Wright State University

CORE Scholar

Physics Faculty Publications

Physics

8-1-2001

Predicted Maximum Mobility in Bulk GaN

David C. Look

Wright State University - Main Campus, david.look@wright.edu

J. R. Sizelove

Follow this and additional works at: <https://corescholar.libraries.wright.edu/physics>

Part of the [Physics Commons](#)

Repository Citation

Look, D. C., & Sizelove, J. R. (2001). Predicted Maximum Mobility in Bulk GaN. *Applied Physics Letters*, 79 (8), 1133-1135.

<https://corescholar.libraries.wright.edu/physics/70>

This Article is brought to you for free and open access by the Physics at CORE Scholar. It has been accepted for inclusion in Physics Faculty Publications by an authorized administrator of CORE Scholar. For more information, please contact library-corescholar@wright.edu.

Predicted maximum mobility in bulk GaN

D. C. Look^{a)}

Semiconductor Research Center, Wright State University, Dayton, Ohio 45435 and Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433

J. R. Sizelove

Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433

(Received 14 May 2001; accepted for publication 22 June 2001)

A 300 K bulk (three-dimensional) mobility of $1245 \text{ cm}^2/\text{V s}$ has been measured in free-standing GaN. Temperature-dependent Hall-effect data on this particular sample are fitted to obtain unknown lattice-scattering parameters, as well as shallow donor (N_D) and acceptor (N_A) concentrations, which are $N_D = 6.7 \times 10^{15}$ and $N_A = 1.7 \times 10^{15} \text{ cm}^{-3}$. Realistic values of the *maximum* mobility attainable in bulk GaN are then obtained by assuming two-orders-of-magnitude lower values of N_D and N_A , leading to a maximum 300 K mobility of $1350 \text{ cm}^2/\text{V s}$, and a maximum 77 K mobility of $19\,200 \text{ cm}^2/\text{V s}$. © 2001 American Institute of Physics. [DOI: 10.1063/1.1394954]

The last decade has seen a surge in research and development on GaN-related materials and devices.^{1,2} The driving force has been the potential for blue/UV light-emitting diodes (LEDs) and laser diodes, and also high-frequency transistors operating at high powers and temperatures. In fact, blue LEDs have already been commercialized, and blue lasers will soon be employed in consumer products. However, these successes are a mystery to many researchers, because even the best GaN materials have high concentrations of donors, acceptors, point defects, and dislocations, compared with those of, say, Si and GaAs. Moreover, it is generally acknowledged that development of commercial electronic devices, and further improvements in photonic devices, will require better materials. Recently, a marked improvement in electron mobility, the most commonly used figure of merit, has been realized by two types of GaN growth: (1) hydride vapor-phase epitaxy (HVPE) on Al_2O_3 , with subsequent separation of the GaN from the Al_2O_3 ,^{3–7} and (2) molecular-beam epitaxy on templates consisting of metal-organic chemical-vapor deposition on Al_2O_3 .⁸ Each of these techniques has produced a sample with a 300 K mobility of close to $1200 \text{ cm}^2/\text{V s}$, a world's record for bulk (three-dimensional) conduction in GaN. (Of course, two-dimensional mobilities in AlGaIn/GaN heterostructures can be significantly higher because of confinement and screening effects.⁹) In this article, we fit the temperature-dependent mobility μ and carrier concentration n of the highest-mobility bulk GaN sample available⁶ to get accurate values of donor concentration N_D , acceptor concentration N_A , donor activation energy E_D , acoustic-mode deformation potential E_1 , and piezoelectric coefficient P (or piezoelectric constant h_{pz}). Other, better-known parameters important for scattering, such as the effective mass, are taken from the literature. Fortunately, the fitted values of E_1 and h_{pz} are quite representative of those available in the literature, giving credence to our model. We then can calculate mobility

curves for the smallest estimated realistic values of N_D and N_A , and thus find the maximum mobility in bulk GaN at a given temperature.

