INTERFACE EFFECTS ON THE PERSISTENT PHOTOCONDUCTIVITY IN THIN GaN AND AlGaN FILMS

O. P. Seifert *, O. Kirfel *, M. Munzel *, M. T. Hirsch *, J. Parisi *
M. Kelly **, O. Ambacher **, and M. Stutzmann **

* University of Oldenburg, FB8/EHF, D-26129 Oldenburg
** Technical University of Munich, Walter Schottky Institute, D-85748 Garching

Cite this article as: MRS Internet J. Nitride Semicond. Res. 4S1, G5.5 (1999)

Abstract

Thin films of GaN and its alloy AlGaN are investigated with respect to their properties of the persistent photoconductivity (PPC). In this work, we show that the film-substrate interface plays an important role for the metastable electrical effect. Strongly absorbed bandgap light causes an increase of photoconductivity which is about one order of magnitude higher when the sample is illuminated from the substrate side near the interface than from the growth side. To access the interface properties at the substrate, we use temperature-dependent Hall effect measurements. The smallest PPC effect was observed for the GaN film with the best interface properties grown on SiC.

I. Introduction

GaN and its alloys with In and Al have become the most favorite candidates for blue light emitting diodes, laser diodes, and high-temperature, high-power electronic devices [1,2]. It has been shown very early that intrinsic defects play an important role in the electrical behavior of these materials [3,4]. Extensive studies on defect-related behavior like, e.g., the "yellow band luminescence" or the consequences of additional defect-rich layers for Hall measurements [5,6] have been performed. Also the persistent photoconductivity (PPC) observed by several groups [7,8], is discussed as a result of native defects in GaN. However, since the PPC seems to be present independent of the doping, alloying and growth method, other sources for the long-time constants connected with the metastability have to be considered. In this work, we investigate the influence of the interfacial and defect-rich layer on the PPC and Hall effect measurements.

II. Experiment

The samples were grown by metal-organic chemical vapor deposition (MOCVD) as well as by molecular beam epitaxy (MBE). As substrate material, both sapphire and SiC were used. For some samples, a 50nm thick GaN low-temperature buffer layer was also grown. Ohmic contacts were prepared in a coplanar van der Pauw geometry by electron beam evaporation of 20nm Ti and 100nm Al and subsequent annealing in N_2 atmosphere at 900°C for around 60s. For the light-dependent PPC measurements, an Oxford cryostat CF1204 was used in combination with a Xenon lamp and a Bentham M300 monochromator. In this setup, it is possible to mount the sample for front- and backside illumination. Temperature-dependent Hall effect measurements were carried out in a Janis ST300 cryostat and Bruker B-E 10 magnet system. In Table I, the samples under investigation are summarized.

Table I: Samples used in this work for PPC and Hall effect measurements
* the grower did not provide any details about the buffer

Sample	Alloy	Growth	Buffer	Substrate	dopant	n_{eff} [cm^{-3}]
SM3	GaN	MBE	none	sapphire	unint. n-type	3,0x10^{17}
SM5	Al$_{0.15}$Ga$_{0.85}$N	MBE	none	sapphire	Si, n-type	2,1x10^{18}
SI3	GaN	MOCVD	yes*	sapphire	Si, n-type	7,5x10^{18}
SM1	GaN	MOCVD	50nm GaN	sapphire	unint. n-type	5,5x10^{17}
SI6	GaN	MOCVD	yes*	SiC	Si, n-type	1,7x10^{18}

III. Results of photoconductivity measurements

The buildup transients for the PPC have been measured for different values of the excitation wavelength. PPC was observed in all samples. However, the PPC magnitude under similar illumination conditions varied significantly for GaN and AlGaN and also showed differences with respect to samples with different interface regions.

