Surface Brillouin scattering measurement of the elastic constants of single crystal InAs\textsubscript{0.91}Sb\textsubscript{0.09}

L M Kotane\textsuperscript{1}, J D Comins\textsuperscript{1}, A G Every\textsuperscript{1} and J R Botha\textsuperscript{2}

\textsuperscript{1}Materials Physics Research Institute, School of Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa
\textsuperscript{2}Department of Physics, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

E-mail: Lesias.Kotane@wits.ac.za

Abstract. Surface Brillouin scattering of light has been used to measure the angular dependence of the Rayleigh surface acoustic wave (SAW), pseudo surface acoustic wave (PSAW) and longitudinal lateral wave (LLW) speeds in a (100)-oriented single crystal of the ternary semiconductor alloy InAs\textsubscript{0.91}Sb\textsubscript{0.09}. The wave speed measurements have been used to determine the room temperature values of the elastic constants \( C_{11}, C_{12} \) and \( C_{44} \) of the alloy. A simple and robust fitting procedure has been implemented for recovering the elastic constants, in which the merit function is constructed from explicit secular functions that determine the surface and lateral wave speeds in the [001] and [011] crystallographic directions. In the fitting, relatively larger weighting factors have been assigned to the SAW and PSAW data because of the greater precision with which the surface modes can be measured as compared with the lateral wave.

1. Introduction
The III-V ternary semiconductor alloy, InAs\textsubscript{1-x}Sb\textsubscript{x}, is important in the development of long-wavelength optoelectronic devices due to its room temperature band gap ranging from about 0.17 to 0.35 eV \cite{1}. The alloy with a composition \( x = 0.09 \) is of importance as it has a room temperature energy gap corresponding to a wavelength of about 4.2 \( \mu \)m which is within the infrared wavelength range 3-5 \( \mu \)m, the transmission window in the atmosphere, where long-range detection is of interest \cite{2, 3}.

In this paper we present the results of a study which makes use of the surface Brillouin scattering (SBS) technique to measure the room temperature elastic constants of the InAs\textsubscript{0.91}Sb\textsubscript{0.09} ternary semiconductor alloy. The elastic constants are essential in furthering the understanding of the mechanical properties of devices that are fabricated from such alloys. The utilised SBS technique is a nondestructive measurement that exploits light scattering in the analysis of the characteristics of surface acoustic waves (SAWs).

2. Experimental method
For opaque materials such as InAs\textsubscript{0.91}Sb\textsubscript{0.09}, where only very limited light penetration occurs, laser light incident on the surface is inelastically scattered by surface acoustic waves via the so-called surface ripple mechanism \cite{4, 5}. The backscattering geometry used in our experiments leads via wavevector conservation to the relation \( k_{//} = 2k_{\parallel} \sin \theta_{l} \), where \( k_{//} \) is the component of the wavevector parallel to the surface, \( \theta_{l} \) is the incident angle and \( k_{\parallel} \) is the wavevector of the incident light. The phase velocity \( V \) of the SAW is related to the spectral frequency shift \( (\omega_{l} - \omega_{s}) \) by \( V = (\omega_{l} - \omega_{s})/2k_{\parallel} \sin \theta_{l} \).
The rotation of the sample about the azimuthal angle $\phi$ selects different SAW propagation directions. The phase velocities of the (SAWs) are then used to determine the elastic constants of the material.

Undoped samples with a mirror-like finish were grown by atmospheric pressure metalorganic vapor phase epitaxy (MOVPE-grown) on an InAs substrate. The samples were measured to be about $2.7 \mu m$ thick, thick enough to be regarded as bulk material in SBS, by the Nomarski differential interference method [6] and were lattice matched to the (100) orientation of the InAs substrate.

X-ray diffraction measurements were carried out on the specimen to determine its lattice constant and hence its density. The measurement was done at room temperature using a Philips PW1050 diffractometer (Cu K$_\alpha$ radiation at 40kV and 20 mA). From the X-ray diffraction measurements, the lattice constant was determined to be 6.0811 Å. The density of this cubic zinc-blende structure was then calculated from the lattice constant and the total atomic weight in a unit cell and was found to be 5.729 g/cm$^3$.

The experimental arrangement used for SBS measurements is described in Comins [5]. In brief, measurements were done at room temperature using an argon-ion laser of wavelength 514.5 nm operated in a single axial mode for illumination. The laser light was focused onto the sample by a 120 mm focal length lens and the scattered light was collected with the same lens in the backscattering geometry. The scattered light was analysed by a Sandercock-type (3+3)-pass tandem Fabry-Pérot interferometer fitted with a JRS Scientific Instruments vibration isolation system. The light was detected by an EG&G Optoelectronics Canada SPCM-200-PQ detector, which is a silicon avalanche photodiode device. The scattering angle $\theta_s = 71^\circ$ used in the measurements is close to a maximum for the p-p scattering (polarisation in the sagittal plane) cross section.

