Remote infrared radiation detection using piezoresistive microcantilevers

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A novel micromechanical infrared (IR) radiation sensor has been developed using commercially available piezoresistive microcantilevers. Microcantilevers coated with a heat absorbing layer undergo bending due to the differential stress between the top layer (coating) and the substrate. The bending causes a change in the piezoresistance and is proportional to the amount of heat absorbed. The microcantilever IR sensor exhibits two distinct thermal responses: a fast one (<ms) and a slower one (~10 ms). A noise equivalent power (at a modulation frequency of 30 Hz) was estimated to be ~70 nW/Hz$^{1/2}$. This value can be further reduced by designing microcantilevers with better thermal isolation that can allow microcantilevers to be used as uncooled IR radiation detectors. © *1996 American Institute of Physics.* [S0003-6951(96)04946-7]

Remote temperature measurement of the thermal distribution of spatially extended objects has attracted great interest in a number of technical application.[1–6] From the various IR radiation sensors the class of thermal detectors has a very broadband response since it is based upon thermal conversion of the absorbed energy. However, most of these sensors suffer from slow response times (>ms). On the other hand, quantum detectors for the IR region have fast response times but require the device to be kept at a reduced temperature to minimize the effects of internal thermal noise. For sensitive imaging in the mid-to-far infrared region ($1.5<\lambda<10$ μm), the sensor element must be cooled to liquid nitrogen temperatures (i.e., ≈77 K) or lower, thus, greatly increasing the cost, size, and complexity of the detector. Therefore, new approaches leading to compact, light-weight, highly sensitive detectors with low power consumption are desirable.

The principle of operation of the sensor investigated in this study is based on the bending of a microcantilever upon absorption of IR radiation.[7–9] These microcantilevers are typically 100–200 μm long, 0.3–4 μm thick, and 10–50 μm wide, and made out of materials such as silicon nitride, silicon, or many other types of semiconducting materials.[10,11] Coating one side of these microcantilevers with a different material, such as a metal film, makes them sensitive to temperature variations due to the bimaterial effect resulting in microcantilever bending.[8,9,12–23]

Microcantilever deflections resulting from changes in temperature have been observed and reported by many researchers.[8,9,13,19–22] In some cases,[19–22] the bending of the microcantilever was due to heating from the diode laser beam used in atomic force microscopy (AFM) optical detection systems. Recent studies[8,13–16] have reported the use of microcantilever bending for calorimetric detection of chemical reactions with energies as low as a few pJ. It was demonstrated[15] that the microcantilever had an observed sensitivity of 100 pW corresponding to an energy of 150 fJ and proposed using the sensor as a femtojoule calorimeter. However, these studies[8,13–16] have reported the response of the microcantilever sensor to optical or near IR photon; in contrast, the present study demonstrates the remote detection of IR photons (with wavelengths ranging from 1 to 15 μm) using piezoresistive microcantilevers. An estimate[15] of the minimum detectable power level was of the order of 10 pW, corresponding to a detectable energy of ~20 fJ and a temperature sensitivity $\approx 10^{-5}$ K on the microcantilever. Using an optimally designed microcantilever, the temperature sensitivity may be improved even further.[9,22,23]

The extent of the deflection is proportional to the energy absorbed by the microcantilever. Assuming a spatially uniform incident power, dQ/dt, onto a bimaterial microcantilever the maximum deflection, $z_{\max}$, depends on the temperature rise[24] and is proportional to the incident power.[8,9,15,22] The deflection of the microcantilever can be detected with high sensitivity using detection techniques commonly used in scanning force microscopy. In the present study we employed a piezoresistive technique. A schematic diagram of the piezoresistive microcantilever deflection detection technique is given elsewhere.[25] The design and construction of the piezoresistive microcantilevers is described in detail elsewhere.[12,26,27] The total resistance of the microcantilever was approximately 2000 Ω that was electrically connected to one arm of a dc biased Wheatstone bridge circuit.

The change in the total resistance is directly proportional to the maximum deflection of the microcantilever,[26] i.e., $\Delta R(T) \approx 3Rz_{\max}(T)\times 10^{-6}$, where $z_{\max}(T)$ is in units of nm. The thermally induced deflection of the microcantilever is caused by the bimaterial effect that 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 $V_0(=9\ \text{V})$ 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 and is given as $\Delta V(T) \approx 3/4 V_0 z_{\max}(T)\times 10^{-6}$. The commercially available piezoresistive microcantilever[10] was coated with ~50 nm of gold-black, which served as the IR absorbing material. IR radiation was then focused on the sensor with 2.54 cm diam

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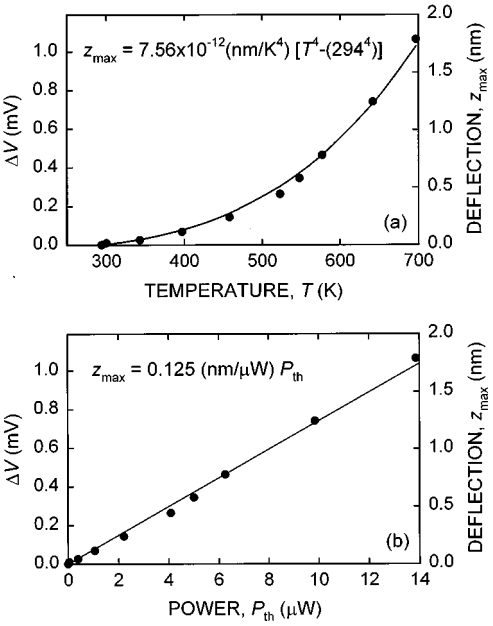

FIG. 1. (a) Response of the Wheatstone bridge detection circuit, ΔV, and deflection, z_{max}, of the piezoresistive microcantilever as function of the IR source temperature. (b) Response as function of the absorbed thermal power.