The GaN sample discussed here was grown in the (0001) orientation (Ga face up) on Al_2O_3 by the HVPE technique at the Samsung Advanced Institute of Technology. Separation of the GaN and Al_2O_3 was effected by laser irradiation on the N face, through the Al_2O_3 substrate. This particular sample, as well as several others prepared in the same way, have been extensively characterized by optical, electrical, and structural techniques.^{3–7} In particular, earlier Hall-effect measurements on this sample have demonstrated a world's record mobility,⁶ and the optical and structural properties are also consistent with very high quality. However, it is well known that HVPE GaN/ Al_2O_3 layers always have a thin, degenerate layer in the interface region, and this layer typically has a strong influence on the overall Hall-effect measurements, even at high temperatures.¹⁰ It is possible to correct for the effects of the interface layer, but sometimes the accuracy of the corrections is uncertain. Thus, we have used reactive-ion etching to remove about $30 \text{ }\mu\text{m}$ of material from the N face of our sample, effectively eliminating the degenerate layer and leaving a total thickness of about $220 \text{ }\mu\text{m}$.

The van der Pauw-Hall-effect measurements were performed with a LakeShore model 7507 apparatus, including a closed-cycle He cooling system operating from 15 to 320 K. Under a heating cycle, the thermometer and sample temperatures differed by only 0.7 K at a nominal temperature of 300 K; even so, a simple, linear temperature correction was implemented to account for this small difference. Thus, temperature accuracy was well within 0.5 K over the whole range. The magnetic field was set at 2 kG, which had a negligible effect on the Hall coefficient R and conductivity σ , even at the highest mobility, which occurred at about 70 K. (Note that at the more commonly used field of 10 kG, the measured field-induced error in R at 70 K is 3%, and in σ , 5%. At 300 K, the field-induced error in either is negligible.) From measurements of R and σ , the Hall mobility $\mu_H = R\sigma$ and the Hall concentration $n_H = 1/eR$ could be calcu-

^{a)} Author to whom correspondence should be addressed; electronic mail: david.look@wpafb.af.mil

FIG. 1. Mobility data (circles) and theory (solid line), using the given parameters.

lated at each temperature. These results are shown in Figs. 1 and 2, respectively. It should be remembered that the conductivity mobility μ_c is related to the Hall mobility by $\mu_c = \mu_H/r$, where r is the so-called Hall r factor;¹¹ also, the true carrier concentration n is related to n_H by $n = rn_H$. In practice, μ_H is of more interest than μ_c , because μ_H is much easier to measure and thus is a better figure of merit. However, n is of more interest than n_H , because N_D , N_A , and E_D are calculated from the temperature dependences of n , not n_H ; thus, for the highest accuracy, it is necessary to calculate r (discussed below). In Fig. 2, both the raw n_H and the r -corrected n values are shown. For this sample, $r = 1.1$ – 1.2 from 50 to 320 K.

The theoretical fits of μ_H and n are shown as solid lines in Figs. 1 and 2, respectively. In principle, the fits must be carried out simultaneously, since μ_H is a function of n . A convenient way to implement this process is to first fit μ_H vs. T , with $n = n_H$, and get an approximate set of values for r vs. T . Then, a new set of n values can be calculated from $n = rn_H$, and μ_H vs T can be refitted with the new values of n , obtaining a new set of r values. However, it is usually found that the new set of r values differs little from the first set. The mobility is calculated by using an iterative solution of the Boltzmann equation, as developed by Rode.¹² We have

FIG. 2. Hall concentration n_H (solid circles), and the true electron concentration $n = rn_H$ (open circles). The solid line is a two-donor fit to n vs $10^3/T$, using the given parameters.

used Nag's treatment¹³ of this method and have included scattering terms arising from polar-optical lattice modes; deformation-potential and piezoelectric-potential acoustical lattice modes; and ionized impurities and defects, treated in the Brooks–Herring model. We have also included neutral impurity/defect scattering, following Erginsoy's formulation.¹⁴ However, dislocation scattering¹⁵ has been ignored, because the measured edge dislocation density on the Ga face is only about 10^5 – 10^6 cm^{−2}. (Further discussion on this matter is presented below.)

