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PYROELECTRIC DEVICES

Devices utilizing the pyroelectric effect are broadly categorized as *pyroelectric devices*. In pyroelectric materials the polarization vector is a function of temperature, so that the surface charge varies with temperature. Essentially, whenever a pyroelectric material undergoes a small change of temperature (ΔT), a proportional change in its electric polarization (ΔP) is produced, such that

$$\Delta P = p\,\Delta T \tag{1}$$

where p is the *pyroelectric coefficient*. As an illustration, the pyroelectric material tourmaline, at room temperature, produces a charge of about 10 μC/m^2 for a 1° C change in temperature. The reason for the change in polarization is the relative displacement of ionic sublattices within the material. The order of this displacement is only about 10 fm. Further, the magnitude of the pyroelectric effect depends on whether the pyroelectric material is mechanically clamped (the *primary pyroelectric effect*) or free (a superposed *secondary pyroelectric effect*). The secondary pyroelectric effect arises as a consequence of the thermal expansion and the attendant piezoelectric polarization. This is because all pyroelectrics are also piezoelectrics. It is interesting to note that the pyroelectric effect is exhibited by biological materials also—both living and nonliving tissues in animals and plants.

Pyroelectric devices work by sensing infrared (*IR*) radiation. In general *IR* sensing and measurement is achieved either by *thermal detectors* or by *photon detectors*. Thermal detectors, of which pyroelectric detectors are one type, respond to the heat produced by incident radiation, independent of its wavelength, where as photon detectors are spectrally selective. Further, compared to other thermal detectors (bolometers, thermopiles, etc.), pyroelectric devices respond to the rate of change of temperature. If a constant-intensity radiation is to be sensed, such as from a stationary object, an artificial change has to be created. This is generally done by periodically chopping the incoming radiation before allowing it to fall on the pyroelectric detector. Applications include intruder alarms, fire alarms, laser detectors, gas spectrometry, thermal scanning and imaging, pollution monitoring, radiometry, biomedical thermography, and night vision devices.

To appreciate the increasing popularity, accessibility, and use of pyroelectric devices, it is important to recognize the advances made in pyroelectric materials, device fabrication processes, and integration with peripheral electronics. The earliest devices were based on bulk pyroelectric materials. The advent of *ferroelectric* pyroelectrics, with their large pyroelectric coefficients, popularized the use of pyroelectric detectors and devices. For these materials the pyroelectric effect usually exists below a characteristic temperature the *Curie point* T_c. Some common ferroelectric pyroelectrics are barium titanate ($BaTiO_3$), lead–zirconium titanate (PZT) compositions, lithium tantalate ($LiTaO_3$), and lithium niobate ($LiNbO_3$). A drawback of bulk devices is their large thermal mass (heat capacity), leading to low frequency of operation.

A new generation of pyroelectric devices was based on pyroelectric *thin films*. These not only have very small thermal mass, but can also be designed and fabricated to improve the thermal insulation of the detector array. Through *micromachining* of underlying substrates and films, architectures such as air-bridge and insulating layers can be realized for the purpose. If the substrate is also a semiconductor, such as silicon, the pyroelectric detecting element can be integrated with peripheral (readout, processing, etc.) electronic circuitry. Popular pyroelectrics used in thin-film form include PZT (ceramic), $LiTaO_3$, lead titanate ($PbTiO_3$) (a crystal), and polyvinylidene fluoride (PVDF) (a polymer). The techniques used in the fabrication of these thin films and devices are equally diverse. Special mention needs to be made of yttrium barium copper oxide ($YBa_2Cu_3O_{6+x}$), which, apart from being a well-known high-temperature superconductor, has recently been used in capacitor structures for pyroelectric *IR* detector technology (see “pyroelectric *IR* Detectors” in *infrared detector arrays, uncooled*).

In practice the value of the pyroelectric coefficient p alone is not a good criterion for judging pyroelectric materials and devices. For this purpose, various figures of merit have been evolved. Depending on the application, frequency, and temperature range of operation, one will maximize either the output voltage (voltage responsivity), the output current (current responsivity), or the detectivity (ability to detect signal against a background of noise).

