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Optical immersion of IR photodetectors as an effective way to reduce cooling requirements

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Optical immersion is an effective way to improve the performance of photodetectors operating at elevated temperatures. The main difficulties in practical implementation of optical immersion are problems in optical and mechanical matching of sensitive elements to the immersion lens which lead to serve the transmission and reflection losess. The problems have been solved by using the monolithic approach developed at VIGO, in which the lens is formed directly in the transparent substrate of epitaxial layer. The practical optically immersed photoconductors, photovoltaic and photoelectromagnetic IR photodetectors are reported.

Let us consider a simplified model of a photodetector [1] as a slab of semiconductor with the actual "electrical" area A_e and thickness d (Fig. 1), in which the quantum efficiency η and the photoelectrical gain g remain constant. The current responsivity of the device is

$$R_i = \frac{\lambda\eta}{\mathrm{hc}}qg \tag{1}$$

where λ is the wavelength, h is the Planck constant, c is the light velocity, and q is the electron charge.

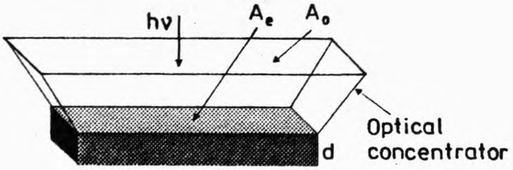

Fig. 1. Scheme of IR photodetector

The device current is noisy due to the statistical nature of generation and recombination processes. Assuming the current gain for the thermally generated carriers being the same as that for the optical ones, the noise current is [2]

$$I_n^2 = 2(G+R)dA_e\Delta f q^2 g^2 \tag{2}$$

where G and R are the generation and recombination rates, and Δf is the frequency band. Detectivity D^* is the main parameter characterizing normalized signal to noise performance of the detectors being equal to

$$D^* = \frac{R_i(A_o\Delta f)^{1/2}}{I_n} \tag{3}$$

where A_o is the "optical" area of the photodetector. According to (1)–(3)

$$D^* = \frac{\lambda}{\mathrm{h}c}\left(\frac{A_o}{A_e}\right)^{1/2} \frac{\eta}{d^{1/2}}\left(\frac{1}{2(G+R)}\right)^{1/2}. \tag{4}$$

Cooling of detector is a natural and a very effective way to reduce the $G+R$ term. At the temperature of liquid nitrogen temperature, the thermal generation and recombination in semiconductors being used for MWIR and LWIR detectors become negligible, compared to the 300 K backgroud thermal radiation generation. This enables the BLIP limit of performance to be achieved. The need for cooling creates a considerable problem which inhibits the more widespread of IR systems. The cooling requirements add significantly to the cost, bulk, weight, power consumption and inconvenience of infrared system operation, and its elimination or reduction would be highly desirable. So, the question arises – what can be done to improve the performance without cooling?

As follows from expression (4), one possible way to maximize the detectivity is the proper selection of detector material band gap and doping up to the maximum value of $\eta/[2d(G+R)]^{1/2}$.

Another possibility is to reduce the actual or "electrical" area of the detector, as compared to the apparent "optical" area, by the use of a non-imaging radiation concentrator. A possible way to achieve this is to immerse the photodetector in the hemispherical or hyperhemispherical lenses (Fig. 2), [3]–[6]. Due to immersion, the linear size of the detector area increases by a factor of either n or n^2 for hemispherical and hyperhemispherical immersion, respectively. As a result, the detectivity is increased by the same factor. Germanium ($n = 4$) is the most frequently used material for immersion lens. The use of immersion technology has been limited due to problems in mechanical matching of the detector and the lens material, severe transmission and reflection losses and limited acceptance angle of the devices resulting from the total reflection at the lens-glue interface at large angles.

