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In(Ga)As- and InAs(Sb)-Based Heterostructure LEDs and Detectors for the 3÷5 μm Spectral Range

Boris A. Matveev, Meyrhan Aydaraliev, Nonna V. Zotova, Sergey A. Karandashov, Maxim A. Remennyi, Nikolai M. Stus', Georgii N. Talalakin

IOFFE Physico-Technical Institute, Russian Academy of Sciences, Polytechnicheskaya ul. 26, St. Petersburg, 194021 Russia, e-mail: bmat@iropt3.ioffe.rssi.ru, Tel/Fax: (812) 247 7446

Over the last decade there has been sufficient progress in design of ambient operating mid-infrared (λ=3÷5 μm) QC lasers and QW detectors that will find numerous applications in spectroscopy of gases and free space communications. However, among cost effective candidates for the above applications we can also consider electrically [1] and optically [2] pumped (OP) light emitting diodes (LEDs) as well as negative luminescent (NL) devices [3]. The latter are especially attractive for high temperatures/long wavelength applications.

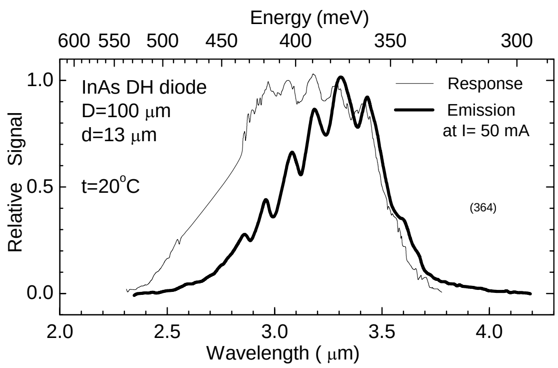

Fig.1 Emission and photoresponse vs wavelength in 13-μm thick InAs double heterostructure episide down bonded diode

Here we present episide down bonded mid-IR LEDs and photodiodes grown by the liquid phase epitaxy with active layer compositions close to InAs and operating in the 20÷120°C temperature range.

"Short wavelength" diodes with peak wavelength λ < 3.4 μm consisted of ~10÷100 μm thick heavily doped n+-InAs substrate (Sn, n=(3÷6)·10^{18} cm^{-3}), ~1 μm thick n-In(Ga)As undoped active region with small amount of gallium grown from the Gd doped melt and finally 2÷3 μm thick wide-gap p- $InAs_{1-x-y}Sb_xP_y$ (Zn) (0.05≤x≤0.09, 0.09≤y≤0.18, p=2÷5 10^{17} cm^{-3}) contact or cap layer.

InAsSbP/InGaAsSb double heterostructure (DH) with 1-2 μm thick quaternary layers onto ~100 μm thick n-InAs substrate (n=2·10^{16} cm-3) and was used for the "medium" wavelength devices with λ =3.8÷3.9 μm.

"Long wavelength" LED structures (λ > 4 μm) constitute 60-80 μm thick n-InAsSbP graded band gap (∇E_g=1÷2 meV/μm) window layer and 5 μm thick p-InAsSb (Zn) layer with curved structure features and high crystalline perfection as described elsewhere [4].

The above heterostructures were processed into "flip chip bonded" (or "backside illuminated") circular mesa constructions (D=100÷430 μm) with nonalloyed broad gold anode, "horse shoe" cathode, output being extracted through transparent outer n- or n^+- surface as described in [5]. In the latter case the benefits were not only substrate transparency at 3.3 μm due to Moss-Burstein effect but also low serial resistance amounting to 0.1 Ω for the best devices. Current saturated in the reverse bias while zero bias resistance (R_o) was reciprocally proportional to square mesa diameter (~D^{-2}). Emission band exhibited slight longwave shift with respect to responsivity spectra peak wavelength both being not broader than ~0.1 λ_{max} for ~100 μm thick devices. The highest achieved room temperature R_oA values faded from 3 for diodes with λ_{max}=3.3 μm to 0.003 Ω·cm^2 for λ_{max} =5.4 μm correspondingly. Similarly the $D^*_{\lambda max}$ values dramatically decline from 1.6·10^{10} at 3.3 μm (InAs) to 4.7·10^8 $cmHz^{1/2}$/W at 5.4 μm (InAsSb).

