

Miniature Uncooled Infrared Sensitive Detectors for *in Vivo* Biomedical Applications

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ABSTRACT

Broadband infrared (IR) radiation detectors have been developed using miniature, inexpensive, mass produced microcantilevers capable of detecting temperature differences as small as 10^{-6} K. Microcantilevers made out of semiconductor materials with dimensions of 50 to 200 μm long, 10 to 30 μm wide and 0.4 to 4 μm thick, undergo bending when exposed to IR radiation and can be used either as uncooled photon or thermal detectors. Mounted on a probe 1 mm in diameter a number of microcantilevers can be accommodated in the working channel of existing endoscopes for *in vivo* proximity focus measurements inside the human body.

Keywords: infrared detection, photon detector, thermal detector, *in vivo*, temperature mapping.

1. INTRODUCTION

Infrared (IR) radiation is the second most intense radiation band in our environment and its detection and imaging can find extensive uses in a number of industrial, commercial, and scientific applications. It is well known that the temperature of the human body may not be homogeneous at all times^{1,2}. Body activities and disease can be the cause of the temperature variations³⁻¹⁰. The external temperature of the body can be imaged using infrared cameras. For *in vivo* temperature measurements inside the human body, the size of the IR detector should be small to be accommodated in small probes (such as the working channel of existing endoscopes) for minimally invasive operation while short response time and high sensitivity are necessary.

Presently, there is a number of families of commercially available IR detectors, including thermopiles, bolometers, pyroelectrics, and various solid state detectors¹¹⁻¹⁶ which can be smaller than 1 mm in size. Thermopile detectors typically have a large thermal mass, low detectivities and long response times (> 10 ms). Microbolometers have much better rise times due to their reduced mass and thermal conductivity but they must be kept in vacuum conditions for adequate performance and are relatively expensive¹. Pyroelectric detectors require a modulated (AC) incoming IR signal for appropriate operation. Solid state (photon) detectors for the IR spectral region must generally be operated at reduced temperatures due to inherently high thermal noise. As a result, none of the above detectors is a good candidate for *in vivo* measurements inside the human body.

In this work, a new approach for producing light-weight, highly-sensitive, inexpensive micromechanical IR detectors is demonstrated. Microcantilever technology is used which is based on the bending of a microcantilever as a result of absorption of IR energy⁷. When a microcantilever is exposed to IR radiation, its temperature rises due to absorption of this energy. This microcantilever based IR detector operates at room temperature, is small in size, offering high sensitivity and short temporal response. Furthermore, by making two-dimensional arrays of small individual elements, IR imaging can be accomplished without the need for scanning a single element IR detector. These properties, makes this detector suitable for *in vivo* measurements inside the human body or in a remote location.

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2. OPERATIONAL PRINCIPLE

Bimaterial microcantilevers are constructed from materials exhibiting dissimilar thermal expansion properties (such as silicon nitride coated with a thin gold film). The bimaterial effect causes the microcantilever to bend in response to this temperature variation¹⁷. The extent of bending is directly proportional, in first order, to the rate of energy absorption, which, in turn, is proportional to the radiation intensity. Previous work has shown that microcantilever bending can be detected with extremely high sensitivity¹⁸⁻²⁰. For example, metal-coated microcantilevers that are commonly employed in atomic force microscopy (AFM) allow sub-Angstrom ($< 10^{-10}$ m) sensitivity to be routinely obtained. Recent studies have reported²¹⁻²⁴ the use of microcantilever bending for calorimetric detection of chemical reactions with energies as low as a few pJ. It was demonstrated²⁴ that a similar detector had an observed sensitivity of 100 pW corresponding to an energy of 150 fJ and use of the sensor as a femtojoule calorimeter was proposed. An estimate of the minimum detectable power level was on the order of 10 pW, corresponding to a detectable energy of 10 fJ and a temperature sensitivity 10^{-5} K. However, using an optimally designed microcantilever, the sensitivity may be improved even further. Hence, for applications in IR radiation detection, microcantilevers can be coated with appropriate absorptive materials such that they undergo bending upon exposure to photons (such as infrared or near infrared radiation). IR sensing microcantilevers can be 20 - 400 μm long, 0.2 - 4 μm thick and 5 - 50 μm wide, and made out of materials such as silicon nitride, silicon or other types of semiconductor materials. In Fig. 1, we show the electron scanning micrograph of a piezoresistive microcantilever that was used in the present studies. Due to the monolithic nature of these devices, they can easily be produced in one-dimensional and two-dimensional arrays with hundreds of microcantilevers on a single wafer. This type of fabrication scheme possesses obvious advantages when considering the production of infrared imaging systems with these microcantilever devices.

