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Low-cost uncooled infrared detector using thermo-mechanical micro-mirror array with optical readout

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Abstract

We report on the realization and characterization of a novel infrared imaging system. The prototype setup serves as a technological platform for a low-cost uncooled infrared camera. The core component of the infrared imager is a novel-type surface micro-machined sensor consisting of a micro-mirror focal plane array. A micro-mirror represents one pixel and exhibits a linear deflection upon long wave infrared irradiation (7-14 µm). The thermo-mechanical deflection is captured by an optical configuration and real-time, full-frame thermal imagery is generated. The sensor does not require any power for operation and can be micro-fabricated with as little as three lithographic steps using standard CMOS technology.

Key words: Micro-Mirror Sensor, Infrared Detector, thermo-mechanical, uncooled thermal imaging, optical readout

Introduction

Infrared (IR) detection has been originally developed for military applications. Since its declassification in the beginning of the 1990s the commercial market on IR technologies is continuously growing. Applications such as thermal imaging, environmental monitoring and vision enhancement play crucial roles in today's energy and safety industry. The current $2.5B commercial IR technology market is dominated by the micro-bolometer sensor technology [1]. The bolometer sensor is a thermo-resistive transducer and based on complex multi-thin film micro-fabrication. Worldwide less than ten manufacturers are in the possession of the technological knowhow in order to produce micro-bolometer sensors [2]. A majority of these manufacturers are established in the defense industry.

The IR community is since many years on the search for a low-cost bolometer alternative. One promising candidate is a micro-mirror sensor. This sensor-type is a thermo-mechanical transducer, converting absorbed heat into a mechanical deflection of a micro-mirror element. The tilt of the micro-mirror is detected by a standard optical configuration using a laser diode and a CCD imager.

Development activities on this field of technology have been demonstrated in the past [3-5]. In contrast to previous developments our work focuses on a low cost sensor production which is the fundamental base for an affordable IR system. Our aim is to develop an IR imaging system which is suited for mass consumer applications such as fire detection or private property surveillance systems.

This article presents our latest development and results, focusing on the IR imaging system while characterizing the imager's sensor-level, sensor-module-level and ultimately overall system-level.

Sensor

The micro-mirror sensor is a focal plane array (FPA) consisting of a two dimensional matrix of IR sensing pixels. Each pixel consists of four functional regions: *(i)* an long wave IR (LWIR) absorbing area (7-14 µm wavelength), *(ii)* a reflective mirror-area on the top side of the absorber plate, *(iii)* a bi-material region and *(iv)* a thermal isolation region. Last is crucial to generate a thermal gradient on the structure by absorbed IR radiation. The bi-material region is a compound of two materials with a mismatch of coefficient of thermal expansion. The micro-mirrors are free standing structures on a Si-substrate fabricated via surface-micromachining using a polymer sacrificial layer. The microstructure's design is most critical for the overall IR detectors performance. We have developed a specific design which has higher sensitivity than conventional dielectric-metal bi-material compounds which were presented by others in the past, by using a dielectric-polymer bi-morph region [6, 7]. The sensor's micro-fabrication process consists of deposition and structuring three thin films of which one is the sacrificial layer. A micro-mechanical micro-mirror array can be produced with as little as three lithographic steps using standard micro-technology processes.

An important merit of performance on the sensor-level is the pixel's sensitivity *S*. This factor defines the amount of maximum out of plane deflection per degree Kelvin temperature change on the structure. The sensor used in the presented experimental setup was of a specific design and had a sensitivity of 360 nm/K. The sensitivity was determined by using a hotplate to change the structures temperature while evaluating its out of plane movement with an optical microscope with high magnification and small depth of focus. Other critical parameters are the micro-structure's resonant frequency to allow mobile usage of the IR detector for e.g. automotive applications. In the case of the demonstrated design the resonant frequency was 8.1 kHz. Last, the thermal time constant is an important merit. It needs to be adjusted via thermal conduction ratio to enable dynamic imagery of >20 frames/second. In this case it was 38 ms.

Sensor Module

The sensor module is per our definition a configuration consisting of IR optics and the mounted sensor. The sensor is packaged in vacuum. The operating pressure in our setup is 1E-2 mbar. The sensor packing consists of one IR transparent Ge-window on the incoming IR radiation side (back side) and a visually transparent silica-window facing the front of the free standing micro-mirrors (front side). The optical windows are coated with corresponding antireflective (AR) coatings. The sensor is operated in back-irradiation mode, where IR radiation is focused by the IR optics on the sensor through the IR transparent Si-substrate. The sensor's front side (mirrors-side) is illuminated by the optical readout's visible light. An illustration of the sensor module is shown in Fig. 1.

