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RECENT PROGRESS IN DETECTION OF LONG WAVELENGTH INFRARED RADIATION WITH ADVANCED HETEROSTRUCTURE PHOTOTODETECTORS

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ABSTRACT

Cooling is a direct way to suppress the thermal generation that limits performance of uncooled long wavelength photodetectors. But affordable high performance infrared systems require cost-effective infrared detectors that operate without cooling. This paper discuss approaches and technologies aimed at the elimination of cooling requirements of infrared photodetectors operating in the middle 3-8 μm (MWIR) and long 8-14 μm (MWIR) wavelength range of the infrared spectrum.

1. INTRODUCTION

The common believe is that infrared photodetectors of long wavelength radiation need to be cooled to achieve a high sensitivity. The long wavelength IR radiation is characterized by a low photon energy. Therefore, detection requires electron transitions with threshold energy lower than the photon energy. At near room temperatures the thermal energy of charge carriers becomes comparable to the transition energy resulting in a very high rate of thermal generation of charge carriers. The statistical nature of this process is the source of signal noise. As a result the long wavelength detectors become very noisy when operated at near room temperature.

Cooling is a direct, straightforward, and the most efficient way to suppress the thermal generation. At the same time cooling is a very impractical method. The need for cooling is a major limitation of photodetectors, and inhibits the more widespread application of infrared technology. Affordable high performance infrared systems require cost-effective infrared detectors that operate without cooling or, at least, operated at temperatures compatible with long-life, low power and low cost coolers.

Since cooling requirements add considerably to the cost, weight, power consumption and inconvenience of an IR system it is highly desirable to eliminate or reduce the cooling requirements. A number of concepts to improve performance of photodetectors operating at near room temperatures have been proposed [1-18 and related references therein]. This paper discuss approaches and technologies aimed at the elimination of cooling requirements of infrared photodetectors operating in the middle 3-8 μm (MWIR) and long 8-14 μm (MWIR) wavelength range of the infrared spectrum.

2. FUNDAMENTAL LIMITATIONS TO PERFORMANCE OF IR PHOTODETECTORS

Let us consider a generalized model of a photodetector, in which absorber of infrared radiation with physical area A_e and thickness t is coupled by optical concentrator with its optical area A_o to the beam of infrared radiation [8] (Fig. 1).

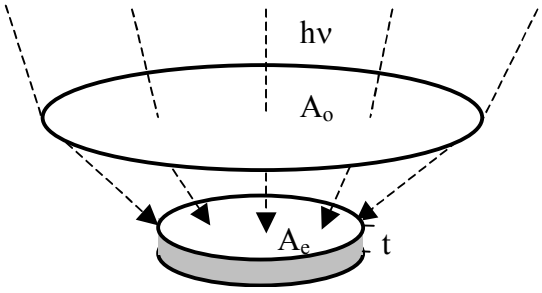


Fig. 1. Model of a photodetector

The detectivity of the thermal generation-recombination limited device can be expressed as

$$\mathbf{D^*} = \frac{\lambda}{2^{1/2}\mathbf{hc}} \cdot \left(\frac{\mathbf{A_o}}{\mathbf{A_e}}\right)^{1/2} \cdot \frac{\eta}{\mathbf{t}^{1/2}} \cdot \frac{1}{(\mathbf{G}+\mathbf{R})^{1/2}}$$

where η is the quantum efficiency, G and R are the volume generation rates. As this expression shows, the detectivity can be improved by i) maximizing A_o/A_e using an concentrator of optical radiation e.g. immersion lens, ii) maximizing $\eta/t^{1/2}$ with proper geometry of the device, and iii) minimizing G+R with suitable selection of semiconductor material.

Consider minimizing the $\eta/t^{1/2}$ ratio. It can be shown, that for optimized thickness this ratio is proportional to $\alpha^{1/2}$, where α is to the absorption coefficient. For favorable conditions of double pass of infrared radiation through the detector with negligible/perfect reflection at front/back surfaces of the detector, respectively, the optimized thickness is $0.63/\alpha$. It is worth to note, that the D*-optimized detector is characterized by only ≈76% quantum efficiency, reflecting a tradeoff between requirements of a high quantum efficiency and a low total thermal generation.

