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Infrared detectors: outlook and means

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Abstract. New materials and technologies for large scale IR arrays, readouts for them and several principal trends of IR large scale array detectors development as well as their applications in different weather conditions are briefly discussed. Uncooled arrays should be much more widespread both for civilian and military applications. Another trend is previewed in enhanced capability readouts. For military and space applications, e.g., for satellites observation, surveillance and reconnaissance in near future high performance mercury-cadmium-telluride (MCT) based detectors hardly can be replaced for two main atmospheric transparency regions, 3 to 5 and 8 to 14 microns. Because of similarity of technological operations MCT large scale arrays for 1 to 3 microns applications can become even more preferable compared to III-V detectors.

Keywords: infrared technologies, focal plane arrays, mercury-cadmium-telluride detectors, read-outs.

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1. Introduction

The characteristic feature of the scientific-technical progress up to date is that the technical potential of the developed countries is characterized by the scientific-research sphere of activity, which is defined by close connections of scientific-technological investigations and elaboration for military, scientific and civilian purposes, which is frequently called «dual technology applications». To technologies of dual applications belong and infrared (IR) microphotoelectronic technologies which drive at the moment to a large degree a scientific-technological potential of developed countries.

One should point out the growing utilization in the latest time of IR technologies of «dual applications» in civilian sphere at the expense of new materials and technologies, and also due to noticeable price decrease of these high cost technologies. Demands to the use of these technologies are quickly growing which are due to their effective applications, e.g., in global monitoring of environmental pollution and climate changes, longtime prognoses of agriculture crop yield, chemical process monitoring, Fourier transform IR spectroscopy, IR astronomy, car driving, etc. IR imaging in medical diagnostics is another important example of IR technologies (see, e.g., [1,2]). The combination of high sensitivity and passive operation of IR systems is also leading to many commercial uses.

Satisfaction of these, and especially, military demands, is based now on utilization, in the first place, large scale arrays for different spectral ranges. These detectors can not operate without different type signal processing electronics (readout devices) in the focal plane to provide charge-to-voltage conversion, integration, amplification, multiplexing, etc.

Traditionally, IR technologies were connected with controlling functions and night vision problems with earlier applications connected simply with detection of IR radiation, and later by forming IR images from temperature and emissivity differences. And up to now majority of developments in this direction are concentrated on military systems. For example, one can mention systems for recognition and surveillance, tank IR sight systems, anti-tank missiles, air-air missiles, etc.

Nowadays, along with other technical advances, IR technologies are fast progressing, in spite of the fact that they are high cost technologies as yet, and even for many military and most of civilian applications the high cost, weight and size of previous generation systems have limited their deployment.

IR technologies belong to the so-called «high level technologies» and can be initiated successfully only in highly developed countries as they need for their design and production several important conditions: presence of highly qualified specialists in various spheres, developed scientific and industrial base, education system, and some others.

2. Short history and remarks

Observing a history of the development of the IR detector technology, and taking into account that a high percentage of condensed matter effects fall in the range of about 0.1÷1 eV and even lower energies, a simple theorem can be stated [3]: «All physical phenomena in the range of about 0.1÷1 eV can be proposed for IR detector».

Among these effects are: thermoelectric power (thermocouples), gas expansion (Golay cells), pyroelectricity (pyroelectric detectors), photon drag effect (e.g., low temperature long wavelength InSb free carriers detectors), Josephson effect (Josephson junctions, SQUIDs), internal emission (PtSi Schottky barrier detectors) fundamental absorption (intrinsic photodetectors), impurity absorption (extrinsic photodetectors), electron confinement (superlattice (SL) and quantum well (QW) detectors), different type of phase transitions, etc.

Data given in Fig.1 show the approximate chronology of the most widespread semiconductor detectors. In Fig. 1 shown are the detectors for three main atmospheric transparency windows: 1.5 to 2.5 microns (short wavelength IR (SWIR)), 3 to 5 microns (medium wavelength IR (MWIR)), and 8 to 14 microns (long wavelength IR (LWIR)), which are the most actual from the standpoint of both civilian and military applications: reconnaissance, recognition and surveillance, space applications, communications, agriculture monitoring, meteorological studies, astronomy applications, tank IR sight systems, target recognition, etc. For a lot of IR imaging applications the last two spectral bands are of primary importance, since the atmospheric transmission is highest in these bands and the emissivity maximum of the objects at T=300 K is at wavelength $\lambda \approx$ 10 micron.

