Challenges in mid-IR LED dimensions

Fig.1. Crying girl with a broken jug (Pushkin, Russia)

1. Introduction. Ancient Greeks were clever enough to establish strict standards for woman’s beauty and dimensions. The copies of these beauties (90-60-90 cm) can be found nowadays everywhere (see **Fig 1**). It is far more difficult to establish similar “mass production” standards for mid-IR light emitting diodes regardless to numerous publications available in libraries and internet. Some aspects of the above problem have been partly disclosed in two overviews erected in 2006 [1] and 2008 [2] correspondingly. Here we intend to narrow the subject with respect to the abovementioned overviews and briefly describe physical phenomena whose impact is a Procrustean bed for the designer and end user of the light emitting diodes operating in the 3-5 um spectral range.

2. Basic Principals. The “unlucky” peculiarity of the sources for the mid-IR region is their low internal quantum efficiency that is, the number of photons produced by one electron-hole pair injected into the active region. In GaAs and GaAs like materials the above value approaches unity which is in contrast to narrow gap materials such as InAs and InSb that form basis for most photonic sources in mid-IR. It will be not true to announce that the basic reason for the efficiency decline as the longwave spectral region is approached is clearly understood. One of the simplest approach describing dependence of the conversion coefficient in a flat surface device can be found in [3] where current at saturation at a reverse bias (I_{sat}) and negative luminescent power (NLP) were considered as basic diode parameters that define device efficiency. **Fig.2** taken from [3] describes dependence of the uppermost value of heterostructure LED conversion coefficient (NLP/I_{sat}) (upper solid line) vs energy gap of the active region. As follows from **Fig.2** the maximum expected efficiency for the 3 μm LED amounts to ~3 mW/A with a decline down to ~0.3 mW/A for the 8 μm LED.

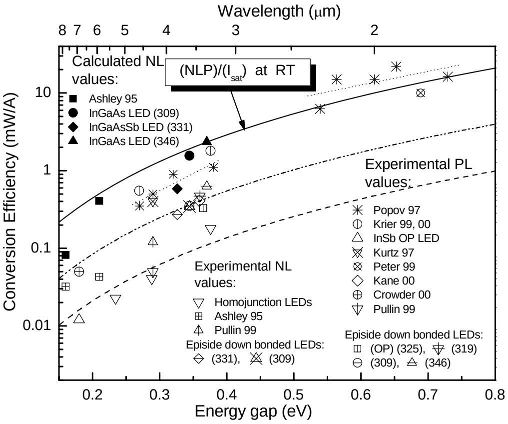

Fig.2 Conversion efficiency of the mid-IR LEDs vs energy gap. Solid line and solid points are the NPL/I_{sat} values calculated using the lowermost saturation currents and calculated NLP.

The above estimations constitute an uppermost values that are valid at extremely low injection currents only; the later is not the case for real LED operation conditions when high output power is of major importance. Unfortunately in real operation conditions (high injection currents) LED exhibits sufficiently reduced conversion efficiency with respect to values presented in **Fig.2**. Basic aspect of this stems from the fact that internal quantum efficiency strongly depends on the injected electron and hole density. Current understanding of the above impact is usually described as a competition of three main recombination processes: nonradiative Shockley-Read recombination (with a coefficient A), radiative recombination (with a coefficient B) and finally nonradiative Auger recombination (with a coefficient C). The quantum efficiency vs injected electron concentration (n) is then described by a simple relation:

$$\eta = \frac{Bn^2}{(An + Bn^2 + Cn^3)} \qquad (1)$$

As was shown by Zotova et al and later by Krier et al the Shockley-Read recombination has usually weak influence onto InAs-like LED performance at least near room and above room temperatures. However this is not the case for the Auger recombination: the drop of the efficiency at high pumping currents (that is, at high n) predicted by the above formula has numerous experimental confirmations, and is a fundamental feature of narrow gap materials in contract to broad band semiconductor (say GaAs) in which C is negligible and conditions $\eta \propto 1$ are easily achieved even at high pumping.