The scattering rates depend on various parameters, as follows: polar optical, $\sim (m^*)^{1/2} T_{po} (\epsilon_0^{-1} - \epsilon_\infty^{-1}) / [\exp(T_{po}/T) - 1]$; acoustic deformation potential, $(m^*)^{3/2} E_1^2 / c_L$; acoustic piezoelectric potential, $(m^*)^{1/2} P_\perp^2 / \epsilon_0$; ionized-impurity/defect, $(2N_A + n)f(n)/(m^*)^{1/2} \epsilon_0^2$, where $f(n)$ is a weak function of n ; and neutral impurity/defect, $(N_D - N_A - n)\epsilon_0 / m^*$. In these formulas, m^* is the effective mass, generally accepted¹⁶ as $0.22m_0$; ϵ_0 and ϵ_∞ are the relative static¹⁷ and high-frequency¹⁸ dielectric constants, respectively, taken to be $\epsilon_0 = 10.4$ and $\epsilon_\infty = 5.15$, although other values are also commonly used;^{16,19} T_{po} is the polar-optical temperature, well accepted as $T_{po} = 1057$ K ($= 735$ cm^{−1} = 91.1 meV);²⁰ E_1 is the acoustic deformation potential (the change of conduction-band energy per unit strain), given in one reference²¹ as 9.2 eV, for the hydrostatic component, but having no firm consensus;²² c_L is the longitudinal elastic constant, defined for the wurtzite structure by Eq. (104) of Ref. 12, and calculated as $c_L = 3.82 \times 10^{11}$ N/m² from components of the elastic tensor determined from x-ray measurements;^{23,24} and $P_\perp$ is the perpendicular component of the piezoelectric coefficient, defined for the wurtzite structure by Eq. (101) of Ref. 12, and given theoretically as $P_\perp = 0.113$ (dimensionless), from theoretical components²⁵ of the piezoelectric tensor e_{ij} (with an assumption that $e_{15} = e_{31}$), and experimental components²⁴ of the elastic tensor c_{ij} . Finally, N_D , N_A , and n ($= rn_H$) are determined from the n_H vs T and μ_H vs T data.

In the mobility fitting process, we take m^* , ϵ_0 , ϵ_∞ , and T_{po} as fixed, since the literature values for m^* , ϵ_0 , and ϵ_∞ are nowadays consistent within about 10%, and T_{po} , within about 2%. However, there is wide uncertainty in the other lattice parameters, E_1 , c_L , and $P_\perp$, so we must fit the quantities E_1^2/c_L and $P_\perp$, along with N_A . If we use x-ray values²⁴ of the elastic tensor, then $c_L = 3.82 \times 10^{11}$ N/m², and our fitted value of E_1 becomes 13.5 eV per unit strain; this compares favorably with a hydrostatic value of 9.2 eV, determined from optical measurements.²¹ Also, our fitted value of $P_\perp$, 0.083, is acceptably close to the theoretical value given above, 0.113. In zinc-blende materials, the piezoelectric scattering strength is often quoted in terms of $e_{14} \equiv h_{pz} = (\epsilon_0 c_L)^{1/2} P / (1 - P^2)^{1/2} \approx 0.49$ C/m², in our case. Finally, the last unknown parameter in the scattering formalism is N_A , and here we get $N_A = 1.7 \times 10^{15}$ cm^{−3}. Then, from the n vs T data, we can also obtain $N_D = 6.7 \times 10^{15}$ cm^{−3} and $E_D = 25.7$ meV. We believe that the values of N_D and N_A are the smallest obtained in GaN, and E_D , the largest, attesting to the high quality of the material. With regard to E_D , the donor potential can be screened by free and bound charges, and the effects of the screening are usually modeled by a

FIG. 3. Experimental Hall mobility (circles), fitted with $N_D = 6.7 \times 10^{15}$ and $N_A = 1.7 \times 10^{15} \text{ cm}^{-3}$, and a hypothetical mobility curve for $N_D = 6.7 \times 10^{13}$ and $N_A = 1.7 \times 10^{13} \text{ cm}^{-3}$. The other scattering parameters are listed in the figure.

simple formula, $E_D = E_{D0} - \alpha N_D^{1/3}$. Although the value of α is not well known, one study²⁶ has suggested $\alpha \approx 2.1 \times 10^{-5} \text{ meV cm}$, which would lead to $E_{D0} \approx 30 \text{ meV}$, in our case. The hydrogenic donor formula, $E_{DH} = 13.6 m^*/\epsilon_0^2$, would then predict a static dielectric constant $\epsilon_0 = 10.0$, comfortably within the literature range,^{16,17} 9.5–10.4. Thus, our Hall-effect analysis seems to be solidly based in all aspects, and we believe that it can be used to predict mobilities for other values of N_D and N_A .

