

Photoconductive detectors based on partially ordered $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys grown by molecular beam epitaxy

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Photoconductive detectors based on partially ordered $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys with AlN mole fractions up to 45% were fabricated and evaluated. The degree of ordering in these alloys was found to increase with the AlN mole fraction and it has a maximum value at about 50%. The resistivity of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films was found to increase from 10 to $10^8 \Omega \text{ cm}$ by increasing the Al content in the films. Correspondingly, the mobility-lifetime ($\mu\tau$) product, which was determined by measuring the photoconductive gain, was found to decrease from 10^{-2} to $10^{-5} \text{ cm}^2/\text{V}$. These high values of the $\mu\tau$ product at the high AlN mole fraction are attributed to spatial separation and indirect recombination of the photogenerated electron hole pairs, due to band-gap misalignment of the ordered and disordered domains in these films. © 1999 American Institute of Physics.

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Ternary $\text{Al}_x\text{Ga}_{1-x}\text{N}$ is a key material for fabrication of ultraviolet detectors because the long wavelength cutoff can be varied from 365 to 240 nm by increasing the AlN mole fraction, thereby allowing solar blind detection of ultraviolet radiation. It has been recently reported by our group that $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys grown by molecular beam epitaxy (MBE) on (0001) sapphire substrates can undergo long range atomic ordering.¹ The exact mechanism of ordering in these wurtzite structures is not yet understood. Ordering along the (0001) direction during growth along the same direction should not have been allowed based on the theoretical and experimental observations in cubic III-V alloys.² In cubic alloys ordering occurs along the (111) direction during growth along the (001) direction.² No ordering has been observed during growth along the (111) direction which is equivalent to the (0001) direction of wurtzite structures.³

X-ray diffraction studies suggest that $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys are partially ordered and that the material consists of a mixture of ordered and disordered domains.¹ This is similar to what has been reported in cubic III-V alloys^{4,5} and, more recently, in $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloys.⁶ The band structure of the ordered $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys has not been investigated yet. However, in analogy to similar studies of cubic III-V ordered alloys, we expect that ordering should lead to a reduction in the magnitude of the energy gap.⁷ In the case of $\text{In}_{0.55}\text{Ga}_{0.45}\text{As}$ and $\text{In}_{0.48}\text{Ga}_{0.52}\text{P}$, local domains formed by partial ordering on the cation sublattice were found to produce a number of interesting transport phenomena, including lifetime variations which were attributed to band-gap misalignment of the ordered and disordered domains.⁵ Although several researchers have reported on the performance of photoconducting detectors based on $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films,⁸⁻¹⁰

there are no reports on the effects of ordering on transport and recombination phenomena in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys. In this letter we report on the photoconducting properties of partially ordered $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys. We show that detectors based on such films have significantly higher photoconductive gain than detectors based on pure GaN and suggest a model involving spatial separation and indirect recombination of the photogenerated electron-hole pairs in the ordered and disordered domains of the film.

The $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films used in this study were grown by electron cyclotron resonance microwave plasma-assisted MBE (ECR-MBE). Details of the growth apparatus and procedures have been described earlier in several papers.^{1,11} Here, we present a short description of the process. The deposition system consists of a Varian GenII MBE unit with an ASTeX compact ECR source. The films were deposited on (0001) sapphire substrates whose surface, after chemical cleaning and thermal outgassing, was converted to AlN by exposing it to an ECR nitrogen plasma. The films were deposited by a two-step growth process in which an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ buffer, about 300 Å thick, was deposited at 500–600 °C and an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ single crystal film, 1–1.5 μm thick, was deposited at 700–800 °C. The composition of the films was adjusted by varying the beam equivalent pressure of the Ga and Al fluxes. All the films were doped *n* type, with the Si cell kept at a constant temperature. Using x-ray diffraction, ordering in these alloys was investigated by studying the superlattice diffraction peaks (0001), (0003), and (0005), which are forbidden in random alloys.¹

Standard photolithography and lift-off techniques were used to pattern detectors of 1 mm² in area with interdigitated electrodes. The electrode width and interelectrode spacing varied from 5 to 20 μm, corresponding to optical areas from 0.4 to 0.6 mm². Ohmic contacts were formed by depositing a thin film of Ti (200 Å thick) followed by a film of Al (2000 Å thick) by thermal evaporation.