PHOTON DETECTORS AND THERMAL DETECTORS

Different physical and chemical effects have been used for sensing of radiant electromagnetic energy. Detectors based on these effects are broadly categorized as either photon or thermal detectors. If the detector responds to an increase in *temperature*, caused by the absorption of radiant energy, then it is called a thermal detector. On the other hand, a photon detector achieves its response when incident photons excite carriers across the *bandgap* (energy difference between valence and conduction bands), usually in a semiconductor.

Photon detectors respond to individual quanta of radiation and hence are spectrally selective. The absorption of incident photons initiates internal changes in the detector, which manifest themselves as an electric signal at the output. Such detectors are more sensitive than thermal detectors, and are either photoemissive (based on the *photoelectric effect*, whereby absorption of photons leads to ejection of electrons) or photoconductive (based on a change in resistivity or conductivity due to absorbed photons). The *photomultiplier tube*, perhaps the most widely used photoemissive detector, is capable of recording absorption of even single photons. For *IR* detection, semiconductor photodiodes and photovoltaic elements are very popular. They are generally based on lead sulfide (PbS), indium antimonide (InSb), and mercury cadmium telluride (Hg–Cd–Te).

In thermal detectors the temperature increases until the rate of absorbtion of heat equals the rate of heat loss to the surroundings. Loss of heat can occur through conduction, convection, and reradiation. A good thermal detector would

(1) Maximize the absorbtion of incident radiation
(2) Minimize the loss of heat to the surroundings
(3) Have the smallest possible thermal capacity.

While the first two criteria maximize sensitivity (i.e., achieve the largest rise in temperature for given incident radiation), the last criterion additionally ensures rapid changes in temperature and hence fast response. The response time of a detector is approximately the reciprocal of its response bandwidth (the frequency bandwidth over which it can respond).

Bolometers, thermopiles, and pyroelectrics are some of the common thermal detectors. As discussed, thermal detectors absorb radiant power nonselectively (independent of wavelength); this power is turned into heat, and the temperature is thus raised. In *bolometers* the rise in temperature results in a change of conductivity of a metal resistor, semiconductor, or superconductor. In a *thermocouple* the temperature change effected in a junction of two dissimilar metals, with respect to a reference junction, results in a change of

Table 1. Comparison of Important Types of Thermal and Photon Detectors

Type	Spectral Response Range (μm)	Responsivity R_v (V/W) R_i(A/W)	Typical Detectivity D^* (cm · Hz$^{1/2}$ · W^{-1})	Response Bandwidth (Hz)
Bolometer	0.2 to 3×10^3	10^{-5} to 2×10^2	10^8	10^2 to 10^7
Pyroelectric	0.1 to 10^3	10 to 5×10^3	10^7 to 10^8	10^{-2} to 10^9
Thermopile	0.2 to 35	1 to 50	10^8	1 to 10^3
Photomultiplier	0.2 to 0.9	10^{-3} to 10^{-1}	—	10^8 to 10^9
Photovoltaic and Photoconductive	0.1 to 26	0.1 to 20	10^{10} to 10^{13}	10^5 to 10^{10}

voltage (the *thermoelectric effect*). A series-connected circuit of thermocouples is called a *thermopile*, and is a simple way to increase the output voltage for a given temperature differential.

Table 1 briefly compares the important performance characteristics of some photon and thermal detectors. The thermal detectors generally respond over a wider range of frequencies (broad spectral response), while photon detectors are generally more sensitive and respond faster (larger response bandwidth).

An important aspect of these various detectors is the requirement of cooling. Photon detectors at room temperature are noisy because of dark current. To minimize noise and hence enhance detectivity, they have to be cooled to cryogenic temperature. However, thermal detectors have no such cooling requirement and are commensurately cheaper.

With this brief introduction, the article will now concentrate on pyroelectric (thermal) detectors and devices.

