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Direct Synthesis of Low-Dimensional Semiconductors for Device Applications

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We demonstrate that the unusual electronic properties of III-V-semiconductor quantum-wires and dots directly grown on corrugated high- index GaAs substrates by MBE are preserved up to room-temperature. The pronounced optical anisotropy is clearly detected even above 300K and no reduction of the integrated luminescence intensity could be observed up to 400K. These findings highlight the potential of these novel low-dimensional structures for advanced semiconductor device concepts.

1. INTRODUCTION

The precise fabrication of low-dimensional semiconductors with quantum confinement of free carriers in more that one dimension is currently of great importance in the field of microstructure materials science. Size quantization in these nanometer scale semiconductor structures leads to exciting new electronic properties which have a dramatic impact on the development of novel device concepts [1].

We have recently introduced new methods to directly synthesize III-V semiconductor quantum-wire and dot structures by MBE based on the evolution of well ordered surface corrugations on non-(100)-oriented GaAs and AlAs surfaces defined by surface energy [2] and on the controlled step bunching [3]. This approach allows the precise fabrication of nanometer scale structures with an inherently high package density which is an important prerequisite for device applications. The quantum confinement of carriers in these structures is revealed in a pronounced red-shift of the photoluminescence (PL), an enhancement of the exciton-phonon interaction, increased exciton continuum energies, and a strong polarization anisotropy of the excitonic resonances in low-temperature photoluminescence excitation (PLE) spectroscopy of quantum- wire and asymmetric quantum-dot structures. In addition we have observed a strong anisotropic conductance in modulation-doped quantum-wire structures. As an example, we present in this paper for our quantum-wire structures directly grown on (311) oriented GaAs substrates (see Fig. 1)that these unusual electronic properties are preserved up to high observation temperatures and thus have the potential of exploitation in novel semiconductor devices working at room-temperature.

2. SAMPLE PREPARATION AND EXPERIMENTAL SETUP

After the removal of the oxide from the GaAs surface at 580°C in the MBE growth-chamber, 80 period 56Å GaAs/50Å AlAs multilayer structures and 56Å GaAs single layers embedded in a GaAs/AlAs waveguide structure were grown side by side on (311) and (100) GaAs substrates as reference. The waveguide structure consisted of symmetrically arranged 20 period 34Å GaAs/19Å AlAs, 13 period 20Å GaAs/19Å AlAs, 10 period 20Å GaAs/30Å AlAs, and 100 period 22Å GaAs/60Å AlAs multilayer structures. The growth rate was 1μm/h for GaAs and 0.5μm/h for AlAs. The As_4/Ga flux ratio was 5, and the substrate temperateure was 600-620°C. The structural parameters of the samples were determined by reflection high- energy electron- diffraction (RHEED),X-ray diffraction and high- resolution transmission- electron microscopy (HRTEM). The optical properties were characterized by PL and PLE spectroscopy. For PL, the red (647.6nm) line of a Kr^+- Laser, and for the PLE measurements, the light from a broadband 600W halogen lamp dispersed by a monochromator were used as excitation sources. The luminescence was detected by a cooled GaAs photomultiplier operating in the photon counting mode.

3. RESULTS AND DISCUSSION

The analysis of the RHEED patterns directly shows the breaking up of the nominally flat (311) surface into a periodic array of upward and downward steps oriented along [23$\bar{3}$]. In this azimuth the streaks are alternatingly split into sharp satellites giving the 32Å lateral periodicity and along their length, giving the 10Å step height (Fig 1a). RHEED intensity dynamics reveals a pronounced oscillation during the deposition of the first monolayers of GaAs on AlAs and vice versa due to a phase change of the surface corrugation during the heterogeneous growth on the facets. This phase change indeed generates an as-grown quantum-wire structure comprising alternating narrow and wide channels of GaAs embedded in the AlAs matrix (Fig. 1b) which has been directly confirmed by HRTEM.