The incident IR radiation is passing through different optical media (IR-lens, Ge-window and the Si-substrate) before reaching the micro-structure's absorber region. Within our research and development activities we have characterized the losses of incident IR transmission. As can be seen in Fig. 2 the transmission peak is at ca. 10 µm wavelength. The characteristic spectral transmission curve is defined by the AR coating and the overall transmission in the LWIR region is <50 %. The major transmission loss comes from the ~50 % constant spectral reflection of the Si-substrate. To eliminate this loss the Si-substrate can be either coated with an AR film, or spatially removed by a dry or wet etch micro-fabrication process as demonstrated in [3, 4].

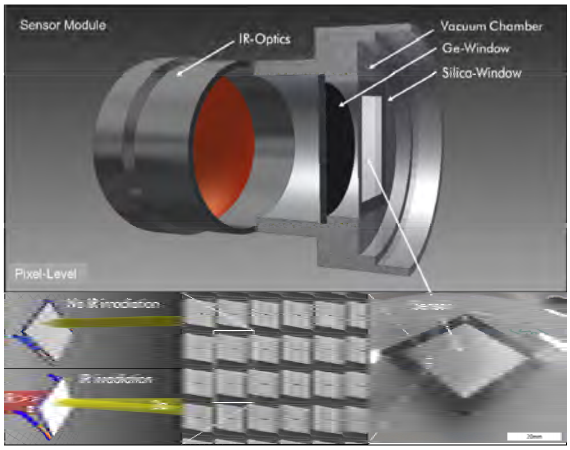

Fig. 1. Illustration of a sensor module with a photograph of a 512 x 512 pixel 50 µm pitch sensor (bottom right), a SEM detail of the micro-mirror FPA (bottom middle) and a schematic working principle sketch of an IR sensitive micro-mirror pixel (bottom left).

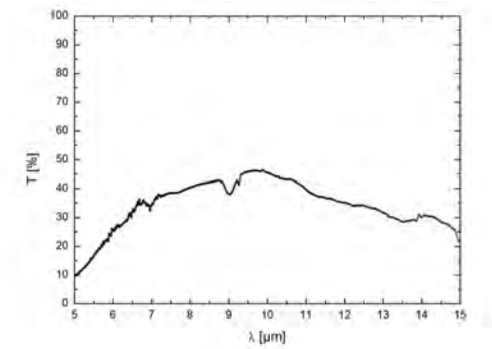

Fig. 2. Transmission of sensor module measured with FTIR spectroscopy.

Assuming the operating pressure is constant at a level where the micro-structure's dominant heat dissipation mechanism is conductance, following critical merits can be defined for the sensor module level: a temperature-transfer factor *D* and the module's responsivity R_M. The first merit describes the structure's temperature change according to one degree Kelvin temperature change of a black-body object placed in front of the module (F_{no} = 1) and the second merit describes the mirror's maximum out of plane deflection with one degree blackbody object temperature change. The relation to the sensors sensitivity S is:

$$R_M = DS \tag{1}$$

Typically the module's responsivity is given in [nm/K] and for the sensor used in this study was >2 nm/K for object detection near room temperature. This value has been determined experimentally with a laser interferometer setup, while the sensor was irradiated with a blackbody source. The temperature-transfer factor was obtained in the ~10 mK/K range.

Micro-Mirror's Signal Readout

The purpose of the readout is to convert the micro-mirrors deflection into an electrical signal to enable full-frame real-time thermal imaging. Within the past academic activities on micro-mechanical radiation sensors a number of readout techniques (capacitive, piezoresistive, optical) were introduced. The distinctive advantage of an IR imager with an optical readout is that the sensor is electronically passive, hence easy and inexpensive to fabricate, easy to scale, it does not consume any power, and issues such as self-heating and electrically induced noise do not exist. Therefore the sensor is a key component of a thermo-mechanical IR camera. The disadvantages of an optical readout are its bulky configuration, fine adjustment of optical components and photon-induced noise.

An optical readout can be categorized into two techniques: one, where a displacement of a light beam corresponds to the micro-mirror tilt – similar to a single cantilever standard AFM readout, and the second, where the micro-mirror deflection is converted into a light intensity change. In both cases the beams reflected from each micro-mirror are captured simultaneously by a CCD / CMOS imager. Both setups must be able to detect micro-mirror's angular changes in the 1E-2 mrad range (corresponding to nm resolution of the deflection). First technique can be realized using laser-needle-arrays. Second one using a 4*f* optical configuration with a knife-edge aperture (see Fig. 3).

System

The realized prototype setup is a 4*f* optical readout with a sensor consisting of various small pixel format fields (e.g. 40 x 30 pixel) of different cantilever designs. The 4*f* configuration uses an 8-bit low-cost CCD imager. Standard convex lenses were used and the light source was a Nd:YAG Laser of 532 nm wavelength. The laser intensity has been adjusted according to the saturation level of the imager and a diffusor was not necessary.

