Critical National Need Idea Title:

Active Mode Detection with Enhanced Pyroelectric Sensitivity

Symetrix Corporation - Submitting Organization

Jolanta Celinska, Ricardo Unglaub , Christopher McWilliams, Greg Jones, and Carlos Paz de Araujo
Symetrix Corporation, 5055 Mark Dabling Blvd., Colorado Springs, Colorado 80918
Ph.: (719) 594-6145, Fax: (719) 598-3437, e-mail: jolanta@symetrixcorp.com

Delphi Technologies, Inc. - Contributing Organization

Scott Jones, Andrzej Pawlak, Jayson Pankin, and Timothy Forbes
Delphi Technologies, Inc., 5725 Delphi Drive, Troy, Michigan 48098
Ph.: (248) 813-4518, Fax: (248) 813-5008, e-mail: scott.jones@delphi.com

Key Words

Uncooled Multispectral Detector, Chopper-less, MEMS-less, Enhanced Pyroelectric Sensitivity

Abstract

Current pyroelectric detectors based on ferroelectric thin-films depend on an unbiased (passive) pyroelectric coefficient. They exhibit large fluctuations in the polarization values of the pre-poled materials (pedestal noise) and small signal values of the pyroelectric current. The team of Symetrix Corporation describes a comprehensive development program of focal plane array (FPA) detectors that incorporate active multispectral detection and are capable of providing greatly enhanced imaging performance using very low-cost fabrication techniques. Our MEMS-less pyroelectric sensor employs an active detection mechanism based on a strontium bismuth tantalate (SBT) ferroelectric sensing material. The device operation is based on fundamental pyroelectric effect of ferroelectrics in which the polarization state of the material is actively interrogated enabling improved signal to noise ratio, greater effective pyroelectric coefficient, and low fabrication cost chopper-less design. In addition to excellent sensor responsivity in the Infrared and lower wavelength bands and unlimited endurance, the unique design also enables selective wavelength tuning of the insulating layer and the absorber material to maximize the device responsivity to pre-selected wavelength bands down to a Middle UV wavelength range. This observed phenomenon of responsivity to shorter wavelengths in a pyroelectric device is presently being investigated as a "Broad-Band Spectrum Domain-Driven Dynamic Pyroelectricity Effect".

Introduction

The impact of infrared detectors continues to positively impact society through better monitoring of threat, infrastructure deterioration, extensive military applications, manufacturing processes and energy efficiency in buildings. The conventional infrared detectors are based on the VOX Microbolometer technology that was developed in the 1990's under DARPA funding and commercialized by Honeywell, L-3 and others for civilian and military markets. Over the years, the cost of IR detectors has dropped as annual volumes have reached 100,000 globally. However, the typical cost of an IR camera rarely drops below $5,000-15,000. This has stifled wide spread deployment in established markets e.g. only one per firehouse instead of one per fireman; lack of first responders deployment, and limited use in medical field among others. Uptake in the largest potential market, automobiles is in the low thousands.

New novel uncooled IR detector technologies potentially could drive down the cost of the "IR engine" and associated components leading the way to moving the market above 1M units per year. This would allow for real time, autonomous wireless networks to monitor for threat and failure key infrastructure-chemical and power plants, the electric grid as well as enable the departments of homeland security and defense to fulfill the various goals of surveillance and security that IR Detectors provide.

One such novel uncooled IR detector technology has been under development by Colorado based Symetrix Corporation in collaboration with auto supplier giant Delphi and Argonne National Laboratory. The transformation of a novel material, SBT from its established uses as a "memory material" for data systems to an IR Detector has been under development for several years. Delphi was the first company to introduce IR Detectors in motor vehicles in the 1990's in the Cadillac but the high cost made that "option" short lived. Recently BMW and Honda have introduced expensive IR Detection systems for high end vehicles. At the annual SPIE Conference, the gathering of the IR Detector industry promotes the peer review of new novel technologies. There is no shortage of compelling new technologies like Symetrix's SBT but there is a shortage of funding and a preoccupation with the industry leaders to take the mature VOX technology slowly down the technology lifecycle, investing little in disruptive technologies.

