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A comparative study of UV electro-absorption modulators based on bulk III-nitride films and multiple quantum wells

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In this paper we present studies and compare the performance of UV electroabsorption modulators based on bulk GaN films and GaN/AlGaN multiple quantum wells. In both types of devices, the absorption edge at room temperature is dominated by excitonic effects and can be strongly modified through the application of an external electric field. We find that when similar active layer thicknesses and device geometries are employed, the electroabsorption modulators based on bulk nitride films can provide similar performance levels as those of GaN / AlGaN multiple quantum well devices. This should be compared to the case of arsenide, phosphide, or antimonide semiconductors, where the electroabsorption effect in quantum wells is an order of magnitude stronger than in the bulk. This is primarily due to the strong ionic character of the nitride semiconductors, which lead to very large exciton binding energies at room temperature.

1 Introduction Despite the remarkable progress made in the development of III-nitride optoelectronic devices such as light emitting diodes, lasers and photodetectors, one class of devices that has received relatively little attention is that of the electroabsorption modulators [1-6]. These are electro-optic devices in which a change in the absorption coefficient $\Delta\alpha$ (or refractive index Δn) is induced by an applied electric field. In the past several years, near-infrared electroabsorption modulators based on arsenide, phosphide and antimonide semiconductors have been developed with impressive performance metrics, for a variety of applications in fiber-optic communications such as data transmission, photonic switching and optical interconnects. In general, particularly strong modulation can be obtained when the absorption edge is dominated by excitonic effects. However, in mostly covalent bulk semiconductors such as GaAs the exciton binding energy (~4 meV) is substantially less than the thermal energy k_BT at room temperature. As a result, the excitonic nature of the absorption edge at room temperature is not obvious due to thermal broadening, and the associated benefits for electroabsorption modulation are lost. On the other hand, the exciton binding energy becomes substantially larger in quantum-well (QW) structures, leading to well resolved excitonic absorption peaks even at room temperature. High-performance optical modulators have therefore been developed over the years based on the quantum confined Stark effect (QCSE) in QWs [7-9], where large changes in the excitonic resonance are obtained through the application of an electric field along the growth direction.

Similar devices based on InGaN or AlGaN alloys also have important applications in several areas of visible/UV optoelectronics, and can be expected to provide the same advantages as their near-infrared counterparts. Of particular interest is their development for non-line-of-sight free-space optical communications based on atmospheric light scattering [10], where the use of short-wavelength radiation is advantageous due to its large scattering cross-section. External optical modulators in these systems would allow for higher transmission rates, without the deleterious transient heating effects that are typically associated with direct current modulation of semiconductor light sources. A basic property of nitride semiconductors that is particularly important in this context is provided by their large exciton binding energies (about 25 meV in GaN), which is a result of the strong ionicity of its chemical bonds. In fact, a UV optical modulator based on a 0.4-μm-thick GaN film grown by metal-organic chemical va-

por deposition (MOCVD) has been reported recently [2]. However, this device was found to require a prohibitively large applied voltage (> 80 V) to produce any appreciable change in transmission, with a maximum modulation depth under normal-incidence operation of 18% at 305 V bias. Significantly stronger electroabsorption modulation at similar wavelengths (near 350 nm) has been demonstrated based on the QCSE in GaN/AlGaN QWs [3]. In particular, a comparable normal-incidence modulation depth of about 20% was obtained in this device with a modest reverse bias of only 10 V. Similar devices operating at blue/violet and deep-UV wavelengths have also been demonstrated based on InGaN/GaN and GaN/AlGaN QWs, respectively [4-6].

In this paper we report the fabrication and characterization of UV electroabsorption modulators based on bulk GaN films and on GaN/AlGaN QWs, grown by molecular beam epitaxy (MBE) under similar conditions and featuring similar active-layer thickness and device geometry.

2 Electroabsorption modulators based on bulk GaN All devices developed in this work were grown by RF plasma-assisted MBE on (0001) sapphire. A schematic cross-sectional view of the bulk modulators is shown in Fig. 1. Following nitridation of the sapphire surface, a relatively thick (0.5 µm) AlN film was initially grown in this structure, so that all subsequent epitaxial layers are under compressive strain which reduces their probability of developing cracks. A transparent contact layer consisting of Si-doped *n*-$Al_{0.16}Ga_{0.84}N$ was then deposited, followed by a nominally intrinsic $Al_{0.3}Ga_{0.7}N$ film whose function is to electrically isolate the GaN active region from the bottom contact layer. The active region is also nominally undoped (with an estimated density of unintentional donor impurities of 10^{17} cm^{-3}) and has a nominal thickness of 0.4 µm.

