Tuning and tailoring of broadband quantum-well infrared photodetector responsivity

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Infrared spectroscopy is a widely used technique in both ground and space-based remote sensing instruments to obtain critical scientific information as well as real time detection and identification of targets. High resolution imaging spectrometers or interferometers performing such investigations require small-pixel, large-format focal plane arrays (FPAs) with high uniformity and operability. The GaAs/AlGaAs-based quantum well infrared photodetectors (QWIPs) technology is an excellent choice for the development of such FPAs.

Unlike in narrow band QWIPs, broadband QWIPs show considerable spectral shape change with bias voltage, particularly near the cut-off wavelength region. Two alternatives to the typical broadband QWIP design have been demonstrated. These designs consist of two multiquantum-well (QW) stacks or alternatively placed QWs and produce nearly fixed spectrums within the operating bias voltages. Flexibility in many design parameters of these detectors allows for tuning and tailoring the spectral shape according to application requirements, specifically for spectral imaging instruments. © 2005 American Institute of Physics. [DOI: 10.1063/1.1900313]

FIG. 1. Bias dependence spectral responsivity of a broadband QWIP structure which is created by replacing single-QWs in the narrow-band structure by few period superlattices.
tronic charge, and $h\nu$ is the photoexcitation energy.$^{1,7}$ For longer wavelengths, it is necessary to apply a higher bias voltage to obtain a reasonable nonzero value for $g_p$, while for shorter wavelengths $g_p$ starts from zero bias. This can be attributed to the behavior of transmission probability factor ($\gamma$) in $g_p$, i.e., $g_p \propto \gamma$. The $\gamma$ is smaller for low energy photoexcited electrons, i.e., longer wavelength transitions, because those electrons need to tunnel through a barrier to contribute to the photocurrent.

This change in spectral shape due to the bias voltage is an undesirable property for spectral imaging instruments because it could complicate the calibration process. If the spectral shape is fixed, the operating bias voltage of the FPA can be used as a parameter to optimize instrument performance during the imaging of different targets against different backgrounds. In order to accommodate this flexibility, we have considered two alternate designs for broadband QWIPs based on discrete narrow band QWIPs. Figure 2 shows a schematic conduction band diagram of the “stack design,” which consists of two stacks of MQW structures designed to respond at two different wavelengths within the required broadband wavelength band. A similar design scheme was used in the past for tunable multi-band QWIPs.$^9,10$ If the two MQW structures have dissimilar impedances, a disproportional bias voltage drop across the structures could lead to a dominant photocurrent response from a single structure. As the bias voltage changes, response could switch to the other structure, effectively acting as a voltage tunable detector.$^9,10$ Therefore, in order to keep the broadband spectral shape unchanged, it is essential to design two MQW structures with similar impedances, at least within the desired operating temperatures and bias voltages.

Table I shows three different structural parameters for “stack design” broadband QWIPs. Detector SB1 consists of two MQW structures, with similar barrier thickness and one designed for $\lambda_p = 6.8$ $\mu$m and the other for $\lambda_p = 8.5$ $\mu$m peak wavelength. Despite having a higher carrier density, the 6.8 $\mu$m QWIP has higher impedance than the 8.5 $\mu$m QWIP. Therefore, as the bias voltage increases, most of the bias drops across the 6.8 $\mu$m QWIP and then spreads over to the 8.5 $\mu$m QWIP. Figure 3(a) shows the spectral peak wavelength switching from $\lambda_p = 6.8$ $\mu$m to $\lambda_p = 8.5$ $\mu$m within a small bias voltage change (from $V_B = 3.5$ to 5.0 V) demonstrating the highly sensitive wavelength tunability of the device. Unlike detector SB1, SB2 and SB3 were designed to produce minimal spectral shape changes as bias voltage is varied. Detector SB2 comprises two MQW structures with $\lambda_p = 11.2$ $\mu$m and $\lambda_p = 13.8$ $\mu$m while detector SB3 comprises two MQW structures with $\lambda_p = 11.4$ $\mu$m and $\lambda_p = 13.4$ $\mu$m peak wavelengths. In order to reduce the impedance of the shorter wavelength MQWs to the level of the longer wavelength MQWs, bound-to-continuum QWs with thinner barriers were utilized, with the design parameters

