Temperature-Independent Near-Zero Power Flame Detector Based on MEMS Photoswitch

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***Summary*— This paper reports on the first demonstration of a near-zero power flame detector with a consistent detection accuracy and a wide operating temperature range (-35°C to 85 °C) that satisfies industrial applications. The core sensing element of the flame detector is a plasmonically-enhanced micromechanical photoswitch (MP) that harvests infrared (IR) energy from a hydrocarbon flame through a spectrally-selective IR absorber to generate a wake-up signal without relying on active electronics (hence zero standby power consumption). The temperature compensation is achieved through passively tuning the detection threshold with a temperature-dependent bias voltage (2.70 – 4.37 V) applied to the open-circuit MP hence preserving the near-zero standby power feature. Furthermore, the required voltage values corresponding to the changing ambient temperature are decided based on a self-check of the pull-in voltage of a pre-calibrated device, which saves the need for a temperature sensor that would increase the cost and power consumption. Thanks to such a temperature compensation mechanism, the flame detector prototype shows an *x19* improved stability compared to our previous demonstration.**

Keywords—zero-power; flame detection; temperature; MEMS

I. INTRODUCTION

Wildfires are becoming significant ecological threats to national forests with increasing frequency and severity. Additional to prevention methods, 24/7 surveillance for early detection enables extinguishing the fire before reaching large areas. For open-space fire detection, flame detectors are more suitable than the most common smoke detectors since there is no accumulation of smoke particles. The continuous monitoring in remote environments requires the flame detectors to be cable-free and to work without range reduction in changing ambient conditions with minimum maintenance. However, the state-of-the-art flame detectors based on pyroelectric IR sensors require complex read-out circuitry which is highly affected by the temperature induced noise above 60 °C [1]. Moreover, they continuously consume electrical power, draining limited battery supply, making them unsuitable for deployment in hard-to-reach areas where frequent battery replacement isn't available. Recently maintenance-free, wireless sensor nodes with zero power consumption standby have been demonstrated [2-4]. The improvements in these event-driven IR detectors have enabled long range fire detection (~70 m for industry-standard heptane pan-fire) with ultra-wide field-of-view (~125°) for large areal-coverage [5]. In this paper, we first analyze the ambient temperature response under different bias conditions then, experimentally demonstrate a new concept, dynamic biasing, that enables temperature-independent device operation between (-35°C-85°C) with ~ ±0.5 m projected detection accuracy for industry standard fire (Fig. 1).

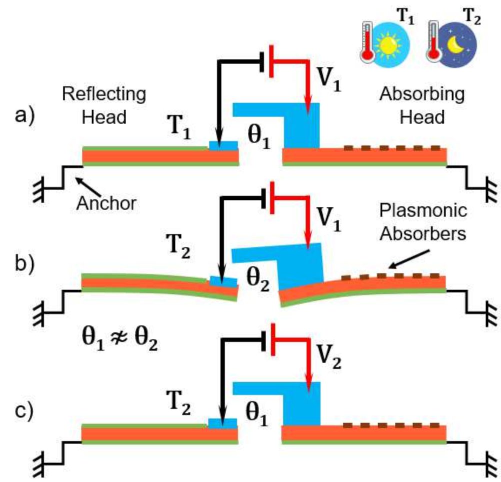

Figure 1: The simplified schematics of the detector a) at temperature T_1 with bias voltage of V_1 resulting in threshold of θ_1, b) at T_2 with bias voltage of V_1 where the device experiences different threshold of θ_2. The different material stack in the opposite heads and unsymmetrical fabrication mismatches create un-even thermal expansion affecting the contact gap. c) at T_2 with adjusted bias voltage of V_2 to keep the threshold level at θ_1. for temperature independent detection performance at different ambient conditions.

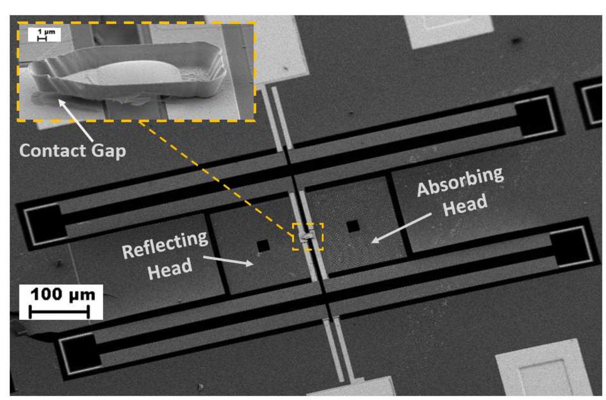

Figure 2: Scanning electron microscope (SEM) image of the MP. The close-up of the gap between contact tip (on absorbing head) and bottom contact (on reflecting head).

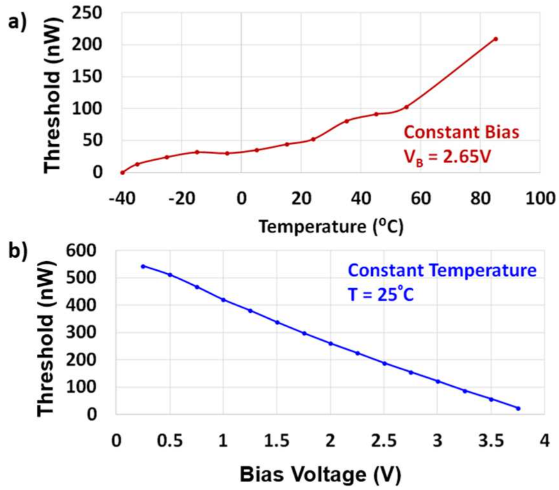

Figure 3: Measured power absorption to close the switch's contacts a) at constant bias of 2.65 V in the temperature range of (-40°C,85°C) where the pull-in voltage at -40°C is 2.65 V, therefore no absorbed power is required to turn on the MP. The required absorbed power increases with temperature due to increase in the contact gap. b) at 25°C under various bias voltages.