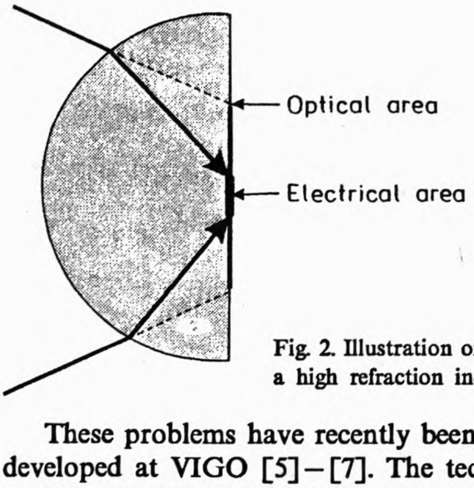

Fig. 2. Illustration of the principle of the optical immersion of a detector to a high refraction index hyperhemispherical lens

These problems have recently been solved by the use of monolithic technology developed at VIGO [5]–[7]. The technology is based on epitaxy of HgCdZnTe on CdZnTe. The HgCdZnTe serves as the sensitive element, while the immersion lens is formed directly in the transparent ($n = 2.7$) substrate. Figure 3 shows schematically the structure of monolithic optically immersed photoconductor.

As can be seen from the Table, the monolithic optical immersion results in significant improvement of the most important detector parameters. The gain factors achieved with hyperhemispherical immersion become substantially higher if compared to those for the case of hemispherical immersion. The hyperhemispherical one may exhibit a restriction of the acceptance angle of the detector and impose more severe manufacturing tolerances. These restrictions are not so severe as for germanium lenses and have no practical importance in most cases. For example, the numerical aperture of the main optical system is limited to about 1.4 by the immersion lens.

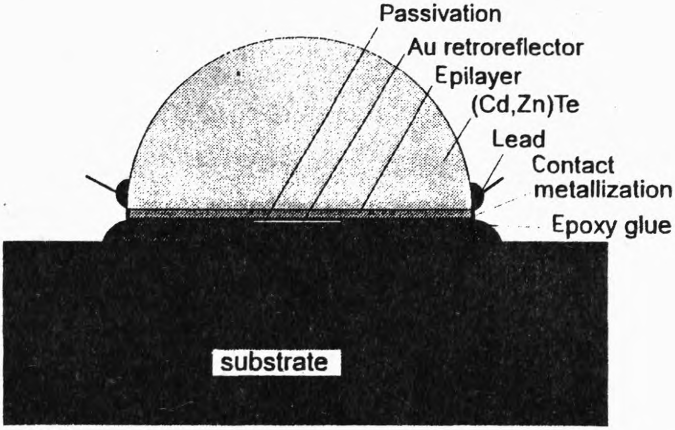

Fig. 3. Structure of the monolithic optically immersed photodetector

Some gains are specific for particular types of photodetectors. For example, the reduction of bias power dissipation is important in the case of either photoconductors or some types of photodiodes which require strong bias for the best performance [6]. The immersion also reduces significantly the heat load of both heat sinks and cooling devices, making possible the reduction of size, weight, price and power consumption of the cooling systems.

The reduction of capacitance due to immersion is of the utmost importance for high frequency photodiodes which make it possible to improve dramatically the high frequency performance of RC limited devices.

In the case of photoelectromagnetic detectors, the reduced size of active elements allows us to achieve a strong magnetic field with miniature permanent magnets. Figure 4 shows practical optically immersed photodetectors manufactured by VIGO The photosensitive (Hg, Zn)Te elements are prepared by the isothermal vapour phase epitaxy in a computer controlled reusable semiclosed growth system [8]. The ion beam technique is extensively used in device technology including element delineation, activation of surface prior to the contact metallization and for p-to-n conversion [9], [10]. The immersion lenses are formed in the (Cd, Zn)Te

