Mid-Infrared (1.6-4.6 μm) Light Emitting Diodes and Spectral Matched Potodiodes for the Ecological Monitoring and Medical Diagnostics

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Content

- Introduction
- Design of Light Emitting Diodes for the spectral range 1.6-2.4 μm
- Spectral and Power characteristics of 1.6-2.4 μm LEDs
- Design of Light Emitting Diodes for the spectral range 2.7-5.0 μm
- Optical characteristics of 2.7-5.0 μm LEDs
- Design of Photodiodes with cut-off 2.4 μm and 3.8 μm
- Photoelectrical characteristics of mid-infrared photodiodes
- Conclusion

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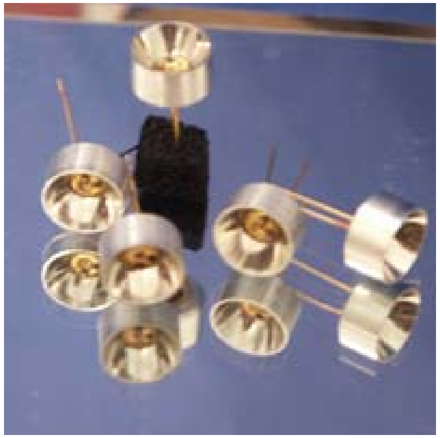
Introduction

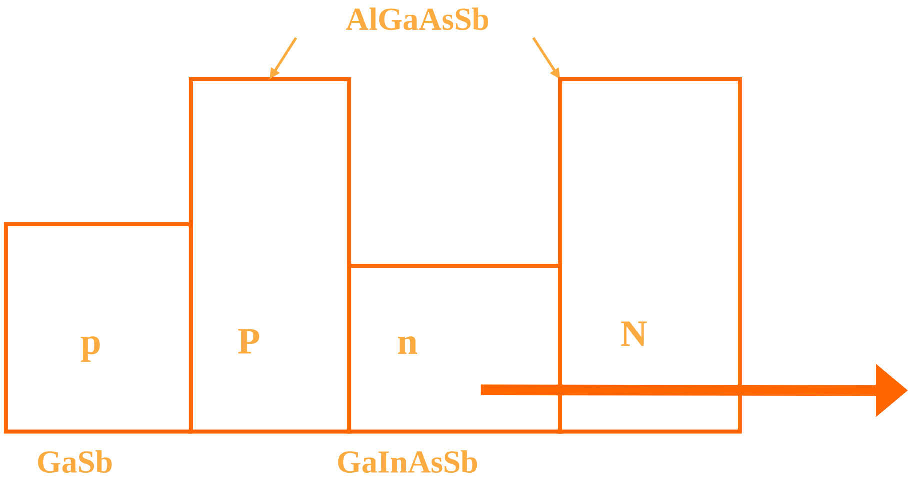
The optimal way of precise and reliable gas-analyze is grounded on an optical spectroscopy, i.e. measurement of absorption intensity of fundamental gas absorption lines. The wavelength range of 1.6-5.0 μm is the most effective spectral range for gas monitoring. A number of such relevant gases as H_2O, CO_2, CO, CH_4, N_2O, SO_2, NH_3, HF and others have strong fundamental absorption lines in the mid-infrared spectral range that are 50-500 times stronger in comparison with near- Infrared overtone bands at shorter wavelength. Therefore, not expensive, low power consumption portable gas analyzers with sensitivity of the order of a new ppm can be developed based on spectral matched light emitting diode (LED)- photodiode pair.

GaSb-InAs solid solutions based on III-V compounds are an attractive material for use in optoelectronic devices operating in this spectral range. The original epitaxial technology of lattice-matched narrow-gap heterostructures was developed in A.F.Ioffe Institute and IBSG Co.Ltd. Layers of gallium-rich GaInAsSb solutions grown on GaSb substrates can be used to create an active area for the 1.6-2.5 μm LEDs and photodiodes, while for the 2.7-4.8 μm spectral range the indium-rich In(Ga)AsSb layers grown on InAs substrates are of suitable materials. 1.6-2.5 μm LEDs based on GaInAsSb/GaAlAsSb heterostructures were grown by liquid phase epitaxy, while 2.7-4.6 μm LEDs were fabricated on the base of MOCVD grown n-InAsSbP/p-InAsSbP heterostructures.

LED Structure for the Spectral Range 1.6-2.4 μm

Unique technology is used to fabricate lattice-matched to GaSb substrate LED structures which allows us to increase lifetime of the devices. Energy band diagram of the structures for spectral ranges 1.65÷2.35 μm is schematized here. The output emission can be modulated by current flowing in a forward direction.





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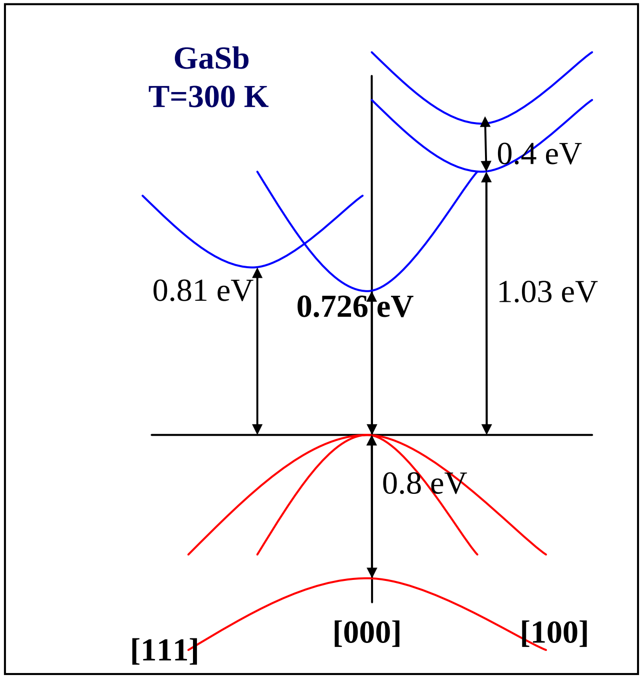
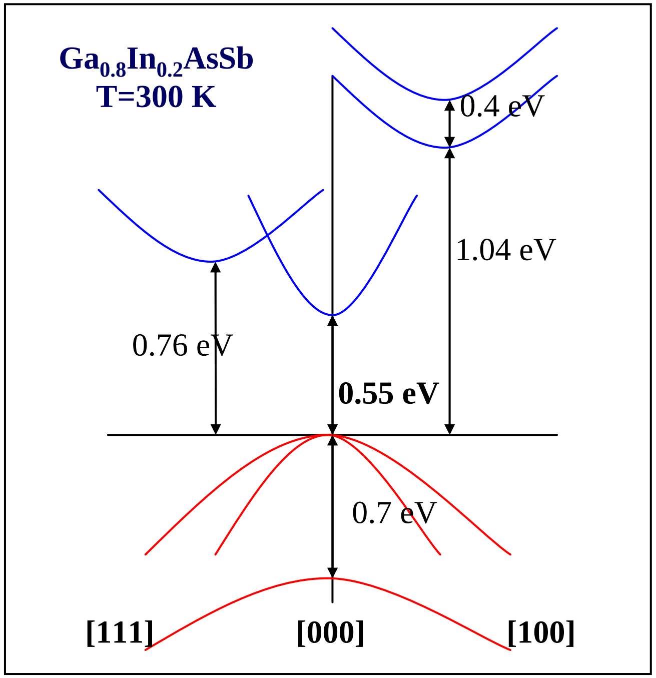
Materials for 1.6-2.4 µm LEDs

Materials that we use in the active layer are quaternary solid solutions $Ga_{1-x}In_xAsSb$ lattice matched to the GaSb substrate with indium content x from 0 to 24%. Energy gap structures of GaSb and $Ga_{0.8}In_{0.2}AsSb$ are presented below. Wide band gap layers AlGaAsSb with aluminum content 64% (E_G=1.1 eV) provide very good electron confinement.

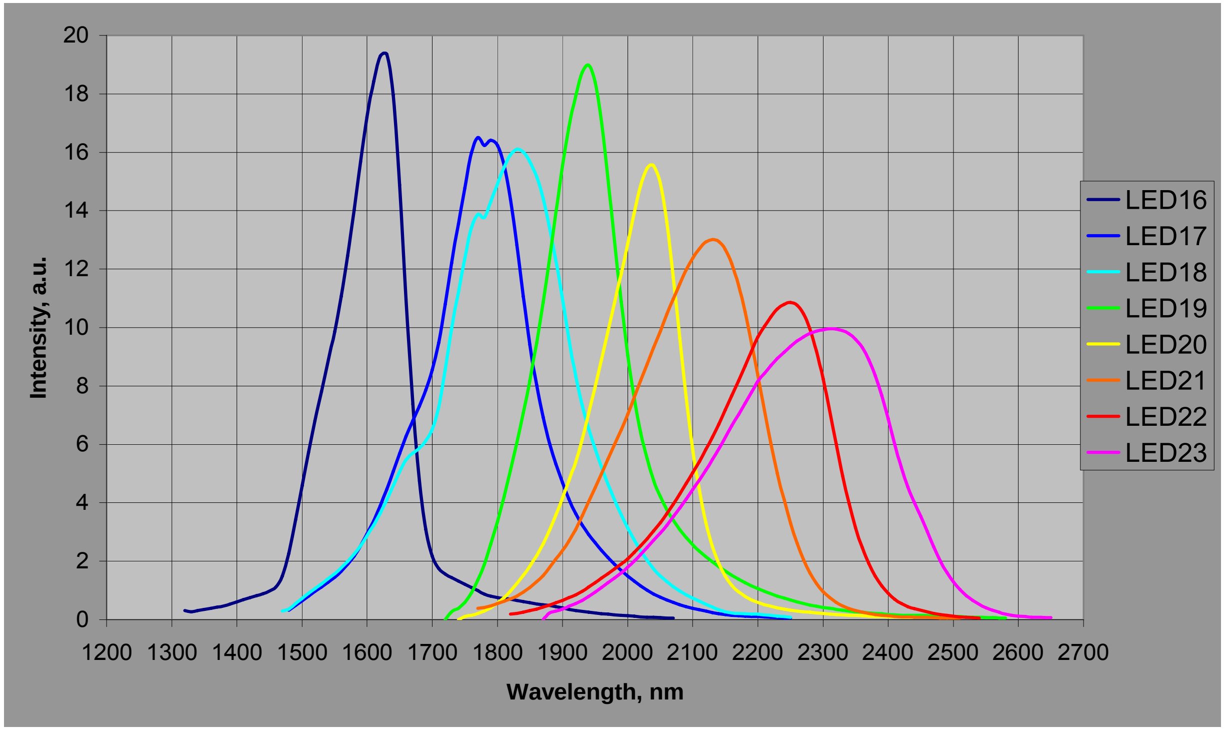
Our flexible technology gives us possibility to cover all spectral range 1.6÷2.4 µm by changing composition of the active layer GaInAsSb. IBSG offers 8 standard models for this range: LED16 (with central wavelength between 1600nm and 1700nm): LED17 (1700nm-1800nm), LED18 (1800nm-1900nm), LED19 (1900nm-2000nm), LED20 (2000nm-2100nm), LED21 (2100nm-2200nm), LED22 (2200nm-2300nm) and LED23 (2300nm-2400nm).





Spectral Characteristics of 1.6-2.4 μm LEDs

All Light Emitting Diodes can operate at room temperature in CW regime or in different pulse regimes. Short switching time of these devices make possible using of high frequency (hundreds of MHz) modulation or nanosecond pulse regimes. Standard regime of operation that we recommend for receiving maximum average optical power is quasi steady-state regime (quasi-CW) with repetition rate 500 Hz.



As far as standard full width at half maximum (FWHM) of these spectra lie between 150nm (LED16) and 200nm (LED23), you can choice suitable model for any application that requires light emitter in the range 1.6÷2.4 μm.