Global competition to innovate in the area of IR Detectors is keen with China, France and other countries providing a robust R & D environment for innovation. ITAR constraints limit collaboration with US firms who are cash constrained. NIST should provide incentives to catalyze the scientific community to meet the challenge of provide low cost IR Detectors for the myriad of applications that affect every American's safety and prosperity.

Significance of Development

In its developments for novel LWIR and other bands detectors, Symetrix has achieved a major breakthrough. Devices exhibit an effective pyroelectric coefficient much higher than competitive IR devices, an extremely reduced "noise-pedestal" (i.e. baseline thermal fluctuations) and a high signal/noise ratio during operation as described in [1]. In addition to the enhanced pyroelectric coefficients obtained, the device allows for spectral optimization of its responsivity using interferometric approach via quarter-wavelength tuning of the nanolaminates that comprise each pixel (absorber, ferroelectric, and thermal insulation).

It is now apparent that the Active IR Detection technique of pixel interrogation results in a responsivity across a much wider band of wavelengths than would be expected from passive irradiation-induced lattice absorption. The voltage response in preliminary trials appears roughly equivalent across the LIWR to UV range. We term this effect "Broad-Band Domain-Driven Dynamic Pyroelectricity Effect." Our recent understanding of this effect will underpin development of the Symetrix Active Multi-Spectral Detector.

The novel multi-spectral detector to be developed incorporates several key Symetrix innovations. These innovations are summarized below and are described more fully in the sections that follow:

- Use of a new sensing material platform, $SrBi_2Ta_2O_9$ (SBT), in film form, which exhibits a non-switching (passive) pyroelectric coefficient at least two times larger than that corresponding to the state of the art $Ba_xSr_{1-x}TiO_3$ (BST) material for films with thickness <200 nm.
- Operation based on continuous polarization switching of the SBT material at 10 – 20 kHz as the image is detected and strobed at 30 frames per second. The detector array is row scanned and buffered for charge accumulation.
- Due to the electronic switching in AC-mode, the image is produced without a chopper, yielding orders of magnitude reduction in noise, lower fabrication cost and improved long-term reliability (no moving parts).
- Strong in-pixel noise reduction achieved by a novel differential sensing scheme (similar to a memory sense amplifier) whereby a "reference pixel" is kept dark while switching. The signal from the reference pixel (noise pedestal) is subtracted from the exposed sensing pixel.
- Enhanced pyroelectric coefficient via optimization of the polarization switching voltage, switching frequency and integration over a number N of interrogation cycles which results in a drastic noise reduction and hence an increase in the SNR..
- Reduction in device noise by an order of magnitude. Noise drops by $\sqrt{N}$, where N is the number of charge integration cycles during the polarization switching in detector operation.
- Novel thermal isolation schemes: 1) use of a passive multi-spectral absorption layer based on the same SBT material used for the active layer; 2) use of a novel thermal barriers involving nanolaminate layers with embedded in-situ grown TiO_2 nanoparticles, which enhance phonon scattering, strongly reducing thermal transport below that of well known thermal insulation nanoscale heterostructure metal (W)/oxide (Al_2O_3) layers.
- Novel low-cost device fabrication process eliminates several etching steps. The Bi-based SBT detector material provides the basis for the development of a completely photosensitive film, which can be patterned without the need for costly reactive ion etching (RIE).