However 3 to 5 and 8 to 14 microns spectral bands differ substantially with respect to background flux, scene characteristics, temperature contrast, atmospheric transmission under diverse weather conditions, and some other parameters. An ideal IR system require dual spectral band operation, as it allows, to discriminate the targets, measure temperature of the objects, etc. Factors which favor MWIR applications are higher contrast obtainability, superior clear weather performance (favorable weather conditions, e.g., in most countries of Asia and Africa), higher transmittivity in high humidity, higher resolution due to smaller optical diffraction. For example, at 4 micron wavelength a diffraction limited optical spot (Airy disk) is about 10 microns for f/1 optics and 3 times larger for 12 microns spectral band.

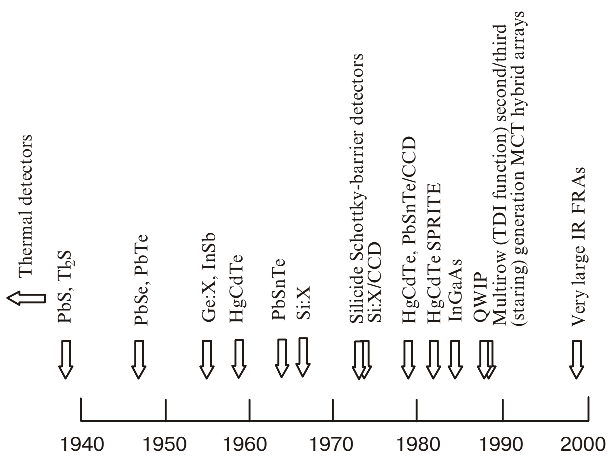

Fig. 1. Development of semiconductor IR detectors. Here «x» denotes dopants in Ge and Si: Hg, In, As, Ga, Sb,...

Factors which favor LWIR applications are better performance in fog and dust conditions, winter haze (typical weather conditions, e.g., in West Europe, North USA, Canada), higher immunity to atmospheric instabilities, reduced sensitivity to solar glints, fire flares, and some others. Possibility to get higher signal-to-noise ratio due to greater radiance levels is not persuasive because of the background photon fluxes are higher the same, and also because of readout limitation possibilities. In this spectral band the temperature contrast resolved is lower than for 3 to 5 microns spectral band but it is similar for day and night time conditions. And for 8 to 14 microns spectral band, the temperature of the targets to be detected and observed is sufficiently lower compared to 3 to 5 microns region, and in the last case difference in target/background metrics can be substantial.

3. Infrared detectors

IR detectors convert IR photons to electrical signals. IR applications require a wide range of specific types of IR detectors in order to meet system needs. And totally there were proposed a lot of solutions for IR detectors.

However, two families of, first of all, multielement detectors now can be considered for principal military and civilian IR applications to meet the present-day and near future system needs: one used for scanning systems and the other one used for staring systems.

The simplest scanning linear focal plane array (FPA) consists of a row of detectors (Fig. 2a). An image is generated by scanning the scene across the strip using, as a rule, a mechanical scanner. And at standard video frame rates, at each pixel (detector) a short integration time has applied and the total charge is accommodated.

A staring array is a two-dimensional array of detector pixels (Fig. 2b) which are scanned electronically. These types of arrays can provide enhanced sensitivity and gain in camera weight. Theoretically, in these arrays, charge can be integrated for the full frame time, but because of restrictions of charge-handling capacity of the read-out cells, it is much less compared to the frame time, especially for long wavelength IR (LWIR) detectors for which background photons flux exceed the useful signals by orders.

The scanning system which does not include multiplexing function in the focal plane belongs to so-called first generation scanning systems. The typical example of this kind of detectors are linear photoconductive arrays (PbS, PbSe, HgCdTe, etc.) with preamplifiers in each channel, as a rule, out of the cooling zone (or multiplexer out of

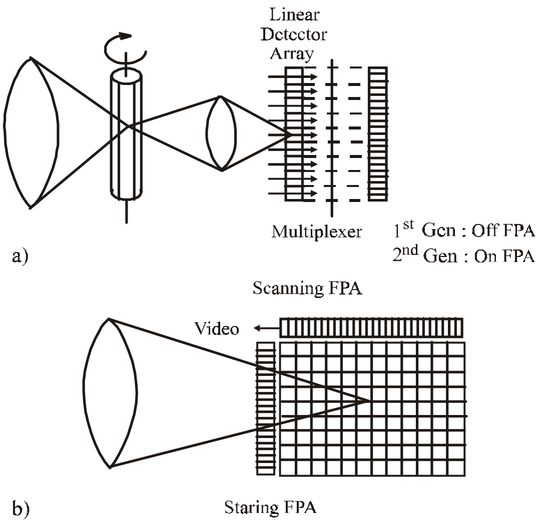

Fig. 2. Scanning focal plane array (a) and starting focal plane array (b).

the FPA plane). These kinds of detectors are still widely used (e.g., tank sight systems, missile seekers, etc.).

