Numerical Analysis for Voltage Responsivities of an Improved Multi-Frequency Band Pyroelectric Sensor

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***Abstract*—This article proposes an improved multi-frequency band pyroelectric sensor for extending the sensing frequency with a fine voltage responsivity to detect subjects with various velocities. The proposed sensor is built on a silicon substrate, consisting of four pyroelectric layers with various thicknesses deposited by sputtering and aerosol deposition (AD) method, top and bottom electrodes and a silicon nitride layer. The thinnest ZnO layer deposited by sputtering with a small thermal capacity and a rapid response shoulders a high-frequency sensing task, while the thicker ZnO layers deposited by the AD with a large thermal capacity and a tardy response shoulders a low-frequency sensing task. The improved design is further for redeeming drawbacks of thicker pyroelectric layers with a tardy response at a high-frequency band and a thinner pyroelectric layer with a low voltage responsivity at a low-frequency band. The improved multi-frequency band pyroelectric sensor is successfully designed and analyzed in the present study, which could indeed extend the range of the multi-frequency band sensing.**

***Index Terms*—pyroelectric sensor, multi-frequency, zinc oxide, thin film, aerosol deposition, sputtering**

I. Introduction

Pyroelectric sensors function by making use of the pyroelectric effect. The pyroelectric effect has been applied to environmental energy-harvesting systems. Pyroelectric energy conversion also offers a novel and direct way to convert time-dependent temperature fluctuations into electricity for micropower generators and low-energy-consumption systems [1]-[3]. Pyroelectric devices are useful in many applications, such as pollution monitoring, hot image detectors, intruder alarms, gas analysis and temperature sensors. Thin-film pyroelectric sensors have many advantages, such as integration with on-chip circuitry, uncooled detection, room-temperature operation, speed, lower system costs, portability and a wide spectral response with high sensitivity [4]-[7]. A general pyroelectric sensor consists of a pyroelectric layer sandwiched between top and bottom electrodes, which is built on thermal-isolation structures or substrates for minimizing heat loss. The dynamic pyroelectric response current (i_p) of pyroelectric sensors is proportional to the absorption coefficient of radiation (η), the pyroelectric coefficient of the pyroelectric film (P), the electrode area (A) and the temperature variation rate of pyroelectric films (dT/dt). At a low frequency ($\omega \ll \tau_T^{-1}$), R_v is proportional to the frequency, and is shown as the following equation:

$$R_v = \frac{R_G \eta P A \omega}{G_T} \tag{1}$$

Equation (1) can easily maximize R_v by minimizing G_T (i.e., by adding a thermal insulation layer between the pyroelectric film and the substrates, adopting a suspended structure fabricated by a bulk micromachining technique using anisotropic silicon etching or by using a substrate with a low thermal conductivity). At a high frequency ($\omega \gg \tau_T^{-1}$; $\omega \gg \tau_E^{-1}$), R_v is inversely proportional to the frequency, and is shown as the following equation:

$$R_v = \frac{\eta P}{c' d (C_E + C_A)\omega} \tag{2}$$

Equation (2) can easily maximize R_v by minimizing the thermal capacity of the pyroelectric element H (i.e., decreasing the thickness of the pyroelectric element). Hence, the frequency at τ_T^{-1} is a watershed to distinguish the ranges of low and high frequencies, and the pyroelectric element's thickness determines the value of the thermal time constant ($\tau_T = c' \times d \times A/G_T$) under the decided pyroelectric materials and electrode areas. Therefore, a thicker pyroelectric element increases the thermal time constant, which is suitable as the sensor for a low-frequency range. Unlike the thicker element, a thinner pyroelectric element reduces the thermal time constant, which is suitable as the sensor for a high-frequency range. Therefore, in the present study, an improved structure consisted of four pyroelectric ZnO films with various thicknesses, top and bottom electrodes, a thermal isolation layer and a substrate for designing an improved multi-frequency band pyroelectric sensor. The four pyroelectric layers were mainly deposited by sputtering and aerosol deposition (AD). The thinnest layer in pyroelectric layers was grown by sputter, the others were deposited by the AD with shadow mask method. The improved design was further for redeeming drawbacks of a thicker pyroelectric layer with a tardy

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response at a high-frequency band and a thinner pyroelectric layer with a low voltage responsivity at a low-frequency band.

