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Intrinsic optical confinement and lasing in InAs–AlGaAs submonolayer superlattices

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We study the optical properties of structures composed of stacked InAs submonolayer insertions in an AlGaAs matrix grown on a GaAs(100) surface. The increased refractive index in the active region necessary for waveguiding is caused by the absorption peak due to excitons trapped by monolayer-height InAs islands. Despite a very low *average* InAs concentration, a thin AlGaAs buffer layer and an absorbing GaAs substrate photopumped lasing in the visible spectral range is already realized at low excitation density. © *1999 American Institute of Physics.*
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Recently, significant interest has arisen principally in new devices which utilize specific properties of quantum dots (QDs).[1–3] The stability of QD excitons with respect to thermal dissociation and the absence of exciton screening in QDs up to very high excitation densities allow us to use many intrinsic advantageous properties of excitons, e.g., for lasers operating both in edge- and surface-emitting geometry.[2] Semiconductor heterostructures with submonolayer (SML) insertions of a narrow gap material[1,3,4] present an alternative to Stranski–Krastanow growth and are particularly promising for such applications as they allow us to realize narrow luminescence and absorption peaks,[1,3,4,5] and simultaneously very high oscillator strength.[6] Spontaneous formation of arrays of uniform two-dimensional islands during SML deposition has been directly demonstrated by transmission electron microscopy[1,7] and scanning tunneling microscopy[8] for II–VI and III–V materials systems, respectively. These structures, which can be also considered as arrays of quantum dots in view of the lateral sizes involved (about 4–5 nm), exhibit unique optical properties: increased exciton binding energy due to lateral confinement,[9] high photoluminescence (PL) efficiency,[1,3] and large exciton oscillator strength (or peak absorption) even for very dilute SML coverage.[6] From the Kramers–Kronig equation, which relates real and imaginary parts of the dielectric constant, one can obtain the exciton-induced energy-dependent modulation of the refractive index, which is strong if the maximum absorption is high. Enhancement of the refractive index occurs on the low-energy side of the absorption peak.[1,7] In the case of carrier injection, the gain peak is typically located at the lower-energy side of the absorption peak. Then, the enhancement of the refractive index at this energy can be even more pronounced. For photons in this range, optical confinement is still most efficient for absorbing substrates, and minor optical losses will occur. Earlier it was shown that for stacked CdSe SMLs in a ZnMgSSE matrix lasing without external optical confinement by an additional waveguide can be realized up to and above room temperature.[1,7,10]

In this work we study the optical properties of III–V structures for a model system of SML InAs insertions in an AlGaAs matrix. Lasing under photoexcitation in the red spectral range is demonstrated for a structure without any external optical confinement by, e.g., a thick AlGaAs waveguide typically used for lasers. Lasing already occurs at low excitation density on the low-energy side of the exciton resonance energy derived from the optical reflectance spectrum. Obviously, also in III–V structures excitons localized by SML insertions are not screened by free carriers at high excitation densities and the structures proposed can be of great importance for improvement of optical confinement and reduction of degradation of AlGaAs injection lasers operating in the infrared to red range, for realization of excitonic waveguides, and for self-adjusted microcavities.[11]

The structures are grown by molecular-beam epitaxy on GaAs(100) substrates. In the case of the most extensively studied structure, first a 0.3 μm thick GaAs buffer is grown, and is followed by a 0.7 μm thick $Al_{0.32}Ga_{0.68}As$ layer. The active region is comprised of 20 GaAs quantum wells (QWs) of 1 nm width separated by 5 nm thick $Al_{0.32}Ga_{0.68}As$ spacer layers. InAs insertions having an average 0.5 ML thickness are introduced in the center of these GaAs quantum wells. From both sides the active region is confined by thin 10 nm $Al_{0.4}Ga_{0.6}As$ layers to prevent transport of carriers towards the surface or the semi-insulating substrate. A 100 nm thick $Al_{0.32}Ga_{0.68}As$ layer followed by a 10 nm GaAs cap layer is grown on top. The growth temperature for the buffer and cladding layers is 600 °C. The active region is grown at 485 °C to prevent reevaporation and surface segregation of indium atoms.