When multiplexed (readout electronics) scanned photodetector linear array with, as a rule, time delay and integration (TDI) function in use, the system belongs to the so-called second generation system. The typical examples of the second generation arrays are SOFRADIR MCT multilinear 288×4 array both for 3 to 5 and 8 to 10.5 micron bands [4,5] with signal processing in the focal plane (photocurrent integration, skimming, partitioning, time delay and integration (TDI) function, output preamplification and some others).

And the third generation system includes multiplexed staring arrays. Based on second generation IR detectors, staring systems are developed now with high rate both for 3 to 5 and 8 to 12 micron spectral region, and include, e.g., pixel deselection, antiblooming on each pixel, subframe imaging, output preamplification, and some other functions.

In order that IR technologies become a widespread reality, taking into account cost, weight and size of such systems, the key questions are connected with high performance IR cameras supplied with large scale detector arrays and operating at temperatures which are compatible with long life low cost coolers, or, better, without any cooler. Not all IR detectors are good candidates for large scale arrays, which for these aims should operate with low power readouts. And only detectors with high impedance can be used in such kind of arrays. Such requirements restrict to rather narrow circle of possible detectors.

Today, it seems, one can select only several principal trends of IR large scale array detectors development. Among them mercury-cadmium-telluride (MCT) based arrays for MWIR and LWIR applications both military and civilian, uncooled integrated thermal imaging sensors for LWIR mainly civilian application (e.g., helmet mounted fire-fighter's imaging cameras, car driving aids), and for some type of military ones (personal surveillance sensors, airborne driving aids, weapon sighting systems, etc.), photovoltaic Schottky barrier detectors, and for some special applications, perhaps the quantum well infrared photodetector (QWIP) arrays (see, e.g., Refs [6,7]). For LWIR applications, especially at low background flux conditions, the most popular photoconductive material system is doped extrinsic silicon (the most advanced among them are Si:As and Si:Ga). These detectors still require serious cooling conditions (about 20 to 30 K, see, e.g., [8]). As to SWIR detectors, which can find two main types of applications, namely: space applications with earth observation and advanced optical communications, there can be used some quaternary III-V alloys, but because of some mismatch-induced defects these are ranged now in 1.8 micron cut-off wavelength region. For instance, InGaAs exhibits high performance for material with composition matched to InP substrate (cut-off wavelength is close to 1.7 μm) but its performance decreased substantially for longer wavelength region [9,10].

Now the time of rebirth of uncooled sensor technology seems to have come. It has accelerated rapidly in the past decade. The new features which favor the interest of this type detectors rebirth are connected with higher performance, electronics integration, and enhanced signal processing which generates new application areas. New characteristics of uncooled arrays are based, first of all, on novel levels of electronic technology applied to their fabrication. But because of thermal character of their performance, even the smallest size detectors, can not overcome rather moderate detectivity level, which is still, at least, an order lower compared to cooled detectors for the same spectral band (as a rule, 8 to 14 μm). Also, these detectors are rather «slow» (time constant, as a rule, is about 10-100 ms). However, new phase of uncooled detectors is characterized by new ideas and possibilities for thermal detector arrays operating near the theoretical limit (see, e.g., [11,12]).

The technology advances in uncooled IR arrays have generated a number of new applications. Some previously seen areas only for cooled arrays now are being considered for uncooled detector arrays, too. Among new applications there are, e.g., helmet mounted sensors, sensors for robotics, driver's thermal imaging viewers, etc.

Rather large number of materials are good candidates for fabricating uncooled FPAs. But regardless of the material type, the integration of new material should require the following issues [11]: compatibility with standard silicon processing, low one-over f (1/f) noise, thin film deposition technology with minimum stress, stability of operating point, uniform large area deposition, low power bias.

