"Self-leveling" uncooled microcantilever thermal detector

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Bimaterial microcantilevers can be used as highly sensitive uncooled infrared (IR) detectors. Since the transduction efficiency of microcantilevers depends on their deflection, it is important to minimize cantilever deflections caused by factors other than IR radiation (e.g., intrinsic mechanical stresses and ambient temperature fluctuations). In this letter we report on a design of a microcantilever IR detector that is immune to ambient temperature changes and other sources of interfering mechanical stresses. We modeled and experimentally measured responses of such devices to IR radiation as well as to ambient temperature changes. Both modeling and experimental results indicate that the implemented innovative designs can combine excellent IR sensitivity with negligible sensitivity to the ambient temperature changes. © *2002 American Institute of Physics.*
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Detection of infrared (IR) radiation is of great importance to a number of civilian and military applications. However, the high cost of IR imagers has limited their use to primarily military applications. Advances in microelectromechanical systems have led to the development of highly sensitive micromechanical thermal detectors that can also operate as low-cost uncooled infrared detectors.[1–7] Previous studies[7,8] have shown that bimaterial cantilevers respond sensitively to ambient temperature changes as well as to absorbed IR photons. Since the signal transduction in microcantilever IR detectors relies on the measurement of the microcantilever deflections, several readout techniques that provide information not only from single microcantilevers[4,9] but also from IR-imaging arrays[8] have been developed. The performance limits of microcantilever thermal detectors depend on a number of parameters and, under ideal conditions, are mainly defined by temperature fluctuation noise. In fact, the contribution of the readout to the total noise can be neglected when an optical readout is used.[2,9–11] Detailed comparative analysis of the performance of uncooled thermal IR detectors and cooled quantum IR detectors has been a subject of several studies.[12,13] Cooled IR photon detectors typically have noise equivalent temperature (NETD) in the range of 1–20 mK and uncooled thermal IR detectors have NETD in the range of 20–200 mK. Microcantilever IR detectors can have NETD as small as 5 mK[6] which can make them competitive with both cooled photon detectors and uncooled thermal detectors.

However, several important issues need to be addressed before the full potential of microcantilever IR imaging detectors can be realized. They are (i) mechanical noise inherent in micromechanical systems, (ii) nonuniformity of microcantilevers in large arrays, and (iii) very high sensitivity of thermal IR detectors to the ambient temperature changes. The effects of mechanical noise can be largely eliminated, by tailoring the resonance frequencies and the stiffness of microcantilevers.[9–11] The goal of this work is, therefore, to address the two remaining issues, i.e., the pixel nonuniformity in microcantilever arrays and their high sensitivity to the ambient temperature. It is important to emphasize that all types of thermal IR detectors developed previously are equally responsive to local temperature changes, due to IR signal, and ambient temperature changes.[12] In addition to direct interference between the IR input and the ambient temperature, this means that the dynamic range of any thermal IR detector is dramatically reduced unless the device temperature is constant. In the case of traditional thermal IR detectors, such as microbolometers,[12] thermoelectric coolers are used in order to stabilize the detector temperature and, therefore, eliminate the adverse effects of ambient temperature changes. In the case of microcantilever IR detectors, it is also important to minimize initial intrinsic mechanical stress, which is the main cause of nonuniformity in large microcantilever arrays. In fact, it is a formidable challenge to reproducibly fabricate large uniform microcantilever arrays with each pixel parallel to the substrate plane.

In this letter, we report on a microcantilever design which provides a built-in mechanism of distinguishing between the heat produced by absorbed photons, and the interfering effects of ambient temperature fluctuations and fabrication-induced stresses. Our computational and experimental studies of the microcantilever detector clearly demonstrate that its optically probed area remains practically unaffected by these interfering factors. Our previous work on microcantilever detectors involved designs, such as the "pentalever" geometry[14,15] with folded (serpentine-shaped) bimaterial regions. While the main rationale of the pentalever geometry was to improve thermal isolation, the neighboring bimaterial legs tended to cancel each other's thermal response. The latter phenomenon substantially reduced the detector sensitivity to the ambient tempera-

