due to carrier injection from the contacts themselves. Using a titanium-rich ohmic contact reduced the contact resistance and stopped the carrier injection. The final test structures had an etch constriction with varying lengths and widths (8×2, 10×3, 12x3, 12×4, 15×5, and 16×4 m) and massive contacts. A pulsed voltage input and a four-point measurement in a 50 Ω environment was used to determine the current through and the voltage dropped across the constriction. From these measurements, the drift velocity as a function of the applied electric field was calculated and thus, the velocity-field characteristics in *n*-type bulk GaN and AlGaN/GaN test structures were determined. These measurements show an apparent saturation velocity near to 2.5×10^{7} cm/s at 180 kV/cm and 3.1×10^{7} cm/s, at a field of 140 kV/cm, for the bulk GaN and AlGaN heterostructure samples, respectively. These experimental drift velocities mark the highest velocities measured in these materials to date and confirm the predictions of previous theoretical models using ensemble Monte Carlo simulations.

Keywords: Gallium Nitride (GaN), High Electron Mobility Transistors (HEMTs)

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CONTENTS

INTRODUCTION

High electron mobility transistors (HEMT's) fabricated from AlGaN/GaN heterostructures have shown great potential for microwave power devices [1,2,3,4]. In these heterostructures (and in the HEMTs made with these heterostructures), there is a difference in the polarization field between the top layer (AlGaN) and that in the bottom layer (GaN). In addition, strain in one, or both layers leads to additional built-in fields due to the piezoelectric effect. As a result, the discontinuity in the normal electric field at the hetero-interface leads to a significant sheet carrier concentration on the GaN side of the interface [5,6]. Because of the spontaneous polarization in wurtzite GaN and AlN, the discontinuity in the fields can lead to carrier densities that are ten times higher than in conventional semiconductors, by which we refer to the more normal HEMTs fabricated in GaAs/AlGaAs heterostructures. These effects can cause field (differentials) up to 3 MV/cm, which can produce high interface charge densities (up to 2×10^{13} cm^{-2}).

One reason for the interest in this heterostructure is the high velocity that is expected in GaN itself [7,8,9], and the high thermal conductivity, both of which, together with the high breakdown field, lead to expectations of high power semiconductor devices [10]. In the AlGaN/GaN heterojunction, even higher velocities have been predicted for the electrons in the accumulation layer at the interface [11], with a peak velocity above 3×10^7 cm/s at around 140 kV/cm, based upon ensemble Monte Carlo techniques utilizing an empirical pseudopotential band structure. This high velocity arises in part from the high mobilities that have been observed in these heterostructures [12,13]. In contrast to this, however, there are both experiments and Monte Carlo simulations which suggest that a much lower value of the velocity occurs, of the order of 1×10^7 cm/s at fields above 10 kV/cm [14,15,16]. This same group has, however, obtained a drift velocity above 2×10^7 cm/s at around 140 kV/cm [17], with essentially linear behavior at lower fields, by using short pulses. They attribute the lower values observed earlier to carrier heating. Nevertheless, neither of these reports have the velocity predicted for this heterostructure, and the importance of non-equilibrium phonons was suggested as being important in lowering the velocity [17].

While not making direct measurements of the velocity, groups making AlGaN/GaN HEMTs have estimated the effective velocity from the cutoff frequency of the device. In the case of HEMTs, the effective electron drift velocity (v_d) can be related to the microwave cut-off frequency through $v_d=2\pi f_T L_g$, where L_g is the gate length and f_T is the cutoff frequency. Using this relationship, groups have obtained estimates of the effective velocities of less than, but of the order of, 1×10^7 cm/s [2,4]. Of course, this effective velocity is not the peak velocity discussed above, but is usually thought to be closely related to the valley velocity at very high fields. This observed value is considerably below that expected from the previously mentioned simulations of Yu and Brennan [11].

It is therefore apparent that a further study of the transport properties, including the effects of the polarization charge, in these materials is needed if we are to maximize the device speed and power density and therefore increase device performance. In particular, further study of the drift velocity of electrons in these systems is crucial and should provide additional information about the velocity-field characteristics of these heterostructures. In this document, we report measurements of the velocity-field characteristics in bulk GaN and AlGaN/GaN test structures, with an etched constriction, using a pulsed voltage input and a four-point measurement in a 50 Ω environment. These measurements show an apparent saturation velocity near to 3.1×10^7 cm/s, at a field of 140 kV/cm, which is comparable to the predictions of Yu and Brennan [11].

