



Dielectric functions of $\text{In}_{1-x}\text{Al}_x\text{Sb}$ alloys for arbitrary compositions with parametric modeling



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ABSTRACT

By determining the parameters of the parametric model (PM) for selected Al compositions x of $\text{In}_{1-x}\text{Al}_x\text{Sb}$, we provide the information needed to accurately calculate the room-temperature dielectric functions $\varepsilon = \varepsilon_1 + i\varepsilon_2$ of these alloys from 1.5 to 6.0 eV as a continuous function of x over the entire composition range $0 \leq x \leq 1$. Our parameters are determined from data obtained by spectroscopic ellipsometry for Al compositions $x = 0.00, 0.142, 0.341, 0.539, 0.754$, and 1.00. The PM dielectric functions are found to be in excellent agreement with the data. These results will be useful in many aspects of research and technology.

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1. Introduction

In the race to develop portable equipment for data processing, communication, imaging, and sensing applications, high speed, high frequency, and low-power electronic components are needed. To address these needs, semiconductors with tunable, low bandgaps are a primary concern. Antimonides have the smallest direct band gaps among all III–V compound semiconductors, proving to be suitable candidates for these applications. $\text{In}_{1-x}\text{Al}_x\text{Sb}$ and its heterostructures with other antimonides offer wide band gap coverage along with high electron mobility. In addition, the large conduction band offset between InSb and AlSb provides excellent carrier confinement, which yields improved radiation tolerance [1] with the smallest lattice mismatch [2]. Due to this unique combination of properties, the use of $\text{In}_{1-x}\text{Al}_x\text{Sb}$ can be foreseen in many applications, including infra-red detectors and emitters, laser diodes, and high-electron-mobility transistors [3–5].

To design more efficient devices, the dielectric properties $\varepsilon = \varepsilon_1 + i\varepsilon_2$ of these materials over their operating energy ranges need to be known. There have been few studies of the optical properties of $\text{In}_{1-x}\text{Al}_x\text{Sb}$ alloys [6], with ε data reported for only a few fixed Al compositions x . Spectra for intermediate compositions are unknown. Among other applications, these data are expected to be important for in-situ monitoring of growth processes including monitoring epitaxial strain and critical thicknesses of epitaxial layer for lattice-mismatched heterostructure systems [7]. Here, we report parameters that can be used to construct room temperature ε spectra of $\text{In}_{1-x}\text{Al}_x\text{Sb}$ alloys over the entire composition range $0 \leq x \leq 1$ from 1.5 to 6.0 eV. We

use the parametric model (PM) to provide the analytic representation and same frame-work as reported by Hwang et al. [8].

2. Experiment

Dielectric function spectra of $\text{In}_{1-x}\text{Al}_x\text{Sb}$ alloys with $x = 0.142, 0.341, 0.539$, and 0.754 are taken from Ref. [6]. These data were obtained on $\text{In}_{1-x}\text{Al}_x\text{Sb}$ films grown on a semi-insulating (001) GaAs substrate in a Riber compact 21E solid source molecular beam epitaxy system with a rotating sample stage for uniform film growth. The substrate was first heated to 620 °C under As_2 to remove surface oxides. A GaAs buffer layer approximately 200 nm thick was then grown at 580 °C. This was followed by the growth of an approximately 1.2 μm thick $\text{In}_{1-x}\text{Al}_x\text{Sb}$ layer. Growth temperatures ranged from 400 to 470 °C. Al and In growth rates ranged from 0.5 to 1.82 Å/s and 0.4 to 2 Å/s, respectively. The beam equivalent pressure of the Sb_2 flux was $\sim 2 \times 10^{-6}$ Torr. The compositions of the deposited layers were confirmed by high-resolution X-ray diffraction. Being 1.2 μm thick, the layers were completely relaxed and any possible complications arising from optical features of the substrate do not occur. Room-temperature pseudodielectric function spectra $\langle \varepsilon \rangle = \langle \varepsilon_1 \rangle + i \langle \varepsilon_2 \rangle$ were measured from 1.5 to 6.0 eV using a rotating-compensator spectroscopic ellipsometer. The angle of incidence was 67.08°.

Spectroscopic ellipsometric data are highly surface-sensitive, so any oxide overlayer causes $\langle \varepsilon \rangle$ to differ from the true dielectric function ε of the material. To minimize this difference, and to ensure that our $\langle \varepsilon \rangle$ spectra are an accurate representation of ε , we minimized overlayer effects by performing wet-chemical etching in situ and assessing the results in real time. Details are provided in Refs. [9,10], and explained briefly as follows. The sample was mounted vertically and optically prealigned on the measurement system. Oxide layers

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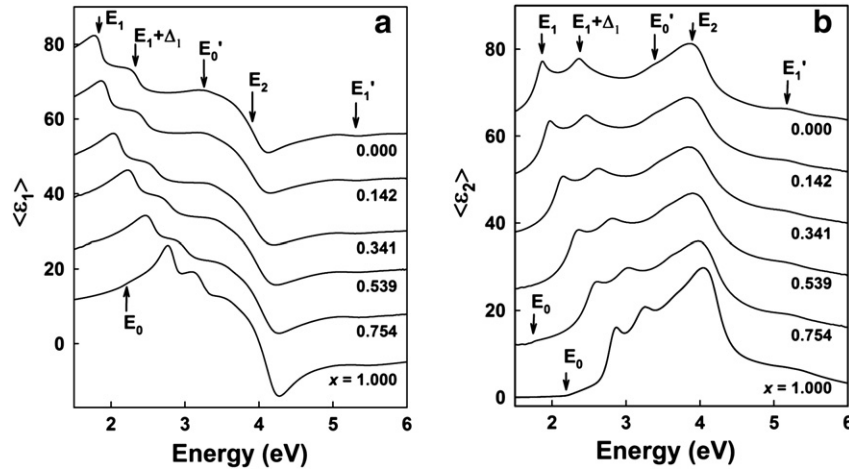


