Uncooled thermal imaging using a piezoresistive microcantilever

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The operation of an uncooled, microcantilever-based infrared (IR) imaging device is demonstrated. Bending of the microcantilever is a function of the IR radiation intensity incident on the cantilever surface. The infrared image of the source is obtained by rastering a microfabricated cantilever over the image formed at the focal plane of a concave mirror. The bending variation of the microcantilever, as it scanned the focal plane of the mirror, is used to construct an infrared image of the source in front of the mirror. The thermal image obtained by scanning a single element cantilever is presented. © *1996 American Institute of Physics.* [S0003-6951(96)04247-7]

Infrared (IR) imaging has extensive industrial, military, and commercial applications, including: remote monitoring of facilities and equipment; process control; surveillance; night vision; collision avoidance; and medical imaging. At present there are several families of commercially available IR detection devices which may be classified either as quantum, such as photoconductors (intrinsic or extrinsic), photovoltaics (photodiode), photocathode materials; or as thermal detectors, such as bolometers, pyroelectrics, thermopiles, Golay cells, and superconductors [photoelectromagnetic detector (PED)].[1–4] For the quantum (or photon) detectors, incident IR radiation is converted into an electronic response through a direct interaction of the radiation with the atomic lattice of the material, while the thermal detectors IR radiation is converted into heat which is subsequently detected through temperature changes in the detector. For the quantum detectors, cryogenic cooling is often necessary to reduce the contribution of thermally generated electrons (dark current).[3] Typically, the size limiting component for these cryogenically cooled IR detectors is the cooling element itself. Additional complications arise when considering the power needs for maintaining the low temperatures of these devices. Therefore, an uncooled IR detection technique has many advantages including reduced size, lower power consumption, and diminished cost.

Traditionally, IR imaging is based on detectors fabricated from compound semiconducting films which offer small element sizes and fast response times. This technique, however, requires complex process technology and the elements typically require cooling, as mentioned before. These limitations make them unsuitable for a considerable number of applications. During the past decade great strides have been made in the development of uncooled infrared imagers. These uncooled imaging arrays are based on thermal detection. Recently, uncooled microbolometers and ferroelectric based devices have achieved sufficient resolution and speed to obtain real-time images of high quality.[5] Nevertheless, there remains a need for further technological improvements resulting in more sensitive, inexpensive, and rugged uncooled thermal imagers.

It has been shown by several groups that instrumentation methods originating from scanning probe microscopy concepts have been applied to a variety of both chemical and physical sensing applications.[6–31] Among these are the detection of IR and thermal energy. Kenny *et al.* have employed a tunneling junction on top of a enclosed volume topped with a membrane surface as a method for IR detection.[15–17] Majumdar *et al.* have developed a thermocoupled atomic force microscopy cantilever for obtaining contact-mode thermal images of surfaces.[18–20] Both Marti *et al.*[21] and Allegrini *et al.*[22] have investigated laser-induced thermal processes on force microscopy cantilevers while Umeda and co-workers have utilized photothermal-induced vibrations for imaging purposes.[23] Chmielowski and Witek have proposed a tunneling thermometer design that converts the energy of thermal oscillations of a cantilevered beam into electrical signal through a modulated tunneling junction current.[24] Gimzewski *et al.* have investigated the application of microcantilevers for calorimetry and photothermal spectroscopy on the lever surface.[25–28] Our group has investigated the application of microcantilevers for remote IR detection utilizing both piezoresistive and optical deflection monitored cantilevers.[5,29–31] In this letter we present the first remotely obtained IR image with a microfabricated cantilever sensor. The IR image of the object was obtained by scanning the thermal image of the object formed at the focal plane of a spherical mirror using a single cantilever element.

The temperature sensitivity of the cantilever arises due to a differential expansion from a temperature gradient within the cantilever profile (vertical depth) upon exposure to IR radiation which induces vertical deflection of the cantilever, or by the bimetallic effect when a dissimilar material is plated upon the cantilever structure. In both situations the IR radiation flux upon the cantilever was converted into a measurable cantilever deflection. Sensitive microcalorimeters using cantilevers have been demonstrated with theoretical sensitivities of 10^{-5} K.[25,32] Details pertaining to the principle of operation of microcantilever IR detectors have been previously reported by many researchers; further elaboration on this subject along with specific characteristics of the IR sensor used for these results can be found in several references.[5,25,26,29–33]

Thermal imaging was carried out using commercially available piezoresistive cantilevers (Park Scientific Instru-

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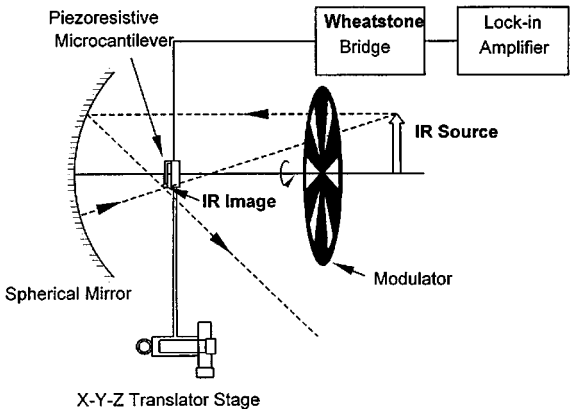

