B. Matveev and M.Remennyy

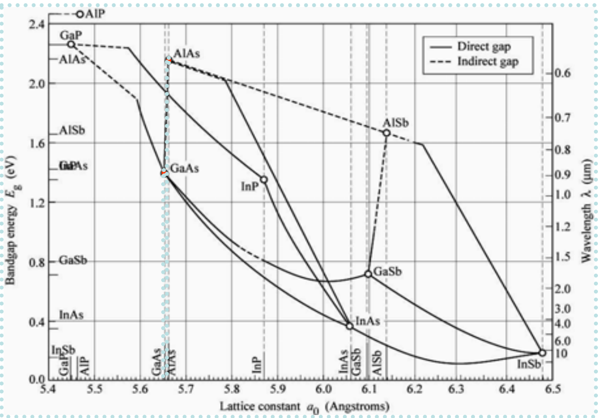
# "Mid-IR diodes for applications in pyrometry and gas sensing"

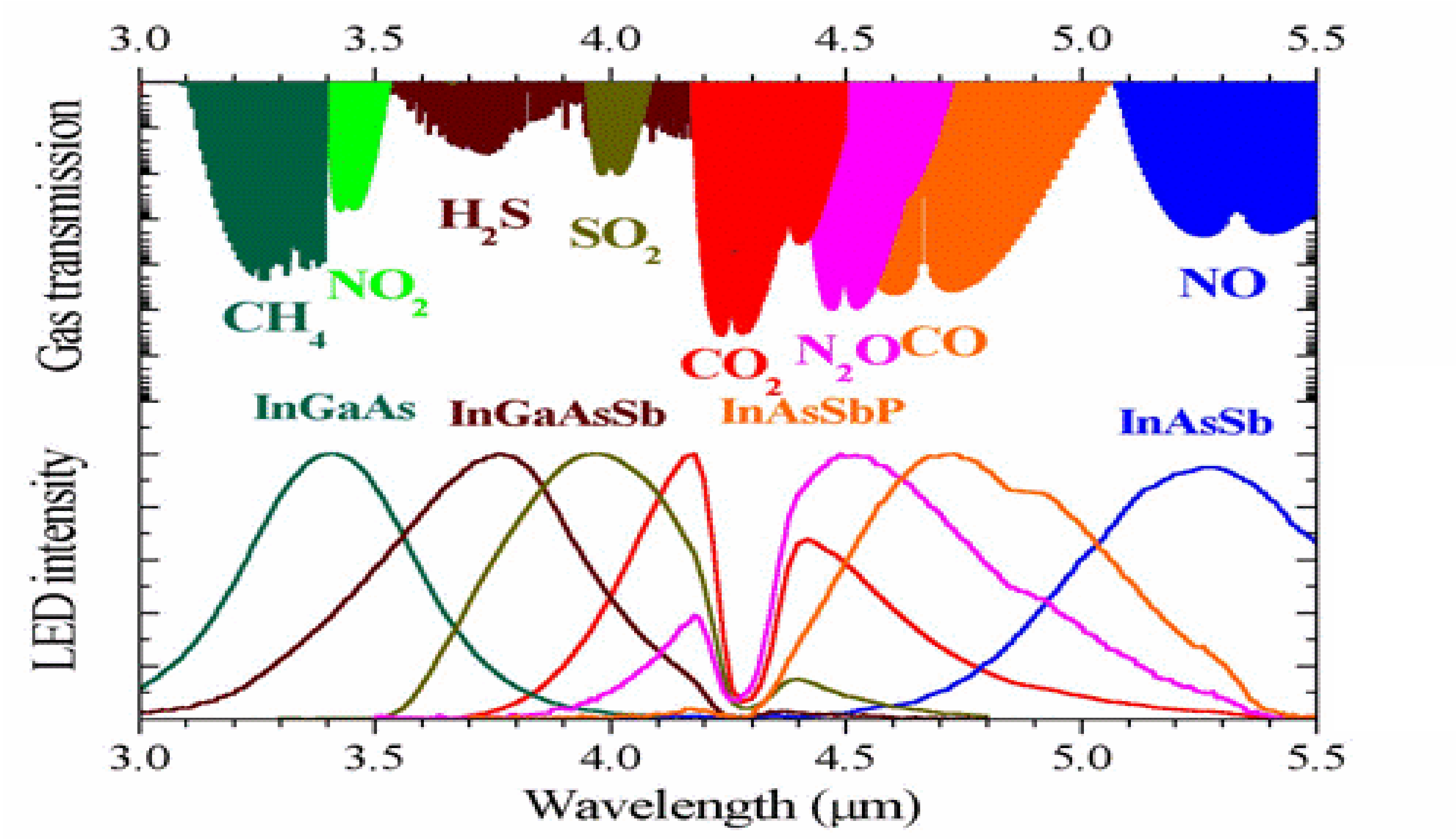
**Introduction.**

1. **LEDs: injection, extraction of nonequilibrium carriers or optical pumping?**
2. **LEDs and photodiodes (PDs): compromise between efficiency and cost. Immersion lens technology.**
3. **Gas absorption measurements ($C_nH_m$, $CO_2$, trace measurements ( open path), miniature gas cells with LED-PD pairs and photoacoustic detector.**
4. **Low power measurements (experiment and expectations).**

*Introduction (motivation) :*

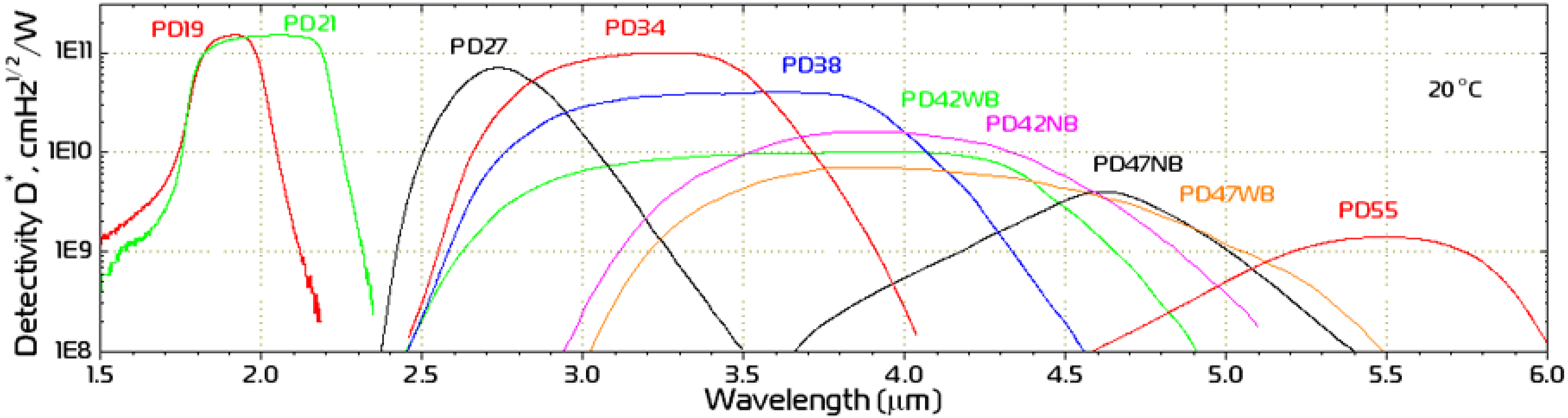
# Mid-IR region is full of ”fingerprints” of gases and $A^3B^5$ materials

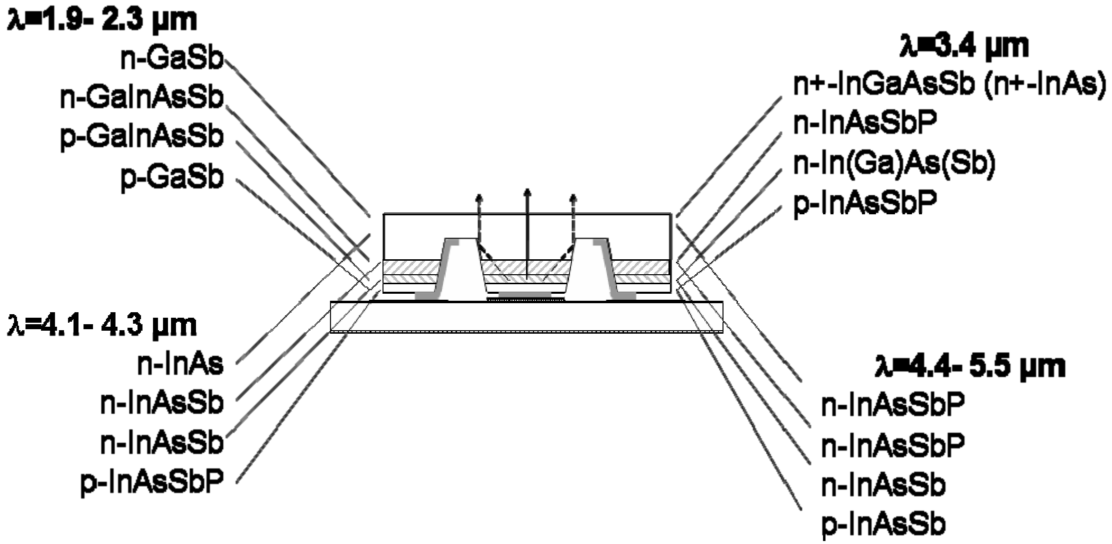


*Introduction (motivation) :*

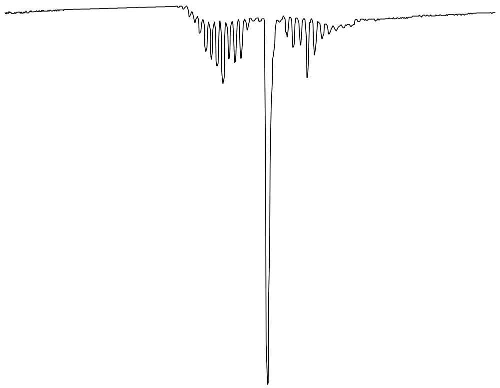
# $A^3B^5$ heterostructure PD/LED types



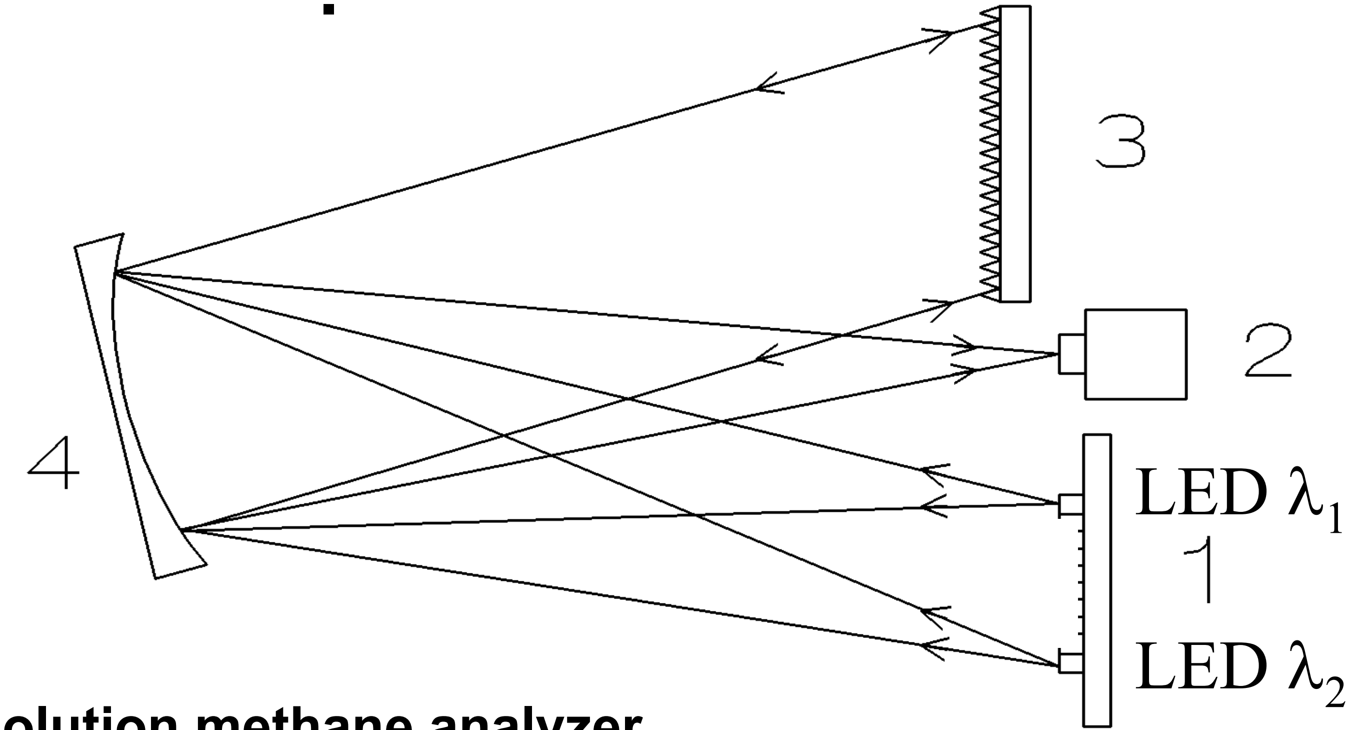




All developed **InAs** and **GaSb** based heterostructures enable flip-chip assembling technology and mounting of an immersion lens on top of the broad band “window” surface (Patent numbers 2261501, 2286618 )

# Advantages: small dimensions, high brightness.



$\lambda$=3.32 μm



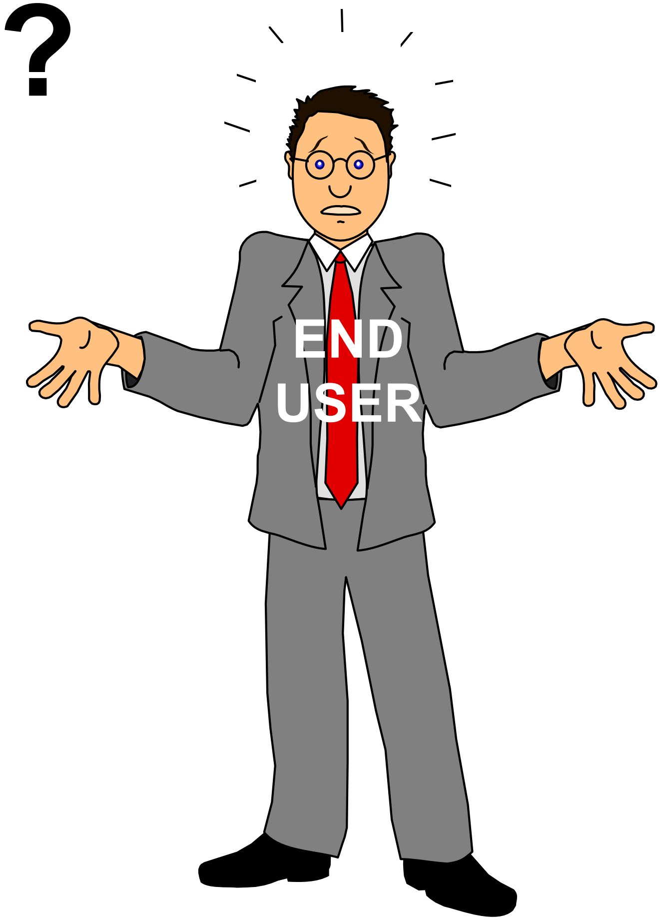

**High resolution methane analyzer**

LOD=0.002 % $CH_4$ v/v (L=1 m)

