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Photoconductivity Studies of $Al_{0.18}Ga_{0.82}N$/GaN Single Heterostructure

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We present spectral photoconductivity (SPC) and transient photoconductivity (TPC) studies in a $Al_{0.18}Ga_{0.82}N$/GaN single heterostructure. We attribute near bandgap peaks in the SPC between 300K and 500K to a deep trap-conduction band transition. The trap distribution lies approximately 100meV above the valence band edge, for both GaN and AlGaN layer. In TPC studies we show that charge buildup after strong pulsed laser excitation can be detected by anomalous photocurrent decay.

Introduction GaN/$Al_xGa_{1-x}N$ interfaces play an important role in nitride based devices like high electron mobility transistors [1]. Besides of band-bending induced built-in fields at interface and surface these structures may show strong bulk built-in fields, due to spontanous and piezoelectric polarizations. This is especially emphazised in AlGaN layers with high aluminum content grown pseudomorphically on GaN [2].
It is interesting to see if and how the built-in fields influence the lateral transport of photogenerated carriers. In this work, we present spectral photoconductivity (SPC) and transient photoconductivity (TPC) studies in a $Al_{0.18}$GaN/GaN film.

Samples and experimental techniques The experiments were carried out with a single heterostrucure (SHL), deposited by metal-oxide chemical vapor deposition (MOCVD) on a sapphire substrate. On a thin GaN buffer a GaN film of 1.6 µm thickness was deposited. The top $Al_{0.18}Ga_{0.82}N$ (AlGaN) layer was 0.2 µm thick. Lateral ohmic contacts, about 10 mm apart, were formed on the top of the AlGaN layer, with indium annealed at 380°C. The film was characterized by photoluminescence spectroscopy and Hall measurements as described earlier [3].

For SPC measurements a Xe-lamp was used in connection with a monochromator and lock-in technique. Illumination was made from the top, far from the contact area. For TPC measurements, pulsed excitation was carried out with the 4^{th} harmonic (266 nm) of Nd:YAG laser pulses of 5ns duration. Pulse energies varied from 4 to 400 µJ at a repetition rate of 10 Hz. The photoluminescence was excited with the 325 nm line of a He-Cd laser at a cw power of 15 mW. The micrograph was measured with a commercially available Digital Instruments AFM.

Dark- and photoconductivity at 300K and 500K The dark resisitivity at room temperature was 5Ωcm. Hall measurements carried aut at 300K and 500K showed that, while the electron density increased from $3x10^{16}$ cm^{-3} at 300K to $1x10^{18}$ cm^{-3} at 500K, the mobility decreased from 50 to 20 cm^2/Vs. These are typical values for weak (unintentional) doping and defect-scattering limited bulk mobilities. The two dimensional electron gas (2DEG) at the GaN/AlGaN interface, if present, would be masked by the high resisitivity AlGaN. Both the dark conductivity and the overall photoconductivity show a weak temperature dependence: changes between 300K and 500K were always significantly below one order of magnitude.

Surface morphology The AFM picture in figure 1 shows an overall flat surface morphology, except for a number of 200 nm wide hollow-core screw dislocations ("nanopipes") which extend along the c-axis up to the surface. We have a density of $2x10^8cm^{-2}$ and conclude that, due to this high value, the strain resulting from the lattice mismatch at the sapphire/GaN and AlGaN/GaN interface is at least partially relaxed. Associated strain-induced piezoelectric fields should therefore be strongly reduced.

On the other hand, it is generally accepted that screw dislocations in GaN create electrically active defects. As the current path in our experimental configuration is perpendicular to the nanopipes, is is likely that scattering at these defect levels limits the observed mobility in the Hall measurement, and will also have a strong influence on the photoconductivity measurements.

