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Exciton resonance reflectivity study of quantum well wires

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Abstract: We report on the first observation of the exciton resonant reflection from a directly grown array of isolated quantum-well-wires. Structures contained 30 GaAs/AlAs double layers were grown on (311) GaAs substrate by conventional elemental source MBE. GaAs wire-like clusters with an orientation along $[\bar{2}33]$ and size of 32/10.2 Å were introduced inside one of the central AlAs layers. The expected distance between nearest clusters is about 160 Å. In spite of much smaller effective volume occupied by excitons in these clusters, as compared to that in a single quantum well, the quantum-well-wire structures demonstrate much larger resonance amplitude of the reflection spectra. We extracted excitonic parameters from these spectra and found that the exciton oscillator strength in the quantum-well-wires is more than 10 times higher than that in the environment superlattice. A 30% anisotropy of the exciton oscillator strength in the quantum-well-wire has been observed. The theory of non-local dielectric response is extended to calculate reflection spectra from the structures with a grating of quantum-well-wires. A functional relationship between the reflection coefficient and the envelope wave function of an exciton in the structure has been established.

Quantum wire and quantum dot structures attract growing interest in the recent years [1]. The interest to such structures is caused by potential technical applications and conditions for novel physical phenomena arising due to the reduction of dimensionality. Such novel physical phenomena are connected first of all with the modification of interaction between quasi-particles (electron-electron, electron-hole, electron-phonon, etc.) in low-dimensional systems. In the present paper we present the results of theoretical and experimental investigation of excitonic states in the system of quantum well wires.

The samples contained 30 GaAs/AlAs double layers grown on (311)A GaAs substrate by conventional-source MBE (Fig. 1). In this case, an interface is formed by a periodic array of upward and downward steps oriented along $[\bar{2}33]$ with lateral periodicity of 32 Å and step height of 10.2 Å [2]. The average thicknesses of GaAs and AlAs layers were 35 Å and 30 Å, respectively. GaAs wire-like clusters were introduced inside one of the central AlAs layers in the way described in [3,4]. According to [3] the clusters (covering ~20% of the layer surface) are responsible for the formation of wire-like quasy-one

Fig.1 Schematic representation of light reflection geometry and (311)A corrugated superlattice with

wire-like clusters introduced inside one of AlAs layers $x\| [01\bar{1}], y\| [\bar{2}33]$.

Fig.2 Normal reflection and photoluminescence spectra taken from a GaAs/AlAs multy-layered structures with a grating of wire-like clusters. Dotted line shows the reflection spectrum in the vicinity of ω_0^{QWW} with fitting parameters: $\hbar\omega_0^{QWW} = 1.690\text{eV}$, $(2\gamma)^{-1} = 3\text{ps}$, $\hbar\Gamma = 6.6\text{meV}$.

dimensional (quasi-1D) free-carrier states. The expected distance between nearest clusters d_x is 160 Å and the interaction of quasi-1D excitonic states seems to be negligible.

Fig.2 shows the reflection spectrum taken at normal incidence in the $E\|y$ polarization (E -electric vector of reflected light, $y\| [\bar{2}33]$) together with the spectrum of photoluminescence excited by the 6328 Å line of a He-Ne laser. The arrows indicate the resonance frequencies of ground-state excitons in the corrugated superlattice (ω_0^{SL}) and of quasi-1D excitons attached to wire-like clusters (ω_0^{QWW}). We note the large intensity of photoluminescence signal from QWW clusters in comparison with superlattice.

