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Recent developments in low temperature infrared detectors

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Abstract : this paper indicates the state of progress of advanced infrared detection arrays in the world. This presentation is focused on high-performance cooled detectors i.e. CdHgTe photovoltaic arrays (which are more particularly emphasized), InSb detectors, PtSi Schottky barrier diode arrays, extrinsic silicon photoconductors and III-V multi-quantum well detectors. It is shown that interest may be focused on parameters other than the intrinsic detector performance alone. Future trends concerning the technologies are briefly presented. A more detailed description of the CEA-LETI-Laboratoire Infrarouge (LIR) and SOFRADIR technology is given.

1. INTRODUCTION

Over the last twenty years, a great deal of activity has been devoted to study and fabrication of "second generation" infrared detectors. Today, the trends are towards detector developments which are sometimes contradictory, as the demand is focused simultaneously on :

- high performances (detectivity or NEDT) which generally require cooling systems,
- achievement of television-like formats,
- integrated signal processing (smart sensors),
- if possible, reduced cooling requirements,
- low-cost manufacturing which implies compatibility with silicon integrated technology.

The progress which has been observed since the seventies on semiconductor materials used for detection and on integrated circuit technologies enables this multi-target objective to be achieved. The new detectors are characterized by their high level of integration ; they are either monolithic (PtSi) or hybrid (the others).

This paper is focused on recent developments on high-performance cooled detectors and gives some prospects for each of them. The technology developed and industrialized in France (LIR and SOFRADIR) is more particularly described.

2. TECHNOLOGICAL APPROACHES

2.1. Monolithic structure

In monolithic infrared detectors, the detection sub-module is directly implemented on its readout and multiplexing circuit. Because of the required compatibility between these two elements, monolithic infrared

detectors can be envisaged only on silicon wafers. When this compatibility is fulfilled, it obviously represents the major advantage of this structure. Today, the only detectors built-up with such a structure and being operational are PtSi/Si Schottky barrier diode arrays (see chapter 5).

2.2. Hybrid structure

Hybrid devices comprise two separate circuits (i. e. a detection circuit and a readout circuit generally manufactured on silicon) which are electrically and mechanically interconnected. Two main techniques enable these detectors to be built-up in this way :

- the indium bump technique which is widely used all over the world (Figure 1),
- the loop-hole technology mainly used by Texas Instruments (United States) and GMIRL (Great Britain).

Both these technologies present many advantages, among which :

- separate optimization and manufacturing of detection and readout circuits,
- possible assembly of circuits from various foundries provided they are prepared for this operation,
- backside illumination.

Figure 1 : schematic view of a hybrid infrared detector

In the recent past, the geometrical limitations (increase of format and reduction of pixel size) were real problems but, at present, technological improvements have been made and enable television-like formats to be achieved.

3. CdHgTe DETECTORS

Due to its remarkable basic properties, CdHgTe (cadmium and mercury telluride) is the most studied material in the field of infrared detection. The cadmium composition governs the bandgap width and therefore the cut-off wavelength of the detectors made with this material. Furthermore, CdHgTe presents a very high optical absorption coefficient and a low thermal generation rate, so that a 77 K operating temperature is commonly used for both the 3-5 μm and 8-10 μm spectral bands and up to 200 K can even be envisaged for 3-5 μm applications.

Due to the confidential nature of most of the applications (military programmes), it is difficult to know the state of the technologies precisely, but the main published achievements are given hereafter.

3.1. 3-5 μm band, 77 K operation

In this range, two-dimensional arrays which are generally hybrid and backside illuminated detectors can be found.

Table 1 : state of the art in the 3-5 μm CdHgTe range

Countries	Companies	Detectors
United States	Rockwell	640 x 480 elements
	Hughes/SBRC	256 x 256 elements
	Fermionics	128 x 128 elements
	Texas Instruments	128 x 128 elements
Great Britain	GMIRL	128 x 128 elements
France	CEA/LETI/LIR	128 x 128 elements
	and SOFRADIR	256 x 256 under way

It is reasonable to think that television-like products will be soon on the market with a cost compatible with military applications.