FIG. 1. Experimental setup used for infrared image acquisition.

ments, Inc., Sunnyvale, CA) with nominal dimensions of 151 μm long by 50 μm wide by 4 μm thick with a double-legged geometry in each leg having a width of 15 μm.[34–38] Typical vertical force constants for these levers were of the order of 10 N/m. The experimental setup for the cantilever infrared imaging device is shown in Fig. 1. The imager consists of an aluminum coated spherical mirror to collect and focus the radiation from the object to be imaged. The mirror focused all of the radiation (including visible) to the focal plane forming an image. The IR image that was formed in the focal plane was imaged with a piezoresistive cantilever. The IR image represents the variations in lock-in amplified cantilever bending signal caused by thermal bending of the cantilever as it was scanned over the image plane of the focusing mirror. This bending was monitored as resistance changes in piezoresistive layer on the cantilever and was displayed as a two-dimensional image of the object. The position of the cantilever 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-diam aluminum coated mirror with focal length approximately 7 cm. The IR source was 1.3×1.3 cm^2 optically black copper plate of 1 mm thickness with a shape shown in Fig. 2. 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 IR

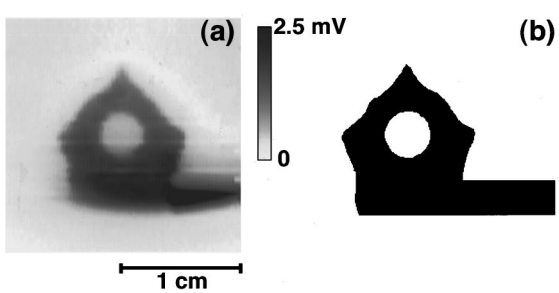

FIG. 2. (a) Shows the infrared image acquired with the micromechanical detector. Calibration of the grey-scale image is given in signal output of the lock-in amplifier (LIA) with dark color representing hotter area and light areas cooler. (b). A properly scaled silhouette view of the heated metal piece used in generating the infrared image.

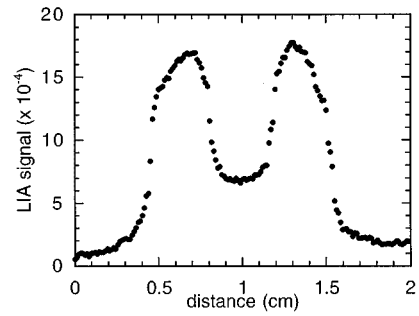

FIG. 3. Shows a horizontal cross-sectional cut of the lock-in amplifier signal through the center of the hole in the infrared image of the previous figure.

image of the object that was formed at the focal plane of the mirror was scanned by a thermally sensitive cantilever attached to an $X-Y$ translational stage with steps of 114 μm in X and 400 μm in Y over a 2 cm area in both planar directions (X and Y are defined as the horizontal and vertical directions of the image, respectively, as shown in Fig. 2). The cantilever bending magnitude (ac) varies with photon flux (heat) of thermal image and was monitored through the recording of changes in the piezoresistance of the cantilever using a Wheatstone bridge circuit with an instrumentation amplifier programmed with a gain of 100.[5,31] 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 50.9 Hz and lock-in amplifier time constant of 300 mS.

The left-hand image in Fig. 2 shows the IR image of a copper piece with a definite shape and a hole (right-hand image) heated to a temperature of 250 °C. With the area scanned by the cantilever sensor of 2×2 cm^2 and the average steps in X and Y mentioned above, the corresponding pixel density of the image was 175×50 in the X and Y directions, respectively. Although smaller translation steps were possible with our scanning device, larger ones were selected to save time needed to scan the image with this single detector element. The sharpness of the image can be seen in Fig. 3 which shows a horizontal line scan along the center of the object (cross section).

Several experiments have been performed to eliminate the possibility that the resistance variation in the piezoresistive cantilever was due to photogenerated carriers. First, in experiments using an infrared source with broad-bandpass IR filters of 3–5 and 8–12 μm with optical deflection monitoring of the piezoresistive cantilever shows substantial deflection of the cantilever.[30] Second, measurements of piezoresistive cantilever response for optical wavelengths of 2–14 μm in a dark room showed an appreciable deflection signal.[31] Furthermore, the IR image showed no appreciable change with room lighting levels. From these results, it was concluded that the most significant contribution to the image originated from infrared radiation.

In summary, we have demonstrated the infrared imaging capability of a cantilever using a single cantilever element.

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The images were obtained by scanning the focal plane of the IR image using a piezoresistive cantilever controlled with a biaxis translation stage and displaying the cantilever response with a lock-in amplifier. Even at this early stage the ability of the cantilever device to form 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.

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