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Pulsed sub-band-gap photoexcitation of AlN

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Abstract

Since AlN is a wide band-gap semiconductor it is usually not possible to induce photocurrents with light below 6.2 eV of energy. However, employing high power density laser pulses of 266 nm (4.66 eV) and 532 nm (2.34 eV), we succeeded to monitor the transient photocurrent (TPC) in transverse and parallel configuration using metal-insulator-metal (MIM) structures and single films, respectively. Absorption is possible due to excitation from deep defects, which are indicated by the power-law decays of the photocurrents with exponents below unity. The thickness dependence of the magnitude of the photocurrent and RBS profiling lead us to believe that photocurrents originate mainly from an oxygen-rich transition layer. Films down to a thickness of 5 Å can still be characterized by TPC measurements.

Keywords: Photoexcitation; AlN; Band-gap

1. Introduction

Transient photoconductivity (TPC) after pulsed laser excitation is an often used method to characterize carrier life times in semiconductor films. From the peculiarities of the photocurrent decay it is possible, under certain conditions, to extract information about the defect distributions in the upper half of the band-gap [1]. In previous work, we have used TPC to characterize AlGaN alloy films deposited by MOCVD [2,3]. For photoexcitation we had used mainly UV light pulses of 266 nm (4.66 eV) with an energy well above the band-gap of 3.4 eV of GaN. In this work we use the same equipment for the analysis of pure AlN films that were prepared by reactive sputtering [4].

AlN is an intensively studied nitride material with a large band-gap of 6.2 eV. It shows good insulating properties, a high breakdown field and a high thermal conductivity of approximately 2 W/cm K [5]. Low diffusivity for dopants makes it an excellent passivation material. Since it is lattice-matched to GaN a number of interesting heterostructures can be fabricated, like field effect transistors suitable for high temperature operation [6]. Another application being intensively studied concerns the use of AlN as alternative to AlO_x in magnetic tunnel junctions (MTJ). The MTJ consists of an ultrathin insulating barrier (approx. 10-Å thick), which is sandwiched between ferromagnetic layers [7]. We have previously studied such AlN films embedded in MIS structures to perform I–V and C–V measurements and we could obtain an estimate of the defect density of 10^{11}–10^{12} cm^{-2} eV^{-1} at an energetic level of 0.7 to 0.8 eV [8]. Here we use a range of thickness of AlN films with the idea of detecting deep defects in extremely thin-films by transient photoconductivity (TPC).

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2. Sample preparation

The AlN insulator films with nominal thickness of 10, 40 and 100 nm were deposited by reactive sputtering in an Ar/N_2 plasma of an Al target onto quartz glass substrates [8]. The process pressure was held at 3 mtorr, the nitrogen flow at 10 sccm and the d.c. plasma power density was approximately 10 mW/cm^2. Part of the substrates were covered by Al which served as back contact. Front Cr contacts were deposited onto the films for secondary photocurrent measurements using pulsed Nd:YAG laser beams at 532 and 266 nm with a pulse length of 5 ns.

In addition, we used p-type crystalline silicon wafers with a doping concentration of 10^{14} cm^{-3} as substrates to form metal–insulator–semiconductor (MIS) structures. The photoresponse as a function of bias voltage was then compared with reference Schottky barrier devices (SB) having Cr top contacts.

3. Transient photoconductivity measurements

Fig. 1 shows the photocurrent decays after pulsed excitation with the UV and the green laser line. The beginning of the decay is situated at much longer times than the width of the laser pulse due to the relatively large capacitance of a few nF per cm^2 in the perpendicular layout. The decay starts at much shorter times in Fig. 2 where a co-planar measurement was performed and where the capacitance is below some 100 pF. Fig. 3 gives the field dependence which is slightly superlinear.

Fig. 4 shows the field dependence of the MIM structure of Fig. 1 on a linear scale. Obviously, the dark current increases rapidly at the fields of typically 10^5 V/cm. For the discussion of the fit to a Poole–Frenkel ansatz we have repeated this plot in a semi-logarithmic representation in Fig. 5.

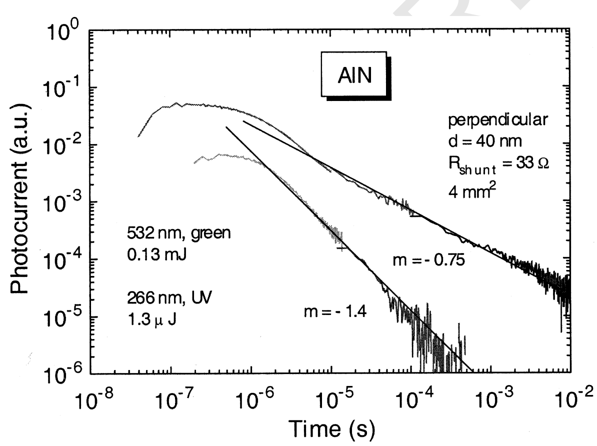

Fig. 1. TPC of AlN (40-nm thickness) with 532 nm (green, upper curve) and 266 nm (UV lower curve) laser pulses in a transverse MIM structure.

