Electroabsorption modulators based on bulk GaN films and GaN/AlGaN multiple quantum wells

Chen-Kai Kao, Anirban Bhattacharyya, Christos Thomidis, Roberto Paiella, and Theodore D. Moustakas

Citation: Journal of Applied Physics **109**, 083102 (2011); doi: 10.1063/1.3567921
View online: http://dx.doi.org/10.1063/1.3567921
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/109/8?ver=pdfcov
Published by the AIP Publishing

Electroabsorption modulators based on bulk GaN films and GaN/AlGaN multiple quantum wells

Chen-Kai Kao, Anirban Bhattacharyya, Christos Thomidis, Roberto Paiella, and Theodore D. Moustakas[a)]
Department of Electrical and Computer Engineering and Photonics Center, Boston University, 8 Saint Mary's Street, Boston, Massachusetts 02215, USA

(Received 19 November 2010; accepted 17 February 2011; published online 18 April 2011)

Ultraviolet electroabsorption modulators based on bulk GaN films and on GaN/AlGaN multiple quantum wells were developed and characterized. 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. In the bulk devices, the applied voltage causes a broadening and quenching of the excitonic absorption, leading to enhanced transmission. In the quantum-well devices, the external field partially cancels the built-in polarization-induced electric fields in the well layers, thereby increasing the absorption. Unlike optical modulators based on smaller-bandgap zinc blende semiconductors, the bulk devices here are shown to provide similar performance levels as the quantum well devices, which is mainly a consequence of the uniquely large exciton binding energies of nitride semiconductors. © *2011 American Institute of Physics*. [doi:10.1063/1.3567921]

I. INTRODUCTION

Electroabsorption modulators are semiconductor electro-optic devices in which a change in absorption coefficient is induced by an externally applied electric field. Such devices based on zinc blende *III−V* compounds have found widespread application in optical communications for data transmission, photonic switching, and optical interconnects. In general, particularly strong modulation can be obtained when the absorption edge is dominated by excitonic effects, due to the sharp nature of the resulting absorption features. However, in smaller-bandgap 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,[1–3] where large changes in the excitonic resonance are obtained through the application of an electric field along the growth direction.

On the other hand, visible/ultraviolet (UV) electroabsorption modulators based on wide-bandgap III-nitride semiconductors have so far received limited attention,[4–8] despite a number of promising potential applications. Of particular interest is their development for nonline-of-sight free-space optical communications based on atmospheric light scattering,[9] 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. Nitride electroabsorption modulators incorporated within a laser cavity could also be used for the generation of short pulses of visible/UV radiation via *Q*-switching.[4] Additional applications include the development of dynamically reconfigurable transparencies for visible/UV spatial light modulation, as well as UV spectroscopy and sensing based on phase-resolved techniques for improved sensitivity.

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 and even higher in ternary AlGaN alloys). This is a direct consequence of the heavy electron and hole effective masses of these materials, which in turn are directly related to their large bandgap energies. As a result, even in bulk samples at room temperature the optical absorption edge is dominated by excitonic effects,[10] so that strong electroabsorption of near-bandgap radiation can be expected. In fact, a UV optical modulator based on a 0.4-μm-thick GaN film grown by metalorganic chemical vapor deposition (MOCVD) has been reported recently.[5] 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.[6] 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.[7,8]

[a)]Electronic mail: tdm@bu.edu.

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. The bulk modulators provide dramatically improved performance over the devices of Ref. 5 (including 30% modulation depth at an applied bias of only 12 V), which is attributed to excellent material quality and simplified fabrication process. At the same time, only slightly larger modulation depth (34%) at the same bias is obtained with the QW devices. By comparison, in the case of infrared electroabsorption modulators based on arsenide, phosphide, or antimonide semiconductors, the use of QWs rather than bulk active layers commonly leads to order-of-magnitude improvements in the device characteristics.[2] The results presented in this work therefore experimentally confirm the prediction that, due to their strong excitonic absorption, bulk nitride films are already suitable to the development of high-performance optical modulators. At the same time, the intrinsic advantages brought about by quantum confinement appear to be limited in the present case, which is mainly attributed to the large internal electric fields of nitride QWs.