Spectral photoconductivity (SPC) The photoconductivity spectrum from the blue to the mid UV for temperatures between 300K to 500K is shown in figure 2. The respective bandgaps at 3.4 eV and 3.8 eV at room temperature can be clearly identified. In this experimental configuration, the heterostructure acts as a midpass photoconductive UV detector. Near to the GaN bandgap we find for all measured temperatures a distinct peak. Its position follows the temperature dependence of the GaN bandgap, and its amplitude increases for temperatures above RT and shows a clear maximum at 100-150°C, as shown in figure 3. Figure 2 shows that at about the same temperature, the SPC curve "bends up" for energies between the two bandgaps, and a second peak appears at the higher AlGaN bandgap. This second peak increases in amplitude up to 500 K, and its position follows, as the first one, the bandgap reduction at higher temperatures.

The PC spectrum for GaN subbandgap excitation is shown in figure 4 for 300K and 500K and compared with the respective

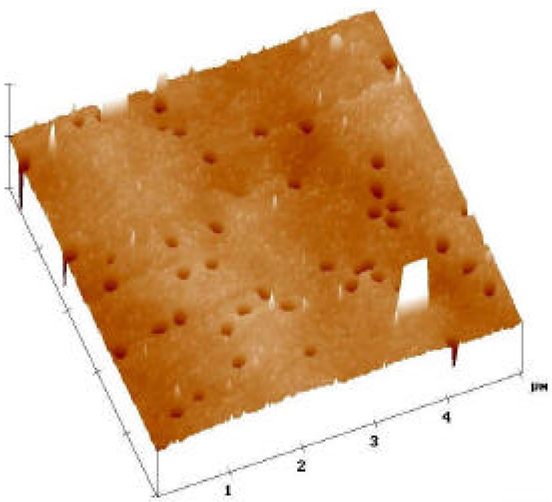

Fig.1: Surface morphology by AFM

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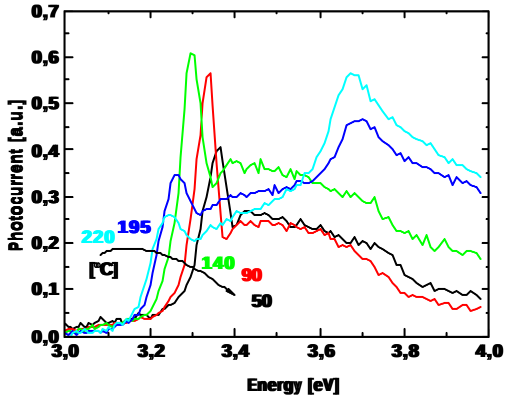

Fig.2

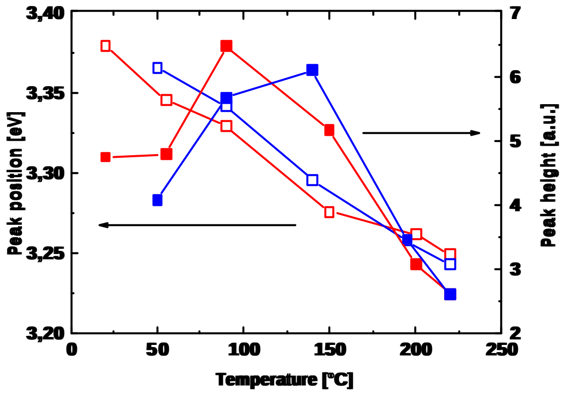

Fig. 3

Fig.2 Photocurrent spectrum of $Al_{0.18}$GaN/GaN between 220°C and room temperature

Fig. 3 Near bandgap peak position (open) and amplitude (filled) for heating (red) and cooling (blue) cycle

PL spectrum. The PC at 300K shows a fast exponential decrease from the bandgap down to approximately 3.3eV, which is probably connected to an Urbach-tail-like region in the density-of-states below the GaN conduction band edge. Below 3.3eV, the PC gets dominated by deep impurity level absorption. An abrupt PC slope change at 2.9eV is an indication for the low energy threshold of a broad defect distribution. This is consistent with the PL spectrum: a broad violet luminescence band begins at 2.9 eV, and has a maximum at 3.1eV. The luminescence intensity from this band is quenched strongly at higher temperatures, which goes along with a much steeper exponential decrease of the PC. Assuming that no drastic change in lifetime would occur between 300K and 500K, the combined PL and PC data for the violet band indicate that the transition probability decreases for higher temperatures and disappears at 500K.

