Role of the wetting layer in the enhanced responsivity of InAs/GaAsSb quantum dot infrared photodetectors

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InAs/GaAs$_{1-x}$Sb$_x$ Quantum Dot (QD) infrared photodetectors are analyzed by photocurrent spectroscopy. We observe that the integrated responsivity of the devices is improved with the increasing Sb mole fraction in the capping layer, up to 4.2 times for $x = 17\%$. Since the QD layers are not vertically aligned, the vertical transport of the carriers photogenerated within the QDs takes place mainly through the bulk material and the wetting layer of the additional QD regions. The lower thickness of the wetting layer for high Sb contents results in a reduced capture probability of the photocarriers, thus increasing the photoconductive gain and hence, the responsivity of the device. The growth of not vertically aligned consecutive QD layers with a thinner wetting layer opens a possibility to improve the performance of quantum dot infrared photodetectors.
standard photolithography and wet chemical mesa etching. A ring-shaped metallization using AuGe–Au was deposited on top of the mesas and then alloyed under forming gas at 350 °C to obtain ohmic contacts. The bottom contact was chosen as the ground in all measurements. Standard tapping mode AFM measurements with Sb-doped Si tips were used to characterize the surface QDs. Photoresponse was measured by means of a Nicolet 760 Fourier Transform Infrared Spectrometer (FTIR) using a glowbar as the light source and a KBr beam splitter.

A key aspect in devices based on Sb is the interplay between In and Sb, either in the capping layer or inside of the quantum dot. The cross-sectional scanning tunneling microscopy (X-STM) is a critical technique for determining the distribution of the chemical species. Measurements of QD layers grown under the same conditions than those studied here have shown that the GaAsSb capping layer modifies the resulting WL. The details about the measurements are published by the authors in Ref. 11. Under high voltage conditions, the STM contrast reveals mainly the topography of the outward relaxation of the cleaved surface due to the compressive strain from the QDs, the WL and the capping layer. The relaxation profile can be simulated by a finite element method. This model has been used in the past in the study of GaAs,

In Fig. 3, we display the potential profile along the growth direction of one of the QDs of sample A. (The black arrow in the inset indicates the equivalent region along the semiconductor sample.) A realistic QD size, shape, and composition derived from X-STM measurements are considered in the calculations. The QD model takes into account the impact on the electronic structure of the strain distribution resulting of the different lattice constants of the materials involved in the formation of the nanostructure and its associated linear piezoelectric field and uses an $8 \times 8 \mathbf{k} \cdot \mathbf{p}$ method. This model has been used in the past in the study of the electronic structure of InAs QDs capped with GaAsSb and containing Sb inside.

Furthermore, also in Fig. 3, we show the electron ground state (GS) and the first bound state (1ES) in the QD. The simulation reveals that actually there are more bound states...
in the QD, however, the difference in energies between two consecutive levels is less than 30 meV in any case (which corresponds to intersubband transitions above \( \lambda = 41 \mu m \)). We focus our analysis only in the atmospheric transmission window (3–5 \( \mu m \)). This wavelength range can be reached taking advantage of the transition from the GS to the continuum in the QD. In our case, for sample A, this corresponds to a difference in energies of 210 meV. According to this value, we expect an absorption peak at 5.9 \( \mu m \) for the QD of sample A. Similar calculations have been performed for samples B and C, although they have been omitted here for simplicity. For those samples, the calculated absorption peaks are: 5.2 \( \mu m \) in sample B and 5.0 \( \mu m \) in sample C.

The low temperature (12 K) responsivity of the samples is shown in Fig. 4. The spectra have been taken by FTIR in normal incidence conditions. The peaks corresponding to the QD intersubband transitions at \( \sim 5 \mu m \) are clearly visible. The resulting absorption peaks match reasonably well with the calculated energies for the transition from the GS to the continuum. Besides, there is an improvement in the integrated intensity of a factor of 4.2 between samples A and C. As it was aforementioned, we attribute this improvement in the responsivity to the thinner WLs of the samples with higher Sb content, since the photoelectrons are swept towards the contacts through those WLs. The responsivity of a photonic detector depends on the wavelength (\( \lambda \)), the quantum efficiency (\( \eta \)), and the photoconductive gain (\( g \)) as

\[
R = \frac{q}{h c} \lambda \eta g.
\]

Since the conduction band is barely affected by the presence of Sb and the position in energy of the ground state does not change significantly in the samples, the variation in the quantum efficiency (\( \eta \)) is expected to be very small. Therefore, assuming that the quantum efficiency is approximately equal in the three samples and that the slight variations in the peak wavelength are negligible, we find that the enhancement of the integrated responsivity must be associated with the photoconductive gain. The capture probability (\( p_c \)) can be expressed as

\[
p_c = 1 - \exp \left(-\frac{l_w}{L_c}\right),
\]

where \( l_w \) is the QW width and \( L_c \) is a decay constant. According to this expression, \( p_c \) increases with the well width, supporting our model: the thinner WL gives rise to a higher gain as deduced from Eq. (2). In Table I, we show the ratio of the integrated responsivity of samples B and C with respect to that of A, together with the ratio of the photoconductive gain (\( g \)) calculated from Eqs. (2) and (4) taking \( l_w \) as the WL thickness. The values obtained using the theoretical model are in good agreement with the experimental values, showing a raising tendency of \( g \) when the Sb molar fraction is increased. This indicates that the WL thickness is the critical factor that explains the enhanced responsivity of these devices.

In conclusion, we find a raising tendency of the integrated responsivity of InAs/GaAs_{1-x}Sb_x quantum dot infrared photodetectors with the increasing Sb molar fraction in the capping layer. This value is as high as 4.2 times for \( x = 17\% \) with respect to \( x = 0\% \). While the photogenerated carriers are created at the QD, the fact that the QD layers are not vertically aligned makes the vertical transport of these carriers to take place mainly through the bulk material and the WL-capping layer. The lower thickness of the WL for high Sb contents results in a reduced capture probability of the photocarriers, and hence, in an improvement of the device responsivity. Consequently, the growth of consecutive not vertically aligned QD layers with a reduced WL thickness gives rise to the possibility of developing high performance quantum dot detectors.

![FIG. 3. Potential profile of the conduction band of a QD in sample A along the growth direction (one period of the active region). The inset displays the structure of one period where the simulated region is indicated by the black arrow.](image)

**FIG. 4.** Low temperature (12 K) normal incidence responsivity of QDIPs A, B, and C as a function of wavelength. The integrated value increases with the Sb content due to the increment in the photoconductive gain (\( g \)).

<table>
<thead>
<tr>
<th>Sample</th>
<th>WL thickness</th>
<th>Integrated responsivity ratio with respect to sample A</th>
<th>Photoconductive gain (( g )) ratio calculated from Eqs. (2) and (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.48 ML</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1.16 ML</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>C</td>
<td>1.06 ML</td>
<td>4.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

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TABLE I. Integrated responsivity ratio of samples B and C with respect to that of A, and photoconductive gain ratio calculated from Eqs. (2) and (4).
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