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Asymmetric Hybrid Al(Ga)SbAs/InAs/Cd(Mg)Se Heterostructures for Mid-IR LEDS and Lasers

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ABSTRACT

A hybrid double heterostructure with large asymmetric band offsets, combining AlAsSb/InAs (as a III-V part) and CdMgSe/CdSe (as a II-VI part), has been proposed as a basic element of a mid-infrared laser structure design. The p-i-n diode structure has been successfully grown by molecular beam epitaxy (MBE) and exhibited an intense long-wavelength electroluminescence at 3.12 μm (300K). A II-VI MBE growth initiation with a thin ZnTe buffer layer prior to the CdMgSe deposition results in a dramatic reduction of defect density originating at the II-VI/III-V interface, as demonstrated by transmission electron microscopy. A less than 10 times reduction of electroluminescence intensity from 77 to 300K indicates an efficient carrier confinement in the InAs active layer due to high potential barriers in conduction and valence bands, estimated as $\Delta E_C = 1.28$ eV and $\Delta E_V \sim 1.6$ eV. An increase in the pumping current results in a super-linear raising the EL intensity. The type of band line up at the coherent InAs/$Cd_{1-x}Mg_xSe$ interface is discussed for $0 \le x \le 0.2$, using experimental data and theoretical estimations within a model-solid theory.

INTRODUCTION

Fabrication of room temperature cw semiconductor laser diodes for the 3-5 μm spectral range is still a big challenge. A hole leakage from an active region of pure III-V laser structures due to the particular valence band line up of InAs usually used in the active region may hamper the achievement of a low threshold current and a high output power [1].

To solve the problem of efficient hole confinement in InAs, taking a benefit of type I and type II band alignment, we have proposed a hybrid III-V/II-VI double heterostructure with large asymmetric band offsets in conduction (AlAsSb/InAs) and valence (InAs/CdMgSe) bands, as a basic element of a new mid-IR laser structure design [2]. In this case AlAsSb and CdMgSe form a strong type II heterojunction, while InAs layer interfaces are of type I, that leads, on the one hand, to high optical gain and quantum efficiency like in conventional type I double heterostructure lasers and, on the other hand, to significant suppression of both electron and hole leakage from the active region. The important feature of the proposed structure that it can be grown pseudomorphical as a whole because both AlAsSb and CdMgSe are lattice-matched to the InAs at appropriate ternary alloy compositions. An improvement of the structural quality is shown to be achieved by growing a thin ZnTe buffer layer at the III-V/II-VI interface.

EXPERIMENTAL DETAILES

The III-V part of the hybrid structures was grown by molecular beam epitaxy (MBE) in a Riber 32 chamber on a p^+-InAs (100) substrate at temperature T_S=480°C. It consists of a 0.1 μm thick p^+-InAs:Be buffer layer, a 1 μm thick p-AlGaAsSb:Si layer followed by a 20 nm thick p-AlAsSb:Si barrier and an undoped 0.6 μm-InAs layer ($n < 10^{17}$ cm^{-3}). Thereafter, the III-V structure was transported to a separate II-VI home-made MBE chamber through air under an As cap which then was removed by annealing the sample at T_S in the 460-480°C range. A reflection high-energy electron diffraction (RHEED) system was used to monitor surface conditions. Due to the relatively high annealing temperature an intermediate (2×4)As&(4×2)In surface reconstruction has been usually obtained. Two types of growth initiation procedure at the III-V/II-VI heterointerfaces were used. At the first one, a 10 nm thick CdMgSe layer was grown in a migration enhanced epitaxy (MEE) mode at ~200°C to reduce the defects density on the InAs/CdSe interface [3], which usually resulted in a streaky RHEED patterns. The deposition times of Cd and Mg were chosen to provide desirable alloy composition. At the other, T_S=280°C was kept constant from the very beginning of II-VI growth which was initiated with a deposition of a ~5 nm thick ZnTe buffer in the MBE mode, as was proposed by Grabs et al. [4]. The growth of the following CdMgSe structure occurred at 280°C in the MBE mode under the (2×1)Se-stabilized conditions. It consists usually of 50 nm of nominally undoped CdMgSe followed by 0.3 μm of n-type CdMgSe:Cl and capped with 10-nm-CdSe:Cl. $ZnCl_2$ is used as the n-doping source in this case. The electron concentration in the CdMgSe is of 4×10^{17} cm^{-3}, as indicated by C-V measurements. The Mg mole fraction in the layers ranges within 15-17%, as it follows from x-ray diffraction (XRD) measurements confirming also a pseudomorphic nature of the II-VI layers, although the $Cd_{1-x}Mg_xSe$ composition lattice-matched to InAs corresponds to x~0.10.

