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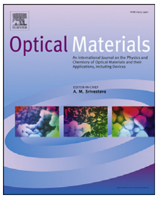

Below-band-gap absorption in undoped GaAs at elevated temperatures

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ABSTRACT

This paper presents results of measurements of optical absorption in undoped epitaxial GaAs for photon energies below the band gap. Absorption spectra were determined from transmission spectra of a thin GaAs layer at several temperatures between 25 °C and 205 °C. We optimized our experiment to investigate the long-wavelength part of the spectrum, where the absorption is relatively low, but significant from the point of view of applications of GaAs in semiconductor lasers. Absorption of 100 cm^{-1} was observed over 30 nm below the band gap at high temperatures.

1. Introduction

Gallium arsenide is one of the most important materials for optoelectronics. Its properties has been studied for many years, and many of them are known with a good accuracy, especially at room and low temperatures. On the other hand, even as fundamental parameters as band gap, are still known with a limited accuracy at temperatures higher than room temperature. This also applies to optical absorption which is a crucial parameter in light-emitting or light-absorbing devices. Recently, methods to increase light absorption in solar cells by nano-structuring the surface of a thin GaAs layer have been studied [1,2]. On the other hand, in light-emitting devices, such as lasers, absorption of the emitted radiation should be avoided. Although it is well-known that semiconductor materials strongly absorb photons whose energies exceed the material's band gap, also photons of energies slightly below the band gap can be absorbed. In the absorption spectrum it is manifested by the presence of so called *Urbach tail* [3] which can play a significant role, especially in light emitting devices in which the emitted wavelength does not follow the thermal reduction of band gap of the gain material, and where temperature inside the device can be high (over 100 °C). A good example of such a device is the Vertical External Cavity Surface Emitting Laser (VECSEL). Due to its short optical cavity, the emission wavelength is determined by refractive indices and dimensions of the materials in the optical cavity rather than by the band gap. Active region temperatures can be higher than 100 °C [4–6], because VECSELs are usually high-power devices, often pumped with powers of tens of Watts, operating without cryogenic cooling. Gallium arsenide is widely used in such devices operating at wavelengths around 1 μm, as the barrier for quantum wells, like in other semiconductor lasers emitting in this spectral region. It is usually assumed that GaAs in such barriers or in distributed Bragg reflectors (DBRs) does not absorb the emitted radiation. However, even relatively low absorption of the order of a few tens of cm^{-1} can significantly worsen the device's performance.

In this paper we show measurements of absorption of undoped, epitaxial GaAs, below the band gap, up to the value of 5000 cm^{-1} at elevated temperatures up to 205 °C. Additionally, one measurement at room temperature has been performed, in order to verify our method by comparing the results with available room-temperature data. Although the Urbach tail has been analyzed even at higher temperatures [7–9], we have not found

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experimental data concerning high-purity epitaxial GaAs reaching so high absorption values.

2. Experiment and results

In order to observe absorption over 1000 cm^{-1} in transmittance spectra a thin sample is necessary. We also wanted our sample to be made from GaAs only, in order to avoid any impact of other materials on our transmittance spectra. Because thin samples are very fragile, we needed a sample thicker than 10 μm. Our sample was prepared in the following way. A 30-nm thick etch-stop layer and a ~14 μm thick layer of GaAs were deposited on a 2-inch semi-insulating GaAs substrate using molecular beam epitaxy (MBE). Because of the non-uniformity of the growth over the wafer [10], the exact thickness of the measured sample was determined from the optical measurements described later. From the wafer a 2×2 cm chip was cut and then the sample epitaxial side was metalized with 30 nm of Ti and 50 nm of Au leaving a window of diameter of 3 mm in the center of the chip. In the next step the sample was lapped and then chemo-mechanically polished to 100 μm of thickness. Cleaned and thinned chip was protected with a photoresist leaving a window in the chip center on the substrate side. The unprotected GaAs substrate was etched away at room temperature in a 4:1 solution of 50% citric acid and H_2O_2. Then the AlAs etch-stop layer was etched with 1.5% HF leaving the GaAs epitaxial layer in the window. The sample was bonded with a die-bonder to a 5 cm×10 cm copper plate with a 2 μm indium layer in such a way that the etched part of the sample overlapped a hole drilled in the plate. A cross-section of the plate with the sample is presented in Fig. 1. As a result, we obtained a layer of epitaxial GaAs for transmittance spectra measurements. The metal plate was equipped with an electric heater and a Pt100 thermistor to control the temperature of the plate. We assume that it is also the sample's temperature.

