Contributed paper

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Conductivity anisotropy of CdHgTe MBE layers with a periodic surface microrelief

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The surface microrelief of CdHgTe layers grown by molecular beam epitaxy (MBE) method has been studied by means of atomicforce microscopy. A periodic surface microrelief in the form of an ordered system of extended waves with the characteristic period 0.1–0.2 μm has been detected on epilayers grown at increased temperatures. Angular dependencies of the conductivity at 77 K have been measured and the conductivity anisotropy has been detected with a minimum in the direction transverse to microrelief waves. A feature of the transmission spectrum and the spectrum change after film annealing are observed. It is assumed that walls growing in the direction from the substrate to the surface are formed under microrelief wave slopes. Such structure can cause the observed feature of the transmission spectrum if the adjacent walls have different composition. In this work a calculation of spectral characteristics taking into account the influence of variable gap composition and nonuniformity of the composition through the depth has been carried out.

Keyword: CdHgTe layers, MBE, surface microrelief, spectral characteristics.

1. Introduction

CdHgTe solid solution is a basic material for manufacturing of photodetectors of IR range. For the growth of large area CdHgTe films, molecular beam epitaxy (MBE) method is used which allows utilization of alternative substrates such as GaAs and Si. The temperatures of MBE growth (180–200°C) are lower as compared to other methods and the formation of microrelief of the growing surface is a complex function of growth conditions such as growth temperature and rate, Hg vapour pressure, orientation and the substrate material. Formation of the microrelief on initial stages of growth can result in nonuniformities in the bulk, which will influence electrophysical parameters of grown structures.

Conductivity anisotropy, transmission spectrum features and periodic surface microrelief have been detected for CdHgTe films grown by MBE method at increased temperatures (≈210°C). The aim of this work was to establish a correlation between spectral characteristics of MBE CdHgTe films and the surface microrelief.

2. Experimental results

CdHgTe films grown by MBE method on (013) GaAs substrates of 50.8 mm diameter were studied [1]. The substrates had a primary flat along (001) orientation about 14 mm long at the distance 1.2 μm from the wafer edge. Buffer CdTe layers, 5–7 μm thick, were grown on the substrates followed by 8–12 μm thick CdHgTe films with x = 0.21–0.24. The results of investigation of the film surface by means of atomic force microscopy are the following. The surface microrelief of films grown at temperatures 180–200°C is shown in Fig. 1(a). It can be seen that the microrelief is flat and irregular. When the growth temperature increases up to 210°C, the surface irregularities are rearranged to a system of ordered waves, as it is shown in Fig. 2(b). The irregularity characteristic period is 0.1–0.2 μm and the wave slope angle reaches 5–7 degrees. The waves direction in relation to the primary flat substrate is equal for the whole film area and for different films it makes an angle of 45–60° with respect to a perpendicular to the primary flat. It should be noted that such periodic microrelief was observed for other unmatched heterosystems, for example, (111) GeSi/Ge, SiGe/Si and InGaAs/GaAs [2]. It is pointed out that such surface microrelief can cause anisotropy of transport and optical properties of heterostructures.

In CdHgTe films with a periodic surface microrelief, anisotropy of the conductivity (with the anisotropy coefficient about 10 at T = 77 K) was detected.

A summation of the obtained results makes possible to conclude that the conductivity anisotropy is caused by the difference of conductivity along parallel and perpendicular directions to microrelief waves. Since the film thickness (10 μm) is substantially larger than the periodic microrelief