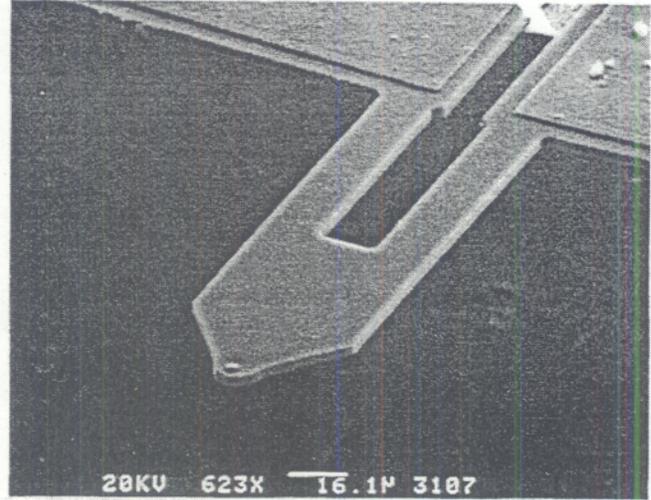


Figure 1. Electron scanning micrograph of a piezoresistive microcantilever used in the present studies.

When considering the bending of the microcantilever, a relationship between bending and the absorbed energy by the microcantilever is obtained by assuming a spatially uniform incident power, dQ/dt , onto a bimetallic microcantilever. The maximum deflection, z_{max} , due to differential stress is given by^{24,25}

$$z_{\text{max}} = \frac{5}{4} \frac{(t_1 + t_2) l^3}{(\lambda_1 t_1 + \lambda_2 t_2) w t_2^2} \frac{(\alpha_1 - \alpha_2)}{4 + 6 \frac{t_1}{t_2} + 4 \frac{t_1^2}{t_2^2} + \frac{E_1 t_1^3}{E_2 t_2^3} + \frac{E_2 t_2}{E_1 t_1}} \eta \left(\frac{dQ}{dt} \right) \quad (1)$$

where l and w are, the length and width of the microcantilever, respectively, t_1 and t_2 are the thicknesses of the two layers, λ_1 , λ_2 ; α_1 , α_2 ; E_1 , E_2 are the thermal conductivities; thermal expansion coefficients and Young's moduli of elasticity of the two layers; $\eta dQ/dt$ is the fraction of the IR radiation power absorbed. In order to increase the IR detection sensitivity of a microcantilever, the maximum deflection should be maximized which is strongly dependent on the geometry and thermal properties of the two layers. In the present work we demonstrated the importance of the microcantilever thickness on the deflection z_{max} and overall response to IR radiation.

3. INFRARED RADIATION DETECTION MEASUREMENTS

We used piezoresistive microcantilevers (Fig. 1) to perform IR radiation measurements in order to determine the response characteristics of our infrared detector. The experimental setup used is depicted in Fig. 2. A heated carbon rod was used as blackbody radiator and served as the IR source. An iris was used to reduce the spatial extent of the blackbody. A spherical mirror was used to collect the emitted IR radiation and focus it on the microcantilever detector. The use of a chopper allowed us to determine the modulation

frequency response of the microcantilever to IR radiation. The bending of the microcantilever was determined by measuring the change in the piezoresistance of the microcantilever. This signal was directly digitized and stored, or sent to a lock-in amplifier (SR850, Stanford Research Systems) for signal extraction and averaging. The piezoresistive microcantilever used consisted of a doped layer (boron) in the silicon microcantilever. The design and construction of these microcantilevers are described in detail elsewhere^{26,27}. The piezoresistance of these microcantilever varies when they undergo bending due to absorption of heat emitted from an IR source. Assuming a uniform heat dissipation over the entire length, l , of the microcantilever (of thickness t) the change in temperature at the tip, ΔT , ($\approx l^2/2\lambda t dQ/dt$) depends on geometrical factors such as l and t . A temperature change of $\Delta T = 10^{-4}$ K leads to deflections of ~ 1 nm which, in turn, results in a change in electrical resistance of $\Delta R/R \approx 3 \times 10^{-6}$. This can be used to determine the bending of the microcantilever as it absorbs IR photons.

