Immersion – direct way for photons and applications

One of the important aspects of LED design is the outcoupling of radiation born inside semiconductor active area usually having high refractive index n=3.5-4 and plane geometry. Light beam coming from p-n junction area is refracted at the interface with low index media (say air – case A) so that $\frac{\sin(\alpha)}{\sin(\beta)} = \frac{\bar{n}_2}{\bar{n}_1}$ where $\bar{n}_1, \bar{n}_2, \alpha, \beta$ - are the refractive indexes and angles of beams in high and low density materials correspondingly (see Fig.1). As a result at curtain critical angle (β=π, $\alpha_{crit} = \arcsin(1/\bar{n}_1)$) great majority of beams will be reflected back inside semiconductor slab as shown by dashed lines in Fig.2. The internally reflected light with $\alpha > \alpha_{crit}$ will not normally leave the semiconductor slab with the result that outcoupling efficiency (the portion of photons inside the escaping angle shown by cross hatch in Fig.2) will be as low as $\frac{1}{(\bar{n})_1^2}$ or $\frac{1}{2\cdot(\bar{n})_1^2}$ depending on weather the emission region is optically thick or thin. For InAs refractive index is 3.52 and thus only 4 ÷ 8 % of photons will be useful.

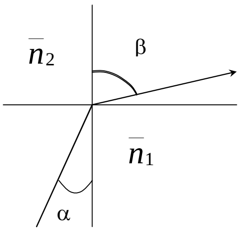
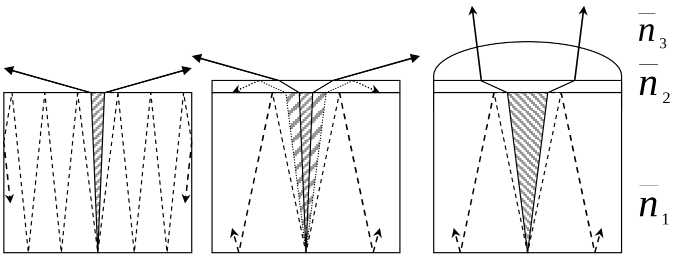


Fig.1 Refraction at an interface for the light beam coming from high index media into a low index one $(\bar{n}_1 > \bar{n}_2)$.



(A) (B) (C)

Fig.2 Beam paths at several incident angles in uncoated (A), covered with plane layer (B) and lens (C) diodes. Case “C” is presented for $\bar{n}_1 = \bar{n}_3$ conditions when solid angles of beam inside semiconductor and lens are the same. Dense cross hatch indicate solid angles of beams that leave the assembly.

Simple incorporation of a lens (without immersion) will change the far field pattern but will leave the same the efficiency since total reflection conditions are unchanged. Here we assume that the chip (slab) and lens surface are not ideal and hence actual distance between semiconductor and lens is greater than the wavelength. In this situation the gap between semiconductor and lens will be sufficient enough to produce total internal reflection effect.

Deposition of an optical coating ($\bar{n}_1 > \bar{n}_2 > 1$) onto an outcoupling surface (case B) will lead to an increase of radiation intensity that leaves semiconductor slab due to the increase of critical angle (shown as cross hatch with poor density). However this coating will not affect the overall efficiency since total reflection conditions will occur at the additional interface coating/air (shown as dotted lines). So the efficiency will be the same as in case A) defined by small angle of total internal reflection (dense cross hatch).

Strictly speaking introduction of layer with intermediate value of refractive index will reduce the total normal reflection but the above effect is not sufficient and could be ignored in our considerations.

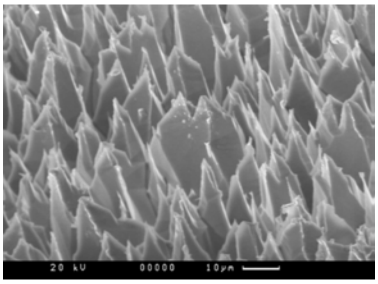


Fig. 3 Photo of the selectively etched n-InAs (111) out-coupling surface of the deep mesa LEDs. The white horizontal scaling line corresponds to a distance of 10 μm.

It is obvious that in order to suppress total reflection losses one has to change planar geometry into something more sophisticated. One of the options is the creation of microrelief that allows multiple reflections with chaotic set of incident angles. Such reflection was realized in a roughened surface devices fabricated by selective chemical etching with typical relief shown in Fig.3. [1, 2] with the gain of about 1.3. Much bigger gain was obtained in periodic structures (photonic crystals) with typical distance between elements of about wavelength [3] however this technology has been not implemented to mid-IR injection sources so far.