There are a lot of different phenomena and materials proposed mainly in last decade for uncooled arrays: thermoresistance, thermoelectric power, pyroelectricity and ferroelectricity, electronic stress in metal-semiconductor interface, etc.

The thermal detectors class includes thermistor bolometers, pyroelectric and ferroelectric detectors, thermopiles, and microcantilever sensors.

One of the commonly used materials is vanadium dioxide, which has of 2-3% responsivity change in resistance with temperature (operation at phase transition point), ferroelectric ceramics (with transitions from ferroelectric to paraelectric close to ambient temperature), metallic films, amorphous silicon, barium strontium titanate, lead scandium titanate, lead scandium tantalate.

But if the cooling system is a drawback for cooled arrays, for uncooled arrays severe demands are temperature stabilization requirements (see, e.g., [13]), which increases the complexity and power dissipation of an uncooled systems. Since uncooled imaging efforts are to produce compact, low cost systems, temperature stabilization problem will eventually become the important one.

For military and space applications, e.g., for satellites observation, surveillance and reconnaissance in near future, high performance MCT based detectors hardly can be replaced for two main atmospheric transparency regions, 3 to 5 and 8 to 14 microns. Because of similarity of technological operations, MCT large scale arrays for 1 to 3 microns applications can become even preferable compared to III-V detectors [14].

MCT semiconductor material is unique since, as a ternary compound, its composition can be tuned to detect IR emission over a range from 2 and 20 microns (chemical composition from $x \approx 0.52$ to $x \approx 0.19$). And for these detectors almost the same technologies are used without any duplication of used equipment. This material can be applied in both the photoconductive (PC) and photovoltaic (PV) modes to produce different kinds of detector arrays that satisfy a wide range of system requirements. Because $Hg_{1-x}Cd_xTe$ material is intrinsically doped, one of the main advantages of this material is its ability to operate at high temperatures with respect to other candidate materials and therefore to reduce the cooling constraints (size, cost, power consumption, etc.) [15].

Schottky-barrier emissive detectors are the most mature for large monolitic FPAs (see, e.g., [16]). For Schottky-barrier IR detectors there are five silicides known: platinum silicide (PtSi), iridium silicide (IrSi), nickel silicide (NiSi), palladium silicide (Pd_2Si), and cobalt silicide (Co_2Si). The important advantages of the Schottky barrier IR FPAs are monolitic construction with standard LSI processing and high uniformity of characteristics, high producibility that is limited only by SI readout circuits. The drawbacks which limit their wide applications are low quantum efficiency η (for PtSi $\eta < 0.1$ % at $\lambda > 4$ µm, the cutoff wavelength is at $\lambda \approx 5$ µm), and because of rather large internal photoemission dark currents these detectors require cooling below 77 K. These arrays can be produced in large formats [17].

Various type QWIP structures from chemically stable wide band-gap systems were proposed (see, e.g., [6,7]) as low-cost alternatives to MCT LWIR detectors. The most widely proposed is photoconductive GaAs/AlGaAs QWIP in which the detection of IR radiation is realized via intersubband or bound-to-extended state transitions within the multiple QW (MQW). Because of maturity of technology these detectors are promising due to high yield and uniformity of the pixel parameters. The wavelength of the peak response can be adjusted by changing both chemical composition and thickness of the wells. But there are several drawbacks in *n*-type GaAs/AlGaAs QWIPs which limit their applications: (i) due to polarization selection rules the electric field component of the electromagnetic wave should ensured along the MQW axis and special technological operations are necessary to do that; (ii) the QWIP detector spectral response is narrow band ($\Delta l/l$ is, as a rule, less than 20%); low quantum efficiency (less as a rule than 10%); the performance of QWIP is principally inferior to those of HgCdTe or related photodetectors at $T \geq 40$ K within the same spectral band because of similarity nature of absorption to extrinsic detector.

4. Signal processing (read-out) electronics

IR FPA sizes have consistently increased due to advances in detector and complementary metal-oxide-semiconductor (CMOS) multiplexer technologies, as well as hybridization and packaging technologies. Charge coupled devices (CCD) technology is used now for not very large scale arrays [18,19], and their technology is more complicated compared to the CMOS technology production line. For all second and third generations arrays the signal processing electronics is an integral part of the sensor design. For uncooled FPAs, signal processing electronics plays even more critical part in sensor performance compared to cryogenically cooled FPAs.