II. 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(a). 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

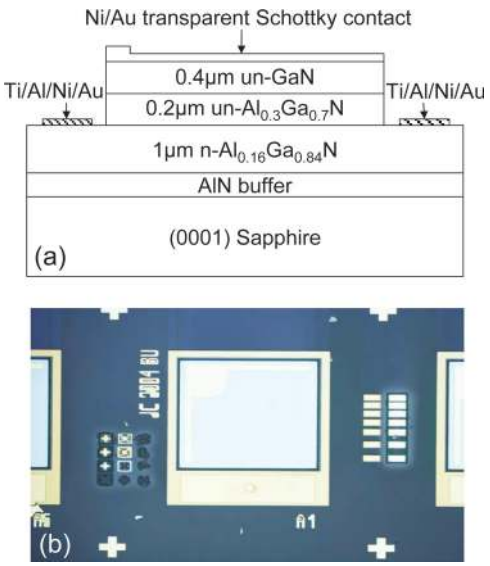

FIG. 1. (Color online) (a) Schematic cross-sectional view of the bulk GaN electroabsorption modulators developed in this work. (b) Top-view micrograph of a fabricated device.

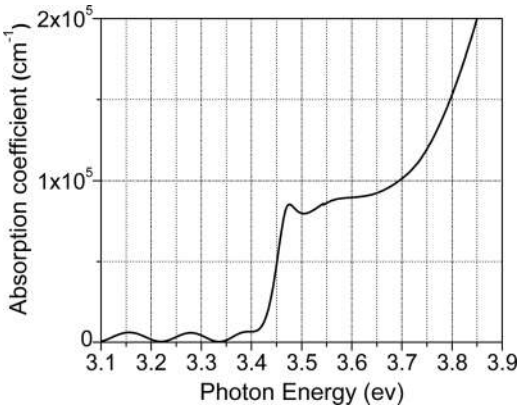

FIG. 2. Absorption spectrum of the epitaxial material used to fabricate the devices of Fig. 1.

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. 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 even without cryogenic cooling 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.

Electroabsorption modulators based on the device geometry of Fig. 1(a) were fabricated using standard photolithographic techniques. 800 $\mu m \times 800$ μm mesa structures were first formed by inductively coupled plasma etching in a chlorine-based chemistry, followed by annealing at 600 °C in a forming gas environment in order to passivate dangling bonds on the mesa sidewalls. 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 semitransparent 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. A micrograph of a fabricated modulator is shown in Fig. 1(b). Other than the growth method employed, the use of a Schottky contact is the main difference between these devices and those of Ref. 5, where a SiO_2 capping layer was used between the active region and the top electrode.

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 through each device were then normalized to

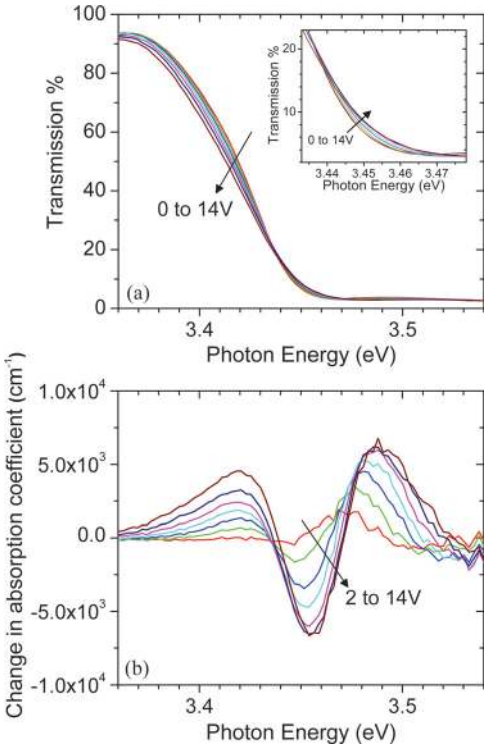

FIG. 3. (Color online) (a) Normalized transmission spectra through a bulk GaN modulator for different values of the applied reverse bias voltage from 0 to 14 V in steps of 2 V. The inset shows a zoom-in of these traces near the excitonic resonance. (b) Differential absorption spectra derived from the traces of (a).

similarly measured transmission spectra through a sapphire substrate. The resulting traces for a representative bulk GaN modulator under various reverse bias voltages from 0 to 14 V are shown in Fig. 3(a). 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. A zoom-in of the transmission spectra near the excitonic resonance is shown in the inset of Fig. 3(a). From these traces 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 $\delta a(V) = a(V) - a(0)$ 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 Δa obtained with this procedure for the same device of Fig. 3(a) are shown in Fig. 3(b). The maximum change in absorption coefficient here is found to increase with applied voltage up to a peak (absolute) value of about 7×10^3 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 $\Delta\alpha$ is obtained at higher voltages.