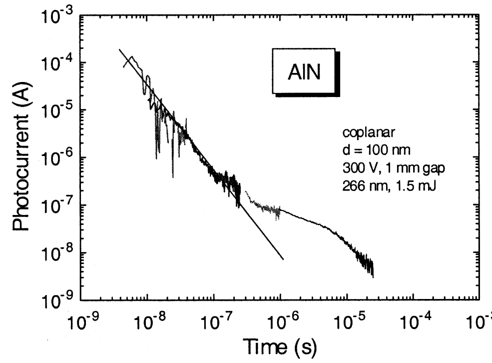

Fig. 2. TPC of AlN (1-mm gap) with 266- and 532-nm laser pulses in a coplanar structure.

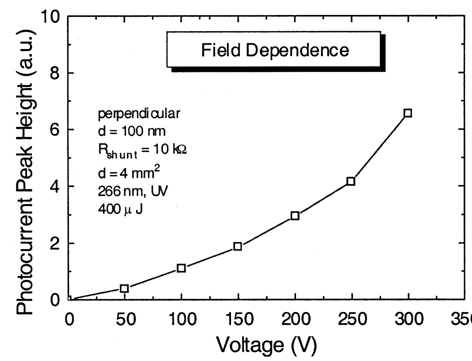

Fig. 3. Field dependence of photocurrent peak.

4. Photoresponse in Schottky barrier and MIS device structures

In order to see the influence of an AlN layer on top of a silicon substrate we have co-deposited metal–insulator–semiconductor (MIS) structures and Schottky barrier diodes (SB). Fig. 6 shows the a.c. photoresponse

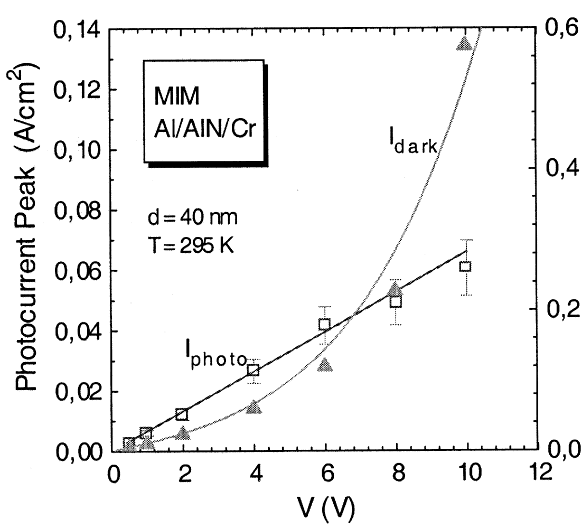

Fig. 4. Dark and photo I–V curve of MIM structure shown in Fig. 1.

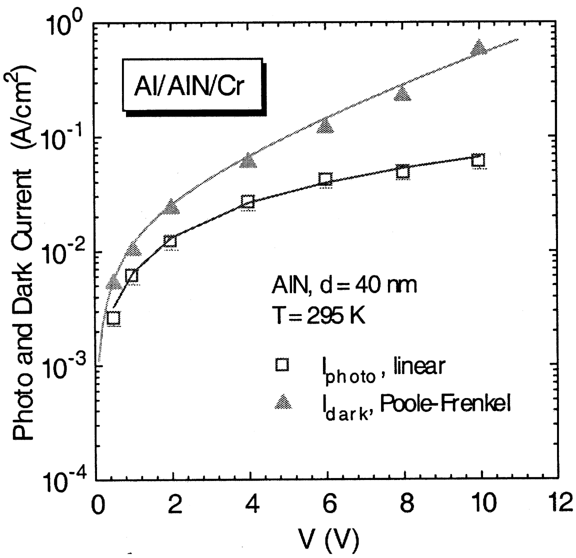

Fig. 5. Fit of Poole–Frenkel ansatz to the I–V curve of Fig. 4.

when chopped HeNe laser light is incident through the semitransparent top metal contact. We can see that the dark current characteristic is quite opposite to the photoresponse, in other words, only under reverse bias can we detect a reasonable photosignal.

For comparison, Fig. 7 shows the dark and the photoresponse of the corresponding SB structure. The dark I–V curve has a more pronounced rectification behaviour. The photoresponse is much higher and it is saturating already at small reverse bias as expected for a good diode. We can use these structures to detect defects at or near the heterostructure interface as was shown in a previous publication [8].