PYROELECTRIC DETECTOR—THEORY

At the heart of any pyroelectric device lies a pyroelectric detector element. Figure 1 depicts a basic pyroelectric detector system for measuring incident thermal (infrared) radiation. Physically, the typical detector element is a thin piece of pyroelectric material with electrically conducting electrodes deposited on opposite faces. Electrically, it resembles a parallel-plate capacitor (C_E) with a pyroelectric dielectric medium. One of the electrodes is, by design, a good absorber of thermal radiation. Whenever such radiation is incident, it is absorbed, and the accompanying change in temperature causes electric charge to develop across the pyroelectric material in accordance with Eq. (1). A current i_p proportional to the incident radiation will flow if external electric elements are connected across the pyroelectric detector element. This results in the development of a potential difference, v_G, across the conducting electrodes. The induced charge, voltage, and current are small and need to be amplified. Generally, as shown in Fig. 1, an amplifier based on a field-effect transistor (FET) is used for the purpose. A FET has high input impedance and therefore does not load the signal source (the pyroelectric detector, in this case). The resistor R_G biases the FET, while R_A and C_A are the input resistance and capacitance, respectively, of the FET. The amplified output voltage v_o, developed across the load resistor R_L, is then proportional to the i_p and hence to the incident thermal radiation.

Current and Voltage Responsivity. An obvious index of characterization for a pyroelectric detector is the ratio of the generated pyroelectric current i_p to the incident (infrared) radiant power W_i. This is termed the current responsivity R_i. At the outset we again note that, as implicit in Eq. (1), pyroelectric materials respond to *changes* in temperature, caused by changes in incident radiant power. Assume therefore that W_i is

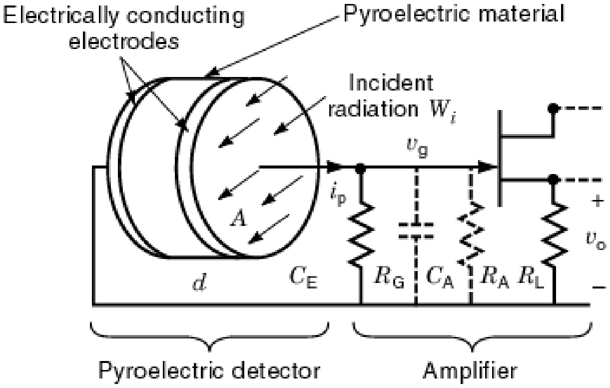

Fig. 1. Schematic of a basic pyroelectric detector system for measuring thermal radiation. The pyroelectric element output is fed to the gate of a FET for amplification and measurement.

sinusoidally varying at angular frequency ω (the *radiation modulation frequency*), and has an amplitude W_0, i.e. $W_i = W_0 e^{j\omega t}$. For the pyroelectric detector element in Fig. 1, let the pyroelectric piece of thickness d and area A have a material density ρ and specific heat c. The heat (thermal) capacity H of the element is then defined as $H = \rho c A d$. Further let the electrode, on which the incident radiant power is W_i, have an emissivity η. Then the power absorbed by electrode per interval of time dt is $\eta W_i\, dt$. This causes a rise of temperature dT in the element such that $\eta W_i\, dt = H\, dT$. However, some of the absorbed power is reradiated or lost by conduction or convection. This is taken into account by defining G, the thermal conductance to the surroundings. The energy balance equation is then given by:

$$\eta W_i\, dt - GT\, dt = H\, dt$$

which can be solved for T, the temperature difference between the element and its surrounding, as

$$T = \left(\frac{\eta W_0}{G + j\omega H}\right) e^{j\omega t} \tag{2}$$

To arrive at the pyroelectric current i_p we note that it is the time rate of change of the total instantaneous (polarization) charge Q. Thus from Eq. (1), $i_p = dQ/dt = pA\, dT/dt$, and dT/dt can be calculated from Eq. (2).

Finally, the *current responsivity* R_i, defined as the ratio i_p/W_i, is given by:

$$R_i = \frac{pA\eta\omega}{G}\left(1 + \omega^2 \tau_T^2\right)^{-1/2} \tag{3}$$

where $\tau_T = H/G$ is known as the thermal time constant of the detector system.