J.Appl.Spectrosc.,v.42 (1985),pp. 465-467

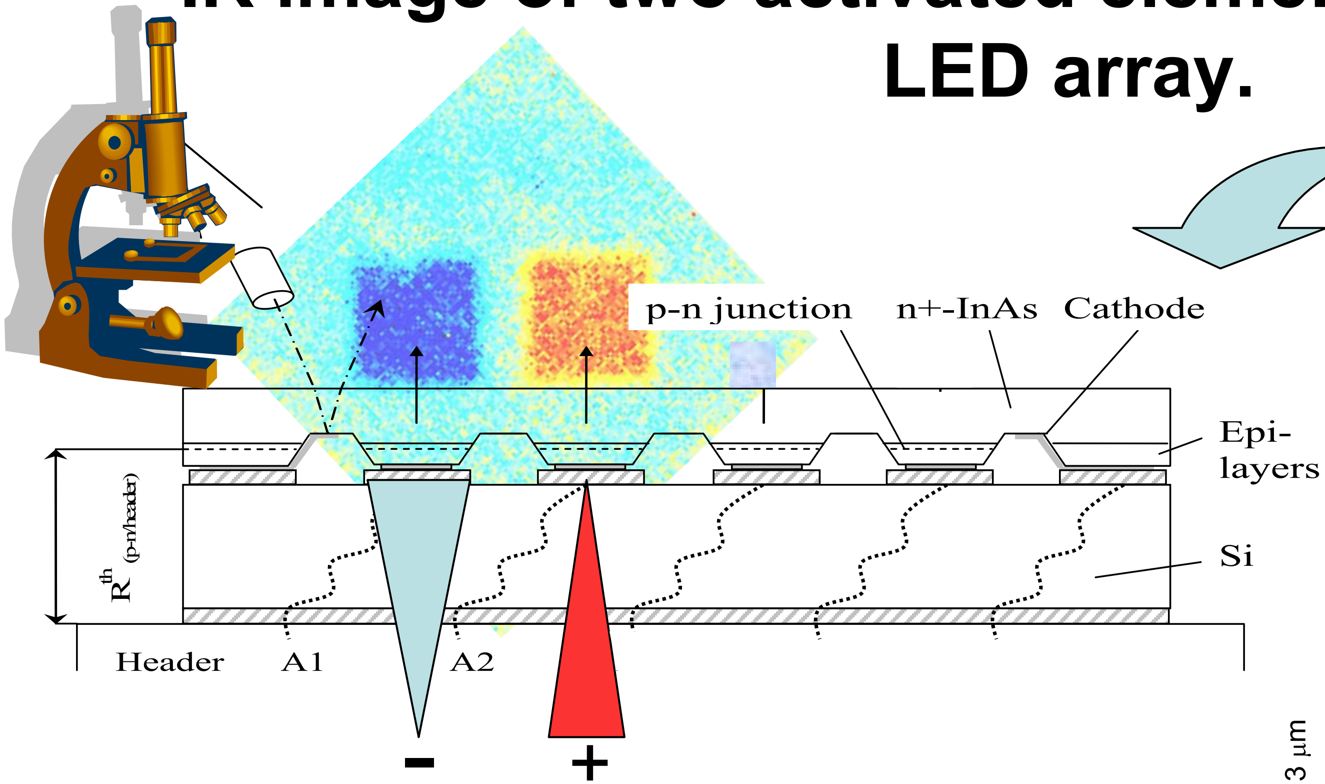
Patent numbers: 1648166 , 1672814

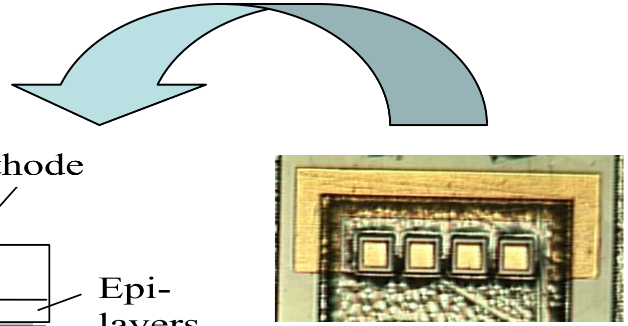
# 1.LEDs:
# injection,
# extraction of nonequilibrium carriers or optical pumping?

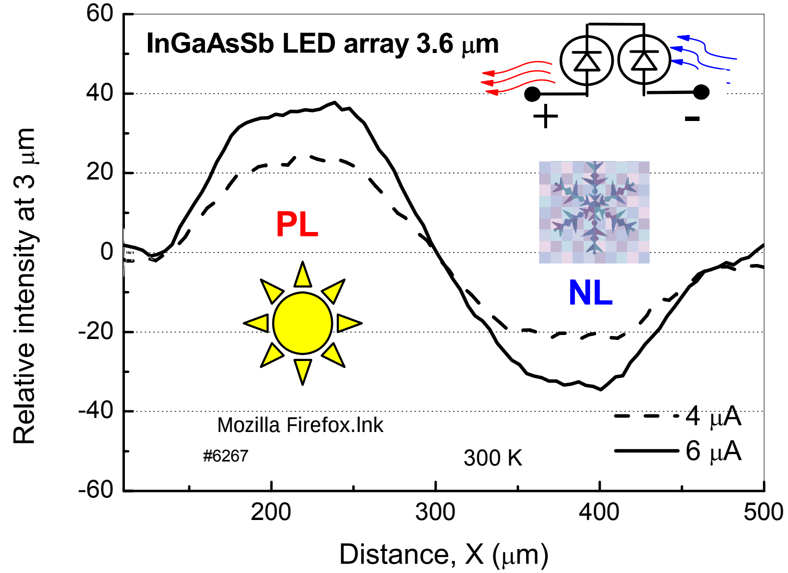


# 1. LEDs: injection, extraction of nonequilibrium carriers or optical pumping?

# IR image of two activated elements of the flip-chip LED array.

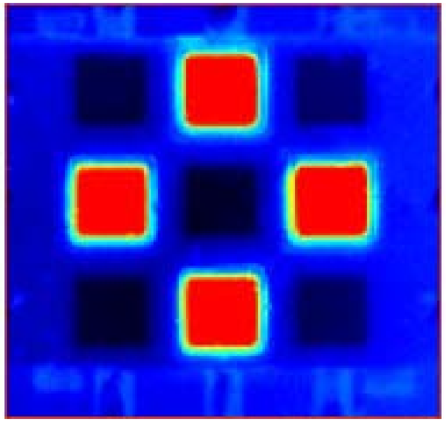




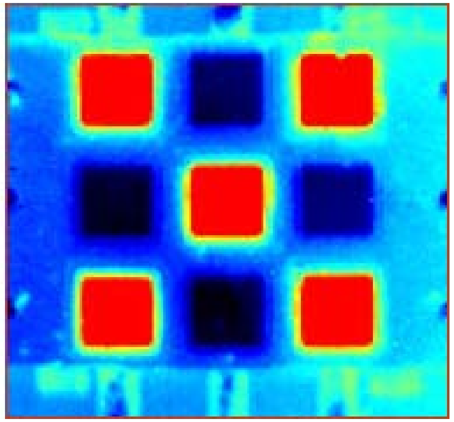
# 1. LEDs: injection, extraction of nonequilibrium carriers or optical pumping?

# IR image of the 9 activated elements of the flip-chip LED array.



4el. – PL

5el. - NL



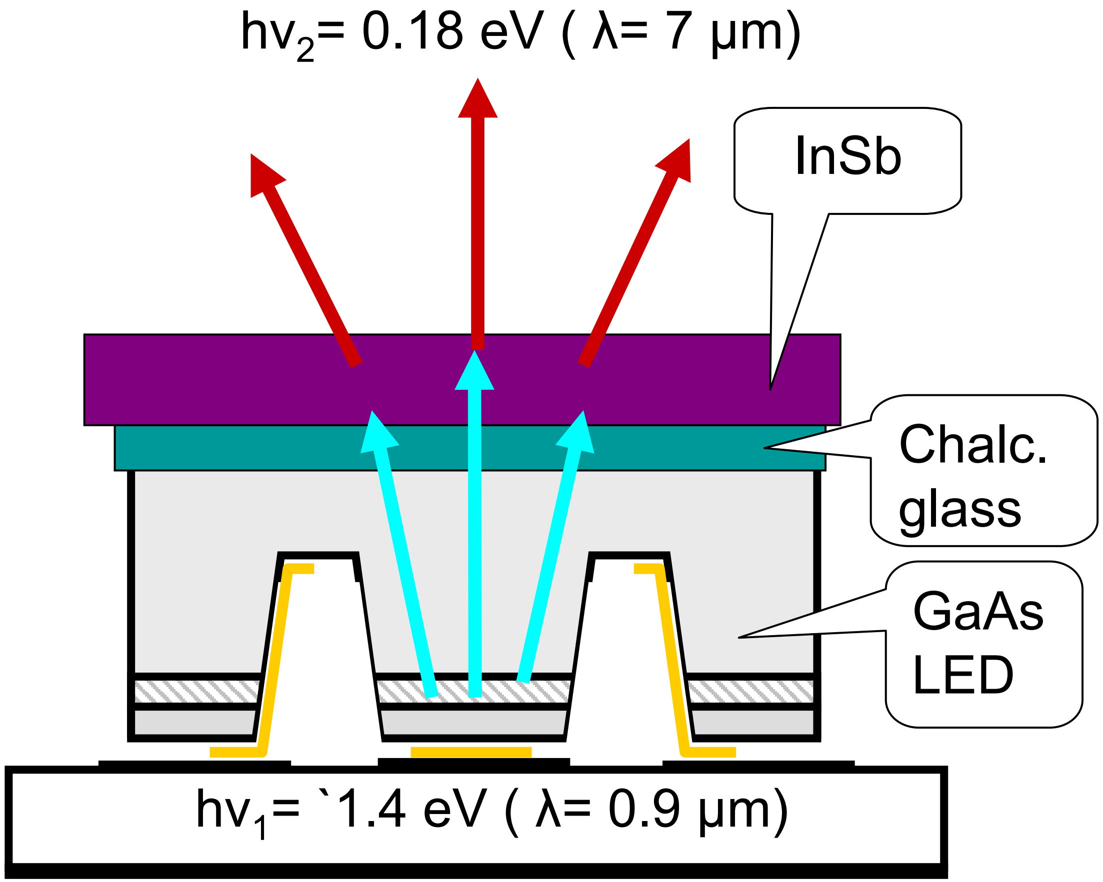
5el. – PL

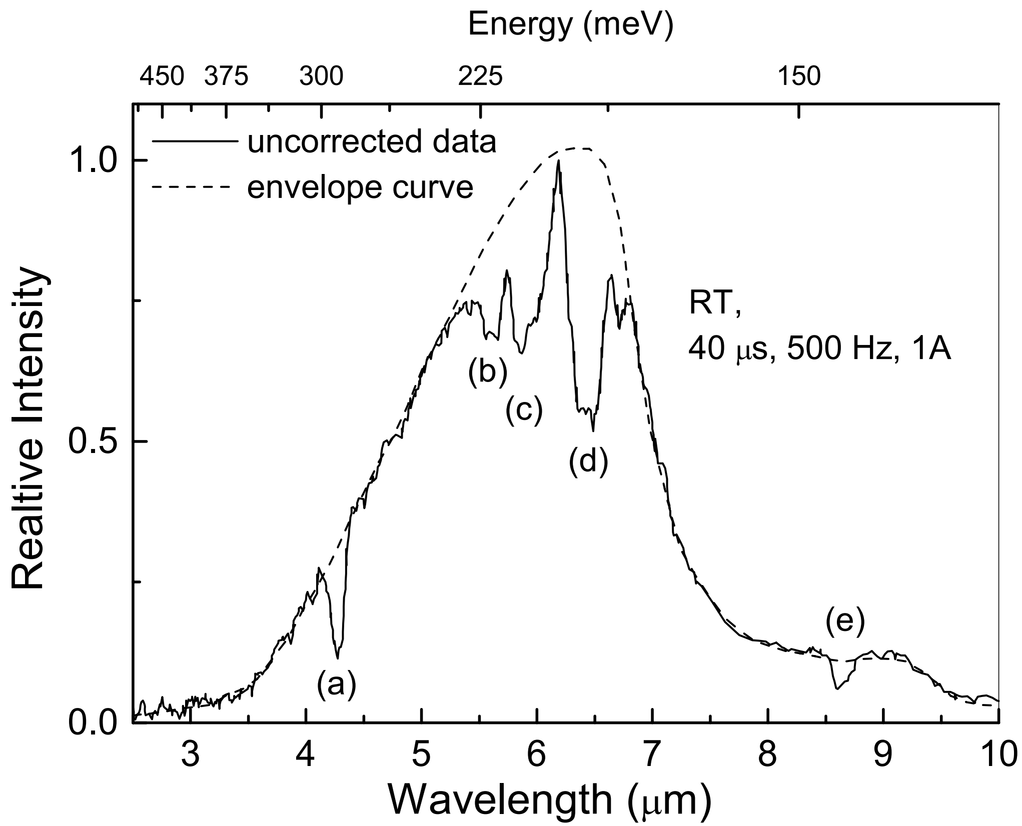
4el. - NL

# Optically pumped LEDs – simple solution for sophisticated cases

**GB patent 2363906**

**US patent 6876006**



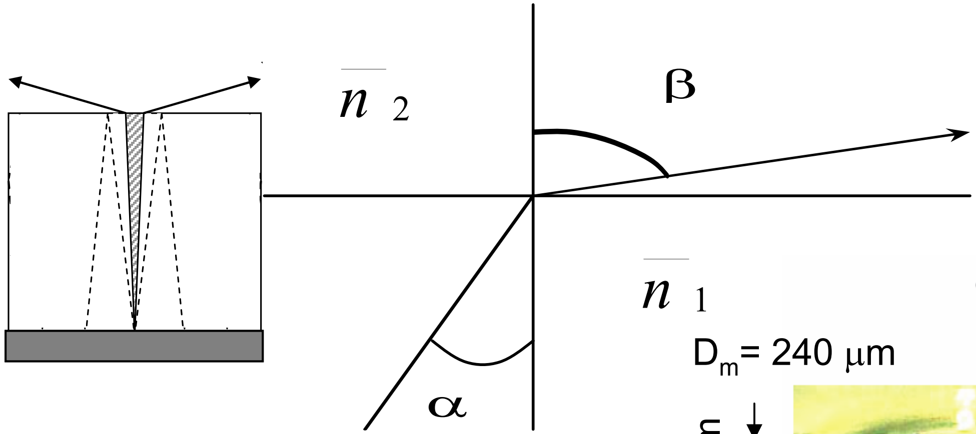



## 2. LEDs and photodiodes (PDs): compromise between efficiency and cost. Immersion lens technology.

.

