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G.W. Charache

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Spectral Ellipsometry of GaSb: Experiment and Modeling

M. Muñoz ^(a), K. Wei and Fred H. Pollak ^(b,c)

Physics Department and New York State Center for Advanced Technology in Ultrafast
Photonic Materials and Applications

Brooklyn College of the City University of New York

Brooklyn, NY 11210

and

J.L. Freeouf

Interface Studies, Inc.

Katonah, NY 10536

and

G.W. Charache

Lockheed-Martin Corp.

Schenectady, NY 12301

The optical constants $\epsilon(E) [= \epsilon_1(E) + i\epsilon_2(E)]$ of single crystal GaSb at 300K have been measured using spectral ellipsometry in the range of 0.3-5.3 eV. The $\epsilon(E)$ spectra displayed distinct structures associated with critical points (CPs) at E_0 (direct gap), spin-orbit split $E_0 + \Delta_0$ component, spin-orbit split $(E_1, E_1 + \Delta_1)$ and $(E'_0, E'_0 + \Delta'_0)$ doublets, as well as E_2 . The experimental data over the entire measured spectral range (after oxide removal) has been fit using the Holden model dielectric function [Phys. Rev. B 56, 4037 (1997)] based on the electronic energy-band structure near these CPs plus excitonic and band-to-band Coulomb enhancement effects at E_0 , $E_0 + \Delta_0$ and the E_1 , $E_1 + \Delta_1$ doublet. In addition to evaluating the energies of these various band-to-band CPs, information about the binding energy (R_1) of the two-dimensional exciton related to the E_1 , $E_1 + \Delta_1$ CPs was obtained. The value of R_1 was in good agreement with effective mass/ $\vec{k} \cdot \vec{p}$ theory. The ability to evaluate R_1 has important ramifications for recent first-principles band structure calculations which include exciton effects at E_0 , E_1 , and E_2 [M. Rohlfing and S.G. Louie, Phys. Rev. Lett. 81, 2312 (1998); S. Albrecht *et al*, Phys. Rev. Lett, 80, 4510 (1998)].

Our experimental results were compared to other evaluations of the optical constants of GaSb.

- (a) Permanent address: Departamento de Fisica; CINVESTAV; Mexico DF, Mexico
- (b) Also at the Graduate School and University Center of the City University of New York, New York, NY 10036
- (c) E-mail address: FHPBC@CUNYVM.CUNY.EDU

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I. INTRODUCTION

The semiconductor GaSb is of interest from both fundamental and applied perspectives.¹ The spin-orbit splitting of the valence band at the center of the Brillouin zone (BZ) is almost equal to the direct gap (E_0) leading to high hole ionization effects. Among compound III-V semiconductors, GaSb is particularly interesting as a substrate material because its lattice parameter matches solid solutions of various ternary and quaternary III-V compounds whose band gaps cover the spectral range from ~ 0.8 - $4.3 \mu\text{m}$. Also detection at longer wavelengths, 8 - $14 \mu\text{m}$ is possible with intersubband absorption in antimonide based superlattices. From a device point of view, GaSb-based structures have shown potential for application in laser diodes with low threshold voltage, photodetectors with high quantum efficiency, high frequency devices, superlattices with tailored optical and transport characteristics, booster cells in tandem solar cell arrangements for improved efficiency of photovoltaic cells and high efficiency thermophotovoltaic cells.²

However, in spite of its significance, relatively little work has been reported on the optical properties related to the electronic band structure. Both Aspnes and Studna³ and Zollner *et al*⁴ have performed spectral ellipsometry (SE) measurements of the complex dielectric function $\epsilon(E)[=\epsilon_1(E)+i\epsilon_2(E)]$ only in the range of 1.5 - 5.5 eV . The former investigation was at room temperature while the latter study was in the range from 10K - 740K . Patrini *et al*⁵ have published results on the optical constants at room temperature in the range of 0.0025 - 6 eV using a combination of methods including reflectance, transmission, and SE (1.4 - 5.0 eV). Several authors have investigated the optical properties (absorption coefficient, index of refraction) in the region of the fundamental gap.⁶⁻¹¹ Paskove⁸ has presented a model for the optical constants which includes both discrete and continuum exciton contributions at E_0 but not at the E_1 critical point (transitions along the equivalent $\langle 111 \rangle$ directions of the BZ). Adachi¹² has modeled the optical constants (0.5 - 5.5 eV) using the data of Ref. 11 in the vicinity of E_0 and Ref. 3 in the range of 1.5 - 5.5 eV . However, his treatment does not include continuum exciton contributions, i.e., band-to-band Coulomb enhancement effects

(BBCE), at either E_0 or E_1 .