Up to date high performance IR imaging basically include focal plane arrays (FPAs) with multielement scanning linear (or multilinear) and staring two-dimensional matrix of PV detectors cooled down to cryogenic temperatures with a signal processor in the focal plane (see Fig. 3). The FPA technologies mainly include two major technologies, hybrid and monolithic. The concept of the IR FPA hybrid technology is widespread as permits to optimize separately parameters of detector array with a large number of sensitive elements and typically silicon readout device coupled with detector array [19]. The major hybrid technology uses MCT

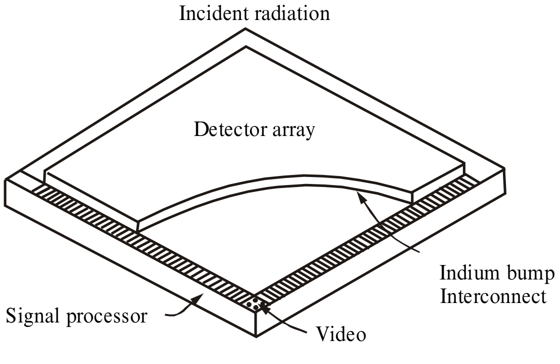

Fig. 3. Schematic illustration of starting array with signal processor in the focal plane.

PV detector chips and silicon CCD or CMOS chips for readout and multiplexing the sensed charge from the detectors; there are a lot of various design of interface but really it is source coupling or gate coupling [18, 20, 21]. Important thing is that the number of transistors per unit cell is between 2 and 7 in dependence on the circuit architecture, and most of these transistors perform analog functions compared to the functions in digital circuits in, e.g., CPU chips. That puts on much more severe requirements to the quality of read outs.

The performance requirements for IR FPAs are highly varied with respect to wavelength region, background photon flux, operating temperature, dynamic range, noise, readout rate, power dissipation, detector bias, and some other parameters. IR FPAs are mainly clustered in the atmospheric window wavelengths 1-2.5, 3-5, 8-12 μm and in dependence of the wavelength region applications are aimed at $T \approx$ 250-300, 77-150, 20-90 K operating temperatures, respectively.

The primary function of a read-out device for IR arrays is to provide an IR detector charge-to-voltage conversion, integration of the electrons generated in photodetector, permition to perform some preliminary treatment of the signals, e.g., skimming, partitioning, amplification and time multiplexing of signals from the detectors in the array [22], to much less number of outputs from, as a rule, cold zone. In the case of array used in scanning mode, TDI function should be included to improve the performance of the array. Present IR FPA for 8-12 μm spectral region due to large (at $T \geq 300$ K) background flux are facing the problem of large charge integration implying a large charge integration capacitor. Thus, the background signal suppression should be used and this function must be performed in a short time compared with a total integration time.

One of the principal problems limiting the performance of IR FPA deals with limited readout circuit charge handling capacity. To extend the application range of IR imagers to higher background fluxes, higher FPA operating temperatures, higher cut-off wavelengths (λ_{co}) the read-out integrated circuits (ROIC) should suppress large useless currents (dark or background) compared to scene photon currents. This situation limits sensitivity and thermal resolution and imposes large constraints on the detector ROICs in terms of dynamic range requirements.

To achieve the suppression of the useless currents prior to CMOS or CCD multiplexing, several possible solutions exist [23,24,25]. Among them are: reduction the incoming photon flux by narrowing spectral band and field of view (FOW) of the detector; reduction of integration time (at a price of lower signal-to-noise ratio); oversampling (multiple detector signal read-out during one sampling); design various circuits (subframe readout, DC level subtraction, antiblooming, charge partitioning, charge skimming, in-pixel current memory cell, which enables PV direct current suppression [25]), etc.

For operation, these circuits need the inverted bias to be applied to detector. Thus, all the time the diodes should be biased and one need to choose the proper point for better operation of the diode, namely, maximum impedance, which is at the maximum of differential resistance. Is this any difference for n^+-p- or p^+-n-type MCT diodes as it was earlier shown that at zero bias the R_0A-product is higher for second type diodes? The technology fabrication of the read-outs has some differences for these two cases because of need to use n- or p-channel MOS transistors. As one can see from calculations of the diode currents [26] (see Fig. 4) really at zero bias the R_0A-product can be much higher for p^+-n-diodes compared to n^+-p-diodes. But for reverse-bias operation (as a rule $V_{rb} \geq 30$ mV) the RA-product is the same for both types of the diodes because at these biases the trap-assisted (TAT) current via the deep states in the gap dominates in MCT diodes, and diffusion current, which is responsible for difference of the resistance at $U = 0$, is small at reverse bias.

