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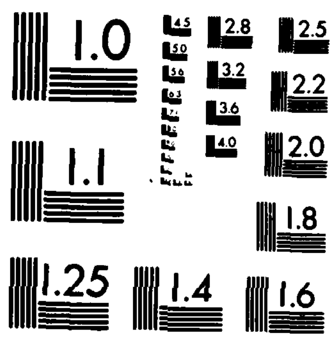
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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

BOUNDARY VALUES OF PARAMETERS AND PERSPECTIVES FOR THE DEVELOPMENT OF SENSORS FOR THERMAL IMAGING EQUIPMENT

by

B. Livada

FOREIGN TECHNOLOGY DIVISION

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BOUNDARY VALUES OF PARAMETERS AND PERSPECTIVES FOR THE DEVELOPMENT OF SENSORS FOR THERMAL IMAGING EQUIPMENT

by Branko Livada

Introduction

Thermal imaging devices convert the infrared (IC) rays of objects into visible rays, that is to say, they allow the conversion of thermal images into the visible images of objects. This expands the possibilities of the eye even in other spectral regions of rays: medium IC (3-6 μm) and long IC (6-14 μm). The possibilities of thermal imaging devices are considerably less in relation to the eye [1], [2]: the threshold of the eye's sensitivity is 10^{-17}W and the image is stereo and in color, while the threshold of the sensitivity of the best thermal imaging device is 10^{-15}W and the image is in black and white or quasi-color. The eye receives information about the objects through the reflected rays of the sun in the visible part of the spectrum and is weakly sensitive to IC rays (around 10^{13} times less than for visible rays). The information source for thermal imaging devices are the object's own rays, which in the region of the atmospheric windows of transparency (3-5 μm and 8-14 μm) spread well through the atmosphere. Objects, heated to temperatures of around 700 K, maximally emit within the 3-5 μm region, and objects, heated to temperatures of around 300 K maximally emit within the 8-14 μm region.

Thermal imaging devices can be used under difficult conditions (increased atmospheric humidity, total fog, smokey atmosphere, camouflaged objects, etc.), when they have expressed advantages over active and passive devices with image amplifications, which permit them broad application in military observation and detection equipment, as well as in firing-control equipment. These possible applications have caused great interest in these devices and their components (the research and development of sensors based on HgCdTe alone have cost several million dollars [3]).

The basic components of thermal imaging devices are shown in illustration 1 [4]. The optical system, together with a scanning system, breaks down the thermal image into the image's elements which are projected on an IC ray receiver. By the electronic processing of the signal from the IC receiver, which contains the information about the object's own rays, it is possible to form a visible image, which corresponds to the image's thermal image, on the screen. The manner of scanning and the signal's electronic processing directly depend on the type of IC sensor, which can be used in the thermal imaging device. On the basis of the type of sensor used to convert the thermal image, three generations of the thermal imaging devices can be differentiated.

The first generation is made up of devices which use single element sensors. The devices of this generation, therefore, have a very complex scanner, which decreases their reliability and their performance is poor.

Second generation devices use multielement sensors (detector lines or matrices) which are made up of a relatively small numbers of detectors. This permits the instantaneous formation and analysis of the thermal image's very parts, it simplifies the scanning system, but does not eliminate it, and it increases sensitivity. These systems use serial, parallel or combined serial-parallel scanning.

Third generation devices use multielement sensors with a sufficient number of elements (10^5-10^8), which allow the obtaining of information about an object with a sufficiently good analysis, without using mechanical scanning (by momentary illumination). In producing this generation of thermal imaging devices, the greatest problem is the obtaining of qualitative sensor matrices with detectors of uniform characteristics.

First and second generation thermal imaging devices have already been produced and improved, while second [sic] generation devices still have not been developed, because matrices with a sufficient number of detectors have not been developed. In order to perceive the possibilities and paths for the development of thermal imaging devices, it is necessary to analyze the possibilities and perspectives of the development of sensors.

