Determination of the homogeneity of quantum wells in the InGaAs/GaAs system from photomodulation spectra

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Measurements of the intensity of a photorefection peak and its spectral position during scanning of a sample by the light beam were used to determine inhomogeneities of the width and composition of quantum wells in the InGaAs/GaAs system.

INTRODUCTION

The strong optical nonlinearity and the large electrooptic coefficients of quantum-well structures are observed in a relatively narrow spectral interval (=10 meV) close to an exciton absorption peak. The spectral position of this peak is governed, with an error on the order of the binding energy of an exciton (6–8 meV for quantum wells in the InGaAs/GaAs system), by the separation between the size-quantization levels of electrons and holes \( E_{e_1} - E_{h_1} \), which depends on the well width \( L \) and on the composition (indium concentration \( x \)). For typical values \( x = 0.2 \) and \( L = 80 \) Å a change in \( x \) by 1% and in the width by 1 molar layer (=3 Å) alters the transition energy by 9 and 4 meV, respectively, which imposes stringent requirements on the homogeneity of quantum wells with respect to the widths and composition.

Optical experiments — involving determination of the transmission and reflection spectra, of the luminescence spectra, and of the luminescence-excitation spectra — with a test beam scanning a sample can be used to determine the changes in the separation between the size-quantization levels. Measurements indicate that such a change can reach =20 meV over a distance on the order of several millimeters. It is normally not possible to determine from these measurements whether the spectral shift of an exciton peak is due to inhomogeneity of the quantum-well width or due to variations of the composition.

We shall describe a method which makes it possible to study the homogeneity of quantum wells with respect to the width and composition by photomodulation measurements.

1. EXPERIMENTS

In our experiments we determined the change in the transmission spectrum \( \rho(\omega) = \Delta T(\omega)/T(\omega) \) or in the reflection spectrum \( \rho(\omega) = \Delta R(\omega)/R(\omega) \) \( (\omega \) is the optical frequency) due to photomodulation, i.e., due to changes in the optical parameters of a structure under the influence of additional illumination with light of frequency lying within the fundamental absorption region of a semiconductor.2 Our pump and test radiation sources were, respectively, an He–Ne laser and a halogen lamp, from which radiation passed through an MDR-12 monochromator. The test radiation was focused on a sample in a spot of 1 mm\(^2\) area and the pump radiation covered an area several times larger. The parameters of the investigated structures with one quantum well, grown by the metal-organic chemical vapor deposition (MOCVD) technology, are listed in Table I. Typical modulation spectra and the spectral dependence of the change in the absorption \( -\delta(\omega L) \), calculated in accordance with Ref. 3 for sample Z313, are shown in Fig. 1. The intensity of a modulation peak \( A \) increased with increasing pump power \( P \) and reached saturation at a pump power density 0.1 W/cm\(^2\) (Fig. 2). This type of dependence \( A(P) \) made it possible to reliably identify the photomodulation mechanism. The very low values of the pump power density and the nature of the \( \rho(\omega) \) and \( \tau(\omega) \) spectra corresponding to a mechanism associated with the surface charge screening. Other possible mechanisms of changes in the absorption and reflection in the presence of additional illumination — filling of an energy band, screening of an exciton by photocarriers, heating of a semiconductor — require much higher pump powers.4

According to the mechanism of screening of the surface charge, modulation of pump radiation is equivalent to modulation of a surface electric field acting on quantum wells. The electric-field-induced shift of the size-quantization levels (and the associated change in the amplitude of the modulation

![Graphs and figures]

FIG. 1. Typical spectra of photomodulated reflection \( \delta R/R \), transmission \( \delta T/T \), and spectral dependence of the change in the absorption \( -\delta(\omega L) \), calculated in accordance with Ref. 3 for sample Z313.
The absorption spectrum of a quantum well \((\omega)\), which is associated with optical transitions between the size-quantization levels, shifts by \(\delta \omega = \delta E_{e_1 - h_1}/\hbar\) [sic] as a result of application of an external electric field, and its intensity changes proportionally to \(\langle \Psi_{e_1} | \Psi_{h_1} \rangle^2\):

\[
\delta \alpha (\omega) = \alpha (\omega) - \alpha_F (\omega) = -2\\langle \Psi_{e_1} | \Psi_{h_1} \rangle \alpha (\omega) + \delta \omega \alpha (\omega)/\delta \omega.
\]

