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Novel electrode layout for relaxor single crystal pyroelectric detectors with enhanced responsivity and specific detectivity

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ABSTRACT

A distributed electrode structure of sensitive element based on Mn-doped $Pb(Mg_{1/3}Nb_{2/3})O_3$-0.29$PbTiO_3$ single crystals for high-end pyroelectric infrared detectors has been proposed, demonstrating a notably superior pyroelectric response. Under the optimal electrode distance of 0.5 mm, the figure of merit for detectivity is up to 39.9×10^{-5} $Pa^{-1/2}$. An ultrahigh responsivity of 864 V/W and specific detectivity of 1.49×10^9 cm $Hz^{1/2}$/W at 10 Hz are observed, approximately 3.6 and 1.4 times higher, respectively, than that of the conventional faced electrode structure. The enhanced responsivity and specific detectivity of the distributed electrode structure will make PMNT based detectors with voltage mode promising in practical use of sensors.

Pyroelectric materials have received increasing attention by engineers and scientists in the past decades owing to their multifunctionality, such as energy harvesting [1], infrared detection [2], phase transition studying [3], and field emission for X-rays, electrons, ions, and neutrons [4–6]. Pyroelectric infrared detectors which are portable, low cost, and high sensitivity today are used for a wide range of applications in temperature sensing, fire and gas detection and thermal imaging [7,8].

Some ferroelectric materials show pyroelectric behavior, in which an induced variation of spontaneous polarizations occurs in response to the temperature change. Triglycine sulfate (TGS), lithium tantalite (LT) and barium strontium (BST) [9–12], as traditional pyroelectric materials, have been widely used in infrared detectors. However, the deliquescent properties, low pyroelectric coefficient or needing bias voltage of these materials are still far from the demands in high-end detective fields. Among the many pyroelectric materials, the single crystal of Mn-doped (1-*x*)$Pb(Mg_{1/3}Nb_{2/3})O_3$-*x*$PbTiO_3$ (Mn-PMNT) exhibits exceptional pyroelectric properties with pyroelectric coefficient up to 17.2×10^{-4} C/(m^2 K) [13], which is almost 3 times higher than that of TGS [9], 9 times higher than that of LT [10], and 55 times higher than that of polyvinylidene fluoride (PVDF) [14]. Moreover, Mn-PMNT based infrared detector with dissymmetrical electrodes under the widely used voltage mode has been fabricated. The specific detectivity (D^*) is up to 1.05×10^9 cm $Hz^{1/2}$/W at frequency of 10 Hz, which is the highest values reported so far [15]. However, the responsivity with a low value of 236.5 V/W is far from the practical applications. How to further improve the responsivity is an important research topic to meet the practical application demands for the PMNT based pyroelectric infrared detectors.

In this letter, we have designed a novel structure of sensitive element for infrared detectors with distributed electrodes and an optimal electrode distance is obtained, which effectively enhanced the responsivity, specific detectivity and high-frequency performances. Compared with that of the traditional faced electrode structure, the responsivity and the specific detectivity of the proposed structure at 10 Hz are 3.6 times and 1.5 times higher, respectively. In addition, the 100 Hz performances are also enhanced by similar values. These results were identified to be due to the ultralow capacitance and dielectric loss of the novel structure sensitive element.

The ⟨1 1 1⟩ oriented Mn doped PMN-0.29PT pyroelectric single crystal was grown directly from the melt by a modified Bridgeman method and then cut into a square plate with dimensions of 20 mm × 20 mm × 0.5 mm [16]. The plate was completely bonded on a glass substrate by adhesive wax and then thinned to a film thickness of 20 μm using grinding and subsequent chemical mechanical polishing (CMP). After that, the as-thinned plate was

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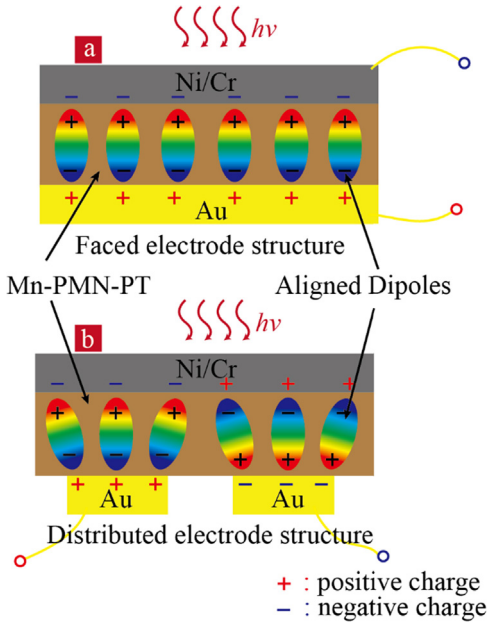

Fig. 1. Schematic illustration of the traditional faced electrode structure (a) and the proposed distributed electrode structure (b) of sensitive elements for pyroelectric infrared detectors.

cut to chips with a size of $2.5 \times 2.5\,mm^2$, and annealing at 500 °C for 10 h in an oxygen environment was then carried out to reduce the strain caused during the polishing process. Electrode layers of Au (2 mm × 0.5 mm) with adequate center-to-center distance l and Ni/Cr electrode were deposited on the bottom and top surfaces of the chips, respectively, using magnetron sputtering. After that, polarization of the chips was carried out using an exclusive polarization method. The dielectric properties of the chips were measured using an impedance analyzer (Agilent 4294A), and the pyroelectric coefficient was characterized by a dynamic technique at a low frequency of 45 m Hz [17]. Single-walled carbon nanotubes were sprayed on the top-face of the chips to further enhance the absorption of infrared incidence [18]. The blackened chips were then assembled in a TO39 housing to fabricate the pyroelectric infrared detectors, coupling with a resistance with value of 100 GΩ and a low noise junction field effect transistor (JFET). Performances of the detectors were measured by a dynamic signal analyzer (Agilent 35670A), associated with a blackbody (HFY-200B), running at 500 K.

