A Cantilever-Type Uncooled Infrared Detector With High Fill-Factor and Low-Noise Characteristic

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Abstract—A capacitive microcantilever-type infrared (IR) detector having a unique structure that has high immunity to thermomechanical noise (TM-noise) is proposed. The device has a capacitive readout scheme and is compared with a conventional design using the same readout method by finite element model simulation. The total cantilever length was halved, compared with the conventional device structure, in order to increase the device’s spring constant, and the IR absorber area was consequently increased as the portion of the leg in the given pixel area is decreased. Large spring constant and increased absorber area are the main causes of the TM-noise reduction. The feasibility of the device was shown by fabrication, and measured parameters demonstrated the structure’s superiority. It was shown that the proposed structure potentially has low TM-noise and an overall noise-equivalent temperature difference (NETD) value that is lower than that of the conventional designed device. The NETD of the proposed device was found to be 5.7 mK.

Index Terms—Fill factor, microcantilever-type infrared (IR) detector, noise-equivalent temperature difference (NETD), thermomechanical noise (TM-noise).

I. INTRODUCTION

O WING TO THEIR high-sensitivity and low-noise characteristics [1]–[5], microcantilever-type infrared (IR) detectors are known to have potentially superior performance than conventional thermal IR sensors [6], [7].

The major noise sources of the cantilever-type IR detector are temperature fluctuation noise (TF-noise) and thermomechanical noise (TM-noise). The former originates from the conductive heat exchange between the device and the substrate [8]. The latter is a thermal noise existing in all mechanical systems, which follows a (4\(k_B T\))\(1/2\) nature, where \(k_B\) is Boltzmann’s constant, \(T\) is the temperature, and \(B\) is the measurement bandwidth. TM-noise should be carefully considered for bimaterial-type IR detectors because it results in the unexpected cantilever vibration. In this letter, a microcantilever-type IR detector design having low TM-noise is investigated by adjusting the cantilever dimensions and IR absorber area (fill factor).

II. EXPERIMENT AND RESULTS

TM-noise, expressed as an rms vibration (\(\sqrt{\Delta z_{TM}^2}\)) of the cantilever tip, is a function of the cantilever-type IR detector’s mechanical properties, such as the spring constant (\(k\)), quality factor (\(Q\)), and resonance frequency (\(\omega_0\)) [9]

\[
\sqrt{\Delta z_{TM}^2} = \sqrt{\frac{4k_B T A B}{Q k \omega_0}}.
\]

TM-noise can be converted into a noise-equivalent temperature difference (NETD) form using the following equation:

\[
\text{NETD}_{TM} = \frac{\Delta T_z}{\Delta z} \times \sqrt{\Delta z_{TM}^2}, \quad \text{where} \quad \frac{\Delta T_z}{\Delta z} = \beta \times \frac{\Delta T_d}{\Delta z}
\]

Parameters of \(T_z\) and \(z\) are the target (scene) temperature and the bimaterial leg tip’s height from the substrate, respectively. \(\beta\) in (2) is the optical transfer coefficient

\[
\beta = \frac{d T_z}{d T_d} = \frac{g_{th}}{\frac{4 \eta}{\pi} \frac{d R}{d T}}
\]

where \(g_{th}\) is the thermal conductance, \(A\) is the absorber area, \(\eta\) is the IR absorbance, \(F_{no}\) is the F-number of the system’s optics, and \(d R/d T\) is a constant (= 8 \times 10^{-5} \text{ W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{K}^{-1}\) for 8–12-\(\mu\text{m}\) IR range) that quantifies the target’s radiance change due to its temperature change [8]. Our approach for TM-noise reduction is to increase both \(k\) which is proportional to \(1/L^2\) and \(A\) by halving the leg length \(L\) in the given pixel area. Although the sensitivity [temperature coefficient of capacitance (TCC)] of the device is decreased since \(\Delta z/\Delta T_d\) is proportional to \(L^2\) [6], the overall TM-noise can be reduced.

The top view of a conventional cantilever-type IR detector is shown in Fig.1(a) [2]. Each leg has two components of bimaterial leg and thermal isolation leg. The former is a stack of Al(2000 Å)/SiO\(_2\)(2000 Å) whose thermal expansion coefficients are 25 and 0.35 ppm/K, respectively [10], and the latter is composed of Al(50 Å)/SiO\(_2\)(2000 Å) having a \(g_{th}\) of 1.1 \times 10^{-7} \text{ W/K}. With a minimum pattern size of 2 \(\mu\text{m}\) and a 50 \(\times\) 50-\(\mu\text{m}^2\) pixel pitch, both legs have an area of 48 \(\times\) 2 \(\mu\text{m}^2\), neglecting the post area of 2 \(\times\) 2 \(\mu\text{m}^2\). Thus, the IR absorber area is 48 \(\times\) 32 \(\mu\text{m}^2\). The capacitor (\(C_{Cc}\)) uses a bottom electrode on the substrate and a top electrode that also acts as the IR absorber [Fig. 1(a) bottom]. This approach offers high sensitivity (TCC: 19.3%\%/K) in that one pixel length of the bimaterial leg
can contribute to deflection. However, its excessive length can be a source of large \( \Delta z_{\text{TM}} \). Thus, we propose an alternative structure whose leg length is half that of the conventional one [Fig. 1(b)]. The structure has a bimaterial leg area of 38 \( \times \) 2 \( \mu \text{m}^2 \) with Al(2000 Å)/SiO\(_2\)(2000 Å). However, SiO\(_2\)-only thermal isolation leg having a 10 \( \times \) 2 \( \mu \text{m}^2 \) area with 2000-Å thickness allows the device to have the same \( g_{\text{th}} \) of 1.1 \( \times \) 10\(^{-7}\) W/K as the conventional design. Simultaneously, the IR absorber area \( (A) \) is increased up to 48 \( \times \) 40 \( \mu \text{m}^2 \). For the capacitor formation, a one floating top electrode (IR absorber) and two bottom electrodes approach is proposed [Fig. 1(b) bottom], because the device loses electrical connection to the IR absorber. The total capacitance is a series connection of \( C_{\text{P}a} \) and \( C_{\text{P}b} \), and the bias \((V_B)\) is applied between the two bottom electrodes. This structure has lower sensitivity (TCC: 14.2\%/K) and \( \Delta z/\Delta T_d \) than the conventional design for its short legs. However, the device’s \( k \) value is mainly decided by the shorter bimaterial leg (larger \( k \)), and the increased IR absorber area provides lower \( \beta \) than the conventional design. Therefore, the structure potentially has higher immunity to TM-noise.