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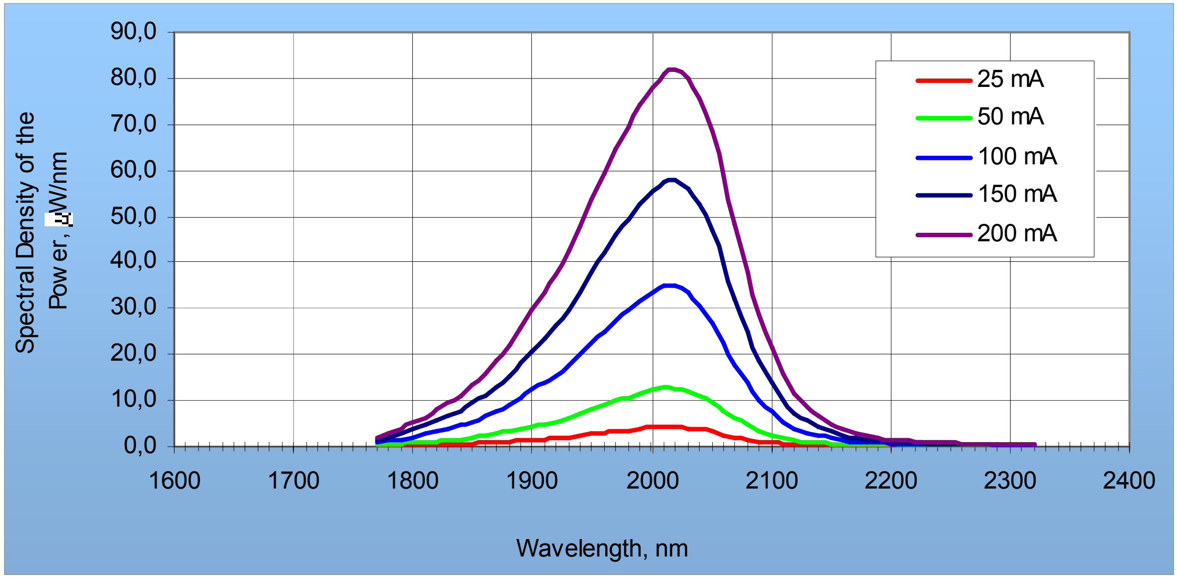
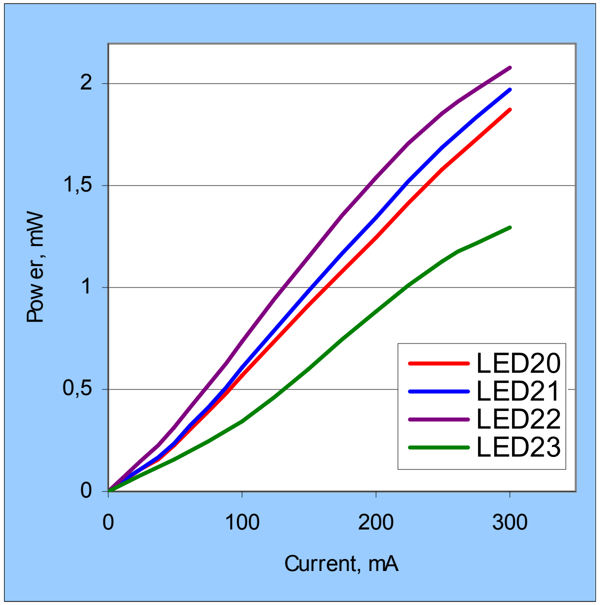
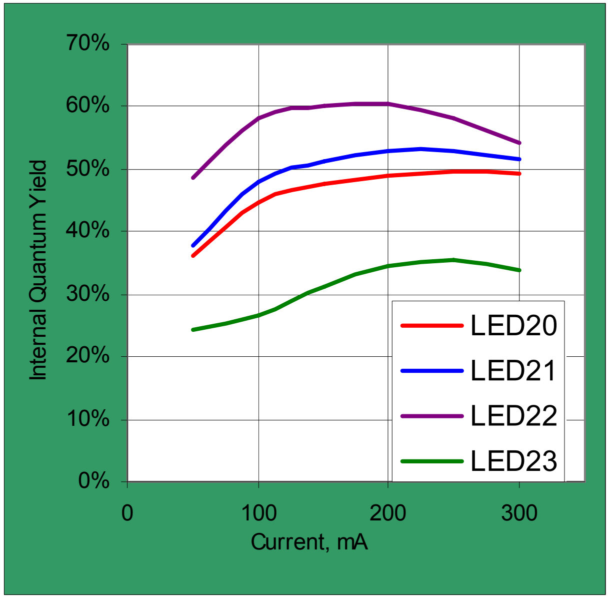
Current Dependence of the Optical Power for 2.0-2.4 μm LED

Here are presented typical power-current characteristics of our standard 2.05-2.35 μm LED structures. Optical power at quasi-steady state regime reaches 2.0 mW. Internal Quantum Yield is 55%. Similar values of quantum yield were obtained for 2.15 and 2.25 μm LEDs.







At currents lower then 150 mA quantum yield is limited by Shokly-Read-Hall nonradiative recombination. At currents higher then 250 mA quantum yield is limited by Auger nonradiative recombination.

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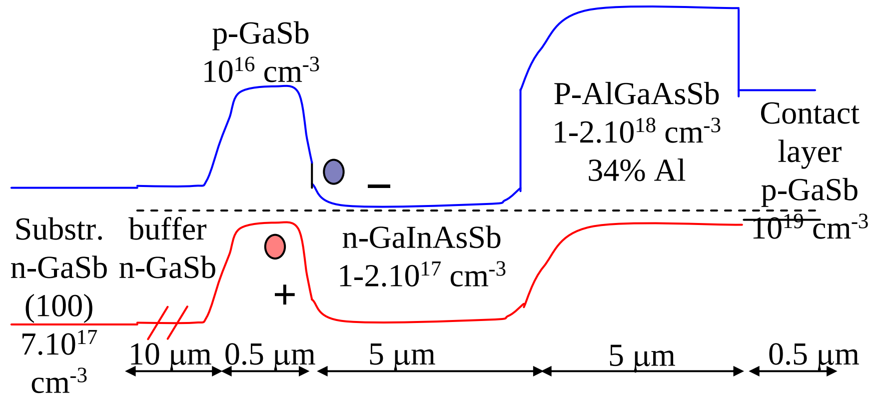
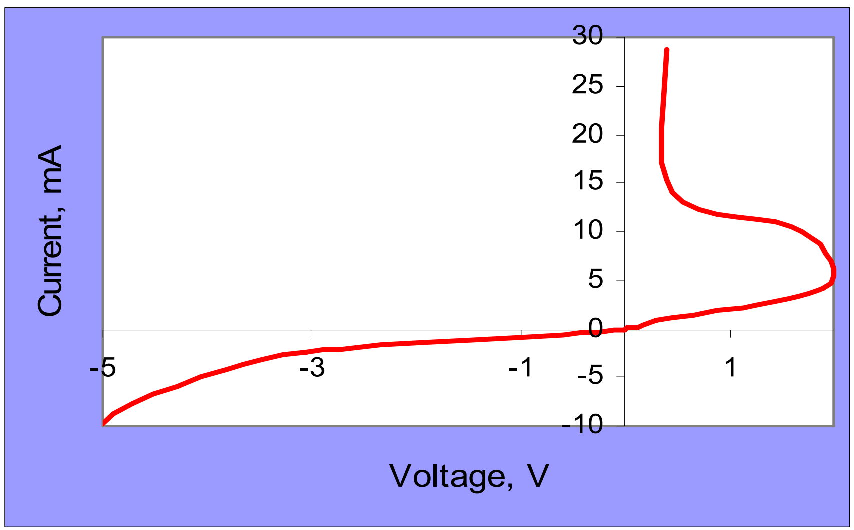
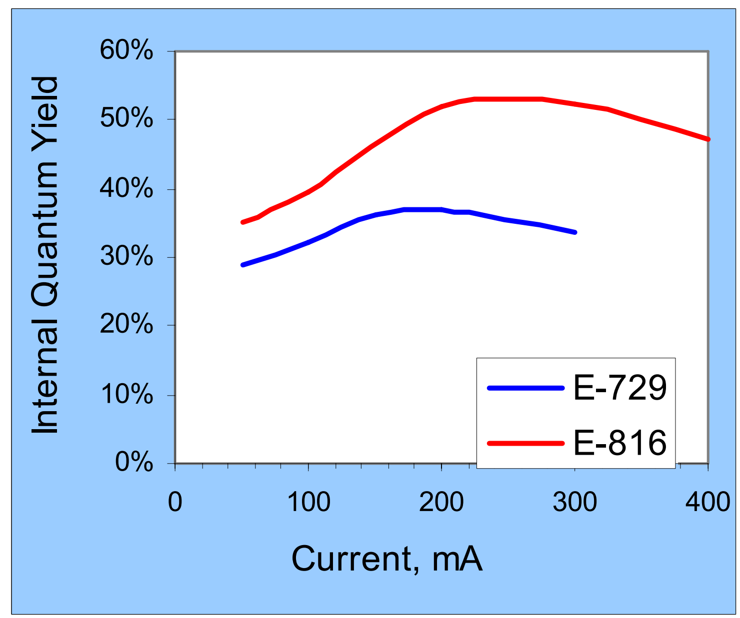
Tiristor 1.85 μm and 1.95 μm LED structures with improved Quantum Efficiency

Special tiristor structure was used for increasing of quantum yield of LEDs with active layer close to GaSb. In this design electrons and holes are concentrated at the both sides of p-GaSb/n-GaInAsSb boundary that increases probability of radiative recombination. Current-voltage characteristic and Internal Quantum Yield of the tiristor structure (E-816) in comparison with standard structure are presented here.







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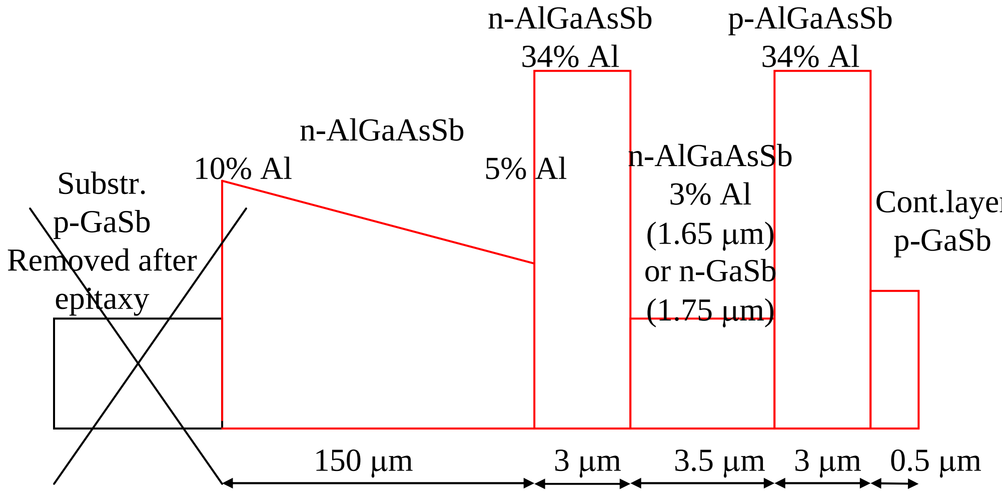
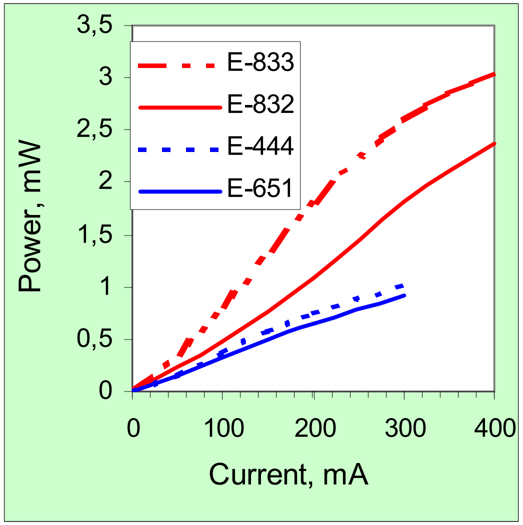
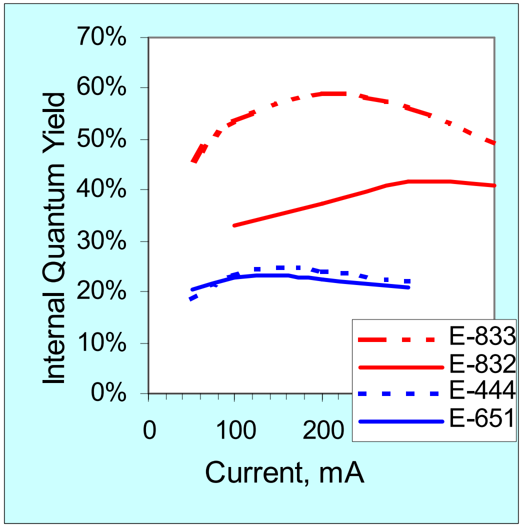
1.65 μm and 1.75 μm LED structures with removed substrate

For providing of minimum thermal resistance and space homogeneity of the current LED chips should be mounted active layer down, closely to the package. In this case LED emits trough the substrate. But GaSb substrate is not transparence for wavelengths 1.65-1.75 μm. In these LED structures wider band gap very thick (150 μm) is grown. Then GaSb substrate is removed.

