Thermal detectors – breakthrough in infrared technology

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Progress in infrared (IR) detector technology is connected mainly to semiconductor IR detectors, which are included in the class of photon detectors. In this class of detectors the radiation is absorbed within the material by interaction with electrons, either bound to lattice atoms, or to impurity atoms or with free electrons. The observed electrical output signal results from the changed electronic energy distribution. The photon detectors show a selective wavelength dependence of the response per unit incident radiation power.They exhibit both perfect signal-to-noise performance and a very fast response. But to achieve this, the photon detectors require cryogenic cooling. Photon detectors having long-wavelength limits above 3 μm are generally cooled. This is necessary to prevent the thermal generation of charge carriers. The thermal transitions compete with the optical ones, making non-cooled devices very noisy. Cooling requirements are the main obstacle to the more widespread use of IR systems based on semiconductor photodetectors, making them bulky, heavy, expensive and inconvenient to use. Depending on the nature of the interaction, the class of photon detectors is further subdivided into different types. The most important are: intrinsic detectors, extrinsic detectors, photoemissive (metal silicide Schottky barriers) detectors, and quantum well detectors.

The second class of infrared detectors is composed of thermal detectors. In a thermal detector shown schematically in Fig. 1, the incident radiation is absorbed to change the temperature of the material, and the resultant change in some physical properties is used to generate an electrical output. The detector element is suspended on lags, which are connected to the heat sink. The signal does not depend upon the photon nature of the incident radiation. Thus thermal effects are generally wavelength independent; the signal depends upon the radiant power (or its rate of change) but not upon its spectral content. This assumes that the mechanism responsible for the absorption of the radiation is itself wavelength independent, which is not strictly true in most instances. In pyroelectric detectors a change in the internal electrical polarisation is measured, whereas in the case of thermistor bolometers a change in the electrical resistance is measured. In contrast to photon detectors, the thermal detectors are typically operated at room temperature. They are usually characterized by modest sensitivity and slow response (because heating and cooling of a detector element is a relatively slow process) but they are cheap and easy to use. They have found widespread use in low cost applications, which do not require high performance and speed. Being unselective, they are frequently used in IR spectrometers.

In comparison with photon detectors, thermal detectors have been considerably less exploited in

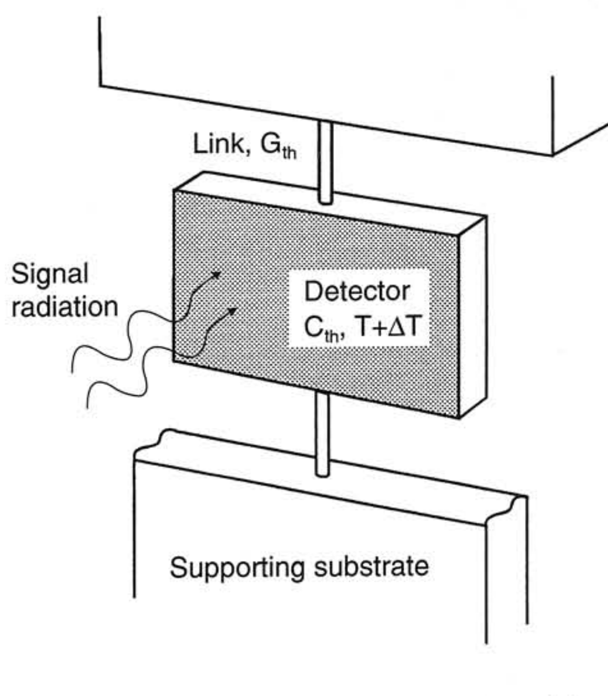

Fig. 1. Thermal detector mounted via lags to heat sink.