A finite element method simulation with CoventorWare was performed to verify the feasibility of the structures (Fig. 2). \( w_0 \) change as a function of thermal isolation leg length \((L_{\text{C}th} \text{ and } L_{\text{P}th} \text{ in Fig. 2 inset})\) was acquired. The \( k \) of each model was subsequently extracted from the simulated \( w_0 \) values. By using parameters of \( T_d = 300 \text{ K}, B = 60 \text{ Hz}, \) and \( Q = 1000 \) (typical value in vacuum [3]), TM-noise and TF-noise elements were extracted as NETD\(_{\text{TM}}\) and NETD\(_{\text{TF}}\), respectively. NETD\(_{\text{TOTAL}}\) is the rms sum of these two values. NETD\(_{\text{TM}}\) of the proposed structure reaches its minimum (~1 mK) at an \( L_{\text{P}th} \) of ~10 \( \mu \text{m} \). Large NETD\(_{\text{TM}}\) below this point is due to the large \( g_{\text{th}} \) from the short \( L_{\text{P}th} \) and small \( k \), owing to the relatively long bimaterial leg. When \( L_{\text{P}th} > 10 \mu \text{m} \), NETD\(_{\text{TM}}\) increases, experiencing decreased overall \( k \) by long \( L_{\text{P}th} \). The conventional device showed a decreasing NETD\(_{\text{TM}}\) tendency as \( L_{\text{C}th} \) became longer. Increased \( g_{\text{th}} \) in short \( L_{\text{C}th} \) region makes large NETD\(_{\text{TM}}\). The lower NETD\(_{\text{TF}}\) of the proposed design is due to its increased absorber area [6]. The simulation results indicate that the proposed structure has improved noise characteristics.

The proposed structure was fabricated (Fig. 3) by the following steps: 1) Au bottom electrode formation on glass wafer; 2) 0.5-\( \mu \text{m} \)-thick polyimide sacrificial layer coating and curing; 3) post hole etching by RIE; 4) SiO\(_2\)/Ti/SiO\(_2\) stack (IR absorber) deposition and patterning; 5) Al(2000 Å)/SiO\(_2\)(2000 Å) deposition and patterning for the leg formation; and 6) release by O\(_2\) plasma. \( \Delta z/\Delta T_d \) was measured to be 64 nm/K using a 3-D profiler whose laser beam scans vertically to measure the bending of the cantilever. The value is almost identical to the calculated value (67 nK). Capacitance change by \( \Delta T_d \) was measured [Fig. 4(a)] from parallel-connected 50 \( \times \) 50 pixels to quantify the small capacitance variation (~4F) of single pixel. The capacitance was normalized by 2500 thereafter. Temperature was controlled by the thermoelectric cooler with temperature resolution of 1 K (±0.1 K) for the
The fabricated device was accurately controlled by the thermoelectric cooler whose resolution was $<0.1$ K. It was assumed that the temperature change in the measurement provided the same condition as the detector temperature change by IR absorption. Resonance frequency of the fabricated device was measured to be 18.5 kHz [Fig. 4(b)]. The measured $k$ of 0.014 N/m was also smaller than the simulated value of 0.021 N/m due to a smaller $f_0$. Under these parameters and the assumed $Q$-factor of 1000 (typical value in vacuum), the NETD$_{TM}$ is extracted to be 1.6 mK. Including an NETD$_{TF}$ of 5.5 mK, the proposed device could have an NETD$_{Total}$ of 5.7 mK, which is in reasonable agreement with the simulated value of 5.6 mK.

### III. Conclusion

A capacitive microcantilever-type IR detector having lower TM-noise was proposed and fabricated. It has an NETD$_{TF}$ of 1.6 mK, which is much smaller than that of the conventional design. The spring constant and absorber area were increased by halving the microcantilever length. Although the structure has low sensitivity to temperature change of the device by IR absorption, the NETD$_{Total}$ could be reduced relative to the conventional design by increasing the spring constant and the IR absorber area.

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### References