3.2. 8-12 μm band, 77 K operation

In this range, because of the electrochemical sensitivity of the CdHgTe material, many more technological difficulties arise and we therefore mainly find linear arrays which are designed for scanned imaging systems. These detectors are hybrid and backside or frontside (indirect hybridization) illuminated. The existing two-dimensional arrays present formats limited to 128 x 128 elements.

Table 2 : state of the art of 8-12 μm CdHgTe products

Countries	Companies	Detectors
United States	Rockwell	480 x 4 elements
	Hughes/SBRC	
	Amber, Loral, etc.	64 x 64 elements 128 x 128 elements
	Texas Instruments	
	Fermionics	
Germany	AEG	288 x 4 elements
France	SOFRADIR	288 x 4 elements
		480 x 4 elements
		64 x 64 elements

Advanced prototypes of 960 x 4 elements are not mentioned in this table because they are not for sale. However, they were presented in 1992 by Hughes/SBRC and LIR/SOFRADIR, which reveals the maturity of the technologies for both these manufacturers.

In fact, the international situation is very complex because of the variety of potential manufacturers particularly in the United States, but only a few of them are able to propose products for sale and in this context, the French industry (SOFRADIR) is presently in the best position.

3.3. The LIR and SOFRADIR technology

The basic technology which was developed at LIR in the eighties and transferred to SOFRADIR for industrialization is the so-called IRCCD technology. This is a hybrid technology as shown in Figure 1 and presented in more detail hereafter.

3.3.1. CdHgTe material

For infrared applications, a reduced number of defects, appropriate doping level and good uniformity of composition of the material are required. For these purposes, liquid phase epitaxy (LPE) growth of CdHgTe on CdZnTe substrates was chosen. Vapour phase techniques are still in progress because they

seem to be the way forward for future developments. Recent results are very promising, but these techniques are not yet ready for integration in an industrial process.

3.3.2. *CdHgTe photodiode technology*

The photovoltaic detectors are achieved by a planar process on p-type material, the n region being formed by ion implantation (this method requires only low heating treatments). The technological process for junction formation, interfaces, insulators and achievement of electrical contacts is very well mastered and leads to high yield for production of high-performance detectors.

A new n-on-p planar process for photodiode fabrication is being studied at LIR. It gives dark current values which are close to the theoretical limits and comparable to data published in the United States for p-on-n heterojunctions. This remarkable result remains to be mastered before the process is transferred to SOFRADIR for industrialization.

3.3.3. *Hybridization*

At the beginning of the eighties, the choice was made in France to use the indium bump technique which enables high-performance CdHgTe photodiode arrays to be combined with various silicon readout circuits (CCD or CMOS or possibly others). This technique has been thoroughly studied and high-precision automated machines developed leading to excellent fabrication yields close to 100 %.

3.3.4. *Readout and multiplexing circuits*

As previously mentioned, the readout and multiplexing silicon circuits can be provided by various foundries, but the French manufacturer for specific applications i.e. Thomson-TCS, the production lines of which being qualified for low temperature operating conditions, is generally used.

3.4. SOFRADIR products

3.4.1. *3-5 μm applications*

Today, the basic products are the 128×128 element IRCCD arrays. The development of 256×256 element arrays is under way at LIR and SOFRADIR and should be ready for production in 1995.

3.4.2. *8-12 μm applications*

The main available products are 288×4 linear arrays operating in a Time & Delay Integration (TDI) mode (typical detectivity = $2.10^{11} \text{ cm.Hz}^{1/2}.\text{W}^{-1}$). These detectors have been sold in many countries for evaluation and successfully tested in military environmental conditions. As a matter of fact, they are now in production for larger quantities in order to be integrated in American systems. This shows the maturity of this technology which is available in France and not yet in the United States. The more recently developed 480×4 products (see Figure 2) are now also available with typical performances similar to those of the 288×4 .

Figure 2 : SOFRADIR 480×4 element linear array (8-12 μm)

4. InSb DETECTORS

The InSb material is particularly well suited for infrared detection in the 3-5 μm spectral range as its bandgap width is 225 meV at 80 K, which corresponds to a 5.5 μm cut-off wavelength.

