Midinfrared diode arrays and LEDs based on In(Ga)As(Sb) with Photonic Crystals

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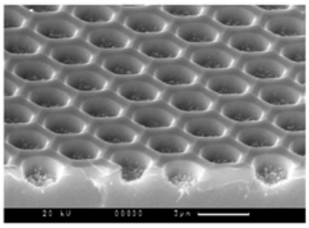
Mid-IR LEDs emitting in the 3-5 µm range can replace existing thermal emitters used for portable and low power consumption gas analyzers designed for detection of many industrial and natural gases such as CO_2, CO, CH_4, H_2S etc.. Multielement light sources with individual element addressing have potential use in miniature grating spectrometers that are capable recording transmission spectra using sequential activating of elements. Immersion optics and flip-chip technology have been implemented for efficiency enhancement in LEDs [1, 2] while further improvements of LED arrays could arise from photonic crystals implementation. However to the best of our knowledge there is only one paper describing photonic crystal structures for mid-IR spectral range [3] and there are only few papers on mid-IR LED arrays.



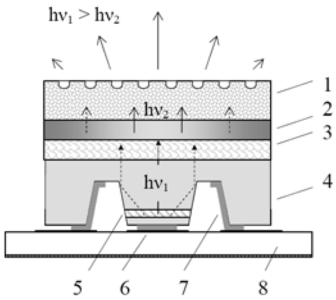


Fig. 1 Scheme of an optically pumped LED with PC (bottom) where 1- n^+-InAs substrate with periodic structure, 2- n^o-InAs layer, 3- optical glue, 4 –GaAs LED in which 5- active area, 6- anode, 7- cathode, 8- Si submount. Upper part: SEM image of n^+-InAs outcoupling surface. Horizontal white line corresponds to a distance of 3 µm.

Here we present analysis of spontaneous sources emitting in the 3-5 µm range and describe basic properties of In(Ga)As(Sb) based high brightness LEDs and arrays including those with a photonic crystal structures allowing individual addressing of elements and capable simulation of hot (T_a>$T_{env.}$) and cold (T_a<$T_{env.}$) objects.

Photonic crystals (PC) were formed onto n^+-InAs (n^+~10^{18} cm^{-3}) outcoupling surface using ion ("dry") etching through holes in a mask formed by a standard photolithography method. Hexagonally arranged semiholes in n^+-InAs with typical diameters of 0.5÷2 µm and interhole distance of ~3 µm formed PC (see Fig.1, top).

In LEDs with optical pumping [1] GaAs LED (λ=0.8 µm) has been used as a pumping source (see Fig.1, bottom). As seen from Fig.2 normal reflection was blocked at wavelengths related to PC period (~2.4÷3 and 1.3÷1.6 µm), while the outcoupling efficiency was two fold of that of the LED without PC.

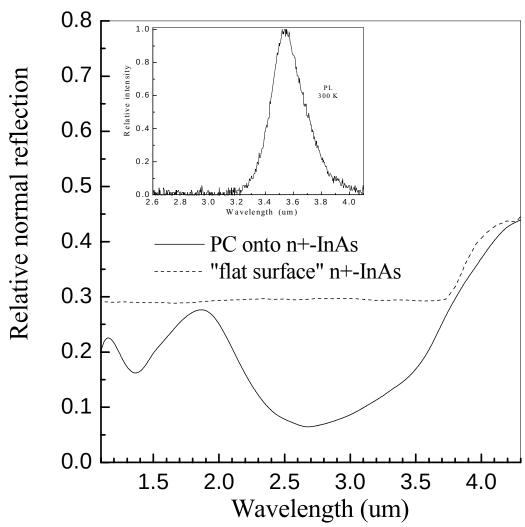


Fig. 2 Reflection coefficients for a normal rays when measured on plane samples from 350 µm thick n-InAs (dotted line) and 500 µm thick n^0-InAs/n^+-InAs structures with PC onto n^+-InAs surface (solid line). Insert – emission spectra

1x4 LED arrays with 130x130 µm element dimensions operating at 3.7 µm consisted of ~2 µm thick broad band contact p-InAsSbP layer (E_g(300 K)~ 420 meV), ~5 µm thick n-InGaAsSb active layer grown onto a heavily doped n^+-InAs (n^+~ 10^{18} cm^3) substrates. Shown in Fig.3 are photo of diode array chip and false IR images taken from epitaxial side (a, b, c) as well as IR device images (d, e) recorded at several conditions:

at thermal equilibrium (b), at diode biasing (d, e) and at external lightening with a 2.9 µm LED (c).