In this paper we report a room temperature SE investigation of $\epsilon(E)$ of single crystal GaSb in the photon energy range of 0.3-5.3 eV. Distinct structures associated with critical points (CPs) at E_0 (direct gap), spin-orbit split $E_0 + \Delta_0$ component, spin-orbit split (E_1 , $E_1 + \Delta_1$) and (E'_0 , $E'_0 + \Delta'_0$) doublets, as well as E_2 were observed. The experimental data over the entire measured spectral range (after oxide removal) has been fit using the Holden model dielectric function¹³⁻¹⁵ based on the electronic energy-band structure near these CPs plus discrete and continuum excitonic effects at E_0 , $E_0 + \Delta_0$, E_1 , and $E_1 + \Delta_1$. The E'_0 , $E'_0 + \Delta'_0$ structures were also included in the analysis. In addition to evaluating the energies of these various band-to-band CPs, it is possible to obtain information about the binding energy (R_1) of the two-dimensional exciton related to the E_1 , $E_1 + \Delta_1$ CPs. The obtained value of R_1 is in reasonable agreement with effective mass/ $\vec{k} \cdot \vec{p}$ theory.¹⁶ The ability to evaluate R_1 has important ramifications for recent first-principles band structure calculations which include exciton effects at E_0 , E_1 , and E_2 .^{17,18}

II. EXPERIMENTAL DETAILS

The sample consisted of bulk GaSb (001) {cut 4° towards [110]}. The optical data in the range of 0.75-5.3 eV [ultraviolet (UV)/visible (VIS)/near infrared (NIR)] was taken using an Instruments SA variable angle ellipsometer. For the interval of 0.3-0.8 eV [mid infrared (MIR)/far infrared (FIR)], a variable angle instrument which used a Fourier Transform Infrared Reflectometer as a light source was employed. Thus, there was some overlap between the two intervals. The UV/VIS/NIR measurements were performed with a 70° incidence angle, and the MIR/FIR measurements were performed with 60° and 70° incidence angles. To remove the surface oxide, an etching procedure was performed on the UV/VIS/NIR ellipsometer with prealigned samples mounted vertically on a vacuum chuck in a windowless cell that maintained the surfaces in a dry nitrogen atmosphere. The details of the etching procedure are given in Ref. 13, except in this study the etch was a 3:1 mixture of HCl:methanol followed by a quick rinse in methanol.

IV. EXPERIMENTAL RESULTS

Shown by the solid lines in Figs. 1(a) and 1(b) are the experimental values of the real $[\epsilon_1(E)]$ and imaginary $[\epsilon_2(E)]$ components of the complex dielectric function, respectively, as a function of photon energy, E . In the ϵ_2 spectrum there is an absorption edge around 0.7 eV, doublet peaks in the range 2.0-2.5 eV, and a large feature with a peak around 4 eV, with some structure on the low energy side around 3.5 eV. However, in contrast to Refs. 3-5 we observe a weak feature at around 1.5 eV.

The solid lines in Figs. 2(a) and 2(b) show the experimental values of $d\epsilon_1(E)/dE$ and $d\epsilon_2(E)/dE$, respectively, as obtained by taking the numerical derivative (with respect to E) of the solid curves in Figs. 1(a) and 1(b), respectively.

The experimental determined real (n) and imaginary (κ) components of the complex index of refraction are displayed in Figs 3(a) and 3(b), respectively, while in Fig. 4 we plot the absorption coefficient, α . The inset of Fig. 4 shows an expanded version of α in the region of the direct gap.