Photoluminescence spectra were excited using an Ar ion laser or a pulsed N_2 laser. PL excitation spectra were recorded using the light of a halogen lamp dispersed through a monochromator. Optical reflectance (OR) spectra are recorded using a nonmonochromatic excitation. Gain spectra

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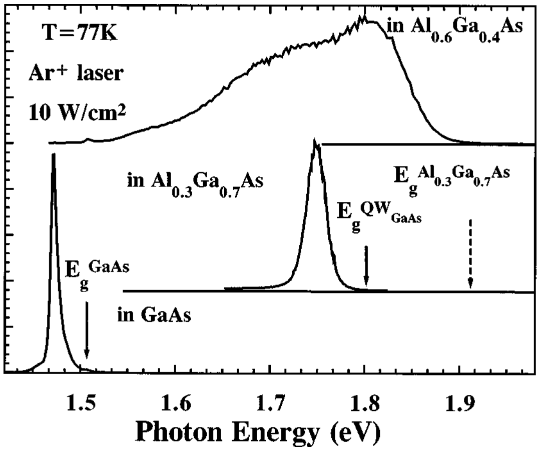

FIG. 1. Photoluminescence (PL) spectra of InAs submonolayer (SML) structures in matrices with different Al content. Band-gap energies for GaAs and $Al_{0.3}Ga_{0.7}As$ barriers are shown by arrows, as well as the energy of the 1 nm thick GaAs quantum well in $Al_{0.3}Ga_{0.7}As$, where InAs submonolayers are shown in the inset.

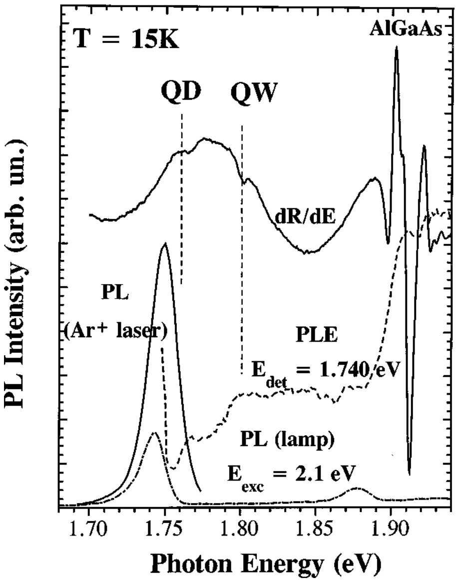

FIG. 2. PL, PL excitation, and optical reflection spectra of a SML superlattice (SML SL) structure with $Al_{0.3}Ga_{0.7}As$ barriers. Lamp excitation density is 10^{-5} W/cm^{2}and the Ar^+ ion laser excitation density is 100 W/cm^2.

are recorded by the variable-stripe length method using a dye laser.[7]

Figure 1 shows PL spectra of InAs SML samples grown in two different matrices. One can see that an increase in Al composition results in a shift of the SML photoluminescence peak towards higher energies. A significant broadening of the PL line appears. The increase in Al composition also increases significantly the energy separation between the InAs SML exciton peak and the Γ states in the matrix material. The electron confinement becomes weak due to the importance of the indirect (X type) conduction-band minimum of $Al_{0.6}Ga_{0.4}As$. Thus, a 30% AlAs composition in the matrix represents a compromise for significant exciton localization and a comparatively low width of 26 meV of the PL peak.

In Fig. 2 we show the PL, PL excitation (PLE), and optical reflectance spectra of this structure. The PLE and OR spectra demonstrate features at energies of 1.761 and 1.801 eV denoted as QD and QW, respectively. At higher excitation densities the PL line due to the InAs SML insertions shifts slightly to higher energies and approaches a position coincident with the energy of the exciton resonance revealed in the OR spectrum. This effect is attributed to filling of SML islands having smaller quantization energies.

Calculations of the heavy-hole exciton energy level in the narrow GaAs QW and a comparison to PL, PLE (e.g., step-like PLE behavior at 1.8 eV) and OR spectra (an oscillation occurs at 1.8 eV) show that the states at this energy are related to the onset of the QW states.

The contribution of the exciton effect to the refractive index enhancement was estimated by fitting the reflectivity curve using the actual structure geometry and exciton oscillator strengths as adjustable parameters. The SML region was modeled as an isotropic medium. The fitting procedure gives the resonant enhancement of the refractive index of 0.04. For in-plane light propagation and the disk-like shape of the QDs, the oscillator strength should be approximately twice higher for the in-plane polarized light. Thus, a reasonable estimate of the resonant enhancement of the refractive index for in-plane light propagation is 0.08. This contribution is larger than the contribution due to the increased average GaAs content in the active layer and the InAs SML insertions ($\Delta n = 0.06$). Both contributions taken together result in the total refractive index enhancement of 0.14, which is enough to confine the lightwave in the active region.

To study lasing, a 1 mm long Fabry–Perot cavity was fabricated by cleaving. Luminescence was excited via the surface after excitation with a pulsed N_2 laser focused to a stripe. The lasing characteristics of the structure are presented in Fig. 3. The inset of Fig. 3 shows a comparison of PL spectra recorded from the surface of the structure and in edge geometry at 77 K. The QD resonance energy recorded at 77 K is also shown. At about 1000 W/cm^2 the PL peak in the edge geometry remarkably narrows and the slope efficiency increases by more than an order of magnitude.