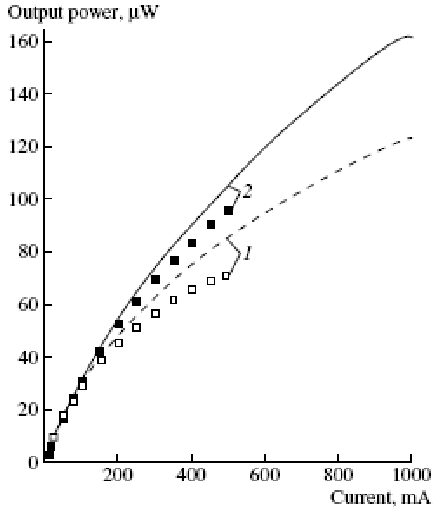

Fig.3 The emission power of InAs-based LEDs with the diameter of mesa 300 μm, diameter of contacts (*1*) 150 and (*2*) 240 μm in the pulsed (lines) and CW (dots) modes. $T =$ 300 K.

3. Improving the efficiency by “geometrical” means.

3.1 Layer thickness. The simplest way to monitor the η is to change to active area thickness. While increasing the thickness the injected carrier concentration goes down all other parameters being the same. The technique is valid to a curtain extent: starting from thicknesses of about $t \approx \frac{1}{\alpha}$, where α - is the absorption coefficient for the photons generated within active area, radiation losses becomes sufficient and total efficiency does not grow any more as thickness is increasing.

It is worth to mention that the majority of published mid-IR LEDs are fairy “thick”, 1 - 4 um being typical thickness of the active area. It may be primarily the Auger recombination responsible for relatively low efficiency of the LEDs produced by modern technologies, like MBE, whose “specialization” is nano- and submicrometer dimensions. We can mention also unsuccessful attempts to design efficient LEDs utilizing transitions between states localized near the Type II heterojunction. The disadvantages arise from too high density of the injected carriers confined in very narrow regions (<100 nm) [2].

3.2 Active area lateral dimensions. As soon as layer thickness is fixed (optimized) we can now consider active area (typically in the shape of a circle) as an adjustable parameter for the further LED optimization. Due to the existence of contact resistance ρ_c $[\Omega \cdot cm^2]$, say between p-type semiconductor layer and anode, one has a task to minimize R_c $[\Omega]$ and the corresponding Joule heating effect; it is vice thus to built the anode as large as possible. According to current understanding [2], the activated area dimensions in mid-IR LEDs at standard application conditions (high current pumping) is smaller than the mesa and coincides with the anode dimensions .

As seen from the equation 1 a fundamental feature of long-wavelength (λ> 3 um) LEDs, including those based on InAs, is the sublinearity of the light–current (L-I) characteristic and thus it can be expected that in samples with smaller contact area, the sublinearity of the light–current characteristic will be more pronounced, and the integral intensity will be less than in samples with a wide contact. This conclusion is illustrated by **Fig. 3 [[4]]**, where it can be seen that at 1 A current the output pulse power is 124 and 162 uW for LEDs emitting at 3.3 um with the anode diameter of 150 and 240 um, respectively. Larger contact area LED demonstrates higher efficiency also in the CW mode as well, which is illustrated by a considerable difference between the CW and pulse power for the LED with a 150-um-diameter of the anode and can be attributed to heating of the region of current flow; the difference in CW and pulse operation for *Da* = 240 um is much smaller. Evidently, the heat removal in the LED with a larger contact is much more efficient than that for a small device, so the difference between the CW and pulse

