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A novel infrared detector using highly nonlinear twisting vibration☆

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ABSTRACT

A new resonant infrared (IR) detector is proposed. The twisting motion of the thin film torsion bar is first used. The resonant frequency gives the information of the temperature change of the moving element caused by IR absorption. The dynamic sensing using the electrostatic force can remove the drift without the heat generation. The large nonlinearity of the thin film torsion bar combined with the frequency measurement increases the advantage of the high sensitivity. The IR detector is fabricated by the surface micromachining using sub-μm thick poly-Si film. Its structure consists of two parts. One is the thin film torsion bars and another is the bending center part. They can be basically designed separately. The center part has bi-layer structure to induce bending against the temperature increase caused by the IR absorption. One fabricated IR detector has the resonant frequency of about 35 kHz and shows the sensitivity of 30 Hz/K and the shifting ratio of 830 ppm/K. This sensitivity is larger than the previously reported Si detectors. The shifting ratio is larger than devices including the high-frequency quartz and ZnO detectors.

1. Introduction

Sensitive infrared (IR) detection is needed in many fields. The potential applications are human sensing, security, power-saving control, molecular detection, environmental monitoring, and so on. However, there is no suitable IR detector. As the visible light for comparison, the detectors are well-developed and the imaging devices are installed in many products which are frequently portable working with the battery power. The essential reason of the delay of the technological development in IR region is the fact that IR photon has smaller energy compared to the visible one. The handling of smaller energy needs the more delicate technique. Generally, there are two types of IR detectors. One is photon type detector, which transduces the incident IR photon into the electric charge using semiconductor materials. Photodiodes or many image sensors for visible light are belonging to this. Historically, the photon detectors have been preferred for the higher sensitivity. The band gap has to be narrow for matching with IR energy [1]. Sensitivity can be enhanced by incorporating quantum dots [2]. The detectors need cooling since they are bothered by the noise due to the thermally excited electric carriers. So, the photon detector is not suited for low power consumption and for portable equipments. As for IR having the relatively short wavelength, the plasmonic excitation and the detection of the hot electron is the recent trial [3].

From the view point of the applications, the thermal type detector is attractive since the cooling becomes unnecessary. The recent advances in micromachining techniques improve the thermal detectors [4]. When the incident IR is absorbed, the local heating in the element occurs and the resultant higher temperature generates subsequent changes. The suspended microstructure improves the thermal isolation making the temperature increase ΔT larger. Various mechanisms are proposed for the thermal detectors. The typical devices are bolometers [5], thermopiles [6–9], bimetals [10–14], and diodes [15,16]. In addition to the above static detectors, the resonant IR detectors are investigated. The potentially higher sensitivity can be achieved because the frequency shift can be measured with high accuracy. The bending-type Si-based bridge and cantilever have been reported [17,18]. When Si is used as the structure material, the temperature sensitivity of Young's modulus is only about −35 ppm/K [19–21]. So, the simple Si structure is not sensitive. They introduce the structures for accumulating the thermal stress inside. The bending of the thin film is influenced by the heat conduction and thermal stress to generate the frequency change. The mechanisms used are essentially unclear and complex having the difficulty in the control and the stable operation. Other resonant IR detectors have been tried using Y-cut quartz resonator [22], and ZnO based film acoustic resonator [23]. They use the large resonant frequency over MHz. The resultant frequency shift becomes large although the ratio is

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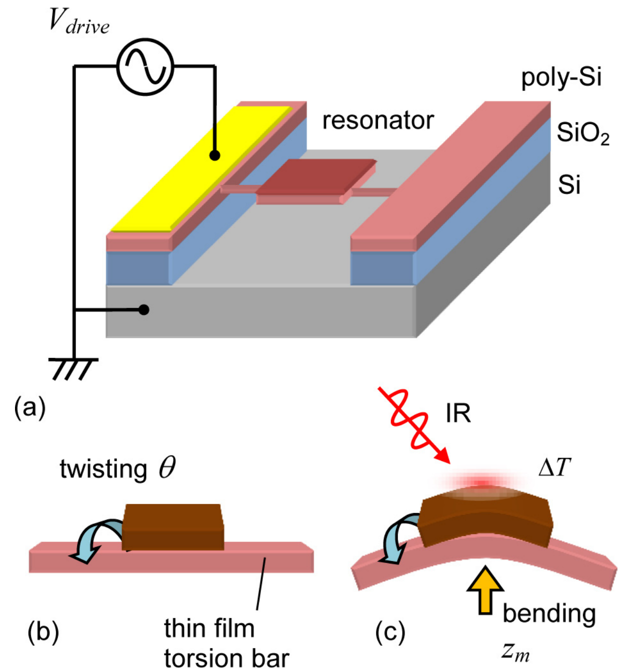

Fig. 1. (a) Schematic drawing of the IR detector using twisting motion. The electrostatic driving is used. Illustration of the moving element. (b) The initial condition for the twisting motion. (c) The bent condition with the twisting motion after local heating due to the IR absorption.

similar value. Y-cur quartz resonator has the resonant frequency of 90 MHz, and gives the sensitivity of 7.2 kHz/K or 80 ppm/K in the ratio. ZnO resonators have the resonant frequency of 1.82 GHz, and the sensitivity of −73 ppm/K in the ratio. The sensing bases on the temperature dependence of the material used. The materials of the quartz or ZnO are not well-matched with CMOS devices. There is also the difficulty for combining with the suspended microstructure for obtaining the thermal isolation and the larger temperature increase ΔT.