The PL shows also a broad yellow luminescence, which is much less temperature sensitive than its violet counterpart.

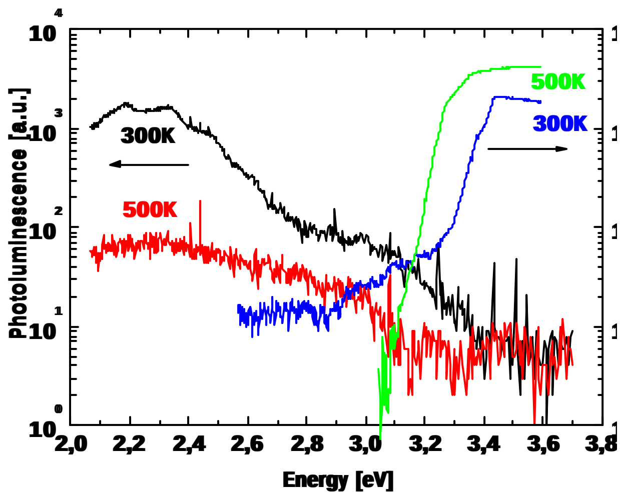

Fig. 4. Subbandgap luminescence and photoconductivity of $Al_{0.18}$GaN/GaN at 300K and 500K.

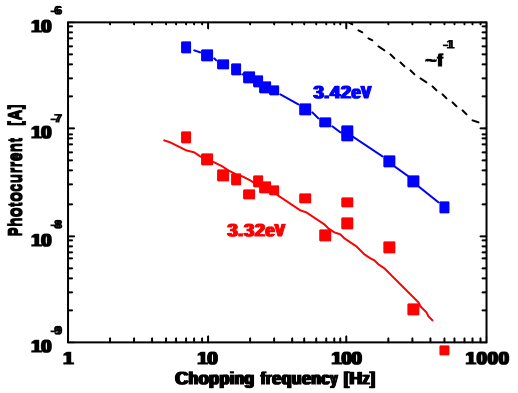

Fig.5

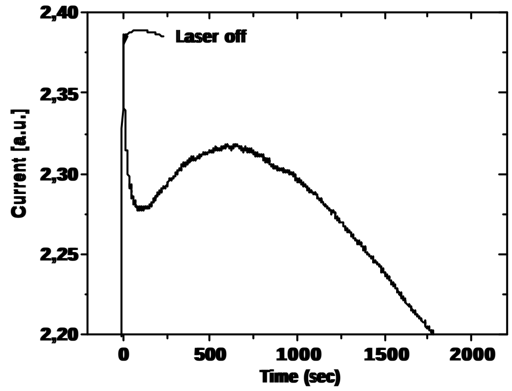

Fig.6

Fig.5: Room temperature photocurrent frequency dependence of $Al_{0.18}$GaN/GaN for illumination above and below the GaN bandgap.

Fig.6: Initial photocurrent decay of $Al_{0.18}$GaN/GaN after prolongated strong pulsed UV excitation.

Transient photoconductivity (TPC) The slow decay in transient photoconductivity, which follows a power law with an index around 0.3 over several orders of magnitude is known for bulk GaN [4]. We measured the photoconductivity frequency dependence of our samples for above and below bandgap excitation. Figure 5 shows that the photocurrent for both cases show similar behaviour: the decay is slower as 1/f as one would exspect if only one lifetime would be dominant. In other words, the graph reflects the fact that there exists in fact a broad distribution of lifetimes. The photocurrent decay extends to much longer times, the so-called persistent photoconductivity (PPC) effect.

Our sample shows a peculiar behaviour of the photocurrent decay after prolongated pulsed excitation with a strong 5 ns pulse at 266 nm. The PC increase during the pulsed pumping was initially superlinear, and a transition to a linear regime occured after some seconds. Up to the end of the laser pulses, the current increased at a constant slope. The initial decay behavior after the last laser pulse is shown in figure 6. The current first decreases fastly, but after a minimum at 100s, the current increases again, and comes finally, at approximately 800 s, to a slow decrease which seems to be monoexponential, with a time constant of the order of 16.000s.