D* of the optimized device is

$$\mathbf{D^*} = 0.64\frac{\lambda}{\mathbf{hc}}\left(\frac{\mathbf{A_o}}{\mathbf{A_e}}\right)^{1/2} \mathbf{G_\alpha^{1/2}}$$

where $G_\alpha = G/\alpha$ is the generation rate within the absorption depth per unity of area. G_α can be considered as the basic figure of merit of any semiconductor material for infrared photodetector of any type. The ultimate background limited performance (D^*_{BLIP}) can be achieved with G_α reduced below optical generation caused by the background radiation. Table 1 shows the main fundamental, less fundamental and technological mechanisms of charge carriers generation and recombination that determine detector performance.

Table 1. Limits to detector performance

Limits	Noise origin	How to reduce?
Fundamental	background radiation noise	spatial and spectral filtering
	signal photon noise	can not be reduced
	heterodyne photon noise	can not be reduced
Less fundamental	Auger thermal generation	Selection of semiconductors, non-equilibrium depletion
	internal radiative generation	design of the detector
	radiative generation from adjacent elements	design of the detector
Technological	Shockley-Read generation	elimination of Shockley-Read centers
	thermal generation at surfaces, interfaces and contacts	improved processing
	low frequency noise	zero bias operation, improved technology
	amplifier noise	improved electronic interface

2. MATERIAL SYSTEMS FOR IR PHOTODETECTORS

Table 1 shows the most important material systems used for intrinsic photodetectors such as the binary narrow gap semiconductors, tunable band gap ternary semiconductors, and band gap engineered superlattice materials. The binary compounds can be used for applications that requires optimum performance at the spectral range corresponding to band gap of the material. Availability of binary compounds is limited; no one can operate in the LWIR spectral range.

Thermal generation and recombination in narrow gap semiconductors at near room temperature is determined by the Auger mechanism [2]. $Hg_{1-x}Cd_xTe$ remains to be the champion material among a large variety of material systems [4, 10,12]. This is mostly due to extreme flexibility of this material for IR detector applications that makes possible to obtain detector of any type for optimized detection at any region of IR spectrum including, dual and multicolor devices. There is no clear indications that some well known binary alloys and tunable band gap semiconductors could be better than $Hg_{1-x}Cd_xTe$ in terms of fundamental figure of merit. Fig. 2 shows the generation-recombination limited performance of ≈5 μm and ≈10.6 μm cutoff uncooled and thermoelectrically cooled $Hg_{1-x}Cd_xTe$ photodetectors. Optical immersion of the devices to GaAs hyperhemispherical lenses may increase the performance by one order of magnitude bringing the performance closer to the BLIP limit due to the quantum noise of the 300 K background radiation.

Table 2. The most important material systems

Material system	Most important	Other
Binary alloys	InSb, InAs	PbS, PbSe
Tunable band gap semiconductors	Hg based	$Hg_{1-x}Cd_xTe$, $Hg_{1-x}Zn_xTe$, $Hg_{1-x}Mn_xTe$
	lead salts	PbSnTe, PbSnSe
	InSb- based	InAsSb, InNSb, InBiTe, InTlSb
Type II superlattices	InAs/GaSb	
Type III superlattices	HgTe-CdTe	

Some new materials may exhibit improved figure of merit. An example is InN_xSb_{1-x} with 15 μm cutoff [13], characterized by the Auger recombination rate one third that of equivalent band gap $Hg_{1-x}Cd_xTe$, due to the higher electron mass and conduction band non-parabolicity.

Intensive efforts are underway at present on artificial narrow gap semiconductors based on type II and type III superlattices (see recent review [12] and related papers therein). Reduction of Auger generation rate at room temperature in InAs/GaAs superlattices resulting in detectivity exceeding 10^8 cmHz$^{1/2}$/W at 10.6 µm at room temperature has been reported [14]. No devices of this type are commercially available at present.