5. Discussion

A first indication for the presence of deep defects

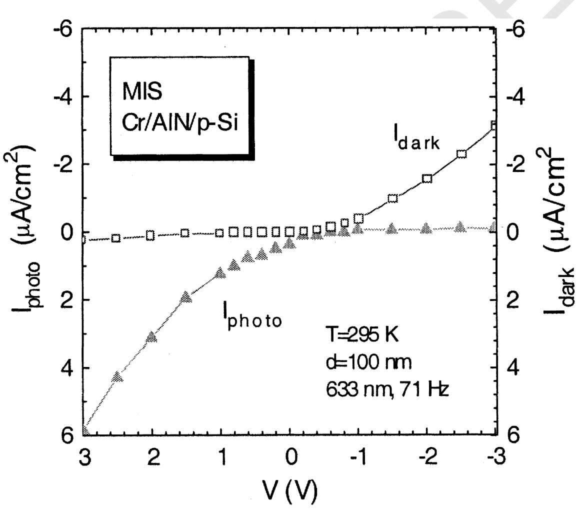

Fig. 6. Dark and photoresponse from the MIS structure with a 100-nm AlN layer.

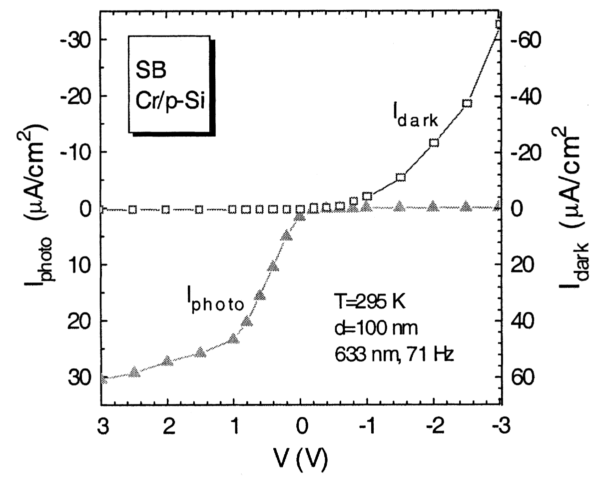

Fig. 7. Dark and photoresponse from the SB diode of AlN on p-Si substrate.

comes from the analysis of the dark I–V curve. If transport is controlled by defects present inside the band-gap we can expect the following Poole–Frenkel type behavior [8]:

$$I_{\text{poole}} = c_t F \exp\left\{-(\phi_0 - qF/\pi\varepsilon_i)^{1/2} q/kT\right\} \tag{1}$$

where F is the applied field, ε_i the dielectric constant and c_t an appropriate constant. The essential features in Eq. (1) are the square-root dependence w.r.t. the electric field and a strong temperature dependence. The full line in Fig. 4 is a good fit of Eq. (1) to the dark conductivity for fields beyond 5×10^5 V/cm, including, however, an additional ohmic contribution due to some shunting.

For comparison, the photoresponse is quite linear with respect to the applied field, as shown in Fig. 3. This result is expected for a range of light intensities where the life-time and the mobility of photogenerated carriers is independent of carrier density.

The second indication of deep defects comes from the power law behavior of the secondary photocurrent transients shown in Figs. 1 and 2. In the perpendicular sample configuration in Fig. 1 an exponent of $m = -0.75$ can be calculated. The current starts to decay after a lower limit of approximately 2 μs. The decay extends up to ms range indicating a broad distribution of trap states [2]. In the co-planar arrangement (Fig. 2) the current decay starts already at much shorter times due to the reduced capacity of the measurement lay-out. This means that shallower states are detected.

The UV excitation a much faster photocurrent decay is seen compared to excitation with the green laser line (exponent of $m = -1.4$). See the corresponding curves in Figs. 1 and 2. We consider this to be a manifestation of the direct band-gap nature of AlN with typical recombination rates of 10^9 s^{-1}.

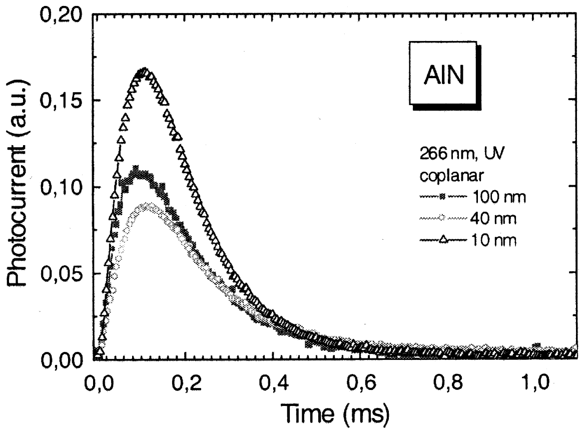

Fig. 8. Signal height of photocurrent peak for different sample thickness.