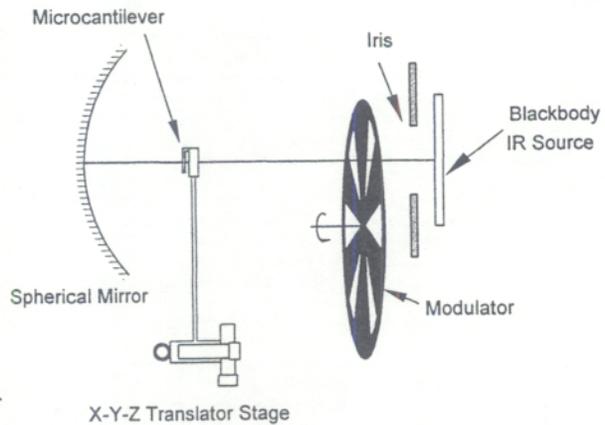


Figure 2. Experimental setup used in the present studies.

A commercially available piezoresistive microcantilever²⁸ was coated with ~ 50 nm of gold black which served as the IR absorbing material. The total resistance of the microcantilever was approximately 2000Ω which was electrically connected to one arm of a dc biased Wheatstone bridge circuit. Assuming a spatially uniform incident power, dQ/dt , onto a bimaterial microcantilever the maximum deflection, z_{max} , depends on the temperature rise²⁹ and is proportional to the incident power³⁰. The thermally induced deflection of the microcantilever is caused by the bimaterial effect which arises due to the difference in the thermal properties of the IR coating, the metal layer, and the native silicon body of the microcantilever. A reference voltage V_0 ($=9$ Volts) was applied across the circuit and the voltage difference $\Delta V(T)$ across the Wheatstone bridge circuit was digitized using a Tektronix TDS 544A digital oscilloscope or fed into a Stanford Research Systems SR850 lock-in amplifier. The measured voltage ΔV is related to the deflection of the microcantilever is given as $\Delta V(T) \approx 3/4 V_0 z_{max}(T) \times 10^{-6}$. We estimated the absorbed thermal power (in Watts) $P_{th} \approx 6.064 \times 10^{-17} [T_s^4 - (294)^4]$ where T_s is the temperature of the blackbody source. In Figure 3 we plotted the maximum bending z_{max} as a function of the P_{th} and it can be seen that they increase linearly with increasing power. From the slope of this line a deflection sensitivity of 0.125 (nm/ μ W) is obtained. Using a Stanford Research Systems SR 540 chopper to modulate the IR radiation at a frequency of 30 Hz, we calculated a noise equivalent power (NEP) of ~ 70 nW/Hz^{1/2}.

Since the response of any thermal sensor depends on both the amount of heat falling onto the detector and the length of time it was exposed to the incoming IR radiation, we measured the deflection, z_{max} , as a function of modulation frequency of the IR radiation (Fig. 4). It can be seen that the detector response (and the deflection of the microcantilever) decreases with increasing modulation frequency. The temporal response of the temperature sensor was also determined by measuring the deflection z_{max} , as a function of time. The microcantilever thermal detector was found to exhibit two thermal response times due to the incoming IR radiation; a time $\tau_{th}^1 < 1$ ms and a time τ_{th}^2 that is somewhat longer (~ 10 ms). The fast thermal response is attributed to thermal equilibrium between the top (exposed to the IR radiation) and the bottom surfaces while the longer thermal response results from the heat flow (along the body of the microcantilever) to the supporting base. Depending on the IR application the short thermal response times can be enhanced to achieve detection in relative short times.

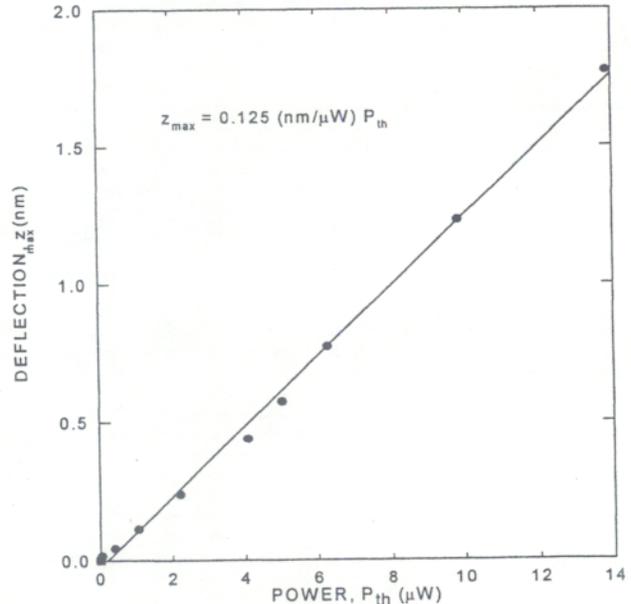


Figure 3. Deflection, z_{max} , of the piezoresistive microcantilever as function of the absorbed thermal power.

