LOW-COST UNCOOLED INFRARED DETECTOR USING MICROCANTILEVER ARRAYS WITH OPTICAL READOUT

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Abstract — We report on characterization of an uncooled infrared (IR) detector set-up which serves as a low-cost IR camera technology platform. The imaging detector consists of a passive microsensor and a simple optical readout. IR radiation is detected by a microcantilever focal plane array (FPA) which working principle is described. The cantilever serves as a thermo-mechanical transducer, converting photon energy in a reversible mechanical deflection on the micro-level. The mechanical deflection is captured by a visual imager (CCD / CMOS) which is part of the simple optical readout and converted into changes of gray scale intensity. Finally, we present first results of real-time thermographic imagery taken by the uncooled IR detector.

Keywords: Infrared, Microcantilever, Array, Optical Readout

I - Introduction

In the last decade a surpassing growing demand for thermography and vision enhancement has been observed [1]. These applications play a crucial role in the commercial safety and security industry, as well as for quality assurance. To 95 % of all uncooled IR systems are represented by the microbolometer FPA sensor [1]. Despite its excellent performance in IR imaging the relative high costs of the complex microbolometer technology will not allow a commercial breakthrough of IR applications [2]. Decreasing the system cost excessively would result in a broad access of IR technology and create new end user applications, such as private property security or drive vision enhancement systems for any-type automobiles. Therefore the IR community is constantly on the search for an innovative low-cost sensor alternative to achieve commercial breakthrough of IR technology. Herein our efforts focus on developing a low-cost and non-complex thermographic imager which is suitable for mass production.

One of the most promising alternatives is the microcantilever IR sensor. Such sensors have been demonstrated by several research groups in the past 10 years [3-10]. The reported microcantilevers are based on a metal-dielectric bimaterial compound such as SiN₆-Au or SiO₂-Al. Some included specific temperature-compensating designs to eliminate the necessity of thermo-electric sensor stabilization [7, 11]. The cantilever design and its materials are critical factors to the overall system’s responsivity. Despite the demonstration of thermal imagery by microcantilever sensors an IR camera based on this technology has not been commercially launched yet. We believe that the previously reported systems are commercially inadequate due to low system’s responsivity and in particular problematic micro-manufacturing processing involving low temperature plasma thin film deposition. We have overcome these problems by developing manufacturing processes which enable high yield, high-sensitive cantilever structures. Implemented in an optical readout we are able to demonstrate first thermal images.

II – Working Principles

One of the costliest components in today’s thermal imaging systems is the microbolometer which can make up to 55 % of the over camera core costs [12]. The complex, low-yield, multi-thin film technology which is currently limited to 150 mm substrate wafer production and only after 20 years of development commencing 200 mm processing disallows to fully employ the scaling advantages of micro-fabrication [13]. Furthermore the non-linear complexity rise of the bolometer’s readout integrated circuit (ROIC) limits its format size to < 0.8 megapixel which is currently considered as an ultimate high-end [1]. The solution for a commercial breakthrough of IR technologies is i) a simple, straightforward, standard MEMS-technology fabrication which must be applicable to large format substrate wafer processing and ii) a readout being within cost constraints, robust and needing to be scalable beyond 10⁶ pixel without a non-linear complexity growth. These criteria can be met only with a microcantilever array with an optical read out. Within our past research and development activities we were able to find an optimum sensor design with high sensitivity and to develop a micro-fabrication which enables high-yield and high uniformity microcantilever arrays [14-17]. We have developed a technological platform which has potential for enabling a commercial breakthrough of IR technology and furthermore extending the imaging applications with formats beyond one megapixel. Beyond the economic and format scale extension advantages this system configuration offers following additional benefits in contrast to the bolometer technology: system’s low energy consumption and no self-heating due to electronically passive IR sensor; solar immunity due to elastic mechanical cantilever deflection; high-temperature operation and high linearity, including
detection in bands beyond LWIR (8 – 14 µm) e.g. dualband, MWIR (3 – 15 µm) or THz (>14 µm).

The disadvantages of the microcantilever IR detector with an optical read out compared to microbolometer systems is its relative bulky configuration and it contains different noise sources which might result in a system’s higher noise equivalent temperature difference (NETD) equaling in systems lower responsivity [18, 19]. For commercial applications the novel IR detectors responsivity must be NETD < 500 mK which has been reported successfully [5].

A. Sensor design

The microcantilever’s working principle is the bi-material effect. The functional part of the microcantilever is a combination of two materials with a maximum mismatch of coefficients of thermal expansion (CTE). The cantilevers typically consist of two thermal isolation legs, which are anchored to the wafer substrate, the functional bi-material part and a free standing absorbing area. The mechanical deflection dz due to the bi-material effect is proportional to the generated temperature gradient dT and is derived by Timoshenko’s beam theory [20, 21]. The generated temperature gradient is defined by the structure’s overall heat loss mechanism and absorbed IR flux [22]. The sensor is operated at sufficient low pressure (< 0.2 mbar) [23] to avoid heat loss through air. The fundamental thermal isolation limit is set by absorber’s re-radiation and in order of 10⁻⁸ W / K [24]. The thermal isolation plays a key role in the sensor’s sensitivity and dynamics. There is a trade of between these critical merits due to the definition of the thermal time constant by the thermal conductance. The cantilever’s thermal time constant must be < 20 ms to have sufficient reaction time to respond to absorbing an dissipating heat for >20 frames per second imaging.