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commercial and military systems. The reason for this disparity is that thermal detectors are popularly believed to be rather slow and insensitive in comparison with photon detectors. As a result, the worldwide effort to develop thermal detectors has been extremely small relative to that of photon detector. In the last five years, however, it has been shown that extremely good imagery can be obtained from large thermal detector arrays operating uncooled at TV frame rates. The speed of thermal detectors is quite adequate for non-scanned imagers with two-dimensional detectors. Uncooled, monolithic FPAs fabricated from thermal detectors may revolutionise development of thermal imagers. Recently, very encouraging results have been obtained with micromachined silicon bolometer [1] and pyroelectric detector [2, 3] arrays.

For IR imaging systems, the relevant figure of merit for determining the ultimate performance is not the detectivity D* but the noise equivalent difference temperature (NETD), i.e. the difference of temperature of the object required to produce an electric signal equal to the rms noise voltage. This parameter takes into account the optics, array, and readout electronics. As it is shown e.g. in Ref. 4,

$$\mathrm{NETD} = \frac{4F^2\Delta f^{1/2}}{A_d^{1/2}t_{op}}\left[\int_{\lambda_a}^{\lambda_b}\frac{dM}{dT}D*(\lambda)d\lambda\right]^{-1} \quad (1)$$

where F is the system f-number, M is the spectral radiant emitance of blackbody (which can be described by Planck's law), and t_{op} is the optics transmission. Regarding the expression (1), the NETD value depends on bandwidth which is determinant for the value of the detector noise. New concepts of large FPAs reduce greatly the noise bandwidth to below 100 Hz. Figure 2 shows the dependence of NETD on noise bandwith for

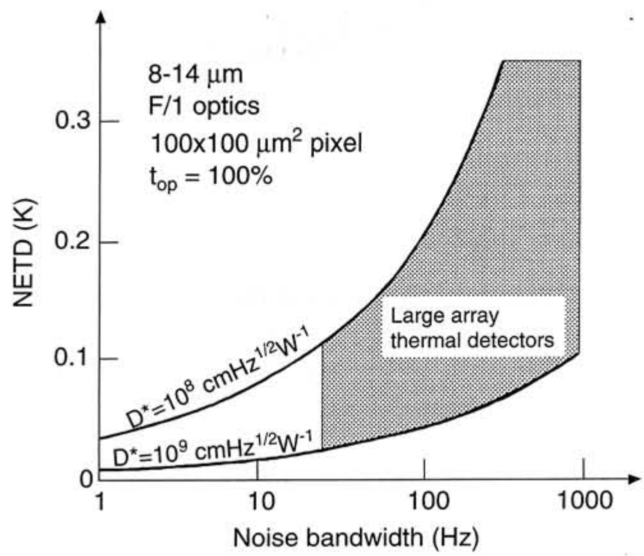

Fig. 2. The NETD versus equivalent noise bandwidth for typical detectivities of thermal detectors (after Ref. 5).

typical detectivities of thermal detectors. The calculations have been carried out assuming 100×100 μm² pixel size, 8-14-μm spectral range, F/1 optics and t_{op} = 1 of IR system. With large arrays of thermal detectors the best values of NETD below 0.1 K could be reached because effective noise bandwidths less than 100 Hz can be achieved. This compares with a bandwidth of several hundred kilohertz for a conventional cooled thermal imagers with a small photon detector array and scanner.

Present-day IR semiconductor imagers use cryogenic or thermoelectric coolers, complex IR optics, and expensive sensor materials. Typical costs of cryogenically cooled imagers around $100000 (see Table 1) restrict their installation to critical military applications allowing conducting of operations in complete darkness (such as tanks and aircrafts) [1]. A new

Table 1. Comparison of IR imagers (after Ref. 1)

Feature	Present scanned cryogenic imagers	Cryogenic staring imagers	Uncooled silicon microbolometer imagers
Approximate system cost	$100 000 (military volume production)	$100 000 (military volume production)	$1000 (high-volume production)
Typical focal-plane temperature	100 K	100 K	Room temperature
IR sensor	HgCdTe, InSb	HgCdTe, InSb, PtSi, GaAs/AlGaAs	Micromachined silicon
Typical NETD	0.1°C	0.01°C	0.05°C
Applications	Military and specialized industrial applications	Military and specialized industrial applications	Widespread applications for military, commerce, research, industry, etc.

