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Device-level vacuum packaged uncooled microbolometer on a polyimide substrate

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HIGHLIGHTS

- Bolometer.
- Polyimide substrate.
- Double layer absorber.
- Optical filter.
- MEMS sensors.

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ABSTRACT

Uncooled infrared detectors (IR) on a polyimide substrate have been demonstrated where amorphous silicon (a-Si) was used as the thermometer material. New concepts in uncooled microbolometers were implemented during the design and fabrication, such as the integration of a germanium long-pass optical filter with the device-level vacuum package and a double layer absorber structure. Polyimide was used for this preliminary work towards vacuum-packaged flexible microbolometers. The detectors were fabricated utilizing a carrier wafer and low adhesion strength release layer to hold the flexible polyimide substrate during fabrication in order to increase the release yield. The IR detectors showed a maximum detectivity of 4.54×10^6 cm Hz$^{1/2}$/W at a 4 Hz chopper frequency and a minimum noise equivalent power (NEP) of 7.72×10^{-10} W/Hz$^{1/2}$ at a biasing power of 5.71 pW measured over the infrared wavelength range of 8–14 μm for a 35 μm × 35 μm detector. These values are comparable to other flexible microbolometers with device-level vacuum packaging which are found in literature.

1. Introduction

Uncooled infrared detectors have been widely researched due to their lower operating cost and room temperature operation compared to their cryogenically cooled counterparts. The addition of self-packaging or device-level vacuum packaging technique where the chip package is fabricated with the detector across the wafer would help to reduce the cost of adding a separate conventional vacuum packaging to the devices [1,2]. Moreover, fabricating the detectors on flexible polyimide substrates helps the IR detector to conform to any non-planar surface such as a robot, night vision goggles, wearable electronic instrumentation, or other non-planar scientific instruments. All these features were utilized during design and fabrication of these IR detectors.

The resistance change of the detecting material with temperature due to the absorption of heat from infrared radiation was used to design the infrared microbolometers [3]. Depending on the material, the resistance may increase or decrease with temperature. There are a variety of materials that can be used as the sensor material or thermometer for room temperature detection of infrared radiation, such as Y-Ba-Cu-O [1], SiGe [4], amorphous Si (a-Si) [5], polysilicon [6], and VO_x [7]. The selection of the material depends on the compatibility of the fabrication process, sensitivity of the material with temperature variation, noise floor, and operating temperature. We previously utilized a-Si as a sensing material for temperature sensors which showed low 1/f-noise [8] and a temperature coefficient of resistance (TCR) of −2.88%/K [9]. For the current work, a-Si was used as the detecting material [10,11] and served as a test bed to prove several concepts that we developed during the microbolometer design while, at the same time,

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focusing on achieving comparable performance with the flexible microbolometer counterparts.

There were two concepts we worked to implement during fabrication of the detectors. The incorporation of a long-pass optical filter with the device-level vacuum package and a double layer absorption structure to allow control over the infrared radiation absorption bandwidth during the design phase. The implementation of device-level vacuum packaging with an integrated optical filter is essential to the development of practical flexible microbolometers. The details of the design and simulation results, as well as, some preliminary work can be found in our earlier publication [12]. Germanium has a high extinction coefficient in visible wavelength range and low extinction coefficient for sub-optical-bandgap radiation [13,14], which means that a germanium long-pass filter will block visible light while allowing the long-wave infrared radiation to reach the detector. Ge is commonly used for long-wave infrared optics. The Ge filter was integrated with the device-level vacuum package providing both optical filtering function while increasing the mechanical strength of the vacuum package. In the current work, the a-Si detecting material was sandwiched between a top and a bottom electrode which both absorbed the IR radiation and transferred the heat to the detecting material, thereby creating a double layer absorber structure. The thickness of different layers was optimized through Monte-Carlo simulation so that the maximum absorption takes place on the electrodes in a wavelength range of 8–14 μm. The integration of the optical filter during the device fabrication would reduce the cost of adding additional external filters to the system.

In addition to those features, the microbolometers on polyimide were fabricated utilizing a new release layer technology as discussed by Ahmed et al. [15] in order to avoid any unwanted destruction of the detectors during the release from the silicon carrier wafer. Though, in this preliminary work, the detectors were characterized before releasing the flexible substrate (holding the detectors) from silicon carrier wafer. Our preliminary results were presented in [16].