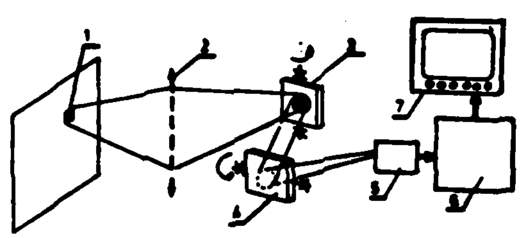

Illustration 1. Basic components of a thermal imaging device
1. the thermal image's element, 2. the optical system (the objective), 3. the vertical scanner, 4. the horizontal scanner, 5. the detector, 6. the electronic system for the image's processing, 7. the screen

The Effect of the Parameters of Sensors on the Quality of a Thermal Imaging System

The concepts of sensor and detector are parallely used in this paper.

The author will attempt to use sensor when he wishes to stress that he is dealing with a part of the thermal imaging device which is used for the conversion of the thermal image into a visible image. The detector will be used to identifiy the element, which makes this conversion possible. Sensors can be single element (they have one detector) or multielement (detector lines and matrices). The quality of the sensor is described through the detectors' parameters, which compose it. Modern thermal imaging systems use sensors which are sensitive within the 3-5 m or 8-14 m spectral regions and are single element or made up of detector lines or matrices based on the following materials: InSb, PbSnTe, HgCdTe and some pyroelectrical materials. The possibility of improving the characteristics of already developed sensors, and especially the production technology and the selection of materials, exists.

The sensor's performance vitally affects the performance of the thermal imaging system. So, for example, the sensor's detection ability directly influences the system's sensitivity. The greater the detection ability, the greater the system's sensitivity, and the system can have a greater range. The detection ability, moreover, affects the system's temperature analysis, so that greater detection ability makes better temperature resolution possible. Matrices with a great number of detectors, which permit the formation of an image by momentary illumination without the use of mechanical scanning, allow the increase of sensitivity, the backround's muting, the signal's processing in one chip, continuous observation and a considerable decrease in the cost and overall dimensions of the system in which it is used. Great attention, therefore, is today being paid to sensors.

The Limits of the Possibilities of IC Sensors

The detector's basic processes, which permit the detection of visible and IC rays, and characteristics are described in detail in [5]. The concepts, defined in this article, will be used in the rest of the paper. The possibility of the application of some sensors and their, theoretically, best characteristics depend on many factors. One of them is the number of photosensitive elements which make up the sensor. The number of elements depends on the sensor's overall dimensions and the minimal dimensions of one element, which can be realized with existing technology. These minimal elemental dimensions amount to 20-50 μm, but with the development of technology can be reduced to several micrometers. The number of elements depends on both the possibilities and the manner of signal separation from each detector and the possibility of using the electronic scanning of signals with matrix elements. The basic problem is the realization of a production technology, which can secure a large number of detectors in the matrix, which have uniform characteristics. Besides this, it is also necessary to secure starting material, which is suitable for combining with CCD circuits or on which CCD circuits can be formed for electronic scanning by means of multiplexing. All these problems are, in principle, solvable and the future development of new sensors depends upon this.

The application of sensors is limited by the sensor's need for cooling to criogenic temperatures for its normal operation. The problems of cooling are successfully solved with the use of various types of miniature refrigeration devices such as: thermal electric coolers, miniature criostats based on the Joule-Thompson effect and criostats on the basis of the Sterling cycle. Cooling can be achieved also by directly pouring liquid gas into the inner part of a Dewar flask in which the sensor is situated. The use of a refrigeration method depends on the necessary operating temperature, the operation's length and the spatial possibilities for situating the sensor in the device.

The detection ability, D^*, determines the possibility of registering optical and IC signals. The detection ability depends on the rays' wavelength, the flux of backround rays, the operating frequency and temperature, and the material's characteristics. The size of the response, that is to say, the intensity of the photodetector's signal depends on the object's temperature and surface and on the conditions of the diffusion of rays through the atmosphere. We will consider some of the enumerated effects on the detection ability and signal of the photodetector.

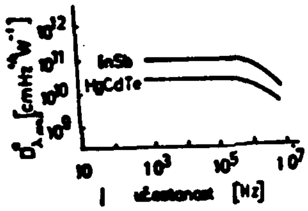

Illustration 2. The frequency ratio of the detection ability
1. frequency

The frequency ratio of the detection ability is, for photon detectors, determined by the material's characteristics, as well as by the service life of the carrier in the material. For InSb and HgCdTe detectors the frequency ratio is given in [6] and shown in illustration 2.

