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Quantum-confined Stark effect of GaInNAs(Sb) quantum wells at 1300–1600 nm

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We report the measurement of electroabsorption spectra from GaInNAs and GaInNAsSb quantum wells grown on GaAs showing quantum-confined Stark effect behavior suitable for optical modulation at 1300 and 1550 nm wavelength, respectively. The high quality of our material is evidenced by sharp exciton resonances with a full width at half maximum <25 meV at 295 K, and peak absorption coefficient of 18 000 cm^{-1} for GaInNAs and 34 800 cm^{-1} for GaInNAsSb. Changes in absorption coefficient 10 000 cm^{-1} with an applied electric field were measured. Device performance from these materials is expected to be comparable to or better than the competing material grown on InP. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1777825]

There has been great interest for several years in the use of dilute nitride–arsenide materials, grown on GaAs substrates, for long-wavelength optoelectronics.[1] Much work has focused on the fabrication of lasers, both in plane and surface emitting. Demonstrations of lasers operating around 1300 nm using GaInNAs active regions have been reported.[2,3] Recently, we have been able to achieve even longer-wavelength emission up to 1600 nm using GaInNAsSb active regions,[4] including a vertical-cavity laser at 1490 nm.[5] However, little work has been done to explore the application of these materials to modulator devices,[6] mainly due to poor material quality precluding the observation of strong excitons and difficulty in achieving long wavelengths. Modulators operating in this wavelength range are important for both optical communications applications and also low-voltage optical interconnects that will enable the future of high-speed computing. In this letter, we report room-temperature measurements of the quantum-confined Stark effect (QCSE)[7] from GaInNAs and GaInNAsSb quantum wells (QWs) around 1300 and 1550 nm, respectively. Both materials show sharp excitonic resonances in the absorption spectra and characteristics suitable for fabrication of electroabsorption modulators. Our results demonstrate the QCSE for GaInNAs(Sb) material and an especially large measured effect for material in the 1550 nm wavelength range.

To measure the QCSE, *p-i-n* diode samples were grown on semi-insulating GaAs substrates using solid-source molecular beam epitaxy employing a radio-frequency plasma N source. Both As and Sb were supplied by cracker cells (valved and unvalved, respectively). GaInNAs(Sb) QW layers (8 nm thick) with 22 nm GaNAs barriers were grown at 420–455 °C in the center of a 0.5 μm GaAs intrinsic region ($\lesssim 1\times10^{15}$ cm^{-3} *n* type), while GaAs cladding regions were grown at ~600 °C. The 1.38 μm *n*-type region was doped 1×10^{18} cm^{-3} with Si, while the 1.0 μm *p*-type region was doped 5×10^{17} cm^{-3} with Be. Growth details have been reported previously.[4,8] Typical compositions were 30% In and 1.6% N, with 2% N in the barriers, for GaInNAs; and 40% In, 2.5% N, and 2.7% Sb, with 2.7% N in the barriers, for GaInNAsSb. Test devices were fabricated by depositing Ti/Pt/Au ring contacts on the top *p* layer using liftoff, etching circular mesas down to the middle of the *n* layer, and depositing Au/Ge/Ni/Au bottom ring contacts. The *n*-type contact was alloyed at 400 °C for 45 s. A well-defined aperture was left in the top contact for optical probing.

Absorption spectra were obtained by photocurrent (PC), with electrical bias applied in series with the device and ammeter. The illumination from a 250 W quartz–tungsten–halogen lamp was passed through a 950 nm long-pass filter and a 0.25 m grating monochromator, then coupled into a quartz fiber bundle and focused onto the device. The PC was detected with a lock-in amplifier by chopping the light at 307 Hz. The acquired responsivity data were converted to values of absorption coefficient (α) by assuming the maximum internal quantum efficiency (at high temperatures and biases) was 100%, and including both QWs and barriers in the interaction length. The calculated values of α were verified with transmission measurements. The interference effects from the multilayer structure on the illumination intensity were included in the calculation by using measured reflectivity spectra.

Figure 1 shows the measured absorption spectra for GaInNAs QWs around 1300 nm. The family of curves represents applied reverse biases of 0–7 V, corresponding to electric fields of 20–70 kV/cm across the QWs (calculated using the depletion approximation). Figure 1(a) shows the results for as-grown material, while Fig. 1(b) shows material that was *ex situ* rapid thermal annealed at 720 °C for 1 min in N_2 ambient after growth. QCSE behavior is observed in both cases, with a clear improvement after annealing. After annealing, the absorption coefficient is increased ~2× and the absorption edge also blueshifts to shorter wavelengths, which is a well-known phenomenon.[9–11]

Figure 2 shows the corresponding results for GaInNAsSb QWs around 1550 nm. For these samples, applied reverse biases of 1–6 V correspond to electric fields of 30–63 kV/cm. The figure shows results for a series of different thermal annealing conditions: [Fig. 2(a)] as grown, [Fig. 2(b)] 760 °C for 1 min, [Fig. 2(c)] 800 °C for 1 min, and [Fig. 2(d)] 800 °C for 3 min. Again, α nearly doubles after the longest anneal and the wavelength experiences a blueshift.[10] However, the magnitude of α for the as-grown GaInNAsSb QWs [Fig. 2(a)] is comparable to that of the

