Temperature dependence of the L_6^c-Γ_6^c energy gap in gallium antimonide

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Electroreflectance spectra are reported for GaSb near the Γ_8^v-Γ_6^c direct transition and the Γ_8^v-L_6^c indirect transition. At 30 K the L_6^c-Γ_6^c gap is 0.063 eV. The temperature variation of the L_6^c-Γ_6^c gap in the linear region is of the order of -1.8×10^{-4} eV/K^{-1}.

The recent development of high-quality optical fibers in the 1.3-μ wavelength range[1] increases the usefulness of Ge or III-V compounds such as GaInAs, GaInAsP, GaAlSb, and GaAlAsSb (Refs. 2–4) which present energy-gap values well adapted to this wavelength.

Within a systematic study of the GaAlSb system we had to determine precisely the band structure of these compounds, especially the band crossing $\Gamma_6^c - L_6^c$. It was essential for us to know the exact energy-gap values of GaSb and its temperature dependence.

Information on the band structure or GaSb has been obtained from various investigations[5-14]. Experimental evidence has shown that L_6^c local equivalent minima of the conduction band of GaSb was slightly higher in energy than the lowest Γ_6^c minimum. The $L_6^c - \Gamma_6^c$ gap was determined by fitting the experimental data obtained by various transport measurements.[15-21] These investigations have yielded different values of the temperature coefficient of this energy gap ranging from -3×10^{-4} to 1.8×10^{-4} eV K^{-1}.[22-26]

Here we present the first direct measurements of the $\Gamma_8^v - L_6^c$ and $\Gamma_8^v - \Gamma_6^c$ transition energies and their temperature variations, using a heterojunction-barrier electroreflectance technique. Details of the heterojunction barrier[27] and the optical technique are given elsewhere.[27,28] The data are stored in a computer.

In a previous study of the interband masses associated to the $\Lambda_{4,5}^v - \Lambda_6^c$ and $\Lambda_6^v - \Lambda_6^c$ transitions in GaSb (Ref. 14) we had to obtain very-high-purity-single-crystalline material. In this present work we used these crystals, grown by one of us. Crystals were obtained by the Bridgman method from antimony-rich liquid solution at growth rates of 7×10^{-6} cm/s. They are p type, with carrier concentrations 2×10^{16} cm^{-3} and Hall mobility 800 cm^2/V s at room temperature, 10^{15} cm^{-3} and 3800 cm^2/V s at 77 K.

The weak second-order $\Gamma_8^v - L_6^c$ transition was very difficult to observe: The associated structure expected in the 0.9-eV energy range did not appear in our low-field[29,30] electroreflectance spectra in spite of a good sensitivity[27] ($\Delta R/R$) $\sim 7\times10^{-7}$). The necessary electric-field increase induced Franz-Keldysh oscillations[31-35] which could hide the expected signal, but in proper experimental conditions this transition was observed with a signal-to-noise ratio of 2.

Illustration of typical experimental spectra we have obtained are given in Fig. 1. We can observe

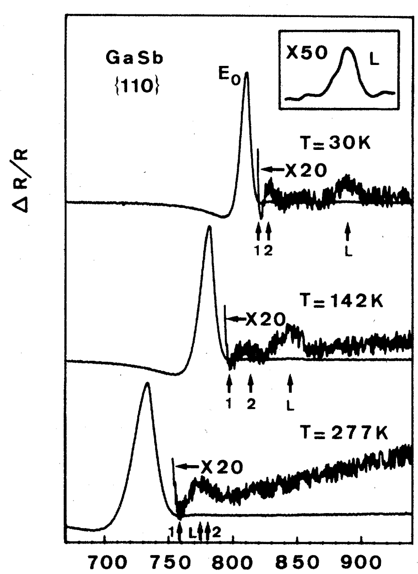

FIG. 1. Electroreflectance spectra of GaSb near the fundamental edge (E_0) and the $\Gamma_8^v - L_6^c$ transition (L) for different temperatures. The first Franz-Keldysh oscillations are noted 1.2. The 30-K computer-filtered spectrum is inserted.