IV. THEORETICAL MODEL

In GaSb the spin-orbit interaction splits the highest lying Γ_{15}^v valence band into Γ_8^v and Γ_7^v (splitting energy, Δ_0) and the Γ_{15}^c conduction band into Γ_7^c and Γ_8^c (splitting energy, Δ_0').¹⁹ The corresponding lowest lying transitions at $\bar{k} = 0$ [three-dimensional (3D) M_0] are labelled E_0 [$\Gamma_8^v(\Gamma_{15}^v) - \Gamma_6^c(\Gamma_1^c)$] and $E_0 + \Delta_0$ [$\Gamma_7^v(\Gamma_{15}^v) - \Gamma_6^c(\Gamma_1^c)$], respectively. The spin-orbit interaction also splits the $L_3^v(\Lambda_3^v)$ valence band into $L_{4,5}^v(\Lambda_{4,5}^v)$ and $L_6^v(\Lambda_6^v)$. The corresponding 2D M_0 CPs are designated E_1 [$L_{4,5}^v(L_3^v) - L_6^c(L_1^c)$ or $\Lambda_{4,5}^v(\Lambda_3^v) - \Lambda_6^c(\Lambda_1^c)$] and $E_1 + \Delta_1$ [$L_6^v(L_3^v) - L_6^c(L_1^c)$ or $\Lambda_6^v(\Lambda_3^v) - \Lambda_6^c(\Lambda_1^c)$], respectively. The E_0' , $E_0' + \Delta_0'$ features correspond to transitions from the Γ_8^v valence to the spin-orbit split Γ_7^c/Γ_8^c conduction levels and related transitions along $\langle 100 \rangle$.¹⁹ The E_2 feature is due to transitions along $\langle 110 \rangle$ (Σ) or near the X point.¹⁹

The data near the E_0 band gap were fit to a function which contains Lorentzian

broadened (a) discrete excitonic (DE) and (b) 3D M₀ BBCE contributions.¹³⁻¹⁵ Both Refs. 7 and 15 demonstrate that even if the E₀ exciton is not resolved, the Coulomb interaction still affects the band-to-band lineshape. Thus, $\epsilon_2(E)$ is given by:¹³⁻¹⁵

$$\epsilon_2(E) = \frac{A}{E^2} \left\{ \text{Im} \left\{ \left[\frac{2R_0}{(E_0 - R_0) - E - i\Gamma_0^{\text{ex}}} + \frac{2R_0}{(E_0 - R_0) + E + i\Gamma_0^{\text{ex}}} \right] + \int_{-\infty}^{\infty} \left[\frac{\theta(E' - E_0)}{1 - e^{-2\pi z_1(E')}} - \frac{\theta(-E' - E_0)}{1 - e^{-2\pi z_2(E')}} \right] \frac{dE'}{E' - E - i\Gamma_0} \right\} \right\} \quad (1)$$

where A is a constant, E₀ is the energy of the direct gap, R₀ is the effective Rydberg energy [= (E₀ - E₀^{ex})], Γ_0^{ex} is the broadening of the exciton, Γ_0 is the broadening parameter for the band-to-band transition, $z_1(E) = [R_0/(E - E_0)]^{1/2}$, $z_2(E) = [R_0/(-E - E_0)]^{1/2}$ and $\theta(x)$ is the unit step function. In Eq. (1) the quantity $A \propto (R_0)^{1/2} \mu_0^{3/2} |P_0|^2$ where μ_0 is the reduced interband effective mass at E₀, and P₀ is the matrix element of the momentum between $\Gamma_8^v - \Gamma_6^c$. The terms in the square brackets and under the integral in Eq. (1) correspond to the DE and BBCE (continuum exciton) contributions, respectively. Since the DE is not resolved, we take $\Gamma_0^{\text{ex}} = \Gamma_0$.

For the E₀ + Δ₀ transition a function similar to Eq. (1) was used, with A → B, E₀ → E₀ + Δ₀, R₀ → R_{so} and $\Gamma_0 \rightarrow \Gamma_{so}$.