For the Al$_{0.15}$Ga$_{0.85}$N sample, the magnitude of the PPC, i.e., the excess conductivity due to illumination compared to the dark conductivity value, is in the order of 250%, whereas for all GaN samples grown on *sapphire* it is between 10% and 60%. However, for the GaN sample grown on *SiC*, the PPC magnitude is only around 1%. One main difference between these GaN samples is given by the substrate. Therefore, a simple but significant test for the influence of the interface between the substrate and the GaN film on the PPC behavior is to use strongly absorbed bandgap light for excitation and observe the PPC buildup transients under frontside illumination (i.e., from the growth side) and backside illumination (i.e., sample is illuminated through the substrate). In Fig. 1, the *excess* conductivity transients for a GaN sample grown on sapphire is shown. For illumination from the substrate side with strongly absorbed bandgap light of λ=300nm (4.1eV), the increase in conductivity is about one order of magnitude higher than in the case of illumination from the growth side.

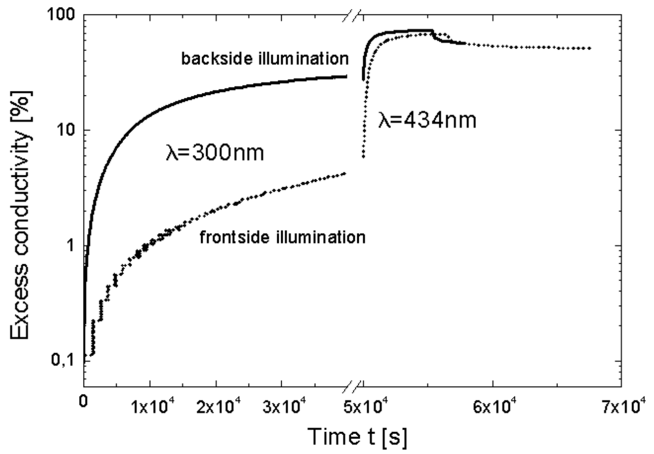

Fig. 1: Comparison of excess conductivity transients under different illumination conditions for a GaN sample grown on sapphire. The dotted line results from illumination from the frontside, the solid line from illumination from the substrate side (backside). At t=0s, the first illumination cycle with strongly absorbed bandgap light (λ=300nm) is started. The second cycle of illumination with subbandgap light of λ=434nm starts at ~5x10^{4}s. For the subbandgap light illumination, both transients exhibit about the same value at the end of illumination. But for illumination with strongly absorbed bandgap light, the excess conductivity is by a factor of ten higher when illuminated through the substrate (i.e., light absorption takes place near the substrate-GaN interface) than illuminated from the growth side.

Comparing this difference with the behavior of the sample under illumination with subbandgap light of λ=434nm (2.9eV), the change in conductivity is the same independent of the illumination direction. For a more detailed understanding of the influence of the interfacial layer between the substrate and the GaN film on the PPC effect, an analysis of the photoconductivity *buildup* transients can be very helpful.

The buildup transient measurements were performed as follows: the samples were kept in the dark at 340K for 2h to reach equilibrium dark conditions and afterwards cooled down to 100K. The conductivity increase due to illumination at each wavelength was then measured for 4h. Then the samples were heated again up to 340K for several hours in the dark. This cycle was repeated for all measurement wavelengths between 400nm and 1000nm. The photon flux for all measurements was kept constant at ~ $2x10^{14}$ $s^{-1}cm^{-2}$. The widely used stretched exponential fit shows good agreement for each transient on a linear time scale. However, the fit was not satisfying on a logarithmic time scale. Therefore, we use a different approach and characterize the conductivity transients in analogy to Ref. [9] by plotting the value of the conductivity after 14400s (4h) of illumination versus the photon energy used for the excitation, as shown in Fig 2. We use a linear fit of the data, to estimate a threshold energy E_{th} for the optical excitation.

In Fig. 2(a), we compare the PPC excitation behavior of MBE grown GaN and AlGaN samples without a buffer layer. The threshold energy for the GaN sample (SM3) is at 1.1eV, whereas for the $Al_{0.15}Ga_{0.85}N$ sample (SM5) we find a threshold energy at 1.6eV. The bandgap of the GaN and the $Al_{0.15}Ga_{0.85}N$ sample are 3.4eV and 3.8eV, respectively. Therefore, we conclude that the optical excitation for both samples occurs from defects located in the bandgap at energies ranging from 2.2eV to 2.3eV. These values correlate well with the energy of the maximum of the yellow luminescence in photoluminescence (PL) measurements [9-13]. A recently published work on depth profiling of the yellow luminescence [14] also shows a strong increase in the ratio of yellow emission to near-band-edge emission near the interface. All these results strengthen the idea that the interface is important for the PPC.