EXPERIMENTAL PROCEDURE AND RESULTS

Both the bulk GaN and the AlGaN/GaN layers were grown on a c-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD). The bulk samples were approximately 2 m thick and the measured carrier concentration and Hall mobility were 1.35×10^{17} cm^{-3} and 250 cm^2/Vs, respectively. The investigated epitaxial AlGaN/GaN heterostructures consists of an 50 nm AlN nucleation layer, followed by a 2.5 m GaN layer, on which a 5 nm AlGaN layer was grown, followed by a 200 nm silicon doped AlGaN, and a 5 nm nominally undoped AlGaN top layer. The aluminum mole fraction in the AlGaN layers was 25%. The average dislocation density in both the bulk and heterostructure samples was 10^8 cm^2. The measured free carrier concentration and Hall-mobility at room temperature are 1.95×10^{13} cm^{-2} and 430 cm^2/Vs, respectively.

Special geometric test structures were fabricated on the above material. These structures have an etched geometry with massive contacts, in order to minimize contact resistance and to reduce the injection of minority carriers in the narrow test region (called the constriction). Since this geometry is etched, special surface treatment must be given to the constriction and other etched regions to reduce irregularities and surface states, which could cause high local fields and surface breakdown, respectively. For each test structure, the mesa was etched with a chlorine-based plasma in an inductively coupled plasma (ICP) etch system. This etch defines a constriction of dimensions: 8×2, 10×3, 12×3, 12×4, 15×5, and 16×4 m (length × width) and approximately 2 m deep. A plasma-enhanced chemical vapor deposition (PECVD) silicon nitride layer of 200 nm was deposited over the etched regions to passivate the heterostructure surface [18], which was later patterned and etched to form via holes for the deposition of ohmic contacts. Different ohmic contact formulations were used in the presented test structures. The ohmic contacts for *sample set 1* and for *sample set 2* were Ti:Al (50 nm:150 nm) and Ti:Al (75 nm:115 nm), respectively. Both types of contacts were deposited by electron-beam (e-beam) evaporation and subsequently annealed in nitrogen for 30 seconds at 900 C. Ti:Au (50 nm:150 nm) for the formation of bonding pads was also deposited using an e-beam evaporator. The lateral dimensions of the constrictions were determined from optical micrographs of the fabricated structures. The processing is essentially similar to that used previously for measurements on bulk GaN [19]. An example of the fabricated test sample is shown in Fig. 1. A pulsed voltage input and a four-point measurement in a 50 Ω environment was used to determine the current through and the voltage dropped across the constriction.

The experimental drift velocities obtained from two devices of the bulk GaN with constrictions of varying dimensions (16×4 m and12×4 m), are shown in Fig. 2. These test structures were fabricated with the ohmic contacts of *sample set 1* and were measured using an applied voltage pulse of 200 ns. The low-field behavior of both of these devices and other devices tested exhibited similar mobility slopes, which corresponded to the Hall measurement values. In the data shown in Fig. 2, the devices failed just above the electric field at which the peak velocity was observed (180 kV/cm). For fields higher

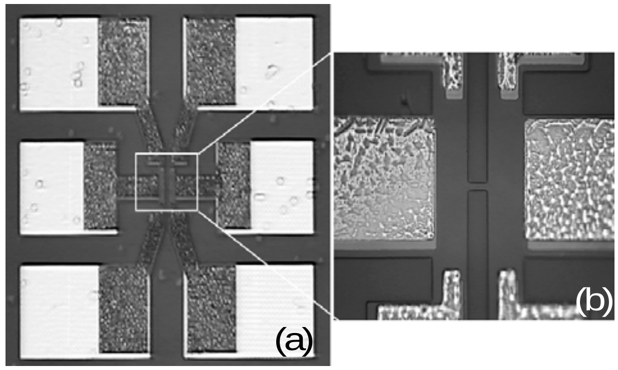

Fig. 1 Optical micrographs of a fabricated test structure, with gold bonding pads (bright areas), ohmic contacts (rough areas), and an etched constriction in the center. (a) Complete structure with massive contacts. (b) A closer look at the etched constriction with dimensions 8×2 m.

than this peak field, the NDC regime begins and a high-field domain is thought to propagate through the sample, which causes high-field breakdown to occur. Device breakdown was seen in the form of a burned track running down the surface at the middle of the constriction, which suggests that the high field in the domain leads to surface breakdown, but at a higher field than in the unpassivated samples. This breakdown effect limits the maximum field in this experiment. The limitation with this measurement technique is that it is only valid for electric fields below the threshold value. The highest velocity measured in these experiments was approximately 2.5×10^{7} cm/s, in complete agreement with the earlier estimates [4,5] and mark the highest measured drift velocity in this system to date.