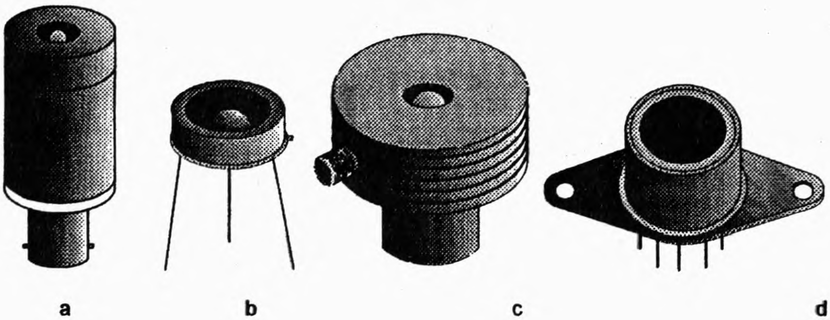

Fig. 4. Optically immersed MWIR and LWIR photodetectors: a — large area ambient temperature photoconductors, b — ambient temperature photoconductors, photovoltaic and Dember effect detectors, c — photoelectromagnetic detector, d — Peltier cooled photoconductors and photovoltaic detectors

substrates of epitaxial layer using ultrasonic and classical mechanical manufacturing technique.

The monolithic approach permits simple and economic manufacturing of high performance photodetectors. Neither separate lenses, nor epoxing of active element to the lens is required. Since the radiation passes through the lens, the sensitive element can be insulated from ambiency with a thick, optically non-transparent coating. The devices are rugged and mechanically stable. They can operate in a very broad spectral band, with very low reflection and absorption losses. The remaining losses are caused by the reflection at the spherical lens surface ($\approx 20\%$). They are smaller compared to the reflection losses at the surface of non-immersed detector. These losses can be eliminated by applying the AR coating to the lens.

Figure 5 shows the spectral detectivities of some optically immersed photodetectors available at present from VIGO [7].

PCL-L. Ambient temperature photoconductor, optimized for the detection of 10.6 μm CO_2 laser radiation. The response time < 1 ns. Applications: detection/monitoring of CO_2 laser radiation, laser warning receivers.

PEMI-L. Ambient temperature photoelectromagnetic detector, optimized for detection of 10.6 μm CO_2 laser radiation. Response time < 1 ns and can be reduced down to 100 ps. Suitable for detection of both CW and high frequency modulated radiation. Exhibits no flicker noise. Applications: detection/monitoring of CO_2 laser radiation.

PCI-M. Family of ambient temperature MWIR photoconductors with spectral response optimizable anywhere in the $3-8$ μm range. Response time $< 0.1-1$ μs. Applications: fast pyrometers, spectroscopy, gas analyzers.

PCI-L-2TE ($n = 1-3$). Peltier cooled photoconductor. Optimized for detection of 10.6 μm CO_2 laser radiation. Response time < 30 ns. Applications: detection/monitoring of CO_2 laser radiation, Fourier spectrometers, fast pyrometers, simple thermal imagers.