Zinc oxide (ZnO) is an important material in the electronic industry. It is a II-VI oxide semiconductor. It has also high ionicity compared with Si,Ge and III-V compounds. Besides, ZnO has some distinct features like non-stoichiometric defect structure, anisotropy in crystal structure, large direct band gap, strong absorption in the UV region, transparency in the visible region, large variation of conductivity, and high surface sensitive catalytic activity in different ambiances. These properties make it useful in many applications, such as pyroelectric devices [6], [7], gas sensors [8] and film bulk acoustic resonators [9]. The thinnest ZnO film was deposited by RF sputtering. Sputter deposited films have a composition close to that of the source material. Moreover, the thicker ZnO film was grown by the AD. The AD provides many advantages for producing films in the range of 1~100μm thickness with a high deposition rate, low deposition temperature and low cost. The AD method can achieve fine patterning and fabricate a dense structure by the reduction of crystallite size by fracture or plastic deformation at room temperature [10]-[12]. In the present study, transient temperature fields in improved multi-frequency band pyroelectric sensors were simulated to probe into temperature variation rates at various pyroelectric layers and estimate the voltage responsivity of the sensors.

II. Materials and Methods

The improved multi-frequency band pyroelectric sensor, consisting of four ZnO pyroelectric layers with various thicknesses, and top and bottom electrodes, was built on a silicon substrate with a thermal-insulation (silicon nitride) layer to reduce heat and electric loss. Fig. 1 shows the schematic diagram of the improved multi-frequency band pyroelectric sensor. The thinnest ZnO pyroelectric layer was deposited by sputtering, and the others were deposited by the AD. The sputtered ZnO layer acted as a producer of the responsivity at higher frequency bands, while the aerosol ZnO layers detected the signals of the sensors at lower frequency bands.

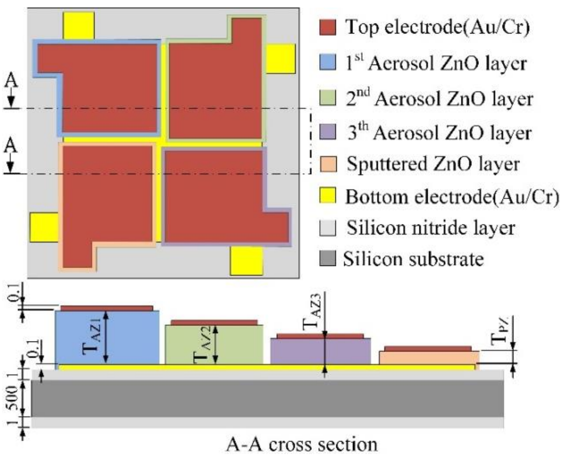

Figure 1. Schematic diagram of the improved multi-frequency band pyroelectric sensor (unit: μm).

The improved multi-frequency band pyroelectric sensor used both sputtering and AD to extract the advantages of the thin and the thick ZnO pyroelectric film to further integrate the electrical outputs. Temperature variation rates in pyroelectric layers markedly affect the responsivity of pyroelectric sensors. The response is in proportion to the temperature variation rate in pyroelectric layers. The dynamic pyroelectric response current of pyroelectric devices can be expressed as [4]:

$$i_p = \eta \times P \times A \times dT/dt \tag{3}$$

That is, higher the temperature variation rate in pyroelectric films, higher response of pyroelectric sensors. However, the temperature variation field is difficult to extract from thin films by experimental measurements. In the present study, a two-dimensional finite element model was constructed using the commercial multiphysics software COMSOL MULTIPHYSICS® 4.2 to explore the temperature variation rate in the multi-frequency band ZnO pyroelectric sensors. The material properties of the films and substrate are shown in Table I. There was an isotropic assumption for the films and substrate properties in this model. The model was meshed using a regular mesh, as shown in Fig. 2. The thickness of the sputtered ZnO layer (T_{PZ}) was fixed as 0.3μm, while the thicknesses of the aerosol ZnO layers (T_{AZ1}, T_{AZ2}, T_{AZ3}) were 3, 1 and 0.6μm. The incident irradiation power applied on the top side of the multi-frequency band pyroelectric device was nearly 1.228×10^{-12}W/μm^2 [13]. The thermal isolation condition was applied to the rear side of the silicon substrate, and the symmetric condition was applied to the two lateral sides as boundary conditions.

In fact, pyroelectric devices use the voltage responsivity for presenting the performance of the sensors. Hence, the voltage responsivities were calculated for estimating the electrical outputs of the sensors. The voltage responsivity (R_v) is defined as the signal generated when pyroelectric sensors are exposed to a modulated radiation. Moreover, when pyroelectric sensors are connected to a high impedance amplifier, the observed signal is equal to the voltage produced by the charge. R_v can be expressed as [4]:

$$R_v = \frac{i_p}{Y \times W_0} \tag{4}$$

where i_p is the dynamic pyroelectric response current, W_0 is the magnitude of the incident radiation and Y is the electrical admittance, as:

$$Y = R_G^{-1} + \mathrm{i}\omega C_T \tag{5}$$

where R_G is the gate resistor, ω is the modulated frequency of the incident radiation, C_T is the sum of C_E and C_A, C_E is equal to $\varepsilon_0 \times \varepsilon_r \times A/d$, ε_0 is the vacuum permittivity (8.85×10^{-12}F/m) and ε_r is the relative permittivity or dielectric constant of the materials. R_v was estimated using the simulated data of the temperature variation rates and (3), (4) and (5). The relative conditions for computing the voltage responsivity are shown in Table II.