Development Status

The broad-spectrum dynamic pyroelectric sensor under development by Symetrix does not rely on bolometers or other high-cost MEMS-based methods for thermal isolation. The detector employs a ferroelectric sensing material consisting of strontium bismuth tantalate (SBT) configured as a capacitor. This capacitor is interrogated using a proprietary active detection mechanism. The pyroelectric effect is based on a property of ferroelectric materials that produces a change in the spontaneous polarization when exposed to a temperature change. The polarization value of the material is interrogated by means of an alternating electrical signal. The resulting sensor response, taken as the difference between the exposed and the dark sensor, is integrated over several cycles thus obtaining a greater effective pyroelectric coefficient and an enhanced signal to noise ratio (by cancellation of the common random noise and by integration of white noise over numerous signal response cycles).This design of the sensing mechanism eliminates the need of a costly, unreliable, and vibration-producing mechanical radiation chopper that is found in other pyroelectric IR systems. Thermal isolation of pixels is achieved using a planar materials system that, like all elements of the pixel array, is compatible with standard CMOS processing.

Preliminary test results of the Symetrix device performance have shown excellent responsivity in the long wavelength infrared band (LWIR), as well as in the medium infrared (MWIR), short infrared (SWIR), near infrared (NIR), visible, and ultraviolet (UV) spectral bands. In addition to the relative high thermal responsivity as compared with other IR sensors, the high endurance and novel design enables maximization of the responsivity for the distinct wavelength bands. This is accomplished by selective wavelength tuning of both the insulating layer and the absorber material using an interferometric approach.

One of the key performance factors applied in comparing IR Sensors is the "Noise Equivalent Temperature Difference" or NETD. Based on the NETD described in *Kruse* [1], a 20μm x 20μm pyroelectric pixel developed and tested at Symetrix provided an NETD of 23mK.

Table 1. Performance comparison of competitive FPA offerings

Manufacturer	IR Band	Model	NETD [mK]	Array Type
AGEMA	LWIR	880 LWB	70	175 pixels, thermal measurement system
Amber	MWIR	Radiance-1	25	256x256, InSb, measurement imager
Amber	LWIR	Sentinel	70	320x320, uncooled
Cincinnati	MWIR	IRRIS-160ST	25	160 pixels, InSb, compact imager
FLIR Systems	LWIR	2000F	100	>350 pixels, surveillance imager
Hamamatsu	MWIR	Themas-50	200	256x256, Microscope, 4um resolution
Inframetrics	MWIR	ThermaCAM	<100	256x256 Thermal measurement system
Mitsubishi	MWIR	IR-M600	80	512x512, PtSi, High definition imager
Nikon	MWIR	LAIRD-3	100	768x576, PtSi, High definition imager
Optronics	LWIR	LITE	200	350x175, hard-held surveillance imager
Quest	MWIR	TAM200	50	Microscope Bench System, 12.5um res.

As shown in Table 1, a very competitive product is achievable relative to other IR sensors and arrays. The process used by Symetrix for obtaining the sensor is relatively simple and economically superior, yielding a high performance FPA product at very low cost. Market research indicates that available applications for FPA products are highly price elastic and that a significant cost reduction will result in an explosive growth. FLIR, a leading supplier of FPA-based products compares this potential growth to the rapid growth of GPS devices that started as military-only and now have penetrated a significant share of the cell phone and other consumer markets.

During development and prototyping of readout circuitry for multi pixel arrays, and due to the sensitivity of the new circuit, it was possible to determine pixel responses from our devices (in the range of ~70mV to 300mV variation) to several non-infrared light sources that include visible and ultraviolet.

The paragraphs below provide the theoretical basis for active IR detection and the various processing requirements and circuit designs employed to realize low-cost, high performance IR as well as other lower wavelength bands FPAs.

Circuit Design

A simplified schematics of an active integration circuit that can accomplish the summation of equation, $Q_{total} = N \bullet Q_s = N \bullet A \bullet P_s$, with either Cf1 or Cf2 the sensing element and the other component the reference element is shown below in Fig. 1.