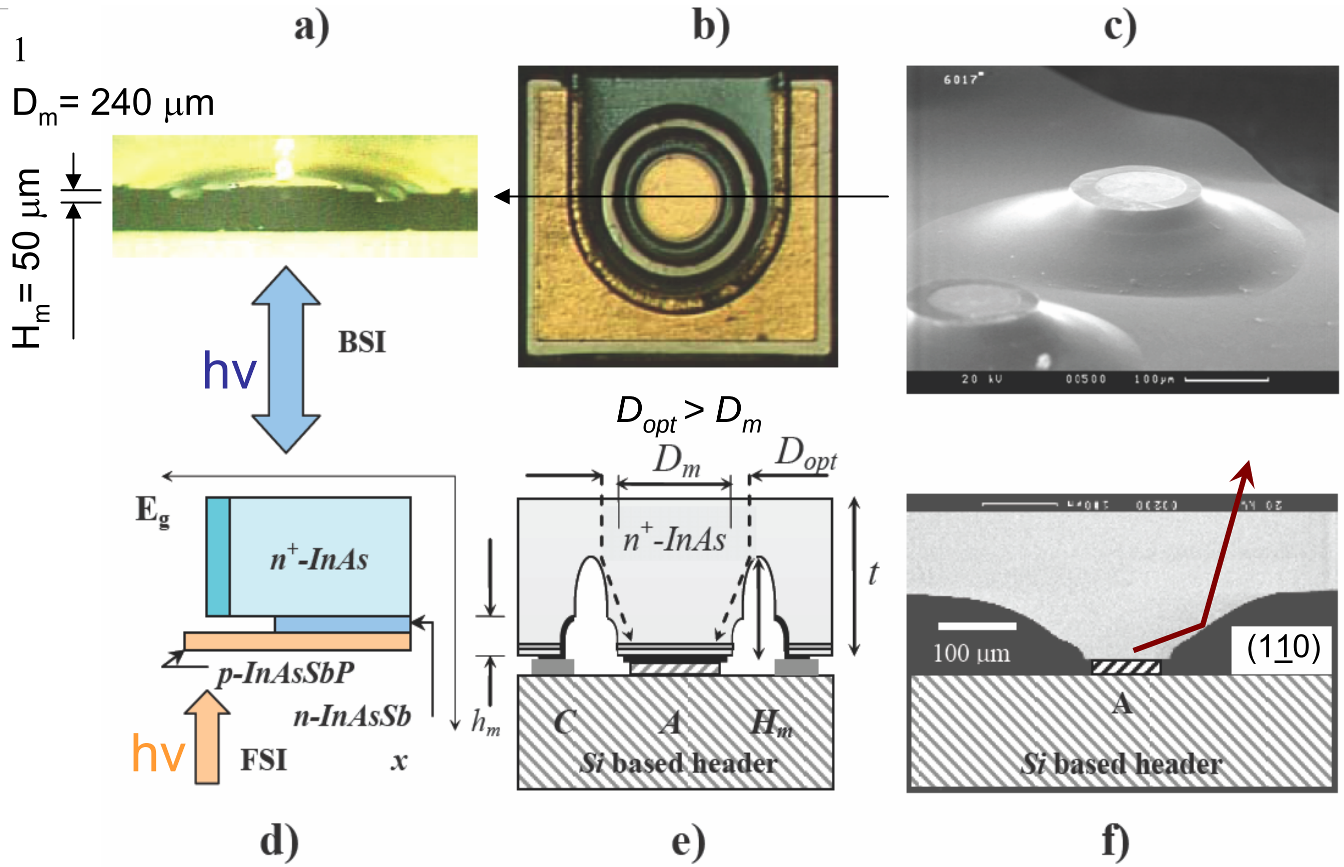
## 2. LEDs and photodiodes (PDs): compromise between efficiency and cost.