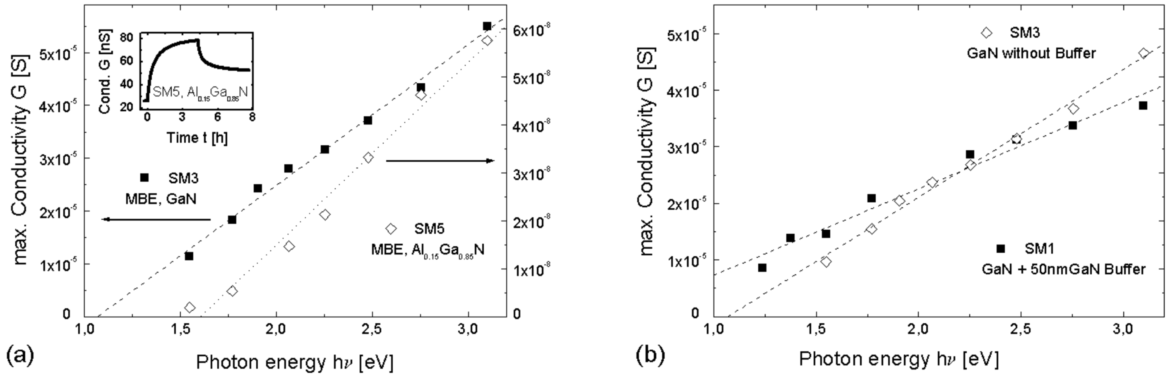

Fig. 2. Conductivity after 14400s of illumination versus the photon energy used for excitation. The dashed and dotted lines are linear fits to the data. The intersection with the energy axis yields an estimation for the lower threshold energy limit E_{th} for optical excitation.

(a) We find a difference in threshold energy for GaN (E_{th}=1.1eV) and $Al_{0.15}Ga_{0.85}N$ (E_{th}=1.6eV) which compares well with the differences of their bandgap energies. The inset shows a typical conductivity transient: illumination with λ=434nm starts at t=0 and ends at t=14400s.

(b) A comparison between two samples with and without buffer yields a threshold energy of E_{th}=0.5eV for the sample with 50nm GaN buffer and E_{th}=1.1eV for the sample without buffer.

Therefore, we compare samples with different interfaces, i.e., SiC as substrate material or an additional GaN buffer layer. The PPC in these samples is, in general, smaller compared to the PPC in films grown directly on sapphire, e.g., the PPC observed in sample SI6, grown on SiC, evaluates to only 1% of total change of conductivity. This change was correlated to a bad signal to noise ratio and, therefore, unfortunately did not allow for a meaningful analysis of the buildup tranients. In Fig. 2(b) a comparison of a sample containing a 50nm GaN buffer (SM1) with a sample without buffer (SM3) is shown. There is a significant difference in the threshold energy for the optical excitation observable. For the sample SM1, grown on sapphire with an additional buffer layer, this energy shifts down to a lower energy of 0.5eV. At this point of our investigations on the buildup transients of the conductivity, it is obvious that the interfacial layer near the substrate plays an important role in the PPC behavior.

IV. Results of van der Pauw and Hall effect experiments

The influence of a defect-rich layer close to the interface can be accessed by Hall effect measurements [5,6]. Therefore, we performed temperature-dependent Hall effect measurements to compare the results of the PPC with the results of the Hall-measurements. The samples were kept in the dark at 350K for around 2h. Afterwards they were cooled down to 10K. Starting from this temperature, the measurements were performed up to 340K. Figure 3 shows the results for the sample SI3 (sapphire substrate), SM1 (50nm GaN buffer), and SI6 (SiC substrate). For each sample the *effective* Hall-carrier concentration n_{eff} exhibits a minimum with respect to temperature. A similar behavior of n_{eff} was observed in GaN grown by hydride vapor phase epitaxy (HVPE) [5,6] and explained with a two-layer model of a GaN and a defective interface region or a continuous increasing defect concentration towards the substrate.