Fig. 1a and b shows a schematic illustration of the traditional faced electrode structure and the proposed distributed electrode structure of sensitive elements for pyroelectric infrared detectors, respectively. The two structures are both composed of three layers: Au, which acts as the bottom electrode, Mn-PMNT as the pyroelectric material and Ni/Cr as the top electrode or black layer to absorb the infrared incidence. The main difference between the two structures is the arrangement of the output electrodes and the operation of the sensitive element. First, for the faced electrode structure, the output electrodes are arranged on the top and bottom faces of the sensitive element, respectively (see Fig. 1a). While for the distributed electrode structure, they are both on the bottom face with a proper distance. Second, in operation, the faced electrode structure works like a plane-parallel capacitor. While the distributed electrode structure is arranged in reversed polarization, similar to the electrical connection of two faced electrode structure in series (as illustrated in Fig. 1b). The working mechanism of the distributed electrode structure can be described as follows. The infrared radiation is absorbed and causes a change in temperature in the sensitive element. The aligned dipoles changes and alters the charge density on the electrodes due to the pyroelectric effect. For the top surface, the induced positive and negative charges offset with each other through the common Ni/Cr electrode. While for the bottom Au electrodes, the positive and negative charges cannot be offset and an electrical signal is created. One advantage of the distributed electrode structure is that the series connection contributes to the decreasing of capacitance, largely enhancing the responsivity and declining the dielectric loss noise. Furthermore, this distributed electrode structure is more compatible with the integrated technology and easier to be compacted in size.

As we know, the voltage responsivity R_V, voltage noise flow u_N, and the specific detectivity D^* of the pyroelectric infrared detectors under voltage mode can be expressed as [2]

$$R_V = \frac{\alpha p}{c'_P d_P} \frac{\omega\tau_T R}{[1+(\omega\tau_T)^2]^{1/2}[1+(\omega\tau_E)^2]^{1/2}}, \tag{1}$$

$$u_N = \sqrt{u_R^2 + u_D^2} = \sqrt{4kT\omega C_P \tan\delta + \frac{4kT}{R}\frac{1}{\omega C_P}}, \tag{2}$$

$$D^* = \frac{R_V\sqrt{A}}{u_N}, \tag{3}$$

where α is the absorption of the black layer, p is the pyroelectric coefficient, c'_P is the specific heat capacity, d_P and A are the thickness and electrode area of the sensitive element, respectively; τ_T and τ_E are the thermal time constant and electrical time constant, respectively. u_D and u_R are the tanδ voltage noise and resistance voltage noise, respectively; k is the is Boltzmann's constant (1.38×10^{-23} J/K); T is the temperature in Kelvin; ω is the angular frequency; C_P is the capacitance of the sensitive element and R is the resistance. Here, the value of voltage noise flow is mainly determined by the internal noise sources, namely resistance noise (i.e., $i_R = \sqrt{4kT/R}$) and dielectric loss noise (i.e., $i_D = \sqrt{4kT\omega C_P \tan\delta}$). The external noise sources such as thermal noise and electrical circuit noise have not been addressed due to the lower value relative to the internal noise sources.

Taking into account the parameter of the sensitive element and thermal conditions, Eq. (1) can be simplified to

$$R_V = \frac{\alpha p}{c'_P d_P}\frac{1}{\omega C_P} T_T, \tag{4}$$

with $T_T = \frac{j\omega\tau_T}{1+j\omega\tau_T}$. The dimensionless function T_T is called complex normalized factor. For a thermally insulated ideal condition (i.e., $G_T = 0$), the complex normalized factor reaches value of 1. For practical interesting modulation frequencies of 1–1000 Hz, it can be approximated with this value of 1 because the thermal time constant reaches considerable value. In addition, considering the dominant noise is the dielectric loss noise for the PMNT based detectors (i.e., $u_R \gg u_D$) [19], Eq. (2) can be simplified to

$$u_N = \sqrt{\frac{4kT\tan\delta}{\omega C_P}}. \tag{5}$$

From Eqs. (4) and (5), we concluded that the decreasing of the capacitance of the distributed electrode structure will contribute to not only the increasing of the responsivity but also the declining of the noise value, leading to an enhanced specific detectivity.

Here, the Mn-doped PMN-0.29PT single crystal was used for the distributed electrode structure due to its excellent pyroelectric properties. Fig. 2 displays the measured dielectric properties of Mn doped PMN-0.29PT as a function of frequency ranging from 1 Hz to 10 kHz and temperature varying from 25 °C to 300 °C, using the Novocontrol Broadband Dielectric/Impedance Spectrometer. From Fig. 1, it can be seen that two peaks in both permittivity and dielectric loss can be distinguished. This behavior is similar to that reported on [1 1 1] poled PMN-0.29PT single crystals [20],