For the E₁ CP, $\epsilon_2(E)$ is written as:¹³

$$\epsilon_2(E) = \frac{C_1}{E^2} \left\{ \text{Im} \left\{ \left[\frac{4R_1}{(E_1 - R_1) - E - i\Gamma_{E_1}} + \frac{4R_1}{(E_1 - R_1) + E + i\Gamma_{E_1}} \right] + \int_{-\infty}^{\infty} \left[\frac{\theta(E' - E_1)}{1 + e^{-2\pi z_3(E')}} - \frac{\theta(-E' - E_1)}{1 + e^{-2\pi z_4(E')}} \right] \frac{dE'}{E' - E - i\Gamma_{E_1}} \right\} \right\} \quad (2)$$

where C_1 is a constant, E_1 is the energy of the gap, R_1 is the 2D Rydberg energy, Γ_{E_1} is the broadening parameter for both the exciton and band-to-band transition, $z_3(E) = [R_1/4(E-E_1)]^{1/2}$, and $z_4(E) = [R_1/4(-E-E_1)]^{1/2}$.

For the $E_1 + \Delta_1$ CP a function similar to Eq. (2) was used with $C_1 \rightarrow C_2$ and $E_1 \rightarrow E_1 + \Delta_1$, $\Gamma_{E_1} \rightarrow \Gamma_{E_1 + \Delta_1}$, etc. In practice the same 2D rydberg (R_1) was used for both the E_1 and $E_1 + \Delta_1$ CP features.

Reference 13 has listed relatively simple analytical expressions for $\epsilon(E)$ for E_0 , $E_0 + \Delta_0$, E_1 , and $E_1 + \Delta_1$ based on the above equations.²⁰

The nature of the E'_0 , $E'_0 + \Delta'_0$, and E_2 features is more complicated in relation to $E_0/E_0 + \Delta_0$ and $E_1/E_1 + \Delta_1$ since the former do not correspond to a single, well-defined CP.¹⁹ Therefore, each was described by a damped harmonic oscillator term:^{8,12,13}

$$\epsilon(E) = \frac{F(j)}{[1 - \chi^2(j)] - i\gamma(j)\chi(j)} \quad \text{with } j = E'_0, E'_0 + \Delta'_0, \text{ or } E_2 \quad (3)$$

where $F(j)$ is the amplitude, $\chi(j) = E(j)/E$, and $\gamma(j)$ is a dimensionless damping parameter.

The fact that Ref. 17 found that E_2 , like the $E_0/E_0 + \Delta_0$ and $E_1/E_1 + \Delta_1$ CP features, contains an excitonic component provides some justification in using a damped oscillator term for this structure.

A constant, $\epsilon_{1\infty}$, was added to the real part of the dielectric constant to account for the vacuum plus contributions from higher lying energy gaps (E'_1 , etc.).^{12,13} This quantity should not be confused with the high frequency dielectric constant $\epsilon(\infty)$.

The dotted curves in Figs. 1(a) and (b) are fits to the experimental data using the above formulas. Since the exciton at $E_0/E_0 + \Delta_0$ has not been resolved R_0 ($= 1.6$ meV) was taken from Ref. 21. Because of the large number of fitting parameters values for the various gaps and their broadening parameters were initialized from values obtained by numerically taking the first-derivative of the dielectric functions with respect to energy.

The details of this approach are given in Refs. 13-15. The final values of the different energies are indicated by arrows in the various figures. All relevant parameters are listed in Table I. The corresponding values of $d\epsilon_1(E)/dE$ and $d\epsilon_2(E)/dE$, are shown by the dotted lines in Figs. 2(a) and 2(b), respectively. These were obtained from our own analytical form for the derivatives of the $E_0/E_0 + \Delta_0$ CPs, the analytical expression of Eq. (A16) of Ref. 13 for the $E_1/E_1 + \Delta_1$ CPs, and the derivatives of Eq. (3). Overall there is very good agreement between experiment and theory for both the dielectric function [Figs. 1(a) and 1(b)] and the first derivative [Figs. 2(a) and 2(b)].