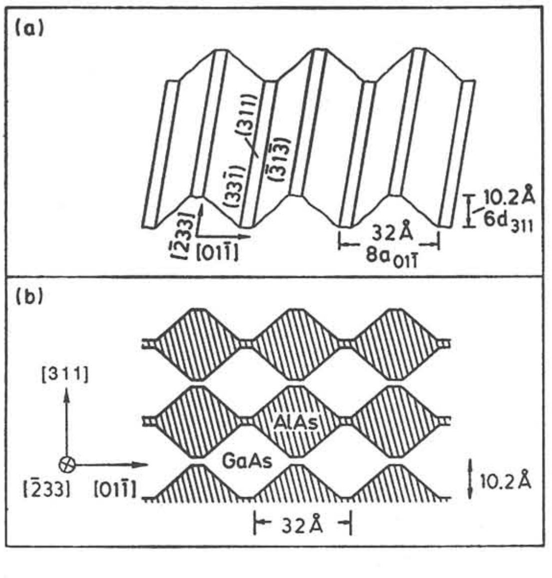

Fig. 1 (a) Schematic of the stepped (311) GaAs surface. (b) Schematic (233) cross section of the GaAs/AlAs quantum-wire structure.

The PL and PLE spectra of the 56Å GaAs(311) quantum- wire structure show a pronounced anisotropy of the excitonic resonances. For the extremely low excitation densities using the halogen lamp (10^{-6}Wcm^{-2}) the PLE spectra can be detected up to 100K (Fig. 2B). The hh-exciton resonance is more pronounced with the exciting light polarized parallel to the wire direction (perpendicular to the direction of lateral quantization) compared to the case with the light polarized perpendicular to the wires, where the lh-exciton resonance is more pronounced. The corresponding behavior is observed up to temperatures above 300K in the polarization of the luminescence (Fig. 2C). Recent calculations of the valence-band structure of (311)- oriented heterostructures have shown that the lowest hh-subband is isotropic, similar in form to that of conventional (100) oriented quantum wells [4]. Hence, the observed optical anisotropy has to be attributed exclusively to the lateral confinement introduced by the interface corrugations in these quantum- wire structures.

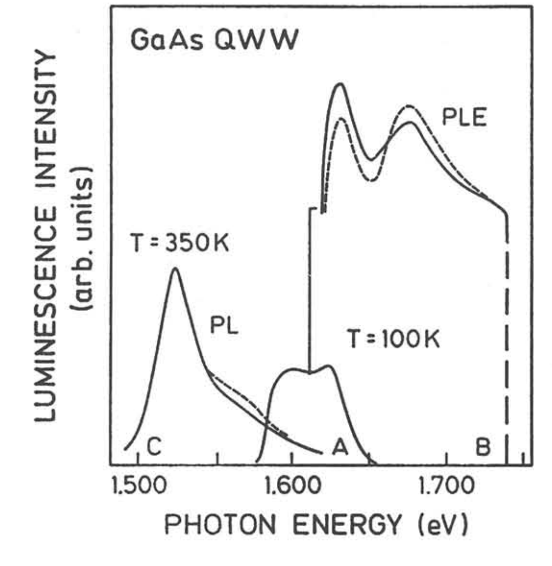

Fig. 2 PL and PLE spectra of the 56Å GaAs/50Å AlAs (311) quantum- wire structure (QWW). The measurement temperatures are indicated. The solid curves correspond to polarization parallel to the wire direction and the dashed curves to the perpendicular polarization.

The optical anisotropy is most evident in the in-plane luminescence from the cleavage plane of 56Å GaAs waveguide structures measured at 300K. (Fig. 3). In agreement with the selection rules, the hh-exciton transition of the (100) quantum-well is polarized perpendicular to the direction of quantization (z- growth direction) [5], whereas for the (311) quantum-wire structure the hh-exciton transition shows a pronounced component polarized parallel to the z-direction. This behavior clearly shows that in the quantum- wire structure efficient quantization is relevant also in a direction perpendicular to the z- direction thus demonstrating the strong lateral confinement.