5. Possible near-future trends

IR technologies still are high-cost technologies. Possible near-future trends of IR technologies development are connected with the pace of progress in three primary technologies [3]: (i) digital computing, both hardware and software, (ii) display formats (the question which was not discussed here), and (iii) communications bandwidth at which digital data can be communicated, as now best LWIR and MWIR arrays are almost background limited. Communication bandwidth is important for communication technologies in general, and communication bandwidth restrictions will be overcome to a large degree in the near future.

Digital computing limitations include processor throughput, memory size, and software complexity. For LWIR arrays they are connected with, e.g., with nonuniformity correc-

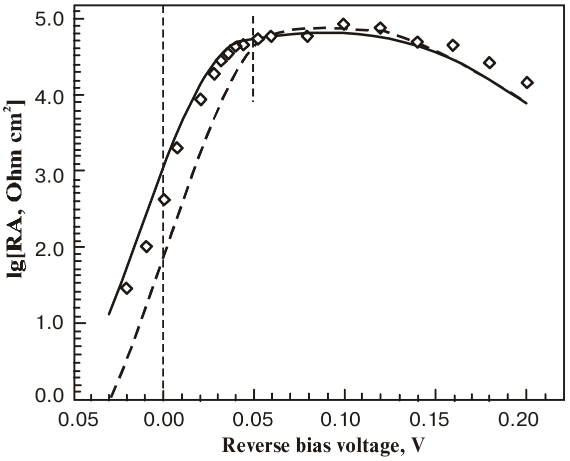

Fig. 4. The RA product for p^+-n-type $Hg_{1-x}Cd_xTe$ diode (x = 0,226, cutoff wavelength λ_{co} = 10 μm). Diamonds are experimental data [26]. Solid curve are calculations for p^+-n-type diode, and dashed line are calculations for n^+-p-type data [27].

tions on a pixel-by-pixel level, which are required especially for LWIR arrays because of the contrast is typically very low for 300 K background flux. As the nonuniformity corrections are performed, as a rule, in software level, it is the subject of digital memory, processor throughput, and software coding limitations.

In spite of the huge achievements in readout chip sizes and their preprocessor capabilities in the focal plane, they are now an order lower compared to memory chip sizes as the design rules for their design and production, as a rule, are one generation older. But it should be pointed out that most FPA transistors perform analog functions. In Fig. 5 [14] compared is the number of transistors in microprocessor and readout chips with pointed design rules. One should anticipate that in the near future more preprocessing functions will be brought into the focal plane readouts.

Best LWIR and MWIR detectors are almost now background limited and it is almost impossible to improve their sensitivities. But readouts in LWIR arrays can utilize now only about 1% of the available signal at f/1 optics and $T \approx 300$ K background, as compared to the background flux signal, as unit cell capacitors are filling up in about 20 to 50 μsec because of background signal influence, while the frame times are about 20 msec. What are supposed to happen is that readout capabilities will evolve to utilize much more value of the signal, thus improving LWIR FPA sensitivities.

But there are some other things which will restrict the IR FPA capabilities principally. For example, one can hardly imagine that IR wavelengths will change. This lead to very important consequences: pixel size can not be significantly reduced, unlike the size of DRAM memory cell, because of a diffraction-limited optical spot. For a typical f/2.0 lens at $\lambda \approx 10$ μm wavelength, the spot size is about 50 μm. Currently, some typical LWIR arrays of 288×4 or 128×128 and 256×256 formats have ≈ 25 μm pixel size. For MWIR and SWIR arrays there can be a reduction of the pixel sizes to about 20 to 10 μm.

Detectivity D* will not change, too, since statistical fluctuations in the background photon flux provides a fundamental limit to D*. Because MWIR and LWIR state of the art of cooled arrays are now almost background limited, again chip sizes need to grow for achieving better performances.

Summary

It is impossible to preview what will happen, e.g., in 50 years. But analyzing the state of the art situation one can suppose to look ahead of about 10 to 20 years. It seems that uncooled arrays should be much more widespread both for civilian and military applications. Another trend is previewed in enhanced capability readouts. The availability of readouts and assosiated with them signal processing hardware and software seem anticipated to appear in several years.