The operating temperature affects the spectral characteristic, but also the noise level, and hence the detection ability. The affect of temperature on photovoltaic HgCdTe detectors is analyzed in [7]. The result is presented in illustration 3. There exists a range of temperatures at which the affect of g-r noise is minimal, and hence, the detection ability is at its maximum. For the majority of materials, now used for thermal imaging sensors, g-r noise can decrease the detection ability for temperatures greater than 100 K.

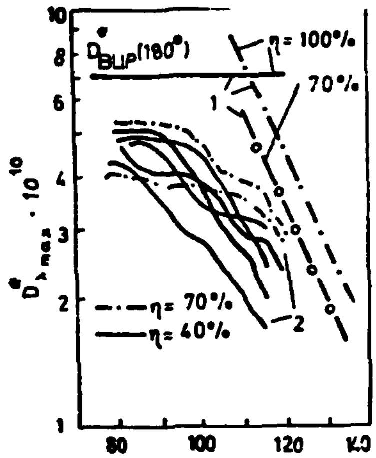

Illustration 3. The dependence of $D\lambda_{max}$ on temperature for high quality HgCdTe detectors
1. the theoretical limit, 2. measured values

For sensors with photodiodes the affect of the material's characteristics on the detection ability is expressed through the product of R_0A (the product of the dynamic resistance R_0 and the detector's surface) and the quantum efficiency of μ [8]. In illustration 4 is given the dependency of the product of R_0A for a photodiode with λ_{max}=11 μm and at an operating temperature f 77 K. It is seen that for R_0A>1 Ωcm^2 the detection ability is maximum, that is it is equal to the BLIP's detection ability, and can be decreased only with the decrease of the backround rays.

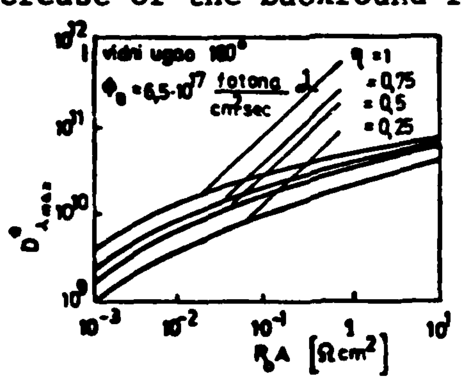

Illustration 4. The dependence of $D\lambda_{max}$ of R_0A for a photodiode with λ_{max}=11 m at 77 K

1. visible angle, 2. photon

The possibility of using detectors depends on both the adaptability of the spectral characteristics to the conditions of the rays' diffusion through the atmosphere and on their purpose. Analyses of the effects of diffusion on the parameter, M*, [9], the detection ability [10] and the photodiode's signal [11] show that the performance of a system, in to which the sensor is built, can be significantly affected by the proper choice of sensors.

Perspectives for the Development of IC Sensors

New types of sensors were developed, above all, because of the nee o improve the characteristics of thermal imaging systems and reduce system's cost. For the designing of a thermal imaging system, ...e improvement of characteristics means increasing the system's sensitivity and analyzing power. The system's ultimate user wishes the following: better object identification, longer operating period, use in difficult conditions (for example: in moist and smokey atmospheres), comparability with existing systems with different applications, automatic operation, application in "start and forget" systems and lower cost. Lower cost is realized by: lessening the number of mechanical elements, using digital data processing, using standard modules, broadening the production scope, decreasing consumption and avoiding cooling. Every designer would like to have a sensor which allows him: greater sensitivity (which can permit a larger number of detectors in the sensor), better resolution (which permits a smaller detector surface), better signal-to-noise ratio (which allows momentary illumination and the use of signal integration), the use of an inertialess electronic system for scanning and a greater field of vision. Therefore, greater attention has been placed on the development of sensors, both in view of improving the detector's performance, and in view of the number of detectors in the sensor. The trend of development is illustrated by the diagram in illustration 5. One of the developmental directions is the realization of a detector with a maximum, theoretically possible performace, and another direction is the development of a sensor with the largest number of elements possible. Both developmental directions are accompanied by the development of new materials and techniques.