The final striking result is the extremely high integrated luminescence intensity of (311) quantum- wire structures which, even at moderate excitation densities, does not degrade up to temperatures as high as 400K (maximum temperature of the measurement system) (see Fig. 4). This behavior is attributed to the reduced diffusion of the photogenerated carriers in quantum- wire structures due to the lateral confinement and strong localization. In these samples, carrier diffusion is free only along the wire direction which drastically diminishes the probability to encounter with non- radiative recombination centers.

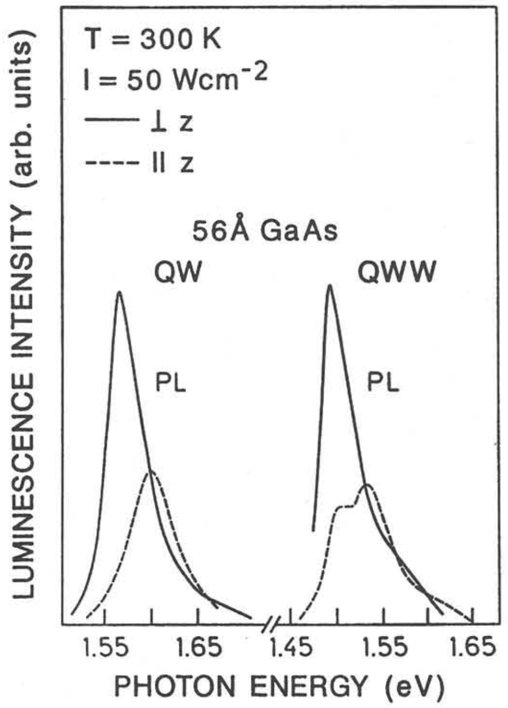

Fig. 3 PL from the cleavage plane of the 56Å GaAs (311) quantum- wire waveguide structure (QWW) and (100) quantum- well structure (QW). The solid line is for polarization perpendicular to the z-(growth) direction and the dashed line for polarization parallel to z.

4. CONCLUSION

In conclusion we have demonstrated that the unusual electronic properties of III-V semiconductor quantum- wire structures directly grown on corrugated (311) GaAs substrates by MBE are preserved up to room-temperature. The pronounced optical anisotropy of the excitonic resonances is clearly detected even above 300K and no reduction of the integrated luminescence intensity could be observed up to 400K. This behavior highlights the potential of these low-dimensional semiconductor structures for advanced optoelectronic devices.

5. ACKNOWLEDGEMENT

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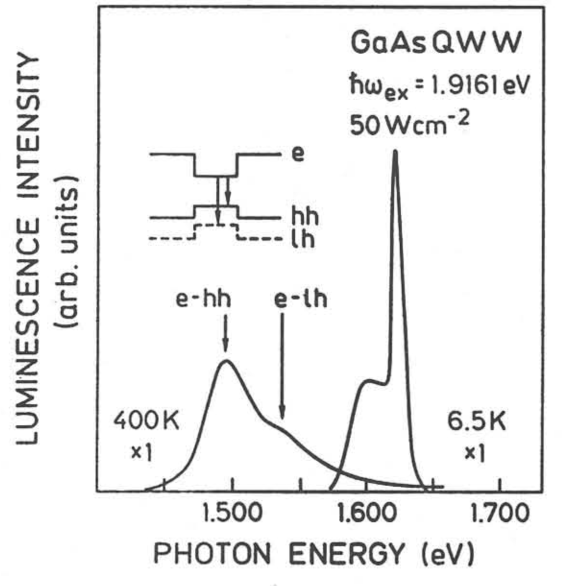

Fig. 4. 6.5K and 400K PL of the 56Å GaAs/50Å AlAs (311) quantum- wire structure. The scale is the same for both spectra.

6. REFERENCES

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