Our initial experiments performed on the AlGaN/GaN heterostructures test samples used an applied voltage pulse with a 200 ns pulse width. The test structures used in this experiment were from *sample set 1* and the experimental data for two samples in this sample set (constriction dimensions: 10×3 and 12×4 m) are shown in Fig. 3. Here, the saturation velocity is approximately 1×10^{7} cm/s and occurs at 150 kV/cm. While the saturation velocity is around the same value as some other experimental studies and that extracted from current HEMT work, it is still significantly lower than that of theoretical predictions.

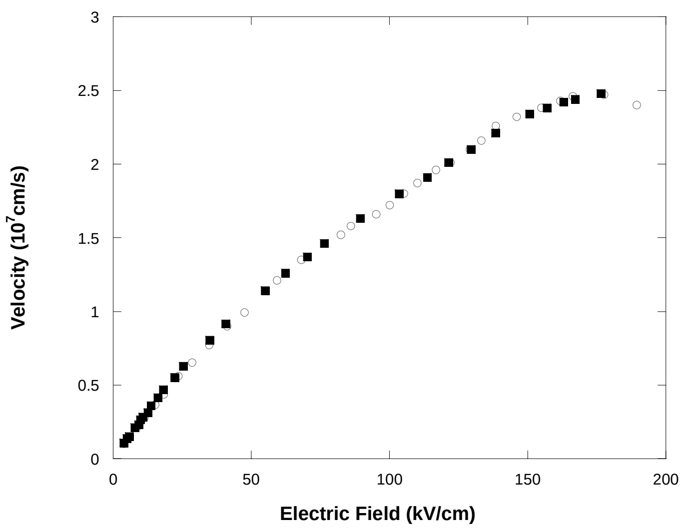

Fig. 2: The experimental velocity-field characteristic for two *n*-type bulk GaN test structures, with varying constriction dimensions, and Monte Carlo results. The squares and circles correspond to experimental test structures with constrictions of dimensions 16×4 m and 12×4 m, respectively. The full diamonds are the simulation results.

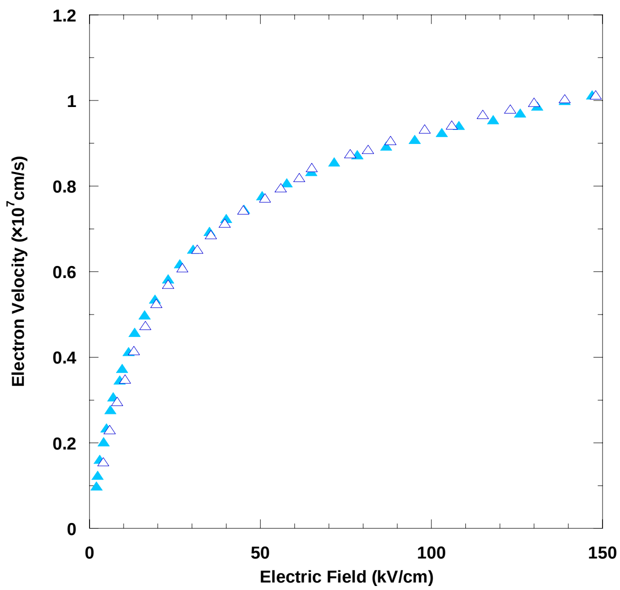

Fig. 3 The experimental data for *sample set 1*, with a 200 ns applied voltage pulse. The open and filled triangles represent samples with constrictions 10×3 and 12×4 m, respectively.

Another sample set (*sample set 2*) was fabricated with Ti-rich contacts that had lower contact resistances and was used in another experiment. In this experiment the new samples were measured using 10 ns applied pulses, in attempt to eliminate the possibility of sample heating. In contrast to both the bulk material and the previous sample set, these measurements show a much higher velocity with an apparent saturation velocity near 3.1×10^{7} cm/s, at a field of 140 kV/cm. The low-field mobility, determined from the velocity-field curve, was 430 cm^2/Vs for both sample sets, which corresponds to previously mentioned Hall data. Figure 4 shows the results of the measurements on three samples in *sample set 2* with constrictions dimensions 8×2 and 12×3 m. The previously mentioned simulation of Yu and Brennan [11] for an AlGaN/GaN heterostructure with an aluminum mole fraction of 30% is also shown in the figure. Therefore, we attribute our lower saturation values from s*ample set 1* to poor contacts. Sample heating may also play a role in limiting the saturation velocity, but we have not seen this as the case in our measurements. Further study is needed to disprove this effect.