In this study, a new thermal type infrared detector is proposed based on the nonlinearity of the twisting spring constant of the thin film torsion bar. The twisting vibration is useful for avoiding the buckling instability. In this mechanical system, the twisting and the bending motions are coupled for obtaining the nonlinear effect. The devices can be fabricated based on the poly-Si surface micromachining having the good compatibility with CMOS circuits and arraying.

2. Principle and basic policy

Fig. 1(a) illustrates the schematic drawing of the detector proposed. A torsional resonator is made from the tense thin film of the poly-Si. Fig. 1(b) shows the condition that the twisting element is straight. The center part has two layers. The top layer is the material (metal) having the larger thermal expansion ratio compared to the bottom poly-Si layer. When the incident IR is absorbed, the resonator is designed to bend upwards due to the larger thermal expansion of the layered structure at the center as shown in Fig. 1(c). This bending makes the torsion bar slant against the line connecting the fixed ends and hardens the torsional spring. The resonant frequency increases as the result. IR sensing is measuring this increase. The frequency measurement is suited for obtaining the high resolution and for reducing the drift. The electrostatic force is used for exciting twisting since this does not generate the heat without disturbing the detection of the local temperature increase generated by the IR absorption.

The hard spring effect of the torsion bar is originally observed in the micromirror developed by our group [24]. The resonant frequency is observed to increase from 360 to 670 Hz. This corresponds to the increase of spring constant more than 3-times. This phenomenon is analyzed and compared with the experiments [24,25]. Here, the phenomenon is reconsidered introducing a new factor of swinging. Counting the shear stress, the torsional spring constant has the well-known formula.

$$k_{shear} \approx \frac{2Gwt^3}{3l}\left(1 - \frac{192}{\pi^5}\frac{t}{w}\tanh\frac{\pi w}{2t}\right), \tag{1}$$

This is for two torsion bars. G, w, t, and l are the torsional rigidity, the width, the thickness, and the length of one torsion bar, respectively. For evaluating the torsional spring constant in this proposed device, the stretching and bending factors have to be included in addition to the shear stress because the device is doubly-clamped requiring the significant force for its deformation. The torsion bar can be modeled as shown in Fig. 2. When the film has the residual stress, the stretching factor can be larger since this is the surface force maintaining its magnitude in the small dimension compared with the bulk force. This twisting spring constant is evaluated based on the energy method [26]. For clearing the design guideline, the model is reconsidered here. Along the torsion bar, x-axis is set placing the origin at its center. The center bending part of the detector device shown in Fig. 1 is omitted connecting two torsion bars. The trial function of the bending profile $\widehat{\omega}_c(x)$ in z-direction is approximated as a form of cosine.

$$\widehat{\omega}_c(x) = \frac{z_m}{2}\left(1 + \cos\frac{2\pi x}{L}\right) \tag{2}$$

The displacement of the torsion bar in xyz directions are expressed as uvw, respectively. The subscript c indicates the center of cross-section of the torsion bar at position x. The bending height z_m increases with IR absorption. $L = 2l$ is the full length of two torsion bars. Here, the twisting is supposed to distribute uniformly supposing the trial function of the twist angle $\widehat{\theta}(x)$ as follows.

$$\widehat{\theta}(x) = \theta_0\left(1 - \frac{2}{L}|x|\right) \tag{3}$$

where θ_0 is the twist angle at $x = 0$. Twisting makes the cross-section slant against the original horizontal surface. The twisting is simply expressed as follows.

$$\widehat{\omega}(x) = \widehat{\omega}_c(x) + \xi\widehat{\theta}(x) \tag{4}$$

In the cross-section S, $\xi\eta$-axes are set as shown in the inset of Fig. 2 ($-w/2 < \xi < w/2$, $-t/2 < \eta < t/2$). Accompanying the bending and the twisting, the torsion bar will swing around the fixed points. The shift in y-direction occurs. The trial function is supposed to be as follows.

$$\widehat{v}(x) = -\widehat{\omega}_c(x)\widehat{\theta}(x) \tag{5}$$

This swinging $\widehat{v}(x)$ is newly counted. $\widehat{\omega}_c(x)$ is used as the approximation. When $\widehat{\omega}(x)$ is used, the result cannot be expressed by the simple polynomial. The length change of the torsion bars is given by as follows.

$$\delta L = \int_{-L/2}^{L/2}\left\{\frac{1}{2}\left(\frac{d\widehat{w}}{dx}\right)^2 + \frac{1}{2}\left(\frac{d\widehat{v}}{dx}\right)^2 dx\right\} \tag{6}$$