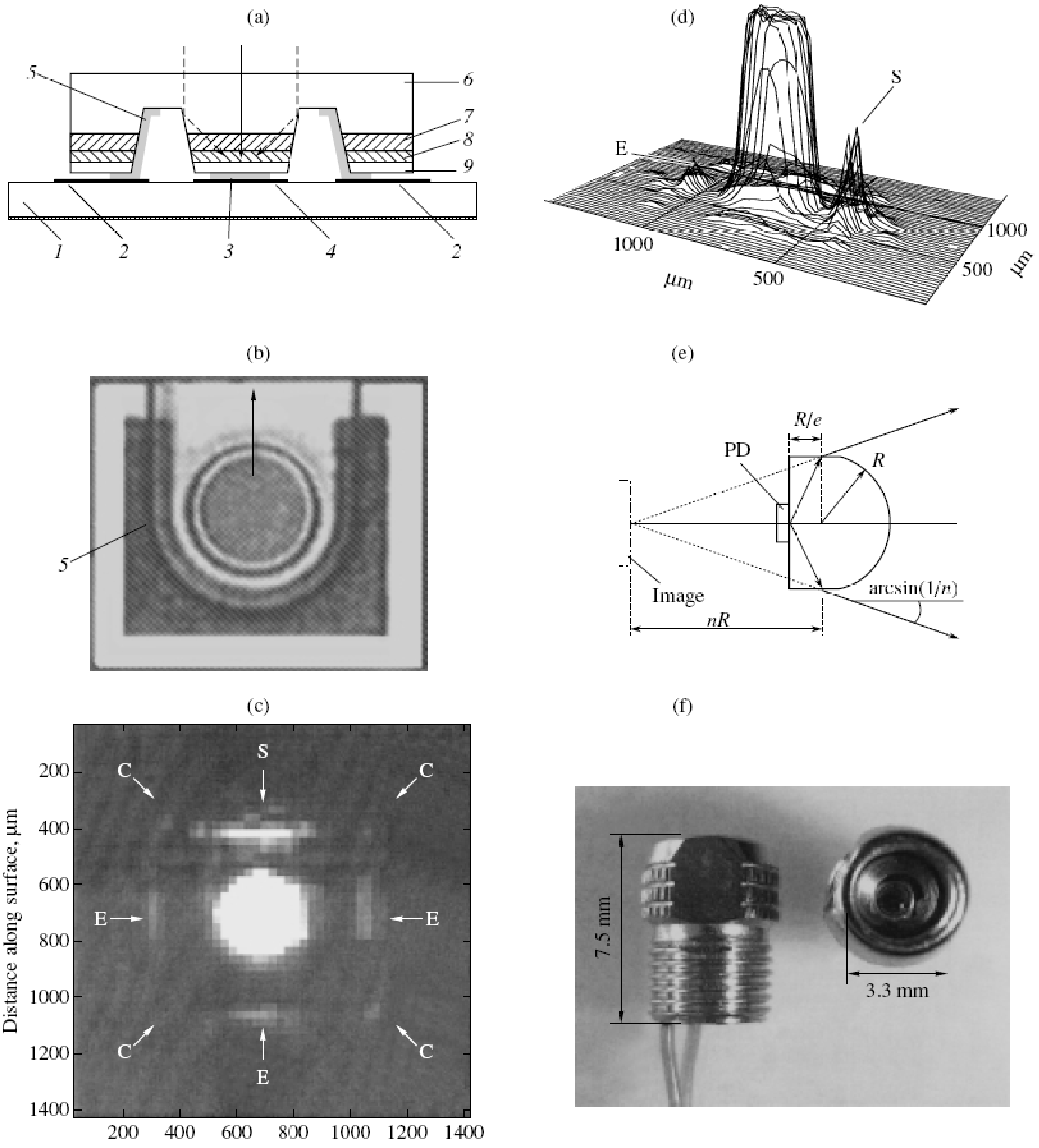

Fig.4

(a) Cross-sectional schematic representation of a flip chip PD mounted on a silicon support: (*1*) Si support (holder), (*2*, *4*) Sn + Pb contact pads, (*3*) Au anode contact, (*5*) *U*-shaped Au cathode contact, (*6*) *n*-GaSb substrate surface to which the planar surface of an immersion lens is subsequently glued, (*7*) *n*-InGaAsSb layer, (*8*) *p*-InGaAsSb layer, and (*9*) p^+-GaSb layer; dashed parts correspond to narrow-gap regions of the structure, and those undashed to wide-gap regions (“windows”). (b) Photograph of the chip from the side of the contact regions (mesa side). (c) IR image of a chip mounted on a support, from the contact-free side, with forward current passed through the chip. (d) Emission-intensity distribution over the surface of a chip mounted on a support, with forward current passed through the chip (published by courtesy of VTT Electronics, Finland). (e) Relative lens dimensions and a schematic of beams in the case of immersion coupling of a lens to a PD in accordance with [8]: *R*, curvature radius of the lens surface; *n*, refractive index of the lens material; *R*/*n*, distance from the center of curvature of the lens to its planar surface; and *nR*, distance from the planar surface of the PD to its image. (f) Photograph of an immersion lens photodiode in a “screw” case.

power is smaller. It is necessary to note that the equality of power in CW and pulsed modes is retained at currents up to 200 mA, which indicates the efficiency of heat removal in these LEDs.

First natural sequence of the above statements and graphs could be an immediate customer proposal to fabricate LED with mesa/anode as large as possible (shortly after he read the text above). And really one can find publications on fairy large (up to 3mm wide) LEDs [5], however we were not able to find such LEDs in any product list. Cost issues (3x3 mm device can cost like 10 ps or even more LEDs with 1x1 mm^2 dimensions) are among the first one to explain why production people are not absolutely happy with large area LEDs. Moreover there are several important aspects that prevent manufacturing of ”giant” LEDs as well.

