Infrared detectors based on InGaAsN/GaAs intersubband transitions

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InGaAsN/GaAs multiquantum well structures have been grown by molecular beam epitaxy with 1% nitrogen in the well. Intersubband transitions have been observed in the infrared region by transmission spectroscopy. Infrared detectors have been processed and an intersubband transition has been observed in the photocurrent spectrum. All the observations are consistent with each other and in very good agreement with a theoretical calculation. Band to band transitions observed by photoluminescence also confirm the position of the levels in the well. © 2009 American Institute of Physics. [DOI: 10.1063/1.3065479]

The field of intersubband transitions (ISBTs) was opened three decades ago in electron accumulation layers in silicon,1 two decades ago in GaAs/AlGaAs quantum wells (QWs),2 and a few years ago in InGaAsN/GaAs QWs.3 In arsenide materials tremendous progress has been achieved from these early observations and has led to important applications including infrared imaging4 and quantum cascade lasers.5 Quantum well infrared photodetectors (QWIPs) based on GaAs are limited to a wavelength of about 4 μm on the high energy side by the GaAs/AlGaAs band offset. Replacing GaAs by InGaAsN in the QWs in principle allows to reach wavelengths below 4 μm.6 A very few studies of ISBTs in InGaAsN/GaAs QWs have been reported.3,7,8 Reports on photodetectors are even more limited in number and are dealing with GaAs QWs only, and not InGaAsN. As InGaAsN allows to reach a much larger conduction band offset than GaAs and also allows to fabricate lattice matched heterostructures (or at least heterostructures with a reduced strain), it is important to investigate InGaAsN QWIPs. Recently, ISBTs at very short wavelengths (1.24 μm) were reported in highly confined InGaAsN QWs.10 The assignment of the transitions remains, however, to confirm due to the complexity of the structure and the corresponding configuration of energy levels.

In this letter, we report the fabrication and characterization of infrared photodetectors based on InGaAsN QWs, with a clear assignment of transitions made by absorption and photocurrent measurements, and in agreement with calculations.

Three samples were grown by molecular beam epitaxy in a RIBER 32 reactor. S1 is a reference sample based on InGaAs QWs, S2 and S3 are InGaAsN QW based samples, with 1% N. In all samples, the indium content is equal to 20%, the GaAs barrier thickness is 30 nm, and the number of periods is 20. The difference between S2 and S3 is the QW thickness: 6 nm in S2 and 4.5 nm in S3. The QW thickness in S1 is 6.5 nm. All samples are Si doped in the center (2 nm) of the QW to reach a donor density of 2 × 10¹¹ cm⁻² per well. The GaAs barriers are not doped. All samples are grown on semi-insulating GaAs substrates, and the active region is sandwiched in between two Si doped GaAs contact regions which will be used to fabricate the detector.

Using the nominal parameters of the wells, we have calculated the level energies in all samples.8 Table I summarizes the results. The calculated transition energies E₁HH₁ could be compared with the experimental values of the photoluminescence peaks. A very good agreement was found as can be seen in Table I, giving us some confidence in the actual value of the QW parameters. The calculated intersubband energy lies in the range of 100–150 meV in all samples. The energy between the first excited level and the barrier conduction band is very small for samples S3 and S1 which is needed in general in a photodetector for a good carrier collection. Indeed photoexcited electrons have to be extracted out of the well and collected in the contacts. Transitions in such a QW are so called bound to quasi-free. This energy is larger for S2 which was designed to be a bound to bound detector. Bound to bound transitions are spectrally narrower and more intense than bound to quasi-free or bound to free transitions but lead to a smaller photocurrent due to a smaller electron collection. Compared to AlGaAs barriers leading to deep QWs, the GaAs barriers used here lead to shallow QWs which support only two levels, the fundamental and the first excited ones. These levels remain far away from the N level and all the complexity (splitting of transitions, decrease of oscillator strengths, . . .) is seen in Table I.