The dark resistivity of the films was calculated by measuring the dark current through the device as a function of

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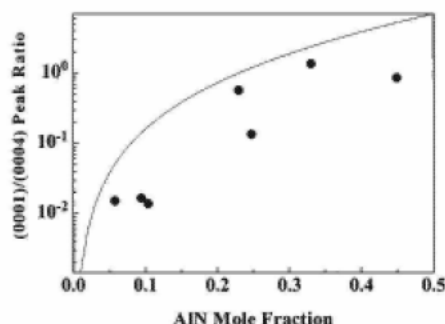


FIG. 1. Relative superlattice peak integrated intensity for a number of samples grown as a function of AlN mole fraction. The solid line is the theoretical prediction in the kinematical limit.

bias voltage. The steady state photoconductivity measurements consisted of measuring the photocurrent induced in the detector in response to an ultraviolet (UV) lamp with emission at 254 nm. The detectors were biased in the range from 5 to 25 V. The photon flux from the source was estimated to be about 5×10^{13} photons/s by measuring the photocurrent induced in a calibrated UV enhanced silicon photodiode, illuminated under identical conditions as the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ photodetectors.

Figure 1 shows the x-ray diffraction data versus AlN mole fraction of the investigated films. In Fig. 1 the superlattice (0001) intensity has been normalized with respect to the (0004) fundamental intensity to account for differences in film thickness and orientational quality. The solid line in Fig. 1 was calculated using the kinematical limit for perfectly ordered alloys.¹ These data indicate that the relative intensity of the superlattice peak, which corresponds to the degree of ordering in the film, increases with AlN mole fraction up to 50%.

The dark current-voltage (I - V) characteristics of the devices were measured and the resistivities of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films at room temperature were calculated. We found that the resistivity varied from 10 to $10^8 \Omega \text{ cm}$ as the AlN mole fraction in the films was increased from 6% to 45%. This increase in resistivity with AlN mole fraction is the combined effect of reduction in both the carrier concentration and in the electron mobility. In another report we investigated the dependence of the transport coefficients of heavily doped $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys using Hall effect measurements.¹² We found that for alloys with AlN mole fractions up to 25%, the carrier concentration for films doped with the same silicon flux decreases with increasing AlN mole fraction. This reduction in carrier concentration suggests that the silicon becomes a deeper donor, which is qualitatively consistent with the Bohr model, if one takes into account the difference in the dielectric constants of GaN and AlN. Correspondingly, the mobility decreases with the AlN mole fraction due to alloy scattering. Additionally, for partially ordered alloys like the ones used in the present study one would expect a further reduction in the mobility since carriers have to overcome barriers associated with the different band gaps of the ordered and disordered domains in the film. In addition to these effects, oxygen incorporation at higher AlN mole fractions may also play a role in moving the Fermi level away from the conduction band and making the material more resistive.

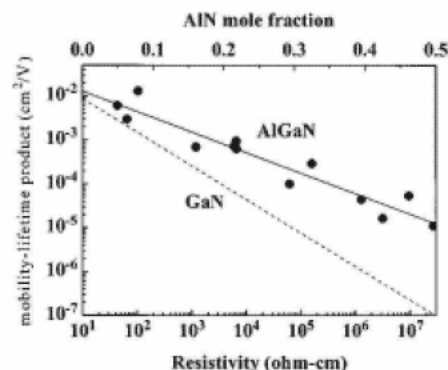


FIG. 2. Mobility-lifetime product for a number of detectors as determined from the measurement of photoconductive gain as a function of the film resistivity. The top axis shows the corresponding AlN mole fraction for the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys.