TABLE I. MATERIAL PROPERTIES USED FOR THE SIMULATION OF TEMPERATURE VARIATION FIELDS

Materials	Thermal conductivity ($Wm^{-1} K^{-1}$)	Specific heat ($Jg^{-1} K^{-1}$)	Density ($g\ cm^{-3}$)	Thick-ness (μm)
Silicon substrate	163	0.703	2.330	5
Silicon nitride	20	0.700	3.100	1
Electrodes	317	0.129	19.300	0.1
Sputtered and aerosol ZnO layers	6	0.125	5.676	T_{PZ}, T_{AZ1}, T_{AZ2} and T_{AZ3}

TABLE II. RELATIVE CONDITIONS FOR ESTIMATING RV

R_G (MΩ)	C_A (pF)	P (10^{-4} $C/m^2\ K$)	A (mm^2)	ε_r (Unit-less)	W_0 ($W/\mu m^2$)
22	6	0.1	9	11	1.228×10^{-12}

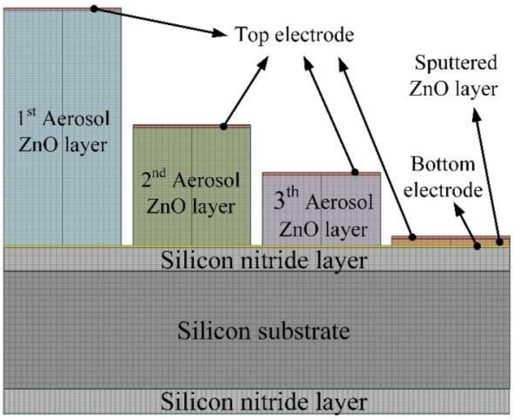

Figure 2. Two-Dimensional numerical model for the improved multi-frequency band ZnO pyroelectric sensor.

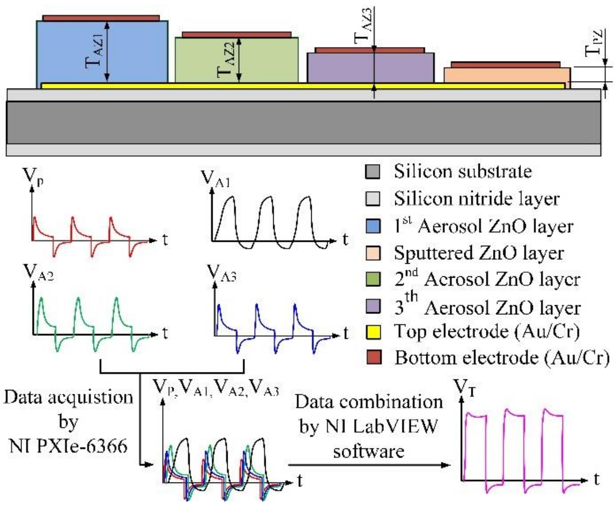

Figure 3. Schematic diagram for electrical signal treatment procedure.

The improved multi-frequency band pyroelectric sensor redeemed the drawbacks of the thinner and the thicker ZnO pyroelectric film to integrate the electrical outputs generated from those films into an all-round signal. A schematic diagram of the signal treatment is shown in Fig. 3. The voltage responsivity of V_P was generated from the sputtered ZnO film for shouldering a high-frequency response, and the voltage responsivities of V_{A1}, V_{A2} and V_{A3} were generated from the aerosol ZnO films for taking a low-frequency response. The integrated and treated electrical signal was V_T. The responsivities of V_P, V_{A1}, V_{A2} and V_{A3} were filtered, amplified, modulated and combined as an integrated voltage responsivity (V_T) by NI LabVIEW software. Moreover, both the integrated voltage responsivity of the sensors and the reference signal of the photodiode were acquired, recorded and displayed using NI LabVIEW system consisted of a case of NI PXIe-1082, a controller of NI PXIe-8135, a data acquisition card of NI PXIe-6366 and NI LabVIEW 2013 software.