3.3 Immersion. Flat surface LED emits broad beam with a Lambertian far field distribution ($I = I_o \cos(\alpha)$) and thus collimation of the beam is an important step in the design of an optical instrument: the higher is the utilization of the output the higher is the signal to noise ratio (S/N). A narrow far field pattern (or narrow beam) for conventional LEDs can be achieved by surface patterning [6] or by other means, e.g. by the formation of an optical concentrator, such as a Winston cone, in the substrate material as an integrated part of a heterostructure [7], as a reflector attached to the emitter holder or as an immersion lens attached to the LED/detector outcoupling surface [8]. Winston cone geometry cannot meet the requirements for high mid-IR output at a low device cost in view of the high cost of semiconductor material whose thickness is to be several times of that of the mesa diameter. Winston cone structure matches well photodiodes or NL devices, whose lateral dimensions and operating current are small [9]. Conventional reflectors, such as aluminum parabolic reflectors, are cheap, however they do not affect the internal reflection of the radiation and the external efficiency is fairly low (the explanation for this is given in **APPENDIX 1**).

The immersion lens technique has been successfully used in mid-IR LEDs with reduced internal reflection losses, directed beam and mW power levels [2, 10]. Recently the technology has been implemented to InAs-like detectors [11]. This technique involves the attachment of an aplanatic hyperhemipshere to a semiconductor device using a high refractive index chalcogenide glass as a “glue”. Typical chip and device dimensions with 300 um mesa and 240 um anode are shown in **Fig. 4** as taken form [12] (note that in this particular case LED and photodiode have the same dimensions and construction). In terms of the integral output power the immersion lens LED is an equivalent to 3-5 ps of “flat” LEDs without immersion lenses, however the advantage of the immersion lens package is more that this if we consider narrow far field pattern with typical FWHM of about 15-20 deg. in the “lensed” LEDs.