Up until now detector matrices have been produced with a 32x32 detector [3], [12]. Development is anticipated according to the following dynamic: 64x64 (by the end of 1983), 256x256 (1985) and 1024x1024 (1987). The application of new sensor concepts is also being considered.

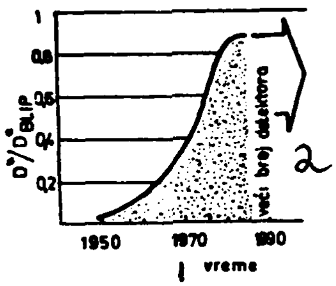

Illustration 5. The developmental trend for sensors
1. time, 2. a greater number of detectors

The SPRITE* Detector

In order to increase the sensitivity of a thermal imaging system, a detector line is used, which operates in the so-called TDI** operating regime, during which the detectors are connected as in illustration 6. The sensor's signal is increased with the application of the TDI operating regime, and therefore, the total detection ability, as well as the system's sensitivity, is increased. The image elements are scanned by a detector line, and the delay lines are designed so that the moment the i detector is illuminated, the signal from the (i-1) detector is gathered with that of the i detector by the delay line.

Signal integration is achieved in this way, by which, besides enlarging the signal, the non uniformity of the detector's characteristics is compensated. If all the detectors are identical, then the sensor's detection ability in the TDI operating regime is increased by $\sqrt{N}$ times in relation to the detection ability of one detector.

*SPRITE is an acronym for "signal processing in the element."
**TDI is an ancronym for "time delay and integration."

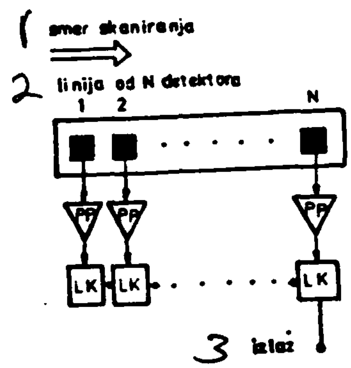

Illustration 6. The TDI operating regime for N detectors
1. scanning direction, 2. the line of N detectors, 3. exit
PP--preamplifier; LK--delay line

The shortcoming of this system is that it uses a large number of electronic elements (PP, LK) and therefore, complicates signal processing and the device's design. This shortcoming has been successfully obviated by SPRITE detectors [13]-[15] which operate the same as a detector line in the TDI operating regime, but have only three leads and one preamplifier, since integration is performed in the element itself.

The design of SPRITE detectors is shown in illustration 7. The proper selection of the materials' parameters, the bias's voltage, V_{BB}, and the rate of the image's elements' scanning, V_s, make integration possible. The SPRITE detector has been developed as a photoconductive band of the HgCdTe n-type. Its dimensions are 1 min long, 50 μm wide and 10 μm thick. The principle of this sensor's operation is as follows: when part of the detector is illuminated by an element of the image, then electrification carriers are generated. Under the influence of the electrical field, which exists in the element because of the application of polarization, these carriers move toward the read-out region. The speed of the carrier's motion is equal to the ambipolar drift-speed, V_a, which depends on the materials' transport characteristics and the bias voltage used. Since, during scanning, the image's element is moved along the photcconducting band at a speed of V_s, it can then be stated that at the moment of the appearance of the image's element and the generation of new carriers in that spot, the carriers generated earlier arrive. Both the integration effect and the accumulation of electrification carriers are ensured by this. In order for this process to be efficient, one must be sure that $v_s = v_a$ and that the integration period is determined, above all, by the period of flight of the image's element through the detector (L/v_s). This means that the carrier's life span must be greater or at least comparable to the period of the flight of the image's element through the detector ($\gamma \geqslant Lv_s$). The advantage of the SPRITE concept lies in the fact that it allows a reverse combination between the scanner's feed and that of the detector, and therefore, the achievement of the automatic compensation of all the variations in the number of the scanner's revolutions, by increasing or decreasing the voltage of the element's feed. If the ideal scanning conditions have been secured, then the SPRITE detector is equivalent to a line of $2v_s\ \tau/w$ photoconducting detectors operating in the TDI regime.