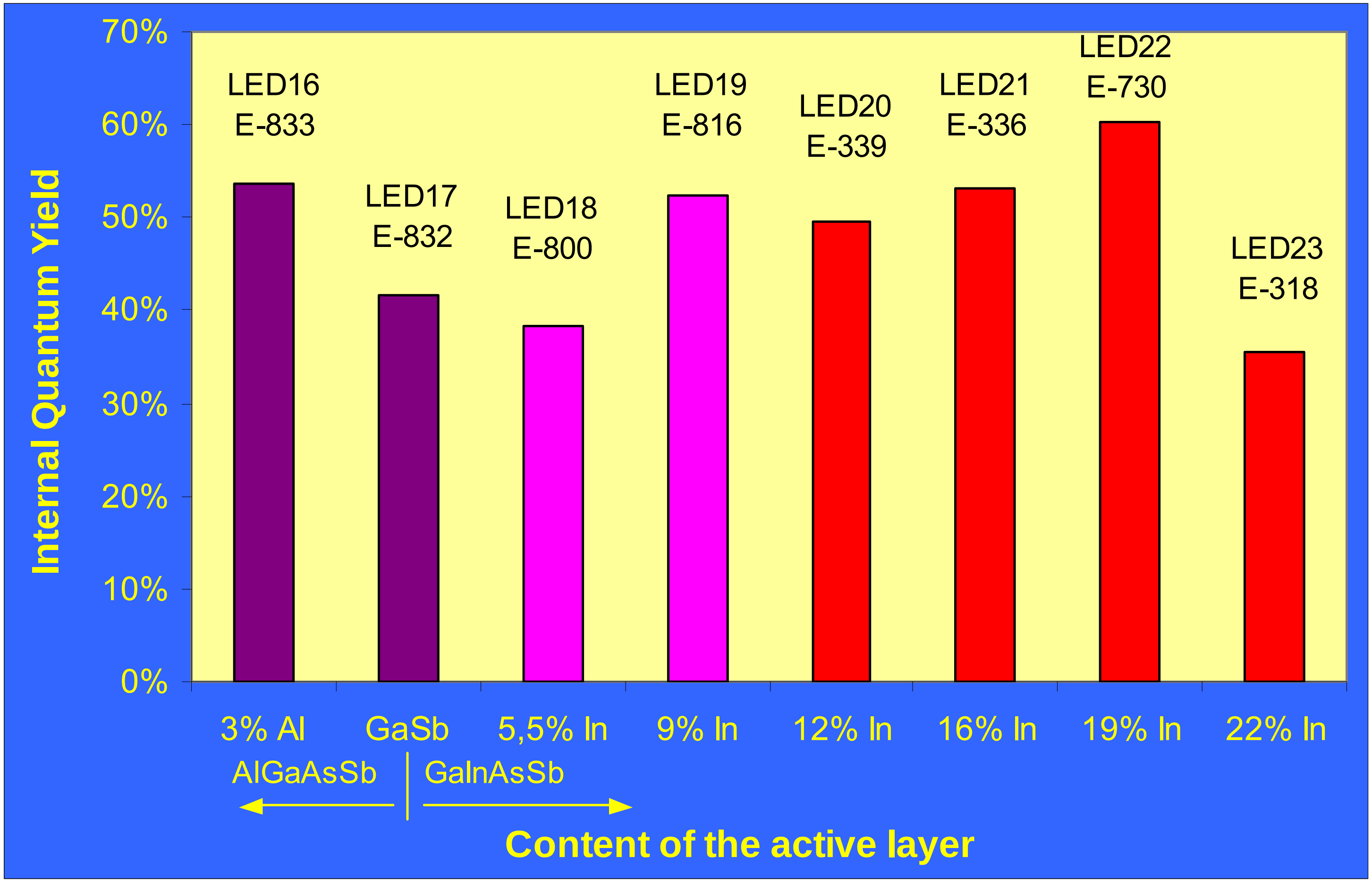






Here are presented Power characteristics and Internal Quantum Yield for 1.65 μm and 1.75 μm structures with removed substrates (E-833 and E-832) in comparison with standard 1.65 μm and 1.75 μm structures mounted GaSb substrate down.

Quantum Efficiency of the final LED structures for the spectral range 1.6-2.4 μm



Internal Quantum Yield is measured at room temperature in quasi steady state regime

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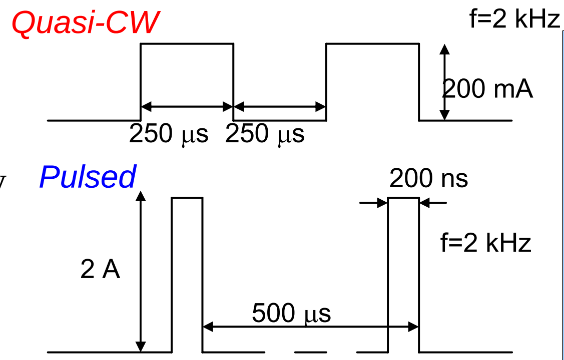
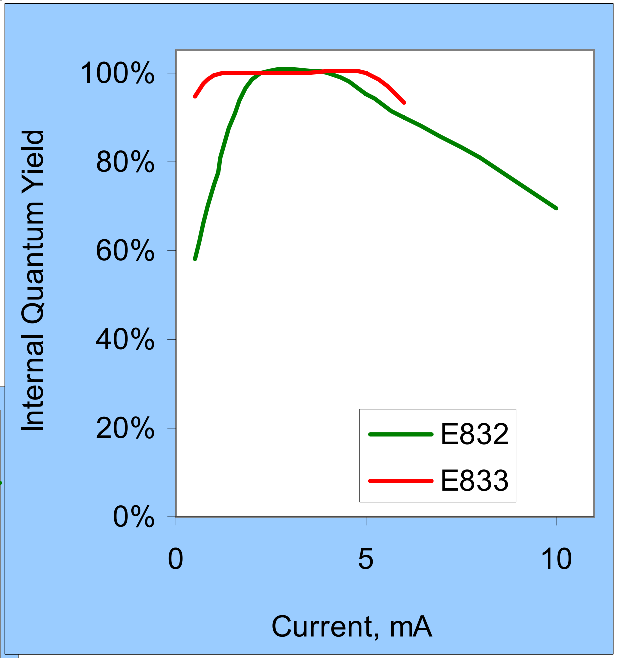
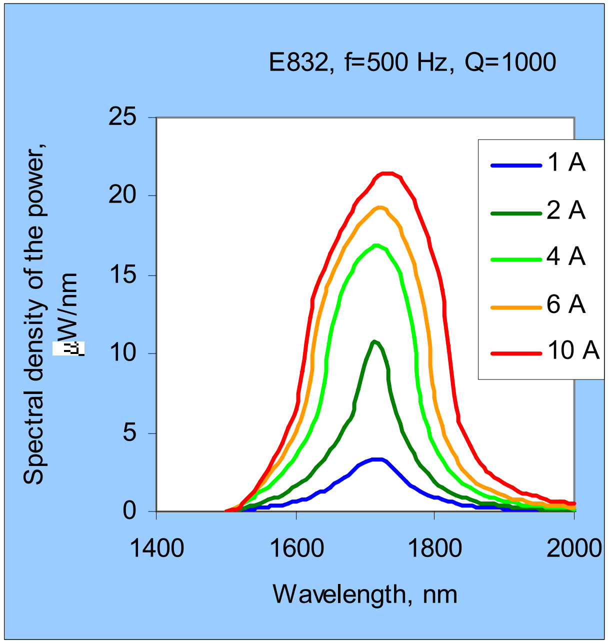
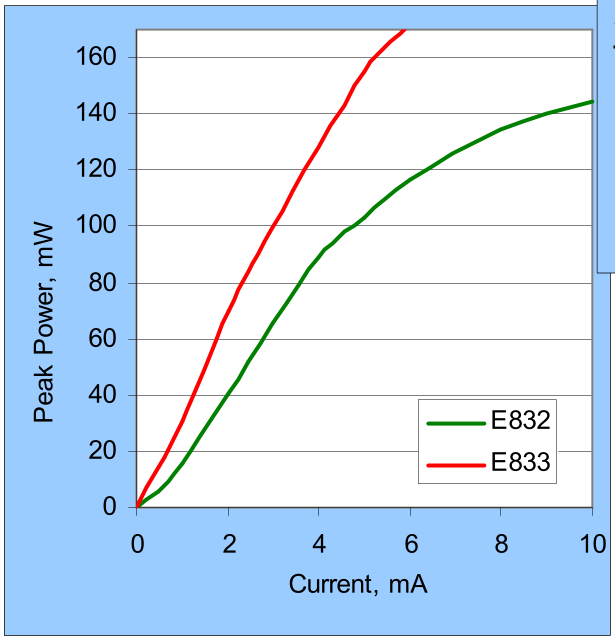
Optical characteristics of 1.6-2.4 μm LED in pulse regime

Maximum average power from mid infrared LEDs can be received using quasi steady state regime (qCW). But short switching time of these devices make possible using of nanosecond pulse regimes. This gives us possibility to decrease nonradiative Auger recombination and to receive much higher values of peak power and quantum efficiency.









100% Internal Quantum Yield and peak power up to 170 mW were obtained in improved mid infrared Light Emitting Diodes.

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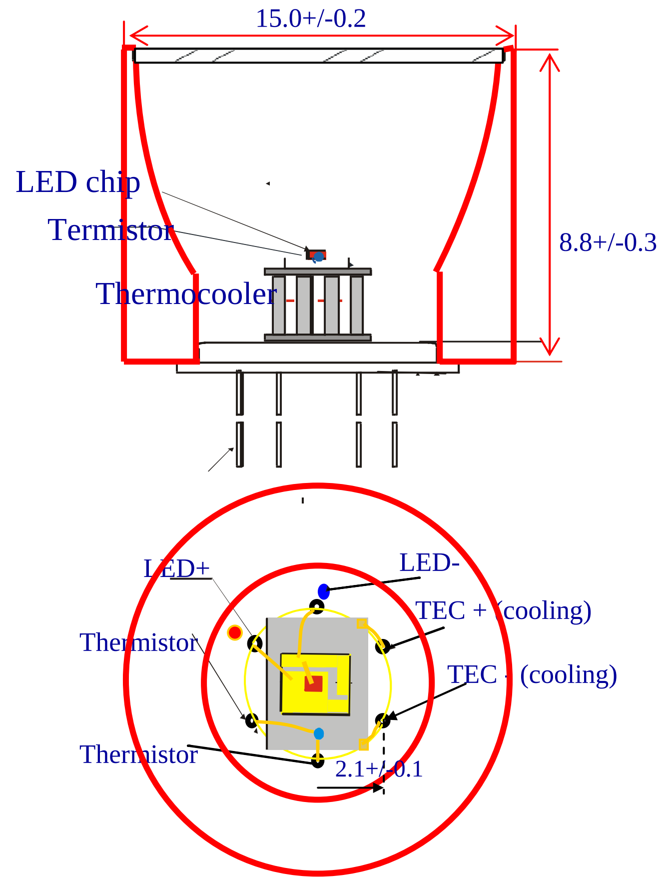
Construction of mid infrared LED with Thermocooler and Parabolic Reflector



Micro thermoelectric cooler (Peltier) and calibrated thermoresistor are included in the 9 mm 6-pin TO-5 package. Using of thermoelectric cooler allows optical power to be stabilized or increased (by cooling). Reflector gives us possibility to focus LED radiation.