that the $\Gamma_6^v - L_6^c$ transition (noted L) is quite well separated at low temperature, while its high-temperature proximity combines it with the Franz-Keldysh oscillations associated to $\Gamma_8^v - \Gamma_6^c$ transition (noted E_0). We have verified the nondependence of this transition-energy position on the applied electric field. The offset we observe at high energies is due to the large $\Lambda_{4,5}^v - \Lambda_6^c$ transition (E_1) located at 2.19 eV.[13,14]

To determine precisely the structure of the L transition from our experimental data we first subtracted from the experimental spectra the theoretical electroreflectance spectra with calculated Franz-Keldysh oscillations associated to E_0, and the calculated offset attributed to the E_1 transition. On the FFT (fast Fourier transform) of the obtained spectra we have eliminated the high-frequency component. The inverse Fourier transform of this modified FFT represented the exact spectrum attributed to the L transition with a signal-to-noise ratio better than the initial spectrum (see insert in Fig. 1).

From the energy value of the peak obtained by this method we can determine the exact $\Gamma_6^v - L_6^c$ transition-energy gap, subtracting from the observed peak the 17-meV value corresponding to the GaSb LA_E phonon[36] responsible for the main structure in phonon-assisted indirect transition.[37] The $\Gamma_6^v - L_6^c$ gap at 30 K is 63 meV.

Figure 2 represents the temperature dependence of the E_0 and L transitions. The E_0 measurements have been deduced from low-field electroreflectance spectra and the precision of the results appears better than that related to the high-field electroreflectance measurements of the weak L structure. We have also reported in this figure the variations of the first Franz-Keldysh oscillations (noted as 1 and 2 on Fig. 1) energy positions to illustrate that there is no confusion between these oscillations and the L structure.

A least-squares fit in the linear range (100, 300 K) gives

$$\frac{dE_0}{dT} = -3.5\times10^{-4}\ \text{eV/K},$$

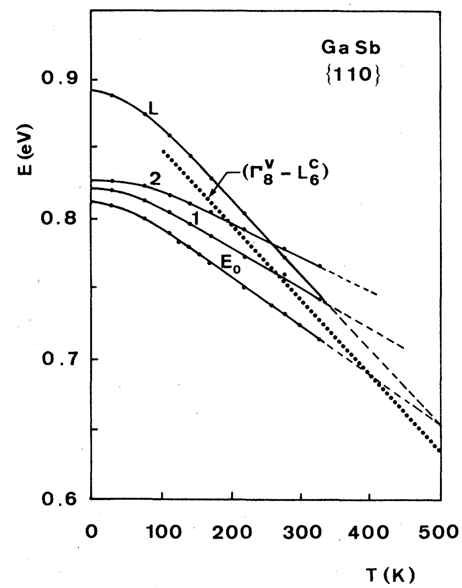

FIG. 2. Temperature variation of the fundamental edge (E_0) of GaSb, the first Franz-Keldysh oscillations and the observed $\Gamma_8^v - L_6^c$ transition (L). The dotted line represents the temperature variation of the $\Gamma_8^v - L_6^c$ gap.

$$\frac{dL}{dT} = -5.3\times10^{-4}\ \text{eV/K},$$

thus we can deduce $d(L_6^c - \Gamma_6^c)/dt = -1.8\times10^{-4}$ eV/K.

The Γ and L minima conduction bands are projected to equalize at 401 K.

Our dE_0/dt value is in good agreement with previous theoretical[38] and experimental[39] results. The other existing studies of the $L_6^c - \Gamma_6^c$ temperature coefficient were based upon a fitting of different magnetotransport measurements; our results stem from a direct measurement and yield greater accuracy.

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