Study of Shubnikov–de Haas oscillations and measurement of hole effective mass in compressively strained InₓGa₁₋ₓSb quantum wells

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Abstract

InₓGa₁₋ₓSb has the highest hole mobility amongst all III–V semiconductors which can be enhanced further with the use of strain. The use of confinement and strain in InₓGa₁₋ₓSb quantum wells lifts the degeneracy between the light and heavy hole bands which leads to reduction in the hole effective mass in the lowest occupied band and an increase in the mobility. We present magnetotransport measurements on compressively strained InₓGa₁₋ₓSb and GaSb quantum wells. Hall-bar and Van de Pauw structures were fabricated and Shubnikov–de Haas oscillations in the temperature range of T = 2–10 K for magnetic fields of B = 0–9 T were measured. The reduction of effective hole mass with strain was quantified. These results are in excellent agreement with modeling results from band structure calculations of the effective hole mass in the presence of strain and confinement.

Keywords:
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Cyclotron resonance
III-V

Recently, there has been significant interest in the use of III–V materials to replace Si as channel material for future CMOS technology nodes. High electron mobility has been demonstrated in n-MOSFET devices using InₓGa₁₋ₓAs channel [1]. In the meantime progress has also been made towards improving the hole mobility in III–V’s which has been less promising in the past in comparison to strained-Si. Biaxially strained InₓGa₁₋ₓAs quantum wells have been studied to enhance hole mobility with maximum reported room-temperature hole mobility in the range of 300–400 cm²/Vs [2,3]. Sb-based channels appear attractive candidates for III–V pMOS because of their high bulk mobility. Recently, we demonstrated high hole mobility in Sb-based quantum wells with biaxial compressive strain [4,5]. Hole mobility of 1200 cm²/Vs in strained InₓGa₁₋ₓSb quantum well [4], and 1350 cm²/Vs in strained GaSb quantum well [5] was obtained (at sheet charge of ~1 × 10¹²/cm²). One of the most important consequences of the presence of strain and confinement in these quantum wells is the lifting of the degeneracy of the light and heavy hole bands, which results in the reduction of the hole effective mass in the lowest occupied band and an increase in mobility [6].

Study of the Shubnikov–de Haas oscillations in the resistivity of a two-dimensional hole gas in a quantum well along with Hall measurements can yield important information about its characteristics, such as the effective mass of the charge carriers, number of bands occupied, spin degeneracy, quantum scattering time, etc. In this letter we present a systematic study of Shubnikov–de Haas oscillations in compressively strained quantum wells with (A) InₓGa₁₋ₓSb and (B) GaSb channels. Biaxial compression, which has been predicted to be optimum for hole mobility enhancement [7], is introduced into the quantum well by engineering the lattice mismatch between the channel and barrier material during MBE growth. Fig. 1 shows a cartoon of the different layers in the stack and cross section TEM image around the channel region. A modulation doping scheme using Be is employed. For the GaSb channel devices the AlAs/Sb₁₋ₓ barrier is grown as superlattice of AlAs and AlSb (Fig. 1) [5]. Details on the growth are available in Refs. [5,6]. Percentage of strain in the channel layers was calculated using X-ray diffraction (XRD) analysis [4,5]. Hall-bar and Van der Pauw structures were fabricated for magnetotransport measurements [8]. A low frequency lock-in amplifier technique was used to avoid any interference from the power line. The temperature was varied from 2 K to 300 K and magnetic field up to 9 T was applied. Details on samples studied...
InXGa1_xSb has the highest hole mobility amongst all III?V semiconductors which can be enhanced further with the use of strain. The use of confinement and strain in InXGa1_xSb quantum wells lifts the degeneracy between the light and heavy hole bands which leads to reduction in the hole effective mass in the lowest occupied band and an increase in the mobility. We present magnetotransport measurements on compressively strained InXGa1_xSb and GaSb quantum wells. Hall-bar and Van de Pauw structures were fabricated and Shubnikov-de Haas oscillations in the temperature range of T = 2?10 K for magnetic fields of B = 0?9 T were measured. The reduction of effective hole mass with strain was quantified. These results are in excellent agreement with modeling results from band structure calculations of the effective hole mass in the presence of strain and confinement.
in this paper and their mobility at 300 K and 2 K measured using Hall measurements are given in Table 1. For samples A1, A2 and B1, high low-temperature mobility in the range 4400–5000 cm²/Vs is obtained. For samples A3 and B2 the target strains were 1.8% and 1.48%, respectively; however, relaxation of strain occurred in these samples due to channel width exceeding the critical thickness. This results in the degradation in the room-temperature mobility and much higher degradation in the low-temperature mobility value in A3, B2 (Table 1). For Shubnikov–de Haas oscillations to occur the required condition is

\[
\frac{c_s}{C^2} \gg 1
\]

where \(c_s\) is the quantum (single-particle) relaxation time and \(c = eB/m^*\) is the cyclotron frequency with \(m^*\) being the hole effective mass and \(B\) is the magnetic field. Thus high low-temperature mobility implying high relaxation time is critical for observation of Shubnikov–de Haas oscillations within the given field/temperature range fixed by the experimental setup.