For our samples, the temperature position of these minima clearly depends on the substrate and buffer layer. For the sample SI3 (sapphire substrate), the n_{eff} minimum is very broad and located at 170K. The sample SM1 (50nm GaN-buffer layer) exhibits a sharper minimum located at 150K. For the sample SI6 (SiC substrate), the n_{eff} minimum is very sharp and shifted down to 60K.

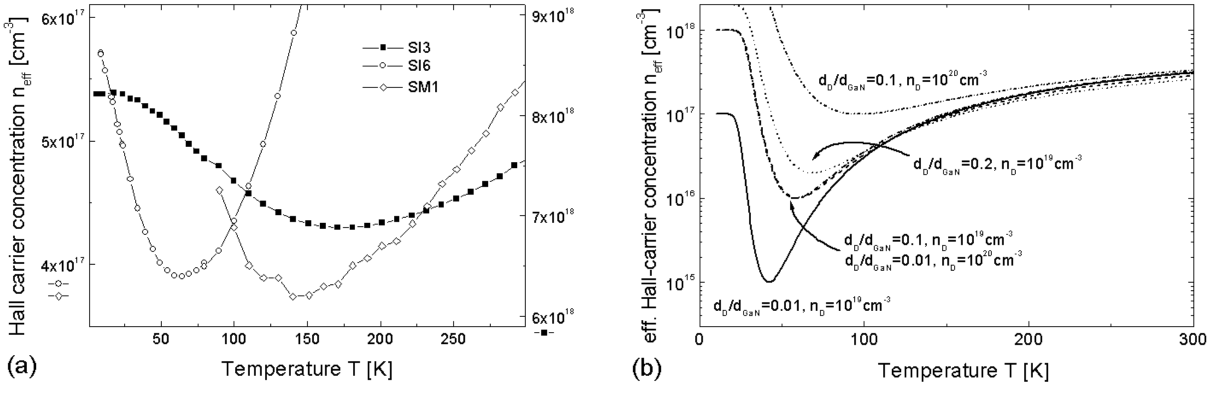

Fig. 3(a) Effective Hall-carrier concentration n_H versus temperature T measured for sample SI3 (GaN/sapphire), SM1 (GaN/GaN-Buffer/sapphire), and SI6 (GaN/SiC). The left vertical axis is for the open symbols, the right vertical axis belongs to the filled symbols.

Fig. 3(b) Simulation of the effective Hall-carrier concentration n_{eff} with varied defect layer thickness d_D at two defect densities n_D of 10^{19}cm^{-3} and 10^{20}cm^{-3}, respectively. For the simulations, the mobility μ_D=1cm²/Vs in the defect layer and μ_{GaN}=400cm²/Vs in the GaN film were kept constant. The carrier concentration in the GaN film was assumed to behave according to $n_{GaN}=10^{18}\text{cm}^{-3}*\exp(-30\text{meV}/kT)$

The position and the shape of the minimum contain information about the thickness and the electrical properties (i.e. the mobility μ_D and the carrier concentration n_D) of the defect-rich layer near the substrate. The minimum gets broader and shifts to higher temperatures with increasing thickness or higher carrier concentration n_D of the defect-rich layer, respectively. Figure 3(b) shows the effective Hall-carrier concentration n_{eff} calculated according to equation (4) in [5], assuming a thermally activated carrier concentration ($N_c=10^{18}cm^{-3}$, $\Delta E=30meV$) and a moderate mobility (μ_{GaN} =400cm²/Vs) of the GaN film and a nearly degenerate interface layer ($n_D=10^{19}cm^{-3}$) with low mobility (μ_D=1cm²/Vs).

The experimental and theoretical results can be explained by differences in the interface quality correlated to the different lattice constants of sapphire and SiC. For the GaN/sapphire system, the lattice mismatch is 16% [15], whereas for the GaN/SiC system it is only 3.4% [15]. The sample SI3 shows the broadest minimum at the highest temperature (170K), i.e., the interface layer dominates the electrical properties of the sample up to room temperature. The sharper minimum at lower temperature (150K) of the sample SM1 is the result of a thinner or less defective interface layer. These better interface properties can be correlated to the buffer layer of this sample. For the sample SI6 on SiC substrate, the sharp minimum at low temperature (60K) indicates the best interface properties. It is this sample which shows the smallest PPC effect as well.