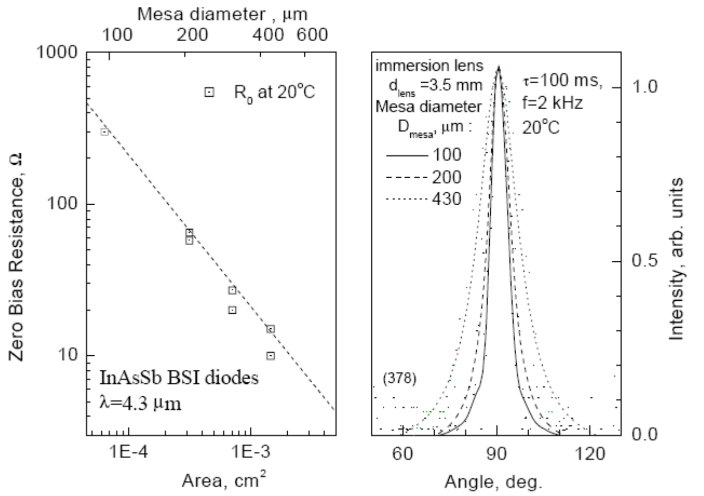

Fig.5

Shunt resistance vs mesa diameter/area (left) and far field diagram of immersion lens InAsSb LED (right) at room temperature. Dotted line on the left: ~1/(D^2) function

The devices shown in **Fig.4** follow “classical” proportion between the source and “passive” optics dimensions ($\approx \frac{1}{10}$). Increasing the ratio will lead to broadening of the beam, decreasing the ratio will have some positive impact on the beam quality (see **Fig. 5** taken from [13]), however one have to remember that decreasing active area will have negative impact onto LED efficiency (see **3.2**). Mirror optics is much better in this respect and large mirrors are relatively cheap, however, external reflectors do not change conditions for the light extraction from semiconductor and efficiency of LEDs coupled with just reflectors (e.g. parabolic ones) is low.

It is clear from **Fig.5** that decrease of the beam divergence at fixed LED active area can be achieved by large diameter lens implementation. Beams as narrow as **5-10** deg. have been achieved in visible (500-800 nm) LEDs with large (D~10 mm) plastic (epoxy) lenses and nominally similar to IR LEDs active area dimensions **(**see dimensions of the IRS-2 LED in **Fig.6** in mm and comments at **http://www.mirdog.spb.ru/NIR%20LEDs.htm).** An increase of the lens/case has also positive impact on the LED efficiency since heatsink management is improving. Unfortunately there are no absolutely transparent materials with low cost such as epoxy in the mid-IR wavelength range: silicon is cheap, however intrinsic absorption prevents creation of large lens mid-IR LEDs like those shown in **Fig.6.**

The above considerations implemented in mid-IR LEDs developed and produced by Ioffe Physico-Technical Institute RAS and spin-off company Ioffe LED, Ltd. are summarized in **Table 1**. The specifications of these "optimized" LEDs could be found in **APPENDIX 2**, the data presented should be considered as a starting point for analysis of the devices (analyzers) with mid-IR sources.

Fig.6

<u>Table 1</u>. Factors affecting typical Ioffe mid-IR LED performance

	Internally generated power	Total output efficiency	Beam far field quality $(\text{FWHM})^{-1}$	Beam near field quality $(\text{FWHM})^{-1}$	S/N
Temperature decreasing	☺	☺	😐	😐	☺
Current increasing	☺	☹	😐	☺	☺
Increasing the contact dimensions	☺	☺	😐	☹	☺
Increasing the anode reflectivity	☺	☺	😐	😐	☺
Increasing the active area (mesa) width	☺	☺	😐	☹	☺
Attaching hemispherical immersion lens*	😐	☺	😐	☹	☺
Attaching hyperhemispherical immersion lens*	😐	☺	☺	☹	☺☺
Increasing dimensions of the hyperhemispherical immersion lens*	😐	☹	☺☺	☹	😐
Increasing dimensions of the hemispherical immersion lens*	😐	☹	😐	☹	☹
Attaching external mirror, say *Al* parabolic reflector*	😐	😐	☺	☹	☺

*- it is assumed that in "standard conditions" (initial point) the active area is appr. 10 times larger than the lateral dimensions of the "passive optical element"

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