To determine the maximum realistic mobilities, we now set N_D and N_A to the lowest reasonable values. From a comparison with the GaAs case, it would seem possible to reduce N_D and N_A in GaN by perhaps two orders of magnitude to 6.7×10^{13} and $1.7 \times 10^{13} \text{ cm}^{-3}$, respectively, maintaining the compensation ratio measured above. At $N_D = 6.7 \times 10^{13} \text{ cm}^{-3}$, we would expect E_D to be 29 meV. These values of N_D , N_A , and E_D then predict the upper curve in Fig. 3. From this curve, $\mu_H = 1350 \text{ cm}^2/\text{V s}$ at 300 K, and $\mu_H = 19\,200 \text{ cm}^2/\text{V s}$ at 77 K. Note that the 300 K μ_H of our present sample, $1245 \text{ cm}^2/\text{V s}$ is not too far below the maximum 300 K μ_H . Thus, for very pure samples, the 77 K μ_H becomes a more definitive figure of merit than the 300 K μ_H .

We have ignored dislocation scattering in the present sample because the measured dislocation density N_{dis} of 10^5 – 10^6 cm^{-2} will not appreciably affect either its 300 or 77 K mobilities.¹⁵ However, a density of 10^7 cm^{-2} would have dropped the 300 K μ_H by about 3%, and the 77 K μ_H by about 38%. Furthermore, N_{dis} will become even more important as N_D and N_A become smaller. For example, in the pure sample discussed above, an N_{dis} of only 10^6 cm^{-2} would have dropped the 300 K μ_H by about 7%, and the 77 K μ_H by about 59%. It also should be noted that a dislocation density of 10^6 cm^{-2} provides an effective acceptor density of $10^6/5.185 \times 10^{-8} \approx 2 \times 10^{13} \text{ cm}^{-3}$, requiring a value $N_D - N_A \geq 2 \times 10^{13} \text{ cm}^{-3}$ to even have free carriers.

In conclusion, we have fitted the best available GaN sample with an accurate scattering theory, and have determined reasonable values of the various lattice-scattering pa-

rameters as well as the donor and acceptor concentrations. The lattice-scattering parameters have then been used in conjunction with the estimated lowest possible values of N_D and N_A to determine the maximum values of mobility in bulk GaN, as a function of temperature. The 77 K mobility in the present sample is compatible only with a value of dislocation density $\rho_D < 10^7 \text{ cm}^{-2}$, consistent with measured values of ρ_D .

The authors wish to thank S. S. Park and K. Y. Lee of Samsung for growing the sample, C. M. Sung and M. Callahan for helping us obtain it, A. Saxler and H. Morkoç for helpful discussions, and T. A. Cooper for the Hall-effect measurements. One of the authors (D.C.L.) was supported by AFOSR Grant No. F49620-00-1-0347 and U.S. Air Force Contract No. F33615-00-C-5402.