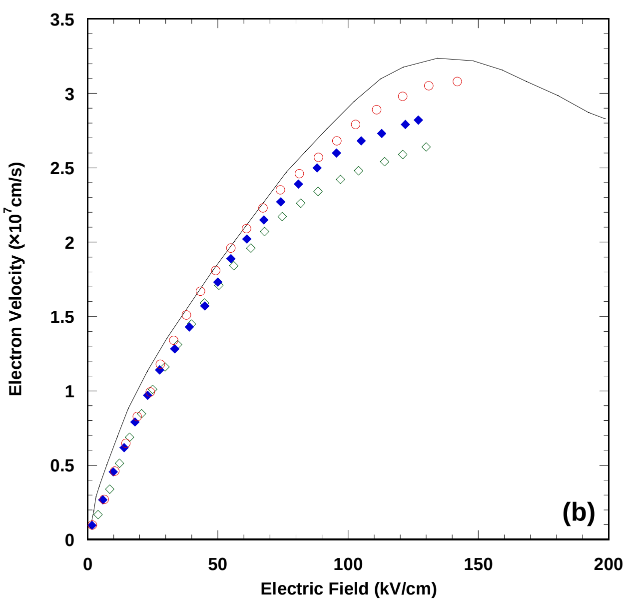

Fig. 4. The experimental data for *sample set 2*, with a 10 ns applied voltage pulse and a comparison to the ensemble Monte Carlo simulation (solid line) of reference [11]. The constriction dimensions for these samples were 8×2 (open circles and filled squares) and 12×3 m (open squares).

While the experimental velocities are significantly higher than previously reported results, they are still lower than the simulation predicts. One possibility leading to the reduction in velocity is an inhomogeneous electric field. While it is well known that negative differential conductance can occur and lead to the formation of field domains in a sample [20], field inhomogeneities can also be induced even prior to the onset of intervalley transfer. The detailed contact dynamics can be quite complicated [21], even between the wide regions and the actual active region being measured. In fact, Kachorovskii *et al.* [22], have suggested a density stratification—a kind of kinetic instability—which is spatially oscillatory through the sample. We have considered a similar problem in which the field is enhanced near the drain and reduced near the source due to a density variation. In short, when the electron density is reduced below its equilibrium value, the field from the polarization discontinuity (in the heterostructure) is no longer balanced by the density. The excess field lines rotate along the channel to be terminated at a locally enhanced density region. Thus, the longitudinal field is larger near the drain where the density is lower (thus maintaining current conservation). Since, the velocity and field near the source, determine the current for the sample, the resulting average velocity is lower than would be expected by the average field V/L. Preliminary calculations suggest that this can be a stable situation.

SUMMARY AND FUTURE WORK

Special geometric test structures were fabricated with an etch constriction and massive contacts to prevent carrier injection from the contacts. Samples of varying constriction lengths and widths (8×2, 10×3, 12×3, 12×4, 15×5, and 16×4 m) were fabricated and passivated with a silicon nitride layer. This layer improved the performance of the test structures and allowed testing up to 180 kV/cm before breakdown occurred. Without this passivation layer, the test structures failed at fields lower than 50 kV/cm and showed visible signs of surface breakdown. The ohmic contacts in the first batch of AlGaN/GaN test structures showed signs of carrier injection at high-fields and therefore limited the measured drift velocity. When titanium-rich contacts were used instead of the previous contacts, the contact resistance lowered and appropriate drift velocities were measured.

Experimental as well as theoretical studies were performed on the velocity-field characteristics of bulk GaN and AlGaN/GaN heterostructures. A pulsed voltage input was applied to the samples and a four-point measurement scheme was used in a 50 Ω environment to determine the room temperature velocity-field characteristic of the structures. Experimental results show saturation velocities of 2.5×10^7 cm/s at 180 kV/cm and 3.1×10^7 cm/s at 140 kV/cm in bulk GaN and AlGaN/GaN heterostructures, respectively. These results exhibit nearly the same saturation velocity expected from earlier Monte Carlo simulations for these materials.