Previously, photoluminescence (PL) studies of the structures have been performed over a wide spectral range at 77K, using single-grating monochromators and different excitation sources for different spectral regions [5]. An InGaAs cw laser diode emitting at 950 nm was used to excite PL in the III-V part of the structure responsible for the emission in the infra-red spectral region, whereas a 325 nm line of a cw He-Cd laser was used to excite PL from the CdMgSe layer. The bright relatively narrow peaks at the energies of 0.41 eV and ~ 2.1 eV attributed to the near-band-edge recombination in InAs and CdMgSe layers, respectively, were observed in the PL spectra. The estimation of Mg content in the CdMgSe layer from the respective PL peak position [6] gives the value of ~15% that corresponds well to the XRD data.

For electroluminescence (EL) studies the mesa diodes of 300 μm diameter with a 50 μm round contact were fabricated using a standard photolithography and deep wet chemical etching. A liquid N_2-cooled InSb photodetector and a lock-in amplifier were used for light detection. EL spectra were measured both under quasi-cw conditions with pulse duration of τ = 2.5 ms and filling factor of 1/2 and in a pulsed mode with pulse duration τ = 1-10 μs and a repetition rate $f = 10^3$-10^4 Hz.

RESULTS AND DISCUSSION

Cross-sectional transmission electron microscopy (TEM) images of the hybrid structures with the two different interface types are presented in Fig. 1. The structure with the InAs/CdSe interface (Fig. 1a) exhibits the stacking fault (SF) density in the 10^7-10^8 cm^{-2} range, which is probably due to the not completely optimized initial surface reconstruction of InAs, allowing an In-Se interaction at the heterovalent InAs/CdSe interface formation. The formation enthalpy of In_2Se_3 characterized by a defect sphalerite structure (-344 kJ/mole [7]) is even smaller than that of Ga_2Se_3, making the probability of In_2Se_3 nucleation at the InAs/CdSe interface very high.

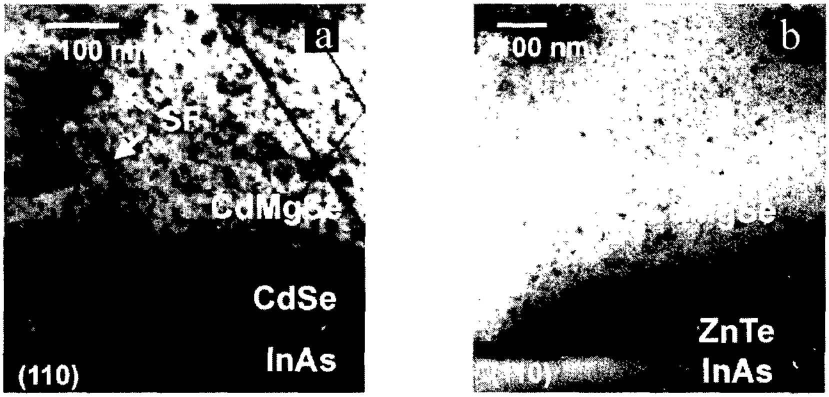

Figure 1. Cross-sectional dark-field TEM images of the hybrid structures: (a) with CdSe/InAs interface ($\vec{g}_{400}$) and (b) with the ZnTe buffer layer at the III-V/II-VI interface ($\vec{g}_{200}$). Electron beam is parallel to the [1 10] direction.

