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Density-of-states distribution in AlGaN obtained from transient photocurrent analysis

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Abstract

Dark conductivity and photoconductivity in $Al_x Ga_{1-x} N$ (x = 0.025, 0.18) films prepared by MOCVD on a sapphire substrate with a GaN bottom layer have been investigated. In the temperature range 300–500 K, the barrier at the heterostructure interface appears to play an important role in the thermal activation of the photocurrent after pulsed laser excitation, for high aluminium concentrations. Transient photoconductivity measurements on $Al_{0.025}$ GaN films have been made and are interpreted in terms of multiple trapping and release of carriers in localised states. The current transient is characterised by an initial rapid decay in the sub-microsecond regime, followed by a much slower power law decay out to tens of milliseconds. These features, which occur for both sub- and super-gap excitation, are consistent with the presence of a steep exponential tail of states at the band edge, followed by a broad peak centered at approximately 0.4 eV below E_c . © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Slow, non-exponential decays of photo-induced currents have been observed in AlGaN films [1], with time constants up to tens of hours. Data are usually phenomenologically fitted in terms of a power law decay [2] or a stretched exponential [3]. Insight into the understanding of this slow response (frequently referred to as persistent photocurrent or PPC) may be obtained in terms of the multiple trapping (MT) model of carrier transport. This model has been applied successfully to the study of localised gap states associated with disordered materials, such as hydrogenated amorphous silicon and its alloys. Transient photocurrent (TPC) spectroscopy is now well-established as a method for investigating the density of states (DOS) distribution in such materials. The analysis of TPC data by Fourier transformation [4] allows the DOS to be deduced to a

resolution of order kT without prior assumption of its form. In this work we have applied TPC spectroscopy to investigate the DOS of Al_{0.025}GaN.

2. Experimental and analytical procedures

0.6 micrometer thick $Al_xGa_{1-x}N$ films were deposited by MOCVD on a sapphire substrate and a 0.6–1.4 µm thick GaN underlayer (see inset of Fig. 1). The samples exhibited the following Hall-mobilities and carrier concentrations [2]: $\mu_e = 170 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $n = 5 \times 10^{18} \text{ cm}^{-3}$ for x = 0.025 and $\mu_e = 30-50 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $n = 7 \times 10^{17} \text{ cm}^{-3}$ for x = 0.18. Current measurements were performed by making two soldered ohmic indium contacts with a distance of ca. 5 mm to each sample. TPC measurements were made by recording the current decay following the application of either 532 nm (2nd harmonic) or 266 nm (4th harmonic) pulses from a Q-switched Nd:YAG laser of 5 ns duration. Pulse energies varied between 0.4 and 4 mJ with a spot size of 5 mm diameter. The current was measured in

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terms of the voltage drop across a small series resistance, and data acquisition was performed using a Tektronix 200 MHz bandwidth transient digital oscilloscope. Analysis of the TPC data to yield a relative DOS was carried out using a Fourier transform method [4], assuming energy-independent capture coefficients and an energy scale $E = E_C - kT \ln(vt)$ with an attempt-toescape frequency of $v = 10^{12}$ Hz. The photocurrent values in Fig. 2 are taken 10 µs after pulsed UV excitation.

3. Results and discussion

3.1. Steady-state photocurrent spectroscopy

Fig. 1 shows the as-measured photocurrent spectra of $Al_{0.18}$ GaN for sub-bandgap illumination. The gradual



Fig. 1. Sub-bandgap photocurrent (as measured) for x = 0.18; inset: sample structure.



Fig. 2. Photocurrent for x = 0.18 (taken 10 µs after UV pulse).

decrease in photocurrent with decreasing photon energy indicates the presence of tail (Urbach) states extending deep into the bandgap. The absorption coefficient for green light is some 2 orders of magnitude lower than for super-gap illumination.

