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Fabrication and characterization of back-incident optically immersed bolometer based on Mn–Co–Ni–O thin films for infrared detection

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ABSTRACT

Optically immersed detectors with high index of refraction lenses were an effective technique to improve the performance of thermistor bolometer for infrared detection. In this paper we described the design and fabrication of back-incident optically immersed bolometer with germanium hemispherical lens using the $Mn_{1.56}Co_{0.96}Ni_{0.48}O_4$ thin films prepared by chemical solution deposition method on amorphous Al_2O_3 substrate. The characteristics of back-incident immersed bolometer operated at room temperature were investigated. It was found that the performance of the detector was significantly enhanced by the use of germanium hemispherical lens. The fabricated bolometer exhibited noise equivalent temperature of 1.56×10^{-7} K/Hz$^{1/2}$, responsivity of 3.2×10^3 V/W, and detectivity of approximate 9.2×10^8 cmHz$^{1/2}$/W at 30 Hz. The thermal time constant of 7.3 ms was about one third of the non-immersion ones. Field of view of $\pm 35^\circ$ and optical immersion gain of up to 14 times were also obtained. The results demonstrated that the feasibility of back-incident optically immersed bolometer could be used to uncooled infrared bolometric applications.

1. Introduction

Thermistor bolometers have been subjected to extensive investigation over the past decades owing to its importance in the applications of uncooled infrared (IR) detection [1–5]. It can convert incident IR radiation into an electrical signal by means of a thermal sensing material with high temperature dependent resistance. There has been an increasing demand for high sensitivity and stabilized IR detectors in a variety of applications in civilian and military, such as automotive thermal and biomedicine imaging, night vision, security and fire detection, as well as defense and space science and technology [5–9].

The sensor materials used in uncooled IR bolometer are resistive in nature which generally have a high temperature coefficient of resistance [$TCR = (1/\rho) \times (d\rho/dT)$]. Many types of thermistor materials have been extensively studied such as metal films [10,11], vanadium oxide [12–17], semiconducting $YBa_2Cu_3\ O_{6+x}$ [18,19], silicon–germanium alloys [8,20–23], amorphous silicon [24,25], multi-component transition metal oxides [26–32]. Among these thermistor materials, spinel ternary transition metal oxides of manganese, cobalt, nickel (Mn–Co–Ni–O) with a general formula AB_2O_4 have been widely investigated for uncooled IR detection because of its high negative TCRs ($\leq$3.5%/K), moderate resistance and long term stability [27,28]. As a lower resistivity material requires a lower bias voltage to obtain the same performance in IR detectors, $Mn_{1.56}Co_{0.96}Ni_{0.48}O_4$ (MCN) is a composition of some specific importance because it is very near the resistivity minimum for this ternary oxide [33]. The thermal, electrical and optical properties of MCN thin films have been extensively investigated [29–32,34,35], which show greatly promising application prospect for uncooled thermometry and bolometry.

However, there are rather a few studies on MCN film thermistor for uncooled IR bolometric applications. The performance is also not very well for the present MCN film bolometers [36]. It cannot sufficiently meet the required characteristics of high signal responsivity and response speed for IR instruments in remote sensing. Hence, we propose to use optical immersion with high refraction index lenses to improve the performance of MCN film detectors so that it can be widely applied in the field of civilian and military.

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Germanium (Ge) is commonly used for immersion lenses because of its high refractive index n of 4 and broad band IR transmission. The purpose of the present research is to study the back-incident optically immersed bolometer with Ge hemispherical lenses using MCN thin films prepared by chemical solution deposition (CSD) method on amorphous Al_2O_3 substrate. The back surface of substrate is cemented to the plane surface of Ge hemispherical lens with arsenic doped selenium glass ($n' = 2.5$) [37]. This approach can focus the incoming IR radiation onto a smaller sensor element area and improve the performance of MCN film bolometers. In this paper, the principles of optical immersion are present first followed by the fabrication and packaging of MCN film bolometers in optically immersed configuration. Then, the paper is devoted to analyze the results of immersed bolometric properties at room temperature (295 K), namely responsivity $\Re$, detectivity D^*, thermal time constant τ and noise equivalent temperature NET.

2. Immersion principles

For a specific optical system, the use of immersion lens reduces the sensor element size and increases the apparent optical area of IR bolometer comparing to the non-immersed ones. Thus, the immersed bolometer responsivity is enhanced with no change in the noise and so detectivity is increased.