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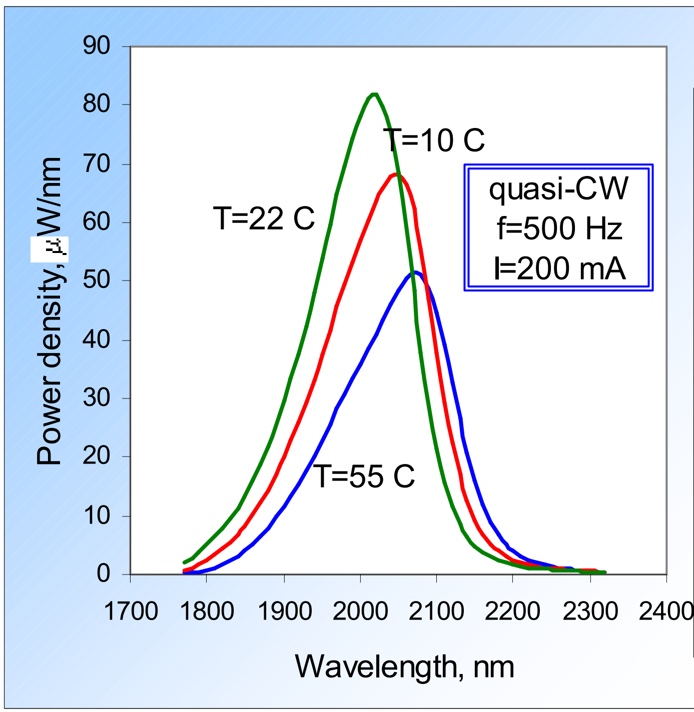
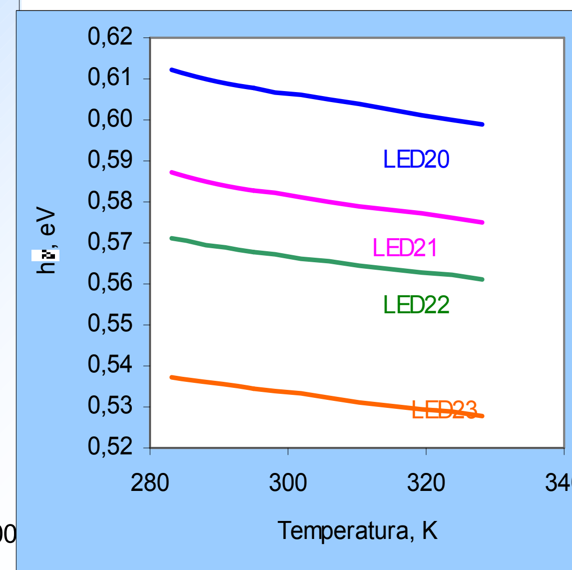
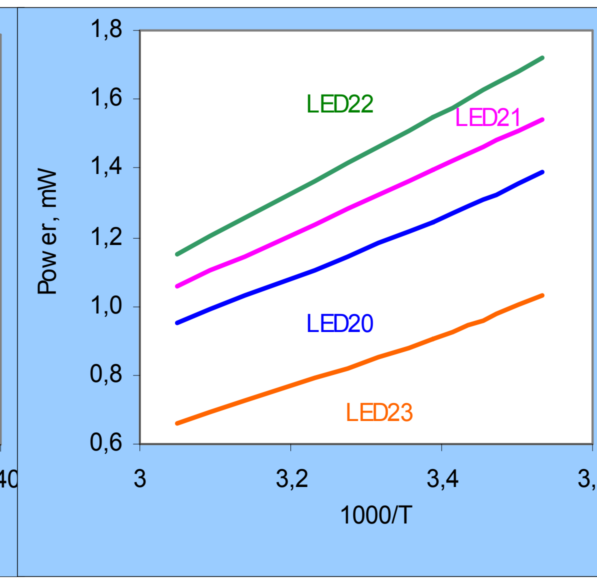
Temperature dependence of characteristics of 1.6-2.4 μm LED with Thermocooler

Presented here temperature characteristics are measured on mid infrared LEDs mounted in TO-5 package with build-in thermocooler. It is well known that peak wavelength and optical power of semiconductor optical devices strongly depends on temperature. Photon energy decreases with increasing of the temperature mainly due to decreasing of the energy band-gap of the active layer. Optical power decreases with increasing of the temperature mainly due to increasing of the Auger recombination (proportionally to the increasing of the carrier density).

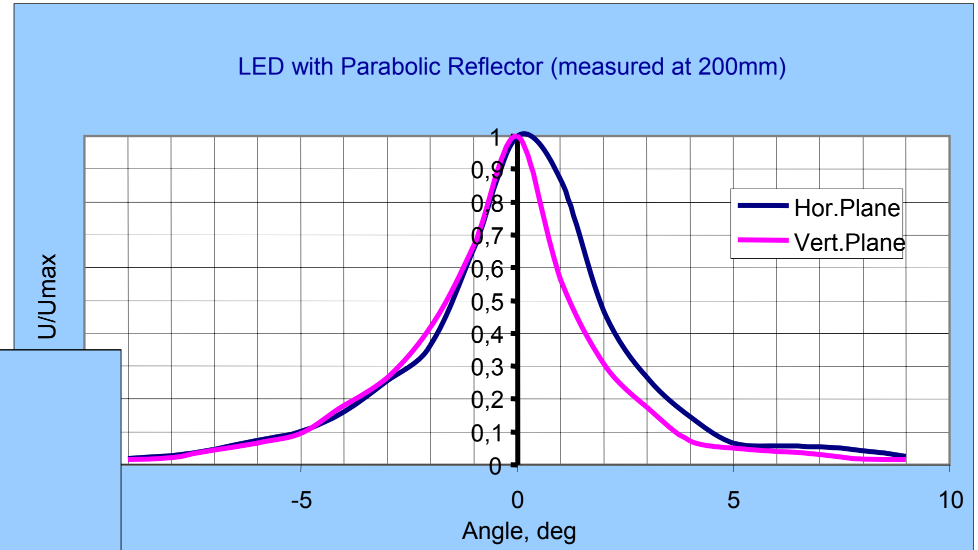


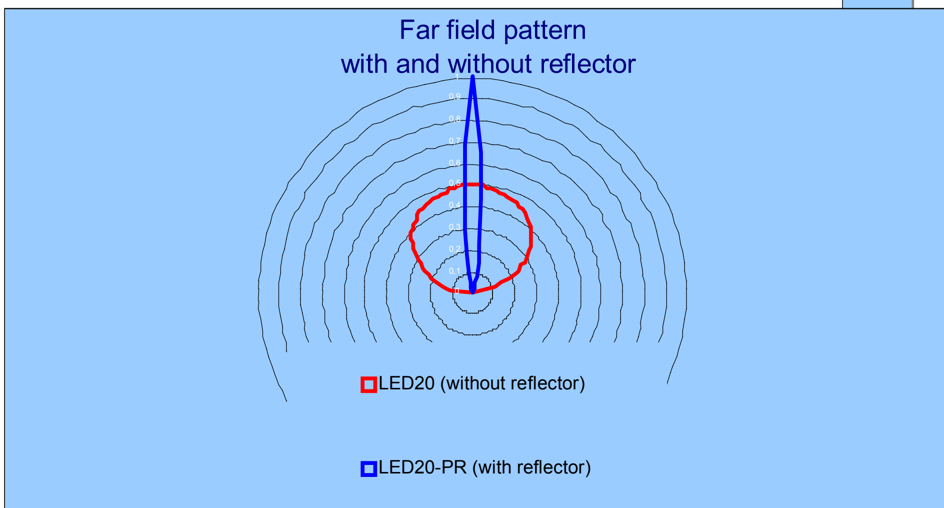
Using of package with thermocooler inside allows us to stabilize optical parameters or to manage tuning of the peak wavelength or power.

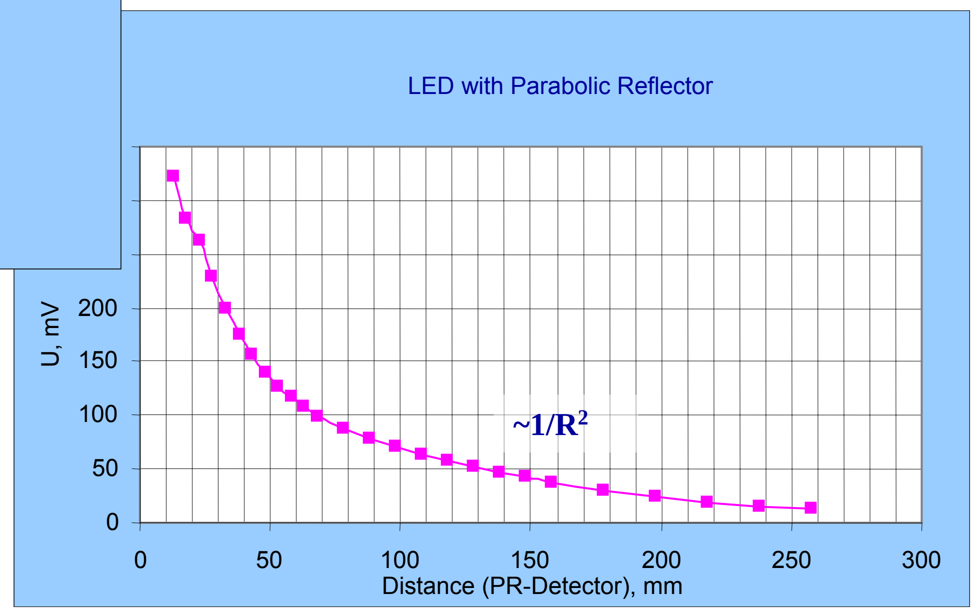




Beam diagram of mid infrared LED with Parabolic Reflector







Special designed for our mid infrared LEDs parabolic reflectors for 5.4 mm package TO-18 and 9 mm package TO-5 with thermocooler inside provides 3-4 degrease angle of radiation distribution (measured at the half of maximum). It is very convinient for using in portable gas sensors. Additionally aluminum reflector improves heat loading from the LED.

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Main Parameters of 1.6-2.4 μm LED

Parameters	LED16	LED17	LED18	LED19	LED20	LED21	LED22	LED23
Wavelength, μm	1.6-1.7	1.7-1.8	1.8-1.9	1.9-2.0	2.0-2.1	2.1-2.2	2.2-2.3	2.3-2.4
FWHM, μm	0.12	0.12	0.15	0.15	0.17	0.18	0.20	0.25
Temperature drift of the band, nm/K	1	1	1	1	1	1	1	1
Maximum Forward Current, mA Quasi-CW Pulsed (200 ns duration, 1 kHz rate)	500 10000	500 10000	400 5000	400 5000	300 5000	300 5000	300 5000	200 5000
Optical Power, mW Quasi-CW @ 200 mA Pulsed@5A	1.40 150	1.20 110	1.20 60	1.40 60	1.30 60	1.35 70	1.5 80	0.90 30
Internal Quantum Yield, % (qCW)	54	40	38	50	48	51	58	32
Temperature dependence of Quantum Yield, %/K	5	6	6	5.5	6	5.5	6	5.5
Switching Time, ns	50	50	50	50	50	50	50	50
Emitting Area Diameter, μm	300	300	300	300	300	300	300	300
Operating Temperature, K	77-320	77-320	77-320	77-320	77-320	77-320	77-320	77-320
Package LEDXX LEDXX-PR, LEDXX-PRW LEDXX-TEC LEDXX-TEC-PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR

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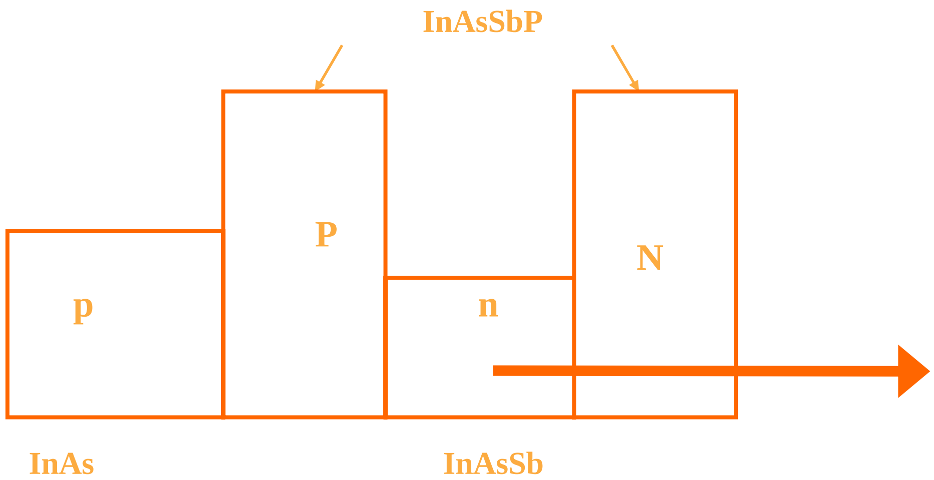
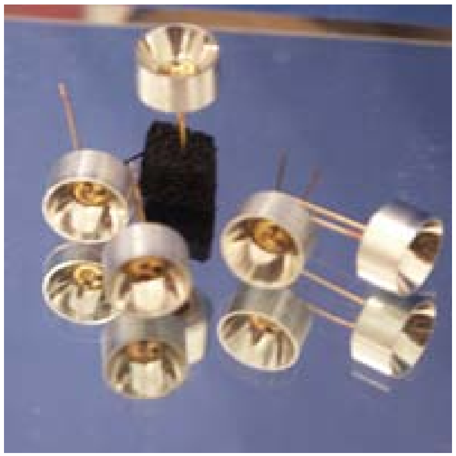
LED Structure for the Spectral Range 2.7-5.0 μm

Light Emitting Diodes for the spectral range 2.7-5.0 μm are based on InAs substrates. Quaternary solid solutions InAsSbP, lattice-matched to InAs substrate are used in active layer for the range 2.7-3.3 μm. Ternary solid solutions InAsSb are used for covering the spectral range 3.6-5.0 μm. Energy band diagram of the structures for this spectral range is schematized here. All LED structures for the range 2.7-5.0 μm are grown by MOCVD.