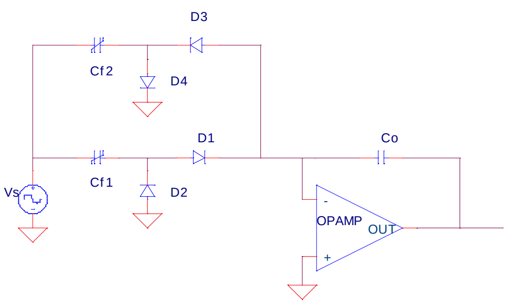


Figure 1. Simplified schematic of the device architecture and circuit design of the IR detector.

The active integration circuit serves a dual purpose. It integrates the available signal to improve the effective input in the follow-on amplifier and it averages the random noise where the signal to noise ratio improves as $N^{1/2}$ for the Gaussian noise. Thus, for N=330, the magnitude of the signal into the amplification element is improved by two orders of magnitude and the signal to noise ratio improves by a factor more than 18. The 10 kHz interrogation signal will be common to all pixels and a column-row selection and scanning mechanism will be utilized to gather the individual pixel charges using resettable row-integrators, a sample and hold matrix, multiplexer, and A/D conversion. The signal processing and control electronics will be implemented using an FPGA that will include defects and nonlinearity correction algorithms. A high definition frame grabber will include compression algorithms, GigE Vision or Camera Link Interface. Intermediate image storage memory as required by the image processing algorithms will be included.

Pixel Fabrication

The ferroelectric capacitors are isolated from the substrate via a novel nanolaminate of metal/oxide layers.

Incorporation of nanoparticles with the oxide layers provides an oxide-metallic thermal barrier that inhibits heat transport via scattering of phonons. Ti, Nb or Ta layers are grown followed by appropriate annealing to induce the growth of TiOx, NbOx, TaOx nanoparticles. Multiple formations of layered Ta/W or Ta/Al_2O_3 film will result in a layer with embedded nanoparticles that can impede the phonon propagation, thus thermal transport, leading to an efficient thermal barrier, as already demonstrated by Symetrix. Further, the unique pixel design shown in Fig. 2 enables selective wavelength tuning using film synthesis techniques applied to both the insulating layer and the absorber material. Such an interferometric approach will maximize responsivity for distinct wavelength bands.

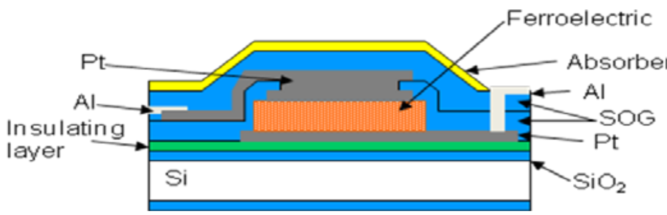


Figure 2: Pixel Crossection

Film Synthesis

Thin films of SBT are deposited on platinum coated silicon wafers (with a configuration of Pt/insulating layer/SiO_2/Si) using a conventional spin-on process in conjunction with Metal Organic Decomposition (MOD). The MOD precursor containing a polyoxyalkylated metal complex such as a metal alkoxide, metal carboxylate, or metal alkoxycarbonate diluted with solvent to a desired viscosity or molarity is dispensed onto the substrate much like a photoresist. The substrate is spun at certain number of revolutions per minute (rpm) to remove the excess fluid, to drive off the solvent, and to uniformly coat the substrate surface with the organic film. The soft metal-organic film is then pyrolyzed at 120°C to 300°C in air or oxygen to convert the metallorganic precursors to their constituent elements, oxides, or other compounds.

During this thermal decomposition, there is a substantial vertical shrinkage of the precursor film thickness. The degree of shrinkage depends on the number and length of the hydrocarbon chains attached to the metal atoms. The next step includes rapid thermal annealing (RTA) temperatures ranging from 700°C to 800°C in an oxygen atmosphere to form a crystalline metal oxide layer. The MOD process allows the deposition of very homogeneous films with high thickness uniformity. The chemical constituents or dopants may be adjusted by varying the concentration of the precursor materials added to the solution.