2. Experimental details

2.1. Fabrication of the bolometers on the flexible substrate

The visual representation of the cross-sectional view, step-by-step fabrication process and top view of detecting part are illustrated in Figs. 1–3 respectively. Most of the depositions were done by rf magnetron sputtering in an Ar-gas environment. The fabrication starts with growth of the flexible substrate on the silicon carrier wafer. For this purpose, the Si_3N_4-PI2611 (release layer)-PI5878G (flexible substrate)-Si_3N_4 layers were deposited to facilitate fabrication of the sensors and their easy removal from the flexible substrate after fabrication (details are discussed in [15]). The thickness of the PI5878G polyimide substrate layer was 70 μm. The top Si_3N_4 passivation layer defines the device plane. First, a 303-nm-thick aluminum mirror layer was sputtered onto the passivation layer and patterned through lift-off process to form reflecting mirrors. Later, thinned HD4104 was spin-coated, patterned and cured at 250 °C to get a final thickness of 548 nm which was named as the thin sacrificial layer. Next, HD4104 was deposited and patterned on top of the thin sacrificial layer. It was cured at 250 °C to achieve a final thickness of 3.2 μm to form a thick sacrificial layer. On top of the sacrificial layers a 109-nm-thick alumina (Al_2O_3) layer was sputtered and patterned through lift-off process to form the base membrane for the thermometer. After that, a metallization layer was formed by sputtering a 130-nm-thick nichrome (Ni 80%-Cr 20%) film and patterned to connect the bottom-electrode to the bond pads. The thin nichrome layer of metallization also served to reduce the thermal conductance from the thermometer to the substrate. Then, a 32-nm-thick aluminum film was sputtered and patterned by lift-off to create the bottom electrode. On top it, an a-Si (500-nm)-aluminum (30-nm)-alumina (20-nm) tri-layer was deposited and patterned by simultaneous lift-off. The a-Si acts as the sensing material or thermometer; where the aluminum acts as the top electrode and absorber for the infrared radiation. The aluminum also prevents oxidation of silicon [9]. The alumina protects the top electrode from oxidation during the surface micromachining process. Later, HD4104 polyimide was spin-coated, patterned by photolithography and cured at 250 °C to achieve a final thickness of 3.2 μm. This polyimide served as the top sacrificial layer to create a vacuum cavity between thermometer and the subsequent encapsulation layer. Then, a 558-nm-thick alumina, encapsulation layer was sputtered onto the sacrificial layer and patterned by lift-off process. This layer contained etch holes to aid the removal of the polyimide sacrificial layers by surface micromachining. After that, all three layers of sacrificial polyimides were removed by a Plasma Therm asher. This process created a cavity below and above the thermometer to form a thermally isolated structure. Then, the etch holes of the encapsulation layer were sealed with a 2-μm-thick Al_2O_3 packaging layer which also covered the bond pads. Here, the thin sacrificial layer helped to decrease the necessity of a thicker packaging layer by forming a small gap between passivation layer and encapsulation layer. Next, the bond pads were opened through wet etching in phosphoric acid. Then, Ge optical filter of thickness 720-nm was thermally evaporated on the detector; followed by the lift-off process to pattern the filter (Fig. 4). After that, HD4110 was spin-coated, patterned by photolithography and cured at 250 °C to obtain a final of thickness of 47 μm (Fig. 5). This final polyimide served as a superstrate layer for the detectors to keep them at a low stress plane. A 1 cm × 1 cm piece of flexible substrate which contains 14 microbolometers (Fig. 6) was removed from silicon carrier wafer to check the performance of the low adhesion strength release layer [15] after the multi-layer processing. The flexible substrate could be easily removed. Though, the sensors that were characterized remained on the silicon carrier wafer in this preliminary work using a custom built IR probe station.

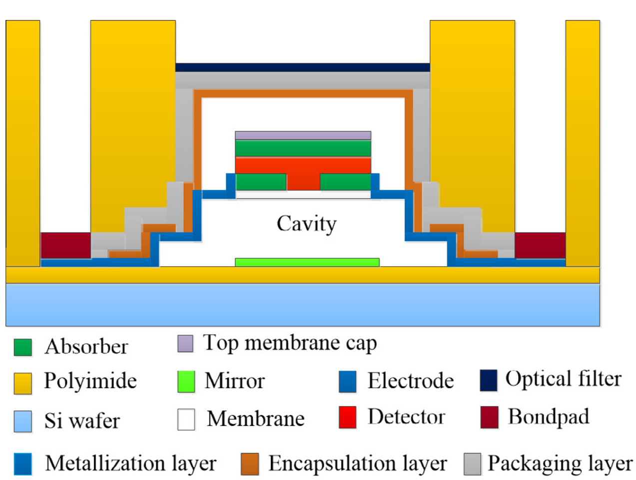

Fig. 1. Cross-sectional view of the surface micromachined bolometer showing different layers and cavity (dimensions are not scaled according to the actual dimension); cavity was created by etching sacrificial layers.

2.2. Microbolometer resistance measurement

The first stage of the characterization was to measure the resistance values of the microbolometers. Each detector had two resis-