II. METHODS/RESULTS

The core element is plasmonically-enhanced micromechanical switch (MP) [6] that comprises a symmetric pair of thermal actuators (legs), a reflector head, and an absorber head carrying the contact tip (Fig. 2). The device thermomechanical modelling [7] and absorption characteristics [8] have been previously explained. The device employs folded beam structures that mitigate the ambient temperature dependence due to the movement of the thermally-sensitive bimaterial legs. However, since the material stacks aren't identical for absorber and reflector heads, their displacement for a change in temperature is uneven, such that the contact gap height and ultimately the device threshold (IR power to close the gap) varies with changing ambient conditions. We solve this issue by measuring the pull-in voltage of the device and adjusting the bias voltage accordingly such that the threshold is kept constant at all temperatures without an external temperature sensor. The applied bias decreases the contact gap without disturbing the zero-standby power consumption [9].

The MP was tested in a vacuum chamber with a temperature control unit facing a micro-torch butane flame through 45° angled-mirror. The temperature dependency of the device threshold was characterized by built-in heater measurements (Fig. 3) where a current-limited sourcemeter is connected to contacts to observe the tip current. For both measurements, the absorbed power is calculated by Joule's heating of the embedded resistive heater (~60 kΩ) on the absorber head. The linear relationship between threshold and the bias voltage was established ($y = mx + V_{PI}(T)$) with $V_{PI}(T)$ temperature-dependent pull-in voltage and m, constant slope (Fig. 4). The temperature-independent slope of the fitting

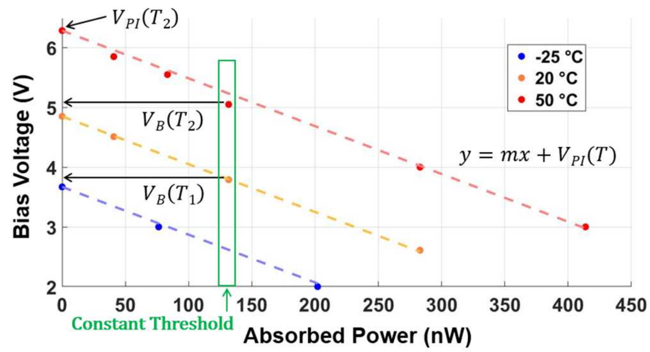

Figure 4: The measured bias voltage vs absorbed power at different temperatures. The temperature dependency of the pull-in voltage was shown in y-axis values where no absorbed power was needed to close the contacts at respective temperatures. Linear approximation was used to fit the measurements that show temperature dependent pull-in voltage ($V_{PI}(T)$) and constant slope (a) as shown in the equation. At any temperature, the fitting curve can be obtained from measured pull-in voltage and line slope at room temperature for constant threshold operation.

curves enable operation without the need of an external temperature sensor. The bias voltage at an unknown temperature (i.e. $V_B(T_2)$) was calculated by $V_B(T_2) = V_B(T_1) - (V_{PI}(T_1) - V_{PI}(T_2))$.

The flame detection distance is measured under constant bias voltage (2.65 V) applied to the device contacts. The detection distance was increased with decreasing temperature. When the applied voltage was controlled by dynamic bias method (0.2 V less than the measured pull-in voltage at each temperature) the detection distance was kept at the same level as room temperature. This improved performance shows $x19$ less variation in flame detection distance compared to when

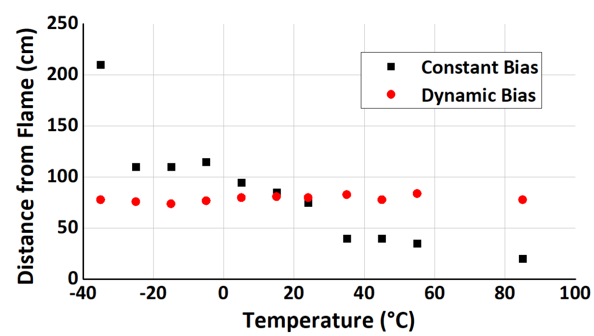

Figure 5: The flame detection distance measured with constant voltage bias and dynamic voltage bias. The dynamic bias concept was implemented to counter balance the effect of temperature and keep the detection distance (~80 cm) at the same level as room temperature conditions where x19 less variation is observed in the detection distance. In the constant and dynamic bias experiments, bias voltage was set to 2.65 V or it was kept 0.2 V less than the pull-in voltage for each temperature, respectively.

constant bias voltage was applied over a temperature range of (-35°C and 85°C) (Fig. 5).

III. Conclusions

This paper reported on the first demonstration of an ambient temperature-independent flame detector based on MP with zero standby power consumption. The unique combination of plasmonically enhanced absorption and temperature-independent performance (x19 stable than previous demonstrations) results in a MEMS-based flame detector characterized by ultra-wide field-of-view (~125°), efficient IR absorptivity (> 85% tailored around 4.3 μm) and wide operation temperature range (-35°C, 85 °C) demonstrating advantages over any technology for long term fire detection system deployment in remote locations. The results here show the experimental verification of temperature-independent flame detection with an uncooled IR detector suitable for open-space applications.

Acknowledgment

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