Lowering the temperature of As cap re-evaporation or growing an InAs buffer layer in a ultrahigh-vacuum-connected III-V MBE chamber is expected to prevent the InAs surface depletion of As, that should suppress the In-Se interaction. Contrary to that, the SF density in the structure with the ZnTe buffer layer (~5 nm), as illustrated in Fig. 1b, is at least two orders of magnitude lower (below 10^6 cm^{-2}), which is obviously explained by the ZnTe passivation of the InAs surface before a Cd(Mg)Se growth.

For EL studies the structures without the ZnTe buffer layer were used. Even in this case an intense electroluminescence has been observed at both 77 and 300K (Fig 2a). The EL spectrum at 77K contains a single emission band with a photon energy maximum at 0.43 eV and a FWHM value of 40 meV. The emission band has a weakly asymmetric shape with the abrupt high-energy side. The room temperature EL spectrum contains also a single emission band with a photon energy maximum at 0.396 eV and FWHM = 68 meV, although the peak has a reverse asymmetry with a noticeable low-energy tail. The photon energy of the spontaneous EL slightly exceeds the InAs peak energy observed in the PL spectra perhaps due to high pumped carrier density.

The dependences of EL intensity on a drive current in a quasi-cw and pulse modes were studied both at low and room temperatures. The behavior of these dependences is similar, while more intense signal is achieved in a quasi-cw mode (Fig. 2b). The intensity of spontaneous emission at 77K increased superlinearly with the drive current rising. With the temperature increase from 77 to 300K, the maximum EL intensity decreases just by 7-10 times. This weaker temperature dependence of the spontaneous emission, as compared to that observed in conventional InAsSbP/InAs-based laser structures [8], evidences higher band offsets and better hole confinement in the hybrid structure.

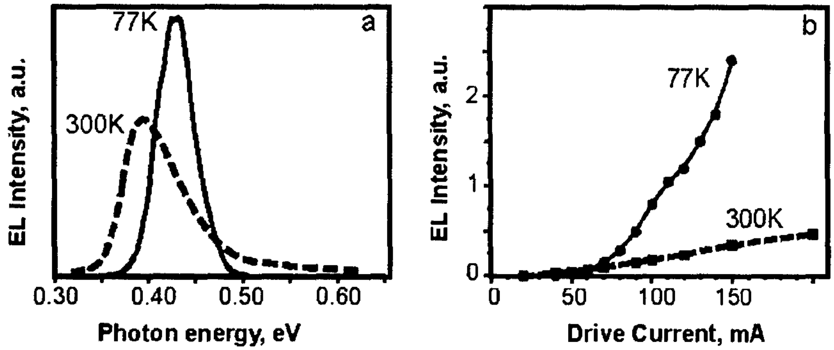

Figure 2. (a) EL spectra of the hybrid structure under quasi-cw conditions at 77K (solid curve) and 300K (dashed curve). (b) The EL intensity versus drive current in quasi-cw mode at 77K (solid curve) and 300K (dashed curve).