### Table I. QW parameters, and calculated and experimentally observed transition energies of samples S1–S3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S1-S695</th>
<th>S2-S692</th>
<th>S3-S693</th>
</tr>
</thead>
<tbody>
<tr>
<td>QW thickness</td>
<td>6.5</td>
<td>6</td>
<td>4.5</td>
</tr>
<tr>
<td>% N</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E₁HH₁ (eV) calc. at 10 K</td>
<td>1.33</td>
<td>1.21</td>
<td>1.245</td>
</tr>
<tr>
<td>E₁HH₁ (eV) PL at 10 K</td>
<td>1.352</td>
<td>1.21</td>
<td>1.265</td>
</tr>
<tr>
<td>E₁E₂ (meV) calc.</td>
<td>108</td>
<td>154</td>
<td>180</td>
</tr>
<tr>
<td>E₂ (μm) (calc.)</td>
<td>11.5</td>
<td>8</td>
<td>6.8</td>
</tr>
<tr>
<td>E₂-barrier (meV) calc.</td>
<td>1</td>
<td>64</td>
<td>10</td>
</tr>
<tr>
<td>E₁E₂ (meV) abs exp.</td>
<td>107</td>
<td>153</td>
<td>175</td>
</tr>
<tr>
<td>E₁E₂ (meV) photocurrent exp.</td>
<td>150/225</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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strength, etc.) introduced by the coupling with the N level is avoided, which a priori should lead to a single well defined transition.

The optical transmission of these layers was measured. The layer was sandwiched in between two mirrors that were fabricated by depositing gold on Si substrates, and which define an optical waveguide of about 1.5 cm. The light incident under Brewster incidence on the sample at one edge of the waveguide is reflected inside the sample until the beam reaches the end of the waveguide (see inset of Fig. 1). The number of passes is estimated to be 10. As the structures include doped regions (QWs and contact regions), the free carrier absorption is a very strong and prevents a clear observation of the ISBTs. Therefore, we need to normalize the transmission spectra in order to remove the free carrier absorption. It is important to note that this geometry is different from the usual zigzag geometry where the light penetrates the semiconductor at normal incidence on the 45° bevel. In that latter case, it is easy to switch the light polarization from TM to TE and normalize the TM transmission spectrum by the TE one. As an advantage, our geometry does not require the fabrication of a bevel and can be performed on a full wafer. The drawback is that the propagation conditions in TE and TM are very different: the reflection coefficient is zero in TM while it is different from zero in TE for each reflection. Hence the effect of the metal mirror is drastically different in both polarizations. As a consequence, the normalization must be done with a transmission spectrum measured in TM polarization. This was the purpose of sample S1 which has a structure and composition (In composition and doping) as close as possible to those of samples S2 and S3. The QW structure was simply adjusted so that its transition wavelength is larger than that of samples S2 and S3. The transmission spectra of the InGaAsN QW samples (S2 and S3) normalized by the transmission spectrum of the InGaAs sample (S1) are shown in Fig. 1.

One observes a dip in each spectrum, at 8.1 and 7.1 μm for samples S2 and S3, respectively. The ISBT in sample S1 is weak which makes the normalization easier. It is hardly observed at 10.5 μm (appearing as a positive bump) in the normalized S2 spectrum, but remains hidden in the S3 spectrum by the residual free carrier absorption (more precisely by the difference of free carrier absorption between samples S1 and S3). The comparison in Table I between calculated and measured values of the transition also makes us confident on the nature of the observed transition. The amplitude of the transition (about 2%) is lower than expected. Indeed one usually measures in an equivalent structure based on GaAs/AlGaAs QWs a dip of about 5%. This reduced amplitude is related to some broadening of the transition, although the broadening is difficult to estimate from Fig. 1. Many factors contribute to this broadening. First, the measurement integrates the absorption over a large distance on the sample (about 1.5 cm) and integrates all lateral nonuniformities. Second, the quality of InGaAsN material is not as good as the one of the AlGaAs/GaAs system. Usually, an annealing step is used in order to improve the crystallographic quality. We have annealed samples at 730 °C during 30 s and measured the transmission. The transitions were actually not better defined after annealing and therefore were not reported here. The last explanation in the broadening lies in the band structure of InGaAsN QWs as explained in Ref. 6. Our calculation gives a full width at half maximum (FWHM) of 30 meV for sample S2 while the observed value is 40 meV. For sample S3, the calculated FWHM is 35 meV and the measured value is about the same. By comparison, our calculation gives a linewidth of 27 meV for sample S1 without N. Hence we can estimate that the transition linewidth in InGaAsN QWs is close to the expectations. Our calculation also indicates that the amplitude of the transition is reduced by factors of about 2.5 and 4 in samples S2 and S3 compared to QWs without N. This is due to the coupling with the N level which reduces the Γ component of the wave function and reduces the oscillator strength. This partially only explains the weakness of the measured transition in InGaAsN QWs as the transition in sample S1 is not much larger (about 3%). Bound to bound transitions would be more intense but less suited for fabricating a detector.