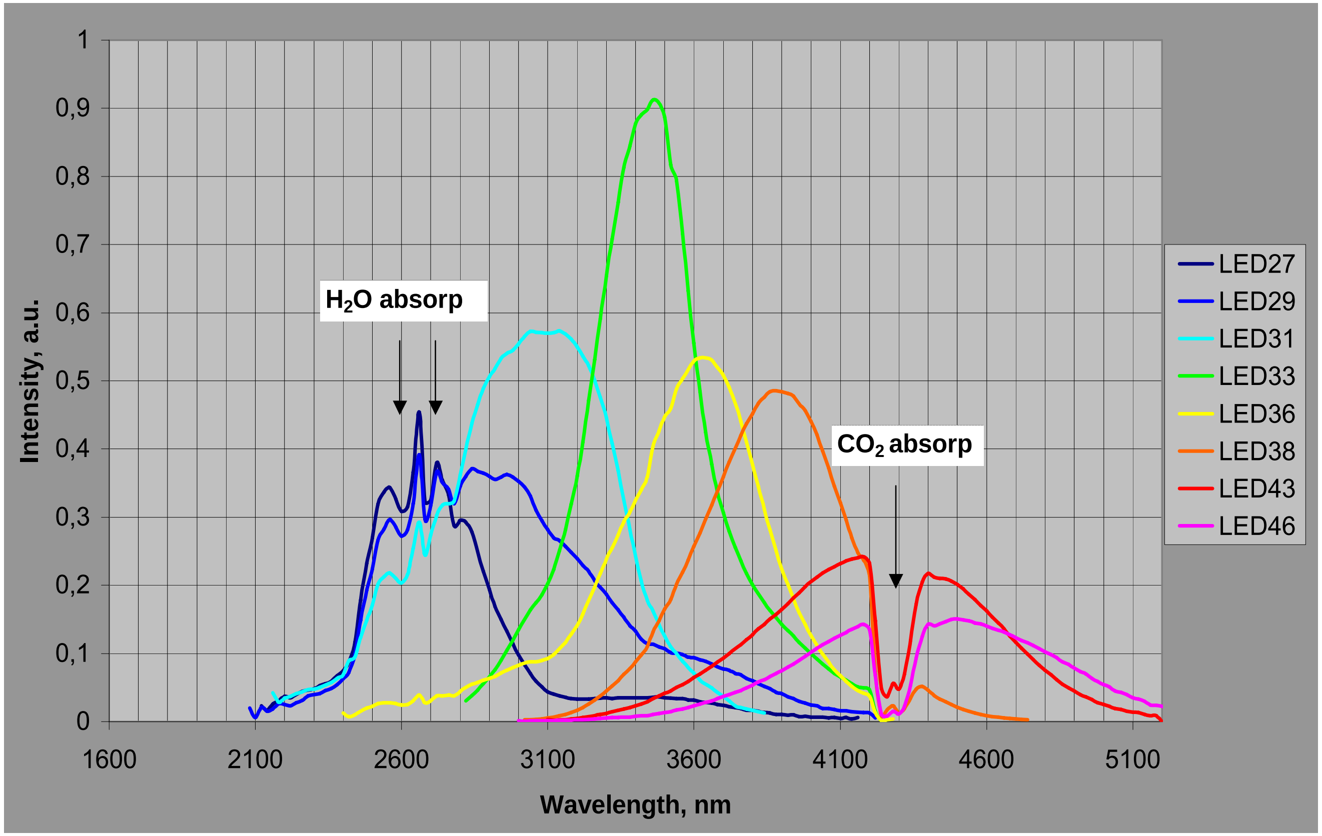




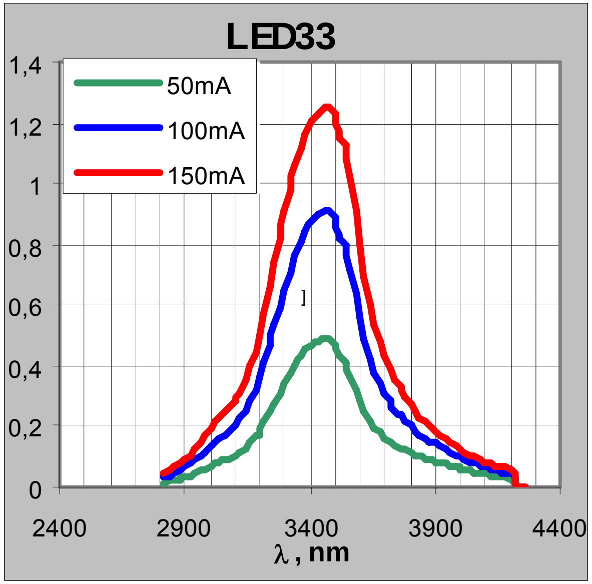
Spectral Characteristics of 2.7-5.0 µm LEDs

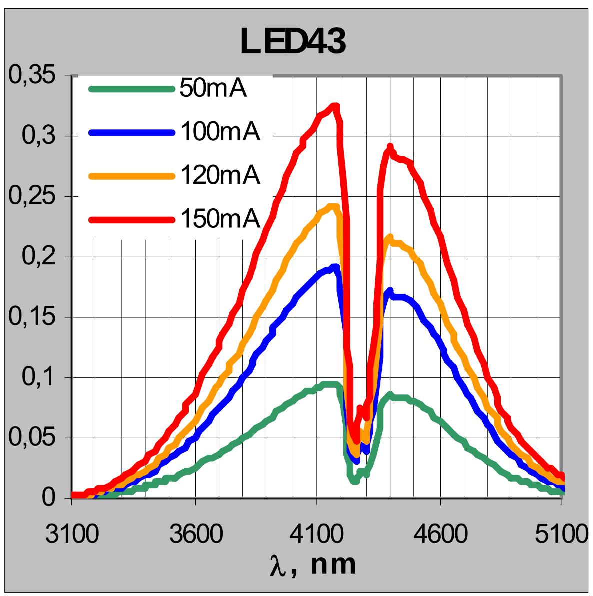
Eight standard models for this range are developed: LED27 (with central wavelength between 2600nm and 2800nm), LED29 (2800nm-3000nm), LED31 (3000nm-3200nm), LED33 (3200nm-3400nm), LED36 (3500nm-3700nm), LED38 (3700nm-3900nm), LED43 (4100nm-4300nm) and LED46 (4400nm-4600nm). As far as standard full width at half maximum (FWHM) of these spectra lie between 150nm (LED27) and 1000nm (LED46), you can choice suitable model for any application that requires light emitter in the range 2.5÷5.0 µm.

All Light Emitting Diodes can operate at room temperature in CW regime or in different pulse regimes. Using of thermoelectric cooler allows optical power to be stabilized or increased (by cooling).

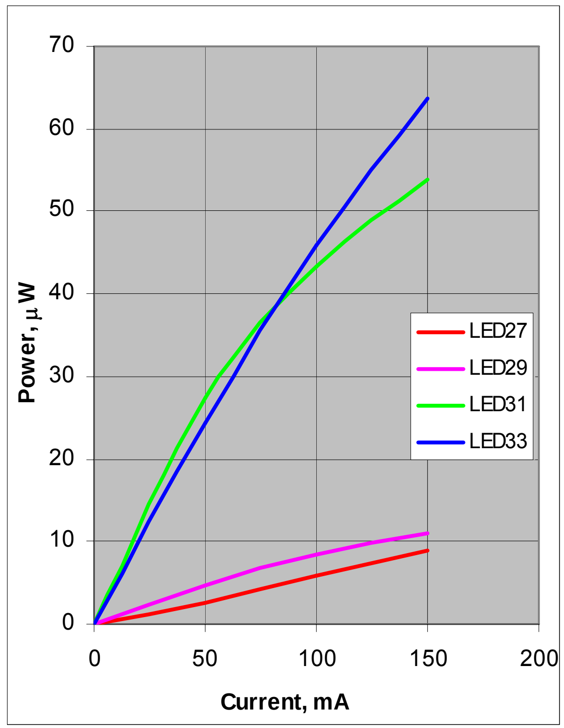


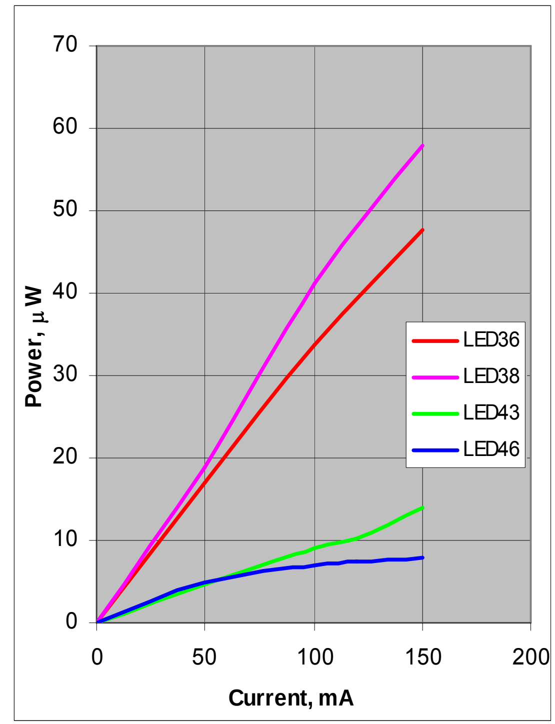
Current Dependences of Optical Characteristics for 2.7-5.0 μm LEDs





Optical power presented here is measured in quasi-CW regime (at square-wave modulated bias). Power of 8 types LED structures is quite different. The most effective are Light Emitting Diodes with binary indium arsenide as an active layer or solid solutions close to InAs (peak wavelengths 3.1, 3.4, 3.6 and 3.8 μm). Quantum yield of 2.7 μm and 2.9 μm LEDs is lower because band-gaps of active layers of these structures are close to band gap of confinement InAsSbP layers, so electron confinement is not good enough. Lower efficiency of 4.3 μm and 4.6 μm LEDs is connected with a significant mismatched between active layers and InAs substrate.