From all the presented results, we conclude that it is either the inhomogenity at the interface itself which causes the PPC effect or that the defects involved in PPC must have an increased concetration in the defective interface region. Enhancement of the quality at this interface may be a way to reduce or fully suppress the PPC.

V. Summary

We have shown that the defect layer at the GaN/substrate interface is important for the PPC effect in GaN and related alloys. Photoconductivity excited with bandgap light from the substrate side is about one order of magnitude larger than in the case the sample is illuminated from the growth side. We used temperature-dependent Hall effect measurements to access the interface properties of the GaN/substrate interface. The GaN film on SiC with the best interface properties according to the Hall effect measurements shows the lowest PPC under subbandgap illumination. From the results of this work it would be interesting to study whether GaN films grown on other substrates like $LiGaO_2$ or $LiAlO_2$ [16] with a lattice mismatch of only ~0.4% to GaN or by the new epitaxial lateral overgrowth technology ELOG [17] will not only improve the growth behavior, but could also eliminate the unwanted metastability of PPC.

References:

1. S. Nakamura, T. Mukai, M. Senoh, Appl. Pyhs. Lett. **84** 1687 (1994)
2. M. Asif Khan, J. N. Kuznia, et. al, Appl. Phys. Lett. **62** 1786 (1993)
3. D. M. Hofmann, D. Kovalev, G. Steude , B. K. Meyer, A. Hoffmann, L. Eckey, R. Heitz, T. Detchprom, H. Amano, I. Akasaki, Phys. Rev. B **52** 16702 (1995)
4. M.S. Feng, H.N. Chen, Y.F. Chen, M.C. Lee, J. Appl. Phys. **82** 899 (1997)
5. D.C. Look, R.J. Molnar, Appl. Phys. Lett. **70** 3377 (1997)
6. W. Götz, L.T. Romano, J. Walker, N.M. Johnson, R.J. Molnar, Appl. Phys. Lett. **72** 1214 (1998)

7. M.T. Hirsch, J. A. Wolk, W. Walukiewicz, E. E. Haller, Appl. Phys. Lett. **71** 1098 (1997)
8. G. Beadie, W. S. Rabinovich, A. E. Wickenden, D. D. Koleske, S. C. Binari, J. A. Freitas , Jr., Appl. Phys. Lett. **71** 1092 (1997)
9. C. V. Reddy, K. Balakrishnan, H. Okumura, S. Yoshida, Appl. Phys. Lett. **73** 244 (1998)
10. E. Calleja, F. J. Sanchez, D. Basak, M. A. Sanchez-Garcia, E. Munoz, I. Izpura, F. Calle, J. M. G. Tijero, J. L. Sánchez-Rojas , B. Beaumont, P. Lorenzini, P. Gibart, Phys. Rev. B **55** 4689 (1997)
11. H. M. Chen, Y. F. Chen, M. C. Lee, M. S. Feng, Phys. Rev. B **56** 6942 (1997)
12. D. Brunner, Diploma Thesis (Technical Univ. of Munich, 1997)
13. W.G. Perry, M.B. Bremser, R.F Davis, J. Appl. Phys. **83** 469 (1998)
14. L.W. Tu, Y.C. Lee, S.J. Chen, I. Lo, D. Stocker, E.F. Schubert, Appl. Phys. Lett. **73** 2801 (1998)
15. M. Lescyczynski, H, Teisseyre, T. Suski, I. Grzegory, M. Bockowski, J. Jun, K. Pakula, J.M. Baranowski, C.T. Foxon, T.S. Cheng, Appl. Phys. Lett. **69** 73 (1996)
16. J.D. MacKenzie, S.M. Donovan, C.R. Abrnathy, S.J. Pearton, P.H. Holloway, R. Linares, J. Zavada, B. Chai, J. Electrochem. Soc. **145** 2581 (1998)
17. S. Nakamura, M. Senoh, S.-I. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, K. Chocho, Appl. Phys. Lett. **72** 211 (1998)