In the vicinity of an exciton peak the ratio \(\delta \alpha (\omega)/\alpha (\omega)\) is on the same order of magnitude as \(\Gamma^{-1}\), where \(\Gamma = 10\ \text{meV}\) is the half-width of the exciton peak and for \(0.2 < x < 1.0\) and \(40 < L < 150\ \text{Å}\) the main contribution to \(\delta \alpha (\omega)\) comes from the second term in Eq. (4). On the other hand, the change in the absorption spectrum caused by additional illumination is a certain linear combination of photomodulation spectra. Consequently, we can see that the intensity of the modulaton signal, like the electric-field-induced shift \(\delta E_{e_1 - h_1}\), is proportional to \((E_h/n)^x\). The shift of the size-quantization levels depends, in accordance with Eq. (2), also on the effective mass \(m^*\) and on the surface field \(F\). We assume that these parameters do not change in the course of scanning a sample. The effective masses of heavy holes in GaAs and InAs amount to 0.34\(m_0\) and 0.32\(m_0\), respectively, so that possible changes in the concentration \(x\) by a few percent may cause relative changes in \(m_h (\text{In}_x\text{Ga}_{1-x}\text{As})\) by no more than \(10^{-3}\). The degree of homogeneity of the surface field was confirmed experimentally. It was found that the photorefection spectra of the investigated samples had a profile near the fundamental absorption edge of GaAs which was that expected because of the Franz–Keldysh effect: there were alternate positive and negative extrema which decreased in amplitude as the frequency moved away from the absorption edge. We observed experimentally 8-10 such extrema and their spectral positions remained constant during scanning of a sample.

FIG. 3. Dependences of the parameters \(C_1-C_3\) on the well width \(L\) plotted for different indium concentrations \(x\) (values alongside the curves).
TABLE I. Parameters of quantum-well structures

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Quantum-well width $L$, Å</th>
<th>Indium conc., %</th>
<th>Thickness of GaAs layer, Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZJ11</td>
<td>73</td>
<td>20</td>
<td>120</td>
</tr>
<tr>
<td>ZJ12</td>
<td>64</td>
<td>30</td>
<td>113</td>
</tr>
<tr>
<td>ZJ13</td>
<td>41</td>
<td>40</td>
<td>123</td>
</tr>
<tr>
<td>ZJ14</td>
<td>28</td>
<td>50</td>
<td>141</td>
</tr>
</tbody>
</table>

Changes in the intensity of the photoreflection peak $A$ in the course of scanning a sample are related in the following way to changes in the well parameters:

$$
\frac{\Delta A}{A} = 4\Delta L_s^2/L_s^2 = C_1 \Delta L/L + C_2 \Delta x,
$$

(5)

where

$$
C_1 = \left( \frac{4L}{L_s^2} \right) \frac{\partial L_s^2}{\partial L}, \quad C_2 = \left( \frac{4L}{L_s^2} \right) \frac{\partial L_s^2}{\partial x}.
$$

The spectral position of the modulation peak is governed by the positions of the size-quantization level and the change in the peak position can also be linearized in terms of $\Delta L/L$ and $\Delta x$:

$$
\Delta E_{el - el} = C_3 \Delta L/L + C_4 \Delta x,
$$

(6)

where

$$
C_3 = \frac{L \Delta E_{el - el}}{\partial L}, \quad C_4 = \frac{\partial E_{el - el}}{\partial x}.
$$

Solving Eqs. (5) and (6) simultaneously, we obtain

$$
\begin{align*}
\Delta L/L &= \left( C_1 \Delta A/A - C_2 \Delta E_{el - el} \right) / (C_1 C_4 - C_2 C_3), \\
\Delta x &= \left( C_3 \Delta A/A - C_4 \Delta E_{el - el} \right) / (C_4 C_3 - C_2 C_4).
\end{align*}
$$

(7)

The changes $\Delta A/A$ and $\Delta E_{el - el}$ during scanning a sample were determined in our experiments. The coefficients $C_1$–$C_4$ are functions of the well parameters ($L$, $x$). They can be calculated by solving the problem of the size-quantization levels in the conduction and valence bands. A sufficiently accurate algorithm for obtaining such solution is known, and it involves modeling of the band offset (discontinuity), with allowance for stresses and for the conduction band nonparabolicity. The physical parameters of GaAs and InGaAs are given in Ref. 10. The dependences of the coefficients $C_1$–$C_3$ on the well width obtained on the basis of this model for different values of $x$ are plotted in Fig. 3. The parameter $C_4$ found in the range $0.2 < x < 1.0$ and $40 < L < 150$ Å is 0.9 eV, within 10%, and it depends weakly on $(L, x)$, so that it is not shown in the figure.