On similar considerations, a *voltage responsivity* R_v can be defined in terms of the voltage developed (v_G) due to the flow of the pyroelectric current i_p in the electric circuit connected across the pyroelectric detector (Fig. 1). Here both thermal and electric aspects of the detector and associated circuitry have a bearing, and hence the voltage responsivity is a figure characterizing the complete detector system, rather than the pyroelectric element alone.

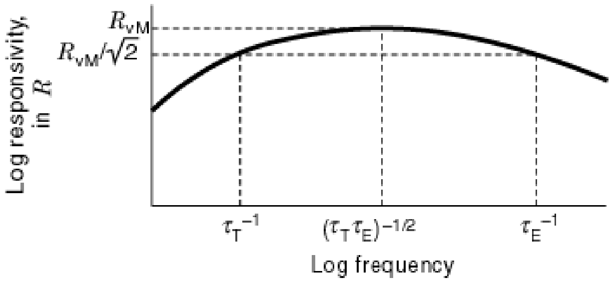

Fig. 2. Voltage responsivity of a pyroelectric detector, illustrating the condition at which the maximum responsivity (R_{vM}) occurs, and the corresponding 3 dB down frequencies.

The total electrical admittance Y as seen at the input (gate) of the FET is

$$Y = R_G^{-1} + R_A^{-1} + j\omega(C_E + C_A)$$

which simplifies to

$$Y \approx R_G^{-1} + j\omega(C_E + C_A)$$

under the assumption, $R_A \gg R_G$ which is usually the case for FETs. Introducing an electrical time constant $\tau_E = R_G\ (C_E + C_A)$, the voltage responsivity R_v is then:

$$R_v = \frac{v_G}{W_i} = \frac{i_p}{YW_i} = \frac{R_i}{Y} = \frac{pA\omega\eta R_G}{G(1+\omega^2\tau_T^2)^{1/2}(1+\omega^2\tau_E^2)^{1/2}} \tag{4}$$

Voltage responsivity is a function of the radiation modulation frequency ω, with the maximum value R_{vM} occurring at $\omega = (\tau_E\tau_T)^{-1/2}$, and the 3 dB down values occurring at $\omega = \tau_T{}^{-1}$ and $\omega = \tau_E{}^{-1}$, respectively. Strictly speaking, this is true only when the thermal and electrical time constants are at least an order of magnitude apart, a condition that, though depending on the structure, geometry, and/or material of the detector, is very often satisfied. Figure 2 plots and illustrates this relationship. Equation (4) embodies the attributes of a good pyroelectric detector. It confirms that a high pyroelectric sensitivity can be achieved (1) by choosing a detector material with a large pyroelectric coefficient p, (2) by increasing the fraction of absorbed incident energy (high emissivity η), (3) by thermally isolating it from the surroundings (minimizing G), and (4) by having a small thermal capacity (minimizing H, with thickness d small) but with a large electrode overlap area A. In practice the thermal and electrical time constants are, typically, of the order of a second. With so many contributing factors to choose from, the frequency responsivity of a system is ultimately dictated by the intended application. For example, profiling of picosecond laser pulses requires the detector system to have a flat frequency response, achieved by decreasing τ_E and minimizing C_E and the amplifier input impedance. Since a pyroelectric element is essentially a high-quality capacitor, leakage of generated charge is slow. This charge storage or retention capability can be used to integrate rapidly changing inputs.

Temperature-Compensating Element. Pyroelectric detectors need to be corrected for outputs due to spurious signals: those due to mechanical vibrations, ambient temperature fluctuations, etc. This is generally achieved by the addition of a compensating dummy element to the basic detector system. The compensating element, while similar to the detector in its construction and its thermal and mechanical placement, has two important differences. Firstly, it is poled in a direction opposite to that of the detector element, and secondly, it is made impervious to the incident radiation. If such a compensating element is now connected in series, the charges developed, due to ambient temperature changes (pyroelectric effect) and/or mechanical vibrations (piezoelectric effect), in the detector and compensating elements are of opposite polarity and hence tend to cancel out.

