Mid-IR LED arrays with Photonic Crystals

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The interface nonuniformity of periodic or quasiperiodic two-dimensional (2D) photonic crystal (PC) pattern violates Snell`s law and provides diffraction of the guided light into the light escaping cone at supercritical incident angles and changes angle pattern in far field as well. There are several cases where photonic structure brings benefits not attainable by other means. Such are compact mid-IR LED arrays with high fill-factor for which immersion lens optics is of no practical use if high contrast and apparent temperature are of prime interest. The latter is important for a variety of applications including miniature spectroscopic modules with gratings that are capable recording transmission spectra by sequential activation of array elements. Formation of a 2D periodic relief on the light-extraction surface was widely used in LEDs operating in the visible and near-IR spectral range. However, to the best of our knowledge there have been no papers describing mid-IR arrays and LEDs with 2D PC. Mid-IR arrays and LEDs with 2D PC will be quite useful in the 3000-5000 nm spectral range where most gases have strong "fingerprint" absorption.

We present PC based n-In(Ga)As(Sb)/p-InAsSbP LED arrays grown on InAs substrates with individual addressing of elements emitting at λ = 3600 nm, their I-V, light-current (L-I) and spectral characteristics as well as radiation distribution at forward (positive luminescence) and reverse (negative luminescence) bias together with analysis of PC impact onto emission power in our PC based devices.

Samples and experimental techniques

Two types of 1x4 LED monolithic arrays with 70x70 μm or 130x130 μm square active elements operating at 3.6 μm (300 K) have been fabricated. They consisted of ~2 μm thick broad band contact p-InAsSbP layer (E_g(300 K) ~420 meV), ~5 μm thick n-InGaAsSb active layer lattice matched to n^+- InAs ($n^+ \sim 10^{18}$ cm^{-3}) ~300 μm thick substrates transparent in the spectral range around 3.6 μm. Wafers were processed into mesa diodes with 40 μm (70x70 μm mesa) or 100 μm (130x130 μm mesa) wide square anode reflective (R=0.6) contacts and "U" shaped cathodes by a multistage "wet" photolithography process described elsewhere [1]. Fig. 1 presents schematic (cross section) of the array element mounted onto a semiinsulating Si submount.

A surface relief of hexagonally packed elements (2D PC) with characteristic dimensions within 0.5–2 μm and a lateral period of ~3 μm was formed on the outcoupling n+-InAs substrate surface by means of the standard photolithography with ion-beam ("dry') etching. SEM imaged of the above relief are presented in Fig. 2 A and Fig.2 B.

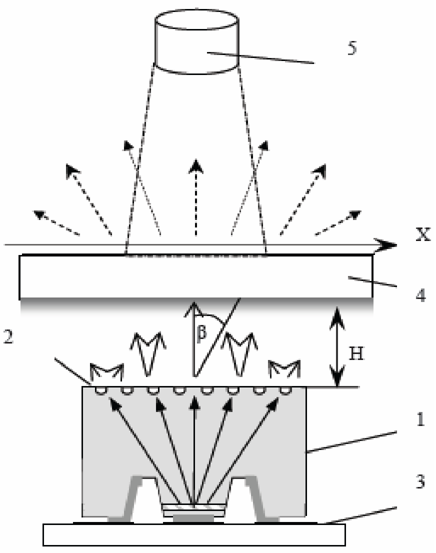
2D spatial output distribution was measured by IR thermovision microscope on the basis of a hybrid microcircuit of matrix cooled 128x128 photodetector InAs device [2] that have working range of 2.5 - 3.1 μm. All measurements were performed with only single LED element turned on. Details on "plane" (without PC) array operation at all elements turned on could be found in references [1, 3].

In "near field" measurements we observed light pattern directly from the n+-InAs outcoulping surface, field of view – 400x400 μm. Far field pattern was measured using Si plate -screen placed at a distance H from the LED as shown in Fig.1. One side of the screen was intentionally roughened to achieve good diffusion of the radiation at Si surface; field of view was different, that is, 2x2 mm as different camera lens was utilized in this particular case.

Reflection of samples was measured at room temperature; the measurements were performed with the incident and reflected light beams oriented close to the normal to the sample surface.

Results and discussions

Reflection spectra of the samples shown in Fig. 2 clearly indicate the presence of periodic structure onto InAs surface as they contain minimums that do not exist in spectra of sample without PC. IR images measured at forward (“positive” luminescence) and reverse biasing (negative luminescence) of a single array element “copy” the shape of the mesa as in our previous devices [1, 3]. The impact of PC is shown in Fig. 2, 3 where one can see that initial square image of an element was “transformed” into a multiplex image with spatial spreading of the 1-st, 2-nd and probably 3-d order