On the sensor level the most significant merit is the deflection-sensitivity (dz/dT). It is defined as the cantilever’s maximum change in amplitude induced by the bimetallic effect per degree Kelvin gradient change on the structure. In general the deflection-sensitivity should be as high as possible for high temperature resolution performance and to reduce resolution demands of the optical readout.

An optimum design includes adjusted thermal isolation legs, adjusted young’s modulus and thickness ratio of functional films, a long bi-material region and an effective large absorbing area. Since the pixel pitch is a crucial factor in terms of cost saving by downsizing system components, such as IR-optics and packaging by downscaling the active sensor area, it is constrained to <80 µm for small formats (< 100 x 100 pixel). For large pixel formats it is crucial to limit the pixel pitch to < 50 µm. Newest bolometer technology offers 17 µm pitch, which can be achieved only with highly sophisticated lithographic systems in the micro-fabrication and structuring process [13, 25]. To increase deflection sensitivity for a defined length of the bi-material region it is essential to lower the thickness of the thin films. Ideally film thickness should be < 200 nm.

B. Sensor fabrication

The microcantilever FPA has been microfabricated via surface micro-machining. Within our research activities we have optimized the microfabrication process using different sacrificial layers, such as oxide or polyimide. Furthermore we have developed a sensor design which can be fabricated using two low pressure chemical vapor deposition (LPCVD) process steps. This high temperature process step can be only implemented if no metals or polymers have been previously applied on the processed wafer substrate, which is the case for our developed ARCH-Type design [17]. The main advantage of this process step is the ability of processing ±20 substrates in one run. Furthermore the thin film quality of the Si₃N₄ is of excellent quality and thin films thickness < 150 nm can be applied. In addition we have developed also an optimum metal-dielectric bi-material compound which is fabricated via inductive coupled plasma chemical vapor deposition (ICP-CVD). Here we report on excellent Si₃N₄ thin film quality, due to the reactors high plasma density. Further on we were able to adjust the stress gradient of the microstructure which plays a crucial role for the complexity of the detector’s optical readout configuration. Ultimately, the uniformity of the cantilevers affects the detectors responsivity. In case of FPA non-uniformity difficulties in sensor calibration, a non-linear behavior and even non-functionality may occur.

Figure 1: Microcantilever IR Sensor with 640 x 480 pixel.

The uniformity is defined by the quality and homogeneity of the deposited thin films. Therefore the thin film deposition is a crucial factor for the operation and responsivity of the IR imaging system. Additionally to these criteria, the thin film has to be of same quality along the entire processing substrate. We have developed and optimized deposition processes using 4 inch substrates. Here we report on fully function four 1
square inch FPAs with a size format of 640 x 480 pixel and 512x512 pixel processed on 4” substrates. We believe the deposition process can be easily up-scaled for 150 mm substrate processing while offering same thin film characteristics and further on optimized for > 150 mm substrates.

Figure 1 presents a 640 x 480 pixel microcantilever FPA IR sensor which has the format of 1 square inch. The outer frame is for handling and mounting purposes and has a width of ~5 mm. This FPA has been process as one out of four using 4 inch substrates. An SEM-image of this FPA is shown in figure 2. Hardly any defects such as sticking or dis-anchored missing structures can be occurred resulting in a pixel-functionality of >99 %. Figure 3 is a close up SEM image of one particular sensor design indicating no malfunctionality due to sticking, high pixel uniformity and structures stress gradient control.

III – Characterization, Results and Discussion

For the evaluation of the different microcantilever designs we have built an experimental set up with a 5-degrees of freedom adjustable evacuated sample holder, optical band filters, a calibrated IR source, a mechanical chopper, and a laser interferometric system to analyze cantilever’s resonant frequency and sub-nm-deflection with integrated IR optics mounted on a double stage damping system to isolate it from disruptive noise from the surroundings. This configuration is shown in Figure 4. In particular the pixel sensitivity, pixel responsivity to a calibrated IR flux, the pixel’s thermal time constant and its resonant frequency have been measured with this configuration. Merits of an optimized 50 µm pitch design are 67 nm / K, 1.2 nm / Wm², 10 ms at 10⁻³ mbar, 73 kHz respectively. Detailed analysis is described elsewhere [17].

For thermal imaging the microcantilevers are read out simultaneously with an optical system. The configuration consist of a visible incoherent light source, an optical system consisting of two lenses and a spatial filter and an visible imager (CCD / CMOS). In the initial set-up a microscope objective with a long working distance has been used. It was built vertically for simplicity purposes and a 45° mirror beneath the integrated IR optics has been placed to image thermal scenery from the surroundings. Figure 5 is showing a first laboratory setup. An initial image was taken by the CCD imager and subtracted from following running images to have a higher contrast of images changes. A thermal image was generated of an 80°C heating spiral and a raw thermal image can be observed in figure 6.
We have demonstrated first image taken by an IR detector using microcantilever FPA and simple optical read out. The setup is in a simple configuration using incoherent light source and a microscope optics. Our future efforts focus on characterizing and optimizing the readout system. One important aspect is the size reduction of the bulky configuration. First analysis has shown that the setup can be reduced to an acceptable size. In conclusion we made an important step towards a low-cost IR detector solution.

Figure 5: First laboratory setup for thermal imaging with a passive microcantilever IR sensor.

Figure 6: First generated thermal image of an 80°C heating coil.

Acknowledgements

This project was funded by Bundesministerium für Bildung und Forschung (BMBF) 03FO2272.

References