As with any detector, it is important to know the sources of noise that tend to corrupt the signal to be measured. Broadly, they are the thermal radiation noise (arising from random fluctuations in the temperature difference between detector and surroundings), and electrical noise (emanating from the amplifier, as well as Johnson noise due to the electrical equivalent resistance between detector and amplifier). Let V_n be the noise voltage, having contributions from all these sources. Then the noise equivalent power (*NEP*) for such a device with voltage responsivity R_v is given by $NEP = V_n/R_v$. An often used criterion for comparing pyroelectric detectors (area A), based on noise considerations, is the detectivity

$$D^* = \frac{A^{1/2}}{\mathrm{NEP}} = A^{1/2}\frac{R_v}{V_n}$$

PYROELECTRIC DETECTOR—MATERIALS AND FABRICATION

Pyroelectric materials are polar. The observed macroscopic pyroelectric effect can be found in ionic crystals, covalently bonded crystals, ceramics, and polymers. Detectors, based on such a wide range of materials, also have a variety of structures and fabrication processes. The pyroelectric polarization in a polycrystalline sample is less than in a corresponding single crystal but can be maximized if the crystallites can be fully oriented along a common polar axis. This is easily achieved in a class of materials known as ferroelectrics, by the application of an electric field. Further, the pyroelectric effect in ferroelectrics is largest at temperatures just below their Curie point T_c.

Which material to use? This question cannot be simply answered on the basis of the pyroelectric coefficient p alone. Depending mainly on the application, various *figures of merit* have been evolved to evaluate pyroelectric materials under defined operational conditions. For maximum voltage responsivity, $F_v = \rho/\rho c\varepsilon$ would be appropriate (with $\varepsilon = \varepsilon_r\varepsilon_o$ being the permittivity); for maximum current responsivity, as in fast pulse detectors, $F_i = p/\rho c$ is used; and for maximizing the detectivity D^* the figure of merit is $F_D = p/\rho c(\varepsilon'')^{\frac{1}{2}}$, where $\varepsilon'' = \varepsilon \tan\delta$ is the imaginary part of the permittivity, $\tan\delta$ being the dielectric loss tangent. Further, these figures of merit vary with temperature and frequency, because of the dependence of their constituent quantities on these parameters. Generally, pyroelectric detectors can be said to work best in the frequency range from 10 Hz to 1 kHz for maximum detectivity and responsivity.

Table 2 lists the characteristics of some important pyroelectric materials.

Among the widely used bulk ferroelectric materials are single crystals of triglycine sulfate (TGS), lithium tantalate ($LiTaO_3$), and strontium barium niobate (SBN); polymeric polyvinylidene fluoride (PVDF); and ceramics of the lead–zirconium titanate (PZT) family.

TGS and its modifications—by deuteration (DTGS), by substitution of glycine by alanine (ATGS), and by further doping with arsenic acid (ATGAS)—provide some of the highest responsivities. However, due to their hygroscopic nature and fragility, their use is generally limited to single-element detectors and some special array-design detectors.

With a T_c of 665°C and a melting point of 1650°C, $LiTaO_3$ is a stable pyroelectric with a moderate pyroelectric coefficient. It is amenable to thin-film preparation (generally by ion-beam milling). In conjunction with low-noise FET amplifiers, thin-film $LiTaO_3$ detectors can provide very high detectivities (Table 2).

SBN, with the composition $Sr_{0.5}Ba_{0.5}Nb_2O_6$, known as SBN-50 in the literature, has high pyroelectric and dielectric coefficients but a low dielectric loss. It is a robust single-crystal material generally grown by the Czochralski method.

Table 2. Important Properties of Some Pyroelectric Materials at Room Temperature

Material	Form	p ($\mu C \cdot m^{-2} \cdot K^{-1}$)	ε_r	tan δ	$c'(= \rho c)$ ($MJ \cdot m^{-3} \cdot K^{-1}$)	T_c (°C)	F_v ($m^2 \cdot C^{-1}$)	F_D ($\mu m^{3/2} \cdot J^{-1/2}$)
TGS	Single crystal	280	38	0.025	2.6	49	0.43	61
$LiTaO_3$	Single crystal	230	47	10^{-4}	3.2	665	0.17	350
SBN-50[a]	Single crystal	550	400	3×10^{-3}	2.3	121	0.07	72
PGO[b]	Single crystal	110	40[c]	5×10^{-4}[c]	2.0	178	0.16	131
PZFNTU[d]	Ceramic	380	290[e]	3×10^{-3}[e]	2.5	230	0.06	58
PVDF	Polymer	27	12[f]	10^{-2}[f]	2.4	80	0.1	9