Surprisingly, we have found nearly the same signal height in the co-planar secondary photocurrent in samples with completely different thickness. Fig. 8 gives the results for the 10-, 40- and 100-nm AlN films. One possible explanation is that absorption is mainly taking place in an intermediate transition layer where the defect density is larger than in the bulk AlN film. This idea is supported by the analysis of the composition profiles obtained by Rutherford backscattering (RBS) of films that were deposited on a carbon substrate (see Fig. 9). Initially, approximately 50% of oxygen is present in a 7-nm-thick transition layer, the bulk AlN film of 77-nm thickness has a small concentration of oxide, which is increased in the surface layer to approximately 7.8%. The Al to N concentration ratio is unity. Both the initial transition layer and the final surface region are candidates for layers with increased optical absorption.

Finally, we want to point out that transverse measurements in the second run of samples was not possible due to frequent shunting of the MIM structures. The AFM images in Fig. 10 give a hint to explain this effect. The films deposited on the conducting metallized substrate region shows a roughness of approximately 20 nm. In contrast, the films on the free glass surface are smooth, as seen in Fig. 10a, with a more than 10 times lower roughness.

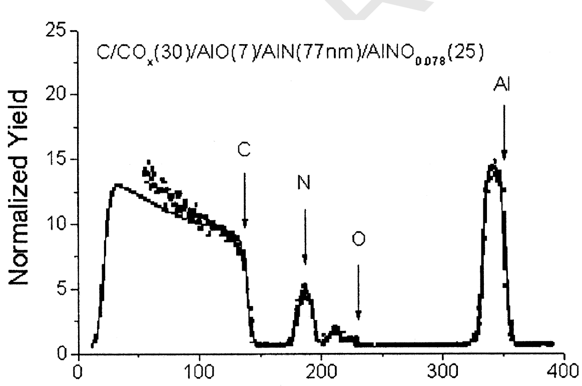

Fig. 9. Rutherford backscattering profiles for composition profiling.

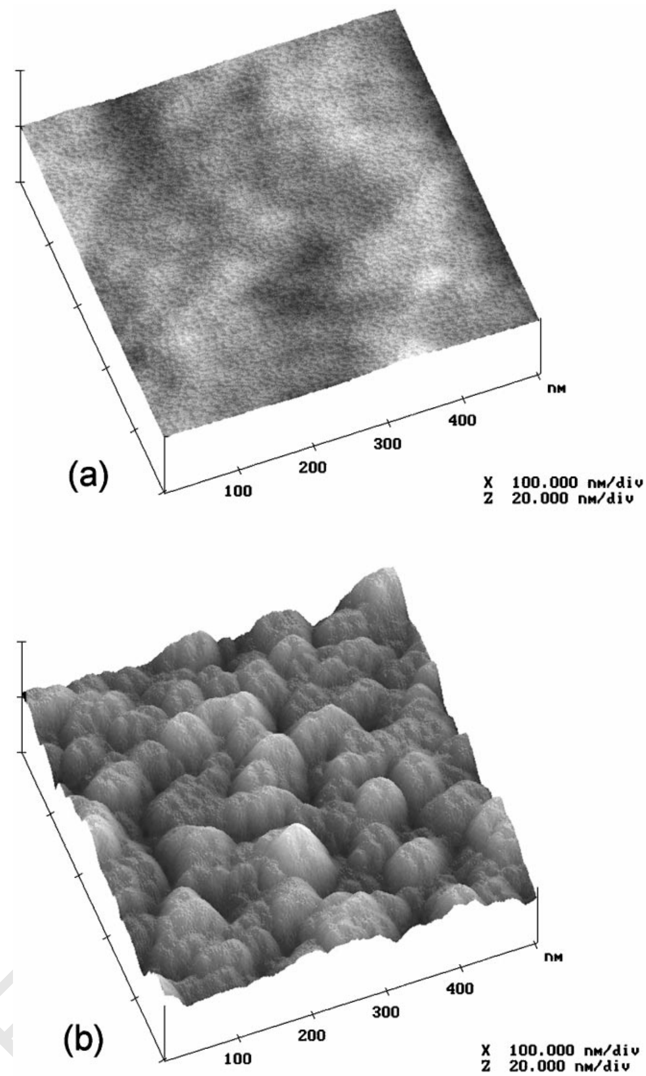

Fig. 10. AFM images of sample surface deposited on (a) glass and (b) metal-coated glass.

6. Conclusion

Using high power pulsed laser excitation at below band-gap energy and with densities of the order of 20 mJ/cm^2 we have succeeded to monitor transient photocurrents in perpendicular and co-planar direction in thin AlN films deposited by reactive sputtering. The power law decay hints to a broad distribution of trap states in the band-gap. Lifetime is reduced for excitation at higher energies.

Inhomogeneities in the film composition especially at the bottom and top surface can explain the independence of the TPC signal height from film thickness. We expect that samples with thickness down to approximately 5 Å can still be characterized.

Acknowledgements

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