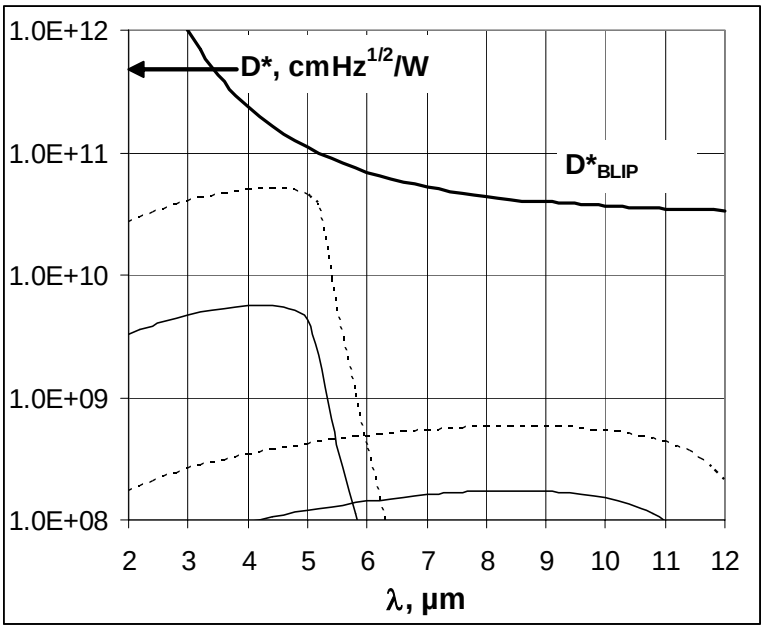


Fig. 2. Generation-recombination limited spectral detectivity of uncooled (solid) and 2-stage Peltier cooled (dashed) $Hg_{1-x}Cd_xTe$ photodetectors. BLIP limit of performance also indicated.

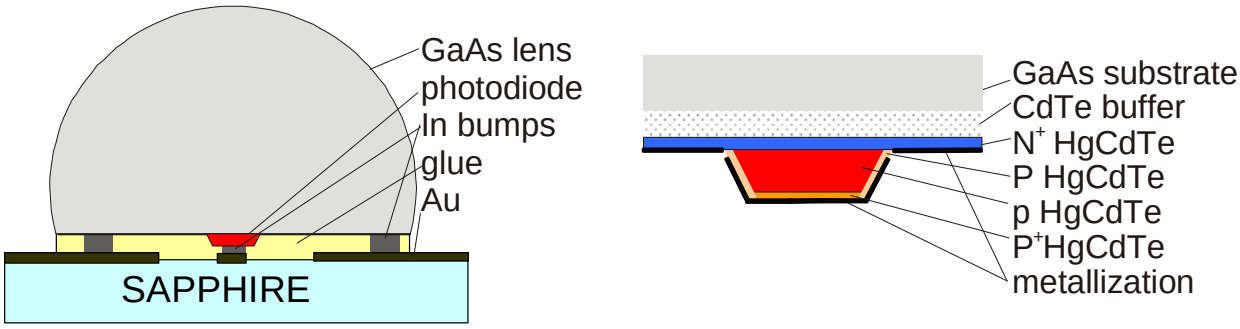
4. $Hg_{1-x}Cd_xTe$ PHOTODETECTORS

Traditionally, photodetectors are related to photoconductors (PC), photoelectromagnetic detectors (PEM) and photovoltaic detectors (PV), basing on the principle by which optically generated carriers in the absorber region are sensed. The recent advances in heterostructure devices made the distinction between PC and PV devices not so clear, however [5].

For a long time PC and PEM detectors were the only devices used for uncooled detection of MWIR and LWIR radiation [1,4]. Now they are being replaced by photovoltaic devices. They do not require electric nor magnetic bias, show no low frequency noise and can operate from DC to very high frequencies. Photodiodes, with their very low power dissipation, can be assembled in large two-dimensional arrays.