Fig. 2a plots the scan of sheet resistance with magnetic field (0–9 T) for sample A1 with mobility of 4500 cm²/Vs and sheet charge \(1.3 \times 10^{12}/\text{cm}^2\) at 2 K. An oscillatory behavior can clearly be seen superimposed on a parabolic dependence with magnetic field. The oscillatory behavior is plotted vs. \(1/B\) for various temperatures, removing the parabolic dependence due to hole–hole interaction. The oscillations are periodic vs. \(1/B\), with a single frequency as verified from taking a fast Fourier transform on the data (inset b).

Fig. 2a. Shubnikov–de Haas oscillations seen in the sheet resistance at 2 K (sample A1). (b) The oscillatory behavior is plotted for various temperatures removing the parabolic dependence due to hole–hole interaction. The oscillations are periodic vs. \(1/B\), with a single frequency as verified from taking a fast Fourier transform on the data (inset b).

Table 1. Details on the samples studied. Mobility at 300 K and mobility and sheet charge \(N_s\) at 2 K measured using Hall measurements are listed. Strain is calculated using XRD analysis [5–6].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Channel (thickness (Å))</th>
<th>Barrier</th>
<th>Strain (%)</th>
<th>(\mu_{\text{Hall}}) (300 K) (cm²/Vs⁻¹)</th>
<th>(\mu_{\text{Hall}}) (2 K) (cm²/Vs⁻¹)</th>
<th>(N_s) (2 K) (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>In₄₁Ga₅₉Sb (75)</td>
<td>Al₀.₇Ga₀.₃Sb</td>
<td>1.8</td>
<td>960</td>
<td>4500</td>
<td>1.3 × 10¹²</td>
</tr>
<tr>
<td>A2</td>
<td>In₄₁Ga₅₉Sb (75)</td>
<td>AlSb</td>
<td>1.9</td>
<td>900</td>
<td>5000</td>
<td>0.94 × 10¹²</td>
</tr>
<tr>
<td>A3</td>
<td>In₄₁Ga₅₉Sb (125)</td>
<td>Al₀.₇Ga₀.₃Sb</td>
<td>1.8ᵃ</td>
<td>621</td>
<td>2210</td>
<td>1.0 × 10¹²</td>
</tr>
<tr>
<td>B1</td>
<td>GaSb (75)</td>
<td>AlAs₀.₂Sb₀.₇Sb₀.₁</td>
<td>1.06</td>
<td>880</td>
<td>4400</td>
<td>1.5 × 10¹²</td>
</tr>
<tr>
<td>B2</td>
<td>GaSb (75)</td>
<td>AlAs₀.₂Sb₀.₇Sb₀.₂</td>
<td>1.48ᵃ</td>
<td>600</td>
<td>1500</td>
<td>1.27 × 10¹²</td>
</tr>
</tbody>
</table>

ᵃ For samples A3 and B2 the ideally targeted value of strain is listed. Mobility degradation is observed due to strain relaxation in these samples due to channel width exceeding the critical layer thickness.
Table 2
Summary of hole effective mass (m*) with strain: extracted value from Shubnikov–de Haas oscillations (SdH), results from band structure modeling (k.p) and verification with cyclotron resonance (CR).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Channel (Å)</th>
<th>Strain (%)</th>
<th>( \mu_{\text{Hall}} ) (2 K) (cm² V⁻¹ s⁻¹)</th>
<th>m* ( (m_0) )</th>
<th>m* when no coupling ( (m_0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>In0.41Ga0.59Sb (75)</td>
<td>1.8</td>
<td>4500</td>
<td>0.099 (SdH), 0.09 (k.p)</td>
<td>( m^*_{\text{min}} : 0.06 ) (k.p, ( p = 1/\gamma_1 + \gamma_2 ))</td>
</tr>
<tr>
<td>A2</td>
<td>In0.41Ga0.59Sb (75)</td>
<td>1.9</td>
<td>5000</td>
<td>0.094 (SdH), 0.085 (k.p), 0.096 (CR)</td>
<td>Strain relaxation: no oscillations</td>
</tr>
<tr>
<td>A3</td>
<td>In0.41Ga0.59Sb (122)</td>
<td>1.8*</td>
<td>2213</td>
<td>0.12 (SdH), 0.10 (k.p)</td>
<td>( m^*_{\text{min}} : 0.07 ) (k.p, ( p = 1/\gamma_1 + \gamma_2 ))</td>
</tr>
<tr>
<td>B1</td>
<td>GaSb (75)</td>
<td>1.06</td>
<td>4400</td>
<td>Strain relaxation: no oscillations</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>GaSb (75)</td>
<td>1.48*</td>
<td>1500</td>
<td>Strain Relaxation: no oscillations</td>
<td></td>
</tr>
</tbody>
</table>

* Target value of strain.
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References