A Pt layer is deposited by sputtering, followed by patterning of the Pt and SBT layers via plasma etching to define the capacitor structure. The capacitors are crystallized and etch damage is usually recovered using the RTA at 750°C for 2 minutes in oxygen. The MOD approach may provide and inexpensive means of film deposition that is compatible with integrated circuit technology.

Multi-Spectral Detector Characterization

The SBT pixels are characterized for the dynamic pyroelectric coefficient at various excitation frequencies, different applied below saturation voltage, and capacitor areas. Hysteresis is measured using

HP54616B oscilloscope and HP8116A function generator. The instruments are operated and the data is recorded with Symetrix Othello software. A circuit with the load capacitor is used to examine the polarization of the device under test (DUT). When a voltage is applied to the DUT, the resultant voltage across the load is proportional to the charge displaced (or switched) within the DUT, related by the expression:

$$\mathbf{Q}_{switched} = \mathbf{C}_{load} \cdot \mathbf{V}_{load}$$

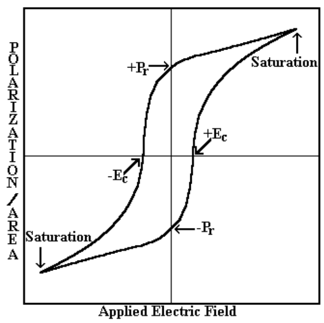


Figure 3

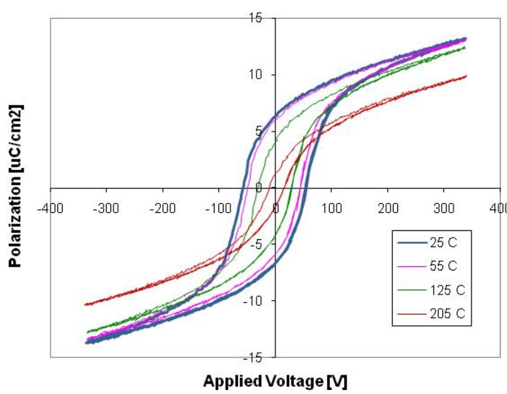
This switched charge is referred to as "polarization"—dipole moment per unit volume. In order to rate the relative performance of a given sample, it is often helpful to calculate this "polarization" (normalized to area) from the relationship:

$$P/A_{DUT} = (C_{load} \cdot V_{load})/A_{DUT}$$

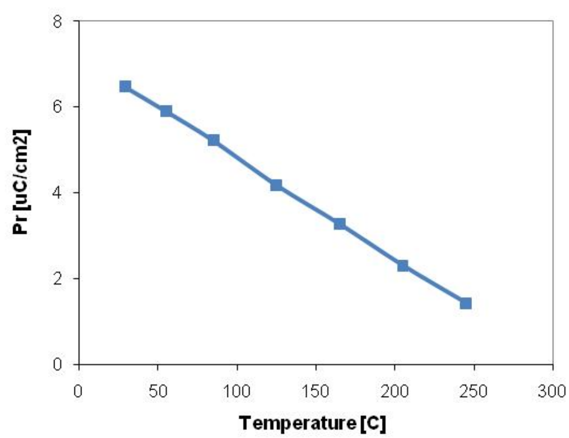
and plot this as a function of the applied electric field (or applied voltage). For a ferroelectric device, this yields the typical hysteresis loop (Fig. 3).