In n^+-InAs based devices the short wavelength responsivity spectra shoulder coincided with n^+-InAs transmission spectra while most of radiation was absorbed at $\lambda=\lambda_{max}$ by a 1÷2 μm thick InAs active layer. We believe that the nonalloyed contact (bottom of the structure) contributes to the device performance in both photodetector and emitter operation modes due to light reflection towards active layer/outer surface. This belief is supported by an existence of several Fabry-Perot modes in both emission and resposivity spectra of a 13-μm thick and 100-μm wide diode (η =1.1, R_s ~2.7 Ω, R_0= 15 kΩ) as shown in Fig.1. Assuming that the reflectivities constitutes to R_1≈0.9 for anode and R_2≈0.3 for the front LED surface we can estimate [6] the resonator finesse as Q≈31. The calculated value Δhν≈9 meV (or Q≈40 for n=3.5) is fairly close to the experimentally observed figure of Δhν≈11 meV (or Q≈31) indicating high quality of both "mirrors" of the LED structure. The described structure is far from being optimal for resonant cavity (RC) LED operation, however, it allows to be improved through "gluing" additional Bragg mirrors on top of the structure.

In our initial "RC" experiments we used a set of standard bandpass filters with λ_{max} =3.3, 3.9, 4.3 and 5.5 μm correspondingly deposited onto Si substrate and attached to the free diode surface by a chalcogenide glass with n=2.6. As an example in Fig.2 we show NL and positive luminescence (PL) emission spectra of $InAsSb_{0.2}$ diode together with filter transmission. As seen from Fig.2 the reduction of the emission bandwidth well below the kT value (down to FWHM=8 meV) for both NL and PL spectra was not followed by a peak power decrease. Unlike the uncoated LEDs the above "RCLEDs" exhibit weak temperature variation of the peak position and output power at saturation. Thus a diode at $I=I_{sat}$ is a power and wavelength "stabilized" NL source that can be therefore used for reference and measurement purposes.

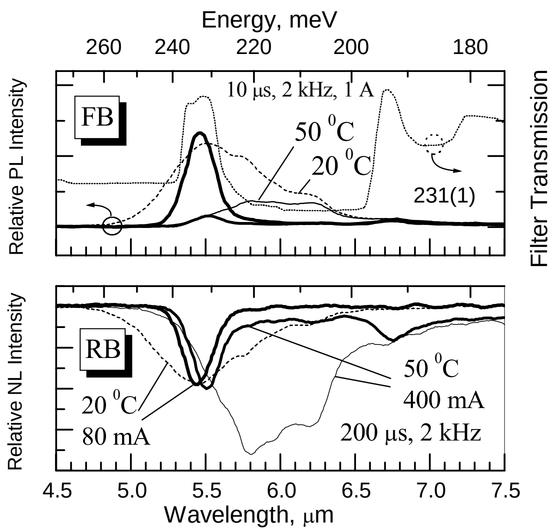

Fig.2 Positive (top) and negative (bottom) emission spectra of 430 μm mesa $InAsSb_{0.2}$ diode with free surface and with filter (thick lines) at 20 and 50°C.

Finally, we would like to mention convenience of the diode device for practical applications. First, the n^+-InAs based diodes can efficiently work as both LED and photodiode. The assumption is supported by simple consideration that the NLP/I_{sat} ratio is merit or source efficiency where NLP – is the negative luminescent power at saturation and I_{sat} is the saturation current. Thus a device with the lowermost dark current is at the same time the source with highest conversion efficiency (mW/A). That's why PL conversion efficiencies as high as ~2 mW/A have been obtained in diodes with high detectivity ($D^*_{3.3\ \mu m}$ =$1.6\cdot10^{10}$ cm $Hz^{1/2}W^{-1}$). Second, the episide down bonded construction can be equipped with the immersion lens giving 3÷5 fold increase of power/sensitivity [2, 5] and making feasible application of optically coupled diode pairs. Such pairs coupled through spherical mirror and activated by single current pulse of only 10 mA exhibited signal/noise ratio as high as 70 (3.3 μm)÷2 (5.4 μm) dB in the Δf= 1 MHz band with corresponding values from 80 to 50 dB at high pumping currents (0.5÷4.5 A).

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