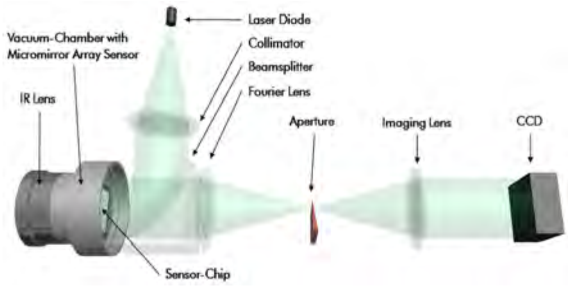

Fig. 3. Illustration of realized 4f optical readout.

Critical parameters on the detector level are system's responsivity R_s, giving the grayscale values (bits) per blackbody's degree Kelvin change in [1/K], temperature measurement range T_s, giving information about the maximum measurable (linear) temperature span, and imaging repetition B in [Hz] or frames/second. The relation for the noise equivalent temperature difference (*NETD*) is:

$$NETD = \frac{1}{R_S} \tag{2}$$

The experimentally determined and set values for the prototype camera were: R_s = 1.8 K^{-1}, T_s = 150 K, B = 30 Hz, and *NETD* ≈ 0.6 K. The prototype setup has been adjusted to enable thermal vision of humans and their environment. A raw, non-processed thermal capture of a human's hand is demonstrated in Fig. 4.

Fig. 4. Raw thermal imagery obtained by thermo-mechanical IR sensor prototype detector. Resolution: 40 x 30 pixels with 30 frames/sec.

Discussion

An IR imager based on a passive thermo-mechanical sensor has been successfully realized within our research and development activities. The aim of our undertakings was to demonstrate thermal imagery of the human environment with a temperature difference detection of less than 1 K. For current system's optimization and further development specific criteria from the designated area of application need to be met. The current system has a major potential for adjustment on specific applications criteria.

On the sensor level a higher pixel size formal can be easily implemented. Applications for security systems require e.g. 320 x 240 or 640 x 480 (VGA) pixel formats. We have successfully realized large scale VGA-equivalent formats with a 50 µm pixel pitch. The pixel-pitch reduction was in our case limited by photolithographic resolution of the used micro-fabrication equipment. Another great potential of a passive thermo-mechanical IR sensor is its usage for multi-band imaging such as mid wave (3-5 µm) or short wave IR (<3 µm) detection by using different thin-films (dielectrics and/or polymers). On the sensor-module level the responsivity R_M can be doubled by eliminating reflection losses of the Si-substrate. We have developed a micro-fabrication process implementing deep Si etch to fully remove the bulk Si substrate underneath the absorbing areas of the micro-mirrors (see Fig. 5).

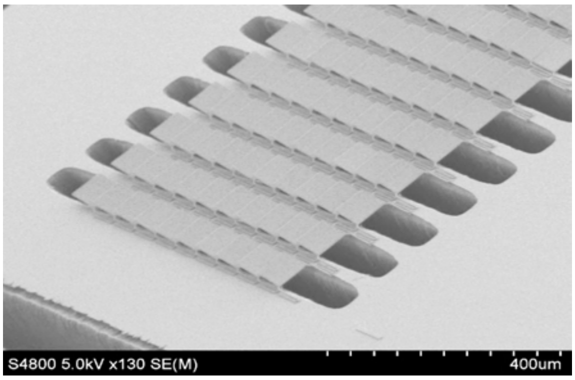

Fig. 5. Partial Si substrate removal through DRIE for increasing sensor-module's responsivity.

However, a deep reactive ion etching (DRIE) process for substrate removal requires an additional lithographic step and the process control is not trivial. Therefore we decided to compensate the module's relatively high transmission losses of >50 % by increasing the sensor's sensitivity.

On system's level the most important optimization is to increase the bit-value of the CCD imager to e.g. 12-bit or above. Automatically the *NETD* will decrease. With our set up a 12-bit CCD would implement a theoretical *NETD* value of <40 mK. In this case the *NETD* would have to be determined experimentally since photon-induced noise would become the dominant noise source in this order of magnitude.

Last, for a high number of low-cost IR imaging applications the volume of the entire 4*f* setup needs to be minimized. In current stage we are developing a concept for a compact optical setup on which we will report soon.

Conclusion

In this paper we have demonstrated first full-frame real-time thermal imaging with a power-less, low-cost thermo-mechanical IR sensor using an optical readout. The system *NETD* is less than 1 K and well suited for thermal imagery of human environment. For further development work distinctive application criteria such as detector size, NETD, pixel format, frame rate and temperature measurement range need to be specified. The demonstrated setup has great potential for adjusting key parameters for designated applications. Due to the sensor's standard micro-fabrication processes and the optical readout using standard low-cost components, the realization of an affordable IR system for mass consumer applications is possible with this technology.

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