The polarization of the DUT at the two points where the hysteresis loop crosses the vertical axis (applied field =0) is the "Remanent Polarization", or "P_r" (+ or -) Thus we have $+P_r$ and $-P_r$**,** respectively. The applied field at the two points where the loop crosses the horizontal axis (polarization=0) is the "Coercive Field"; thus we have $+E_c$ and $-E_c$. These values provide the "figures of merit", $2P_r$ and $2E_c$, where: $\mathbf{2P_r = |{+P_r}| + |{-P_r}|}$ and $\mathbf{2E_c = |{+E_c}| + |{-E_c}|}$

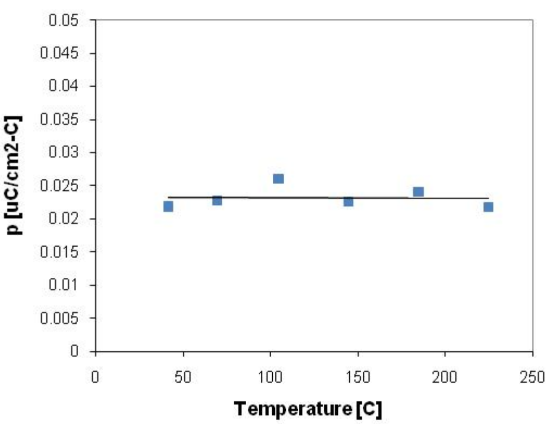
Variations in the remanent polarization and the hysteresis loop area (Fig. 4) with temperature behave as shown below in the polarization versus temperature diagram (Fig. 4b and 4c).



(a)



(b)



(c)

Figure 4. (a) Polarization hysteresis loops as a function of temperature;

(b) Remanent polarization vs. temperature;

(c) Residual from linear fit on (b)

The pyroelectric coefficient is given by $Pyro = \dfrac{\Delta P}{\Delta T}$ were P is polarization and T temperature.

The value of the SBT passive pyroelectric coefficient determined to be in the range of 0.024 □C/cm (a sensitivity two orders of magnitude higher than that of $BaTiO_3$) is expected to improve depending on the processing (film thickness, annealing temperature, etc.) conditions. The read-out electronics detects the polarization state of each ferroelectric pixel as these are interrogated via a triangular excursion signal at a rate of 10 kHz. The response to IR radiation results in a smaller area of the pixel's hysteresis loop. The signal response to IR from each "active" or exposed pixel is compared with that of a reference or "dark" pixel, and this difference is integrated for several cycles (N) of the interrogation signal via a resettable Integrator. A low noise post-amplifier is used to amplify and average, within a frame period (T < 1/30 s), the integrated difference between the active and the dark pixel (see Fig. 5).