- ¹S. Strite and H. Morkoç, *J. Vac. Sci. Technol. B* **10**, 1237 (1992).
- ²O. Ambacher, *J. Phys. D* **31**, 2653 (1998).
- ³D. C. Reynolds, D. C. Look, B. Jogai, A. W. Saxler, S. S. Park, and J. Y. Han, *Appl. Phys. Lett.* **77**, 2879 (2000).
- ⁴F. Yun, M. A. Reshchikov, K. M. Jones, P. Visconti, H. Morkoç, S. S. Park, and K. Y. Lee, *Solid-State Electron.* **44**, 2225 (2000).
- ⁵E. Oh, S. K. Lee, S. S. Park, K. Y. Lee, I. J. Song, and J. Y. Han, *Appl. Phys. Lett.* **78**, 273 (2001).
- ⁶A. Saxler, D. C. Look, S. Elhamri, J. R. Sizelove, W. C. Mitchel, C. M. Sung, S. S. Park, and K. Y. Lee, *Appl. Phys. Lett.* **78**, 1873 (2001).
- ⁷Z.-Q. Fang, D. C. Look, P. Visconti, D.-F. Wang, C.-Z. Lu, F. Yun, H. Morkoç, S. S. Park, and K. Y. Lee, *Appl. Phys. Lett.* **78**, 2178 (2001).
- ⁸B. Heying, I. Smorchkova, C. Poblenz, C. Elsass, P. Fini, S. Den Baars, U. Mishra, and J. S. Speck, *Appl. Phys. Lett.* **77**, 2885 (2000).
- ⁹C. R. Elsass, I. P. Smorchkova, B. Heying, E. Haus, C. Poblenz, P. Fini, K. Maranowski, P. M. Petroff, S. P. Den Baars, U. K. Mishra, J. S. Speck, A. Saxler, S. Elhamri, and W. C. Mitchel, *Jpn. J. Appl. Phys., Part 2* **39**, L1023 (2000).
- ¹⁰D. C. Look and R. J. Molnar, *Appl. Phys. Lett.* **70**, 3377 (1997).
- ¹¹D. C. Look, *Electrical Characterization of GaAs Materials and Devices* (Wiley, New York, 1989), Chap. 4.
- ¹²D. L. Rode, *Semicond. Semimetals* **10**, 1 (1975).
- ¹³B. R. Nag, *Electron Transport in Compound Semiconductors* (Springer, Berlin, 1980).
- ¹⁴C. Erginsoy, *Phys. Rev.* **79**, 1013 (1950).
- ¹⁵D. C. Look and J. R. Sizelove, *Phys. Rev. Lett.* **82**, 1237 (1999).
- ¹⁶J. W. Orton and C. T. Foxon, in *GaN and Related Semiconductors*, edited by J. H. Edgar, S. Strite, I. Akasaki, H. Amano, and C. Wetzel (INSPEC, London, 1999), p. 294.
- ¹⁷Y. J. Wang, R. Kaplan, H. K. Ng, K. Doverspike, D. K. Gaskill, T. Ikeda, H. Amano, and I. Akasaki, *J. Appl. Phys.* **79**, 8007 (1996).
- ¹⁸G. Yu, G. Wang, H. Ishikawa, M. Umeno, T. Soga, T. Egawa, J. Watanabe, and T. Jimbo, *Appl. Phys. Lett.* **70**, 3209 (1997).
- ¹⁹M. Leroux and B. Gil, in *GaN and Related Semiconductors*, edited by J. H. Edgar, S. Strite, I. Akasaki, H. Amano, and C. Wetzel (INSPEC, London, 1999), p. 48.
- ²⁰C. Wetzel and I. Akasaki, in *GaN and Related Semiconductors*, edited by J. H. Edgar, S. Strite, I. Akasaki, H. Amano, and C. Wetzel (INSPEC, London, 1999), p. 52.
- ²¹W. Shan, T. Schmidt, X. H. Yang, J. J. Song, and B. Goldenberg, *J. Appl. Phys.* **79**, 3691 (1996).
- ²²B. Gil and M. Leroux, in *GaN and Related Semiconductors*, edited by J. H. Edgar, S. Strite, I. Akasaki, H. Amano, and C. Wetzel (INSPEC, London, 1999), p. 67.
- ²³A. Polian, in *GaN and Related Semiconductors*, edited by J. H. Edgar, S. Strite, I. Akasaki, H. Amano, and C. Wetzel (INSPEC, London, 1999), p. 17.
- ²⁴V. A. Savastenko and A. U. Sheleg, *Phys. Status Solidi A* **48**, K135 (1992).
- ²⁵F. Bernardini, V. Fiorentini, and D. Vanderbilt, *Phys. Rev. B* **56**, R10024 (1997).
- ²⁶B. K. Meyer, D. Volm, A. Graber, H. C. Alt, T. Detchprohm, A. Amano, and I. Akasaki, *Solid State Commun.* **95**, 597 (1995).