In the investigated range of $(L, x)$ a potential well is sufficiently deep (at least for holes): it can accommodate three or more size-quantization levels. This allows us to drive simple analytic expression for the coefficients $C_1$–$C_3$. The energy $E$ of a particle in a potential well of depth $U$ is given by the following expression derived in the parabolic approximation:

$$
L (2m_e E/\hbar^2)^{1/2} = 2 \tan^{-1}((m_w^* U - E)/U)^{1/2},
$$

(8)

where $m_w^*$ and $m_b^*$ are the effective masses of a particle in the well and in the barrier, respectively. Assuming in Eq. (8) that $E \ll U$ (deep well), we readily obtain the relation

$$
L_s^2 \frac{\partial L_s^2}{\partial x} = - \left( k_s L + 2 \nu_s \right) U_s^2 \frac{\partial U_s}{\partial x},
$$

$$
(L/L_s^2) \frac{\partial L_s}{\partial L} = 1/(1 + 2 \nu_s/k_s L),
$$

$$
L \Delta E_{el - el} / \partial x = 2 \pi^2 \nu_s U_s k_s L (k_s L + 2 \nu_s)^{-1}
$$

+ $\nu_s U_s k_s L (2 \nu_s)^{-1},
$$

(9)

where $\nu = m_b^*/m_w^*$ and the indices $c$ and $v$ refer to the conduction band and valence band, respectively. The coefficients $C_1$–$C_3$, obtained using the relation in the system (9), differ by no more than 15% from those plotted in Fig. 3.

3. RESULTS OF MEASUREMENTS

The proposed method for estimating inhomogeneity of quantum wells with respect to their width $L$ and composition $x$ relies basically on the proportionality of the intensity of a modulation peak to the fourth power of the effective quantum-well width. The dependence $A(L)$ is plotted for our samples in Fig. 4. The deviations from the straight line $\ln(A/4A') = 4\ln(L/L')$ occur at low values of $L$, where the wave function of heavy holes extends well below the limit of a quantum well. The observed dependence $A(L)$ confirms the validity of the adopted model.

The width of the spectrum does not change (within ±3%) when samples are scanned, and the amplitude of the modulation spectrum changes only slightly (by $\Delta A/A < 10\%$), whereas the spectral position of the photomodulation peak changes significantly (by $\approx 20$ meV). If such a large
change in the spectral position would be caused by a change in the quantum-well width, it would be accompanied by a major (by a factor of 1.5-2) change in the amplitude of the modulation peak. Since this was not observed, the change in the spectral position of the modulation peak should be attributed mainly to changes in the concentration $x$ across a sample. More rigorous values of the relative deviations $\Delta L$ and $\Delta x$ can be calculated from the measured values of $\Delta x/L$ and $\Delta E_{21-1}$ using the expressions in the system (7). The results of such calculations carried out for one of the samples are shown in Fig. 3. The changes $\Delta x$ and $\Delta E$ are defined in such a way that scanning of a sample leads to $\langle \Delta A \rangle = 0$ and $\langle \Delta E \rangle = 0$.

It follows from our results that fluctuations of the quantum well width averaged over large dimensions ($=1 \text{ mm}^2$) do not exceed one monolayer for all the investigated samples, in good agreement with the results obtained by other methods used in quality control of similar structures. The rms deviation of the quantum-well width $(\Delta A)^{1/2}$ does not exceed 3 Å for our samples, whereas the concentration varies continuously, probably because of the specific features of the technology used in the fabrication of the quantum-well structures.

We can therefore draw the following conclusions. A simpler optical nondestructive method is proposed for estimating inhomogeneities of InGaAs/GaAs quantum wells with respect to the well width and the composition, which involves determination of the amplitude and spectral position of a photomodulation peak when a sample is scanned with a light beam, followed by calculations of $\Delta L$ and $\Delta x$ from expressions given by the system (7). The method is based on the following propositions: the spectral position of a modulation peak is governed by the size-quantization energy of electrons and holes, which depends in a familiar manner on the parameters of the well ($L, x$); the amplitude of the modulation peak is proportional, subject to certain assumptions, to the fourth power of the effective width of the quantum well calculated for heavy holes.

In the case of a deep well our analysis yields simple analytic expressions relating the changes in the spectral position and amplitude of the photomodulation signal to changes in the quantum-well parameters.

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