Detectors have been fabricated following the usual process. Mesa were etched down to the bottom contact layer. NiAuGe contacts were deposited on the top and bottom contact layers, and subsequently annealed at 380 °C for 1 min. Electrical measurements were then performed at low temperature (22 K) in a step scan Fourier transform infrared spectrometer. The pixel area is about 1 mm². Such a large area was chosen in order not to introduce any parasitic coupling on the mesa edges and in order to verify the polarization selection rule. The drawback was the amplitude of the dark current as will be shown hereafter. The dark current was first measured and turned out to be high (>1 mA at 0.2 V) in the S1 and S3 samples showing that the detector was not working correctly. Photoresponse measurements could not be performed in these samples. Figure 2 shows the dark current in sample S2, which is in the nanoampere range for biases between −0.5 and +0.5 V. The photocurrent was measured in a step scan configuration in s and p polarizations. Figure 3 shows the photoresponse spectrum in sample S2 measured in p polarization. In p polarization, we observe a clear peak at 150 μeV that we can attribute to the E1/E2 transition, in good agreement with the observed absorption spectrum and with the calculation. Note that the response is measured at low temperature while the absorption was measured at room temperature. However, ISBT energies are little dependent on...
temperature as the band gap energy variation with temperature (about 70 meV for GaAs between 22 and 300 K) does not directly affect the $E_1$-$E_2$ energy. The peak is largely broadened on its high energy side up to about 250 meV, in qualitative agreement with the energy separation between the fundamental level and the GaAs conduction band. Indeed, one always observe in QWIPS such a broadening of the photocurrent spectrum compared to the absorption spectrum which is explained in terms of electron escape probability or in other words transitions toward the continuum of states. No photocurrent is observed in $s$ polarization (not shown). It is interesting to note that the coupling with the N level of the conduction band does not suppress the polarization selection rule. This is not surprising in these samples where the coupling with the N level is weak. In deeper QWs with levels closer to the N level, the coupling would be much stronger and the selection rule could be more affected.

The quality of our detector is clearly not ideal yet. Both the epitaxy and the process need to be optimized: strain introduced by the In and defects introduced by N tend to degrade the material quality, when the number of QWs increases.

The transitions that we observed here in our InGaAsN samples remain at quite large wavelength. In order to move the transition toward the 4 $\mu$m range, it is necessary to replace GaAs barriers by AlGaAs barriers. This unfortunately makes the epitaxy more difficult and has not been successfully achieved so far. The reasons for that are the larger strain (the lattice mismatch between barrier and well increases when replacing GaAs by AlGaAs) and the InGaAsN/AlGaAs interface chemistry. Al and N tend to form strong atomic bonds which favor the formation of nitrides. Hence, a GaAs spacer must be inserted in between InGaAsN and AlGaAs. Moreover, residual N in the reactor tend to incorporate so that AlN bonds cannot be completely eliminated. Attempts to solve the problem are under way.

As a conclusion, we have demonstrated an IR detector based on ISBTs in InGaAsN/GaAs QWs with a clear assignment of the transition based on a cross correlation between many measurements and theory. Material issues remain to be addressed before high quality short wavelength detectors can be fabricated.

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