Design of PV devices. Fig. 3 shows an example of mesa photodiode, monolithically integrated with immersion lenses. Heavily doped N^+ layer provides the base contact with a low resistance. The top contact is a heavily doped P^+-type layer covered with contact metallization that also plays a role of retroreflector inducing double pass of infrared radiation. In practice more complex architecture with additional layers and 3D design is used to reduce G-R and tunnel currents generated at interfaces, surfaces and contacts [5,10,11,15].

The thickness of the buffer and other layers within the device is frequently selected to achieve the optical resonance in a required spectral range. Optical immersion is frequently used to improve performance and reduce capacitance.



a) b)

Fig. 3. Schematic cross-section of optically immersed 10.6 µm mesa photodiode for operation at 200-300 K: a)- complete structure and b)-enlarged view of active element.

The single-cell devices can be successfully used only for small area uncooled and Peltier cooled devices operating in the MWIR spectral range. The long wavelength photovoltaic devices operating at near room temperature suffer from i) poor quantum efficiency and ii) low differential resistance [6,7,16].

i) Since the absorption depth of long wavelength IR radiation (λ>6 µm) is longer than the diffusion length, only a limited fraction of the photogenerated charge can contribute to the quantum efficiency. Consider an example of an uncooled 10.6 µm photodiode based on x≈0.17 absorber. The ambipolar diffusion length in the material is less than 2 µm while the absorption depth is ≈13 µm. This reduces the quantum efficiency to ≈15% for a single pass of radiation through the detector.

ii) The resistance of the p-n junction is very low due to a high thermal generation and ambipolar effects. As a result, the noise of parasitic device resistances and preamplifier noise may exceed the thermal generation-recombination noise.

The two problems make the single-cell uncooled LWIR devices not usable for practical applications.

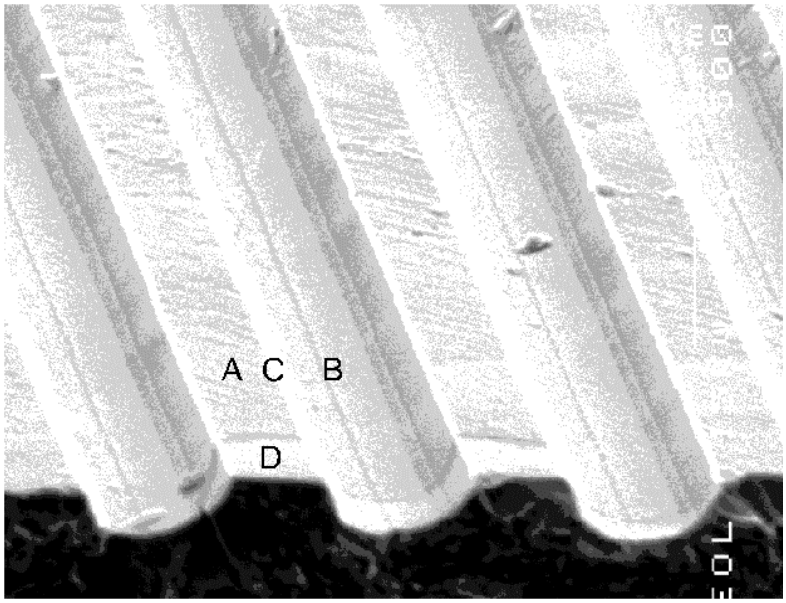


Fig. 4. SEM images of a multi-heterojunction photodetector. a) plan view of the whole device, b) side view of a single cell. A- mesa structure, B-trenches, C- non-metallized wall, D- non-metallized region of the device.

These problems has been solved through adoption of sophisticated architecture of photovoltaic detectors [6] based on multiple heterojunctions. One solution is device with junctions perpendicular to the surface (Fig. 4), the only one LWIR uncooled photovoltaic device on market [17]. Such devices suffer from the non-uniform response across the active area and polarization- dependent response.