The reflectivity spectrum was calculated in the framework of the theory of non-local dielectric response. The dotted curve is calculated using the expression for the interference reflectivity (see [5]).

$$R = r_{01}^2 + 2t_{01}t_{10}r_{01} \text{Re}(e^{i\phi}r)$$

where r_{01}, t_{01}, t_{10} are the amplitude reflection and transmission coefficients on the external boundary, ϕ is the phase shift of the light wave after its direct and backward passage from the external boundary to the wire-like clusters, the resonance reflection coefficient r is given by following equation:

$$r_{s,p} = \frac{i\gamma_{s,p}}{\omega_0 - \omega - i\Gamma}$$

here $\gamma_s = \gamma / \cos \phi$, $\gamma_p = \gamma_s \cos 2\phi$ for s - and p - polarization respectively,

$$\gamma^{QWW} = (Q/d_x) \left[\int \Phi_{QWW}(\rho) d\rho \right]^2$$

$Q = k\omega_{LT}\pi a^2/2$ and, for simplicity, we assumed that $ka, kd_{x,y} \ll 1$ where a is the QWW width along z . In this case the light diffraction by the array of QWWs is absent and the exciton oscillator

strength in reflection γ_η , coincide with $(2\tau_\eta)^{-1}$, τ_η being the radiative lifetime of η -polarized excitons. Note that γ differs from radiative dumping of an exciton in a single QWW. In particular

$$\gamma^{QWW} = (2/kd_x) \gamma_y^{SQWW}, \gamma_y^{SQWW} = 2\gamma_x^{SQWW}$$

Fig.3 demonstrates the lineshape inversion in the reflection spectrum from the wire-like clusters at the Bruester angle ϕ_{Br} . The inversion takes place because the reflection coefficient on the external boundary, r_{01} , changes its sign at $\phi = \phi_{Br}$.

We would like to note a very large amplitude of resonance lineshape of exciton in quantum well wire in comparison with corrugative superlattice. The large value of the modulation indicates the large increasing of the oscillator strength of exciton in 1D structure.

The obtained value of exciton radiative lifetime, $\tau_{QWW} = (2\gamma^{QWW})^{-1} = 3\text{ps}$, appears to be very short as compared with that for excitons in SQWs: $\tau_{SQW} = 11\text{ps}$ for a GaAs/AlAs single quantum well of thickness $a=30\text{ \AA}$, $\tau_{SQW} = 10\text{ps}$ if $a=50\text{ \AA}$ or $100\text{ \AA}$. This signify much stronger exciton confinement in

Fig.3 Oblique reflection spectra measured in the p -polarization at the incidence angle close to the Bruester angle.

Fig.4 Anisotropy of reflection spectra, of QWW clusters. y -direction along wire-like clusters, x -perpendicular direction.

the structure under investigation than in a quantum well and evidences the existence of quasy-1D exciton states in our structure. Moreover, the experimental value of τ_{QWW} is in reasonable agreement with the provided theoretical estimations.

The characteristic peculiarity of these structures is the large value of anisotropy of reflectivity coefficient. That is, the reflectivity coefficient for the light polarization parallel to the wire direction ($E \parallel [233] \parallel y$) is larger than for perpendicular polarization (Fig.4). This anisotropy of reflectance displays not only the anisotropy of QWW exciton resonance contribution to reflectance but the anisotropy of background reflectivity also. We suppose that the anisotropy of background reflectivity display the optical anisotropy of the bulk cubic crystals in the nonsymmetrical orientations [311] and can be discribed by the mixing of the heavy- and light- hole states.

In addition to the anisotropy of background reflectivity we have found the remarkable anisotropy of the exciton resonance contribution to reflectance. By fitting the calculated and experimental spectra we have found the difference in the exciton oscillator strength for light polarized with $E \parallel x$ and $E \parallel y$: $\gamma_y^{QWW} / \gamma_x^{QWW} = 1.5$. This value is in agreement with the theoretical prediction for the $a/b=0.6$. (a - is a width of QWW along z direction, b - is a width of QWW along x direction (see Fig.1)).

In conclusion, the resonant reflectivity from the directly grown array of isolated QWWs have been observed. In spite of the much smaller effective volume occupaied by excitons as compared to that in a SQW, the QWW structure demonstrates essentially higher exciton oscillator strength. The 30% anisotropy of exciton oscillator strength being found for QWW demonstrates quasi-1D character of these excitonic states.

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