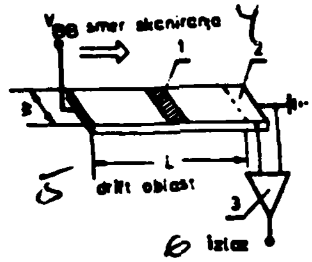

Illustration 7. The design of a SPRITE detector
1. the image's element, 2. the signal separation region, 3. preamplifier, 4. scanning direction, 5. drift region, 6. exit

The shortcoming of this detector is that the detection ability depends on the backround rays, and that it is technologically difficult to produce. Until now an eight band sensor has been produced. It uses a HgCdTe alloy with 20 percent CdTe and 80 percent HgTe, which at 77 K has the following properties: a concentration of larger carriers of $n=5x10^{-14}$ cm^{-3}, a mobility of the smaller carriers of $\mu_h=480cm^2 V^{-1}s^{-1}$, and a carrier life span of $\tau=2$ s. The produced detectors had maximum detection ability on the wave length $\lambda_{max}=12$ μm and average detection ability of D^*_{bb} (500 K, 20kHz, 1)$=2x10^{11}$ cm $Hz^{1/2}W^{-1}$. The possibility of the operation of the SPRITE detector at 190 K (thermoelectric coolers) is being studied, during which the detector's sensitivity is within the 3-5 μm spectral range.

Thermal imaging systems with very good characteristics, which are compatible with the European TV system of 625 lines, have been achieved by using SPRITE detectors. The further development of these sensors will procede in the direction of increasing the number of elements, raising the yield and studying new materials, which can provide better characteristics and the simpler production of sensors.

IC Photosensitive Detector Matrices

Detector mosaics (detector matrices) with sufficient dimensions to ensure the formation of images without using mechanical scanning still have not been developed, but already developed, smaller dimensioned matrices can be used to simplify scanning and increase the sensitivity of the thermal imaging system. In illustration 8 the basic scanning methods, which facilitate the use of detector matrices, are presented. With the use of detector matrices, the entire thermal image or one of its parts can be analyzed, depending on the size of the detector matrix used. The possibility of using linear matrices is rather limited, while linear matrices in the TDI operating regime can have much broader application. Focal matrices have the greatest possibilities and will enjoy broad application.

Since there are a large number of detectors in a matrix, their use is not possible if the possibility of the electron scanning of the signal from the detector, along with the use of small number of generating lines, has not been realized. This problem is successfully obviated with the appearance of CCD circuits. The CCD circuit is based on a MOS structure, which allows the storing and maintenance of the electrification packet under the input contact. Moreover, linear electrification transfer is possible, which can be arranged to allow the reading of the infomation noted by the CCD element. It is also possible to build into the processing chip with CCD circuits other functions, so that the level of signal processing will be significantly increased in the processor. Such functions include: the possibility of achieving a TDI operating regime; saturation prevention (which is important for protection during strong illumination, which can occur during the course of the operation), the possibility of compensating for electrification losses in the circuits with long shift-registers, the possibility of compensating for surrounding radiation (by which better image contrast is achieved) and the possibility of compensating for the non uniformity of detectors' characteristics in the matrix. All these possibilities are the impetus for further work to develop CCD circuits. The greater the detector's thickness in the matrix, the greater is that of the CCD circuit in the processor, and hence the smaller the possibility is to build other functions into the processor.

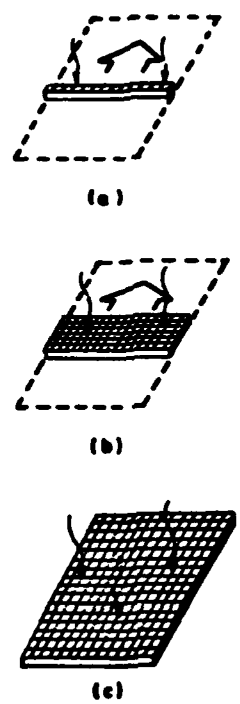

Illustration 8. Scanning methods during the use of detector matrices (a)--the detector line; (b)--the detector line in the TDI operating regime; (c)--the focal mosaic