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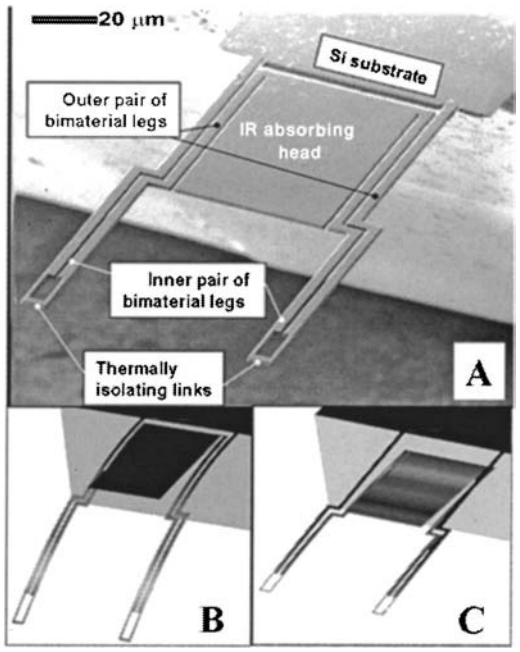

FIG. 1. Microphotograph (inset A) and three-dimensional thermomechanical models (insets B and C) of the microcantilever with a built-in mechanism of compensating ambient temperature changes. Inset B shows deformation of the cantilever caused by an ambient temperature change: simultaneous bending of the two pairs of bimaterial legs does not translate into deflection of the head. Inset C shows bending of the inner pair of legs and associated deflection of the head in response to a heat produced within the head.

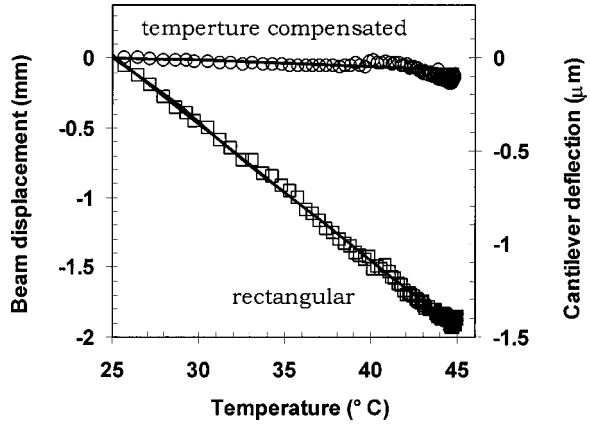

FIG. 2. Comparison of the responses to ambient temperature changes measured for the designed temperature compensated (○) and simple rectangular (□) bimaterial microcantilevers and the respective theoretical predictions (solid lines).

ture and intrinsic stresses. The objective of the refined microcantilever design studied in this work is to further minimize the sensitivity of the bimaterial cantilever to the ambient temperature, to maximize its responsivity to IR photons, and to improve compatibility with large array formats.

We studied a cantilever geometry [Fig. 1(a)] that is composed of four distinct regions: (i) an IR absorbing "head," (ii) an inner, thermally responsive pair of bimaterial "legs," (iii) an outer temperature-compensating pair of bimaterial legs, and (iv) a pair of thermal isolation regions (links) between the bimaterial legs. The IR absorption region consisted of 800 nm thick silicon and a layer of platinum. The bimaterial regions (legs) had a 150 nm gold coating on a silicon layer of the same thickness as in the IR absorbing area. We applied finite element analysis to the geometry shown in Fig. 1 in order to model the microcantilever deflections as a function of temperature and heat flux due to IR absorption. The material properties used in our calculations are given in Table I.

Our thermomechanical modeling for the microcantilever shown in Fig. 1, included two cases: (i) responses to temperature changes and (ii) simulated responses to IR. The substrate was constrained during this analysis and the loading conditions were varied to account for each of these cases. First, the substrate and the suspended structure were simultaneously subjected to a series of uniform temperature loads, corresponding to changes in the ambient temperature from 0 to 45 °C with 2 °C increments. In case (ii), a heat flux of 1 μW was applied only to the head region while the substrate supporting the cantilever was remained at 0 °C. For purposes of comparison, the same analysis was also applied to a simple rectangular microcantilever with the same bimaterial structure and the same effective length as the legs of the structure shown in Fig. 1.

In Fig. 1, insets B and C in the figure show a three-dimensional illustration of our modeling results. Change in the ambient temperature induced pronounced bending of both, inner and outer, pairs of the legs in the same directions. Equal bending of the adjacent legs, however, does not translate into deflection of the head (Fig. 1, inset B). For a uniform ambient thermal load of $\Delta T = 20\,°\mathrm{C}$, the maximum deflection of the head area was only 55 nm, while the corresponding deflection at the outmost ends of the legs was 1.914 μm (Fig. 1 inset B). The latter value agrees well with the response of a rectangular, 150 μm long, microcantilever to the same ambient temperature change (Fig. 2). When a heat flux of 1 μW was applied to the head of the microcantilever shown in Fig. 1, the maximum deflection of the head was 15 nm [Fig. 1(c)]. Under these conditions, the maximal temperature increase of the head area was calculated to be 0.4 °C.