revolution in reducing cost of thermal imagers, which is now underway, is caused by very encouraging results obtained with micromachined silicon bolometer arrays and pyroelectric detector arrays. It is expected that high-performance imager system costs will be reduced by about two orders of magnitude, to less than \$1000, and the preceding IR cameras will become widely available in the next decade. Although developed for military applications, low-cost IR imagers will likely be used in nonmilitary applications such as drivers aid, aircraft aid, industrial process monitoring, community services, etc.

The final microbolometer pixel structure is shown in Fig. 3. The microbolometer consists of a 0.5 μm thick bridge of Si_3N_4 suspended about 2 μm above the underlying silicon substrate. The bridge is supported by two narrow legs of Si_3N_4. The Si_3N_4 legs provide the thermal isolation between the microbolometer and the heat-sink readout substrate. A bipolar input amplifier is normally required, and this can be obtained with biCMOS processing technology. Si3N4 is used because of its excellent processing characteristics. This allowed microbolometers to fabricate with thermal isolation close to the attainable physical limit which is about 1×10^8 K/W for a 50-μm-square detector. It was demonstrated that, with a microbolometer having a thermal isolation of 1×10^7 K/W, a typical incident IR signal of 10 nW was sufficient to change the microbolometer temperature by 0.1 K. The measured thermal capacity was about 10^{-9} J/K what corresponds to a thermal time constant of 10 ms. Honeywell determined that the microbridges are robust structures that can tolerate shocks of several thousand g-forces. Encapsulated in the centre of the Si_3N_4 bridge is a thin layer (500 Å) of polycrystalline VO_x. Vanadium oxide based materials exhibit a very high temperature coefficient of resistance (TCR) (about –2%/K) due the semiconductor-metal phase transition. Moreover, VOx assures good combination of high TCR, electrical resistivity, and fabrication capability, which has resulted in pixels with responsivity of 250 000 V/W in response to 300 K blackbody radiation [6]. An average NETD better than 0.05 K was demonstrated with a Honeywell uncooled 240×336 imager array fitted with an F/1 optics. This sensitivity is better than that attained with scanned cryogenic imagers currently used in military service.

Figure 3 shows the modern structure of a pyroelectric FPA. A detector $LiTaO_3$ active volume is bounded by the common front electrode, the back electrode, and by reticulation cuts. The detector back electrode is connected to the underlying multiplexer by a metallized polymer thermal isolation link which provides connection and support for the detector with controlled thermal conductance. The nominal detector size is 35×35 μm^2, with 10 μm thickness and a 15 μm gap between detectors for an element pitch of 50 μm. For the detector with f = 30 Hz, $Rv \approx 1 \times 10^6$ V/W. The estimated total thermal conductance is about 3.3×10^{-6} W/K, and is higher than obtained for micromachined silicon bolometers. The thermal time constant is then ≈15 ms. The predicted NETD of the prototype system with 330×240 elements array has been estimated as 0.07 K with F/1 optics, an optic transmission of 0.85 and chopper efficiency of 0.85.