By comparison, the bulk GaN devices of Ref. 5 were found to require an applied voltage as large as a few hundred V to produce similar levels of optical modulation. This order-of-magnitude improvement may be attributed to higher material quality, leading to sharper excitonic absorption features, and to the use of a Schottky contact rather than a metal-oxide-semiconductor geometry to introduce the external field in the active region. Presumably, a large fraction of the applied voltage in the work of Ref. 5 falls across the SiO_2 insulating layer and therefore does not contribute to the electroabsorption. On the other hand, a potential concern with the reverse-biased Schottky-gate geometry in general is the possible appearance of undesirable leakage currents due to structural defects in the epitaxial material and/or surface states on the mesa sidewalls. In the present devices, leakage is in fact observed as discussed in the previous paragraph; however, it only appears at sufficiently large reverse bias to allow for strong electroabsorption, which points to the high structural quality of our material and to the effective sidewall passivation provided by the forming gas treatment. In any case, the results presented in Fig. 3 clearly demonstrate the potential of nitride bulk films for electroabsorption modulation, consistent with their uniquely large exciton binding energies.

III. 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

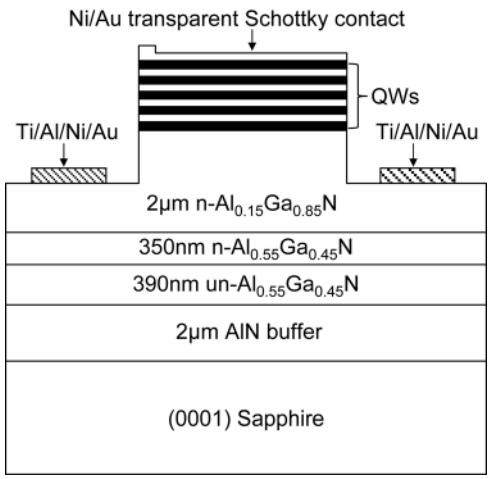

FIG. 4. Schematic cross-sectional view of a GaN/AlGaN multiple-QW electroabsorption modulator developed in this work.

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 semitransparent Ni/Au Schottky contact, deposited over the topmost barrier, is employed to modulate the voltage across the active region.

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 zinc blende *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 toward 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 blueshift of the absorption edge is also expected. This is the exact opposite of what happens in modulators based on typical zinc blende QWs, where no intrinsic electric fields exist so that under zero bias the wells and barriers have a rectangular profile.

In Fig. 5(a) we plot the normalized transmission spectra of a device based on the structure of Fig. 4 for different values of the applied reverse bias. The oscillations observed in the high-transmission portion of these traces are due to thin-film interference effects. The exciton absorption peak is centered at a photon energy of about 3.51 eV in this sample. The resulting transmission dip is barely noticeable under zero or low applied bias, due to the weak overlap of the electron and hole wavefunctions caused by the intrinsic electric fields, and then becomes more and more pronounced as the voltage is increased, as expected. Near the excitonic resonance, the device modulation depth *M* is therefore negative. Its absolute value increases with increasing applied voltage up to a bias of about 15 V, after which the device performance becomes once again limited by electrical leakage, as confirmed by the electrical characteristics shown in the inset of Fig. 5(a). When the applied voltage is 12 V, the magnitude of *M* has a maximum value of about 34%, which is slightly larger than the value obtained with the same bias in the bulk devices of Fig. 1. In Fig. 5(a) we also see a modification of the transmission spectrum near the bandedge with applied voltage, which may be due to the quantum confined Franz−Keldysh effect.[11]

In Fig. 5(b) we plot the differential absorption spectra, $\Delta\alpha$ versus photon energy, obtained from the traces of Fig. 5(a) 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

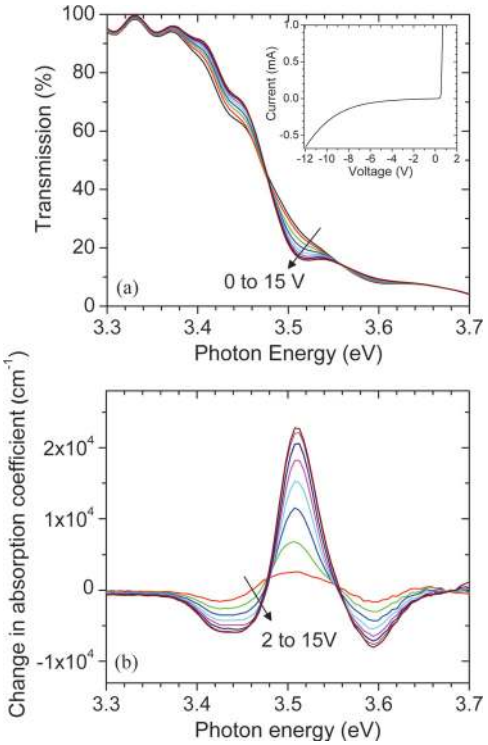

FIG. 5. (Color online) (a) Normalized transmission spectra through a GaN/AlGaN multiple-QW modulator for different values of the applied reverse bias voltage (0, 2, 4, 6, 8, 10, 12, 14, and 15 V). The inset shows the current-voltage characteristics of the same device. (b) Differential absorption spectra derived from the traces of (a).

