CONTROLLING OF THE THERMAL STRESS IN THE MULTIPLE QUANTUM WELLS USING MAGNETOPHONON SPECTROSCOPY

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The paper deals with the changes of band structure parameters under deformation. The values of these changes are calculated for the GaAs/AlGaAs structure of multiple quantum wells (MQW). The role of magnetophonon resonance (MPR) as a method to control the thermal stress in MQWs at the parallel charge carriers transport is emphasised.

1. Introduction

Taking into account the temperature at which the epitaxial growth of the semiconductor layers occurs, as well as the operating temperature of the devices based on these semiconductors, it is natural to expect considerable thermostresses in them. The stresses are caused by the different temperature dynamics of lattice constant change for different semiconductors of which the structures under consideration is composed. The great mismatch is a problem of considerable importance, since the structures based on binary compounds are widely used for the high-speed semiconductor devices, such as InGaAs HEMT produced by MBE technology, as well as by MOCVD [1].

Stresses in semiconductor crystals in case of multiple quantum wells (MQW), as it will be shown, can cause the changes of the structure parameters, including the radical changes in electron transport. The latter, however, plays some positive role, since in this way one can get an additional degree of freedom in the control of the material parameters.

2. Description of the thermostresses in MQWs and the change of band structure parameters under deformations

The GaAs substrate, on which the barrier layers, as well as QW were grown by means of MOCVD technology, was held at 800 K approximately. At this temperature the lattice constants of GaAs and AlAs binary compounds match each other. After finishing the technological process, the samples are cooled and the mismatch increases (See Table 1).

Table 1. Temperature dependence of the lattice constants of GaAs and $Al_{0.3}Ga_{0.7}As$ [5].

Temperature, K	Lattice constant, a_1 (GaAs), 10^{-10} m.	Lattice constant, a_2 ($Al_{0.3}Ga_{0.7}As$), 10^{-10} m	$a_2 - a_1$ 10^{-10} m
800	5,683	5,6840	0,001
350	5,655	5,6575	0,0025
300	5,653	5,6560	0,003
150	5650	5,6535	0,0035
77	5,647	5,6510	0,004

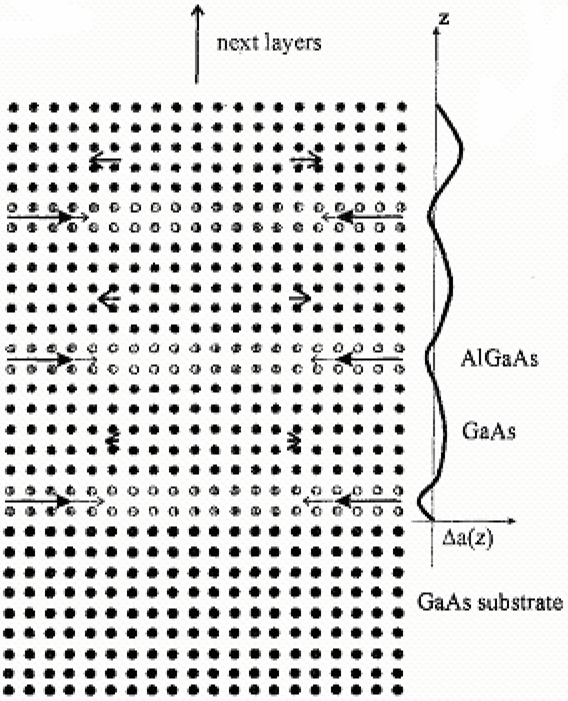

Fig. 1 A sketch of the deformation distributions in the MQW atomic layers.

Considering the temperature influence on the whole structure, one should pay attention to the fact, that thick substrate was used here. This substrate determines the stresses also in the upper layers of QW. For example, the first layer of AlGaAs (of 4 nm thick) is compressed to the most extend due to the displacement of its atoms together with thick substrate, while the next layer of GaAs (10 nm thick) is stretched minimally. The maximum tension occurs for upper GaAs layer because the last layer of AlGaAs is compressed minimally. The diagram of the stress distribution is shown in Fig. 1. The next conclusions follows from that:

1. GaAs-layers are tensed in the direction parallel to the layers (*xy*-plane) and compressed in the direction perpendicular to the layers.
2. AlGaAs layers are compressed in the direction parallel to the layers and tensed in the direction perpendicular to the layers .