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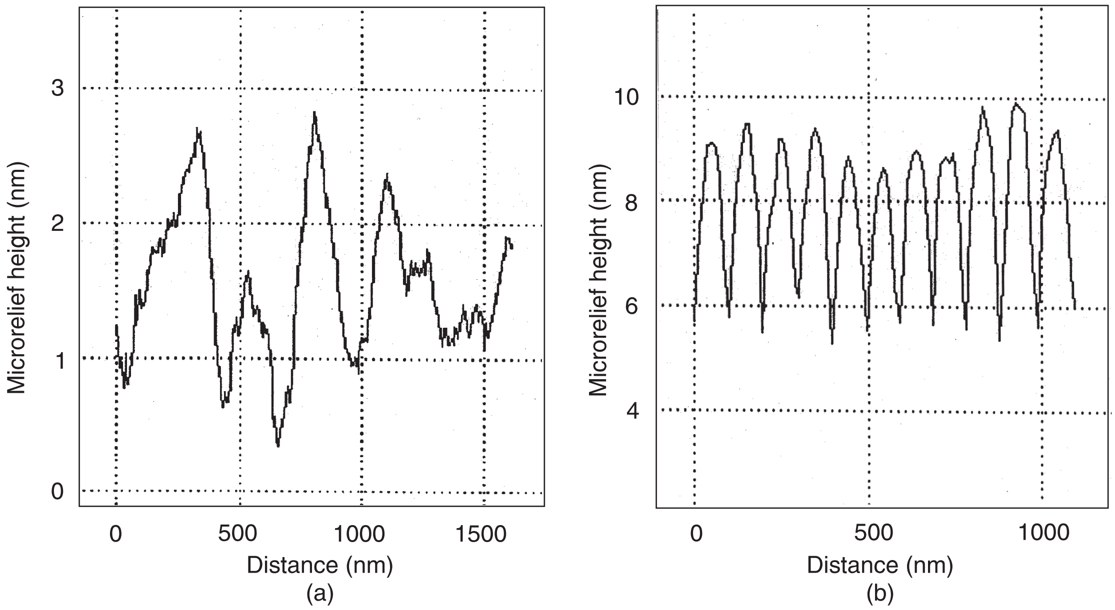

Fig. 1. The relief profile in height for the film surface without microrelief (a) and with periodic microrelief (b) obtained with atomic force microscope.

height (≈4 nm), the microrelief existence is not the only reason for the strong conductivity anisotropy. Therefore one can assume that walls, growing from the substrate to the surface, are formed under microrelief wave slopes as it is shown in Fig. 2. The observed angle dependencies of the conductivity can be attributed to the difference of conductivity along parallel and perpendicular directions to the walls and in case of perpendicular direction the conductivity will be lower due to scattering on the periodic potential or existence of a barrier between walls [for example, p-n (n^+-n^-) transitions if walls have different concentration of charge carriers].

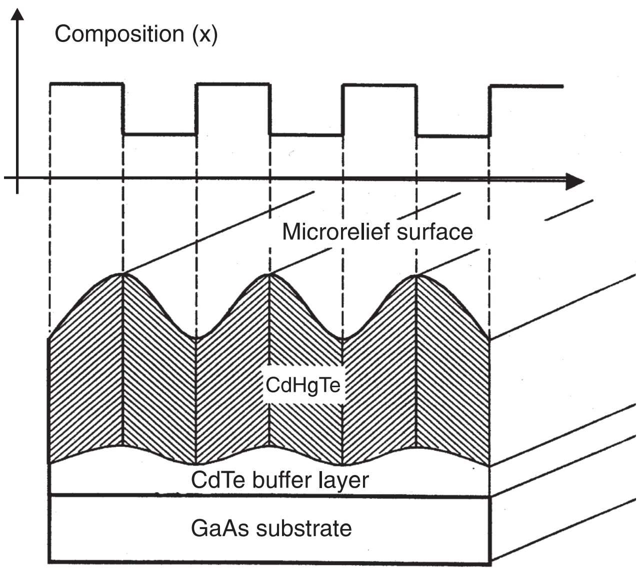

Fig. 2. A schematic cut of the structure and composition distribution in the perpendicular direction to microrelief strips.

The following mechanism of the wall formation can be proposed. A periodic microrelief appears on the surface of growing film due to singularities of the growth mechanism at increased temperatures. The following film growth on surfaces of the opposite slopes of microrelief waves will depend on the slope orientation. The concentration of antisite Te in CdHgTe MBE films is defined by kinetics of crystallisation process. Since the surface orientation of the opposite slopes of microrelief waves is different, walls with different concentration of antisite Te, which is a donor in CdHgTe, will be formed and the adjacent walls will have different concentration of charge carriers. The composition of CdHgTe solid solution can also depend on the orientation of growing surface and walls growing on different wave slopes can have different compositions. Fluctuations in the donor concentration as well as composition fluctuations will result in the potential nonuniformity in the film bulk on which carrier scattering or barrier formation can be possible. The existence of vertical walls with the thickness comparable with the microrelief period and the difference in composition of adjacent walls are confirmed by the following experimental data. The feature of films with periodic microrelief is the more flat spectral characteristic of the transmission coefficient in the region of fundamental absorption edge as compared to films without periodic microrelief and in case of equal thickness and compositions (Fig. 3).