# Total internal reflections and reflectors.



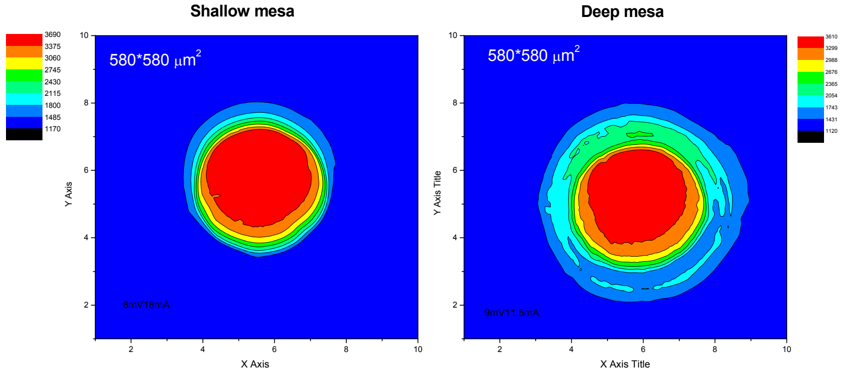

Contacts

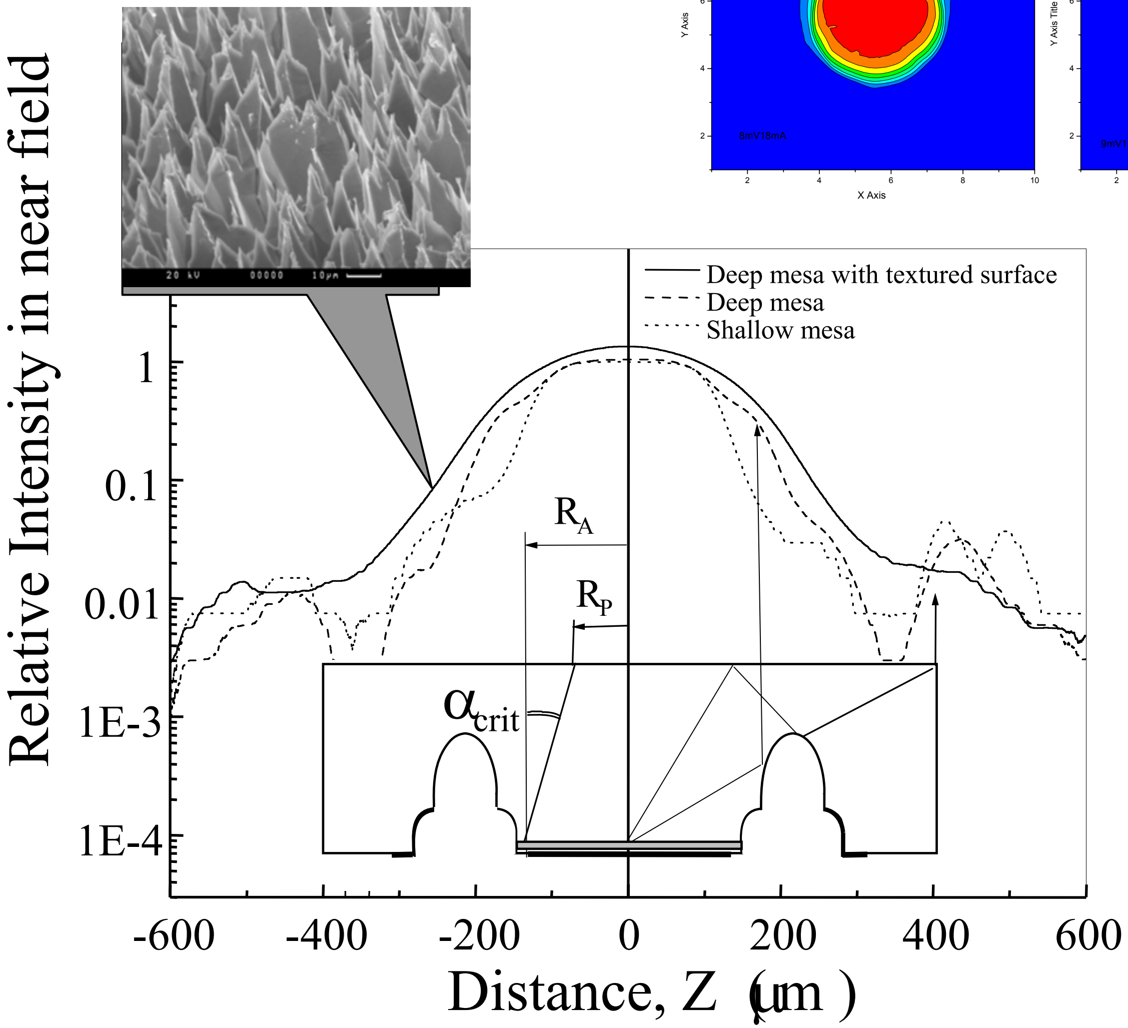
Active layer

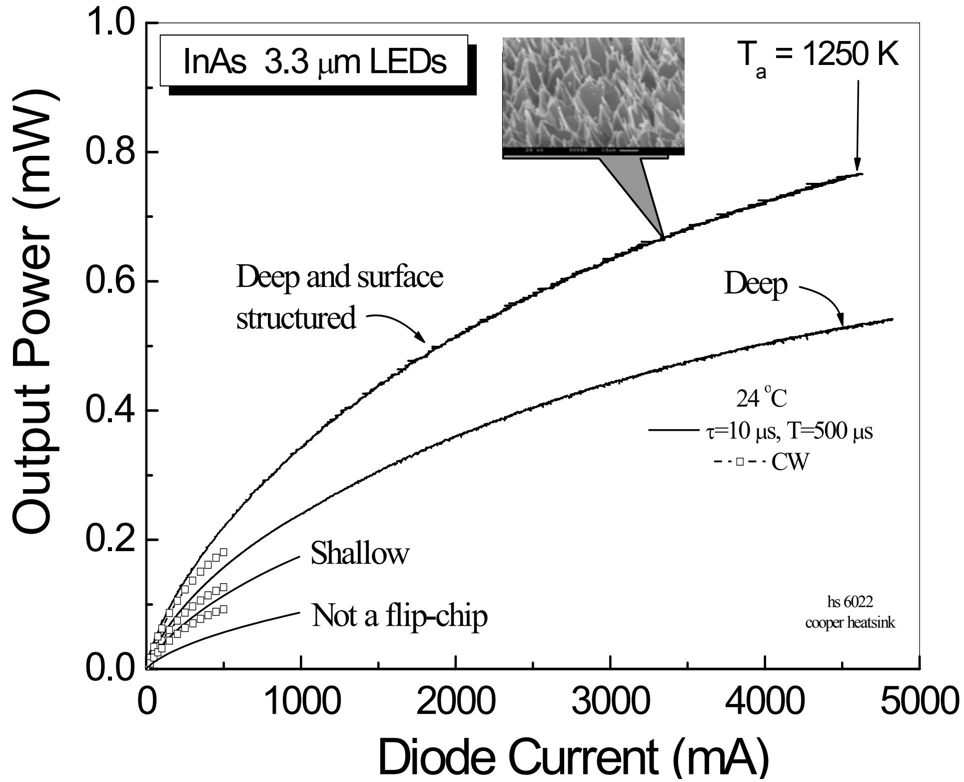


## 2. LEDs and photodiodes (PDs): compromise between efficiency and cost.

# Total internal reflections and reflectors.

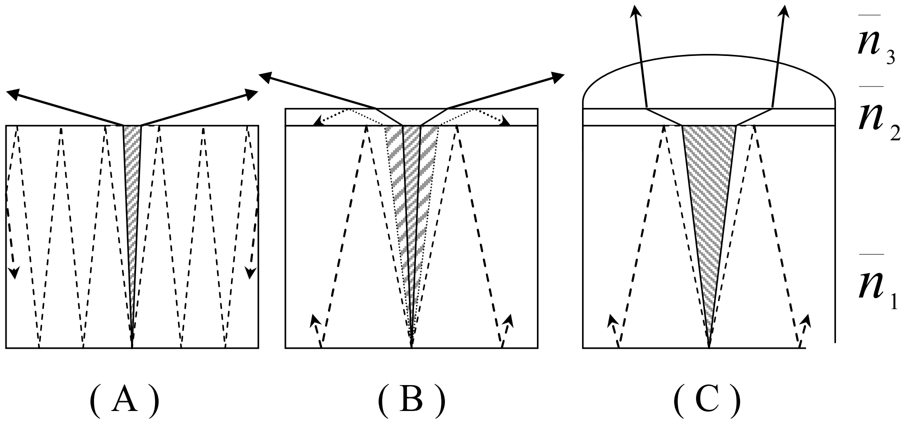


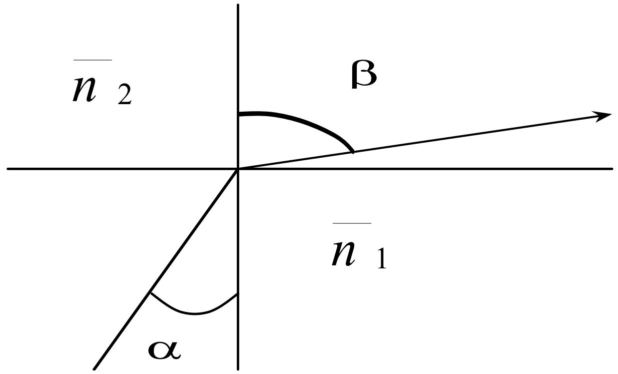



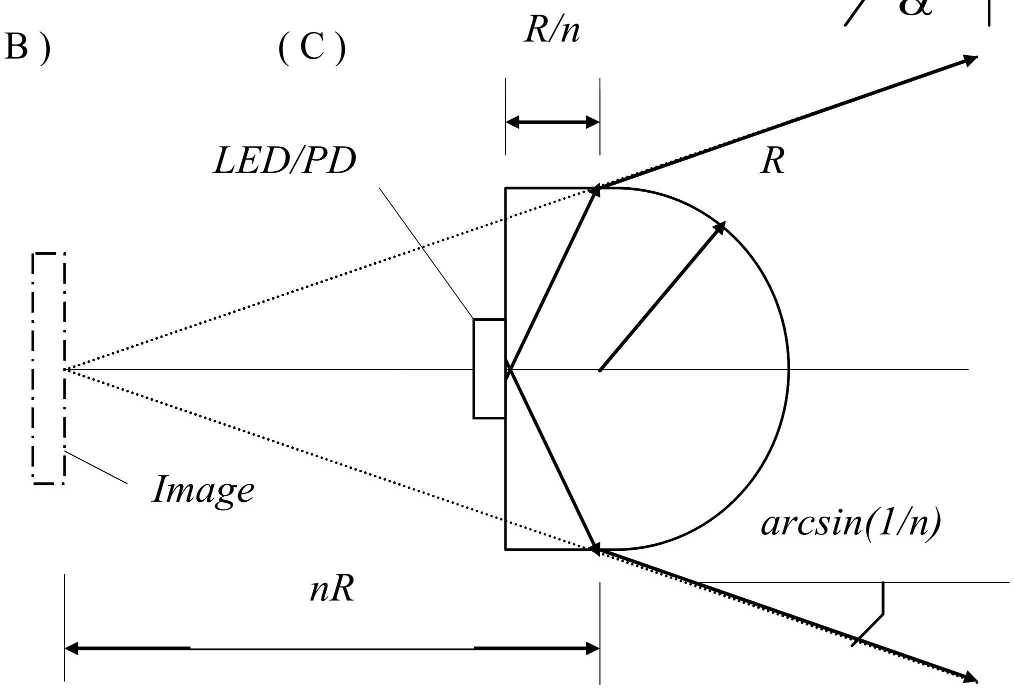



# 2. LEDs and photodiodes (PDs): compromise between efficiency and cost.

# Total internal reflections and immersion.

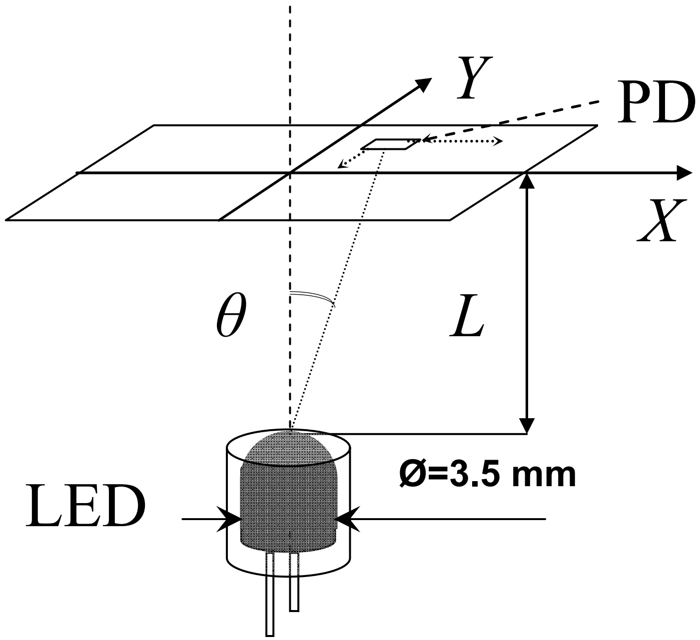


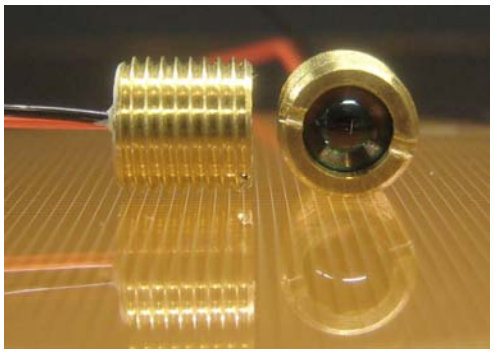



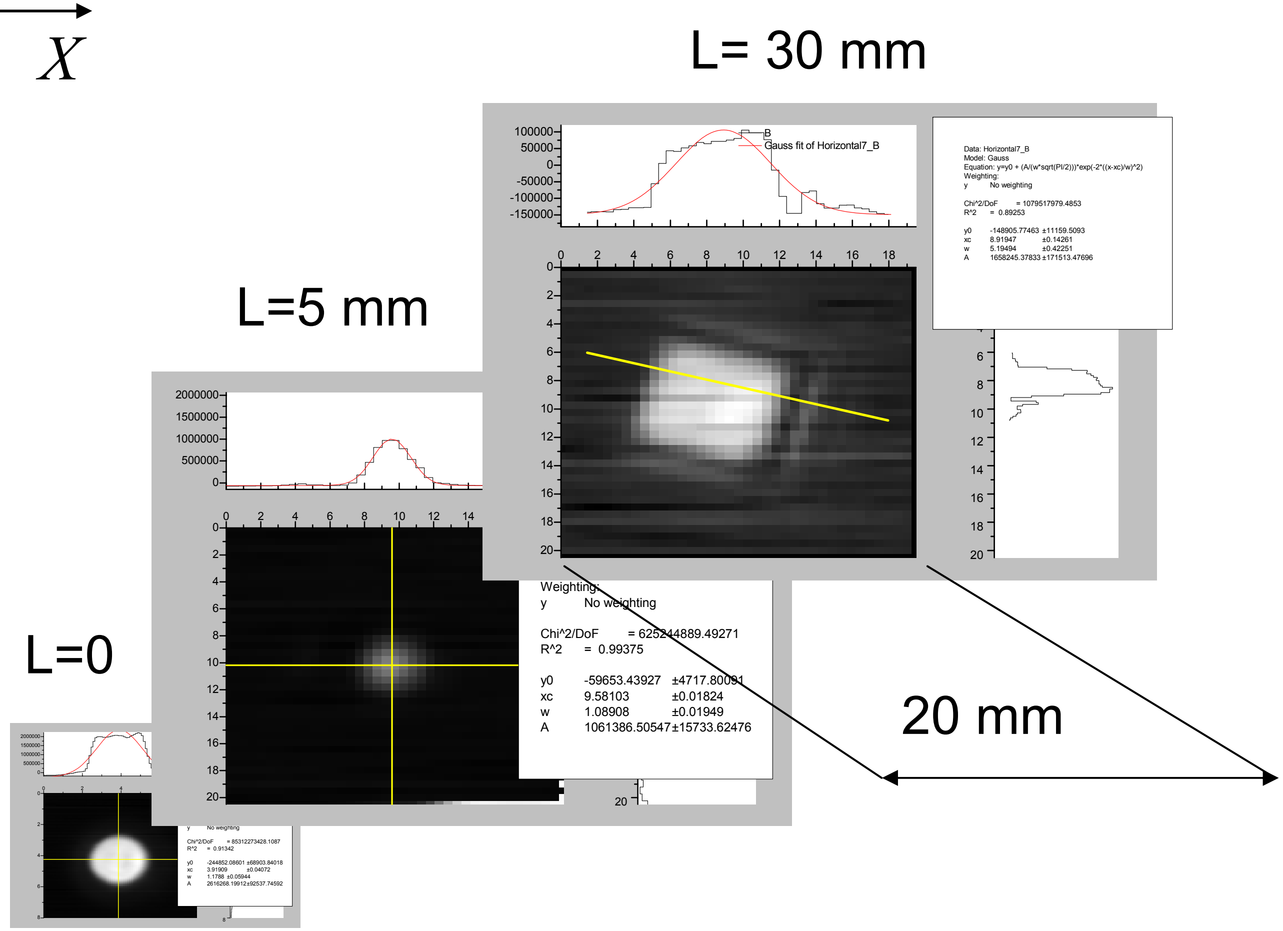
*Background*

# Hyperhemispherical Immersion lens LEDs (Ø =3.5 mm)



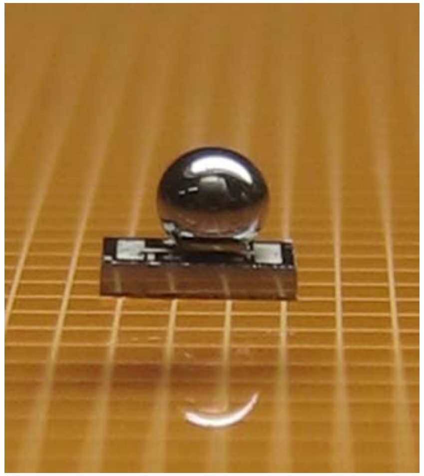

***N. V. Zotova et al  Journal of Optical Technology, Vol. 79, Issue 9, pp. 571-575 (2012)***





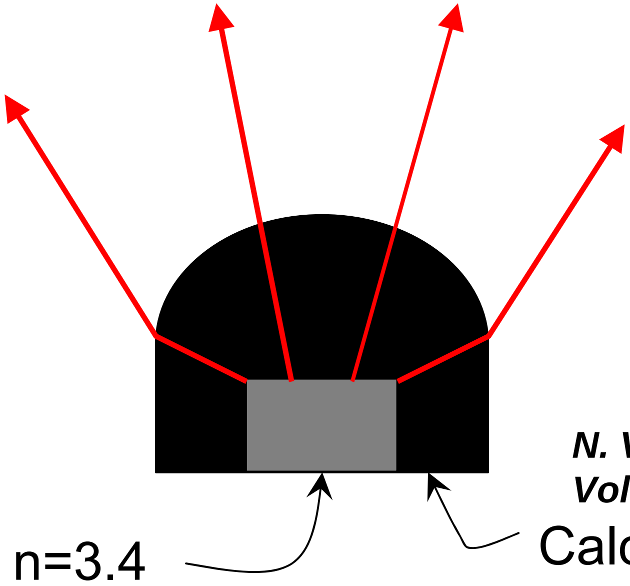
## 2. LEDs and photodiodes (PDs): compromise between efficiency and cost.

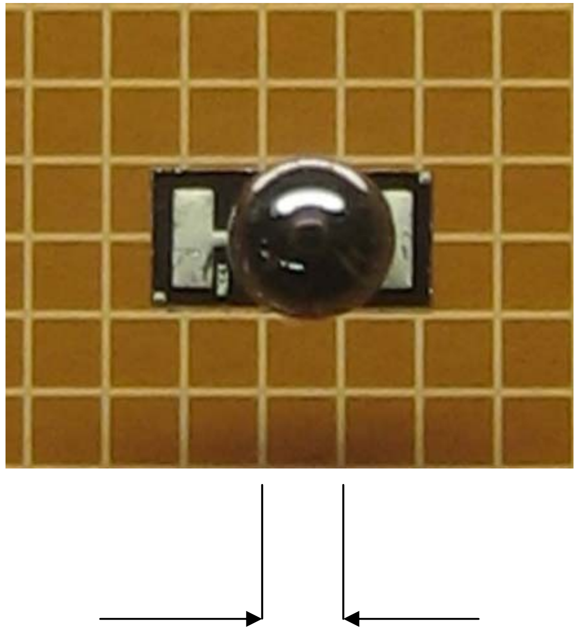
# Reduction of total internal reflection losses in microimmersion lens LEDs (Ø =1 mm)



High radiation outcoupling efficiency at small size!

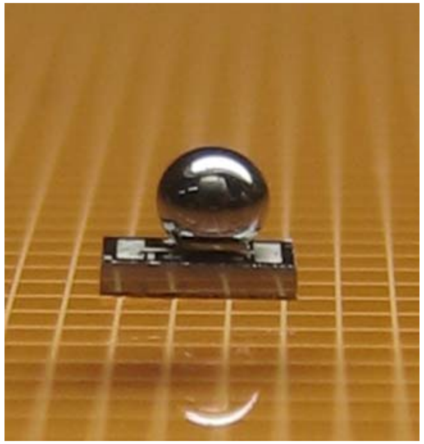
No mechanical polishing – low cost!

