Photomodulated transmittance of GaBiAs layers grown on (0 0 1) and (3 1 1)B GaAs substrates

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A B S T R A C T
In this work, photomodulated transmittance (PT) has been applied to investigate the energy gap of GaBiAs layers grown on (0 0 1) and (3 1 1)B GaAs substrates. In PT spectra, a clear resonance has been observed below the GaAs edge. This resonance has been attributed to the energy gap-related absorption in GaBiAs. The energy and broadening of PT resonances have been determined using a standard approach in electromodulation spectroscopy. It has been found that the crystallographic orientation of GaAs substrate influences on the incorporation of Bi atoms into GaAs and quality of GaBiAs layers. The Bi-related energy gap reduction has been determined to be ~90 meV per percent of Bi. In addition to PT spectra, common transmittance spectra have been measured and the energy gap of GaBiAs has been determined from the square of the absorption coefficient plot.

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Dilute bismides, i.e. Ga(1−x)Bi x As layers with a few percent of Bi atoms, attract much attention because of their unusual fundamental properties [1–6], including a large bandgap reduction (~90 meV per percent of Bi) and a strong enhancement of the spin orbit splitting due to incorporation of Bi. These properties make this material system an attractive candidate to develop GaAs-based applications for long-wavelength optoelectronics as well as for spintronics. From the technological point of view, this material system is still in the first stage of the optimization of growth conditions. The growth of epitaxial layers on high-index planes represents a step forward in semiconductor material engineering, as it offers an additional degree of freedom to develop applications with modified properties with respect to the conventional (0 0 1)-growth devices. In general, the use of non-(0 0 1) substrates can influence growth, impurity incorporation, electronic properties, lasing performance and piezoelectric effects. In the case of dilute nitrides (an analogous system to dilute bismides [6,7]), it has been shown that the nitrogen incorporation exhibits some dependence on the crystallographic orientation of GaAs substrates [8]. Recently, a much larger effect has been observed in the case of GaBiAs [9]. In this paper, we have applied photomodulated transmittance to study the energy gap and optical quality of GaBiAs layers grown on (0 0 1) and (3 1 1)B GaAs substrates at the same growth conditions.

Photomodulated transmittance (PT) is known as a nondestructive and contactless technique to investigate optical transitions in semiconductor structures [10,11]. The derivative nature of this technique emphasizes spectral features, which are associated with interband transitions in semiconductor structures, and suppresses uninteresting background effects. Also weak features that may not have been detected in the absolute spectra are often enhanced and a large number of sharp spectral features can be observed even at room temperature.

GaBiAs 0.1−x layers were grown by molecular beam epitaxy (MBE) on semi-insulating (0 0 1) and (3 1 1)B GaAs substrates at a growth temperature of ~350 °C with different As to Ga flux ratios. The growth was performed in a specially designed MBE reactor (see Ref. [12] for details). Atomic Ga and Bi were used as group-III and group-V sources, respectively, while As in the form of dimers (As 2) was produced by using a two-zone purpose made cell. Other
relevant details of growth conditions are given in Ref. [9]. For this paper, two samples have been selected: one grown on a (001) GaAs substrate and a second one grown on a (311)B GaAs substrate. For the two samples, the beam equivalent pressure for Ga, Bi and As flux was $\sim 9 \times 10^{-7}$, $1.2 \times 10^{-7}$ and $8.0 \times 10^{-6}$ Torr, respectively. Bi concentration has been determined by high-resolution X-ray diffraction measurements to be 3.0% and 3.3% in the (001) and the (311)B epilayers, respectively. The nominal thickness of the GaBiAs epilayers is 1 $\mu$m. A conventional experimental set-up with a tungsten halogen lamp (250 W) as a probe light source, a 0.55 m monochromator and an InGaAs pin photodiode was applied for obtaining transmittance and PT spectra. The pump beam for PT was provided by the 532 nm line of a frequency doubled Nd:YAG (yttrium–aluminum–garnet) laser. Phase sensitive detection of transmittance and PT signal was made using a lock-in amplifier.