Discussion No reliable activation energy could be extracted from temperature dependent dark conductivity data. The resistivity is essentially constant at 300 and 500K. This is, however, no indication for a very shallow donor level creating a degenerate Fermi gas. We think that the Fermi level is pinned due to a high density of defect states. This model is supported by the weak temperature dependence of the photoconductivity. The PC does not change with increasing temperature when the Fermi level lies in a uniform trap distribution.
We can estimate the donor level energy E from the Hall data by:

$$E = -kT \ln \left[\frac{n}{2} \left(\frac{2pmkT}{h^2} \right)^{-\frac{3}{2}} \right]$$

Here, k is the Boltzmann constant, T the absolute temperature, m the electron mass in GaN, h the Planck constant and n the carrier density from the Hall data. For the AlGaN donor level, we calculate a value of 100meV below the AlGaN conduction band edge.

The position of the $Al_{0.18}$GaN bandgap at 3.8eV in figure 2 confirms the finding by the AFM micrograph, that the strain has been released by the formation of threading dislocations. With a linear extrapolation of the Al_xGaN bandgap between $E_G(x=0)=3.4eV$ and $E_G(x=1)=6.2eV$, neglecting strain effects, one would expect $E_G(x=0.18)=3.8eV$ at room temperature. This means that the strain is almost fully released. Though the thickness of the AlGaN layer is slightly above the theoretical critical thickness for the onset of strain relaxation, comparable heterostructures have been reported to be fully strained [2]. So we think that the screw dislocation may extend from the GaN into the AlGaN layer, and may be related to the first steps of the growing process. It was not possible to determine the depth of the nanopipes by AFM.

Tentatively, the first peak in figure 2 could be attributed to excitons at room temperature. However, the temperature dependence of the peak at lower temperatures are facts against excitons. In addition, there seems to be a correlation between the maximum peak at 130°C at the GaN bandgap and the simulatanous rise of a second peak at the AlGaN bandgap. As a hypothesis, we propose therefore that the peak is due to a deep trap-conduction band transition. The trap distribution could lie approximately 100meV above the GaN valence band edge. At the peak height maximum temperature of 130°C, the trapped carriers could then be transferred over the interfacial barrier to a trap in the AlGaN which also lies 100meV above the AlGaN valence band edge. Our data suggest that the trap level is independent of the aluminium composition. It has to be investigated in more detail if the traps are correlated with dislocation induced defects. The fact that deep traps were not observed in optical transmission or reflection is consistent with this model. To further test a possible existence of an exciton-related peak in the PC spectra, we would need to measure also the temperature dependence of the peak width. Most convincing to test any model would be to measure a clear correlation with exciton peaks in photoluminescence. Probably, spectroscopy at high spatial resolution would be needed.

For figure 6 we state that the phenomena of current increase during an electronic relaxation process is known from decay experiments with high insulating bulk dielectrics. It is intimately connected with transient space charge limited currents in the presence of traps. It should be pointed out that this experiment was carried out under intense laser irradiation of the order of tens of kW/cm^2. Phenomenologically, an increase of conductivity may occur when one type of carrier enters into a strong space charge field region which is created by a large quantity of the other type of trapped carriers. The charge-field product enhances strongly if a packet of electrons drifts or diffuses into this region.

Conclusion Between 300K and 500K, peculiar photocurrent peaks appear in the spectra of an $Al_{0.18}$GaN/GaN single heterostructure which we attribute tentatively to a deep trap-conduction band transition.. Our data suggests that the trap distribution lies approximately

100meV above the valence band edge, independently of the aluminum composition. The appearance of qualitatively new features at temperatures above 150°C may have influence for devices working at elevated temperatures. In our samples we found no indication for piezofield enhanced photoconductivity. We showed that charge buildup after strong pulsed laser excitation can be detected by an anomalous photocurrent decay.

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