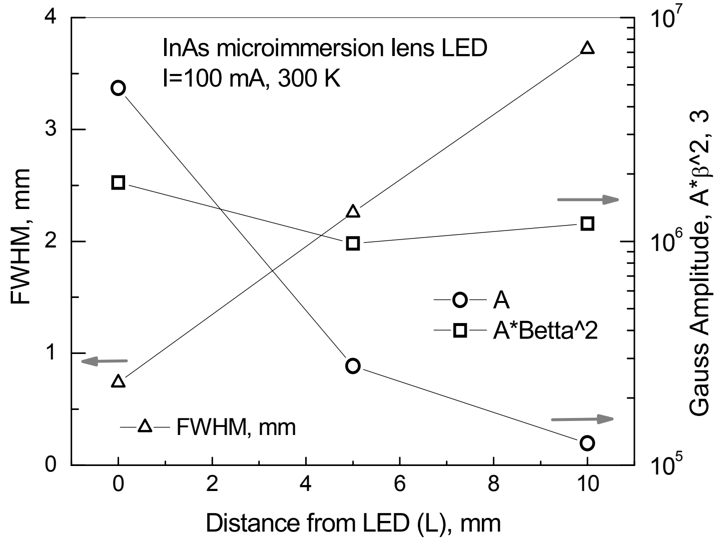


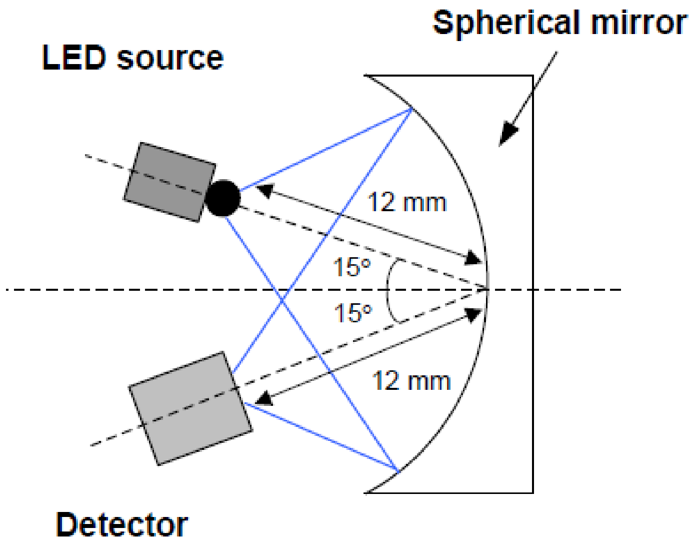




***N. V. Zotova et al Journal of Optical Technology, Vol. 79, Issue 9, pp. 571-575 (2012)***

# Microimmersion lens LEDs from p-InAsSbP/InAs/$n^+$- InAs ($\lambda$= 3.4 µm)





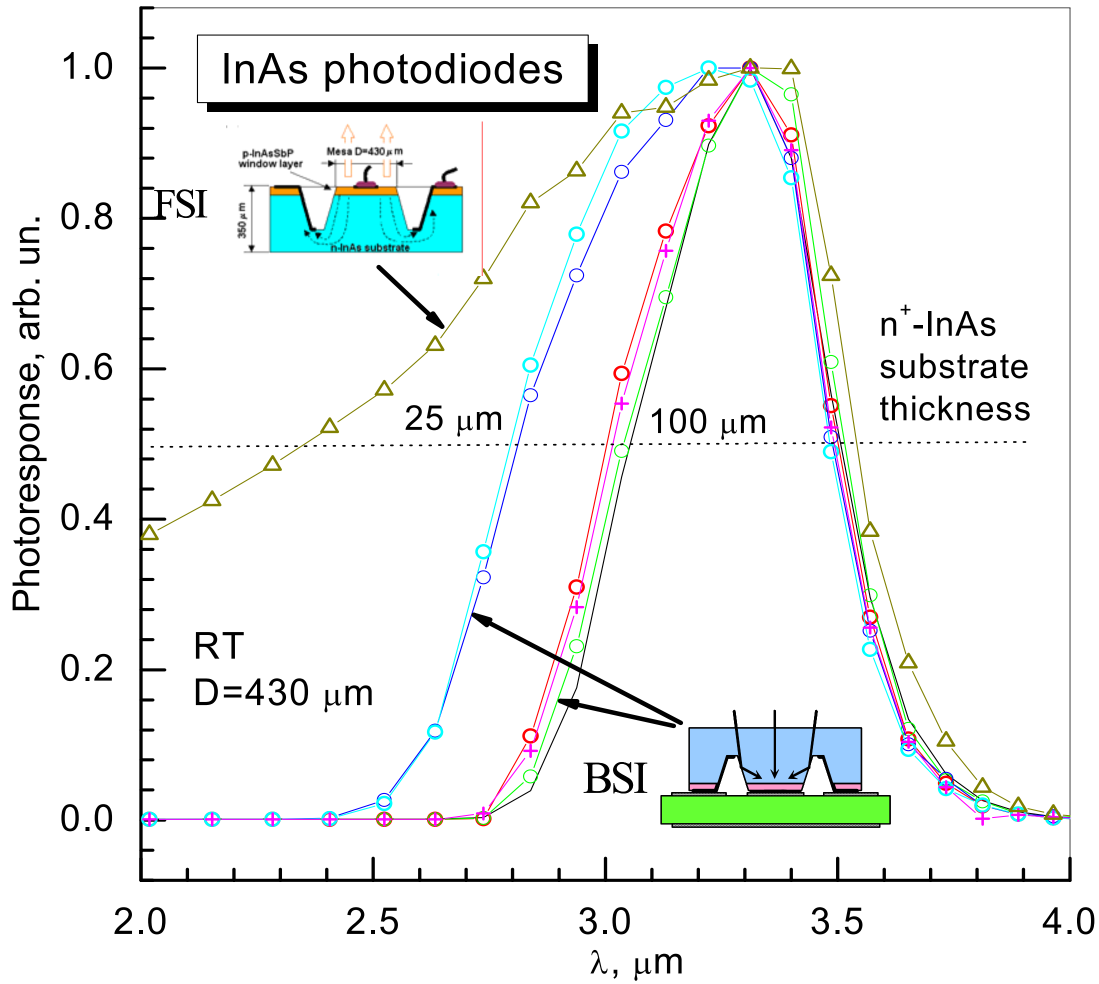

MINIGAS

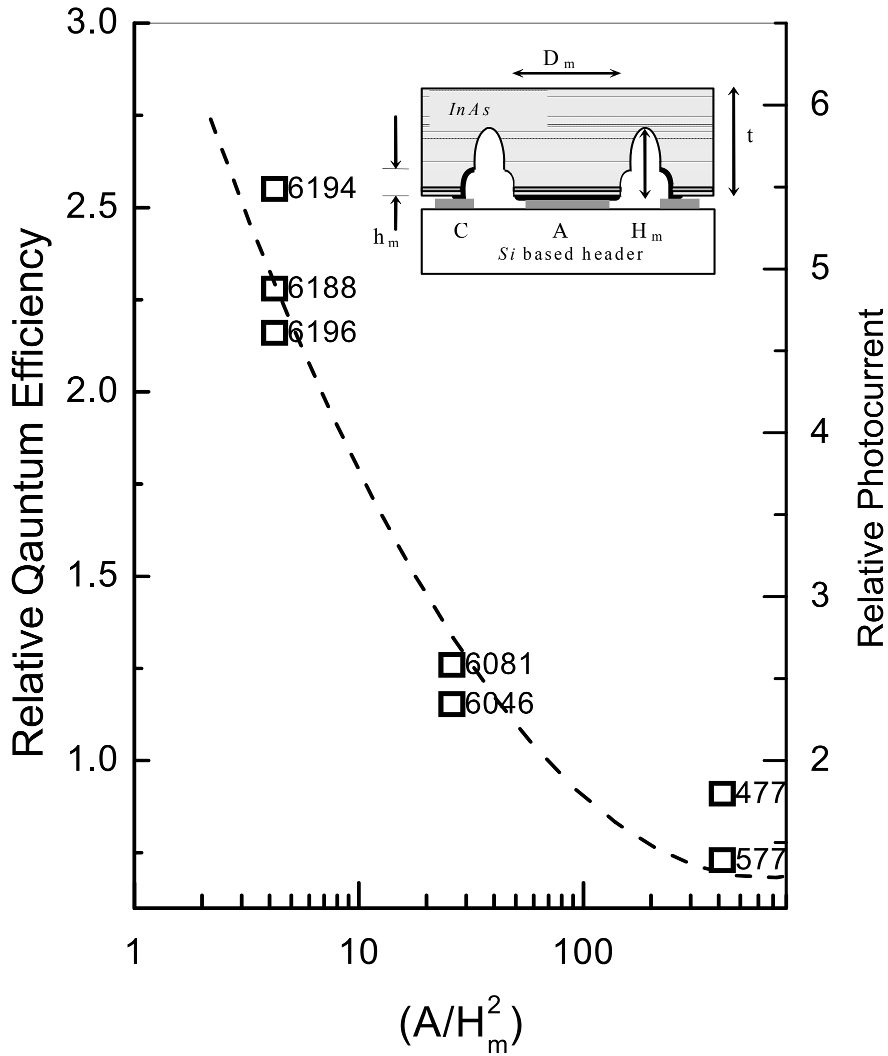
*N. V. Zotova et al Journal of Optical Technology, Vol. 79, Issue 9, pp. 571-575 (2012)*

**P=120 µW at I=100 mA**
**74% collection efficiency at a distance of 12 mm from gold plated mirror R= 12.0 mm (f = 6.0 mm), Ø= 12.0 mm.**
**Image size ~1 mm**

## 2. LEDs and photodiodes (PDs): compromise between efficiency and cost.

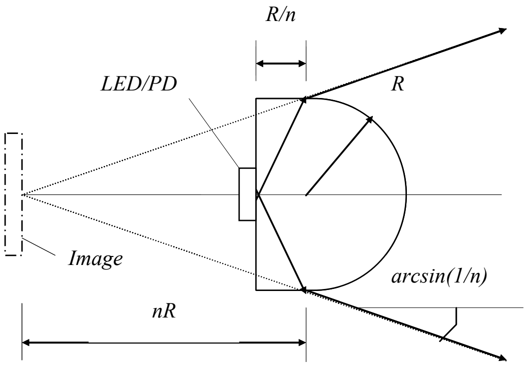
# Internal reflectors in InAs and InAsSb photodiodes

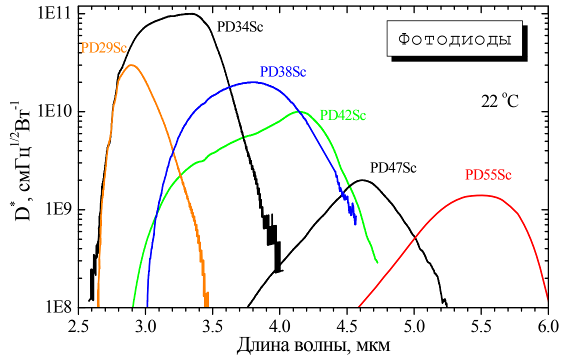


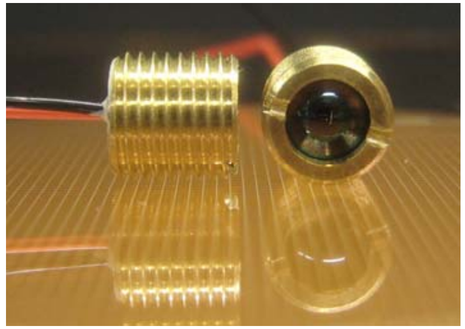



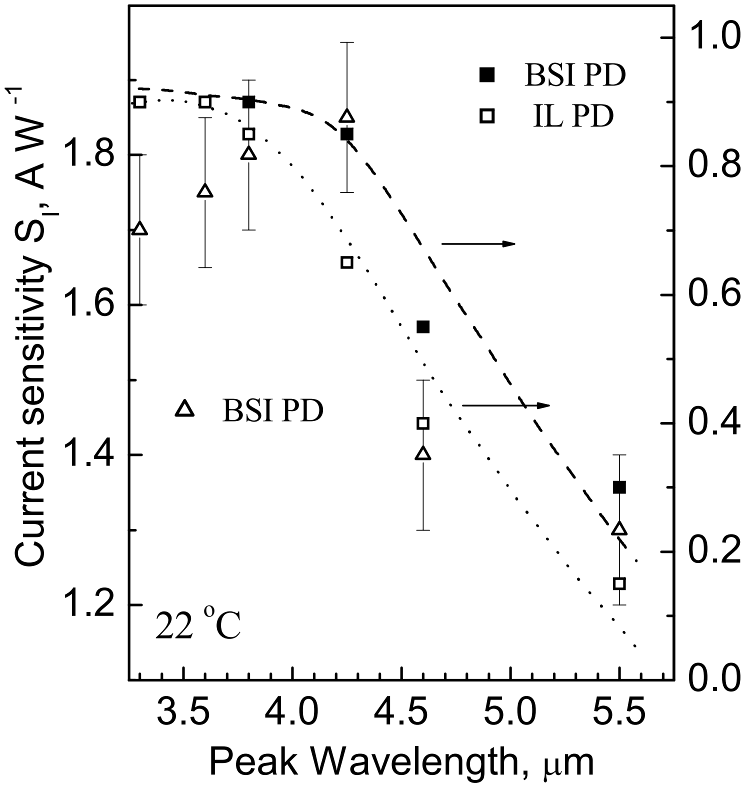
## 2. LEDs and photodiodes (PDs): compromise between efficiency and cost.

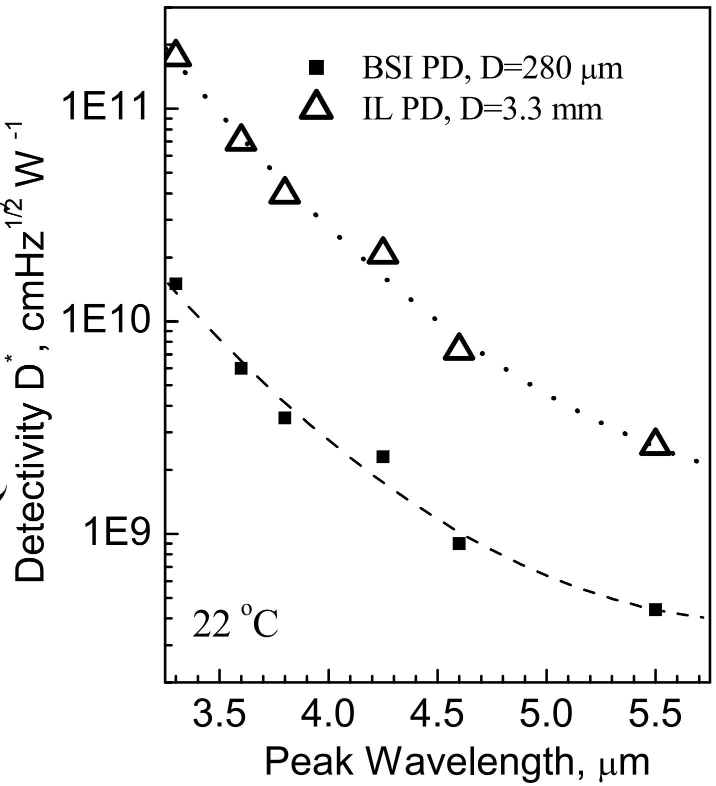
# Characteristics of the immersion lens photodiodes.



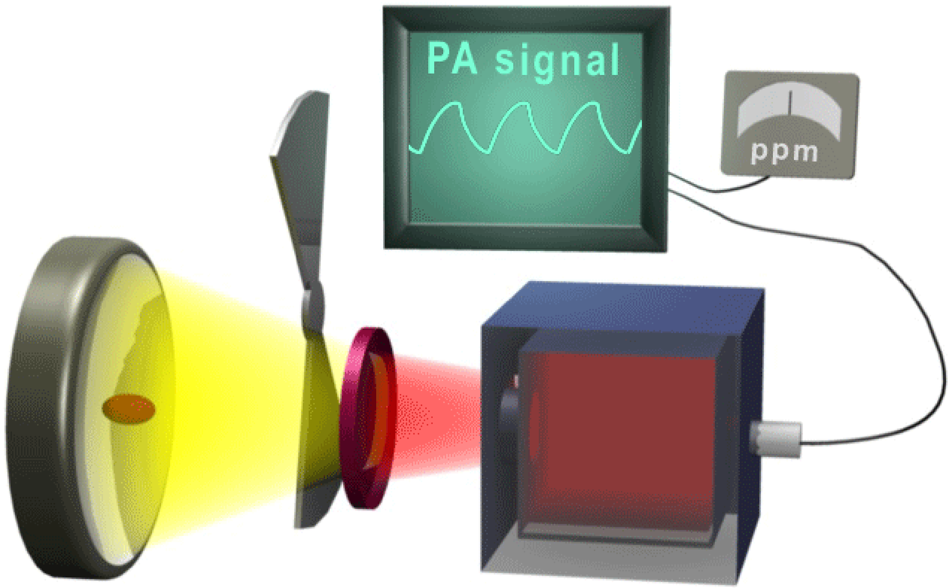





# 3. Gas absorption measurements ($C_nH_m$, $CO_2$, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.



## 3. Gas absorption measurements ($C_nH_m$, $CO_2$, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

# Open path $C_nH_m$ analyzer for petroleum plants based on microimmersion InAs PDs

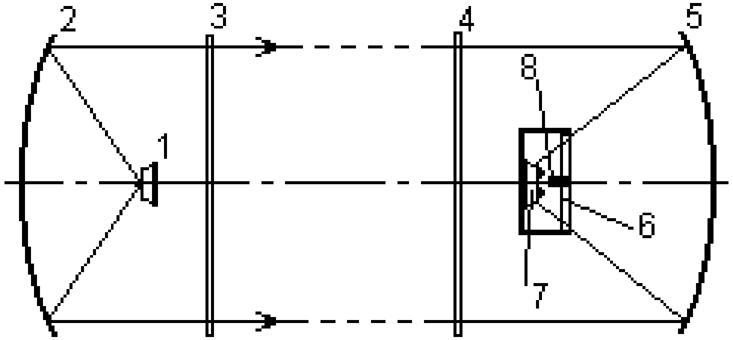
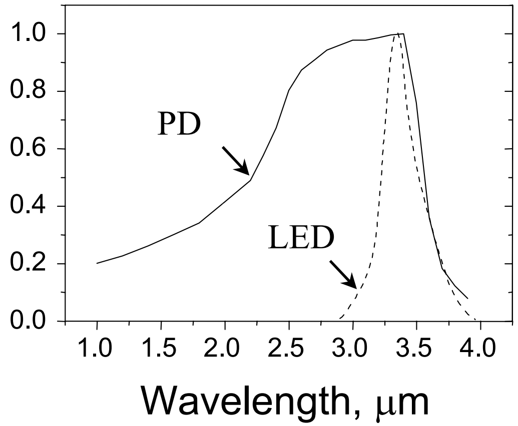



Fig.1. The optical scheme of a trace gas analyzer:
1 - IR LED; 2,5 - spherical mirrors; 3,4 - protective light filters; 6 - composite interference filter; 7 - IR photodetector; 8 - shield.



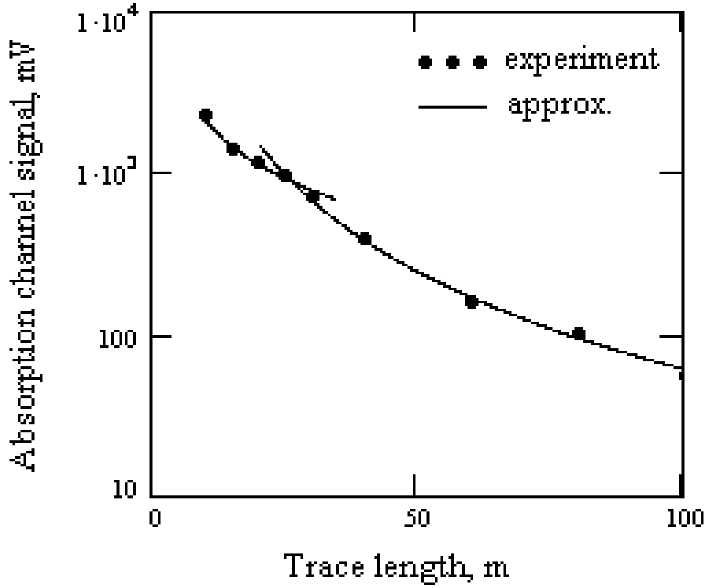
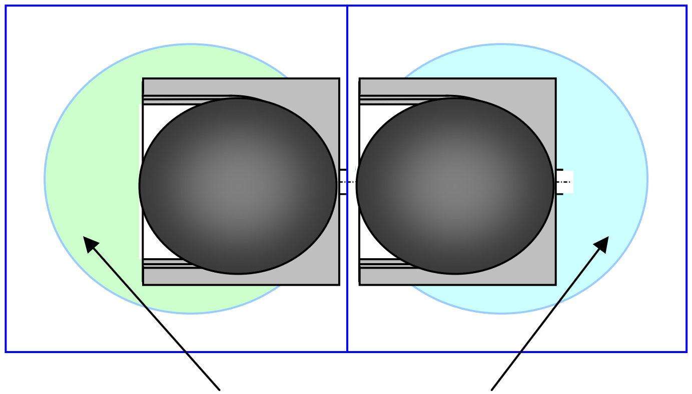




Fig.2. Absorption channel signal vs trace length.