PCI-M-2TE. Two-stage Peltier cooled MWIR photoconductor with near-BLIP

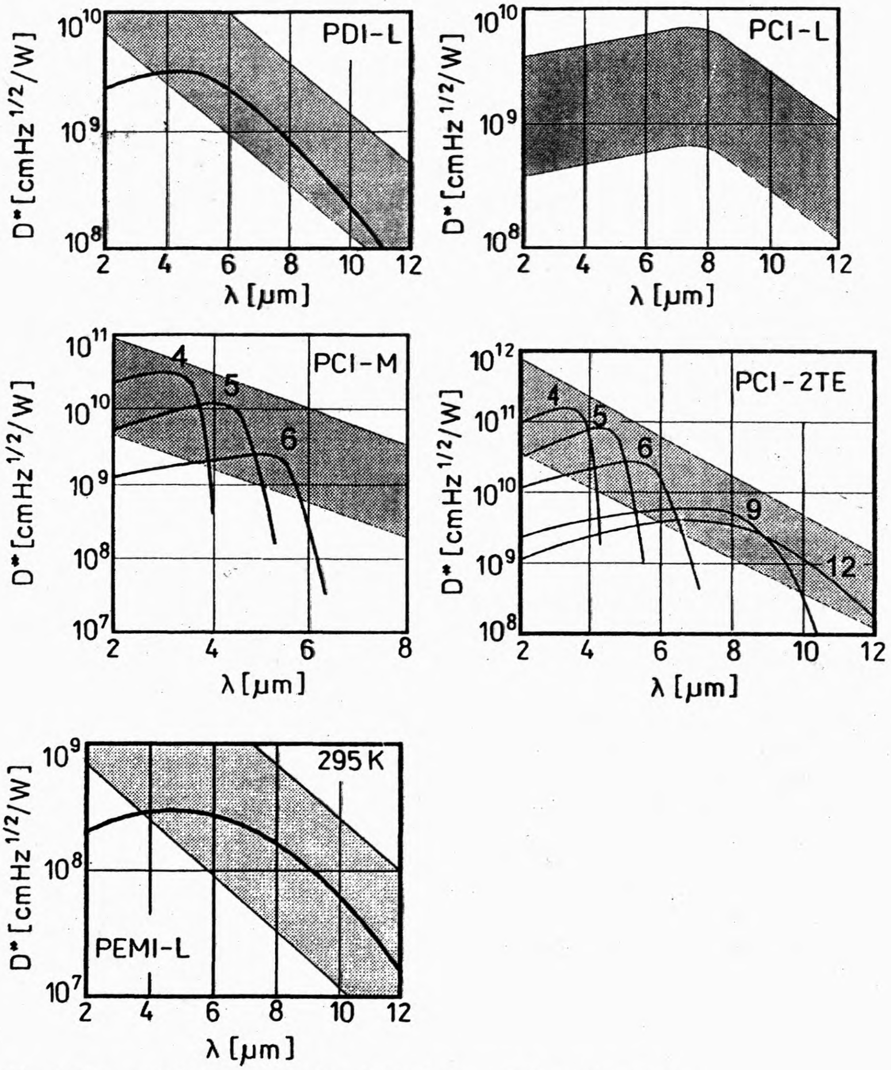

Fig. 5. Spectral detectivities of optically immersed photodetectors

Table. Influence of optical immersion on properties of photoconductors with CdZnTe lens

Value	Hemisphere	Hyperhemisphere	Type of detector
Linear size	n (= 2.7)	n^2 (= 7)	any
Area	n^2 (= 7)	n^4 (= 49)	any
Voltage responsivity	n (= 2.7)	n^2 (= 7)	PC, PEM
Current responsivity	n^2 (= 7)	n^4 (= 49)	PV, Dember
Detectivity	n (= 2.7)	n^2 (= 7)	any
Bias power	n^2 (= 7)	n^4 (= 49)	PC, PV
Capacitance	n^2 (= 7)	n^4 (= 49)	PV
Acceptance angle [°]	180	42	any
Thickness/radius	1	1.3	any
Tolerances	not severe	stringent	any

performance. Response time < 1 μs. Applications: fast pyrometers, simple thermal imagers, spectroscopy, gas analysis.

Actually LWIR photoconductors are being developed operating with 3 – 5 stage Peltier coolers as well as fast p^+n photovoltaic and Dember effect detectors [11]. The use of the one-lens immersion technology is limited to fabrication of the single element and small size arrays. The main limitation comes from optical distortion. This limitation can be overcome by the use of multiple lens arrays of detectors. At the same time, such devices seem to be extremely promising for the future high quality and lightweight thermal imagers. JONES *et al.* [12] reported HgCdTe detector arrays with silicon microlens. In contrast to silicon, the use of CdZnTe lenses offers a better match to HgCdTe and perfect transparency in a very wide spectral band (1 – 30 μm). The recent efforts at VIGO are directed to the monolithic arrays with refractive, diffractive or binary microlens.

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