[a] $Sr_{0.5}Ba_{0.5}Nb_2O_6$.
[b] $Pb_5Ge_3O_{11}$.
[c] at 100 Hz.
[d] $Pb_{1.02}(Zr_{0.58}Fe_{0.20}Nb_{0.20}Ti_{0.02})_{0.994}U_{0.006}O_3$
[e] at 1 kHz.
[f] at 10 Hz.

Applications where low cost is a prime consideration favor the use of the pyroelectric polymer PVDF. It is readily available in large-area thin films, is moderately stable to heat and moisture, and is robust in handling. The major drawbacks are its relatively low values of pyroelectric coefficient and figures of merit, though its voltage sensitivity can be increased by the use of large-area detector films. Its performance also degrades above 80°C.

By far the most popular pyroelectric ceramics belong to the family of PZTs. These ferroelectrics have the perovskite crystal structure. Modifications to the basic lead zirconate (ZT) and lead titanate (PT) forms have led to the development of high-performance pyroelectric ceramics. Various dopants have also been explored, with a view to tailoring specific desired properties. In one such example, doping by uranium oxide (UO_3) reduced the permittivity ε and the loss tangent tan δ, but enabled the resistivity to be controlled. This made the FET gate bias resistor R_G (Fig. 1) redundant, resulting in decreased chip area and cost. This ceramic, called PZFNTU, has the composition $Pb_{1.02}(Zr_{0.58}Fe_{0.20}Nb_{0.20}Ti_{0.02})_{0.994}U_{0.006}O_3$.

Thin-Film Pyroelectric Devices. Compared to bulk devices, thin-film detectors have a lower thermal capacity H and so perform better at higher frequencies—a requirement for gas spectroscopy and image detection applications (see *thin films*, Fig. 10). In addition, heat conduction to the substrate can be reduced by micromachining the substrate so that the pyroelectric elements remain on a submicrometer-thick membrane. To improve the voltage response the detector itself can be arranged as an array of sensing elements (linear or two-dimensional), rather than a simple point detector. If the substrate is silicon, integration of the detector with the processing and readout electronic circuitry can be realized, leading to compact, low-weight, low-cost, small-sized, and reliable systems.

Thin-film pyroelectric devices have mainly been fabricated from zinc oxide (ZnO), polyvinylidene fluoride (PVDF), lead titanate (PT), lead zirconium titanate (PZT), and lithium tantalate compounds. Amongst promising recent thin-film materials for *IR* detectors are variants of the yttrium barium copper oxide ($YBa_2Cu_3O_{6+x}$) family, which is also semiconducting (metallic for $0.5<x<1$ and insulating for $0 \leq x \leq 0.5$) and amenable to integration with CMOS technology (see "*Pyroelectric IR Detectors*" in *infrared detector arrays, uncooled*). There is controversy regarding the origin of pyroelectricity in the various phases of this material, but detectivities of the order of 10^8 cm · $Hz^{1/2}$ · W^{-1} have been measured for thin-film semiconducting YBaCuO capacitor structures. Advances in thin-film technology have played a key role in improving performance of detectors based on all such films. They can be grown with atomic precision on a variety of substrates, and the process (temperature, doping, pressure, concentration, etc.) tailored to maximize the pyroelectric response at desired ambient (e.g., room) temperature. Thin-film growth techniques employed include epitaxy, sol–gel deposition,