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Detector SB1 Stack 1</th>
<th>Detector SB1 Stack 2</th>
<th>Detector SB2 Stack 1</th>
<th>Detector SB2 Stack 2</th>
<th>Detector SB3 Stack 1</th>
<th>Detector SB3 Stack 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak $\lambda$ ($\mu$m)</td>
<td>6.8</td>
<td>8.5</td>
<td>11.2</td>
<td>14.0</td>
<td>11.4</td>
<td>13.4</td>
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<tr>
<td>Number of wells</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Well thickness ($\AA$)</td>
<td>400(4% In)</td>
<td>48</td>
<td>56</td>
<td>75</td>
<td>59</td>
<td>70</td>
</tr>
<tr>
<td>Barrier thickness ($\AA$)</td>
<td>300</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Barrier Al%</td>
<td>28$%$</td>
<td>25$%$</td>
<td>19$%$</td>
<td>15$%$</td>
<td>18$%$</td>
<td>16$%$</td>
</tr>
<tr>
<td>Well doping (cm$^{-3}$)</td>
<td>$1.2 \times 10^{18}$</td>
<td>$6 \times 10^{17}$</td>
<td>$4 \times 10^{17}$</td>
<td>$2 \times 10^{17}$</td>
<td>$4 \times 10^{17}$</td>
<td>$2 \times 10^{17}$</td>
</tr>
</tbody>
</table>

FIG. 2. Schematic conduction band diagram of a “stack design” broadband QWIP which consists of two stacks of MQW structures designed to respond at two different wavelengths ($\lambda_{p1}$ and $\lambda_{p2}$) within the required broad wavelength band. $N_1$ and $N_2$, $N_{D1}$ and $N_{D2}$, and $L_{B1}$ and $L_{B2}$ pairs represent different number of wells, well-doping densities, and barrier thickness in each MQW structure.

FIG. 3. Bias voltage dependence spectral responsivity of three different “stack design” QWIPs. (a) Due to unequal impedance of the two stacks, detector SB1 shows spectral tunability with the bias voltage. As shown in (b) and (c), SB2, and SB3 are designed to produce nearly unchanged spectra within the operating bias voltage range.
shown in Table I. The normalized spectral responsivity plots at different bias voltages in Fig. 3(b) shows nearly an unchanged broadband spectrum of SB2 within a 1–2 V voltage range, while Fig. 3(c) demonstrates the nearly unchanged broad-band spectrum of SB3 within a 1–3 V voltage range.

Figure 4 shows a schematic band diagram of an “intermix design” broadband QWIP consisting of multiple periods of alternatively placed, dissimilar QWs. Each QW in the structure is separated by a 500 Å thick AlxGa1−xAs barrier with a bidirectionally graded Al composition of x=18 to 16%. The impedances of both types of QWs were kept at similar values by utilizing a bound-continuum design with a higher doping density in shorter wavelength QWs. Figure 5 shows the normalized spectral responsivity measured at different bias voltages. As designed, the broadband spectral shape is nearly unchanged within a Vb=1–4 V bias range. The higher responsivity at shorter wavelengths (∆λp=11.4 μm) is attributed to the higher carrier density of the short wavelength QWs. One can obtain a smoother responsivity curve by properly adjusting the doping densities of the QWs or by adding more longer wavelength QWs to the MQW structure.

In summary, several methods for realizing broadband QWIP FPAs for spectral imaging instruments have been discussed. The requisite spectral band can be covered by utilizing a single broadband MQW or by stacking a few narrow-band MQWs, thereby creating a multiband detector. It is important to avoid a change in spectral shape due to the bias voltage of the broadband FPAs utilized in spectral imaging instruments. Several alternatives to the typical broadband QWIP design have been demonstrated. A “stack design” which consists of two MQW stacks produces a nearly fixed spectrum as well as a highly tunable spectrum according to the impedance of each stack.

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