Filters : λ=3.3 µm, λ=3.6 µm

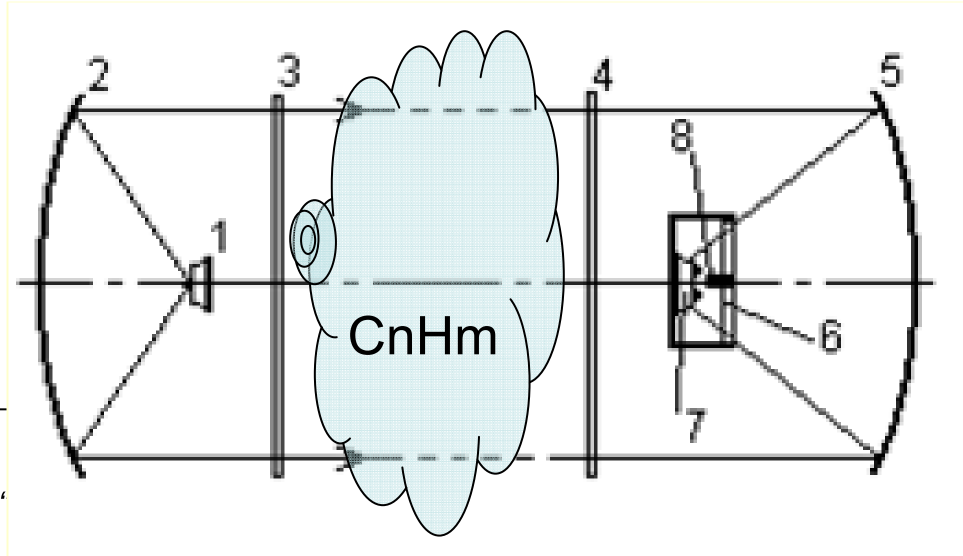
ШИББОЛЕТ
НАУЧНО-ПРОИЗВОДСТВЕННАЯ ФИРМА

## 3. Gas absorption measurements ($C_nH_m$, $CO_2$, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

# Open path $C_nH_m$ analyzer for petroleum plants based on microimmersion PDs

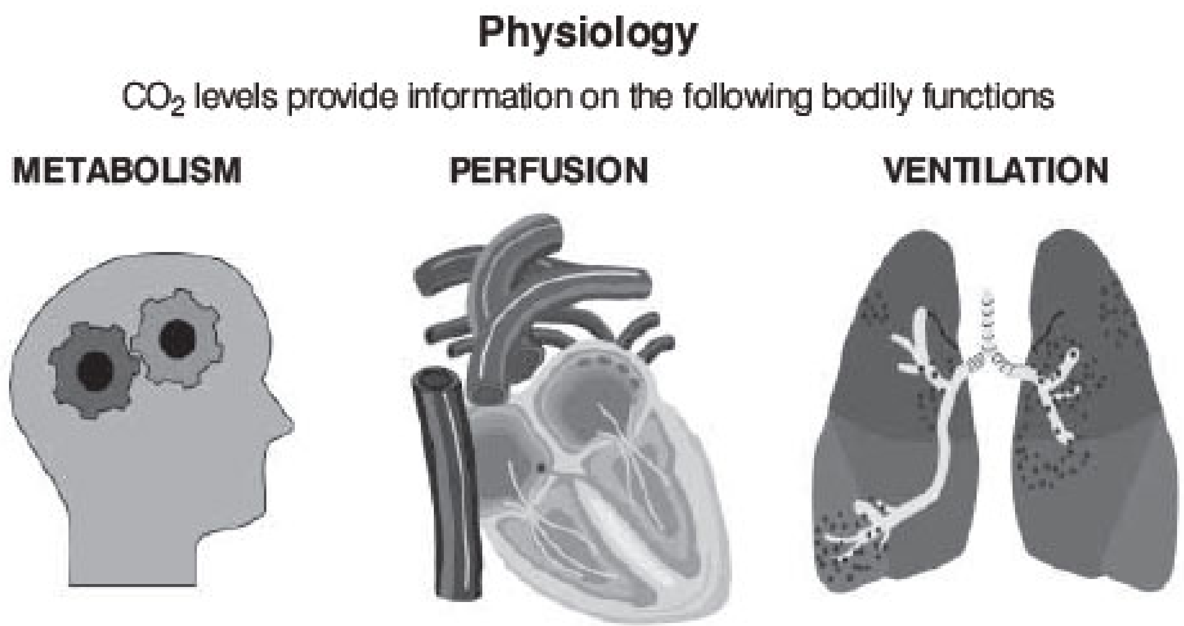

Concentrations: 1 – 100 LEL×m
40˚C ÷ +70˚C
Time response: 8 s

ШИББОЛЕТ
НАУЧНО-ПРОИЗВОДСТВЕНАЯ ФИРМА



3. Gas absorption measurements ($C_nH_m$, $CO_2$, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

# 4.2 μm LED-PD sensor for capnography ($CO_2$ breath measurements)

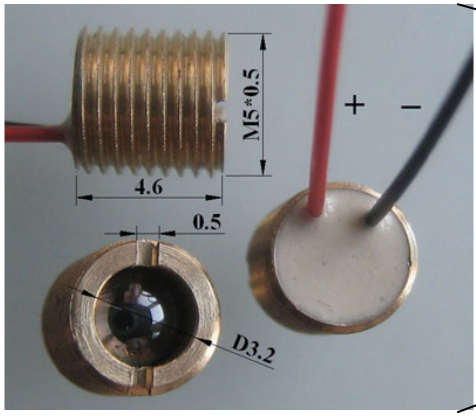


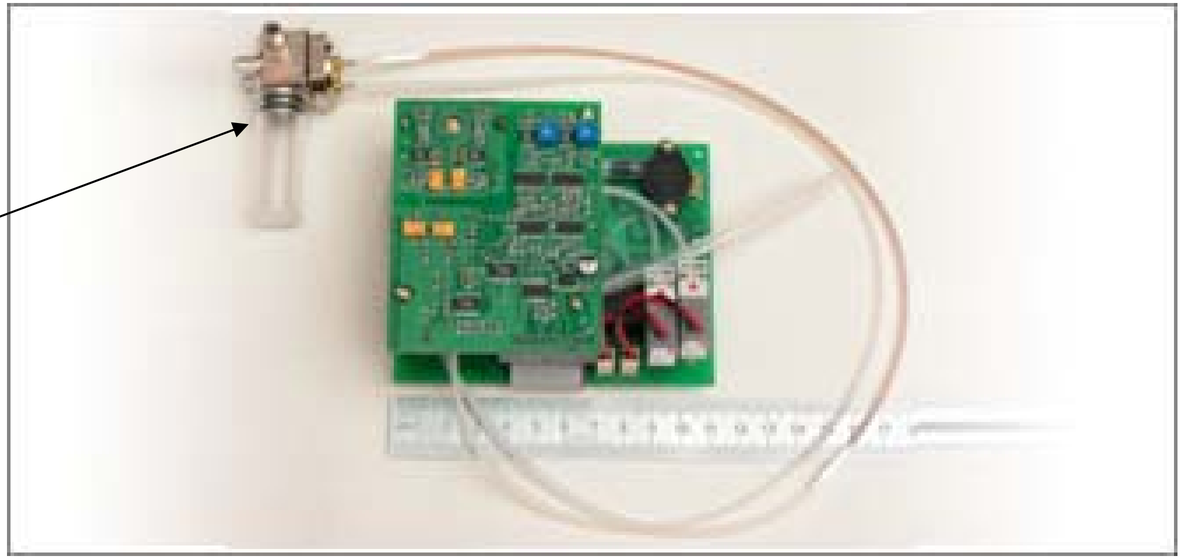

TRITON ELECTRONIC SYSTEMS

**Triton Electronic Systems Ltd.**
Russia, 620063, Ekaterinburg, P/O box 522
Phone: , +7 343 261 58 63

http://www.triton.ru/

# 4.2 µm LED-PD sensor for capnography ($CO_2$ breath measurements)



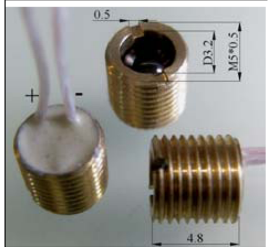



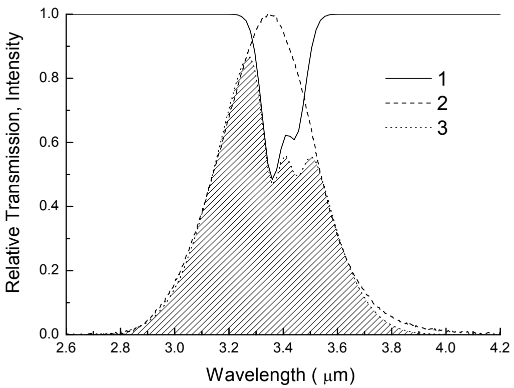
TriTON®
ELECTRONIC SYSTEMS

# 3. Gas absorption measurements ($C_nH_m$, $CO_2$, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

## 3.4 µm PDs for $C_2H_5OH$ measurements.

PD34Sr



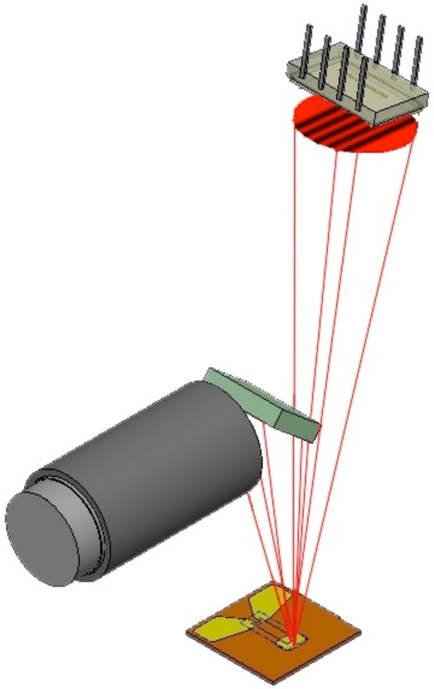



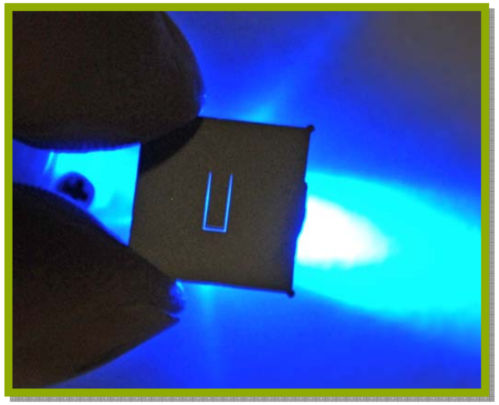

| | | |
|---|---|---|
| λ | µm | 3.35±0.05 |
| $λ_{co}$ | µm | 3.7 |
| $D^*_{λmax}$ | $cmHz^{1/2}W^{-1}$ | $\geq 5\times10^{10}$ |
| $S_I$ | A/W | ≥1.0 |
| $S_U$ | V/W | ≥500 |
| $R_0$ | Ohm | ≥0.5k |
| τ | ns | ≤20 |

META

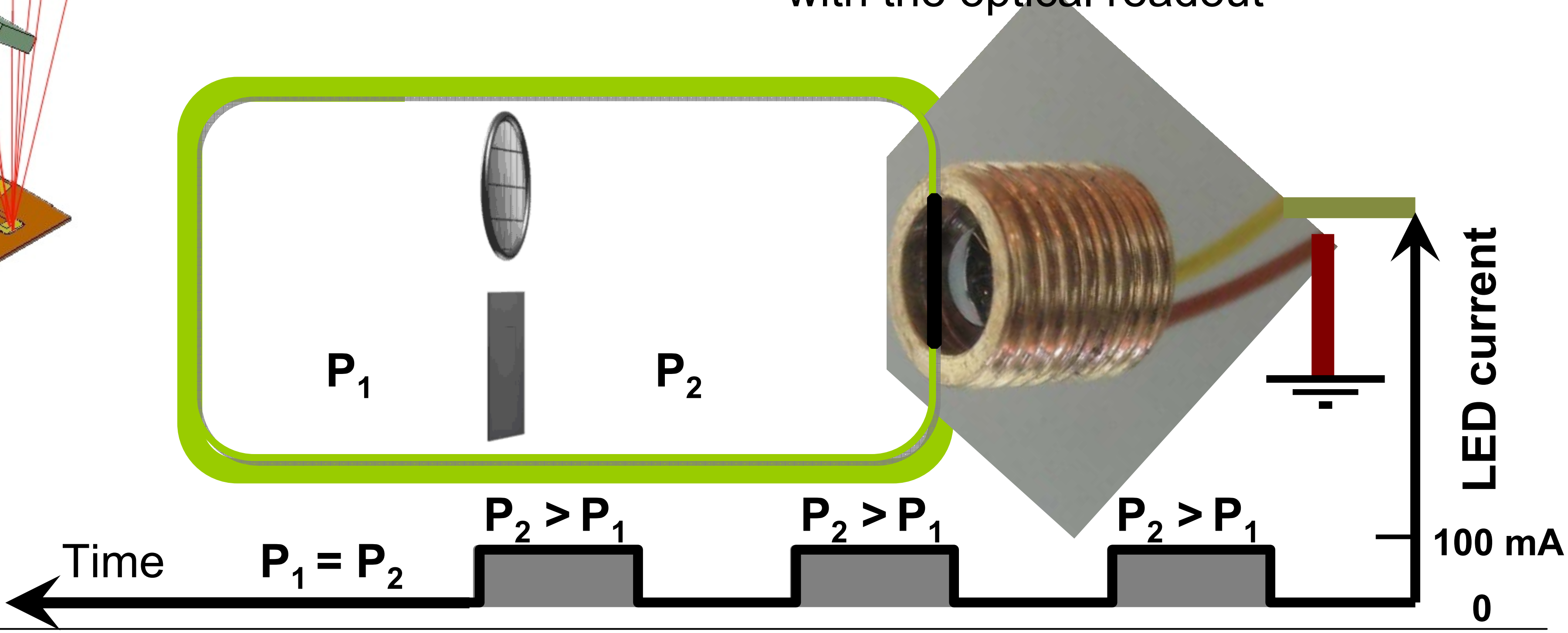
## 3. Gas absorption measurements (CnHm, CO2, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

# Photoacoustic measurements with IL LEDs.





- Cantilever sensor (microphone) is coupled with interferometric measurement of the displacement
- Below picometer ($10^{-12}$ m) displacement can be detected with the optical readout