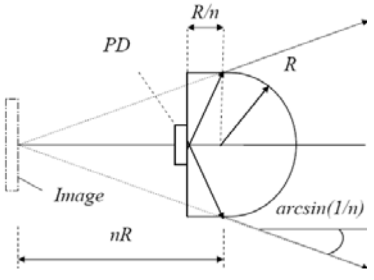


Fig.4 Aplanatic hyperhemipshere lens configuration, n - is the lens refractive index

The situation is dramatically changed when the shape of the outcoupling surface is spherical (or in general concave). The beams now strike the surface at angles close to zero and no total internal reflection takes place. This however is difficult to realize in practice due to high cost of a semiconductor material like InAs and GaAs and the need for sufficient thickness for the lens formation. It is easy, however, to glue a lens from cheap material, say Si ($\bar{n}_3$), on top of the plane diode as shown in Fig.2 on the right. The picture describes the case when $\bar{n}_2 = \bar{n}_3$ and when all beams within large solid angle marked as cross hatch leaves the diode/lens assembly. It should be noted that lens diameter should be at least an order of magnitude larger that the active device dimensions – standard condition in optics. It is clear that the smaller is the optical density of glue the smaller is the solid angle of beams that enter the lens. Unfortunately all known glues have really low refractive index value so that $\bar{n}_1 > \bar{n}_2$ and curtain portion of radiation is lost at the semiconductor/glue interface.

Fig.5 Photo of a ~1 mm wide chalcogenide glass lens (black ball in the photo) formed by a melting process onto a LED chip mounted onto a TO-18 header

There are a lot of lens shapes developed for the immersion lens technology hyperhemisphere being the most famous [4 , see also Fig.4]. With some small deviations from the shape shown in Fig.4 it is possible to obtain small angle of view in PD (or far field pattern in LED) with FWHM amounting to 10-20 deg. in 3.5 mm wide silicon lenses [5].

To the best of our knowledge the chalcogenide glasses is the only class of materials that is both transparent and have high refractive index in the mid-IR spectral range (3-5 μm). That’s why advanced immersion lens diodes incorporate this kind of an optical “glue”. The glass itself can be used a lens formed during the melting and hardening of the latter (see Fig.5), however the lens shape is not very well controlled as seen from comparison of chalcogenide and sapphire ball lens LEDs presented in Fig.6, 7 [6]. Unfortunately sapphire has low refractive index (n= 1.5) and thus there is negligible gain in efficiency associated with the sapphire immersion lens technology. According to the experience of the MIRDOG maximum gain in the output power related to the use of immersion lens technology (Si lens + chalcogenide glue) with respect to the plane uncoated devices is about 3÷4

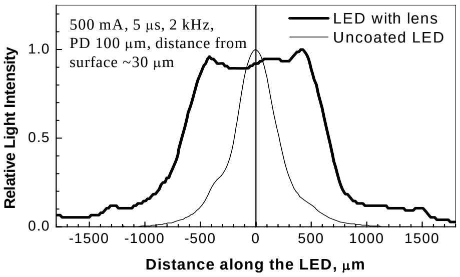


Fig.6 Distribution of radiation along the chip surface in 3.3 μm InAs LEDs; with a flat surface (thin line) and immersed into 1 mm chalcogenide glass (thick line) [6].

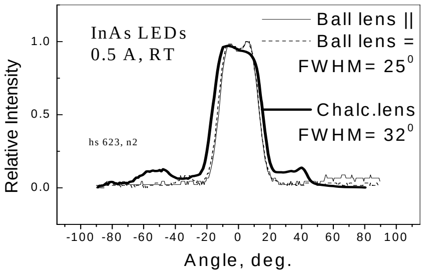


Fig.7. Far field pattern of the emitted radiation from a sapphire ball lens LED in two perpendicular planes (thin and dashed lines denoting “||” and “==” respectively) and from the chalcogenide glass lens LED (thick line) [6].

for the InAs based diodes. Photo of one of these LEDs is presented in Fig. 8. The above enhancement factor is smaller than $(\bar{n}_2)^2$ given by the theory; the discrepancy is possibly caused by nonpoint character of the source (the active area is a 300-500 μm wide circle), misalignment of active area and lens and finally absorption in the glue.