This material is very well mastered on large surfaces (typically 2") and the photodiode technology processed on it is mature enough to lead to manufacture of large format arrays in the United States.

Table 3 : state of the art of InSb infrared detectors

Countries	Companies	Detectors
United States	Amber Hughes/SBRC	512 x 512 elements

If we compare InSb to CdHgTe, it appears as a very strong competitor for 3-5 μm applications at 77 K, but the fact that it does not cover the 8-12 μm spectral range proves to be a major drawback for industrialization (necessity of several production lines to cover all the fields of application). On the other hand, this type of detector cannot accept to work at a higher temperature.

5. PtSi SCHOTTKY BARRIER DIODE ARRAYS

PtSi Schottky barrier detectors operate at 77 K. The major advantage of this technology is the full compatibility with silicon VLSI technology enabling large format arrays to be manufactured (television-like formats are already obtained) with low defect counts, high yields and relatively low fabrication costs.

The following table shows the diversity of potential manufacturers, especially in the United States.

Table 4 : state of the art in the PtSi Schottky detector field

Countries	Companies	Detectors
United States	David Sarnoff Lab	512 x 512 elements
	Ford Aerospace Fairchild, Kodak Hughes, etc.	or 480 x 640 elements
Japan	Mitsubishi	1040 x 1040 elements

Up to recently, these detectors were considered as being very promising, but their admitted drawbacks (low quantum efficiency, limited spectral response, cooling necessity, low frame rate) prove to be drastically limiting for advanced systems, which has now reduced interest in them.

6. EXTRINSIC SILICON PHOTOCONDUCTORS

Extrinsic silicon detectors operate at very low temperature. They cover a large spectral range depending on the doping impurity utilized. These detectors are suited to operation in low background environments where very high performances are required (scientific or specific applications).

The devices presented in table 5 have all been achieved for astrophysics. Most of them are gallium doped silicon photoconductors (cut-off wavelength = 17 μm), operating at very low temperature (down to 4 K) and read by Direct Voltage Readout (DVR) silicon circuits.

The BIB technology is a variant of the extrinsic technology mainly developed in the United States, using the properties of very highly doped silicon (As doped Si). In Europe, this technology has been approached but remains less well mastered.

Table 5 : state of the art of extrinsic silicon detectors

Countries	Companies	Detectors
United States	Hughes/SBRC	} 58 x 62 elements
	Rockwell	
	Amber	128 x 128 elements
	Rockwell	256 x 256 (BIB)
France	CEA/LETI/LIR	32 x 32 (ISO)
		64 x 64 (OBSOL)

Manufacturing of 128 x 192 element gallium doped silicon photodetectors is currently under way at CEA/LETI/LIR. This development will be brought out within the next few months.

7. III-V MULTI-QUANTUM WELL DETECTORS

The concept of infrared detection by inter-sub-band absorption in III-V superlattices was reported at the beginning of the eighties and extensive research work is being carried out on this type of detectors.

The main advantage in multi-quantum well detector development is ease of fabrication, as vapour phase deposition techniques of GaAl/GaAs structures are quite mature and sensor development can benefit from a proven GaAs integrated technology. The potential ability of these detectors to control the detection wavelength electrically is very attractive but remains to be proven.

Among the admitted drawbacks, the low operation temperature required (< 60 K) drastically limits the scope of medium-term applications in the 8-12 μm spectral range. We may foresee that these detectors will be used only for specific applications (niches).

Table 6 : state of the art in the field of III-V multi-quantum well detectors

Countries	Companies	Detectors
United States	Bell Laboratories	256 x 256 elements
Sweden	IMC	128 x 128 elements
France	Thomson/LCR	128 x 128 elements

8. CONCLUSION

Different families of infrared detectors have been dealt with. In conclusion, if we try to compare them, at least three parameters which seem to be essential are to be considered : electro-optical performances, operating temperatures and maturity of the technologies. With such criteria, CdHgTe detectors which are high-performance, well mastered up to production, and cover both the 3-5 and 8-12 μm spectral ranges (with $T \geq 77$ K), will probably remain in a leading position for all "second generation" applications.

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