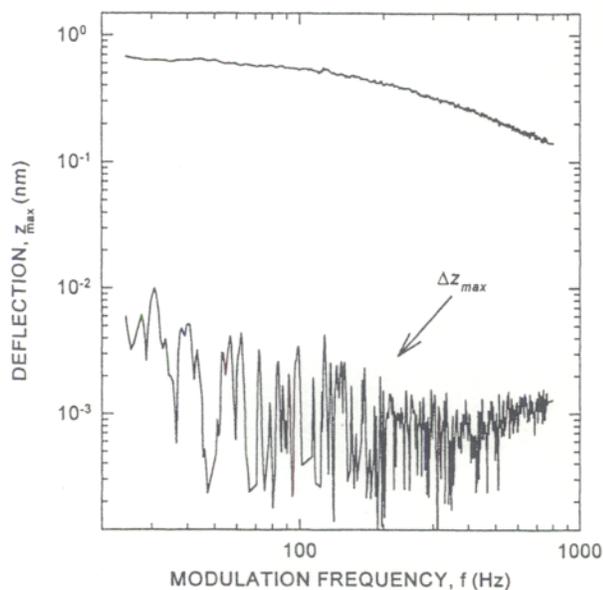


Figure 4. Deflection noise, Δz_{max} , and deflection, z_{max} , of the infrared microcantilever detector as function of modulation frequency.

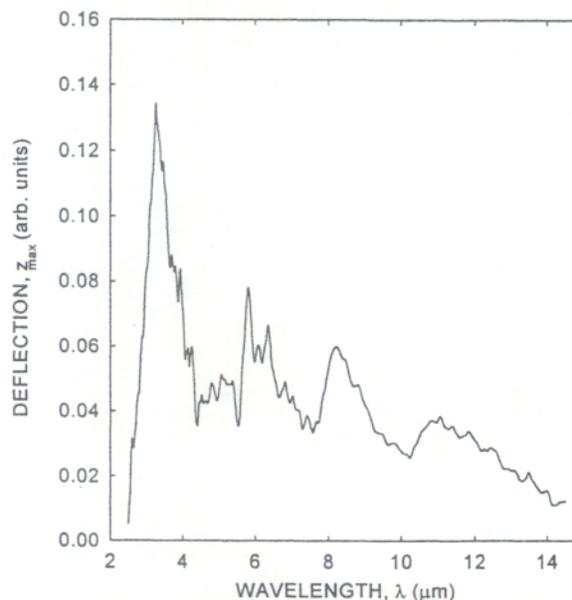


Figure 5. Response(deflection), Δz_{max} , of the infrared microcantilever detector as function of infrared wavelength.

We used a Miran-80 spectrometer to measure the spectral response of the piezoresistive microcantilever in the wavelength region 2.5 μm to 14.5 μm (see Fig. 5). The IR source of the spectrometer consisted of a nichrome wire wound resistor heated at a temperature of ~ 1273 K creating a blackbody radiator. As it can be seen from Fig. 5 the microcantilever exhibits an appreciable IR response over the entire wavelength region. Since the spectral response was measured in ambient atmosphere, IR absorption bands of various species (*e.g.*, CO_2 , H_2O , etc.) can be observed.

The IR response of piezoresistive microcantilevers was determined for a number of different microcantilever thicknesses. The IR response was measured as a function of modulation frequencies up to 1200 Hz for four different values of t and is plotted in Fig. 6. As can be seen from Fig. 6, the thickness of the microcantilever is very important in the performance of this detector. From Fig. 6 it can be seen that the microcantilever thermal detector exhibited no appreciable drop in IR response even for the highest modulation frequencies used. Therefore, an upper limit for the thermal response times of less than a few ms can be obtained.