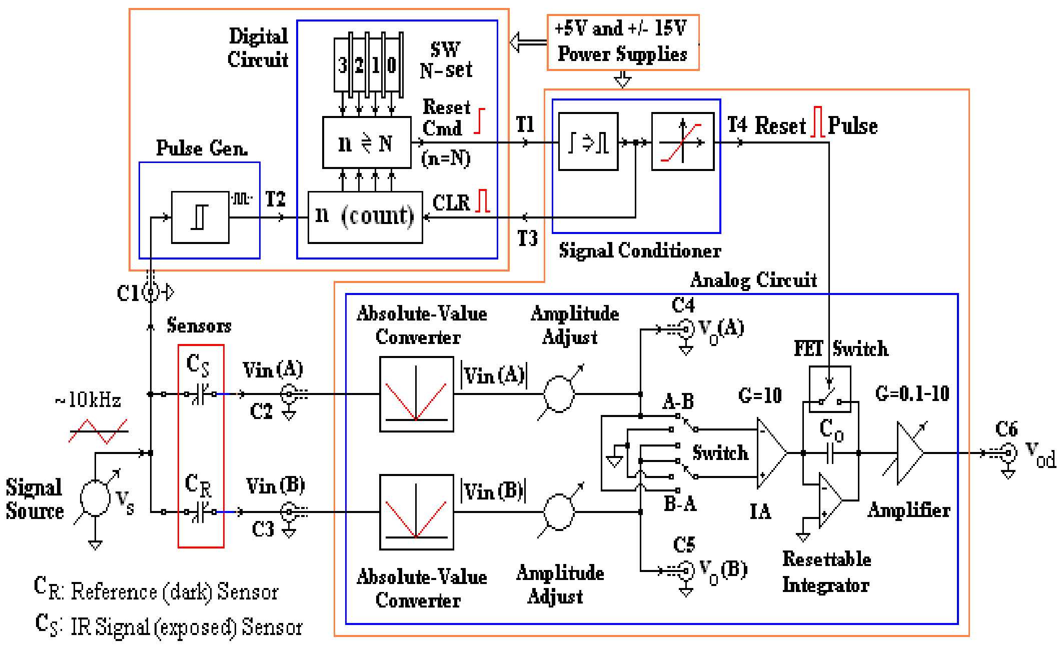


Figure 5: Functional block diagram of the sensing circuit

The pixel response to a thermal source is achieved via a power-controlled and regulated ceramic-type electric irradiance source placed inside an integrating sphere. The emitted radiation is measured using a calibrated Moll thermopile. The thermal source has been developed at Symetrix for the purpose of testing the responsivity of the pixels within different wavelength bands. The heat source also contains a Ge filter with antireflection (AR) coating for the LWIR band. The ability to use high-pass-filter and low-pass filter of different cutoff wavelengths permits the characterization of responsivity at other wavelength bands as well. The filters are commercially available and one-inch diameter filters are utilized in this design. The thermal source can hold between one and three filters.

Performance Measures

The key performance factors for FPA devices are a) Responsivity; b) Noise Equivalent Power; c) Noise Equivalent Temperature Difference (NETD) –Involves array and optics; d) Thermal Response Time; e) Minimum Resolvable Temperature Difference (MRTD) – Involves array, optics, electronics, display, and optics. All these measures, except MRTD, can be applied to a single pixel, to the average of all the pixels, in an array, or in histogram form to the distribution of values within the array. The blackbody temperature appropriate to a given measurement must be specified. Detailed explanation of these performance factors is available in *Kruse* [2] and *Lloyd* [3].

Additional testing to characterize detector responsivity can be performed with a collimated IR source and using a chopper-stabilized lock-in amplifier. The use of a cryogenically cooled and vacuum dewar can be used to test the detectivity (D*) of the pixels at the 77K-300K temperature range. Infrared optics F/1 for the LWIR band are utilized to acquire an image of the IR source. Nonlinearity response and uniformity is measured by exposing the full array to a uniform IR source. Uniformity can be characterized via computer algorithms based on each pixel's response deviation from the averaged or mean response.

Conclusion

Based on the apparent need for wide spread deployment of low cost IR detectors, it is imperative that appropriate investment into high risk disruptive technologies be awarded in order to meet critical goals in areas such as firefighting, first response, medical, security, infrastructure threat/failure detection, military, automotive, and so forth. The reluctance of industry leaders to invest in new and compelling technologies for a preoccupation to the mature VOX detector technologies has made it necessary for government agencies to become financially involved in order to meet the challenges of bringing low cost IR detectors into the hands of those who need them.

Technology such as the novel uncooled IR multispectral detector under development by Colorado based Symetrix Corporation in collaboration with Delphi and Argonne National Laboratory is just one example of the high risk, high reward research needed to address the critical need for low cost IR detectors in the United States. The transformation of a novel SBT material from its established uses as a "memory material" for data systems to an IR detector has been under development for several years with potentially breakthrough results. The use of well established low production cost materials such as SBT for IR detectors could drop the cost of such units down well below the $5,000-15,000 ceiling present in the current market as well as increase production to upwards of 1M units per year.

Due to its increasingly promising results and low cost of production, SBT based IR detectors are an excellent candidate to fulfill the current need of the United States for low cost IR detection systems.

References

1. Joseph V. Mantese et al., Applied Physics Letters **90**, (2007) 113503
2. Paul W. Kruse's book *Uncooled Thermal Imaging*, SPIE Press, 2002
3. J. M. Lloyd, *Thermal Imaging Systems*, Plenum Press, 3rd printing, 1982