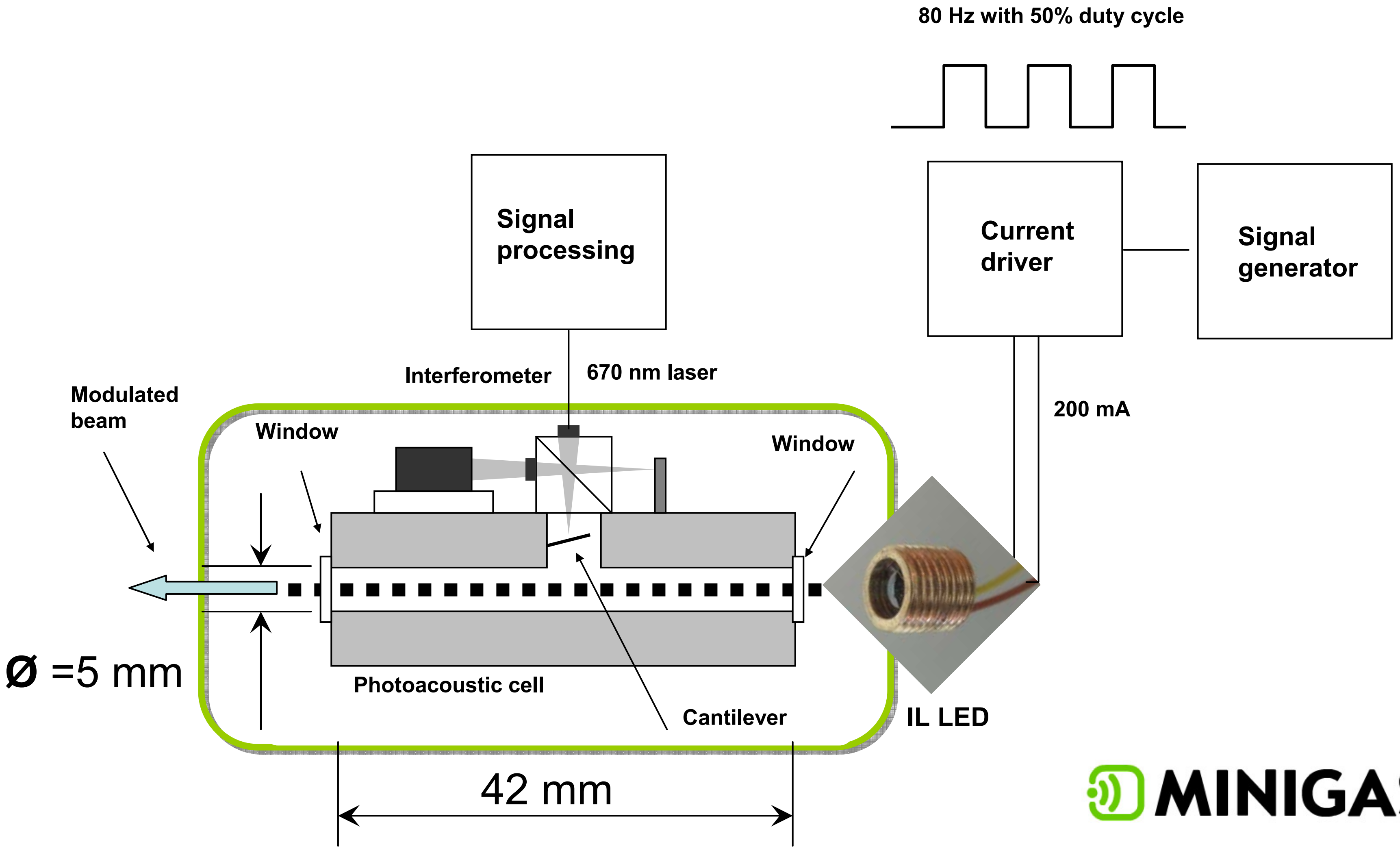



GASERA

UTU.fi
TURUN YLIOPISTO
UNIVERSITY OF TURKU

# 3. Gas absorption measurements (CnHm, CO2, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

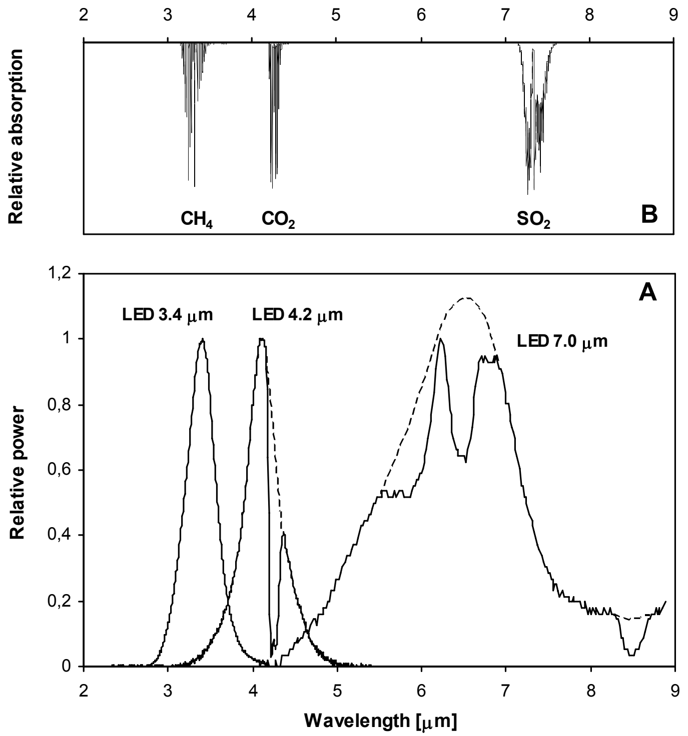
# Photoacoustic measurements with IL LEDs.




T. Kuusela et al Vibrational Spectroscopy, 51(2), 289-293 (2009).

## 3. Gas absorption measurements (CnHm, CO2, trace, open path, gas cell) with LED-PD pairs and photoacoustic detector.

# Photoacoustic measurements with IL LEDs.




| Gas | Detection limit at 1 s integration (ppm) | LED active area | λ (μm) |
|---|---|---|---|
| $CH_4$ | 26 | InAs | 3.1 – 3.5 |
| $CO_2$ | 11 | InAsSb | 4.2 – 4.4 |
| $C_3H_8$ | 6 | InAs | 3.1 – 3.5 |
| $C_3H_8$ | 330 | InSb | 6.5 – 7.5 |
| $SO_2$ | 620 | InSb | 7.1 – 7.6 |

MINIGAS

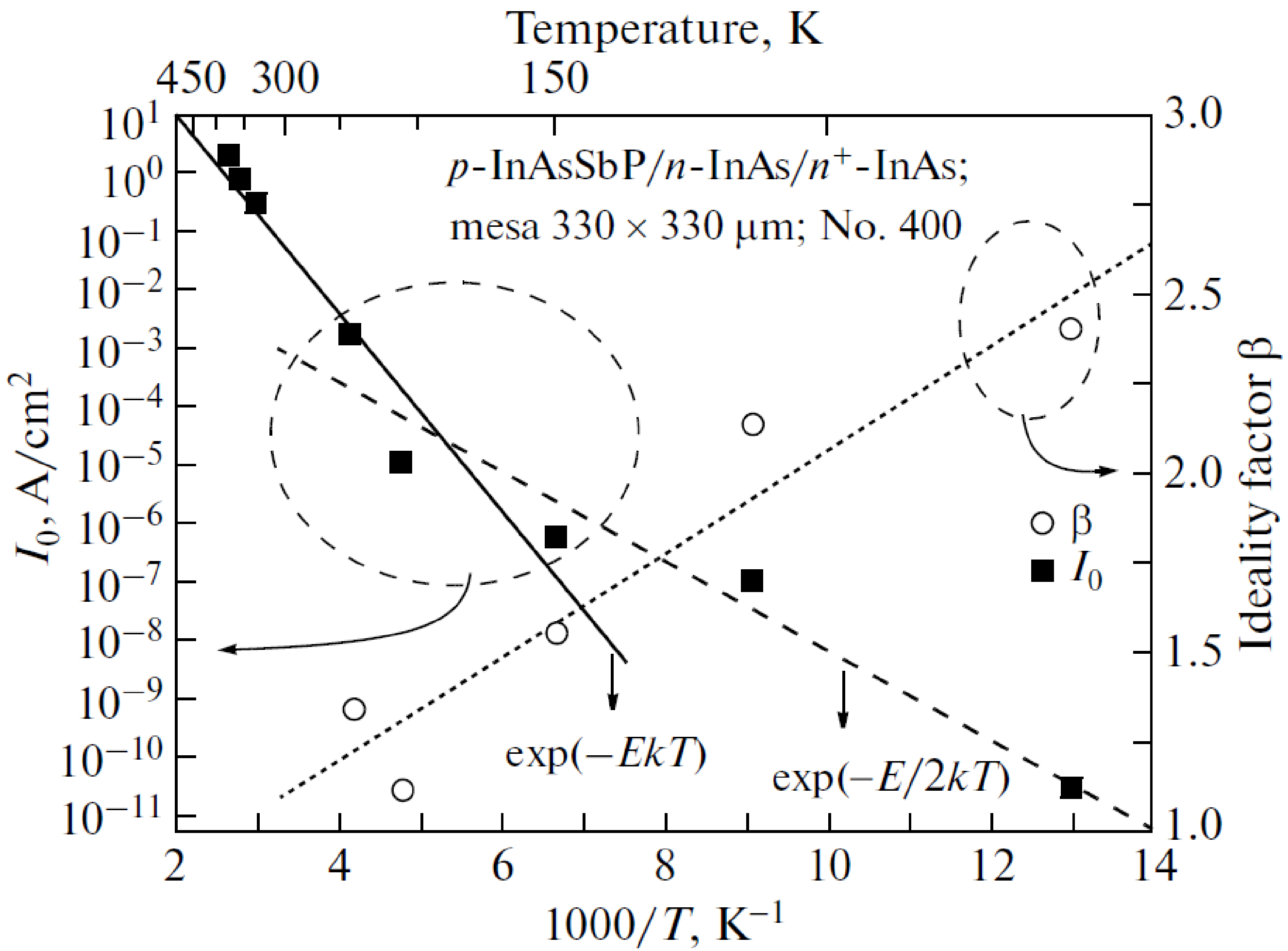
T. Kuusela et al Vibrational Spectroscopy, 51(2), 289-293 (2009).

# 4. Small power measurements ( expectations ).

# 4. Small power measurements (unexpected expectations!).

### 4. Small power measurements

# Cooled PDs for the 3 μm spectral range.




$2.3 \times 10^{13}$ cm Hz$^{1/2}$ W$^{-1}$

N. D. Il'inskaya et al Technical Physics Letters, 2013, Vol. 39, No. 9, pp. 818–821.

## 4. Small power measurements

# Mid-IR LEDs with wall plug efficiency > 100%

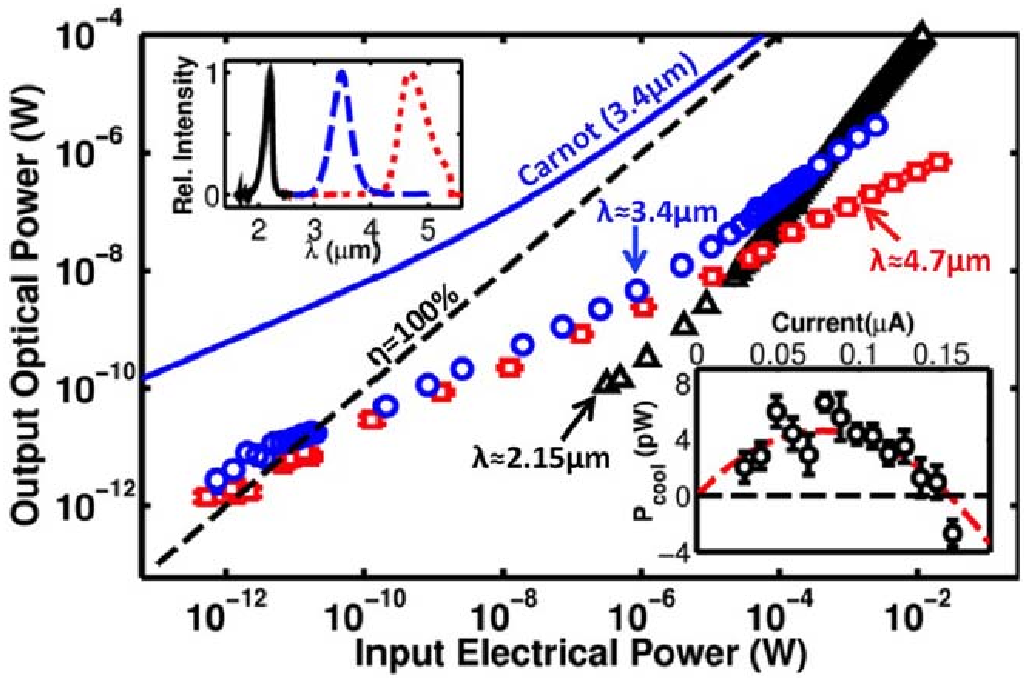



FIG. 2. Output optical power versus input electrical power for three room temperature mid-infrared LEDs. For the devices emitting at 3.4 $\mu$m (area $5.29\times10^{-4}$ cm$^2$, wafer #6341) and 4.7 $\mu$m (area $2.25\times10^{-4}$ cm$^2$, #236), the power at unity efficiency was high enough to be directly observed in our lock-in measurements. For the device emitting at 2.15 $\mu$m, it was not. Note: Data for the 2.15 $\mu$m LED is from Ref. 3. Insets: (top left) Relative intensity spectra for the three devices at room temperature; (bottom right) cooling power versus current for 3.4 $\mu$m device at room temperature.

P.Santhanam et al, Appl. Phys. Lett. 103 (19), 183513 (2013)

## 4. Small power measurements

# PD spectral response and BB power

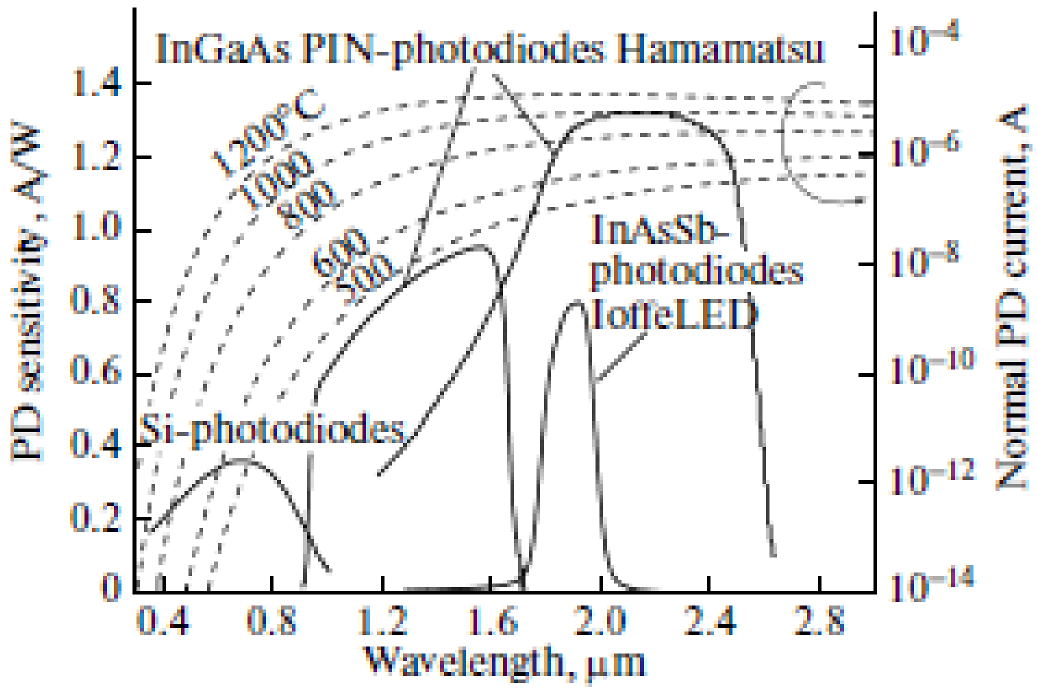



**Fig. 1.** Spectral sensitivity ranges of photodiodes (PD), satisfying the requirements to the developed pyrometric sensor (solid curve), and the "conditional" photodiode currents ($S = 1$ A/W) for various spectral regions when detecting 10% of the thermal radiation of the object (blackbody).