IV. DISCUSSION OF RESULTS AND SUMMARY

The results of this experiment are in good agreement with prior studies of the optical constants of GaSb.³⁻¹¹ Figures 1(a) and 1(b) correspond closely to the relevant data of Refs. 3 and 4 in the range of 1.5-5.3 eV and Ref. 4 in the range of 0.3-5.3 eV, except they have not observed E'_0 , $E'_0 + \Delta'_0$. The real component of the index of refraction (n) in the vicinity of E_0 , as displayed in Fig. 3(a), corresponds to the works of Paskov⁸ and Muñoz Uribe.¹⁰ The lineshape of our absorption coefficient in the range of 0.60-0.80 eV (inset of Fig. 4) is similar to that presented in Ref. 7 in this region. However, our value of $\alpha \approx 10^4 \text{ cm}^{-1}$ in the plateau region above about 0.75 eV is about a factor of two larger in relation to Ref. 7.

Table I shows that the values of the various energy gaps obtained in this investigation, i.e., E_0 , $E_0 + \Delta_0$, $E_1 - R_1$, $(E_1 + \Delta_1) - R_1$, etc. are in good agreement with other selected experiments. An extensive list of these energies obtained by various methods (at different temperatures) is compiled in Ref. 4. There is some scatter in the experimental data, probably due to differences in sample quality, surface preparation and/or lineshape analysis.

The optical constants ϵ_1/ϵ_2 for GaSb³⁻⁵ as well as other diamond-and zincblende-type (DZB) semiconductors, over an extended range, have been investigated by a number of authors,^{13-15,22-27} mainly using SE. However, Aspnes^{3,27} and Cardona and co-workers^{4,23} did not model their results, although the latter fit derivative spectra. In Ref. 12 Adachi

used a model in which the E_0 , $E_0 + \Delta_0$, E_1 , and $E_1 + \Delta_1$ CPs are represented by only Lorentzian broadened band-to-band single particle (BBSP) expressions, i.e., no DE. As will be discussed below the optical structure associated with the $E_1/E_1 + \Delta_1$ CPs is primarily excitonic. In later works Adachi did include DE terms but with separate amplitude factors for the DE and BBSP contributions.^{24,25} However, in the DE plus BBCE approach, for a given CP both terms must have the same strength parameter, e.g., A (E_0) and C_1 (E_1), as indicated in Eqs. (1) and (2), respectively. In Paskov's treatment⁸ the BBCE contribution is included at E_0 but not E_1 .

The inadequacy of the BBSP approach at E_0 has been clearly demonstrated in Refs. 8 and 15. These works showed that in the region of the fundamental gap the BBCE term gave a better fit to experimental values of α and $d\epsilon_2/dE$, respectively, in relation to the BBSP expression. The deficiency of the BBSP model also is illustrated by Fig. 3 in Ref. 28. The fit expressions for the DE plus BBSP are considerably lower than the experimental data, particularly for the 20K measurement. The effect of the BBCE term in relation to the BBSP expression is to both increase the oscillator strength and change the lineshape from a 3D M_0 singularity to one which approximates a 2D M_0 function (within about 8-10 R_0 from E_0). Kim and Sivinathan²⁶ used DE plus BBSP terms with both Lorentzian and Gaussian broadening (increased fitting parameters). However, Aspnes²⁷ found no evidence for Gaussian broadening based on a Fourier analysis of the optical constants of CdTe.

Due to the relatively large values of R_1 (≈ 30 -300 meV)¹³⁻¹⁵, the optical structure associated with the E_1 , $E_1 + \Delta_1$ CPs in DZB semiconductors are actually mainly the excitonic features $E_1 - R_1$, $(E_1 + \Delta_1) - R_1$, respectively, as denoted in the figures. Almost all prior optical^{3-5,22-27} and modulated^{29,30} optical studies have incorrectly labelled these excitonic features as " E_1 , $E_1 + \Delta_1$ ".