The transmittance spectra were collected in the following way. The sample was illuminated by a standard halogen lamp. The transmitted light went through a single-grating monochromator of focal length of 0.55 m, and detected by a silicon photodiode. The probing beam was additionally mechanically chopped at a frequency of 275 Hz and a phase sensitive detection was applied using a lock-in amplifier.

Because our sample was thin and its both surfaces were smooth, we observed Fabry-Pérot oscillations as in Fig. 2. When the refractive index dispersion is known with a very good accuracy, it is possible to use these oscillations to determine the sample's thickness. Using the dispersion relations presented in Ref. [11], and the model described further in this section, we got a very accurate reproduction of the oscillations at room temperature, as it can be seen in Fig. 2, assuming the sample's thickness of 13.94 μm. Both the period of the oscillation and the positions of the minima and maxima fit the experiment very precisely which is an indication of a high accuracy of the determination of the thickness and the dispersion function. The oscillations disappear at shorter wavelengths, where the absorption is big enough to attenuate the radiation reflected inside the sample. The region at longer wavelengths, where the measured spectrum fits the theoretical relations very well, we treat as the reference for further absorption determination. This means that we assume that absorption is 0 in this region. The Fabry-Pérot oscillations in transmittance spectrum are described by the following formula:

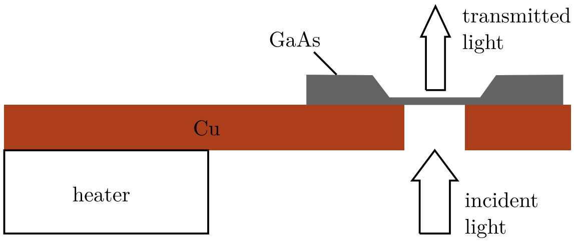

Fig. 1. Schematic cross-section of the metal plate with the sample and the electric heater.

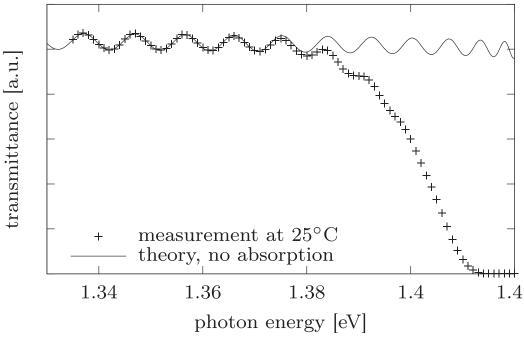

Fig. 2. The measured transmittance spectra at 25 °C and the theoretical spectrum given by equation (1) for a non-absorbing material. The refractive index values are taken from Ref. [11]. The thickness of the sample is 13.94 μm.

$$T(k_0) = \frac{4|n(k_0)|^2}{\left|(n^2(k_0)+1)\sinh(ink_0d) + 2n\cosh(ink_0d)\right|^2} \tag{1}$$

where T is transmittance, k_0 is (vacuum) wave number, n is refractive index (complex in general), and d is the sample's thickness. This formula describes transmittance for perfectly monochromatic coherent radiation. In practice, measured oscillations do not fulfill these idealized conditions. The problem of more realistic theoretical description has been analyzed, for instance in paper [12]. However, we used a different approach. The real spectrum can be considered a convolution of the function (1) and a function describing the spectrum of the radiation leaving the monochromator, for instance a Gaussian function $N(k_0,\sigma)$, where σ is standard deviation:

$$\tilde{T}(k_0) = T(k_0)*N(k_0,\sigma) \tag{2}$$

Function T is periodical (assuming constant n), so can be written as a Fourier series:

$$T(k_0) = A_0 + \sum_{l=1}^{\infty}(S_l\sin(l\xi k_0) + C_l\cos(l\xi k_0)) \tag{3}$$

Using the Fourier transform based method of calculating convolution, we obtain the following formula for $\tilde{T}$:

$$\tilde{T}(k_0) = A_0 + \sum_{l=1}^{\infty}\exp\left(-2(l\pi\xi\sigma)^2\right)(S_l\sin(l\xi k_0) + C_l\cos(l\xi k_0)) \tag{4}$$

From the above formula it can be easily deduced that the amplitude of oscillations is reduced (compared with the function T) and higher harmonics are attenuated. This makes the function $\tilde{T}$ resemble a sum of sine and a constant A_0. A similar effect can be observed when a constant negative imaginary part of the refractive index in equation (1) is added, especially when the actual oscillation amplitude is small compared to the average value of transmittance (as it can be seen in Fig. 2). We verified this approach by comparing theoretical spectrum with a measured spectrum at room temperature, where the refractive index dispersion is known best. We obtained a very good consistency of the measured and