For two main atmospheric transparency regions, 3 to 5 and 8 to 14 microns, and, perhaps, for 1 to 3 microns region, MCT based FPAs in near future will be basic FPAs for military and space applications, as this type of FPA is the only one to have application in all wavelength regions using the same detector material type. After a long gap between first- and second-generation systems, military applications are again entering production [27].

Multicolor FPA, though for broad spectral coverage they need of use now different detector materials to complete multicolor FPA, should find, e.g., space application as they allow to measure the real temperature of the objects.

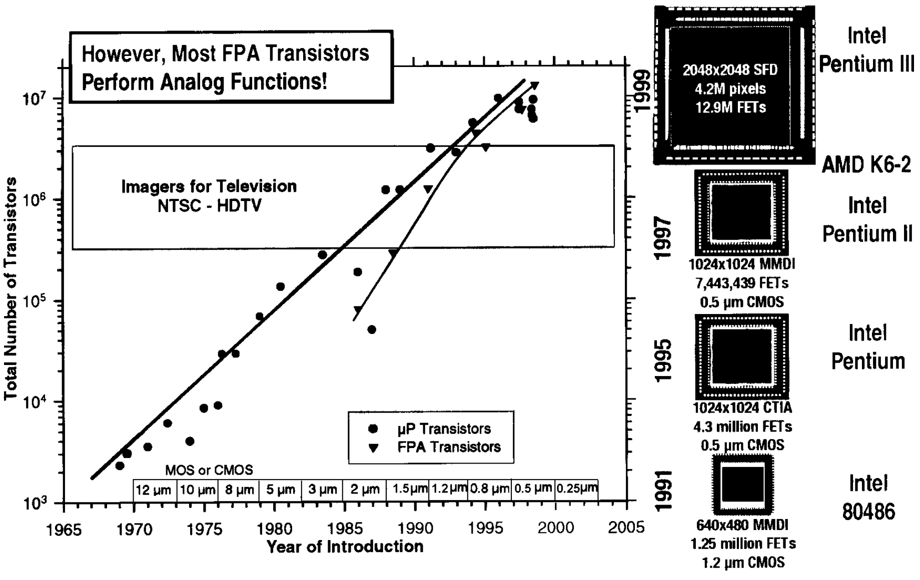

Fig. 5. Timeline for number of transistors in microprocessor and infrared multiplexor chips. The time design rules are shown at the bottom [14].