Thermal imaging was also carried out using piezoresistive cantilevers¹⁸ (Fig. 1). The experimental set-up for the microcantilever infrared imaging device is similar to the one shown in Fig. 2. The IR imager consists of an aluminum-coated spherical mirror to collect and focus the radiation from the object to be imaged. The mirror focuses all of the radiation (including visible) to a focal plane forming an image. The thermal image that was formed in the focal plane was imaged with a piezoresistive microcantilever. The infrared image represents the variations in

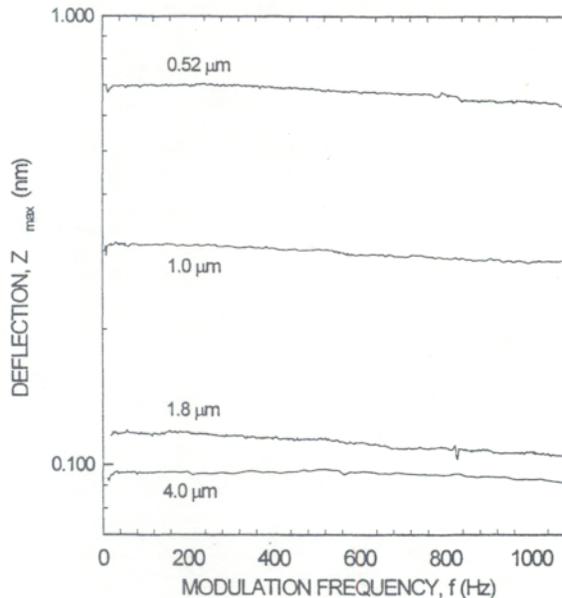


Figure 6. Response (deflection) of a microcantilever as a function of modulation frequency for different values of thicknesses.

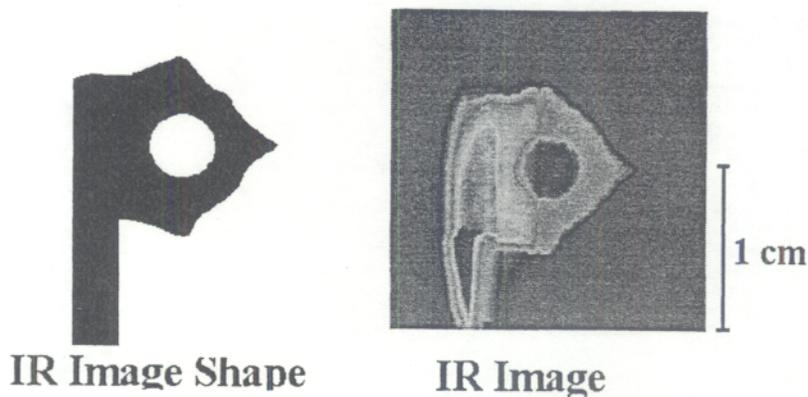


Figure 7. The image on the left shows the shape of the infrared source while the right-hand-image shows the infrared image acquired with the microcantilever thermal detector.

lock-in amplified microcantilever bending signal caused by thermal bending of the microcantilever as it was scanned over the image plane of the focusing mirror. This bending was monitored as resistance changes in piezoresistive layer on the microcantilever and was displayed as a two-dimensional image of the object. The position of the microcantilever at the focal plane was determined by obtaining line scans and adjusting the position for maximum edge contrast.

The focusing mirror consisted of a 14 cm diameter aluminum coated mirror with focal length approximately 7 cm. The IR source was a 1.3cm×1.3cm optically-black copper plate of 1 mm thickness with a shape shown in Fig. 7. The size of the hole at the center of the source was 5 mm. The source was placed at a distance of 27.4 cm from the mirror. To avoid the room temperature background, the source was heated to 250° C using an attached soldering iron. The infrared image of the object that was formed at the focal plane of the mirror was scanned by a thermally sensitive microcantilever attached to a x-y translational stage with steps of 400 μm over a 2 cm area in both planar directions. The microcantilever bending magnitude (AC) varies with photon flux (heat) of the thermal image and was monitored through the recording of changes in the piezoresistance of the microcantilever using a Wheatstone bridge circuit with an instrumentation amplifier programmed with a gain of 100. The quantification of this IR signal was accomplished by using a mechanical chopper positioned at the IR radiation source and using a lock-in amplifier (Stanford Research Systems Model SR850, Palo Alto, CA) with inputs from the synchronous signal of the mechanical chopper as a trigger and from the output of the Wheatstone bridge circuit. Images were acquired with a chopped frequency of 50 Hz and lock-in amplifier time constant of 300 ms. A programmed wait state of 1 second was present within the translation stage's make-up resulting in an appreciable oversampling of the IR signal at each x-y position.