IR lens that had a focal length of 3.5 cm and a wavelength transmission range between 0.6 and 15 μm. A Stanford Research Systems SR 540 chopper was used to modulate the IR radiation. The sensor assembly was positioned ~15 cm from a soldering iron that served as the IR source. A calibrated thermocouple was attached to the IR source so that its temperature could be recorded.

The thermal power absorbed by the detector is proportional to the fourth power of the temperature of the IR source, i.e., $P_{th} \propto \epsilon \sigma_{SB}(T_S^4 - T_B^4)$, where ϵ is the source's emissivity, σ_{SB} is the Stefan–Boltzmann constant ($\sim 5.67 \times 10^{-12}$ W cm^{-2} K^{-4}), T_S is the temperature of the source, and T_B the background (or detector) temperature. In the present studies $\epsilon \approx 0.43$ and $T_B \approx 294$K. In Fig. 1(a) we plotted the response of the piezoresistive microcantilever (given by the response ΔV of the Wheatstone bridge circuit) as a function of the temperature, T_S, of the IR source. Also plotted is the deflection z_{max}, and it can be seen that both ΔV and z_{max} are monotonically increasing function of the source temperature. Assuming an IR source at a distance of 15 cm with an area of ≈ 90 cm^2, a measured emissivity of ≈ 0.43, and effective area for the detector of $\approx 6.2 \times 10^{-5}$ cm^2, and a background temperature $T_B \approx 294$ K, we estimated the absorbed thermal power (in Watts) $P_{th} \approx 6.064 \times 10^{-17}[T_S^4 - (294)^4]$. In Fig. 1(b) we plotted ΔV and 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/μW) is obtained. At a modulation frequency of 30 Hz, a noise equivalent power (NEP) of ~70 nW/Hz$^{1/2}$ was calculated, where NEP$=(\Delta V_n/\Delta V) \times P_{th}$; ΔV_n is the background noise level ($\Delta V_n \sim 10^{-6}$ V).

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,

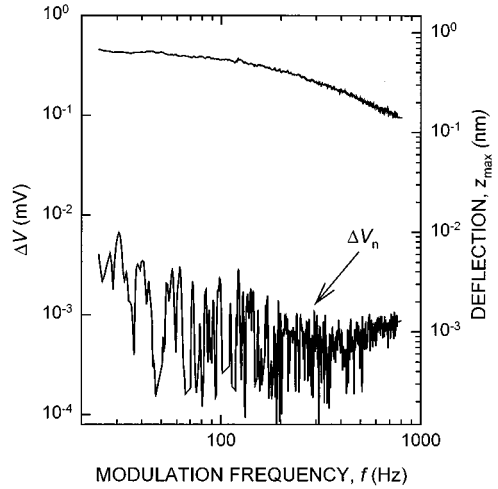

FIG. 2. Response of the Wheatstone bridge detection circuit, ΔV, and deflection, z_{max}, of the piezoresistive microcantilever as function of modulation frequency.

we measured the response of the Wheatstone bridge circuit, ΔV, and the deflection, z_{max}, as a function of modulation frequency of the IR radiation (Fig. 2). 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 ΔV as a function of time. The microcantilever 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.

A Miran-80 spectrometer was employed to measure the spectral response of the piezoresistive microcantilever in the wavelength region 2.5–14.5 μm (see Fig. 3). 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, the microcantilever (coated

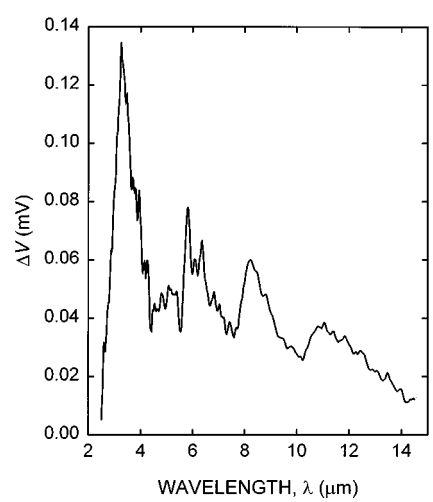

FIG. 3. Response of the Wheatstone bridge detection circuit, ΔV, the piezoresistive microcantilever as function of infrared wavelength.

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with gold-black) exhibits an appreciable response over the entire wavelength region. Since the spectral response was measured in ambient atmosphere, IR absorption band of various species (e.g., CO_2, H_2O, etc.) can be observed.

The results of the present study demonstrate that remote sensing of IR radiation sources is possible using piezoresistive microcantilevers, and piezoresistive microcantilevers represent an important development in uncooled IR detector technology. The microcantilevers employed were based upon commercially available micromachined cantilevers originally developed for AFM applications and designed to minimize thermal sensitivity. 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. Furthermore, 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 binding could also be employed.

Since the spectral response of microcantilevers can be easily tailored through the applications of specific absorptive coatings, the choice of material for fabrication of the microcantilever can be determined primarily by the requirements of the manufacturing process. These 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 cantilever 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.

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