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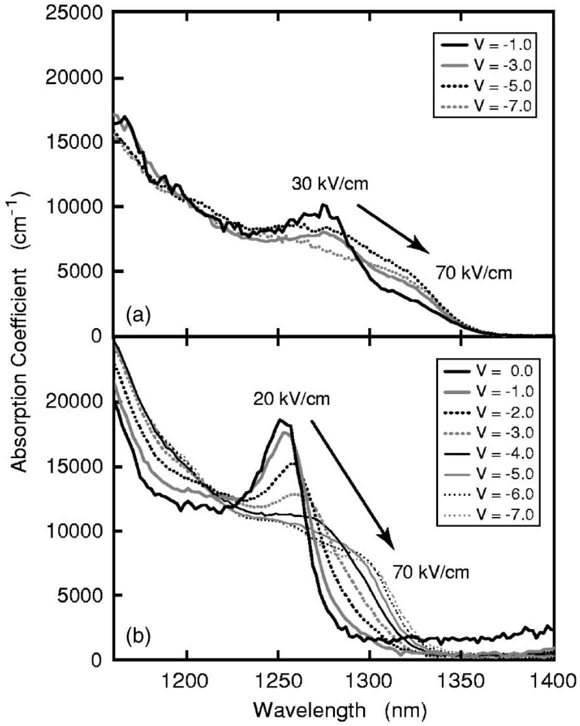

FIG. 1. Absorption spectra from GaInNAs QWs for (a) as-grown material and (b) material annealed at 720 °C for 1 min.

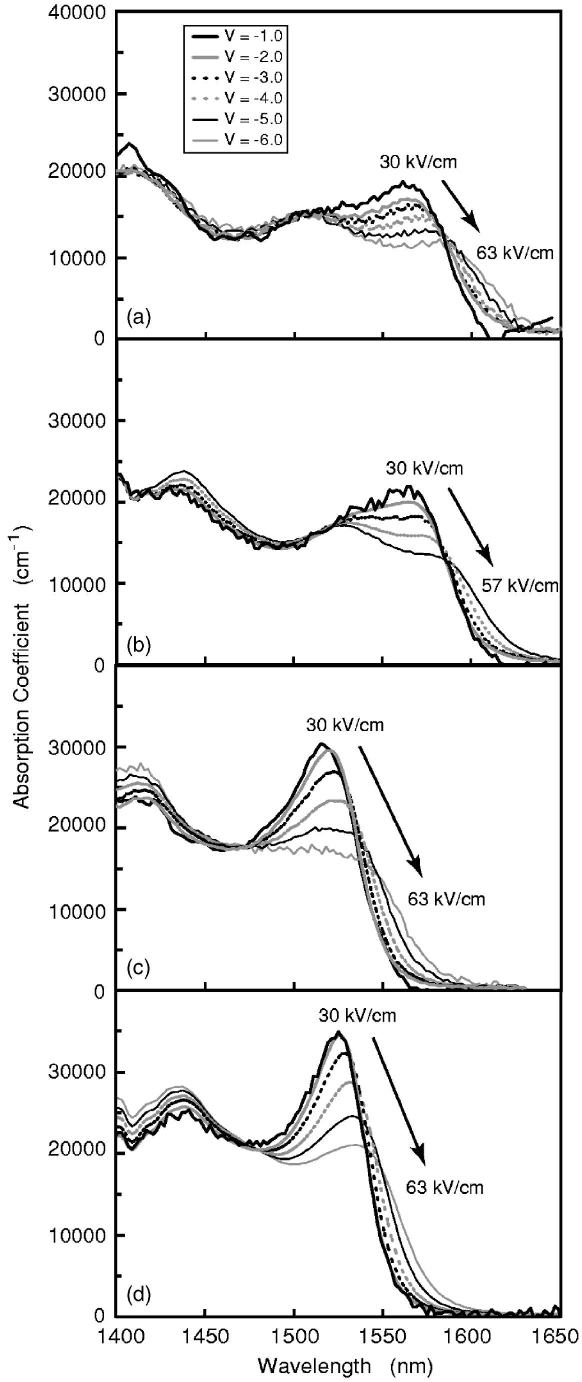

FIG. 2. Absorption spectra from GaInNAsSb QWs for (a) as-grown material and material annealed at (b) 760 °C for 1 min, (c) 800 °C for 1 min, and (d) 800 °C for 3 min.

annealed GaInNAs QWs [Fig. 1(b)]. Furthermore, the annealed GaInNAsSb material [Fig. 2(d)] shows a peak absorption coefficient ($\sim$34 800 cm^{-1}) higher than reported for InGaAs/InGaAsP QWs at 1550 nm grown on InP.[12–14] In addition, the change in α with applied electric field, a critical parameter for modulator device performance, is similar to or larger than that for competing InGaAs/InGaAsP QWs.