Spectral characteristics of photoconductivity (SCP) of CdHgTe epitaxial films have a feature relative to possible nonuniformity of the film composition. Due to this nonuniformity, there appear built-in quasi-electric fields, which can cause a substantial change in the distribution of nonequilibrium charge carriers in the structure.

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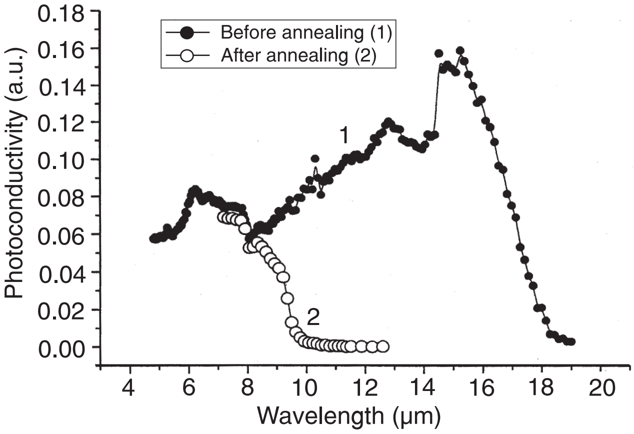

Fig. 3. Spectral of photoconductivity for the samples with $x = 0.20$ and $x = 0.24$ before annealing (1) and after annealing ($T = 220°C$, $\Delta t = 75$ h) (2).

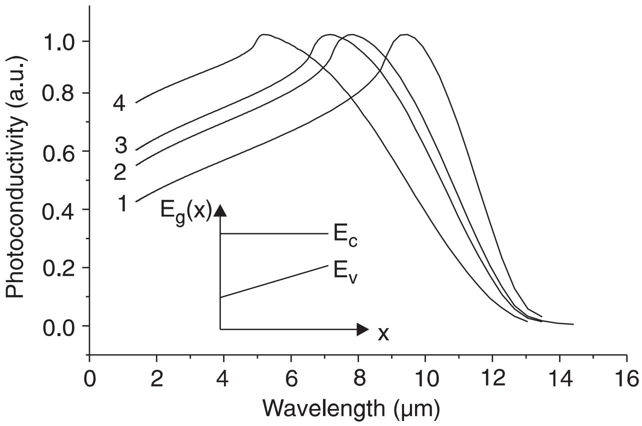

Fig. 4. Spectral characteristics of photoconductivity for a variable gap structures at different gap gradients: 1-$a = 3.5\times10^3$, 2-$a = 5.8\times10^3$, 3-$a = 7\times10^3$, 4-$a = 10^4$ cm^{-1}; $S_{0,d} = 10^5$ cm/s where $S_{0,d}$ – the velocity of surface recombination on boundaries of the sample ($x = 0$, d).

The above processes can essentially change the SCP form. Let us consider several cases of manifestation of SCP features for variable-gap structures based on CdHgTe. A calculation has been carried out in order to evaluate the influence of gap gradient on the SCP form of epitaxial structures. The calculation results are presented in Fig. 4. Parameters of the structures used in calculation are indicated in the figure caption, where a is the gap gradient which can be written as

$$a = -\frac{1}{2kT}\frac{dE_g}{dx} = \frac{[E_g(0) - E_g(d_0)]}{2kTd_0}$$

in case of the linear dependence $E_g(x)$. The composition at the interface epitaxial layer-substrate was $x = 0.2$ at $T = 77$ K.