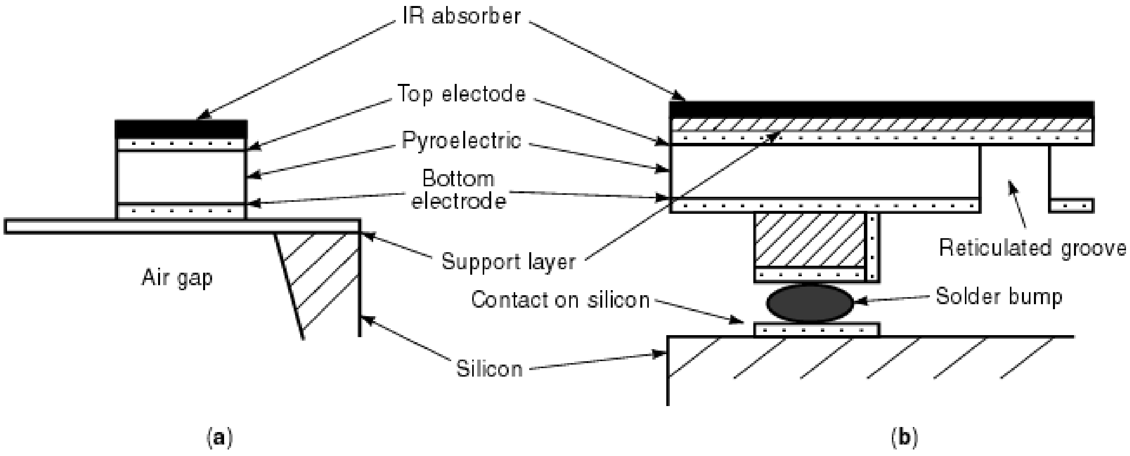

Fig. 3. Schematic structures of two thin-film pyroelectric detectors, based on silicon. (a) The electroded pyroelectric material, with an *IR* absorber coating on its open face, is lithographically fabricated on an insulating support layer, itself grown from or deposited on a silicon substrate. (b) The detector, fabricated on a support layer, makes electrical contact to a silicon chip through a solder bump. The detector unit structure is repeated, with reticulated grooves providing thermal insulation between units.

chemical vapor deposition, metal–organic decomposition, ion milling, ion-beam and RF sputtering, spraying, pulsed laser deposition, etc.

Numerous thin-film pyroelectric structures have been proposed, designed, and implemented with a view to monolithic integration with accompanying electronics microcircuitry. See *thin films*, Fig. 11, which illustrates the fabrication process for a linear-array *IR* sensor. The thin-film pyroelectric material, lanthanum-doped lead telluride (PLT), is first deposited on a substrate (MgO). After providing readout electrodes (Ni–Cr), it is flipped over and bonded to ceramic substrates. The MgO substrate is then etched off, and absorbing electrodes (Ni–Cr) provided.

Figure 3 outlines two topologies made possible by advances in micromachining technology. In both, the aim is to place a thin-film detector element on a semiconducting silicon chip. Typically [Fig. 3(a)], a substrate of oriented silicon wafer ($\approx 400\ \mu$m thick) with thin oxide and/or nitride layer(s) (≈ 100 nm) is micromachined in such a way that the silicon underlying a portion of the thin oxide–nitride layer is etched away, creating an air gap. This oxide–nitride layer then becomes the substrate for depositing pyroelectric films and electrodes. The remaining silicon provides mechanical support and can also be used for fabrication of complementary electronics. Good thermal insulation of the detector element is achieved because of the insulating air gap.

Another technique [Fig. 3(b)] relies on accurately placing pyroelectric detector elements on top of contact pads on the silicon surface. Electric contact between them is effected and ensured through solder bumps. To minimize lateral flow of heat, detector elements are *reticulated*—separated from each other through grooves. For such microstructures, values of 10^{-10} J $\cdot$ K^{-1} for the thermal capacity (H), 10^{-7} W $\cdot$ K^{-1} for the thermal conductance (G), and thermal time constants $\tau_T = H/G$ of the order of a millisecond are typical.

The emergence of thin-film pyroelectric devices has led to the design and fabrication of *multilayer assemblies* with a view to optimizing performance. A typical four-layer pyroelectric structure would have a front layer (for maximizing absorption of incident radiation), a pyroelectric element layer (for efficient thermal-to-electric energy conversion), an intermediate layer (providing thermal insulation), and a back layer (for mechanical support). The structure in Fig. 3(a) has six different strata, including the electrically conducting electrodes across the pyroelectric layer. The complex (solder bump) topology of Fig. 3(b) has even more.