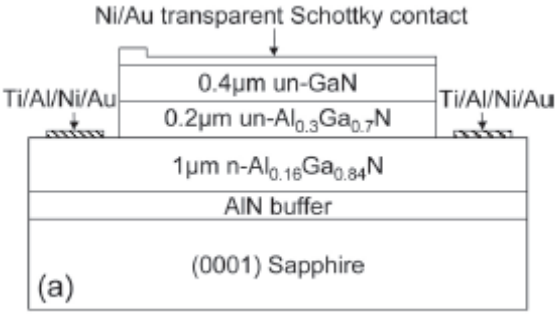

Figure 1 Schematic cross-sectional view of the bulk GaN electroabsorption modulators developed in this work.

Prior to the device fabrication, the material optical absorption spectrum was determined via transmission measurements at room temperature and the results are plotted in Fig. 2. These data clearly show that the absorption edge of this bulk sample is dominated by excitonic effects, leading to a sharp peak at a photon energy of about 3.47 eV. The abrupt increase in absorption at about 3.7eV is due to the 1-µm-thick $Al_{0.16}Ga_{0.84}N$ film.

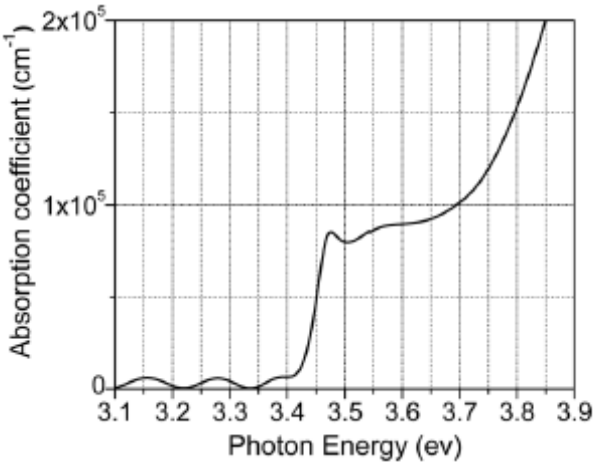

Figure 2 Absorption spectrum of the epitaxial material used to fabricate the devices of Fig. 1.

Electroabsorption modulators based on the device geometry of Fig. 1 were fabricated using standard photolithographic techniques. 800-µm × 800-µm mesa structures were first formed by inductively-coupled plasma etching in a chlorine-based chemistry. A Ti/Al/Ni/Au multilayer film was then deposited by electron-beam evaporation on the exposed n-$Al_{0.16}Ga_{0.84}N$ around each mesa, and annealed at 850 °C to form an Ohmic contact. Finally, a thin semi-transparent Ni/Au film was deposited over the top surface of each mesa, with a thick Au pad added in one corner for wire bonding. The resulting junction with the underlying GaN film is of the Schottky type, so that the external field across the active layer can be controlled through the application of a reverse bias on the Ni/Au contact.

The normal-incidence optical transmission spectra of individual devices under different bias conditions were measured at room temperature using a Varian Cary 5000 spectrophotometer. Bars containing several mesas were used in these measurements, with a small aperture in an otherwise opaque screen carefully aligned to the device under study to ensure that only the light passing through the device could reach the detection apparatus. The measured transmission spectra at various reverse bias voltages from 0 to 14 V through each device were then normalized to similarly measured transmission spectra through a sapphire substrate. As the applied voltage is increased, the excitonic absorption resonance is broadened and quenched, leading to an increase in transmission near the exciton peak and to a decrease in transmission at sufficiently detuned photon energies. From these data we obtain a maximum modulation depth M of about 30% at a photon energy of about 3.45 eV, where M is defined as the ratio $[T(V)-T(0)]/T(0)$ and $T(V)$ is the device transmission as a function of bias voltage V.