Our value of R_1 (32 ± 3 meV) is in good agreement with the effective mass/ $\overline{k} \cdot \overline{p}$ theory of Ref. 16. According to this approach:

$$R_1 \propto \mu_1^{-1} / \epsilon^2(\infty) \quad (4a)$$

where $\mu_{\perp}$ is the perpendicular reduced interband effective mass related to E_1 and $\epsilon(\infty)$ is the high frequency dielectric function. From a three band $\vec{k} \cdot \vec{p}$ formula the perpendicular conduction ($m_{c,\perp}^*$) and valence ($m_{v,\perp}^*$) effective masses (in units of the free electron mass) are given by:

$$\frac{1}{m_{c,\perp}^*} = 1 + E_p \left(\frac{1}{E_1} + \frac{1}{E_1 + \Delta_1} \right) \quad (4b)$$

$$\frac{1}{m_{v,\perp}^*} = 1 - \frac{E_p}{E_1} \quad (4c)$$

where E_p is proportional to the square of the magnitude of the matrix element of the perpendicular momentum between the corresponding conduction and valence bands. In GaSb $m_{c,\perp}^* = 0.12$ (in units of the free electron mass)¹. Hence, using the experimental values of E_1 and $E_1 + \Delta_1$, E_p was calculated from Eq. (4b) and $m_{v,\perp}^*$ was determined from Eq. (4c), to obtain $\mu_{\perp} = 0.088$.

For CdTe $R_1 = 145$ meV, both experimentally¹⁵ and from the considerations of Ref. 16. Therefore, using $\epsilon(\infty) = 7.05$ and $\mu_{\perp} = 0.15$ for CdTe¹⁶ and $\epsilon(\infty) = 14.4$ for GaSb¹ we find $R_1(\text{GaSb}) \sim 25$ meV, in reasonably good agreement with our experimental number of 32 ± 3 meV.

The ability to measure R_1 has considerable implications for band structure calculations, both empirical¹⁹ and first principles.^{17,18} In the former case band structure parameters, e.g., pseudopotential form factors, are determined mainly by comparison with optical and modulated optical experiments, including the " E_1 , $E_1 + \Delta_1$ " features. Therefore, the band-to-band energies are too low by an amount R_1 . Recently Rohlfing and Louie have published a first-principles calculation of the optical constants of GaAs, including excitonic effects.¹⁷ Using this formalism they have also calculated R_0 . Their

approach also makes it possible to evaluate R_1 from first-principles.³¹ Albrecht *et al*¹⁸ also have recently presented an *ab initio* approach for the calculation of excitonic effects in the optical spectra of semiconductors and insulators. However, to date they have presented results for only Si.

In summary we have measured the room temperature complex dielectric function of bulk GaSb in the extended range of 0.3-5.3 eV using SE. Distinct structures related to CPs associated with the direct gap, spin-orbit split $E_0 + \Delta_0$, spin-orbit split (E_1 , $E_1 + \Delta_1$) and (E'_0 , $E'_0 + \Delta'_0$) doublets, and E_2 have been observed. The $E_0 + \Delta_0$ feature has not been reported in previous SE investigations. The experimental data over the entire measured spectral range has been fit using the Holden model dielectric function based on the electronic energy-band structure near these CPs plus DE and BBCE effects at E_0 , $E_0 + \Delta_0$, E_1 , and $E_1 + \Delta_1$. In addition to measuring the energies of these various band-to-band CPs, we have evaluated the 2D exciton binding energy R_1 ($=32 \pm 3$ meV), in reasonable agreement with effective mass/ $\vec{k} \cdot \vec{p}$ theory. The ability to determine R_1 has important ramifications for recent first-principles band structure calculations which have included excitonic effects at various critical points.

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Table I. Values of a number of relevant parameters obtained in this experiment. Also listed are selected values of the energy gaps, broadening parameters, etc. from other investigations.