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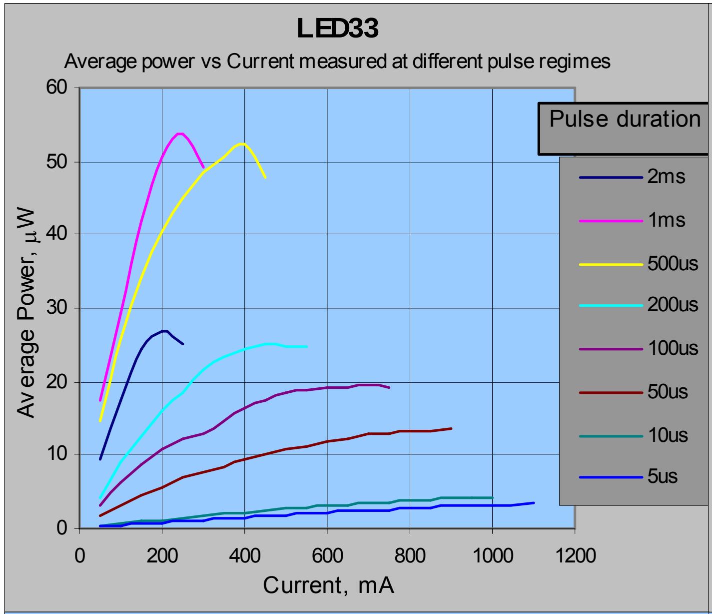
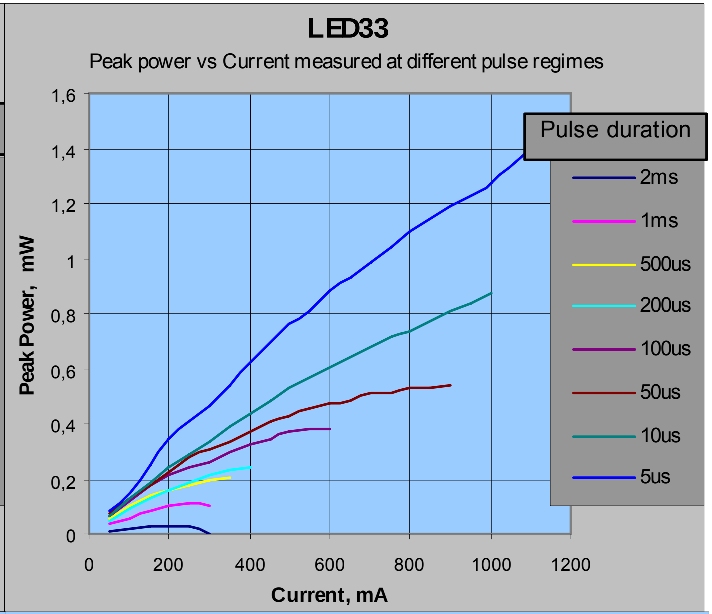
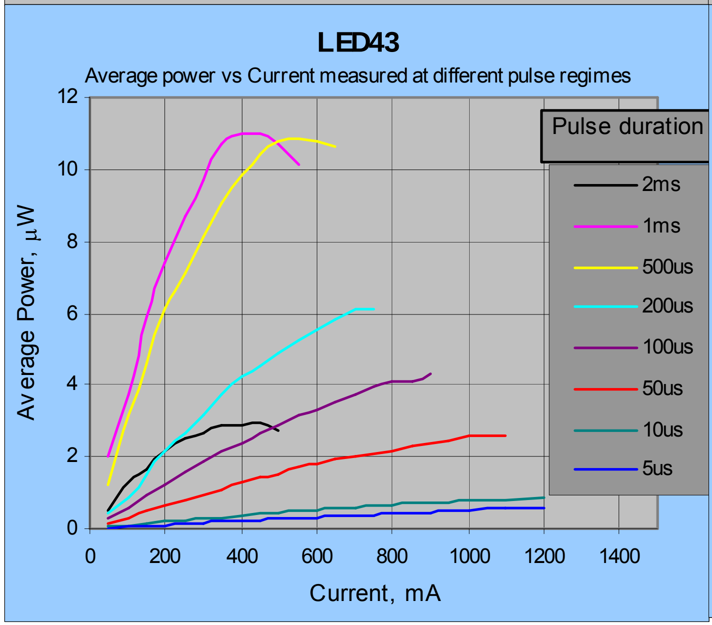
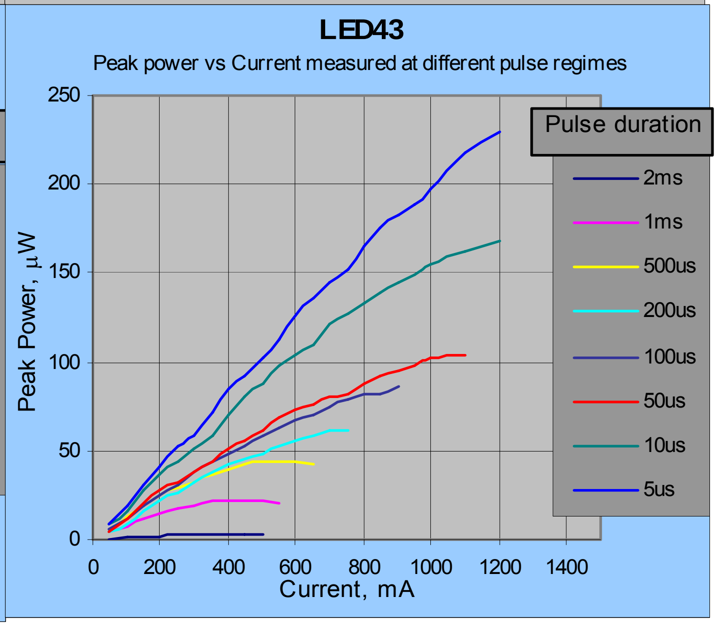
Pulse Dependences of Optical Characteristics of 2.7-5.0 μm LEDs









Here are presented typical average vs. current and peak power vs. current characteristics of LED33 and LED43 measured at different pulse regimes in the range 5 μs ÷ 2 ms. For receiving of maximum average power we recommend using of pulse regimes with duty cycle 50% or 25%, (but not 100% where heating decreases power). For receiving of maximum peak power we recommend using of short pulses (less then 50 μs).

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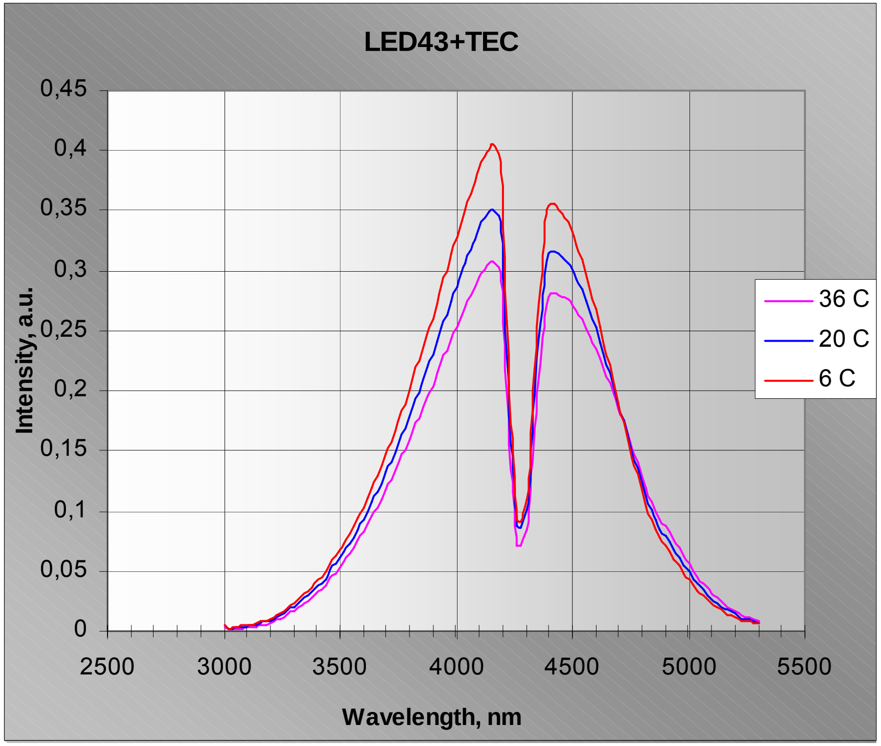
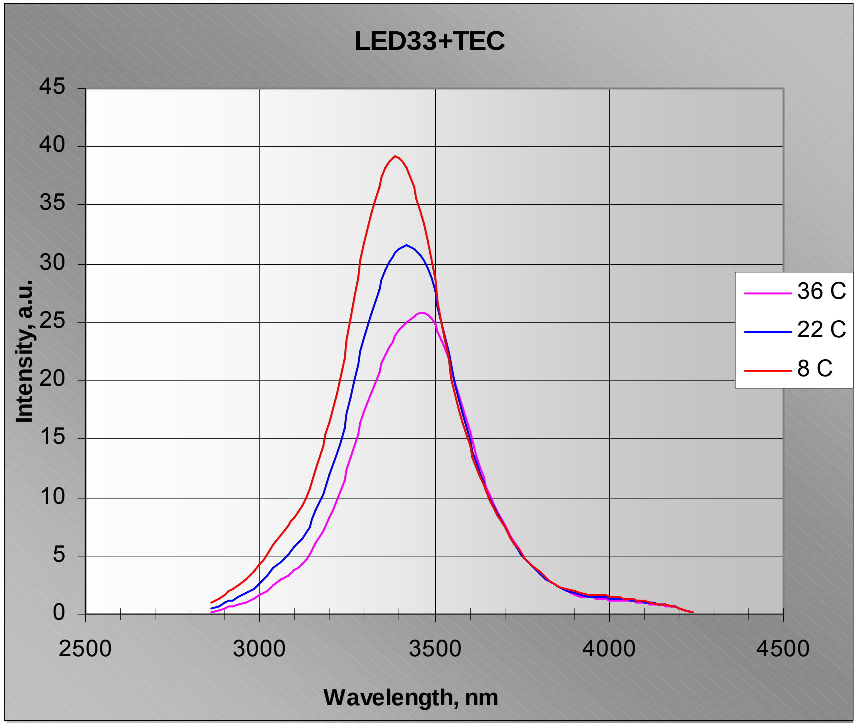
Temperature Dependances of Optical Characterisics 2.7-5.0 μm LEDs

Average temperature shift of the spectra for all 2.7-5.0 μm LED structures is about 1.5 nm/K. Using of package TO-5 with termocooler and control thermistor inside make possible tuning in the spectral range of interest or temperature stabilization of the LED.





For LEDs without thermocooler temperature shift

is necessary to be take in account.

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Main Parameters of 2.7-5.0 µm LED

Parameters	LED27	LED29	LED31	LED34	LED36	LED38	LED43	LED46
Wavelength, µm	2.6-2.8	2.8-3.0	3.0-3.2	3.3-3.5	3.5-3.7	3.7-3.9	4.1-4.3	4.4-4.6
FWHM, µm	0.5	0.12	0.15	0.15	0.17	0.18	0.20	0.25
Temperature drift of the band, nm/K	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Maximum Forward Current, mA Quasi-CW Pulsed (200 ns duration, 1 kHz rate)	300 3000	500 10000	400 5000	400 5000	300 5000	300 5000	300 5000	200 5000
Optical Power, µW Quasi-CW @ 200 mA Pulsed@2A	8 140	10 170	16 220	28 480	20 220	20 220	12 220	8 140
Temperature dependence of Quantum Yield, %/K	8	8	8	8	8	8	8	8
Switching Time, ns	20	20	20	20	20	20	20	20
Emitting Area Diameter, µm	300	300	300	300	300	300	300	300
Operating Temperature, K	77-320	77-320	77-320	77-320	77-320	77-320	77-320	77-320
Package LEDXX LEDXX-PR, LEDXX-PRW LEDXX-TEC LEDXX-TEC-PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR	TO18 TO18+PR TO5 TO5+PR

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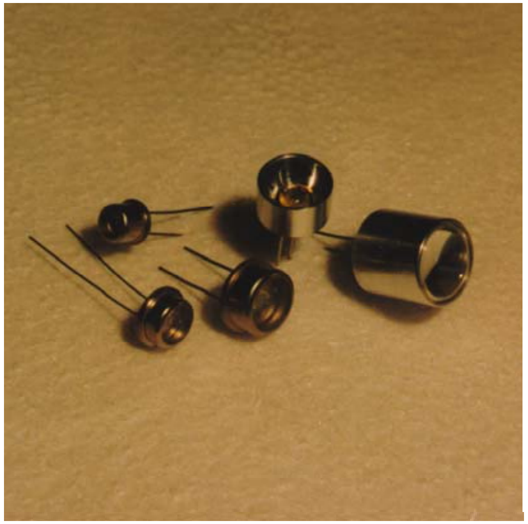
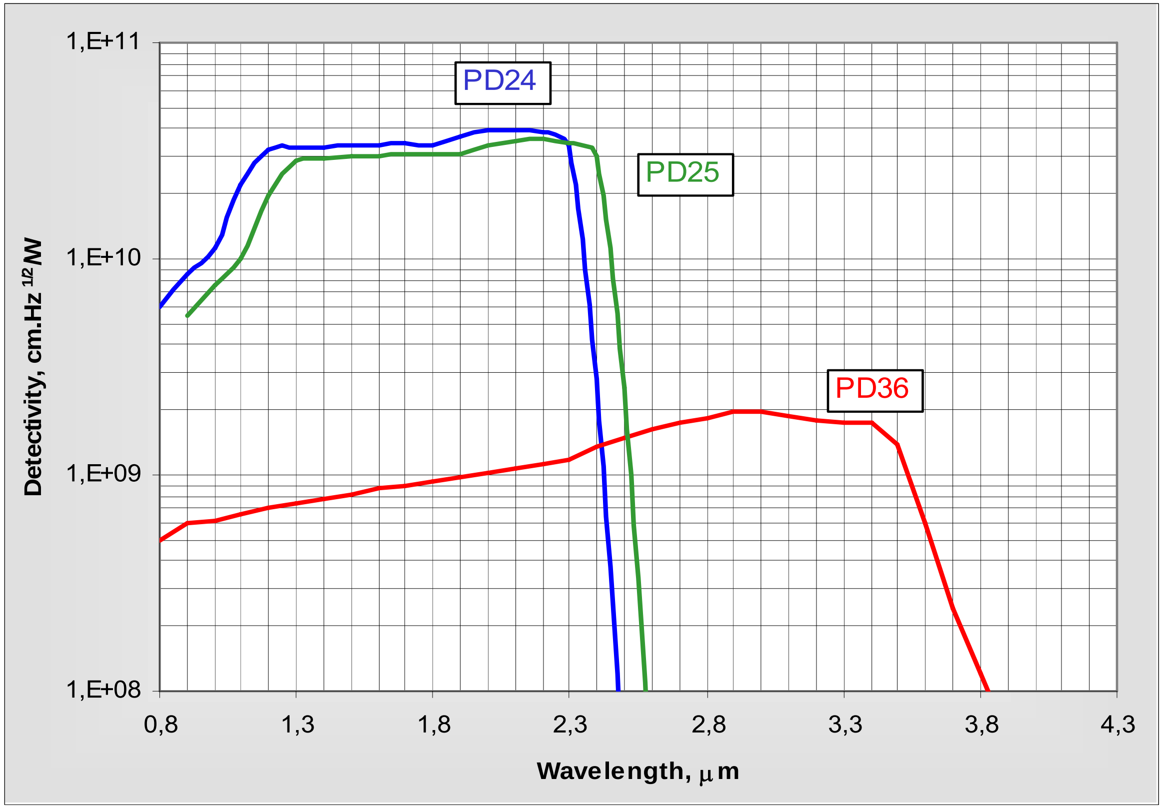
Mid Infrared Photodiodes



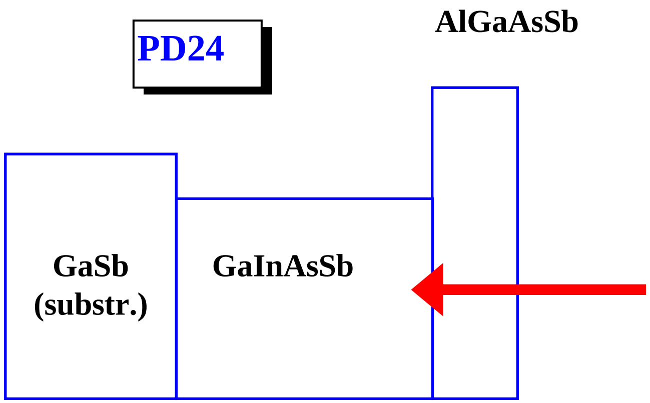
Mid-infrared Photodiodes are based on heterostructures with wide band-gap window. PD24 and PD25 models are based on GaInAsSb/GaAlAsSb structure, PD36 is based on InAs/InAsSbP structure. Fast response time makes them suitable for detection of high-frequency modulated IR laser radiation.