The stresses in different GaAs layers of the structures under consideration are different. The stresses in GaAs-layers starting from the substrate increase, while the stresses in AlGaAs-layers decrease.

At the temperature of 77 K the mismatch between GaAs and $Al_{0.3}Ga_{0.7}As$ lattices has the value $\Delta a=4\times10^{-13}$ m. [5], which makes the biaxial deformation in the plane of the layer equal to $\varepsilon_0=7.1\times10^{-4}$. One can suppose that it is maximum tension to be in upper QW.

In general, the energy gap E_g increases under deformation at overall hydrostatic tension and decreases under overall compression. The energy gap in a crystal under deformation is of the form:

$$E_g^{2D}(\varepsilon_0) = E_g^{2D} \pm \Delta E^V_{hy,un} \pm \Delta E^C_{hy} , \qquad (1)$$

where „+”- sign corresponds to the compressed layers while „-” sign corresponds to the stretched layers. $\Delta E^V_{hy,un}, \Delta E^C_{hy}$ are the shift of the valence band under hydrostatic and anisotropic stress and the shift of the conduction band under hydrostatic stress, respectively; E_g^{2D} is the energy gap of the QW without deformation.

Under tension or compression in *xy*-plane, two valence bands (for the light and heavy holes) are shifted in accordance with [2,3]

$$\Delta E^V_{hy,un}(\varepsilon_0) = 2a\varepsilon_0 \frac{1-2\nu}{1-\nu} \pm b\varepsilon_0 \frac{1+\nu}{1-\nu} , \qquad (2)$$

where sign „+” is for the light holes (*lh*) and „-” is for the heavy ones (*hh*), *a* stands for the potential of hydrostatic deformation, *b* stands for the potential of uniaxial deformation, $\varepsilon_0= \varepsilon_{xx}= \varepsilon_{yy}$ are biaxial deformation, and $\varepsilon_{zz} = -\frac{2\nu\varepsilon_0}{(1-\nu)}$ is the Poisson deformation in z-direction, whereas ν is the Poisson coefficient.

It follows from (2) that under tension in the *xy*-plane caused by hydrostatic component of the deformation, two bands are shifted up decreasing the energy gap.

The uniaxial component of the deformation acts on the *lh*- and *hh*-bands in the opposite direction. Both components of the deformation cause that *lh*-band is shifted up, while for the *hh*-band the uniaxial component is damping the shift caused by the hydrostatic component.

In case of QWs, two valence bands are separated by some value ξ even without any deformation and the first light hole subband (1*lh*) occurs to be under the (1*hh*) subband. For that reason, we can write the valence band shift in the form:

$$\Delta E^{V}_{hy,un} = \max\left(2a\varepsilon_0\frac{1-2\nu}{1-\nu} - b\varepsilon_0\frac{1+\nu}{1-\nu},\quad 2a\varepsilon_0\frac{1-2\nu}{1-\nu} + b\varepsilon_0\frac{1+\nu}{1-\nu} - \xi\right) \qquad (3)$$

Γ_6- band shifts only under hydrostatic component of the deformation into direction opposite to the valence band shift. The value of Γ_6- band shift is twice as much as the valence band one [4]. So, based on these consideration, one can write the next formula for the conduction band shift:

$$\Delta E^{C}_{hy} = 4a\varepsilon_0\frac{1-2\nu}{1-\nu} \qquad (4)$$

The formulae (3), (4), enable us to determine the total change of the energy gap caused by thermostress ε_0 described above. The constants, used in these formulae are: a = -8.7 eV, b = -1.8 eV [3], ξ = 2,7 meV. Therefore those components have the following values: $\Delta E^{v}_{hy}(\varepsilon_0) = 6.707\text{meV}$, $\Delta E^{V}_{un}(\varepsilon_0) = 2.392\text{meV}$, $\Delta E^{C}_{un}(\varepsilon_0) = 13.415\text{meV}$ and the overall change of the energy gap is

$$\Delta E_g(\varepsilon_0) = 22.5\text{meV} \qquad (5)$$

That means the total change of energy gap is 1.5%.