It is seen from the plot that the photoconductivity curve becomes more flat in the long wavelength region with the increase in gap gradient. For example, for a uniform sample ($x = 0.2$) the photocurrent signal decreases from the value 0.9 to 0.1 with the increase in the wavelength of incident radiation from the value 12 to 13.5 μm. For a sample with variable gap profile ($x = 0.3$) the photoconductivity signal decreases from the value 0.9 to 0.1 with the increase in the wavelength of incident radiation from the value 6 to 13 μm. Existence of gap gradient also influence the short wavelength region of photoconductivity. We observed the photoconductivity increase from 0.55 up to 0.75 with the increase in gap gradient from 10^2 cm^{-1} to 10^4 cm^{-1}. This is related to the decrease in influence of the surface recombination rate on the minority charge carrier lifetime. Thus, the flat character of the long wavelength region enables us to judge about the material uniformity level.

During the process of epitaxial layers growth by MBE method, it is not always possible to keep the composition of a growing film with given accuracy. This results in the gap fluctuations in material. In order to evaluate the influence of composition nonuniformity on the photoconductivity spectral characteristic we have carried out a calculation for samples which energy diagrams are presented schematically in insertions of Figs. 5(a) and 5(c). The SCP, shown in Fig. 5(a), has a special shape of the photoconductivity long wavelength limit which can be divided into two regions: in the range of wavelength $2.0 < \lambda < 10$ μm absorption in the wide-gap part of the structure ($x = 0.22$) is dominant. The spectral characteristic in the range $10 < \lambda < 14$ μm is defined by absorption in the narrow-gap part of the structure ($x = 0.2$). The spectral characteristic shape significantly depends on the narrow-gap region size and gap gradients ($a = 10^5$ cm^{-1}) in the transition region between narrow-gap and wide-gap composition. Figures 5(b) and 5(c) show spectral characteristics of structures that are characterized by a lower gap gradient ($a = 2.7\times10^4$ cm^{-1}, 5.8×10^4 cm^{-1}). This result in the increased influence of surface recombination and in formation of a maximum in the long wavelength region with the increase of the nonuniformity thickness up to $d_0 = 5$ μm. Photoconductivity spectral characteristics shown in Fig. 5(d) have two maximums in case of the increased nonuniformity thickness from $d_0 = 4$ μm to $d_0 = 6$ μm due to larger difference in the matrix composition ($x = 0.3$) and nonuniformity ($x = 0.2$) and despite of large gap gradient ($a = 10^5$ cm^{-1}). For $d_0 < 5$ μm, the photoresponse in the shortwavelength range exceeds that in the long wavelength range. This is related to insufficient size of the region which is active in the long wavelength range. A decrease in the short wavelength range due to widening of the region active in the long wavelength range and narrowing of the region active in the short wavelength range is observed at the increase of d_0 up to 6 μm.

3. Conclusions

A periodic microrelief as an ordered system of extended waves has been detected by means of atomic force microscopy on CdHgTe films grown at increased temperatures on GaAs substrates (013) with a CdTe buffer layer. The direc-