Fig. 1 (a) and (b) shows transmittance and PT spectra for GaBiAs layers grown on (001) and (311)B GaAs substrates, respectively. In the case of transmittance spectra, a strong absorption in GaAs substrate is visible above 1.4 eV. In addition, some changes in transmittance spectra are visible at $\sim 1.2$ eV. They are much better visible in PT spectra due to the differential character of this technique. The resonance in PT spectra was analyzed using the low-field electromodulation Lorentzian line shape functional form [13,14]:

$$\Delta T(E)/T = \left[ \sum_{j=1}^{n} C_j e^{i\beta_j (E - E_j + i\Gamma_j)} \right].$$

where $n$ is the number of the optical transitions and spectral functions used in the fitting procedure, $C_j$ and $\beta_j$ are the amplitude and phase of the line shape, and $E_j$ and $\Gamma_j$ are the energy and the broadening parameter of the transitions, respectively. The term $m_j$ is assumed to be equal to 3, which is very similar to the third derivative Gaussian lineshape, i.e. the most appropriate lineshape for highly broadened resonances corresponding to both band-to-band and/or excitonic transitions. The fitting curves are shown by thick gray lines in Fig. 1 together with the modulus of the individual resonance (dashed lines) obtained according to Eq. (2):

$$\Delta \rho_j(E) = \frac{|C_j|}{[(E - E_j)^2 + \Gamma_j^2 m_j^2/2]},$$

with parameters taken from the fit.

Comparing PT spectra and modulus of PT resonances for GaBiAs layers grown on the two different crystallographic orientation of GaAs substrate, it is clearly visible that for the layer grown on (001) GaAs substrate the PT resonance is narrower and observed at higher energy. It means that for this orientation of GaAs substrate, the incorporation of Bi atoms is smaller but the quality of GaBiAs layer is better. Higher Bi concentration in GaBiAs layers grown on (311)B GaAs substrate is confirmed by high resolution X-ray diffraction measurements [9].

The energy gap of GaBiAs layers has been also determined from the square of the absorption coefficient $\alpha^2$ around the band-gap edge (see Figs. 2 and 3). These curves were obtained from conventional optical transmission measurements, which are shown in Fig. 1. For the two samples, $\alpha^2$ displays an almost linear dependence on photon energy $E$, which is a consequence of the direct band gap of GaBiAs. By extrapolating the linear part of $\alpha^2(E)$ to 0, the energy gap is obtained. Some departures from the linear dependence are associated with the tail of density of states in GaBiAs. Figs. 2 and 3 show a comparison of PT spectra with the $\alpha^2$ curves. It is clearly visible that the tail of density of states (TDOS) influences the analysis of $\alpha^2$ curves. The significant TDOS...
appears in this system due to defect states located near the conduction and valence bands, see sketch in Fig. 2. It is expected that these defects are associated with the low growth temperature and/or incorporation of Bi atoms into GaAs. In the case of GaBiAs layer grown on (001) GaAs substrate, the TDOS is small and energy gap determined from PT spectrum (1.195 eV) and $\alpha^2$ plot (1.2 eV) are almost the same. In the case of the GaBiAs layer grown on a (311)B GaAs substrate, the tail of density of states is much higher and therefore the energy gap determined from $\alpha^2$ plot (1.15 eV) is smaller than the energy gap determined from PT spectrum (1.18 eV). Taking into account the TDOS, it has been concluded that the energy gap observed in transmittance spectrum ($\alpha^2$ plot) is the same within the experimental error as the energy gap determined from PT spectrum.

In conclusion, it has been shown that the incorporation of Bi atoms into GaAs reduces the energy gap (~80 meV per percent Bi at x~0.03). This incorporation depends on the crystallographic orientation of GaAs substrate. For samples studied in this paper (GaBiAs layers grown on (001) and (311)B GaAs substrates), it has been observed that Bi concentration is higher (energy gap is smaller) for GaBiAs layers grown on (311)B GaAs substrate. A significant tail of density of states has been observed in $\alpha^2$ plots for the two GaBiAs layers grown on different crystallographic orientation of GaAs substrates.

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