Parameter	This experiment	Other selected experiments
E_0 (eV)	0.724 ± 0.005	$0.725^{(a)}$ $0.72^{(b)}$
A (eV ²)	0.10 ± 0.005	
R_0, R_{so} (meV)	$1.6^{(c,d)}$	$1.6^{(d)}$
Γ_0, Γ_0^{ex} (meV)	15 ± 5	
$E_0 + \Delta_0$ (eV)	1.52 ± 0.02	$1.52^{(d)}$ $1.46^{(b)}$
B (eV ²)	0.20 ± 0.01	
$\Gamma_{so}, \Gamma_{so}^{ex}$ (meV)	15 ± 5	
$E_1 - R_1$ (eV)	2.047 ± 0.003	$2.03^{(e,f)}$ $2.052^{(f,g)}$ $2.05^{(b,f)}$
C_1 (eV ²)	22.0 ± 0.07	
R_1 (meV)	32 ± 3	
$\Gamma_{E_1}, \Gamma_{E_1}^{ex}$ (meV)	95 ± 10	$60^{(f)}$
$(E_1 + \Delta_1) - R_1$ (eV)	2.488 ± 0.005	$2.49^{(e,h)}$ $2.494^{(g,h)}$ $2.50^{(b,h)}$

$\Gamma_{E_1+\Delta_1}, \Gamma_{E_1+\Delta_1}^{\text{ex}}$	220 ± 10	$70^{(g)}$
$C_2 \text{ (eV}^2\text{)}$	30.0 ± 0.01	
$E_0' \text{ (eV)}$	3.40 ± 0.01	$3.27^{(e)}$
$F(E_0')$	1.20 ± 0.01	
$\gamma(E_0')$	230 ± 10	
$E_0' + \Delta_0' \text{ (eV)}$	3.79 ± 0.02	$3.56^{(e)}$
$F(E_0' + \Delta_0')$	1.03 ± 0.01	
$\gamma(E_0' + \Delta_0')$	170 ± 10	
$E_2 \text{ (eV)}$	4.100 ± 0.005	$4.20^{(e)}$ $4.20^{(g)}$ $4.0^{(b)}$
$F(E_2)$	1.87 ± 0.01	$5.69^{(b)}$
$\gamma(E_2)$	125 ± 10	$290^{(b)}$
$\epsilon_{1\infty}$	1.97	$1.0^{(b)}$

- (a) Ref. 1.
- (b) Ref. 12.
- (c) Fixed.
- (d) Ref. 21.
- (e) Ref. 29.
- (f) Incorrectly labelled E_1 .
- (g) Ref. 4.

(h) Incorrectly labelled $E_1 + \Delta_1$.

REFERENCES

1. P.S. Dutta and H.L. Bhat, J. Appl. Phys. **81**, 5821 (1997).
2. G.W. Charache, J.L. Egley, D.M. Depoy, L.R. Danielson, M.J. Freeman, R.J. Dziendziel, J.F. Moynihan, P.F. Baldasaro, B.C. Campbell, C.A. Wang, H.K. Choi, G.W. Turner, S.J. Wojtczuk, P. Colter, P. Sharps, M. Timmons, R.E. Fahey, and K. Zhang, J. Electron. Mat. **27**, 1038 (1998).
3. D.E. Aspnes and A.A. Studna, Phys. Rev. B **27**, 985 (1983).
4. S. Zollner, M. Garriga, J. Humlicek, S. Gopalan, and M. Cardona, Phys. Rev. B **43**, 4349 (1991).
5. M. Patrini, G. Guizzetti, M. Galli, R. Ferrini, A. Bosacchi, S. Franchi, and R. Magnanini, Solid State Comm. **101**, 93 (1997).
6. Z. Bachan, E. Kierzek-Pecold, and J. Kolodziejczak, Phys. Stat. Sol. **42**, K101 (1970).
7. P.P. Paskove, IEEE J. Quant. Electronics **30**, 2771 (1994).
8. P.P. Paskove, J. Appl. Phys. **81**, 1890 (1997).
9. C. Ghezzi, R. Magnanini, A. Parisini, B. Rotelli, L. Tarricone, A. Bosacchi, and S. Franchi, Semicond. Sci. Technol. **12**, 858 (1997).
10. M. Muñoz Uribe, R.S. Miranda, M.B. Zakia, C.F. de Souza, C.A. Riberio, J.H. Clerice, and N.B. Patel, Mat. Sci. and Engin. B **38**, 259 (1996).
11. B.O. Seraphin and H.E. Bennett, in *Semiconductors and Semimetals*, Vol. 3, edited by R.K. Wilardson and A.C. Beer (Academic, New York, 1967) p. 499.
12. S. Adachi, J. Appl. Phys. **66**, 6030 (1989).
13. T. Holden, P. Ram, F.H. Pollak, J.L. Freeouf, B.X. Yang, and M.C. Tamargo, Phys. Rev. B **56**, 4037 (1997).
14. T. Holden, F.H. Pollak, J.L. Freeouf, G.W. Charache, J.E. Raynolds, and C. Geller, *Proc. 4th NREL Thermophotovoltaic Generation of Electricity Conference*, Denver, 1998, ed. T.J. Coutts, J. P. Brenner, and C.S. Allman, AIP Conf. Proc. 460 (American Institute of Physics, Woodbury, 1999), p. 39.
15. K. Wei, F.H. Pollak, J.L. Freeouf, D. Shvydka, and A.D. Compaan, "Optical Properties of $\text{CdTe}_{1-x}\text{S}_x$ ($0 \leq x \leq 1$): Experiment and Modeling", to be published in J. Appl. Phys.
16. Y. Petroff and M. Balkanski, Phys. Rev. B **3**, 3299 (1971).