3. Results and discussion

The values of the elastic constants $C_{11}$, $C_{12}$ and $C_{44}$ were recovered from the SBS measurements taken in the [001] and the [011] directions of the (100) surface of the InAs$_{0.91}$Sb$_{0.09}$ specimen. Our measurements resulted in 4 velocities and with 3 parameters (i.e. $C_{11}$, $C_{12}$ and $C_{44}$) to be determined – this is an over determined problem that is solved by a fitting procedure. One approach would be to do a least squares fit to the 4 velocities. We have, however, adopted a much simpler approach to the fitting, which avoids the necessity of solving the cubic equations for the SAW and PSAW velocities. We do this by taking the merit function to be $\chi^2 = (h_1^2 + h_2^2) + w(h_3^2 + h_4^2)$, where $w$ is the relative weighting factor for the longitudinal velocities as compared with the Rayleigh SAW measurements. $h_1$ and $h_2$ are secular functions that determine the surface and longitudinal lateral wave speeds in the [001] crystallographic direction and are defined as follows

$$h_1 = \rho V_{RSW}^2 = \left( \frac{C_{11}}{C_{44}} \times \frac{C_{44} - \rho V_{RSW}^2}{C_{11} - \rho V_{RSW}^2} \right)^{\frac{1}{2}} \times \left( \frac{C_{11}}{C_{12}} \times \frac{C_{12} - \rho V_{RSW}^2}{C_{11} - \rho V_{RSW}^2} \right)$$

$$h_3 = \rho V_{L}^2 - C_{11}.$$ 

Similarly, expressions for secular functions $h_2$ and $h_4$ that determine the surface and longitudinal lateral wave speeds in the [011] crystallographic direction are defined as follows
\[ h_2 = \rho V_{PSAW}^2 \left( \frac{C_{11}}{C_{44}} - \frac{\rho V_{PSAW}^2}{\frac{1}{2} \left( C_{11} + C_{12} + 2C_{44} \right)} \right)^{\frac{1}{2}} \times \left( \frac{1}{2} \left( C_{11} + C_{12} + 2C_{44} \right) - \rho V_{PSAW}^2 \right) \]

\[ h_4 = \rho V_L^2 - \frac{1}{2} \left( C_{11} + C_{12} + 2C_{44} \right). \]

A perfect fit is obtained when all the secular functions are equal to zero. The quantities \( h_3 \) and \( h_4 \) correspond to the deviation of the squared longitudinal velocities from their measured values and \( h_2 \) and \( h_2 \) are not very different from being the deviation of calculations from squared measured SAW velocities [7].

In the calculation of the elastic constants, the SAW velocities were given a bigger weighting than the longitudinal velocities. This is largely due to the possibility of locating the centre of the SAW peaks by fitting Lorentzian functions whilst on the other hand the longitudinal thresholds presented themselves more as somewhat rounded valleys rather than sharp dips. This can be clearly seen in figure 1. Given this factor of a greater uncertainty in measuring the longitudinal velocities, a weighting factor of \( w = 0.25 \) was assigned to the longitudinal velocities in the calculation of the merit function \( \chi^2 \). A detailed computational approach is found in Every et al. [7], also providing information on elasto-dynamic Green’s function method in the calculation of the surface dynamics.

**Table 1.** Measured and calculated velocities (with a \( V_L \) weighting of 0.25) for the (100) surface of the ternary semiconductor alloy InAs\(_{0.91}\)Sb\(_{0.09}\).

|   | [001] \( V_{SAW} \) (m/s) | [011] \( V_{PSAW} \) (m/s) | [001] \( V_L \) (m/s) | [011] \( V_L \) (m/s) |
|---|-----------------|-----------------|-----------------|-----------------|
| Measured | 2011 | 2139 | 3483 | 4179 |
| Calculated | 1984 | 2156 | 3587 | 4087 |
| % deviation | -1.34 | 0.79 | 2.99 | -2.20 |

On minimisation of \( \chi^2 \) the fitted values of the elastic constants were found to be:

\( C_{11} = 73.7 \) GPa, \( C_{12} = 40.4 \) GPa, \( C_{44} = 38.7 \) GPa.

The SBS spectra were calculated from the determined values of the elastic constants \( C_{11}, C_{12} \) and \( C_{44} \) and compared with spectra measured in the [001] and the [011] directions based on the assumption that the scattering is entirely by the ripple mechanism. The comparison, illustrated in figures 1 and 2, shows a good agreement between measured and calculated spectra particularly for the Rayleigh SAW modes. The uncertainty in locating exact positions of the longitudinal minima is evident when comparing the “valleys” of the measured spectra to the calculated “dips”.

\[ 2nd International Symposium on Laser-Ultrasonics - Science, Technology and Applications \]
\[ Journal of Physics: Conference Series 278 (2011) 012001 doi:10.1088/1742-6596/278/1/012001 \]
Figure 1. The measured and calculated SBS spectra for the [001] direction on the (100) surface of InAs$_{0.91}$Sb$_{0.09}$.

Figure 2. The measured and calculated SBS spectra for the [011] direction on the (100) surface of InAs$_{0.91}$Sb$_{0.09}$.

4. Conclusion
Using a simple and robust fitting procedure employing a merit function, the elastic constants of single crystal InAs$_{0.91}$Sb$_{0.09}$ have been determined from velocity measurements of the Rayleigh SAW, pseudo-SAW and the longitudinal threshold of the Lamb continuum observed in the SBS spectra corresponding to [001] and the [011] directions on the (100) surface.

References
[1] Sze S M 1981 Physics of Semiconductor Devices (New York; John Wiley)
[2] Biefeld R M 1986 J. Cryst. Growth 75 255
[3] Baisitse T R, Forbes A, Katumba G, Botha J R and Engelbrecht J A A 2008 Phys. Status Solidi (c) 5 573
[4] Beghi M, Every A G and Zinin P V 2004 Chapter 10 Ultrasonic Nondestructive Evaluation: Engineering and Biological Material Characterization, ed Kundu T, (Boca Raton; CRC Press)
[5] Comins J D 2001 Chapter 15 Handbook of Elastic Properties of Solids, Liquids and Gases. Volume I: Dynamic Methods for Measuring the Elastic Properties of Solids, edited by Levy et al (San Diego; Academic Press)
[6] Krug T, Botha L, Shamba P, Baisitse T R, Venter A, Engelbrecht J A A and Botha J R 2007 J. Cryst. Growth 298 163
[7] Every A G, Kotane L M and Comins J D 2010 Phys. Rev. B 81 224303