Fig. 1. (a) Real and (b) imaginary parts of the pseudodielectric functions ($\langle \epsilon \rangle$) of $\text{In}_{1-x}\text{Al}_x\text{Sb}$, offset sequentially by 12 for clarity. The data were obtained under conditions where the $\langle \epsilon \rangle$ spectra are accurate representations of the bulk dielectric function ϵ of these materials. Data for $x = 0.142, 0.341, 0.539,$ and 0.754 are from Ref. [6]. Data for InSb and AlSb are from Refs. [12] and [13] respectively.

were removed by flowing chemical reagents over the vertical sample surface, which was finally rinsed with water or methanol. Measurements were done with the samples in a high-purity N_2 atmosphere to prevent reoxidation and the accumulation of contamination layers.

3. Results and discussion

Fig. 1 presents the $\langle \epsilon \rangle$ spectra of $\text{In}_{1-x}\text{Al}_x\text{Sb}$ alloys for $x = 0.000, 0.142, 0.341, 0.539, 0.754,$ and 1.00 that are used as the basis for this analysis. The spectra of InSb and AlSb are from Refs. [11] and [12], respectively. Successive spectra are offset by 12 for clarity. Well-defined E_1 and E_2 spectral regions are clearly observed. The identification of each critical point (CP) structure follows from previous studies [6,12]. To better illustrate the CP positions on Brillouin zone we show the band structure of AlSb in Fig. 2 whose data is borrowed from Ref. [12].

The PM provides a convenient method of accurately reproducing dielectric functions of materials [13,14]. A detailed description of the model is given by Herzinger and Johs [15]. To summarize, ϵ spectra are modeled as sums of ' m ' energy-bounded, Gaussian-broadened polynomials that represent individual CPs. An additional pole P is used to take into account absorption that occurs outside the accessible spectral

range. The general expression for ϵ is

$$\begin{aligned} \epsilon(\omega) &= \epsilon_1(\omega) + i\epsilon_2(\omega) \\ &= 1 + i \sum_{j=1}^m \int_{E_{\min}}^{E_{\max}} W_j(E) \Phi(\omega, E, \sigma_j) dE \\ &\quad + \sum_{j=m+1}^{m+P+1} \frac{A_j}{(\omega)^2 - E_j^2} \end{aligned} \quad (1)$$

where $W_j(E)$ is the joint-density of states of the j th CP. The broadening function Φ is the Kramers–Kronig transform of a Lorentzian or Gaussian. The last term in Eq. (1) represents the contribution of a pole having an amplitude A and energy E to the dielectric function.

The general structure of a ϵ_2 CP lineshape in the PM is shown in Fig. 3. It consists of four parts, each of which is a polynomial. In the present study, regions I and IV are polynomials of second-order, while II and III are fourth-order. The polynomials are defined in Ref. [15]. Five energies and three amplitudes define the break points of the CP lineshape, as shown in Fig. 3. E_C is the energy of the CP. E_L and E_U are the lower and upper limits where ϵ_2 goes to zero, and E_{LM} and E_{UM} join adjacent polynomial regions and thereby control asymmetry. A_{LM} , A , and A_{UM} are the amplitudes at E_{LM} , E_C , and E_{UM} respectively. B , to be used later, is a full-width-half-maximum broadening parameter that is

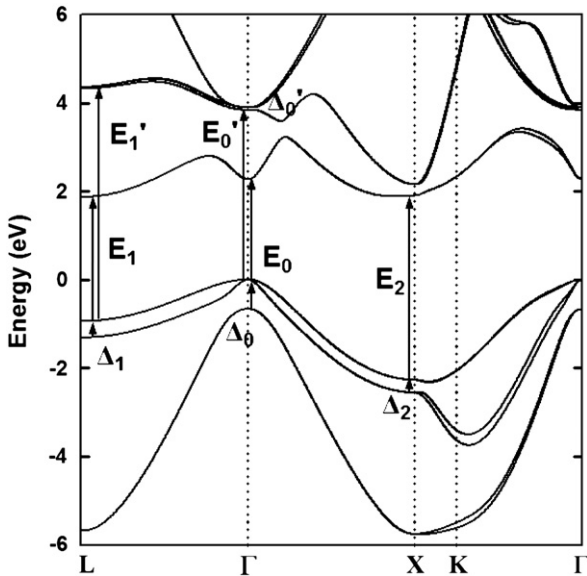


Fig. 2. The band-structure of AlSb. From Ref. [12].

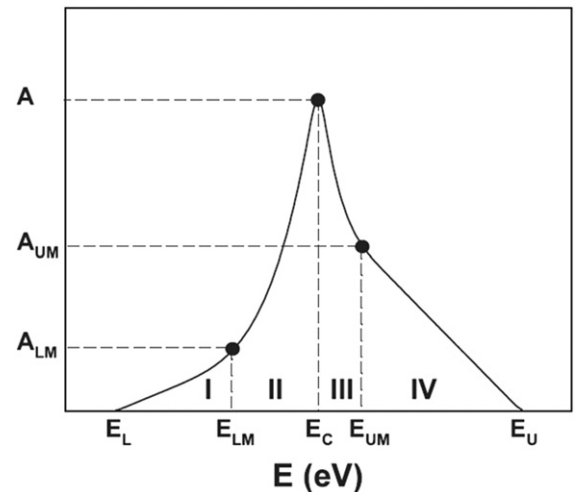


Fig. 3. Structure of a single oscillator in the parametric model, as described in the text.

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