Infrared Physics & Technology 53 (2010) 140–145

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

A new readout integrated circuit for long-wavelength IR FPA

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ARTICLE INFO

Article history:
Received 28 February 2009
Available online 28 October 2009

Keywords:
IR detector
Silicon readout integrated circuits
IR FPA
Adaptive signal processing systems

ABSTRACT

In the present paper, design of a readout integrated circuit (ROIC) for hybrid matrix IR FPA is presented. The design solution involves a ROIC matrix formed by 2 × 2-element fragments (cells) in which all the four cell elements, connected to one common read line, share a common integrating capacity. It is shown that, with the proposed ROIC structure: (i) the ROIC charge capacitance can be increased by a factor of 6–10, thus enabling two–three-fold enhanced NETD value of hybrid far-IR FPAs; (ii) the total number of read lines in IR FPAs can be decreased twice compared to traditional IR FPA designs, thus facilitating, due to doubly increased line spacing, the design of photosignal preprocessing system integrated with ROIC; (iii) improved structural arrangement of adaptive photosignal preprocessing system can be proposed.

1. Introduction

By now, all major engineering and circuit-technology problems met previously in the development of second-generation multi-element FPAs have been solved successfully [1]. Few still unsolved problems involve the development of hybrid FPA-based far-IR thermography systems with maximum theoretically possible NETD figures. It should be noted that it is the read-out-circuit charge storage capacity, instead of the photoelectric characteristics of photodiodes, that imposes limitations on the performance of thermography systems intended for operation in the far-IR region [2].

It is generally believed that in the next generation thermography systems the problems related to IR video signal forming and the majority of video signal preprocessing problems, such as, for instance, image identification and recognition, will be solved immediately in the focal plane array with the help of advanced readout circuits. In turn, this solution will pave the way towards substantial simplification of external IR video signal processing and imaging systems, allowing more cost-efficient thermography systems with lower power consumption and improved weight-dimension figures. Following this, the newly developed readouts will enter the class of special-purpose processors. It is such advanced readout processors that will largely enhance the performance and functionability of next-generation IR FPAs [3].

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doi:10.1016/j.infrared.2009.10.008

2. Analysis of NETD figures of thermography systems as dependent on the spectral range of IR FPA and the value of ROIC charge capacity

Fig. 1 shows the estimated NETD figures of thermography systems as dependent on the operating wavelength of IR FPA at various values of ROIC charge-handling capacity [4]. Curves 1 and 2 were calculated on the assumption that the integration time is equal to the frame time, the latter time being 20 ms. Under such conditions, we arrive at the well-known relation for "ideal" thermography systems [5], according to which the noise equivalent temperature difference of such systems improves with increasing wavelength λ. Under an "ideal" thermography system, we mean a system in which the photodetectors are operated in the background limited infrared photodetector (BLIP) mode, with the ROIC charge capacitance being sufficiently high, allowing the signal to be integrated during the whole frame time.

Curves 3–5 were calculated assuming the ROIC charge capacitance to be limited to values of 2×10^6, 2×10^7, and 8×10^7 electrons, respectively. Here, the integration time is defined by ROIC charge capacity. Inspection of curves 3–5 shows that already at $\lambda \geqslant 3.2$ μm the noise equivalent temperature difference starts exhibiting a substantially modified behavior as a function of λ. Under the condition of limited ROIC charge capacity, as the wavelength λ increases, the noise equivalent temperature difference of "real" thermography systems becomes seriously deteriorated [2]. For the rightmost points in curves 3–5 the integration time is $\leqslant$30–100 μs, this time being shorter than the time required for reading one matrix row. In this case, the application of matrix FPAs provides no advantages in terms of NETD over FPAs based on linear photodetectors.

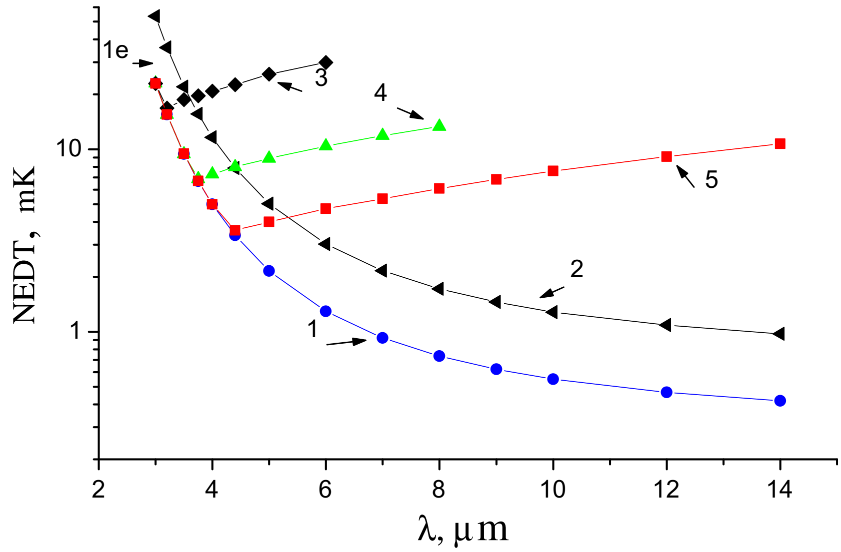

Fig. 1. Calculated NETD versus wavelength λ at various values of ROIC charge capacitance: 1–60°-aperture (2F/D = 3), 2–30°-aperture (2F/D = 10), background temperature 293 K, the accumulation time for curves 1 and 2 is taken to be 20 ms. Curves 3–5 were calculated assuming the NETD value to be limited by ROIC charge capacity, equal respectively to 2×10^6, 2×10^7, and 8×10^7 electrons (60°-aperture).