We investigated a large number of pure GaN films and also found that the resistivity can vary by six orders of magnitude by increasing the microwave plasma in the ECR discharge during growth, while maintaining all other parameters the same. Spectroscopic studies of ECR discharges indicate that the amount of active nitrogen is proportional to the power in the microwave discharge.¹³ Thus we believe the increase of the resistivity of GaN films is due to the increase of the ratio of group V-III fluxes. In analogy to our understanding of the growth of GaAs, higher group V-III fluxes also lead to semi-insulating films. In the GaAs case, this phenomenon was attributed to the formation of arsenic antisite (As_{Ga}) defects, also known as EL2 centers, which pin the Fermi level close to the middle of the gap.¹⁴ We propose that similar nitrogen antisite (N_{Ga}) defects could be the cause of the shift of the Fermi level away from the conduction band as we grow GaN at higher V/III flux ratios.

We determined the mobility-lifetime ($\mu\tau$) products from the measurement of photoconductive gain (G), by using

$$G = \mu\tau V/d^2, \quad (1)$$

where V is the applied bias voltage and d is the effective width of the device.¹⁵ The relationship between the $\mu\tau$ products and the corresponding dark resistivities of the investigated detectors is shown in Fig. 2. It shows that the magnitude of photoconductivity drops dramatically as the dark Fermi level moves deeper into the band gap. Similar results were observed for GaN films, and are shown as a dashed line in Fig. 2.¹⁶ The dependence of photoconductivity versus the position of the dark Fermi level has been observed in other photoconductors also.¹⁷ As shown in Fig. 2, the $\mu\tau$ products of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films vary from 10^{-2} to $10^{-5} \text{ cm}^2/\text{V}$ as the composition of the films is changed.

It is interesting to note that the $\mu\tau$ products of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ detectors with the high AlN mole fractions are approximately two orders of magnitude higher than those of GaN detectors of comparable resistivity. We attribute this improvement in photoconductive gain to partial ordering of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys. Typically, partially ordered films are inhomogeneous on a submicron level, consisting of ordered domains distributed throughout a random matrix. The band gap in the ordered domain is expected to be slightly smaller than that in the disordered domain. Figure 3 shows a schematic of a potential band-gap alignment of ordered and dis-

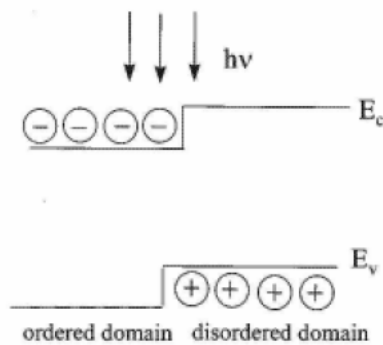


FIG. 3. Schematic illustration of the potential band alignment of ordered and disordered domains in the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys.

ordered domains form a type II heterointerface. In such a model, the photoexcited carriers are spatially separated in different regions of the material. Recombination occurs only when both electrons and holes occupy the same domain by thermal emission or by indirect recombination through defects, both of which result in long recombination times. Furthermore, according to this model, the mobility in lateral transport should be reduced since the carriers have to overcome the barriers between the ordered and disordered domains. Thus, ordering produces extremely long carrier lifetimes because the domain trapping produces charge separation and leads to indirect recombination. Similar effects of ordering on carrier lifetimes have been reported for $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$ and $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ ternaries.^{4,5} Therefore we propose that the increase in the mobility-lifetime product, despite the expected reduction in electron mobility, is a result of the increases in lifetimes of the photogenerated carriers.

In conclusion, we have fabricated photoconducting detectors on partially ordered $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films, and investigated the effect of ordering on the photoconducting properties of recombination mechanisms in the material. We found that the mobility-lifetime product varies over five orders of

magnitude as the composition of the films is changed. We attribute the long lifetimes of the photoexcited carriers in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ films with higher AlN mole fractions to the spatial separation of carriers in ordered and disordered domains, which leads to indirect recombination and to the measurement of long lifetimes.

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