The lasing occurs at 1.751 eV, which is in the vicinity of the exciton feature QD in the OR spectrum (1.757 eV) in Fig. 2. Thus, lasing occurs via the exciton ground state in InAs SML QDs. The threshold excitation density at 15 K is 800 W/cm^2, as shown in Fig. 3(b). The calculated corresponding injection current density value is only about 200 A/cm^2. This value presents an upper limit due to the unknown surface loss of nonequilibrium carriers induced by the near-surface excitation using an ultraviolet laser.

In Fig. 3(a) the temperature dependence of threshold excitation density is shown. At temperatures below 50 K the threshold excitation density is almost temperature insensitive. This behavior agrees with the QD nature of excitons trapped at InAs islands. Qualitatively similar dependence is observed for injection lasers with *three-dimensional* (In,Ga)As/GaAs QDs.[2,12] We note that the temperature stability of the threshold density can be significantly improved by using wider gap cladding layers, narrower GaAs quantum wells, larger barriers, or by using the concept of vertically coupled QDs,[13] which was recently demonstrated for II–VI submonolayer islands.[14,15] Thus, further optimization might result in room-temperature operation of intrinsic waveguides in III–V materials systems and in injection lasing.

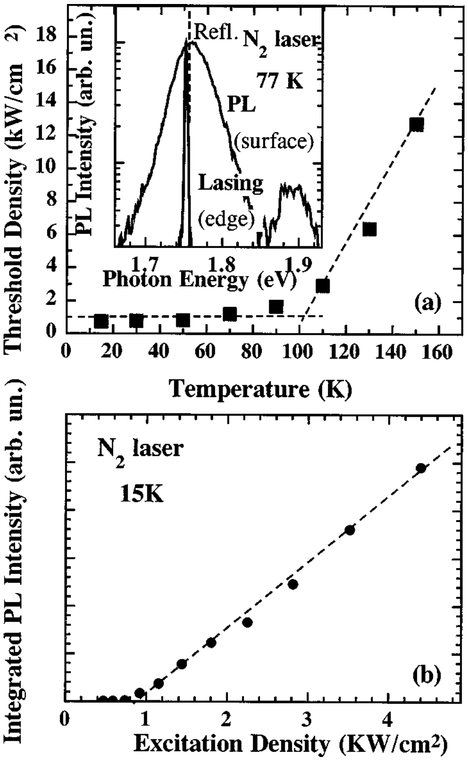

FIG. 3. Temperature dependence of the threshold excitation density (a) and light output vs excitation density dependence (b) of the InAs–$Al_{0.3}Ga_{0.7}As$ SML SL. No external optical confinement is used. Comparison of PL spectra recorded from the surface and the edge of the structure is shown in the inset. Excitation density of 1.5 kW/cm^2 is above threshold for lasing.

In Fig. 4 we show gain spectra of the structure. We note that the gain peak remains narrow and the absorption peak does not disappear up to very high excitation densities in full agreement with the concept of resonant waveguiding. This is in marked contrast to the case of quantum wells or bulk GaAs, where significant broadening of the gain spectrum with excitation density takes place. We observe also a saturation of the QD gain at highest excitation densities and attribute this effect to filling of QD states available in the range of resonant waveguiding.

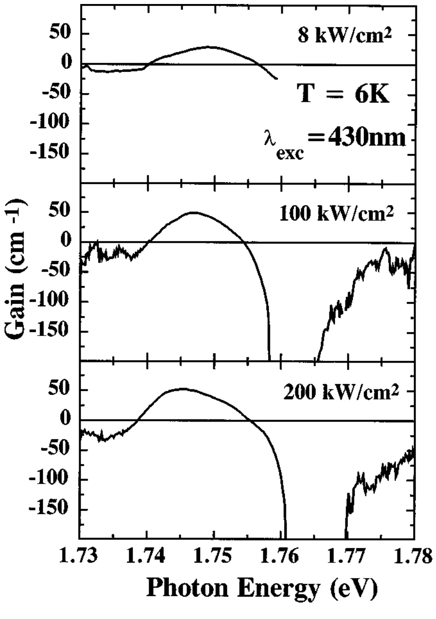

FIG. 4. Gain spectra of the InAs–$Al_{0.3}Ga_{0.7}As$ SML SL at different excitation densities. Note that the absorption peak remains in the spectra up to highest excitation densities and no significant broadening of the gain spectrum occurs.

It is noteworthy that we found no gain or even measurable spontaneous emission from the edge of the structure with four 5 nm thick GaAs quantum wells separated by 30 nm thick AlGaAs layers used as an active region.

To conclude, lasing without external optical confinement is demonstrated in III–V structures with InAs submonolayers in an AlGaAs matrix.

We expect that SML structures will be very attractive for improvement of optical confinement in AlGaAs and InGaAsP lasers operating in the visible spectral range, and for creation of excitonic waveguides and vertical cavity lasers where a self-adjustment of the cavity mode and the gain spectrum can be realized due to resonant modulation of the refractive index caused by the gain peak.[11]

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