The performance of pyroelectric detectors can be

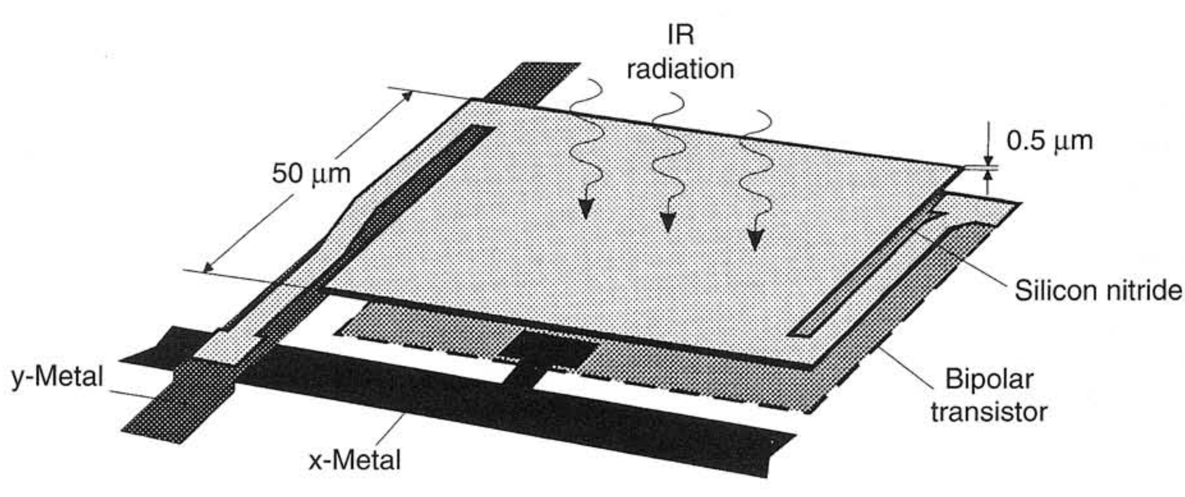

Fig. 3. Bridge structure of Honeywell microbolometer (after Ref. 6).

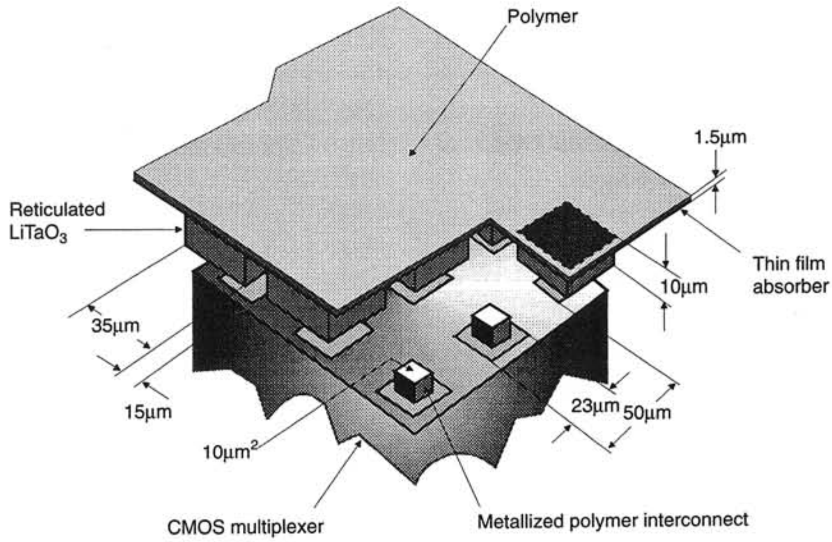

Fig. 4. Hybrid pyroelectric array structure (after Ref. 7).

improved with a bias voltage applied to maintain and optimise the pyroelectric effect near the phase transition [7]. This type of pyroelectric FPAs has been developed by Texas Instruments (TI). The TI detector array comprises 245 × 328 pixels on 48.5 μm centres. Operating near ambient room temperature, ferroelectric BST (barium strontium titanate, $Ba_{1-x}Sr_xTiO_3$) pixels hybridised with a silicon readout integrated circuit consistently yield devices with system NETD of 0.047°C with F/1 optics.

The hybrid design involves features affecting cost through processing time or yield, e.g. the preparation of the thin ceramic wafer to high polishing tolerances, and the solder bond processing. Wafer processing may also lead to some degradation from the bulk properties. The monolithic array structures represent a new approach for achieving high-density and high-performance integrated pyroelectric FPAs [8].

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