References

1. M. Anbar, Ch. A. Brown, L. Milescu, and J. A. Babalola, Clinical Applications of DAT using a QWIP camera // *Proceed. SPIE*, **3698**, pp. 93-102 (1999).
2. A. G. Hargroder, J. E. Davidson, D. G. Luther, and J. F. Head, Infrared imaging of burn wounds to determine burn depth // *Proceed. SPIE*, **3698**, pp. 103-108 (1999).
3. P. R. Norton, Infrared detectors in the next millennium // *Proc. SPIE*, **3698**, pp. 652-665 (1999).
4. Ph. Tribolet, Ph. Hirel, A. Lussereau, and M. Vuillermet, Main results of SOFRADIR IRFPAs including IRCCD and IRCMOS detectors // *Proceed. SPIE*, **2552,** pp. 369-380 (1996).
5. P. Potet, Design of thermal imaging systems with MCT-IRFPA. Design rules and performances. Application to Peltier cooled IRFPA camera, // *Proceed. SPIE*, **2552**, pp.815-821 (1994).
6. F. Sizov, Semiconductor superlattice and quantum well detectors, in: *Infrared photon detectors*, Ed. A. Rogalski, SPIE Optical Engineering Press, Bellingham-Washington, 1995 pp. 561-624.
7. K. K. Choi, *The Physics of Quantum Well Infrared Photodetectors*, World Scientific, New Jersey, 1997.
8. S. Solomon, A. Tribble, N. Lum, J. Venzon, G. Domingo, A. Hoffman, and M. Smith, High background, longwave Si:As IBC 320×240 IR focal plane array // *Proceed. SPIE*, **2816**, pp.161-168 (1994).
9. D.-S. Kim, S. R. Forrest, M. J. Lange, G. H. Olsen, and W. F. Kosonocky, A monolitically integrated InGaAs-InP p-i-n/JFET focal plane array // *IEEE Photonics Technology Letters*, **8(4)**, pp. 566-568 (1996).
10. W.-J. Ho, M.-Ch. Wu, and Y.-K. Tu, Uniform and high performance of monolitically integrated 1x12 array of planar GaInAs photodiodes // *IEEE Transactions on Electron Devices*, **44**, pp. 559-564 (1997).
11. R.L.Balcerac, Uncooled IR imaging: technology for the next generation // *Proceed. SPIE*, **3698**, p.110-118 (1999).
12. K. C. Liddiard, U. Ringh, and C. Jansson, Status of uncooled focal plane detector arrays for smart IR sensors // *Proceed. SPIE*, **2746**, p.72-79 (1996).
13. M. C. Foote, Temperature stabilization requirements for uncooled thermal detectors // *Proceed. SPIE*, **3698**, pp. 344-350 (1999).
14. K. Vural, L. J. Kozlowski, D. E. Cooper, C. A. Chen, G. Bostrap, C. Cabelli, J. M. Arias, J. Bajaj, K. W. Hodapp, D. N. B. Hall, W. E. Kleinhaus, G. G. Price, J. A. Pinter, 2048x2048 HgCdTe focal plane arrays for astronomy applications // *Proceed. SPIE*, **3698**, pp. 24-35 (1999).
15. A. Manissadjian, P. Costa, Ph. Tribolet, G. Destefanis, HgCdTe performance for high operating temperatures // *Proceed. SPIE*, **3436**, pp. 150-161 (1998).
16. M. Kimata, and N. Tubouchi, *Schottky-Barrier Photoemissive Detectors*, in: Infrared photon detectors, Ed. A. Rogalski, SPIE Optical Engineering Press, Bellingham-Washington, 1995, pp. 299-349.
17. A. Akiyama, T. Sasaki, T. Seto, A. Mori, R. Ishigaki, S. Itoh, N. Yutani, M. Kimata, and N. Tubouchi, 1040×1040 infrared charge sweep device imager with PtSi Schottky-barrier detectors // *Optical Engineering*, **33**, pp. 64-71 (1994).
18. J. L. Vampola, Readout Electronics for Infrared Sensors, in *Electro-Optical Components*, edited by W. D. Rogatto, SPIE Opt. Eng. Press, 1993, Ch.5.
19. E. Fossum, and B. Pain, Infrared readout electronics for space science sensors: State of the art and future directions // *Proc. SPIE*, **2020**,pp. 262-285 (1994).
20. J. T. Longo, D. T. Cheung, A. M. Andrews, C.C. Wang, and J. M. Tracy, Infrared focal planes in intrinsic semiconductor // *IEEE Trans. Electron Devices*, **ED-25**, 213 (1978).
21. L. J. Kozlowski, and W. F. Kosonocky, *Infrared Detector Arrays*, in *Handbook of Optics*, edited by M. Boss, W. Van Stryland, D. R. Williams, and W. L. Wolfe, McGraw-Hill, New York, (1995).
22. F.F.Sizov, Yu.P.Derkach, V.P.Reva, and Yu.G.Kononenko. MCT sensor readout devices with charge current injection and preliminary signal treatment. Testing procedure // *Opto-Electronics Review*, **7**, pp.327-338 (1999).
23. K. C. Chow, J. P. Rode, D. H. Seib, and J. D. Blackwell, Hybrid focal plane arrays // *IEEE Trans. Electron Devices*, **ED-29**, 3-13 (1982).
24. L. J. Kozlowski, W. V. Mclevige, S. A. Cabelli, A. H. B. Vanderwyck, D. E. Copper, E. R. Blazejewski, K. Vural, and W. Tennant, Attainment of high sensitivity at elevated operating temperatures with staring hybrid HgCdTe on sapphire focal plane arrays // *Optical Engineering*, **33**, 704-715 (1994).
25. P. Nicolas, Ph. Pantigny, J. Cluzel, M. Vilain, J. L. Ouvrier Buffet, and J. J. Yon, An in pixel self-calibrating IR FPA // *Proc. SPIE*, **2269**, 406-416 (1994).
26. J. V. Gumenjuk-Sichevskaya, and F. F. Sizov, Currents in $Hg_{1-x}Cd_xTe$ photodiodes // *Semicond. Sci. Technol.*, **14**,pp. 1124-1131 (1999).
27. R.A. Rotolante, Why the IR detector market is in flux // *Laser Focus World*, October (1999), pp. 65-68.