The measured transmission spectra can also be used to calculate the corresponding changes in absorption coefficient $\Delta\alpha(V) = \alpha(V) - \alpha(0)$ versus photon energy, for different values of the applied voltage. Specifically, since $T(V)$ is proportional to $e^{-\alpha(V)d}$, where d is the thickness of the absorbing layer (0.4 μm in this case), we can write

$$\Delta\alpha(V) = -\frac{1}{d}\ln\left[\frac{T(V)}{T(0)}\right]. \quad (1)$$

Several spectra of Δα obtained with this procedure are shown in Fig. 3.

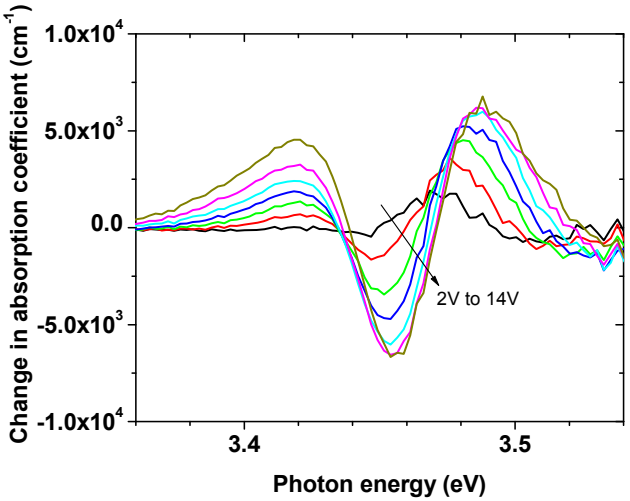

Figure 3 Differential absorption spectra for a bulk GaN modulator for different values of the applied reverse bias voltage from 0 to 14 V in steps of 2 V.

The maximum change in absorption coefficient here is found to increase with applied voltage up to a peak (absolute) value of about 7x10^3 cm^{-1} at V = 12 V. As the reverse bias is further increased, a non-negligible amount of leakage current begins to flow across the active layer. This leads to a thermal modulation of the band edges via resistive heating, which tends to compensate the field-induced changes in the absorption edge. As a result, no further increase in Δα is obtained at higher voltages.

3 Electroabsorption modulators based on GaN/AlGaN quantum wells Electroabsorption modulators based on various multiple-QW structures were also developed, using the same growth, fabrication, and characterization procedures described in the previous section. In the following we present results obtained with the device structure shown schematically in Fig. 4. Here the bottom contact layer consists of a Si-doped n-$Al_{0.15}Ga_{0.85}N$ film, and the active region comprises 50 pairs of nominally undoped 40-Å GaN wells and 50-Å $Al_{0.2}Ga_{0.8}N$ barriers. The overall thickness of this multiple-QW layer (0.45 μm) is therefore similar to that of the GaN film in the device structure of Fig. 1. Once again a semi-transparent Ni/Au Schottky contact, deposited over the topmost barrier, is employed to modulate the voltage across the active region.

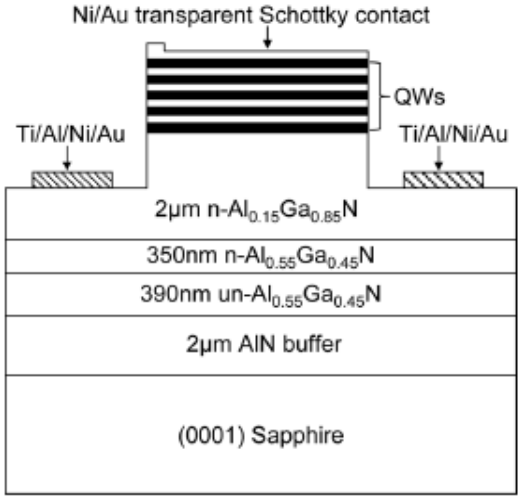

Figure 4 Schematic cross-sectional view of a GaN/AlGaN multiple-QW electroabsorption modulator developed in this work.