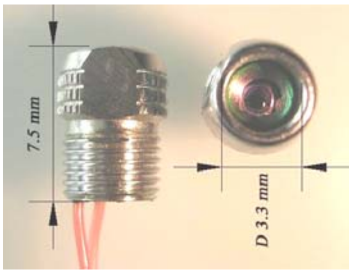


Fig.8 Photo of an immersion lens LED/PD in a screw header designed by MIRDOG

The statements presented in Fig.2 can be confirmed experimentally using for example flip-chip LED emitting at 4.2 μm, 3.5 mm wide silicon (or CdSb) lens and alcohol (C_2H_5OH) as an optical glue (Fig.9) [7] . Shown in Fig.9 is a schematic of the experiment with flat surface LED (black rectangular) onto a header (cross hatch). LED emits light vertically towards photodetector (PD) with fixed position regarding the LED at a distance of about 3-5 cm form the latter. Far field diagram of the activated LED is broad and is close to Lambertian distribution as shown by dotted circle. Light pattern is more or less uniform with unity signal produced by detector (left picture). An introduction of a lens (picture in the middle) increases the detector signal due to collimation of the rays that were extracted from semiconductor (LED). Case in the middle does not represent immersion conditions since no particular measures have been undertaken to do this. Direct penetration of radiation from LED to the lens (without refraction in the air gap) is possible if the distance between them is less than λ/40. This is not the case in our experiment; in general creation of surface with roughness less than λ/40 is a difficult task.

The following will happen if one will put a drop of alcohol onto a lens. First reaction of the system will be the decrease of the detector signal (U=1-2) due to absorption of radiation in the liquid. After a minute or so the signal will be restored (U=5) due to the evaporation of alcohol from the surface. Then the most exiting thing will happen: the signal will start to increase due to capillary penetration of alcohol in the gap between LED chip and lens. The immersion will thus take place with the result of the total reflection angle increase in accordance with the above formulas and Fig. 1 and Fig. 2. The 3-fold increase of the output power with respect to the unimmersed case is achieved with glue having refractive index of only 1.3. It is obvious what will happen next: after several minutes alcohol will evaporate and leave the gap between LED and lens. Obviously the signal will return to the U=5 value. The drop of alcohol can again appear at the LED surface and the above story will repeat.

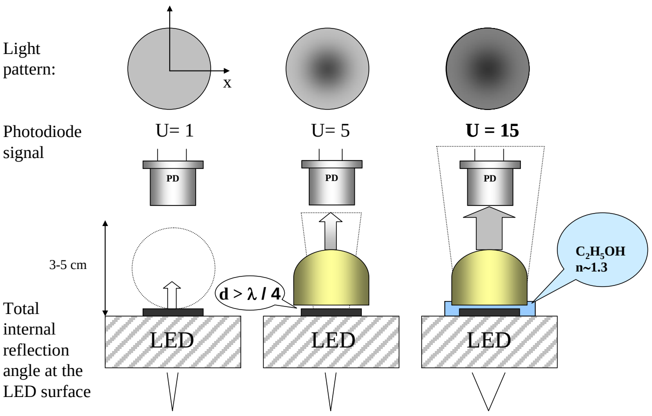


Fig.9 Experimental demonstration of an output increase of a 4.3 μm LED (n=3.5) associated with immersion with hyperhemispherical CdSb lens (n=5) by alcohol (n=1.3).

Similar considerations are valid for the optically pumped LEDs where pump (GaAs LED, n=3.5) is coupled through the glue (n=2.4) to a mid-IR "phosphor" (n~3÷4) [8] . The phosphor itself is usually deposited onto a SiO_2 glass substrate (n=1.3) that is not beneficial in view of the internal reflection losses described above. Incorporation of an immersion lens will reduce the angle of view but will not lead to an increase of the device efficiency since low index substrate will cause losses regardless its position in the assembly pump-glue-substrate-phosphor. It is thus highly desirable to grow phosphor onto a high refractive index substrate (say Si or CaF_2), however this growth should be carefully adjusted in order to avoid defect formation during deposition. The disadvantage of SiO_2 based “phosphors” is partly balanced by relatively cheap component price and simplicity of the assembling procedure.

In conclusion we would like to mention that the immersion lens technology is very attractive for photodiodes as well whose D^* can be sufficiently improved [[4], [9]].

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