The right image in Fig. 7 shows the IR image of a copper piece with a definite shape and a hole (right image) heated to a temperature of 250° C. The area scanned by the microcantilever sensor was 2 cm× 2 cm. The image consists of 175×50 pixels due to the over sampling mentioned before. Although smaller pixel sizes were possible with our scanning device, larger pixel size was selected to save time needed to scan the image with this single detector element. The sharpness of the image can be seen in Figure 7 which shows a horizontal line scan along the center of the object (cross-section).

4. DISCUSSION

The results of the present study demonstrate that IR radiation or temperature measurements are possible using piezoresistive microcantilevers representing a new development in uncooled IR detector technology. The microcantilevers employed were based upon commercially available micromachined cantilevers originally developed for AFM applications. Since the spectral response of microcantilevers can be easily tailored through the application of specific absorptive coatings, choice of material for fabrication of the microcantilever can be determined primarily by the requirements of a particular application. IR imaging devices could be constructed by using two dimensional arrays of such microcantilevers. Although the actual measurement of the microcantilever deflection in the present study was achieved using a piezoresistive technique, other ways to detect the bending could also be employed. The bending of

microcantilevers can be measured with extremely high sensitivity using optical, capacitive or piezoresistive detection schemes. Considerably improved detectors for thermal sensing can be produced by making changes in the geometry and using materials with desired thermal isolation and expansion properties in the fabrication of microcantilevers. For example, high thermal expansion bimaterial coatings (such as films of Al, Zn, Pb, or In) could be used to increase the thermally-induced bending of the microcantilever. Since the spectral response of microcantilevers can be easily tailored through the application of specific absorptive coatings, choice of material for fabrication of the microcantilever can be determined primarily by the requirements of the manufacturing process. This means that microcantilevers can be fabricated using standard semiconductor methods and materials, and as a consequence could be mass produced at very low cost. Hence, two-dimensional microcantilever arrays based on the technology described here could become very competitive with existing technologies due to their inherent simplicity, high sensitivity, and rapid response to IR radiation.

The small size, high sensitivity, short temporal response and easy to use of the microcantilever IR detector makes it an ideal tool for *in vivo* temperature measurements inside the human body or in a remote location using specially designed probes. This IR detector can be positioned at the tip of a probe smaller than 3 mm in diameter to fit in the working channel of existing endoscopes. The bending can be measured using the capacitance or the piezoresistivity of the microcantilever using appropriate wiring located inside the probe. The only requirement may be the enclosure of the detector inside a small IR-radiation transparent capsule in order to isolate the microcantilever from the liquid environment inside the human body. Two dimensional scanning using a microprobe to reach a remote location will allow for a temperature mapping at high scanning speeds attributed to the high sensitivity and temporal response of the detector. The use of 20 μm size microcantilevers in arrayed schemes located at the tip of the microprobe can increase the spatial resolution and scanning speed. Choice of appropriate microcantilever material will allow the desired spectral response to be matched with the photon absorption characteristics of the tissue in the middle and/or far IR which, in turn, will permit *in vivo* superficial or mm-depth color IR imaging. The low cost of this IR detector in combination with the simplicity of measuring the IR-radiation generated signal makes the microcantilever detector a good candidate for continuous monitoring of the temperature in a location in the surface or inside the human body.

5. CONCLUSIONS

In summary, we have demonstrated the infrared detection and imaging capability of a microcantilever thermal detector using a single microcantilever element. The images were obtained by scanning the focal plane of the IR image using a piezoresistive microcantilever controlled with a bi-axis translation stage and displaying the microcantilever response with a lock-in amplifier. Even at this early stage, the ability of the microcantilever thermal detector to obtain thermal images demonstrates its great potential as a sensitive, uncooled infrared imaging device. This concept can be used as a basis for novel, less-expensive, uncooled infrared cameras. Advantages of this concept include its miniature size and ease with which mass production may be initiated due to the monolithic character of the sensing unit. The need for scanning can be avoided by using microfabricated cantilevers in a pixel array which will significantly reduce the time needed for obtaining thermal images.

6. ACKNOWLEDGEMENTS

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