We also experimentally verified that the effect of the ambient temperature was drastically reduced in the case of microcantilevers with the self-leveling geometry (Fig. 1). In these experiments, the microcantilever was mounted on a stage with a resistive heater which was used to vary the

TABLE I. Material properties used in finite elements modeling.

Material	Density ρ (10^3kg m^{-3})	Young's modulus E (GPa)	Thermal expansion coefficient CTE (10^{-6} K^{-1})	Poisson's ratio v	Thermal conductivity g (W m^{-1} K^{-1})
Gold	19.32	77	14.4	0.42	301
Silicon	2.33	112.4	2.5	0.28	163

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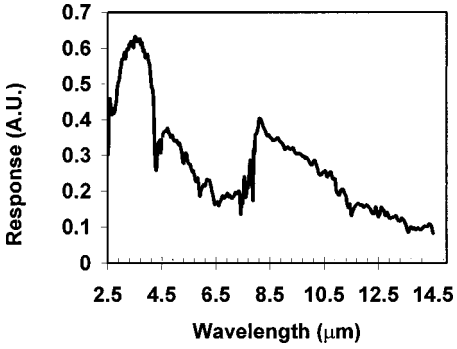

FIG. 3. Measured responses of the temperature compensated bimaterial microcantilever to IR radiation in the range of 2.5 to 14.5μm.

microcantilever temperature. A chromel–alumel thermocouple was used to monitor the temperature of the stage. The optical readout of microcantilever deflections was carried out according to the optical lever scheme[9] with a position sensitive detector positioned at 5 cm from the cantilever. Figure 2 shows the effect of the ambient temperature on the rectangular microcantilever and the designed IR detector with built-in temperature compensation. The effective length of the bimaterial part was the same in the both cases. A significant response to a 20 °C temperature change was produced by the detector with a simple rectangular geometry but not with the ''self-compensating'' design. The data shown in Fig. 2 provide clear experimental evidence that the two pairs of bimaterial legs (see Fig. 1) provided efficient leveling of the probed area when the ambient temperature changed from 25 to 45 °C. The magnitudes of the temperature induced microcantilever deflections experimentally measured for the two types of microcantilevers are in good quantitative agreement with the results of modeling (Fig. 2, solid lines). The small deviations of the measured deflections from the theoretical predictions can be attributed to nonzero gradients of the air temperature in vicinity of the heater and the heated microcantilever.

Finally, responses of the microcantilever shown in Fig. 1 to IR radiation were also measured experimentally in the wavelength range of 2.5–14.5 μm. We used an IR spectrometer to obtain the response as a function of photon wavelength. Figure 3 shows the measured microcantilever deflection responses as a function of wavelength. The specific features of the spectrum shown in Fig. 3 reflect a combination of the spectral power density for a blackbody source, the monochromator throughput, and the detector spectral sensitivity. The overall tendency to stronger responses in the shortwave region correlates with the spectral density of the blackbody source at 900 °C. The two distinct peaks around 3.75 and 8.5 μm are attributable to the enhanced IR absorption in the optical resonance cavity formed by an 800 nm silicon layer and a 150 nm reflecting platinum layer. It should be noted that microcantilever detectors of different shapes, including a simple rectangular geometry (i.e., 50 μm wide and 200 μm long) were investigated and, as expected, found to exhibit similar spectral characteristics when the parameters for the silicon and gold layers were kept the same as before.

In summary, we have demonstrated a design of a microcantilever based thermal micromechanical detector that intrinsically differentiates between the thermal effect of absorbed IR photons and variations in the ambient temperature. Although the microcantilever geometry investigated in this work was applied to the detection of IR photons, the same idea can be used when designing gas and liquid phase microcantilever chemical sensors,[16] which are also adversely affected by ambient temperature fluctuations. This is particularly true when the readout scheme is sensitive to microdevice rotation. More importantly, the approach described here offers the possibility to eliminate the interfering effects of the ambient temperature independently of the materials chosen for microcantilever fabrication.

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