3. Influence of thermostresses in MPR

3.1. MPR as testing technique

MPR is due to the oscillatory behaviour of the electron density of states arising as a result of the Landau quantisation. This line of reasoning presupposes that the Landau levels are well defined, and that their collisional and temperature broadening is relatively small. These two conditions of a strong magnetic field can be represented as follows: $\omega_c\tau >> 1$ and $\hbar\omega_c >> k_B T$, respectively. The magnetophonon resonance appears every time when the phonon frequency ω_{LO} is equal to the cyclotron frequency ω_c of the electron in a magnetic field, multiplied by the small integer M: $\omega_{LO}=M\omega_c$ [6], where: M=1, 2, 3,..., $\omega_c = e\ B\ /m$, e – electron charge, m – effective mass, B- magnetic field induction.

The simplified expression for the oscillatory part of transverse magnetoconductivity including each of the M harmonics (at a constant number of phonons and electrons) is [6,7]:

$$\frac{\Delta\rho^{osc}_{xx}}{\rho_0} = \sum_{M=1}^{\infty}\frac{1}{M}\exp\left[-2\pi M\left(\frac{\omega_{LO}}{\omega_0}\beta^2\right)^{\frac{1}{3}}\right]\cos\left(2\pi M\frac{\omega_{LO}}{\omega_c}\right), \qquad (6)$$

where β is the damping factor, which is related to the damping rate $\Gamma = \hbar/\tau = \hbar\omega_{LO}\beta$. Therefore, the appearance of the MPR, especially of the several harmonics of the MPR, is a direct attestation of the high quality of semiconductor samples.

For example, MPR was already successfully used for the selection of high quality *p*-

InSb samples [8], and hence MPR can be considered as the method of diagnosis of semiconductor crystals and structures.

The study of parallel electron transport in MQWs produced by means of MOCVD technology and described above, has shown the sufficiently high quality of the QW layers [9]. It is confirmed by the obtained MPR oscillations. The theromostresses can make the magnetoconductance peaks in parallel transport to split into a number of peaks due to the stress distribution in QWs layers. These stresses, changing the parameters of band structure in subsequent QW layers, make them to be non-identical. The MPR spectroscopy make it possible to identify the peaks caused by the changes of band structure in different layers.

In this way MPR gives the possibility to control the charge carriers in the layers, due to its unusual sensitivity to the changes of the band-structure parameters. In case of splitting of magnetoconductance in parallel transport into the conductance of separate layers, each peak corresponding to the electron transition to the higher Landau level would be splitted identically. The last one means, that for each layer we would have series of MPR oscillations of its own. The series could be approximated by the formula (6); in that way one can determine for each layer not only the changes of effective mass, but the damping parameter β, and the electron mobility as well.

3.2. Shift of MPR peaks by thermostress

As it was shown above, the maximum change of energy gap caused by thermostresses in GaAs/AlGaAs MQWs is 1.5%. The accompanied change of effective mass at the bottom of the conduction band of QW, evaluated by means of simple three-bands model is about 1.4%. Therefore, the same shift of MPR peaks is expected.

In addition, anisotropic stresses cause phonon frequencies to shift and the LO phonon branches even to split [10]. So, the maximum decrease of LO phonons frequency in the GaAs layer induced by biaxial stress can be evaluated upon the formula [11]:

$$\Delta\omega_{LO} = -4.8\times10^{2}\,\varepsilon_{o}\ [\mathrm{cm}^{-1}] \qquad (7)$$

In our case, a decrease of the LO phonon frequency is equal 0.33 cm^{-1}, which is 0.1% of its value without stress.

For these reasons, changes of E_g and LO frequencies should be shifted in the same direction (i.e. of lower magnetic fields) the MPR peaks and this shift should not be more than 1.5%. It means that e.g. in the case of a peak at 11.2 T (0-2 transition) the maximum split caused by disintegration of magnetoconductivity in the parallel transport resulting from thermostresses disposition in the layers is 0.17 T.

3.3. Experimental results

The MPR research were performed in pulsed magnetic fields up to 30 T. The transverse magnetoresistance was measured between 77K and 340K and the MPR oscillations extracted by subtracting a voltage linear in magnetic field. The oscillating part of magnetoresistance $\Delta\rho_{xx}$ was recorded. Three types of MQW-systems (with different thickness of GaAs layers and barriers) were studied; they consisted of ten QW of GaAs and ten AlGaAs barriers, and were obtained by MOCVD on semi-insulating GaAs. In Fig. 2 the examples of registered curves $\Delta\rho_{xx}$ (B) obtained for MQWs with thick QW 10 nm and the barriers of 4nm, are shown.