The device is mounted on the TO-18 package or TO-5 package with thermocooler inside and can be equipped with the parabolic reflector.



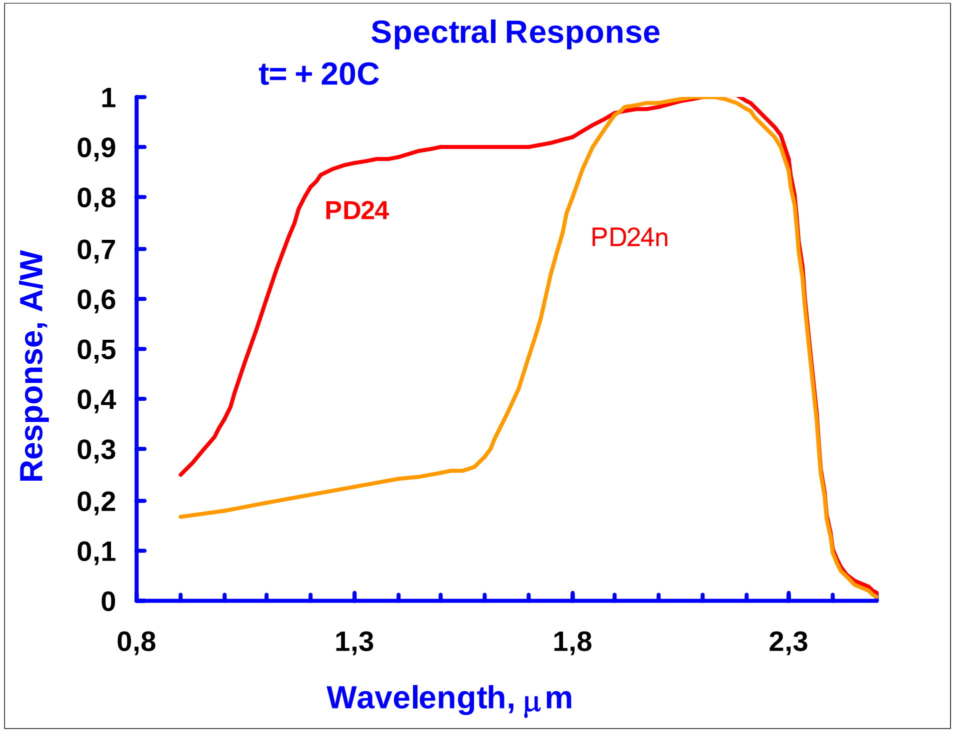
Three types photodiodes - PD24, PD25 and PD36 can operate in photo-voltaic regime or at reverse bias. Here are presented curves of detectivity vs wavelength at room temperature. With increasing temperature (using thermo-electric cooler) detectivity increases and cut-off wavelength shifts to shorter wavelengths.

Spectral Response of photodiodes with cut-off 2.4 μm



Lattice-matched heterostructure with GaInAsSb (24% In) active layer and AlGaAsSb "wide band-gap window" layer is grown on n-GaSb substrate.

Here are presented typical curves of response vs wavelength at room temperature. 2.4 μm cut-off is measured at 10% of the maximum responsivity.



Besides standard models PD24 based on heterostructure with AlGaAsSb wide band-gap "window", narrow spectrum photodiodes (PD24n) with GaSb "window" are also available.

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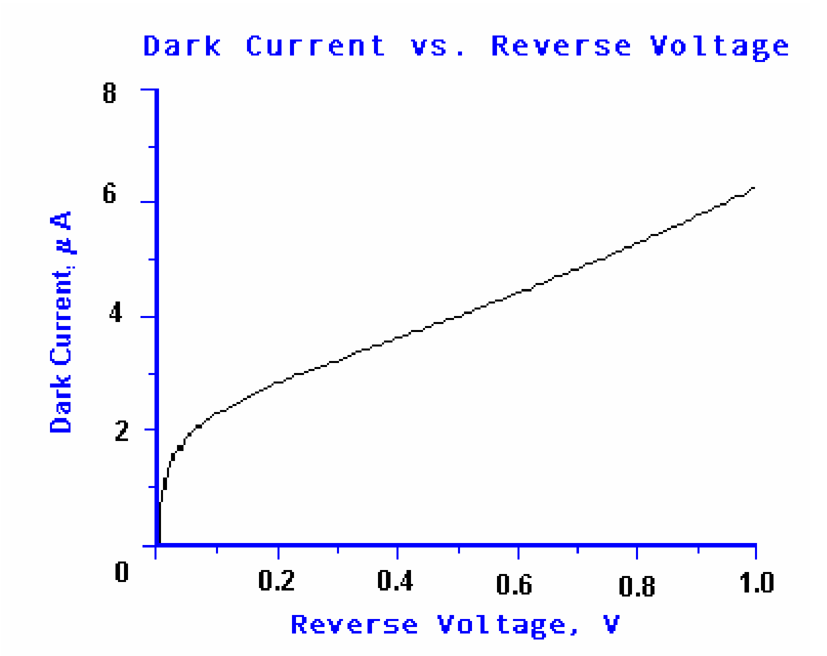
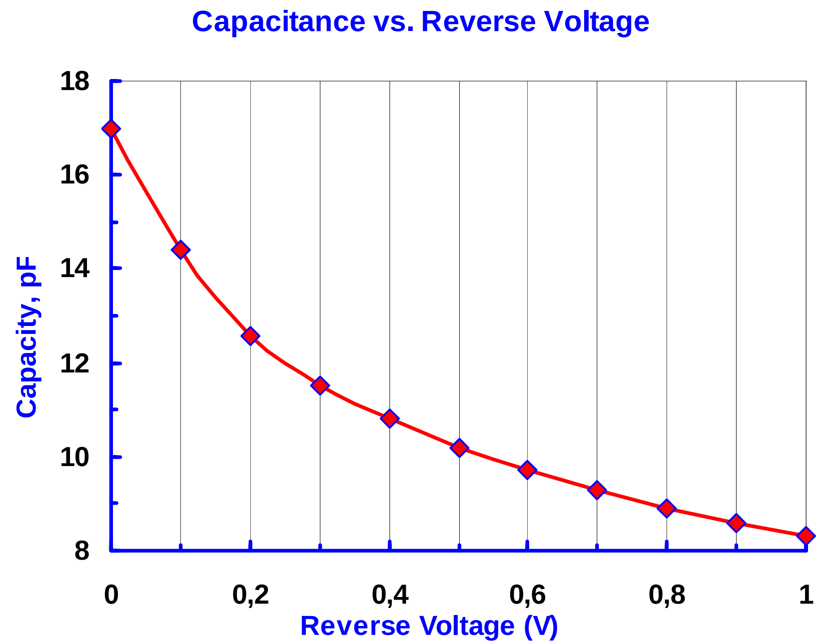
Voltage Dependences of Dark current and Capacitance





Reverse voltage dependences of the dark current and capacitance for PD24-02 are presented here. The same dependences for the other models are similar. As we can see from the second figure, we can improve speed of the response two times by applying 1 V reverse bias.

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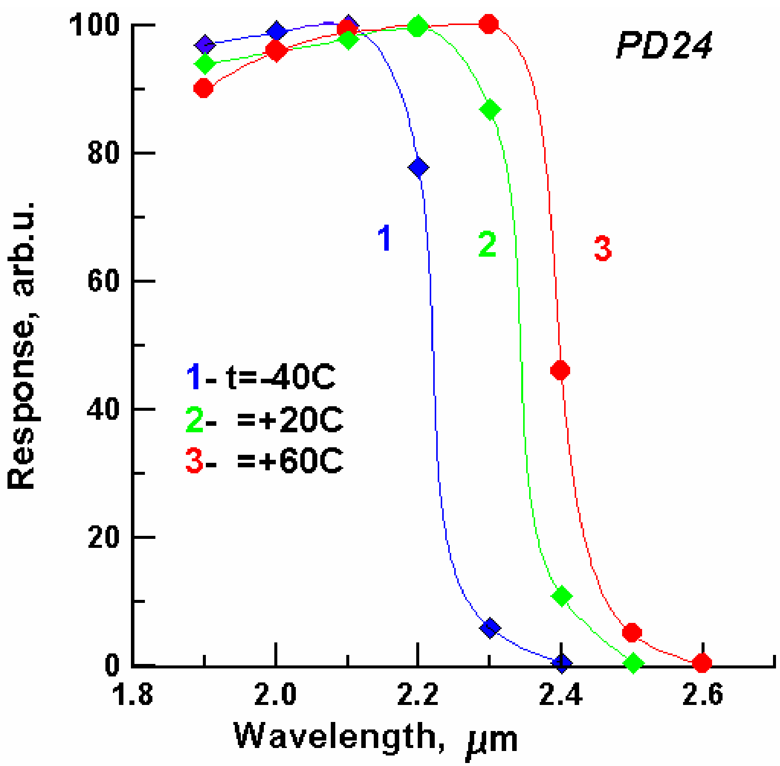
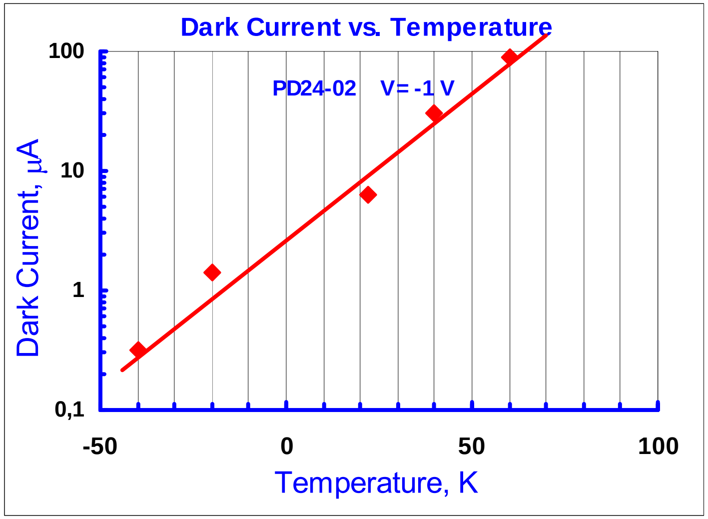
Temperature Dependance of Characterisics of PD24