*Semiconductors, 2014, Vol. 48, No. 1, pp. 129–134.*

## 4. Small power measurements

# Fiber-coupled laser module

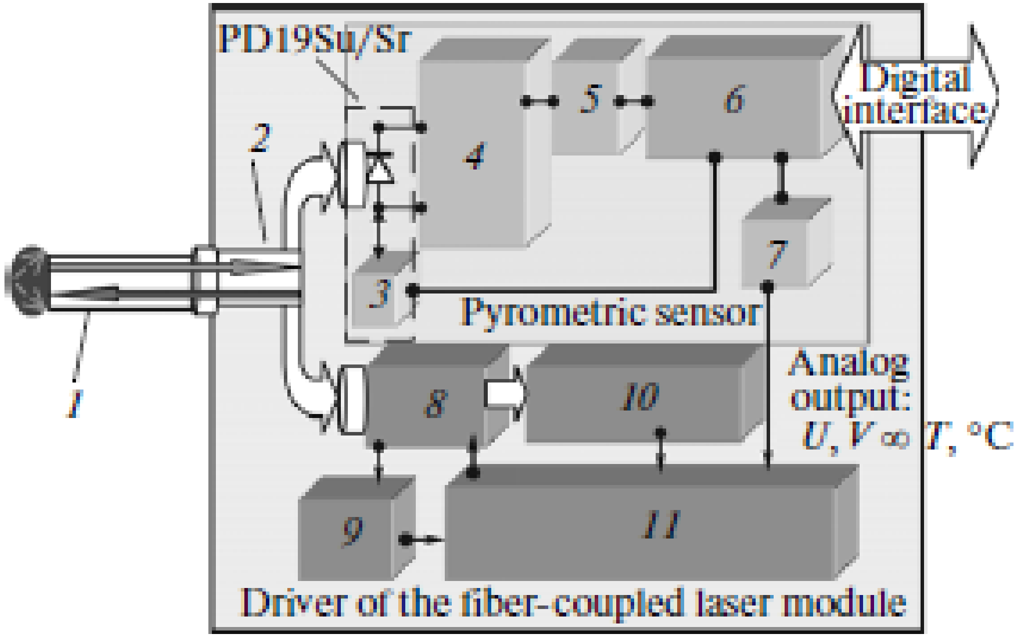
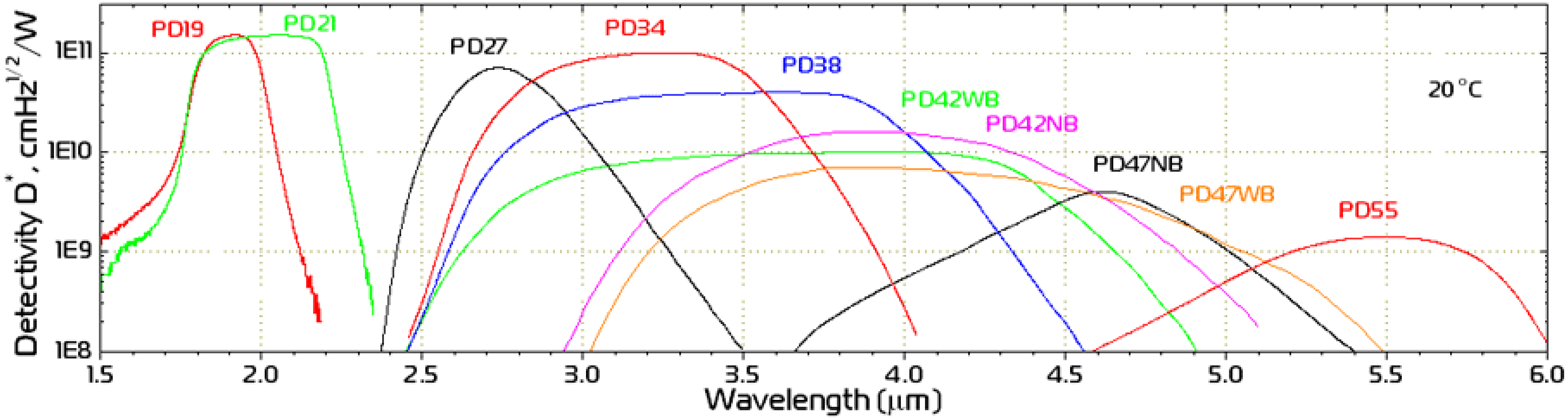
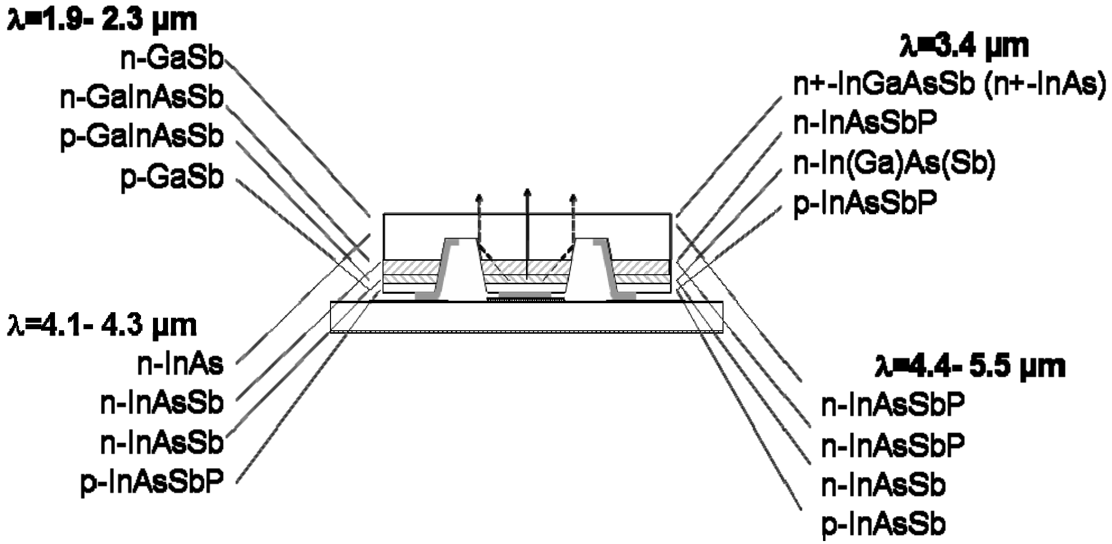



**Fig. 2.** Block diagram of the fiber-coupled laser module driver with embedded pyrometric sensor: (*1*) operating fiber, (*2*) Y-shaped fiber splitter, (*3*) thermoelectric module (TEM), (*4*) current–voltage amplifier–converter, (*5*) ADC, (*6*) control and processing unit, (*7*) DAC, (*8*) laser diode, (*9*) current sensor, (*10*) radiation-power sensor, and (*11*) controllable source of stabilized laser pump current.

*Semiconductors, 2014, Vol. 48, No. 1, pp. 129–134.*

# $A^3B^5$ heterostructure LED types




All developed **InAs** and **GaSb** based heterostructures enable flip-chip assembling technology and mounting of an immersion lens on top of the broad band “window” surface (Patent numbers 2261501, 2286618 )

## 4. Small power measurements

# Experimental tests of the PD based pyrometer

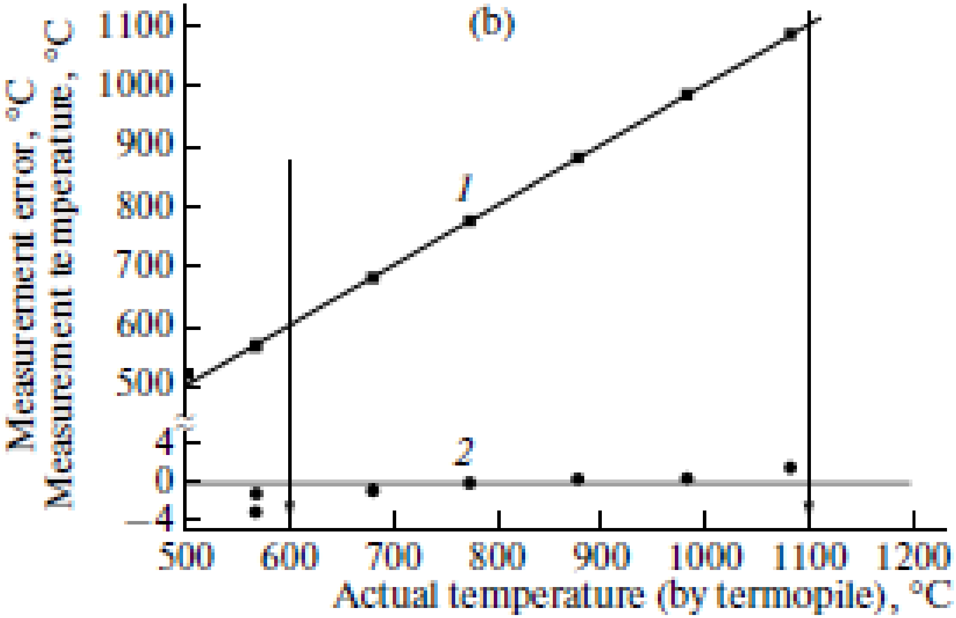



**Fig. 3.** (a) Experimental PD currents (squares *1*), calculated transfer function of the pyrometric sensor (solid line *1*), experimental (circles *2*) and calculated (dashed line *2*) instrumental) errors of the pyrometric sensor. (b) PD sensor readings (*1*) when measuring the temperature at the fiber tip in contact with the emitter and their deviations (*2*) from the emitter temperature measured by a thermocouple.

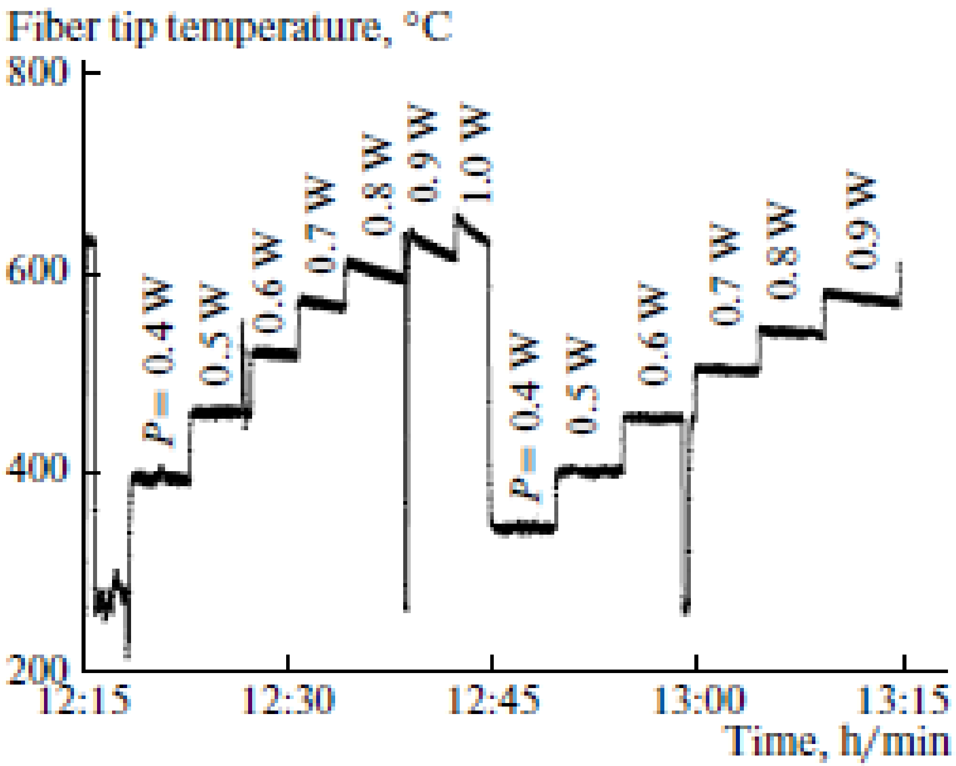



**Fig. 4.** Experiment on measuring the temperature of a fiber tip heated by laser radiation at various pump powers *P*.

*Semiconductors, 2014, Vol. 48, No. 1, pp. 129–134.*

## 4. Small power measurements

# Emission spectroscopy experiments (CH4) at soot plant.


PD34Sc

# Emission spectroscopy experiments (NOx at gas station).

PD53Sc

# 4. Temperature measurements with immersion lens PDs (expectations).

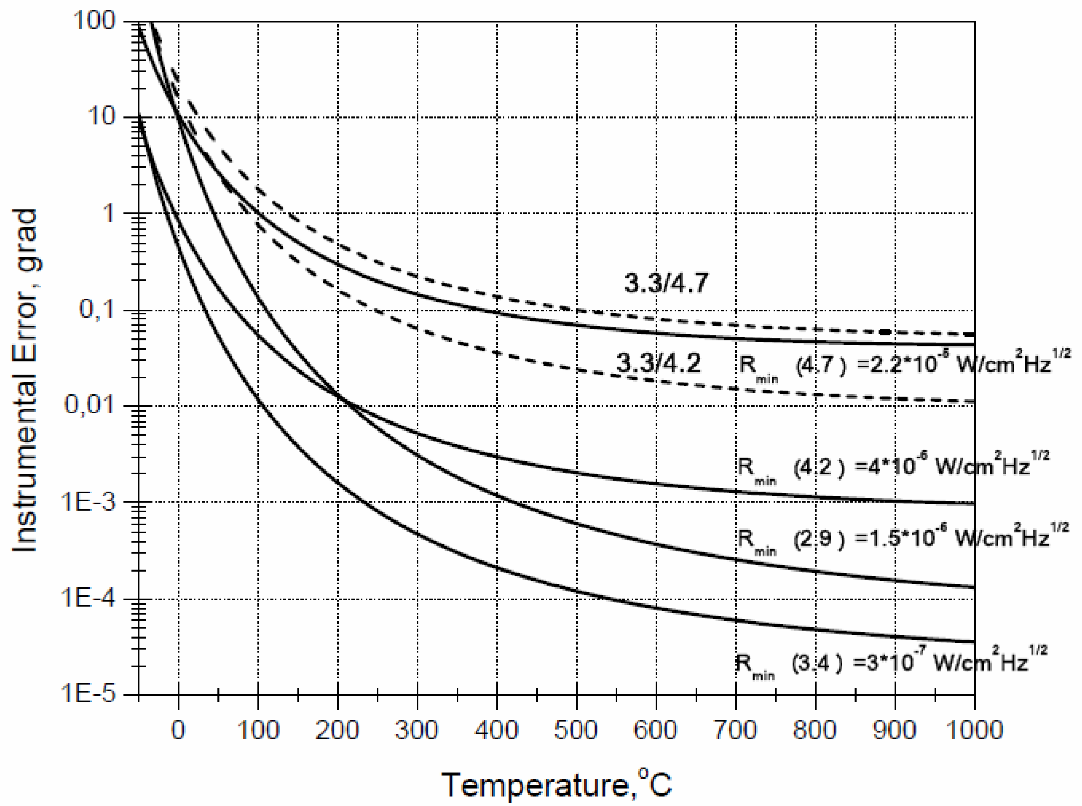



Figure3. Instrumental errors of one-color pyrometric sensors based on A3B5 photodiodes (solid lines) and two-color pyrometric sensors based on pairs of diodes (dotted lines). The time of measurement is equal to 1 s, the linear sizes of the object under measurement are equal to 1 cm, the sighting coefficient is equal to 1:100, the product $\varepsilon(\lambda)\tau(\lambda)=1$.

G. Yu. Sotnikova et al Proc. SPIE **8073**, 80731A (2011).

# Let’s do it!


# Thank you for your attention!