To estimate the band-offsets at the InAs/CdSe interface we used the known values for the CdSe-ZnSe, ZnSe-GaAs, GaAs-InAs hetero-pairs and also the "model-solid theory" of Van de Walle [9] to take into account the strain effect. As a result, type II band line-up for the InAs/CdSe interface has been obtained. InAs represents a ~60 meV potential barrier for electrons at the bottom of the CdSe conduction band, whereas the heavy hole band offset at the interface is as large as ~1.42 eV. An incorporation of a large enough content of Mg changes the situation at the InAs/CdMgSe interface from type II to type I. Our recent experimental studies of optical band bowing of the CdMgSe alloys as well as of the valence-to-conduction band offsets ratio [6] shows the conduction band offset between CdSe and $Cd_{0.9}Mg_{0.1}Se$ alloy lattice-matched to InAs as high as 150 meV, which results in the type I band alignment at the InAs/$Cd_{0.9}Mg_{0.1}Se$ interface with ΔE_C~90 meV. Moreover, in the studied structures, with the Mg content in the CdMgSe layer of 15-17%, the peak energy of the CdMgSe PL band gives the CdSe/$Cd_{0.83}Mg_{0.17}Se$ band gap difference about 350 meV. This leads to even higher band offsets as compared to those evaluated for the lattice-matched structure. Thus, the AlAsSb/InAs heterointerface with the well known ΔE_C=1.28 eV value and the InAs/CdMgSe heterointerface can readily prevent the electron and hole leakage from the InAs active layer.

To elucidate this point, comparative EL studies of the hybrid p-i-n structures with and without a 10nm-CdSe layer grown between InAs and CdMgSe layers have been carried out (samples B and A, respectively, in Fig. 3). Sample A shows the bright InAs related luminescence peak shifting to higher energies with increasing the pumping current. In contrast, sample B exhibits a 30 meV low energy shift of EL peak with respect to InAs one. Moreover, one can observe a dramatic decrease in the EL intensity of sample B. Taking into account these results, we believe that in the latter case EL is defined by electron-hole recombination at the type II InAs/CdSe heterojunction containing large enough density of non-radiative recombination defects, while in the former structures EL originates at the high quality AlAsSb/InAs interface. These conclusions have also been supported by Hall measurements of the electron transport along the respective interfaces, reported elsewhere [5].

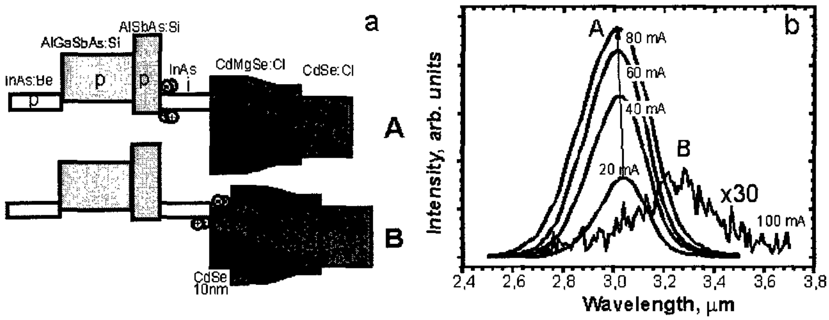

Figure 3. Schematic band diagram (a) and electroluminescence spectra at 77 K (b) of the hybrid structures with (B) and without (A) CdSe QW adjusted to InAs.

CONCLUSIONS

A double p-i-n heterostructures with high asymmetric band offsets, based on a combination of III-V (AlAsSb/InAs) and II-VI (CdMgSe/CdSe) compounds, have been proposed for mid-IR laser applications and successfully grown by MBE on InAs. Intense long-wavelength EL has been observed both at low (77K) and room temperature. Weak temperature dependence of the spontaneous emission is an evidence of the efficient carrier confinement in the InAs layer due to high potential barriers in conduction (ΔE_C = 1.28 eV) and valence (ΔE_V ~ 1.6 eV) bands. A change of the InAs/CdMgSe band alignment from type II to type I with the Mg content increase has been predicted and experimentally demonstrated. Significant lowering of the stacking fault density (below $10^6 cm^{-2}$) has been achieved in the structures by incorporation of ZnTe buffer layer at the InAs/CdMgSe interface, preventing interaction between In and Se atoms. Laser diodes based on the hybrid III-V/II-VI double heterostructures are expected to exhibit a lower threshold current and higher characteristic temperature.

ACKNOWLEDGMENTS

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