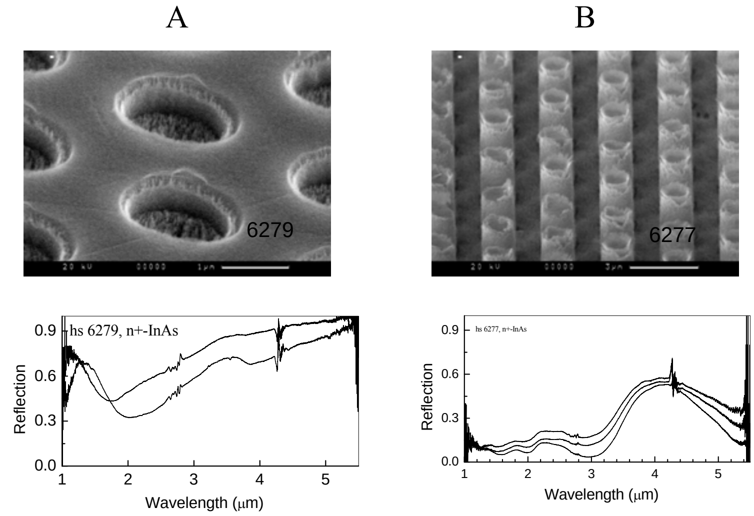
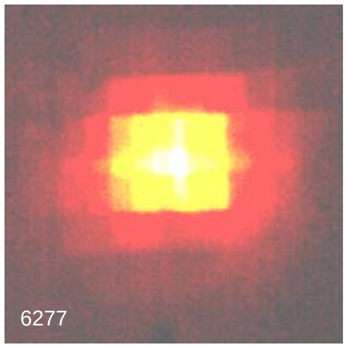


Fig. 1. Scheme of the LED with PC (the remaining 3 LED elements are not shown) and experimental arrangement: 1- LED chip, 2- 2D photonic crystal structure, 3- semiinsulating Si submonut with bonding pads, 4 – transparent Si screen with roughened surface, 5 – IR camera, H – distance between LED emitting surface and Si screen. Drawing not to scale.

Fig.2 SEM images of two periodic structures on top of n+ - InAs (at the top) together with corresponding reflection spectra (in the middle). 400x400 μm false IR image of the biased LED with 130x130 μm element size (“near field”, on the right)



“duplicates” (Fig.3) arranged in a hexagonal geometry. The difference between IR images in Fig.2 and Fig.3 arises from the difference in lateral dimensions. As Fig.2 presents device with rather “big” mesa lateral dimensions (130x130 μm) the overlapping of diffraction images is taking place. Quite small element dimensions of the second LED (70x70 μm) prevents above overlapping and fair good resolution of the “orders” is taking place.

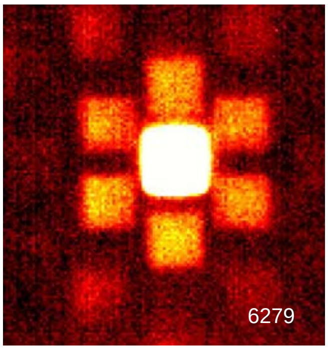
It is evident that in both cases (Fig.2, Fig.3B) the increase of the effective emitting area and output power due to the outcoming rays intersecting n+-InAs/air interface at quite large angles that are large than total internal reflection angle θ_c =arcsin(1/n), n=3.5. The impact of diffraction on light pattern was found in the far field as well (see Fig.3B). At a distance of 10 mm from the LED radiation distribution is quite broad and does not match the Lambert emitter: central area (just above the chip) is “darker” than distant “shoulders”.

It is worth mentioning that the sample geometry is not symmetrical as due to specific fabrication requirements the emitting elements are not in the centre of the chip, they are located closer to one side of the chip. This feature manifests itself for example in difference of spatial position of two side peaks in “near field” distribution (Fig.3 B, H=0) corresponding to the rays escaping from chip side walls. Nevertheless, as seen from Fig. 3 B radiation distribution is modulated by several peaks whose position is quite symmetrical with respect to the emitting area position. The latter is an indication of good PC quality in our LED samples.

Conclusions.

We have developed technique for fabrication mid-IR LEDs (including LED array) with 2D photonic crystal onto n-InAs surface and showed impact of PC on light extraction and near- and far field electroluminescence distribution. The obtained data indicated sufficient increase of the efficient emitting area and output power. The developed emitters could be used in gas spectroscopy and other applications.

A B



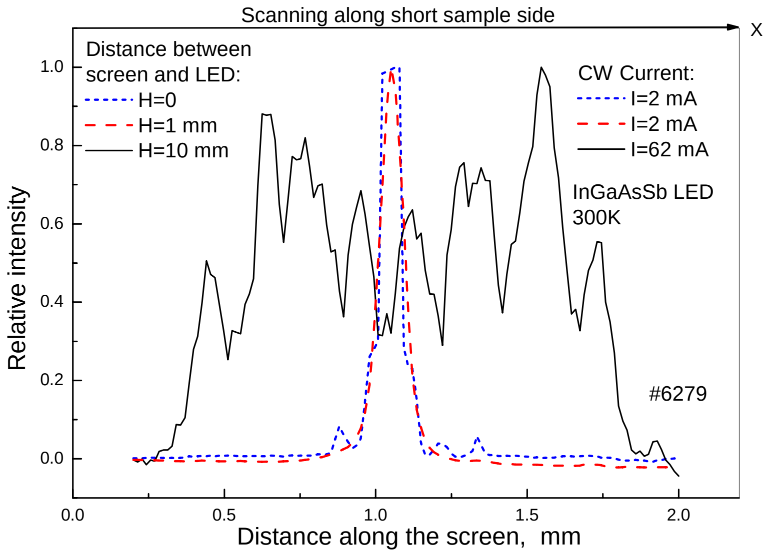


Fig. 3. A – IR image of PC LED emitting surface at forward bias; B - radiation pattern directly over outcoupling surface (“near-field”) and over the screen placed at a distance of 1 and 10 mm from the chip surface. Field of view; 400x400 µm (A) and 2x2 mm (B). See axis X in Fig.1 as well.

Acknowledgments

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