1 Hibridna tehnologija sa sopstvenim poluprovodnicima	6 Monolitna tehnologija sa sopstvenim poluprovodnicima	11 Monolitna tehnologija sa primesnim silicijumom
2 — detektori na sopstvenim poluprovodnicima, vezani sa procesorskom pločicom preko sredine koja može da prenese naelektrisanje 3 — moguća je nezavisna optimizacija detektorske matrice i procesora 4 — koristi već razvijenu tehnologiju integrisanih kola na silicijumu 5 — koriste se različiti materijali, što može dovesti do teškoća zbog nesaglasnosti termičkih koeficijenata širenja	7 — koristi se isti materijal 8 — smanjuje se broj koraka tokom proizvodnje senzora 9 — zahteva da se razvija tehnologija integrisanih kola za nove materijale 10 — najmanje razvijena tehnologija proizvodnje	12 — koristi se isti materijal, ali je neophodna višeslojna struktura 13 — zahteva vrlo niske radne temperature 14 — koristi već razvijenu tehnologiju integrisanih kola na silicijumu

Table 1. Some characteristics of the technology for mosaic focal sensors

1. Hybrid technology with its own semiconductors; 2. detectors on their own semiconductors, connected with a processor chip by a medium which can transmit electrification; 3. the independent optimization of detector matrices and processors is possible; 4. the use of the technology of integrated circuits already developed on silicon; 6. Monolithic technology with its own semiconductors; 7. the same material is used; 8. the number of steps during sensor production is decreased; 9. this demands that the technology of integrated circuits be developed for new materials; 10. the least developed production technology; 11. Monolithic technology with silicon mixtures; 12. the same material is used, but a multilayered structure is necessary; 13. this demands very low operating temperatures; 14. this uses the technology of integrated circuits already developed on silicon
5. Are used different materials and this can lead to the nonagreement of the thermal coefficients of expansion.

Contemporary LSI* technology of integrated circuits can be used for matrices with dimensions of 64x64. VLSI** technology, which has just been developed, can be used for matrices with dimensions of 256x256. For matrices with dimensions of 1024x1024 VLSI technology, which permits elements with micrometrical dimensions, can be used.

*LSI--an acronym for "large scale integration." This technology allows 500-5000 elements per one semiconductor chip.
**VLSI--an acronym for "very large scale integration." This technology allows over 5000 elements per one semiconducting chip.

The combining of detector matrices with the CCD processor can be achieved in two ways (Illustration 9): the detector matrix is of one material and the processor chip another (hybrid technology), and the detector matrix and the CCD processor work on the same material and on the same chip (monolithic technology). Some characteristics of these technologies are given in table 1, and the application possibilities on some various materials are given in table 2. For the use of hybrid technology, silicon is used for the processor chip, photovoltaic detectors are most suitable, since they have a large value for the product of ($R_0A>10^5\ \Omega cm^2$), because of a better compatibility with the highly resistant MOS as the entrance of the CCD circuit.

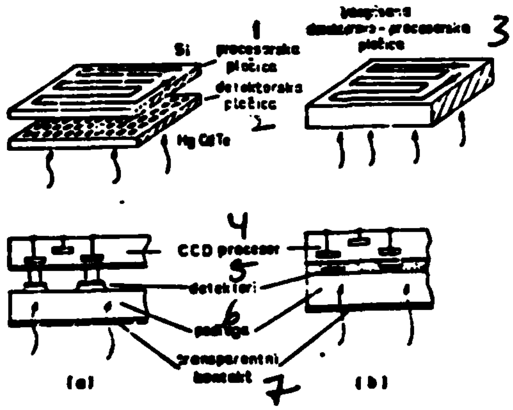

Illustration 9. The formation of focal mosaics
(a)--hybrid technology; (b)--monolithic technology
1. the processor chip, 2. the detector chip, 3. the integrated detector-processor chip, 4. the CCD processor, 5. detectors, 6. bases, 7. transparent contacts

tehnologija 1	spektralni opseg [μm] 4	3—5			8—14		14—22	komentar 6
	radna temperatura [K] 5	15	77	190	25	77	15	
	MATERIJAL							
monolitna 2	Si:As						•	Nije praktično za taktičke primene 7
monolitna 2	Si:In	•						
monolitna 2	Si:XX	•	•					
monolitna 2	InSb	•	•					ograničeno na kraće tal. dužine 8
monolitna 2	InAsSb	•	•	•				
monolitna 2	HgCdTe	•	•	•	•	•		moguća je najšira primena 9
hibridna 3	HgCdTe	•	•	•	•	•		
hibridna 3	InAsSb	•	•	•				ograničeno na kraće tal. dužine 10
hibridna 3	InSb	•	•					