We have used our own ensemble Monte Carlo simulation, which yields results near that of ref. 9 and ref. 11, for both the bulk and heterostructure cases. In the bulk case, a close fit to the low-field mobility was achieved by adding dislocation scattering to the model, which ref. 9 did not include. Thus, in the case of our samples, the low-field mobility was directly dependent on the amount of dislocations in the sample. In the case of the heterostructures, models were created to study the role of non-equilibrium optical phonons and how they can lower the average drift velocity. The velocity observed in the experiments of this study is incompatible with the onset of non-equilibrium phonons that has been suggested earlier to explain low observed velocities [17]. Hence, the reduction observed earlier is unlikely to be due to the onset of non-equilibrium phonons, and more likely to inhomogeneity effects, as well as poor contacts. We note also that the current samples were fabricated on sapphire substrates. The use of a SiC substrate is usually preferred for thermal reasons, so the present measurements can be considered as perhaps worst case in terms of thermal behavior.

Since the results of this study match closely to that of our own simulation as well as previous theoretical models, we are convinced that this measurement technique is accurate in determining the electron drift velocity in these material systems. The experimental drift velocities measured in this study mark the highest velocities measured in these materials to date and confirm the predictions of previous theoretical models. This concludes that GaN and its related heterostructures have great potential in future high frequency, high power applications.

There are several topics that could be studied further to enhance the research of this field. First, a more extensive study should be performed to find better ohmic contacts, especially in the case of the AlGaN/GaN heterostructures. This is a crucial step not only for measuring the velocity-field characteristic, but high power devices will inherently operate at high-fields and will require non-injecting contacts at those fields. Secondly, while ref. 17 claims pulse widths over 3 ns lowers the drift velocity due to sample heating, this was not the case in this study. In fact, applied pulse widths as wide as 25 ns produced the same saturation velocities as pulses 10 ns widths in this study. Therefore, a further study into the role of the pulse width on the saturation velocity should be performed. Along this same line, a more detailed analysis of the role of nonequilibrium phonons and high-field inhomogeneities should be studied. Lastly, new measurements on bulk GaN and heterostructures grown on SiC should be performed. Lower lattice mismatch with growth on SiC substrates should reduce the dislocation density and provide much higher mobility samples.

REFERENCES

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[1] J. R. Shealy *et al.*, J. Phys. Condens. Matter **14** (2002) 3499.

[2] H. Xing *et al.*, J. Phys. Condens. Matter **13** (2001) 7139.

[3] M. J. Manfra, *et al.*, Elect. Lett. **39** (2003) 694-695.

[4] V. Kumar *et al.*, Solid State Electron **47** (2003) 1577-1580.

[5] O. Ambacher *et al.*, J. App. Phys. **85** (1999) 3222.

[6] F. Bernardini V. Fiorentini, and D. Vanderbilt, Phys. Rev. B **56**, (1997) 10024.

[7] D. K. Ferry, Phys. Rev. B **8**, 1544 (1973).

[8] M. A. Littlejohn, J. R. Hauser, and T. H. Glisson, J. Appl. Phys. **26**, 625 (1975).

[9] J. Kolnik *et al.*, J. Appl. Phys. **78**, 1033 (1995).

[10] P. Das and D. K. Ferry, Sol.-State Electron. **19**, 851 (1976).

[11] T.-H. Yu and K. F. Brennan, J. Appl. Phys. **91**, 3730 (2002).

[12] M. Asif Khan *et al.*, Appl. Phys. Lett. **67**, 1429 (1995).

[13] R. Gaska, Appl. Phys. Lett. **74**, 287 (1999).

[14] A. Matulionis *et al.*, Semicond. Sci. Technol. **17**, L9 (2002).

[15] M. Ramonas, A. Matulionis, and L. Rota, Semicond. Sci. Technol. **18**, 118 (2003).

[16] A. Matulionis *et al.*, Phys. Rev. B **68**, 035338 (2003).

[17] L. Ardaravicius *et al*., Appl. Phys. Lett. **83**, 4039 (2003).

[18] J. M. Barker *et al.*, Semicond. Sci. Technol. **19,** 478 (2004).

[19] J. M. Barker *et al.*, Physica B. **314,** 39 (2002).

[20] M. P. Shaw, H. L. Grubin, and P. R. Solomon, *The Gunn-Hilsum Effect* (Academic Press, New York, 1979).

[21] H. Kroemer, IEEE Trans. Electron Dev. **50**, 1251 (1968).

[22] V. Yu. Kachorovskii, I. S. Lyubinskiy, and L. D. Tsendin, Phys. Rev. B **68**, 033308 (2003).

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