APPLICATIONS AND THE FUTURE

Applications of pyroelectric devices are characterized by the following considerations:

1. They are responsive to varying *IR* flux and can detect relatively small variations in a large invariant background radiation.
2. They do not generally require cooling systems, even for use over a wide dc temperature range.
3. Battery operation is feasible due to low power consumption.
4. Both broadband and narrowband spectral operation are possible.
5. Monolithic integration of the detector with microcircuitry leads to low cost.
6. Compensating dummy elements allow for minimization of ambient thermal and mechanical noise, providing a high *S/N* ratio.

Specific applications of pyroelectric devices have progressed from simple detection to more involved imaging. Intruder alarms are based on the thermal perturbation of the ambient by an alien presence. Bodies at room temperature (300 K) have peak power emission at approximately 10 μm wavelength. Therefore such detectors work in the 8 μm to 12 μm region, with a cutoff filter for shorter wavelengths, minimizing their sensitivity to visible radiation.

An interesting development of the intruder alarm is a smart energy management sensor. For example, by pyroelectrically sensing the location and number of persons in a room, utilities like lighting or air conditioning can be controlled for optimal use. Another useful form of the intruder alarm is in detecting fires. The detectors used for this purpose have peak sensitivity at around 4 μm. Another obvious application is in remote temperature measurement, for example, in microwave ovens and in satellite and interplanetary probes (see RADIOMETRY). By introducing a means of wavelength discrimination before the radiation reaches the detector the nature and concentration of gases can be analyzed for the purpose of pollution monitoring, general gas analysis, etc. Pyroelectric detectors are also used for profiling laser beams as well as measuring their intensities. Pyroelectric probing is a proven technique for observing ferroelectric domains.

Photopyroelectric spectroscopy (*PPES*) is a recent application for the determination of thermal and optical properties of solid, liquid, and gaseous materials. Essentially, in this technique, a known thickness of the sample material, in contact with a pyroelectric, is irradiated with visible or *IR* radiation (pulsed or continuous), and the the desired sample material property is then derived from the pyroelectric thermal sensor response.

Pyroelectric thermal imaging requires the use of large-area detectors to enhance the spatial resolution of the object image. The infrared vidicon is one such system, wherein an electron beam reads the charge developed on a pyroelectric target on which radiation from the object is incident. Another approach to thermal imaging utilizes a linear or two-dimensional array of pyroelectric point detectors to cover the entire image. 1-D arrays of 128 elements have been reported, and 2-D arrays of 32 × 32 elements have been successfully integrated on silicon substrates. One of the major problems in such arrays is *thermal crosstalk*: lateral diffusion of heat from one element to another. Apart from reticulation, it is being reduced by using thinner films of low thermal diffusivity and working at higher modulation frequencies. Temperature differences of 0.5 K can be very easily detected, with 0.1 K being specified in an increasing number of commercially available pyroelectric devices. Though other techniques may give better responsivities (Table 1), the pyroelectric devices require little or no cooling. It should be noted that by themselves, pyroelectric materials can respond to and detect temperature variations of the order of a millionth of a kelvin.

The future of pyroelectric devices lies in the monolithic integration of pyroelectric detector elements with peripheral microcircuitry, leading to compact, low-power and low-cost systems with reasonably high sensitivity. Clearly, the strategy, which is gaining ground [Fig. 3(a)], is to grow the pyroelectric element on a semiconductor substrate, rather than mate a separately fabricated pyroelectric element with the substrate. In this connection, many combinations of substrates, pyroelectric materials, absorbing coatings, support layers, and electrode materials, fabricated through a variety of processes, have been proposed and demonstrated. Among materials (see *infrared detector arrays, uncooled*), the semiconducting phase of YBaCuO holds promise, with the potential of a double role as a pyroelectric and a sensor-circuit substrate. Composites with different combinations of ceramics and polymers are being tried out. Graded ferroelectric devices are utilizing thin-film ferroelectrics possessing a material composition gradient. The challenge for all lies in demonstrating devices meeting realistic specifications, with control in uniformity over large areas, repeatedly, and in quantities large enough to bring down the cost.

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