As we move towards longer waves, the requirements imposed on ROIC charge capacity become more and more stringent. Although in the middle IR range of 3–5.4 μm a ROIC charge capacity of $(2–10) \times 10^7$ electrons seems to be quite sufficient, in the longer-wavelength range of 8–14 μm this capacity in an "ideal" thermography system should be made amounting to 10^9–10^{10} electrons. For readout circuits with a charge capacity of 10^7 electrons the storage time in 8–12-μm photocells turns out to be only several per cents of frame reading time, i.e., lasting for a period during which as few as several matrix rows can only be read. It is for this reason that the noise equivalent temperature difference of matrix IR FPAs operating in the far-IR spectral region does not exceed the NETD value of linear IR FPAs with (4–8) TDI cascades.

It can be concluded from the above consideration that enhanced NETD figures can only be achieved in 8–12-μm IR FPAs through the development of readout circuits having a charge capacity sufficiently high to provide for the effective use of the whole information coming to IR detectors.

3. Silicon readout integrated circuit for 2 x 2 cell fragmented 8–12-μm matrix IR FPA

The charge capacity of readout circuits is normally limited by the unit-cell size. Today, however, design opportunities to increase the ROIC charge capacity by reducing the thickness of gate insulator and by adhering to more stringent topological rules seem to be almost fully exhausted.

Another strategy is the search for new design solutions making it possible to appreciably raise the charge capacity of readout circuits. Fig. 2 shows the circuit diagram of the newly designed readout circuit (Fig. 2a) and timing diagrams of control voltages in the new readout structure (Fig. 2b) [6]. A specific feature here is the readout-circuit architecture in which the input FPA matrix consists of 2×2 element cells. Each Si readout device cell additionally involves switch 12 intended for testing the readout circuit; this switch can also be used as anti-blooming tool to feed out an extra-current that may occur if individual cell elements become accidentally extra-flashed under very intense illumination. Integration of photosignals proceeds simultaneously in all 2×2 matrix cells, but only in those cell elements whose input gates have been biased with high control voltage. In Fig. 2 for the sequence of control pulses generated in unit 20 (see the diagram of voltages at nodes 13, 14, 15, and 16, Fig. 2b) this condition sequentially holds for the 1st, 2nd, 3rd, and 4th cell element of each cell (the polling order of cell elements may be arbitrary). The photosignals from a FPA matrix row are transferred in parallel to a preamplifier array and go further through the common output "Output" from the 1st, 2nd, 3rd, and 4th input cell of each 2×2 FPA matrix fragment. With the signal being output to a monitor, a full-size frame in real time is obtained. Thus, in the new FPA matrix, due to increased charge-handling capacity in each FPA matrix fragment, the integration time for photosignals can be increased to ¼ of the full frame time.

Basic structural components of readout-circuitry cell (see Fig. 2) are common for all elements in a 2×2 fragment of FPA; they comprise an accumulation gate, a transfer gate, and an output diode. This makes it possible to enlarge the accumulation-gate area from 30% to 50% of unit-cell area in FPA matrices with traditionally arranged readout circuits to 60–80% of the area of the 2×2 cell in the new FPA matrix. In this way, a 5–10-fold increase in the accumulation-gate area and, hence, in the ROIC charge capacitance can be achieved. Fig. 3 shows the topology of a 2×2 cell fabricated in a 0.8-μm CMOS process with 30-μm readout-device pitch. The accumulation gate occupies 76% of the 2×2 cell area of 60×60 μm^2. With a 12-nm gate insulator (SiO_2) thickness, the accumulation gate capacitance can be made amounting to 8 pF, this thickness translating into a charge capacity of over 2×10^8 electrons. Each 2×2 cell circuit in Fig. 1 contains optional transistor T1 (switch 12 in Fig. 2).

In the proposed structure, all optional operating modes of modern IR FPAs are available: "command register", "window mode", and "snap shot" mode. The only difference from IR FPAs with the standard ROIC configuration is that the accumulation of photosignals from individual elements of a ROIC cell in the new FPA matrix is split in time as it is shown in Fig. 2b. Furthermore, the consecutive readout of signals from individual cell elements offers an additional "window mode", in which, at the expense of the loss of spatial resolution by a factor of 2 yet without limiting FOV, a four times higher frame frequency can be achieved. After four readout cycles, a full-frame image is grasped. The proposed ROIC structure offers more possibilities for implementing multi-spectral IR FPAs. For instance, photodetectors of each spectral range can be con-