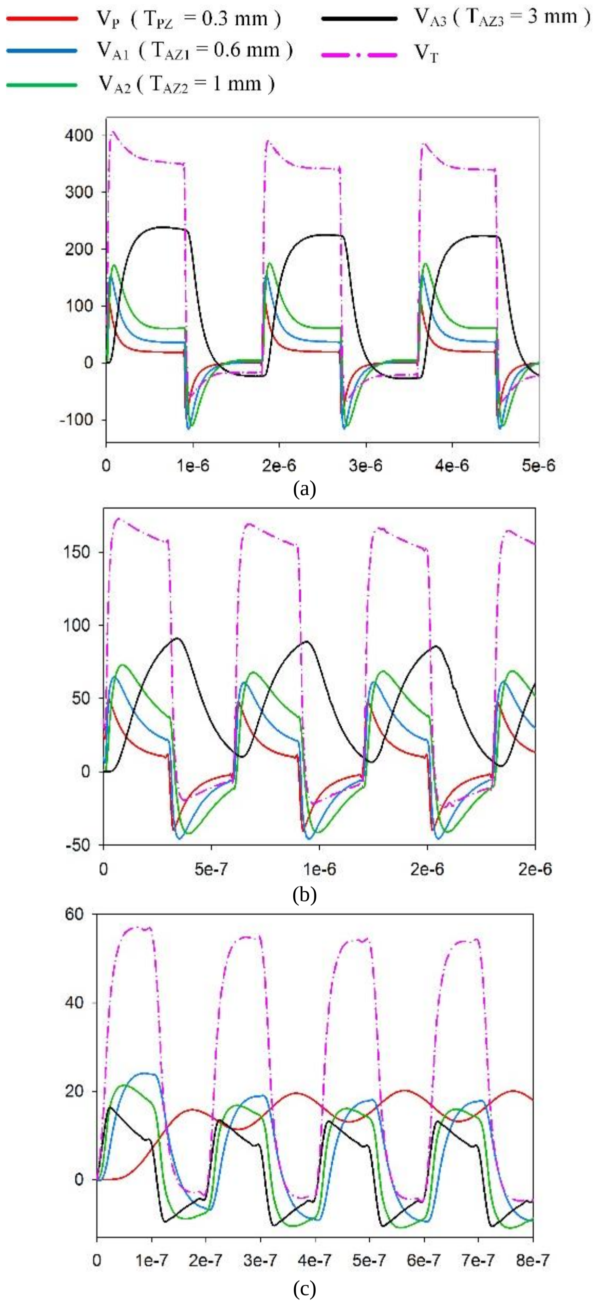

Figure 4. Voltage responsivities of the improved multi-frequency band pyroelectric device with TPZ=0.3μm, TAZ1=3μm, TAZ2=1μm and TAZ3=0.6μm under the incident irradiation power modulated with various chopping frequencies of about (a) 14KHz, (b) 33KHz and (c) 100KHz.

III. Results and Discussion

It clearly shows that a large and rapid temperature variation is a favorable condition for generating high electrical responsivity. Therefore, transient temperature fields in the multilayer ZnO thin film pyroelectric devices were simulated, and the response time of the devices was estimated. The data about temperature variation rates and response time were further used to calculate the voltage responsivity of pyroelectric sensors.

The transient temperature fields with various chopping frequencies were simulated for further calculating voltage responsivities when the improved multi-frequency band pyroelectric devices were exposed to irradiation power with various chopping periods. A square waveform was produced using a programmable function generator to modulate the irradiation power with chopping frequencies of about 14K, 33K and 100K Hz. Fig. 4 shows the voltage responsivities of the improved multi-frequency band pyroelectric device with T_{PZ}=0.3μm, T_{AZ1}=3μm, T_{AZ2}=1μm and T_{AZ3}=0.6μm when the incident irradiation power was modulated with various chopping frequencies of about 14K, 33K and 100KHz. The shape of the integrated voltage responsivity of V_T at three chopping frequencies almost approached to a square wave. Furthermore, the amplitude of the integrated voltage responsivity of V_T at three chopping frequencies was nearly identical. Therefore, V_T generated by gradually increased thickness of the ZnO layers had a compensatory effect among the ZnO layers with various thicknesses. This implied that the integrated voltage responsivity of V_T generated by the improved multi-frequency band pyroelectric devices could present the performances of various pyroelectric devices at various sensing frequency bands.

IV. Conclusion

The general pyroelectric sensor with a single pyroelectric layer has only a single sensing frequency band. However, multi-frequency sensing tasks could improve applications of pyroelectric sensors for detecting subjects with various speeds or frequencies under a fine responsivity. A improved multi-frequency band pyroelectric sensor was successfully designed and analyzed in the present study. The combination of a thinner sputtered ZnO layer and three thicker aerosol ZnO layers proved useful in the present design. The tactic by gradually increased thickness of the ZnO layers presented a compensatory effect for redeeming the drawbacks among the ZnO layers. The ranges of the multi-frequency sensing tasks could be predicted by the proposed design and analysis.

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