3.2. Temperature dependence of current

The conductivity of Al_{0.025}GaN at ambient temperature is approximately $0.5 \text{ S} \text{ cm}^{-1}$, that of Al_{0.18}GaN about 400 times lower. Both dark currents show a very weak temperature dependence. For the sample with the higher Al concentration an activation energy of 40 meV can be deduced over the whole temperature range. Between 300 and 400 K the low concentration sample shows a similarly small activation energy, of 30 meV. Above 400 K, the slope gets even less steep and there is no change in the dark current. Curiously, this change in the slope appears at approximately the same temperature at which the photocurrent in the x = 0.18 sample after pulsed laser excitation shows a minimum in the heating cycle (see Fig. 2). From the cooling cycle, an 'activation' energy of 200 meV can be deduced between T = 370 and 500 K, which we attribute to the interface between the AlGaN and the GaN film. AlGaN and GaN form a heterostructure with an effective barrier height below $E_G(x = 0.18) - E_G(x = 0) = 0.4$ eV [5]. The Richardson equation gives a reasonable fit to the cooling cycle part of our data, and we calculate the barrier height as 0.2 eV. We propose that the difference between heating and cooling curves is due to the thermal quenching of the PPC. We also conclude that the x = 0.18 sample has to be considered as a heterostructure and was therefore not appropriate for TPC spectroscopy. As the Al concentration is small in the x = 0.025 sample, we assume it to be homogenous.

3.3. Transient photocurrent spectroscopy

Fig. 3 shows the photocurrent decay after subbandgap illumination of the sample with x = 0.025. We observe secondary photocurrent for sub- and supergap illumination. The TPC signal is characterised by an initial rapid decay in the sub-microsecond regime, followed by a much slower decay, which shows a power law behaviour with an exponent of about 0.3. A fast photovoltaic contribution adding to the initial current peak, due either to illumination of the indium contacts or the heterostructure interface, has been subtracted. The slight downturn beginning at approximately 10 ms is due to the low-pass filter which is formed by the series sampling resistor and the input capacitance of the oscilloscope. For times longer than 1 s the data fit the persistent photoconductivity decay [3].

The features presented are consistent with the presence of a steep exponential tail of states (slope 35 meV)

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Fig. 3. Transient photocurrent of Al_{0.025}GaN after 532 nm laser pulse.



Fig. 4. Calculated density of states of Al_{0.025}GaN from Fig. 3.

at the band edge followed by a broad peak centred at approximately 0.4 eV below E_c (Fig. 4). The analysis of the DOS below 0.3 eV is influenced in detail by the behaviour of the current decay at times below 100 ns, which are currently not accessible experimentally. It was assumed in the analysis that the current remains constant from t = 0 to the shortest experimental time value. The height of the first peak and the assumed behaviour for shorter times influence strongly the deduced height of the DOS structures. Other assumptions like the absence of pretrapping currents lower the DOS below the peak energy about 1 order of magnitude. The power-law index of 0.3 is in good agreement with the reported phenomenological fitting parameter β which describes the 'stretching' of the exponential $I(t) \propto \exp(-(t/\tau)^{\beta})$ [3].

In our interpretation, the exponent reflects the slope of the density-of-states for energies higher than the peak at about 0.4 eV; the higher the value of the exponent, the steeper will be the DOS for the localised state distribution. The origin of the exponential tail may be due to structural disorder, e.g. alloy fluctuations. PL data gives no unambiguous evidence about the peak we found [2]. However, it is known that a number of different deep defects exist in AlGaN between 0.1 and 0.8 eV.

4. Conclusions

TPC signals obtained from Al_{0.025}GaN films are characterised by an initial rapid decay in the sub-microsecond regime, followed by a much slower power law decay of index approximately 0.3. Analysis in terms of a multiple trapping model indicates the presence of a steep exponential tail of states (slope 35 meV) at the band edge, followed by a broad peak centred at approximately 0.4 eV below $E_{\rm C}$. However, this interpretation may be open to question as the Fermi level must lie fairly close to the band edge in order to account for the dark conductivity magnitude, and the TPC analysis is invalid for predominantly occupied states. The dark current activation mechanism could not be understood completely, and further TPC and PPC measurements over a range of temperatures are required to determine whether this behaviour is consistent with the multiple trapping model.

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