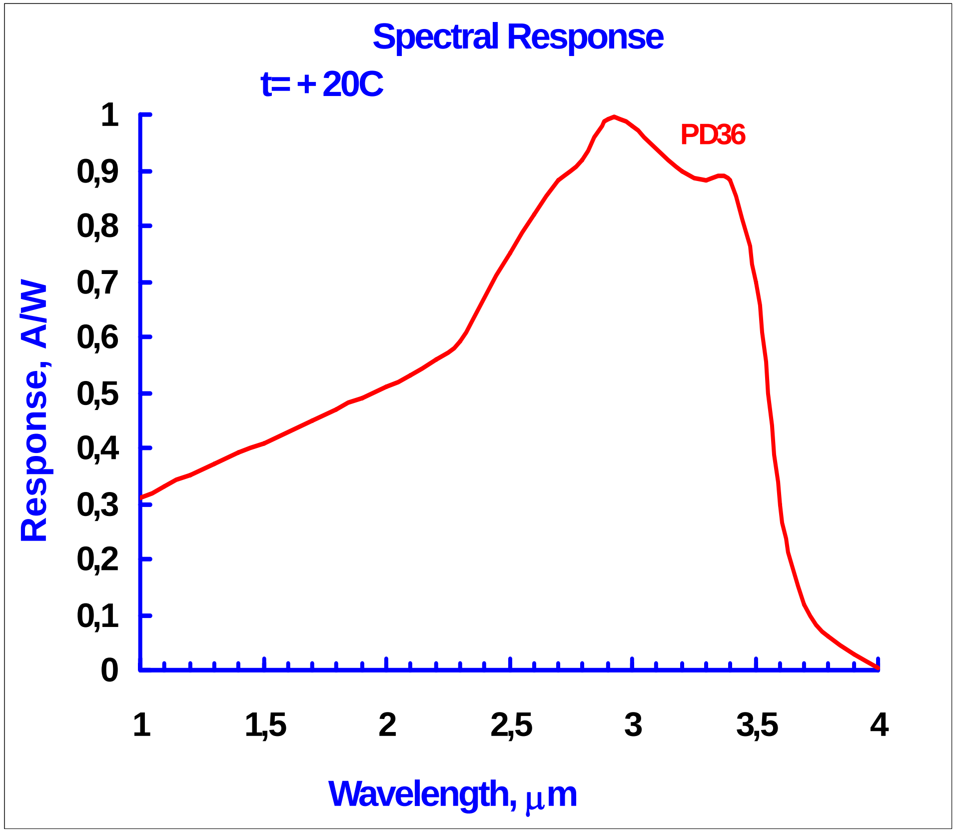


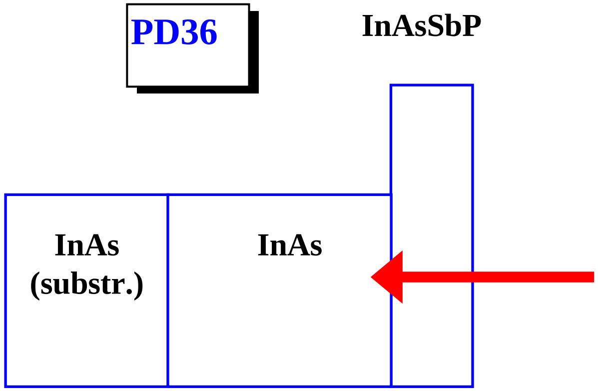
Long-wavelength edge of the spectra, measured at different temperatures and temperature dependence of the dark current for PD24-02 (0.2 mm diameter of the sensitive area are presented here. Temperature dependences of the other models have the same shape.

Main Parameters of Photodiodes with cut-off 2.4 μm

Parameters	Units	Condition	PD 24-02	PD 24-20
Sensitive Area Diameter	mm		0.2	2.0
Cut-off Wave-length	μm	at 10 %	2.4	2.4
Peak Wavelength	μm	>90%	2.0-2.2	2.0-2.2
Responsivity	A/W	at λp	0.9-1.1	0.9-1.1
Dark Current	μA	VR=-0.2 V =-0.5 V =-1.0 V	0.7-3.0 1.5-6.0 2.0-10	50-100 100-200 150-300
Impedance	kOhm	VR=10 mV	30-100	0.3-1.5
Capacitance	pF	VR=0 V f=1 MHz	10-50	1200-3000
Rise and Fall Time	ns	(0V;50 Ohm)	2-10	120-400
Detectivity	$cm.Hz^{1/2}$ /W	(λp,1000,1)	(1-3) $*10^{10}$	(5-8) $*10^{10}$
Package PD24-XX PD24-XX-PR, PD24-XX-PRW PD XX-TEC PD XX-TEC-PR			TO-18 TO-18+PR TO-5 TO-5+PR	TO-5 TO-5+PR TO-5 TO-5+PR

Spectral Response of photodiodes with cut-off 3.8 μm





Photodiode structures are grown by liquid phase epitaxy on InAs substrate. Schematic band diagram of standard PD structure with cut-off 3,8 μm is schematically presented below. Spectral response is measured at room temperature and zero bias. 3.8 μm cut-off is measured at 10% of the maximum responsivity.

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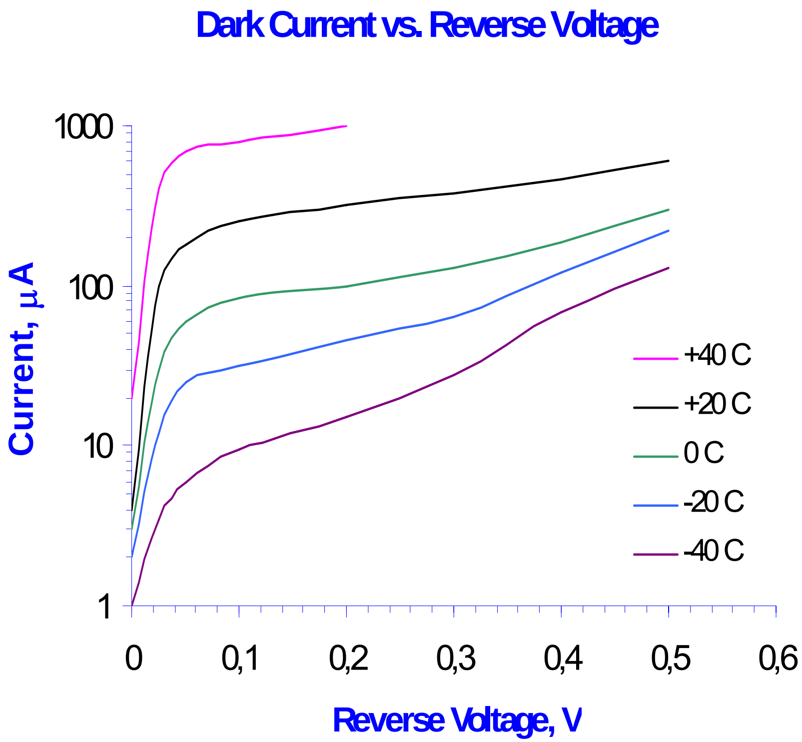
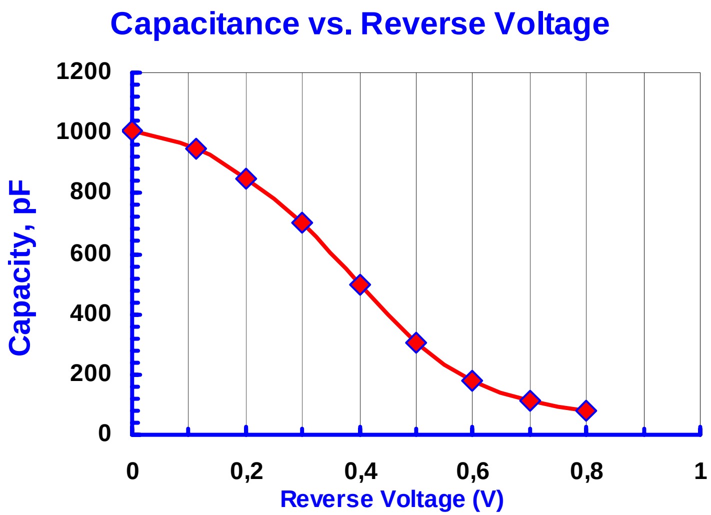
Voltage Dependences of Dark current and Capacitance of Photodiodes with cut-off 3.8 μm





Reverse voltage dependences of the dark current at five different temperatures and capacitance for PD36-02 are presented here. The same dependences for the other models are similar. As we can see from the second figure, we can improve speed of the response five times by applying 0.6 V reverse bias.

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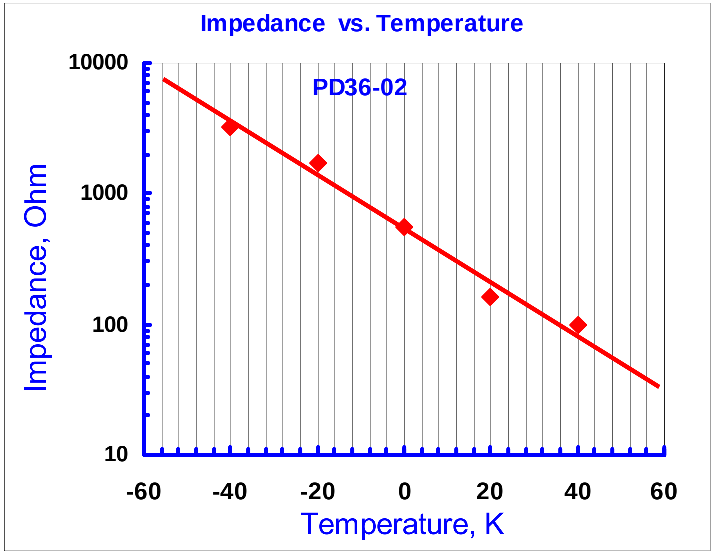
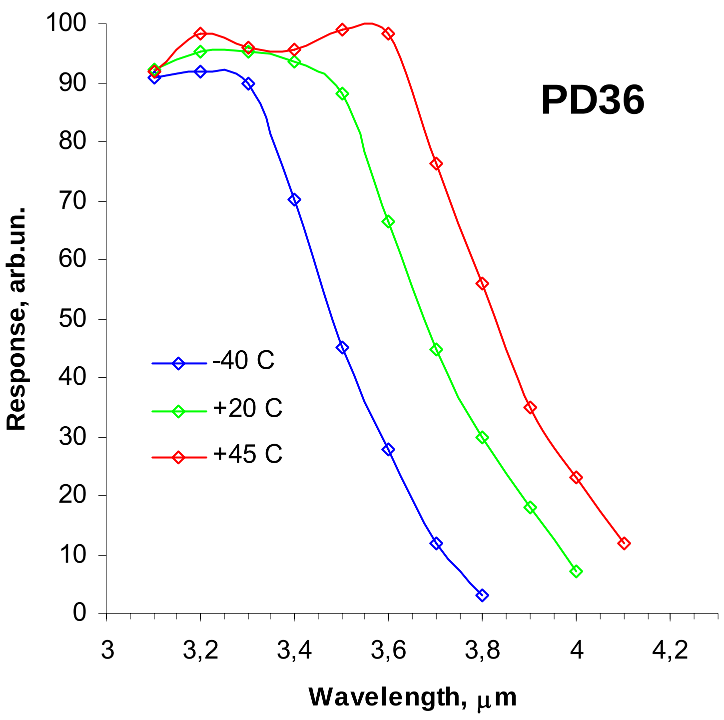
Temperature Dependance of Characterisics of PD36

Long-wavelength end of the spectra, measured at different temperatures and temperature dependence of the Impedance for PD36-02 are presented here. Temperature dependences of the other models have the same shape.





Main Parameters of Photodiodes with cut-off 3.8 μm

Parameters	Units	Condition	PD 36-02	PD 36-05
Sensitive Area Diameter	mm		0.2	0.5
Cut-off Wave-length	μm	at 10 %	3.8	3.8
Peak Wavelength	μm	>90%	2.8-3.4	2.8-3.4
Responsivity	A/W	at λp	1.0-1.2	1.0-1.2
Dark Current	μA	VR=-0.2 V	200-300	500-800
Impedance	Ohm	VR=10 mV	130-200	50-120
Capacitance	nF	VR=0 V VR=-0.5 V (f=1 MHz)	1.3-2.0 0.1-0.3	2.0-3.0 0.4-0.9
Rise and Fall Time	ns	(0 V; 50 Ohm) (0.5V; 50 Ohm)	150-200 20-50	250-350 80-150
Detectivity	$cm.Hz^{1/2}$ /W	(λp,1000,1)	(1-3) *10^9	(1-3) *10^9
Package PD24-XX PD24-XX-PR, PD24-XX-PRW PD XX-TEC PD XX-TEC-PR			TO-18 TO-18+PR TO-5 TO-5+PR	TO-18 TO-18+PR TO-5 TO-5+PR

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Conclusion

• Room temperature LEDs based on InAs-GaSb heterostructures that cover all spectral range 1.6-5.0 μm have been developed.

• Optical power of 2.0 mW at quasi steady state regime and peak power up to 170 mW at 200 ns pulse regime were obtained.

• Current and temperature characteristics of LEDs were investigated.

• Mechanisms of radiative and nonradiative recombination in mid-infrared LEDs were studied.

• Spectral matched room temperature Photodiodes with cut-off 2.4, 2.5 and 3.8 μm were developed and investigated.

• New mid-infrared LEDs and Photodiodes are used in portable gas sensors of H_2O, CH_4 and CO_2.

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