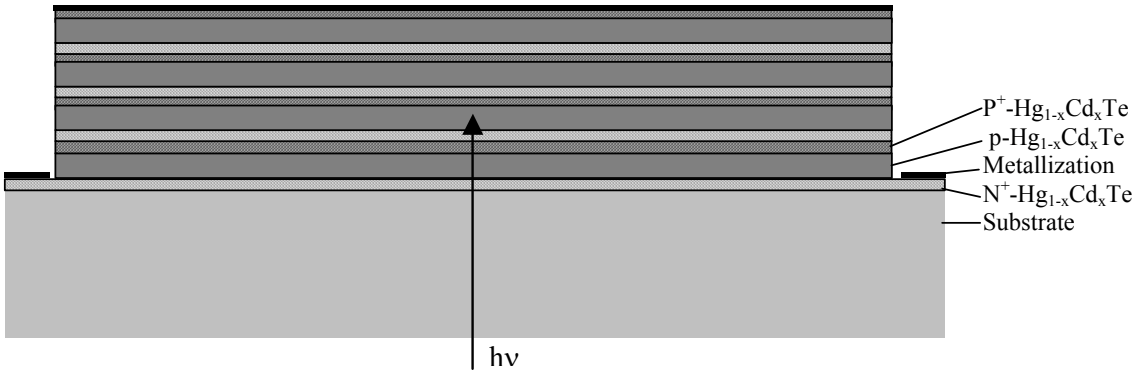
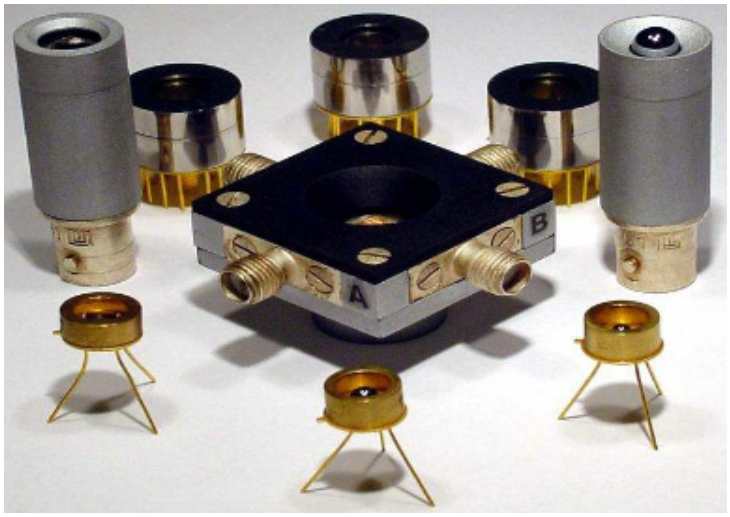


Fig. 5. Schematic cross-section of 4-cells stacked multiple detector. The backside illuminated device is supplied with reflector for double pass of IR radiation.

More promising are the stacked multijunction photodiodes [16], shown in Fig. 5. Such devices are capable of achieving both good quantum efficiency, large differential resistance and fast response. The problem in practical implementation is a low resistance connection of N^+ and P^+ regions of adjacent cells in the device. This can be achieved employing tunneling between at the N^+ and P^+ layers.



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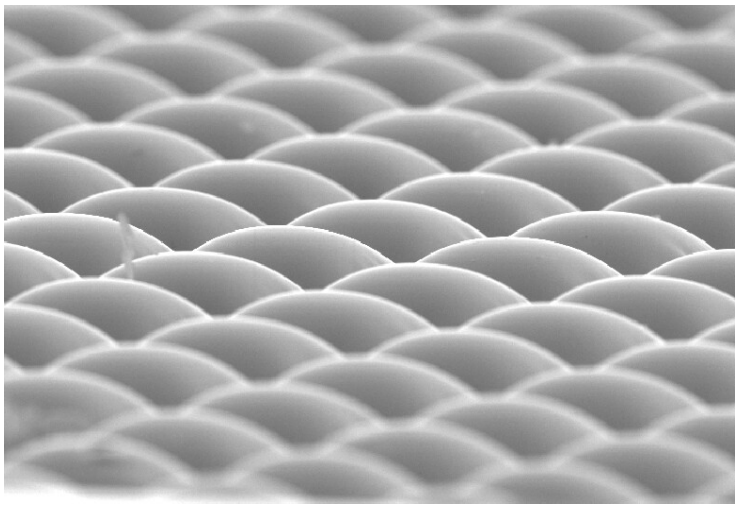

b)