The high quality of the QW material is evidenced by the sharp exciton resonances observed in the absorption spectra, with a full width at half maximum less than 25 meV at room temperature. Even with fields as high as 70 kV/cm, sharp absorption edges are observed. Very high values of absorption coefficient are measured for these materials (compared to InGaAs and GaAs/AlGaAs, for example) due to their high electron effective masses (higher for the antimonide) and consequently increased band edge joint density of states. The QCSE is also especially distinct since the transition at the band edge is strictly heavy hole to electron, with the light hole level more than 100 meV higher in energy.

For optical modulator application, key parameters include the maximum and minimum values of α at the operating wavelength with and without applied bias, and also their ratio. To maximize contrast ratio and minimize insertion loss, a "fully on" state is desired with $\alpha \sim 0$, so operation at wavelengths slightly higher than the zero-field absorption edge is favorable, as opposed to operation at the exciton peak. Electroabsorption spectra, which represent the change in absorption coefficient when a bias is applied, are shown in Fig. 3 for the longest annealed GaInNAs and GaInNAsSb QWs, relative to the 0 V spectra. The plots of Fig. 3 clearly show the suitability of these materials for modulation at 1300 and 1550 nm, with operation in the favored long-wavelength lobe of the electroabsorption spectra. The change in α at 1550 nm of almost 10 000 cm^{-1} for GaInNAsSb, with an applied bias of 6 V (63 kV/cm, or 43 kV/cm change in electric field from 0 V), is notably higher than typical InGaAs/InGaAsP active regions on InP.[12–14] In addition, our QWs were not specifically optimized to maximize the QCSE and improved performance should be possible.[15,16]

Furthermore, Fig. 3 can be used to estimate the expected device performance if a specific architecture is chosen. For an asymmetric Fabry–Perot reflection configuration,[17,18] useful for arrayed optical interconnects, for example, and with the device optimally tuned to operate near the "matching condition" in a normally on configuration, modulation ratios as high as 15–20 dB or more are expected with optical bandwidths greater than 20 nm. One limitation with this configuration is the inability to grow many QWs due to strain in the

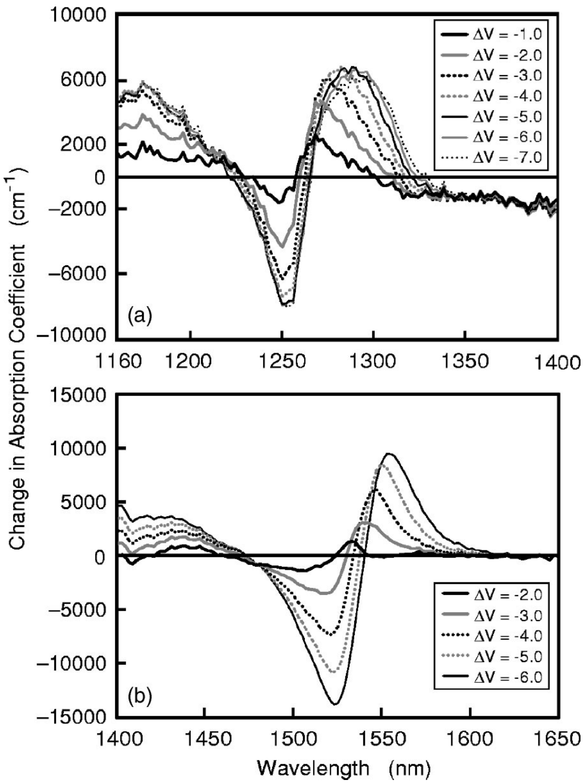

FIG. 3. Electroabsorption characteristics of annealed QWs of (a) GaInNAs and (b) GaInNAsSb, deduced from Figs. 1(a) and 2(d), respectively, relative to the 0 V bias points.

layers; for GaInNAsSb, we can only grow up to 4 QWs, while for GaInNAs, up to ~10 before reaching the critical thickness for dislocation formation. This leads to a short interaction length L. However, the critical parameter for modulator operation is αL, and this value is similar for our QWs as for typical modulator active regions using other material systems and many more QWs, due to the much higher α of our QWs.

In summary, we have presented electroabsorption data for GaInNAs and GaInNAsSb quantum wells grown on GaAs demonstrating excellent QCSE behavior at 1300 and 1550 nm. Growth of other compositions than presented here can cover the entire wavelength range from 1100–1600 nm. Exciton linewidths less than 25 meV at room temperature were observed, and very high peak absorption coefficients of 18 100 cm^{-1} for annealed GaInNAs at 1255 nm and 34 800 cm^{-1} for annealed GaInNAsSb at 1525 nm were measured. With electric fields applied across the QWs, large absorption changes occurred which are suitable for realization of optical modulators at 1300 and 1550 nm, respectively. High performance modulators can be fabricated with these active regions, with predicted modulation ratios up to 15–20 dB or greater and optical bandwidths greater than 20 nm.

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