17. M. Rohlffing and S.G. Louie, Phys. Rev. Lett. **81**, 2312 (1998)
18. S. Albrecht, L. Reining, R. Del Sole, and G. Onida, Phys. Rev. Lett, **80**, 4510 (1998).
19. M.L. Cohen and J.R. Chelikowsky, in *Electronic Structure and Optical Properties of Semiconductors* (Springer, Berlin, 1989).
20. Equation (A13) in Ref. 13 should read $\xi^2(X) = 4(E_f - X)/G$
21. Landolt-Börnstein-Numerical Data and Functional Relationships in Science and Technology, ed. by O. Madelung, M. Schultz, and H. Weiss, Vols. 17a and 17b (Springer, New York, 1982).
22. F.H. Pollak in *1967 International Conference on the II-VI Semiconducting Compounds*, ed. by D.G. Thomas (V.A. Benjamin New York, 1967) p. 552.
23. P. Lautenschlager, M. Garriga, S. Logothetidis, and M. Cardona, Phys. Rev. B **35**, 9174 (1987); P. Lautenschlager, M. Garriga, and M. Cardona, Phys. Rev. B **36**, 4813 (1987).
24. S. Adachi, T. Kimura, and N. Suzuki, J. Appl. Phys. **74**, 3435 (1993); S. Adachi and T. Taguchi, Phys. Rev. B **43**, 9569 (1991).
25. K. Suzuki and S. Adachi, J. Appl. Phys. **83**, 1018 (1998).
26. C.C. Kim and S. Sivinathan, J. Appl. Phys. **78**, 4003 (1995); alos, Phys. Rev. B **53**, 1475 (1996).
27. D.E. Aspnes, Solar Energy Materials and Solar Cells **32**, 413 (1994).
28. S. Adachi, Phys. Rev. B **41**, 1003 (1990).
29. M. Cardona in *Modulation Spectroscopy* (Academic, New York, 1969).
30. F.H. Pollak and H. Shen, Mater. Sci. and Engineering R **10**, 275 (1993).
31. S. Louie, private communication.

FIGURE CAPTIONS

- Fig. 1 The solid and dashed lines are the experimental and fit values, respectively, of the (a) real (ϵ_1) and (b) imaginary (ϵ_2) components of the complex dielectric function of GaSb.
- Fig. 2 The solid and dashed lines are the experimental and fit values, respectively, of (a) $d\epsilon_1/dE$ and (b) $d\epsilon_2/dE$ of GaSb.
- Fig. 3 The solid lines are the experimental values of the (a) real (n) and (b) imaginary (κ) components of the complex index of refraction of GaSb.
- Fig. 4 The solid line is the experimental value of the absorption coefficient, α , of GaSb. The inset shows an expanded version in the region near E_0 .

Fig. 1a

Fig. 2a

Energy (eV)

FIG. 2b

Figure 3.0

Figure 4