Fig. 6. Ambient temperature and Peltier cooled a) and SEM picture of 2D array of 2D immersion lenses photodetectors manufactured by the Vigo Systems [11,17].

Practical devices. Fig. 6 shows ambient temperature and Peltier cooled photodetectors manufactured by the Vigo Systems. The devices are based on epitaxial techniques: ISOVPE, MOCVD and their combinations [11]. Optical immersion has been extensively used for single element and array detectors (Fig. 6).
Performance of photovoltaic devices operating at near room temperatures has been steadily improved. Without optical immersion photovoltaic detectors are sub-BLIP devices with performance close to the G-R limit. Well designed optically immersed devices when thermoelectrically cooled with 2-stage Peltier coolers, show detectivities up to 10^{11}cmHz$^{1/2}$/W at 5 µm, approaching the BLIP limit [11,17].
Situation is less favorable for LWIR photovoltaic detectors. Detectivities exceeding 1×10^{9}cmHz$^{1/2}$/W and $\approx6\times10^{9}$cmHz$^{1/2}$/W have been measured with uncooled λ=8.5 µm non-immersed and optically immersed devices, respectively [10,11]. Optically immersed 10.6 µm PV device cooled with 2-stage Peltier cooler with detectivities of $\approx4\times10^{9}$ cmHz$^{1/2}$/W has been also reported. Despite of all improvements (advanced architecture, optical immersion, Peltier cooling) they show detectivities below the BLIP limit by almost one order of magnitude.

Response time. The frequency response of photovoltaic devices is limited by transport of photogenerated charge carriers through the absorber region and by RC time constant.
Transport through the absorber region is a combination of diffusion and drift. The p-type $Hg_{1-x}Cd_xTe$ is the material of choice for an absorber of a fast photodiode due to a large diffusion coefficient of electrons. The diffusion transit times at are ≈100 ps for extrinsic p-type 2 µm thick $Hg_{0.82}Cd_{0.18}Te$ absorber. Further reduction can be achieved with thinner absorber. Drift transport in reverse biased devices can reduce the transit time further.
The main limitation of response time is usually the RC time constant. For transimpedance preamplifier with a low input resistance, the RC time constant is determined by the junction capacitance and the photodiode series resistance. Reduction of series resistance by almost two orders of magnitude is possible using structures with heavily doped n-type material for the mesa base layer, with corresponding reduction of the RC time constant.
Very short RC time constant is expected in optically immersed photodiodes with very small area of active region. With these improvements photodiodes can be use for gigahertz range detection of IR radiation.
Picture 7 illustrates high frequency capability of the LWIR photovoltaic detectors. Specific features of the pulse are seen.

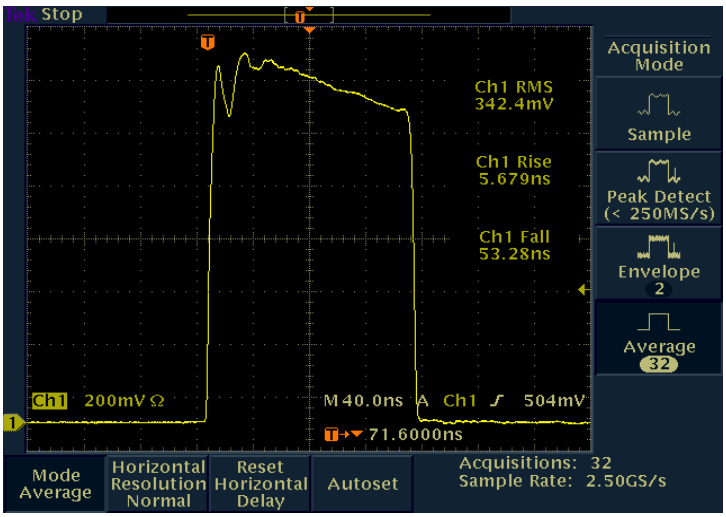

Fig. 7. Observation of quantum cascade 10.6 µm laser pulses with uncooled $Hg_{1-x}Cd_xTe$ PV device [11,17].