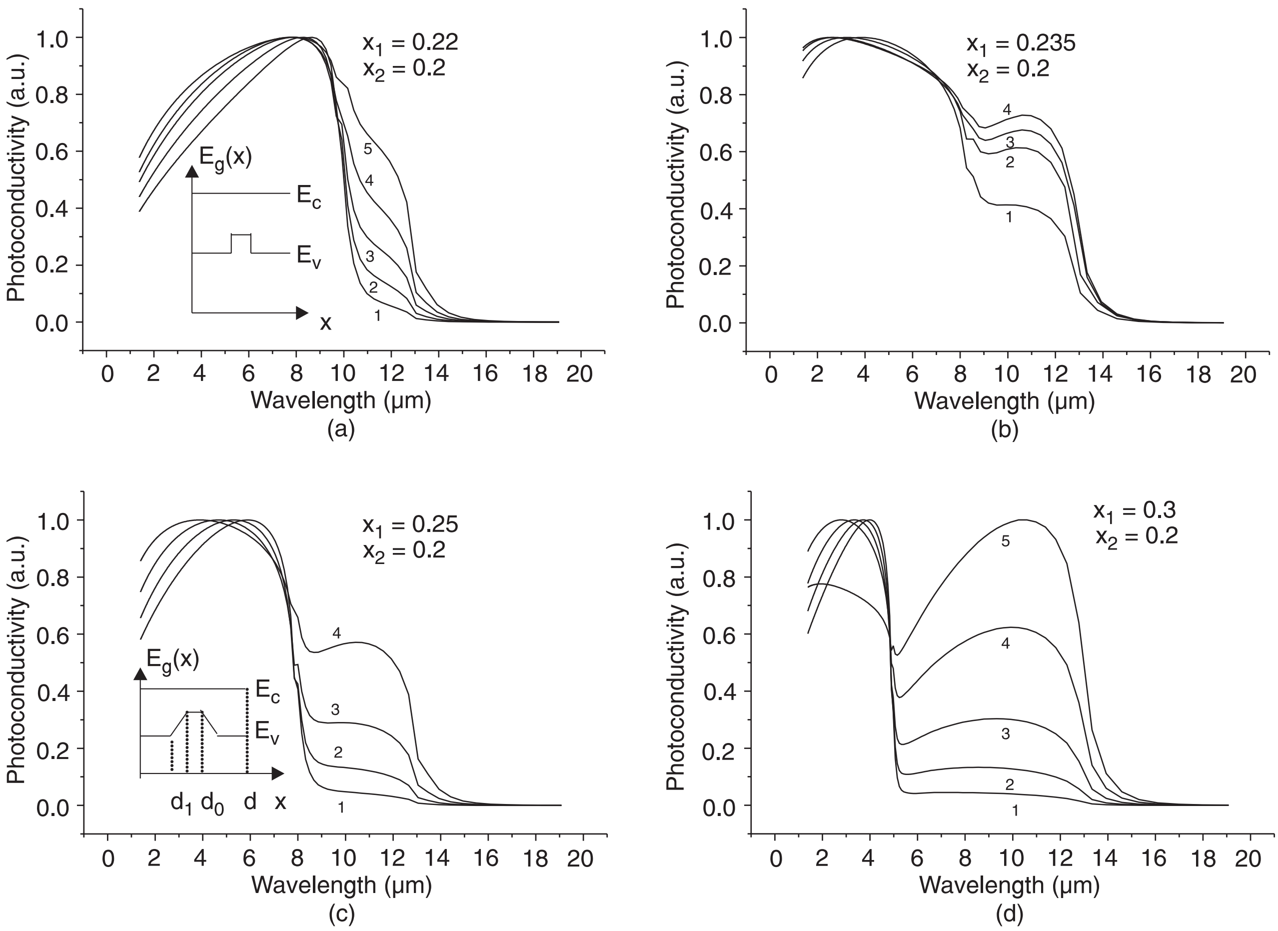

Fig. 5. Spectral characteristics of photoconductivity: (a) 1-d_0 = 1, 2-d_0 = 2, 3-d_0 = 3, 4-d_0 = 4, 5-d_0 = 5 μm; $a = 10^5$ cm^{-1}; (b) 1-d_0 = 4, 2-d_0 = 4.5, 3-d_0 = 4.85, 4-d_0 = 5 μm; $a = 2.7\times10^4$ cm^{-1}; (c) 1-d_0 = 2, 2-d_0 = 3, 3-d_0 = 4, 4-d_0 = 5; d_1 = 1 μm, $a = 5.8\times10^4$ cm^{-1}; (d) 1-d_0 = 2, 2-d_0 = 3, 3-d_0 = 4, 4-d_0 = 5, 5-d_0 = 6, d_1 = 1 μm, $a = 10^5$ cm^{-1}.

tion along waves makes an angle in the range of 30–45° with relation to the primary flat of the substrate along (001) orientation. The microrelief period is 0.1–0.2 μm and the microrelief height is 5–10 nm.

It is assumed that the periodic microrelief is caused by features of growth at the increased temperatures. The film growth on a microrelief surface can be considered as a growth on surfaces with different orientation. As a result, walls with different composition (and probably with different concentration of charge carriers) can be formed under opposite slopes of microrelief waves. The observed features of transmission and photoconductivity spectral characteristics of films with the periodic microrelief can be explained by the difference in composition of the assumed walls.

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