Fig.4 presents I-V and pulse L-I characteristics of array elements. Saturation current was as small as I_{sat}= 39 µA (j_{sat}=0.23 A/cm^2); an ideally factor in the forward part of the I-V characteristic was in the order of γ=1.1. Conversion efficiency decreased from 0.133 mW/A at small currents down to 0.035 mW/A at I= 1A.

a b c d e

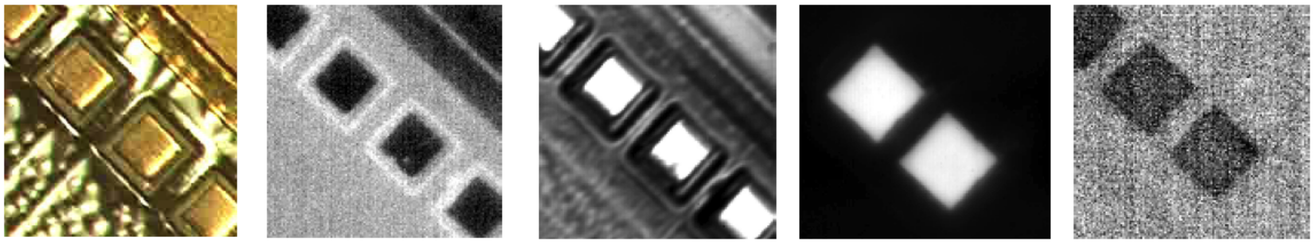


Fig.3 Photo (a) and IR images (b, c, d, e) of a diode array where dark color corresponds to low emissivity/apparent temperature T_a while white color corresponds to high emissivity/apparent temperature T_a. a, b, c – measurements from the epi-side, d, e – measurements from the substrate side (n^+-InAs) with external lightening λ=2.9 µm (c) and bias (d, e). d- forward bias is applied to two array elements, e – reverse bias is applied to three array elements.

Within the assumption of normal reflectivity at semiconductor/air interface of R=0.3 the maximal conversion efficiency (CE) constitutes to NPL/j_{sat} = 0.23 mW/A (NLP=0.054 mW/cm^2), where NLP –negative luminescence power, j_{sat} - saturation current. The above simulated value is only 40% higher than the experimental one indicating high quality of the structures.

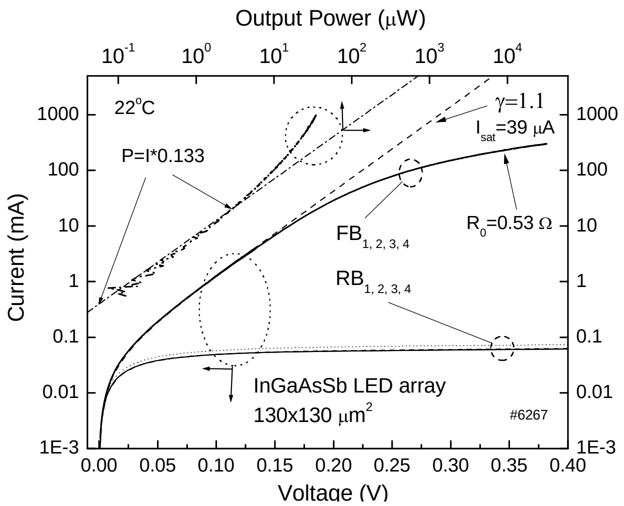


Fig.4 Typical I-V (left and low scales) and L-I (right and upper scales) characteristics of array elements #1, #2, #3, #4. Dotted line presents the function of the form I=0.039(exp(U/γкT-1), γ=1.1, where U- bias voltage, I –current

One can express LED brightness – the key parameter for abovementioned applications – in terms of an apparent temperature, that is black body temperature that produces an equivalent of LED amount of radiation energy [4]. On evaluating the T_a values we assumed that at high currents the emitting area is close to the anode dimensions due to the current crowding effect. Taking into account above considerations the apparent temperature for the narrow band of FWHM=0.05 µm at emission maximum (λ= 3.7 µm) was as high as T_a =835 К (I= 1A, j=10 кА/см^2). This value is smaller than that obtained for the "shortwavelength" LED with deep mesa (λ= 3.3 µm, T_a=1250 К, J=10.6 кА/cm^2 [4]). When considering the whole mesa surface as an emitting area the maximum T_a value reached 750 К (I= 1A, j=5.9 кА/cm^2), which was comparable the T_a measured for samples with W-quantum wells (λ= 3.6 µm, T_a=600 К, [5]). However, our array exhibited much lower operating bias than presented in [5] (0.4 V vs 5 V) and thus smaller consumption power was achieved. The latter is important for devices with fast response time.

Summary

First diode sources with photonic crystals have been fabricated. LED arrays based on InGaAsSb with 130x130 µm^2 active areas and individual element addressing have been manufactured and tested. They exhibited low saturation current (j_{sat}=0.23 A/cm^2) and serial resistance (R_s=0.53 Ohm) as well as capability of simulating black body at a temperature of 835 K. High uniformity of the array

elements and absence of a crosstalk allow their use for detector calibration and in miniature spectrometer modules in mid-IR spectral range.

Further development will include investigations of arrays equipped with a PC as well as development of miniature spectrometers for gas analysis, say for hydrocarbon mixture detection.

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