If the sensor element is immersed on the center of flat surface of a hemispherical lens as shown in Fig. 1(a), then the apparent area of the immersed sensor element will be increased by a factor n^2, yielding a factor of n gain in detectivity [38]. There is no change in the apparent position of the sensor element. The field of view (FoV) is determined by the onset of total internal reflection at the immersion interface, and the angle is $\pm\sin^{-1}(n'/n)$ for immersed detectors with a hemispherical lens. If the immersion lens is a hyperhemisphere that is a sphere truncated a plane, distant r/n from its center, where r is the radius of curvature as shown in Fig. 1(b). This lens will increase the apparent area of n^4 and a detectivity gain of n^2 at aplanatic focal condition. But the FoV of the bolometer is restricts to $\pm\sin^{-1}(1/n)$ and the apparent position is also changed. We employ the Ge hemispherical lens ($n = 4$) with radius of 5.5 mm in the present study to demonstrate the feasibility of back-incident optically immersed bolometer for uncooled IR detection because it has the larger FoV and simple optical configuration.

3. Experiment

3.1. Preparation of MCN thin films

The MCN films were prepared by the starting materials of manganese acetate, cobalt acetate, and nickel acetate. These acetates with an atomic ratio of Mn:Co:Ni = 52:32:16 were dissolved in glacial acetic acid. The mixture solution was filtered through 0.2 μm syringe filters to remove dust and impurities. Then the films were coated onto the amorphous Al_2O_3 substrate of 100 μm thick by spin coating of the solution at 4000 rpm for 20 s. After coating each layer, the wet films were dried at 250 °C for 1 min to remove residual organics, followed by annealing at 750 °C for 5 min. The deposition and heat-treatment procedure were then repeated to obtain the desired film thickness of 5 ± 0.1 μm. The results of X-ray diffraction (XRD) and scanning electron microscopy (SEM) are shown in Fig. 2, which indicate that the MCN films are of single cubic spinel phase and compact surface. The temperature dependent resistance in Fig. 3 shows that the MCN films have negative temperature coefficient (NTC) behavior with a TCR of −3.8%/K and resistance (R) of 400 KΩ at 295 K. It is commonly described by the Arrhenius equation $R = R_0 \exp[B(1//T - 1/T_0)]$, where R_0 is the resistance of films at temperature T_0, B is the thermistor constant. The inset in Fig. 3 plots ln R versus $1/T$ curve. The thermistor constant $B = 3310$ K can be obtained from the slope of plot. The thermal activation energy $E = 0.29$ eV for MCN films can also be calculated according to $E = kB$ (k is Boltzmann constant), which is in agreement with the previous works [27].

MCN thin films are patterned to define sensor area geometry of 500 μm × 300 μm by a suitable photolithography and wet chemical etching. Then metallic contact pads of area 100 μm × 300 μm are applied on MCN thin film by deposition of 30 nm of chromium (Cr) and 150 nm of gold (Au) in sequence using ion-beam sputtering. The specified geometry of metallic contact pads is realized through a lift-off-lithography technique. The schematic diagram of MCN film thermistors with metallic pads is shown in Fig. 4. It consists of identical dual sensor elements with the active area of 300 μm × 300 μm

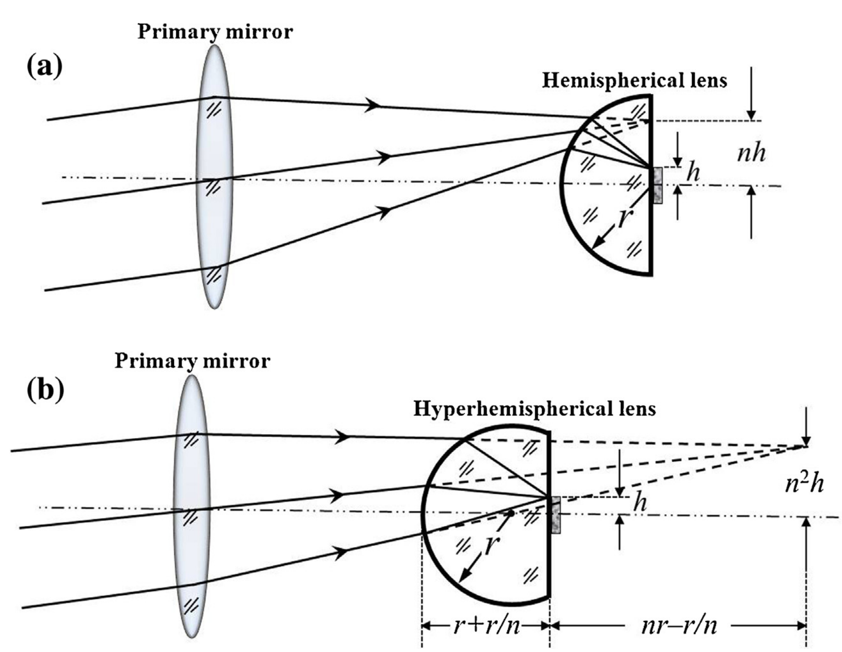

Fig. 1. Principles of Ge optical immersion: (a) hemispherical immersion, (b) hypehemispherical immersion.