Table 2. The application possibilities of some materials for focal detector matrices

1. technology, 2. monolithic, 3. hybrid, 4. spectral range, 5. working temperature, 6. commentary, 7. It is not practical for tactical uses, 8. limited to shorter wave lengths, 9. the widest application is possible, 10. limited to shorter wave lengths

Pyroelectric Detectors and Detector Matrices

Pyroelectrical material absorbs IC rays, which lead to a change in temperature, owing to which appears the current of the dielectrical shift proportional to the time change of the absorbed energy. The material from which this type of detector is made must have the following properties [20]: a large pyroelectrical coefficient, great resistance, a small dielectrical constant and a small thermal conductivity coefficient. Today, a large number of pyroelectrical materials are being tested, but the best results achieved in [20]-[22] are: TGS (triglycerin sulfate), $LiTaO_3$ (lithium tantalate) and $LiNbO_3$ (lithium niobate).

Pyroelectric detectors have better sensitivity and stability than bolometers and are faster than thermal vapor and Golay cells [22]. They have a high detection ability (10^8-10^9 cm $Hz^{1/2}$ w^{-1}) [20], [22] and are less inert, but they are sensitive in a very broad diapason of wave lengths (from UV to the far IC region). Single element detectors, built into a thermal imaging system, allow a temperature resolution of 1-3 K, and lines of 128 elements of TGS, which are combined with CCD circuits, allow a temperature resolution of .3 K [23], while the matrices 10^4 elements will allow a temperature resolution of .2 K [20].

The most efficient reading of signals with matrices of pyroelectric detectors is achieved by connecting to the CCD processor, which means that it is necessary to use hybrid technology, for which the combination's efficiency depends much on the characteristics of the CCD circuit and the manner of connection [19], [23]. Large practical problems await the production of matrices with a large number of detectors, especially because of the incompatibility of the thermal expansion coefficients. Their solution cannot be presently anticipated, although great efforts are being made to obviate them.

Because they operate at room temperature, pyroelectric matrices will enjoy great perspective application possibilities in high performance thermal imaging systems, but first the technological problems of the production of matrices with a large number of elements must be solved.

Conclusion

If the application of individual sensors is analyzed from the aspect of improving the characteristics and easy applicability of a system, it is difficult and almost impossible to make a definitive choice of the most suitable sensor, because each of them has its own advantages and shortcomings. The use of single element detectors, SPRITE detectors, linear detectors and detector matrices with small dimensions has been developed and yields good resuts. But thermal imaging systems in which they are used have drawbacks, because they contain complex scanning systems and use coolers, which hinder use. Detector matrices (focal mozaics) still cannot be practically used, because their technological development has not been totally worked out. However, it is assumed that the technological problems are solvable. The drawback of focal mosaics is that it is difficult to distinguish what emanates from the signal and what from the matrix's eventual damaging.

It is still not possible to totally define and predict the development of sensors which work at room temperature (pyroelectric matrices), but they will be used in thermal imaging systems for tactical and strategic purposes, because the possible solutions to the technological problems of the production of matrices with large dimensions, which are necessary in this case, are not predictable.

New materials and new technology will provide sensors with better characteristics and a greater number of elements in the matrix, as well as allowing the use of more efficient electronic systems for reading the signals from the elements of the matrix and signal processing system.

The system's philosophy and the basic technical problems for all existing and future thermal imaging systems are similar and all technical problems, in theory, are solvable. The basic factor which is directing the development of a concrete thermal imaging system is the sensor, which is attainable at the moment of desiging and production, because it limits and directs the designer in his choice of scanning methods, electronic signal processing and manner of presenting the image.

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