As already discussed, QW electroabsorption modulators rely on the QCSE, whereby an external electric field along the growth direction is used to change the exciton oscillator strength and simultaneously shift the absorption edge. An important difference between the present GaN/AlGaN devices and similar modulators based on zincblende III-V compounds is related to the characteristic intrinsic electric fields of nitride QWs grown along the (0001) direction. These fields are due to the presence of spontaneous and piezoelectric polarizations of different magnitudes in the well and barrier layers (leading to the creation of surface charge on the heterointerfaces), and can be as large as several MV/cm. In the device geometry of Fig. 4, the intrinsic electric fields in the GaN well layers point towards the substrate, and are therefore decreased by the application of a reverse bias on the Schottky contact. As a result, the spatial overlap between the electron and hole wavefunctions in each QW increases with increasing reverse voltage, leading to an increase in the excitonic oscillator strength and absorption; at the same time, a blue shift of the absorption edge is also expected. This is the exact opposite of what happens in modulators based on typical zincblende QWs, where no intrinsic electric fields exist so that under zero bias the wells and barriers have a rectangular profile.

In Fig. 5 we plot the differential absorption spectra, Δα versus photon energy, obtained for the device of Fig. 4 using Eq. (1). For the thickness d of the absorbing layer here we use the sum of the well-layer thicknesses only (0.2 μm), since the electron and hole wavefunctions in these QWs are strongly localized inside the wells (particularly because

of their triangular potential-energy profiles). The maximum modulation depth M for this device was calculated to be 34% when the applied volatage is 12 V. A maximum absorption change of over $2x10^4$ cm^{-1} is observed in this figure. This value compares favorably with that of typical infrared electroabsorption modulators for similar bias voltages [2] which highlights the promise of the present devices for practical applications.

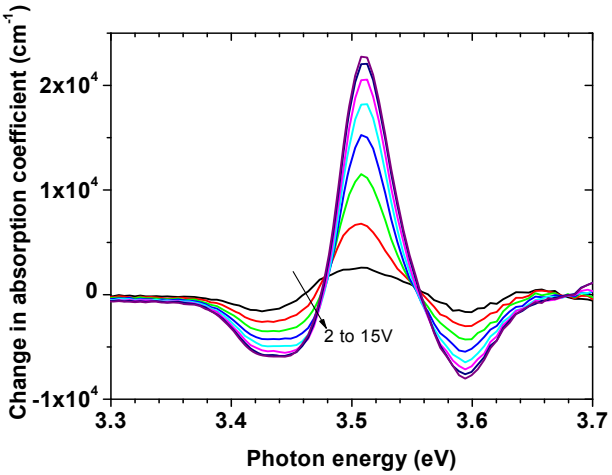

Figure 5 Differential absorption spectra for the GaN / AlGaN multiple-QW modulator for different values of the applied reverse bias voltage (0, 2, 4, 6, 8, 10, 12, 14, and 15 V).

At the same time, the photon energy of maximum absorption change in Fig. 5 is found to undergo a small blueshift of about 10 meV as the applied voltage is increased from 0 to 15 V, reflecting the occurrence of a comparable shift in the excitonic resonance. These results are similar to those reported in Ref. 6, where a theoretical study was then presented indicating that a larger blueshift is in principle expected. The likely source of this discrepancy is the presence of significant population of background carriers in the QWs, which in turn can be attributed to unintentionally incorporated oxygen donor impurities in the AlGaN barriers.

4 Discussion and conclusions The key conclusion of the present study is that, when similar active-layer thicknesses and device geometries are employed, electroabsorption modulators based on bulk nitride films can provide similar performance levels to those of GaN/AlGaN QW devices. This should be compared to the case of arsenide, phosphide, or antimonide semiconductors, where the electroabsorption effect in QWs is an order-of-magnitude stronger than in the bulk [2].

It should be noted that the presence of quantum confinement in QWs is still in principle advantageous, because it can further strengthen the exciton binding. However, the performance of the nitride QW modulators presented in this work is also likely limited by a number of other related factors. First, the bias-dependent screening of the internal polarization fields described in the previous section effectively limits the net Stark shift and related modulation of the absorption edge induced by the applied bias. Second, excitonic absorption features in QWs can experience additional broadening due to thickness fluctuations and interface roughness scattering. While this is a general concern, it may be particularly important in nitride QWs, where relatively small layer widths are typically used to avoid excessive separation of the electron and hole wavefunctions due to the internal electric fields. As a general rule, the narrower a QW the more sensitive its bound states are to interface fluctuations. Finally, the internal electric fields also fundamentally limit the exciton binding strength, because either the electron-hole wavefunction overlap is significantly reduced (near zero applied voltage), or the excitons can be effectively dissociated via thermionic emission and tunneling (under reverse bias), or both (under forward bias).

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