Figure 2 shows experimental curves obtained at three temperatures. The structure of peaks observed was not smoothed off and represented here as it is in view of its astonishing repetition for different MPR harmonics at different temperatures. The thinned and dashed arrows show the resonance fields which would correspond to the resonances caused by absorption of phonons in $Al_{0.3}Ga_{0.7}As$ barrier (LO GaAs-like and LO AlAs-like respectively, the frequencies of LO-phonons of $Al_{0.3}Ga_{0.7}As$ being taken from [4]) together with electron transitions between the corresponding Landau levels.

These levels are the same as in the main series caused by interaction with phonons of the GaAs Quantum Well (bold arrows). The observed peak structure partially can be explained by the introduction to MPR of two kinds of barrier phonons.

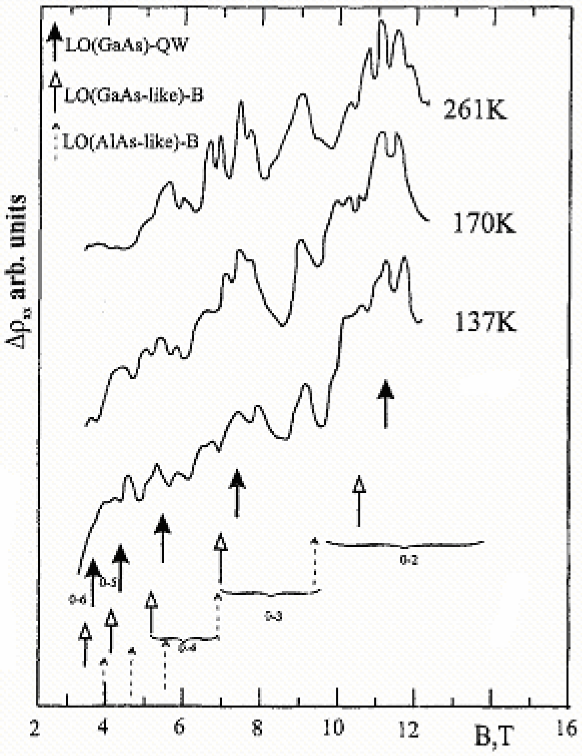

Fig. 2 Experimental recordings of $\Delta\rho_{xx}$ (B) obtained for MQW consisted of ten QW of GaAs and ten AlGaAs barriers, The thickness of the well was 10 nm, the thickness of the barrier was 4 nm.

So, the occurrence of peak at about 9 T can be attributed to 0-3 transition of an electron with the absorption of the AlAs-like LO phonon. The MPRs caused by the interaction between an electron and GaAs-like LO phonon of barrier manifest themselves as the satellites of each main series peak from the side of lower magnetic fields.

If one take into account two additional MPR series mentioned above, then in the range of magnetic field 9–11 T one should expect two additional peaks, each splitted by thermostresses. Such a structure should reappear for other MPR harmonics. In this way one can explain mainly the observed MPR peaks structure.

4. Conclusion

It is shown that even in case of MQWS on the GaAs/AlGaAs, the influence of thermostresses on the MPR peaks structure is observable. The calculations made for this system show that the peak shifts are about 1.5%, which causes the subtle structure of MPR peaks. For the structures with greater mismatch this effect is so considerable, that can cause the series of resolved MPR peaks for each layer. For that reason, MPR can be used for the control of the charge carrier parameters in each layer of the structure.

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КОНТРОЛЬ ТЕПЛОВИХ НАПРУЖЕНЬ У БАГАТОКРАТНИХ КВАНТОВИХ ЯМАХ ЗА ДОПОМОГОЮ МАГНІТОФОНОННОЇ СПЕКТРОСКОПІЇ

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У роботі обговорюються зміни параметрів зонної структури при деформації. Розраховано величини цих змін для структури багатократних квантових ям GaAs/AlGaAs. Підкреслюється роль магнітофононного резонансу як методу контролю теплових напружень у багатократних квантових ямах при паралельному перенесенні носіїв заряду.