QWs are strongly localized inside the wells (particularly because of their triangular potential-energy profiles). A maximum absorption change of over 2×10^4 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. In this respect, optical modulators based on nitride semiconductors therefore benefit from the very large near-band-edge absorption coefficients that are typical of these materials.[10]

At the same time, the photon energy of maximum absorption change in Fig. 5(b) 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.[12] At low bias, these carriers occupy the QW bound states leading to substantial screening of the internal electric fields in the well layers. As the reverse bias is increased, the QWs become increasingly depopulated due to thermionic emission and tunneling through the barriers downstream (which become more and more tilted in the presence of the external field). Correspondingly, the internal fields in the wells layers are no longer screened causing a redshift in the

bandedge, which partly counteracts the blueshift produced by the applied field.[6]

IV. 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] The key distinctive property of nitride compounds in this respect is provided by their very large exciton binding energies, which are comparable to the thermal energy k_BT at room temperature. As a result, strong excitonic effects are observed in these materials even at room temperature, which is desirable for efficient electroabsorption.

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).

In any case, the results presented in this work also clearly indicate that high-performance UV optical modulators can be developed using nitride films and QWs. As already mentioned, our measured absorption changes near the exciton resonance compare favorably with those of typical infrared modulators. Correspondingly, if the nitride active layers of Secs. II and III were incorporated in planar dielectric waveguides, order-of-magnitude changes in transmission could be achieved with reasonably low applied voltages of order 1 V. The same materials are also suitable to integration in asymmetric Fabry-Perot cavities, which would allow further increasing the modulation depth and reducing the drive voltage.[13] Finally, from a material development standpoint further progress may also be possible, if novel multiple-QW structures can be designed specifically to address the aforementioned limitations.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under grant ECS-0725786.

[1]D. S. Chemla, D. A. B. Miller, and P. W. Smith, in *Semiconductors and Semimetals*, edited by R. Dingle (Academic, New York, 1987), Vol. **34**, Chap. 5.
[2]T. H. Wood, J. Lightwave Technol. **6**, 743 (1988).
[3]J. E. Cunningham, Mat. Sci. Eng. Res. **25**, 155 (1999).
[4]M. Kneissl, T. L. Paoli, P. Kiesel, D. W. Treat, M. Teepe, N. Miyashita, and N. M. Johnson, Appl. Phys. Lett. **80**, 3283 (2002).
[5]A. E. Oberhofer, J. F. Muth, M. A. L. Johnson, Z. Y. Chen, E. F. Fleet, and G. D. Cooper, Appl. Phys. Lett. **83**, 2748 (2003).
[6]I. Friel, C. Thomidis and T. D. Moustakas, J. Appl. Phys. **97**, 123515 (2005).
[7]E. Sari, S. Nizamoglu, T. Ozel, and H. V. Demir, Appl. Phys. Lett. **90**, 011101 (2007).
[8]T. Ozel, E. Sari, S. Nizamoglu, and H. V. Demir, J. Appl. Phys. **102**, 113101 (2007).
[9]G. A. Shaw, A. M. Siegel, J. Model, and D. Greisokh, Proc. SPIE **5796**, 214 (2005).
[10]J. F. Muth, J. H. Lee, I. K. Shmagin, R. M. Kolbas, H. C. Casey, B. P. Keller, U. K. Mishra, and S. P. DenBaars, Appl. Phys. Lett. **71**, 2572 (1997).
[11]D. A. B. Miller, D. S. Chemla, and S. Schmitt-Rink, Phys. Rev. B **33**, 6976 (1986).
[12]C. R. Elsass, T. Mates, B. Heying, C. Poblenz, P. Fini, P. M. Petroff, S. P. DenBaars, and J. S. Speck, Appl. Phys. Lett. **77**, 3167 (2000).
[13]R.-H. Yan, R. J. Simes, and L. A. Coldren, IEEE J. Quantum Electron. **27**, 1922 (1991).