Non-equilibrium Auger suppressed devices. One of the most exciting events in the developments of uncooled IR photodetectors was discovery of Auger suppression by British workers [2,3,4,8, 9,12,15 and related references therein]. They proposed to suppress Auger processes decreasing the free carrier concentration below equilibrium values by stationary non-equilibrium depletion of semiconductors.

This can be achieved in reverse biased N^+pP^+ photodiodes with lightly doped absorber. Under strong depletion the majority carrier concentration saturates at the extrinsic level while the concentration of minority carriers is reduced below the extrinsic level. The non-equilibrium mode of operation may reduce the Auger generation rate by a factor n_i/N_d, where n_i and N_d are the intrinsic and donor concentrations, with improvement of detectivity by $(2n_i/N_d)^{1/2}$. The additional gain factor of $2^{1/2}$ is due to the negligible recombination rate in the depleted semiconductor. The gain for p-type material is even larger, taking into account elimination of Auger 1 and Auger 7 recombination. Additional depletion-related improvement can be also expected from increased absorption due to the reduced band-filing effect.
The BLIP limit for 10 μm device at room temperature can be achieved with:

- p-doping at $\approx 10^{13}$ cm^{-3} level
- extremely quality materials with a very low concentration of Shockley-Read centers
- design of the device that prevents thermal generation at surfaces, interfaces and contacts.

Auger suppressed heterostructure photodiodes have been demonstrated and gradually improved [15]. The Auger suppressed devices suffer from a high low frequency noise [11,20,21], proportional to the bias current. Since the bias current of the LWIR devices is large, the 1/f knee frequencies are 100 MHz to few MHz for ≈10 μm devices at room temperature. This reduces their signal to noise ratio at frequencies of ≈1 kHz to level below that for equilibrium devices!
The reason for the large 1/f noise is not clear. The attempts to find the source of 1/f using the perimeter-area analysis give contradictory results [18]. The possible routes to reduce the 1/f noise is to reduce the dark current or/and the I_n/I ratio with improved material technology and better design of the devices.

4. CONCLUSIONS

The elimination of cooling of infrared photodetectors will lead to significant reduction in cost, logistical supply, and an increase in the mean time between failures.
It seems that there is no fundamental obstacle to perfect detection of MWIR and LWIR radiation without cryogenic cooling. The problems are of technological rather than fundamental nature.
The practical uncooled devices still present a challenge, but they have been steadily improved. Where we are now?

- Thermoelectrically cooled and optically immersed MWIR photodetectors closely approach the BLIP limit.
- The best optically immersed equilibrium mode LWIR devices cooled with two-stage Peltier coolers are by one order of magnitude below the BLIP limit of performance.
- The best non-immersed Auger suppressed LWIR devices are also by one order of magnitude below the background limit of performance at frequencies above 1/f knee.
- The performance of the Auger suppressed devices can be improved further by the use of optical immersion. Apart from the usual gain in performance, optical immersion highly reduces the total bias power dissipation, which would be important in large size elements and in future multi-element arrays of extracted photodiodes. Another advantage is significant reduction of radiative exchange between adjacent element in an array.
- The combination of the improvements should lead to BLIP performance already with technologies available at present!

The near room temperature photodetectors have found increasingly widespread civilian (pyrometry and thermography, gas analysis with conventional, laser and Fourier transform spectroscopy, free space high transfer rate optical communications; test equipment) and military (night vision, laser range finder and threat warning devices, gun sights, smart munitions) applications.

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