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Methodology for micro-fabricating free standing micro-mechanical structures for infrared detection

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Abstract

Within our research and development activities on thermo-mechanical infrared sensitive micro-structures we have developed a comprehensive methodology and strategy to develop, fabricate, characterize and evaluate a novel-type micro-device. In this paper we use and explain the example of fabricating two types of micro-mechanical, fully-functional, free-standing structures by using plasma and low pressure chemical vapour deposition technology. Methods of micro-fabrication techniques, such as bulk micro-fabrication and surface micro-machining are analyzed and our critical process-technology findings are explained. Examples of successfully fabricated micro-mechanical IR sensors are given.

Key words: Infrared Sensor, Micro-Fabrication, Surface Micro-Machining, Technological Strategy, Methodology

Introduction

In the last two decades micro-fabrication has become a distinctively important industry with the production of MEMS and micro-sensors for automotive, safety, energy, consumers, telecommunication, etc. [1]. Through the miniaturization, economy of scale and effective fabrication our society benefits from the reliability, preciseness and cost-efficiency of these devices. One important technology for safety, security, environmental monitoring or automotive applications is uncooled infrared (IR) detection, which is currently represented by the micro-bolometer focal plane array (FPA). A bolometer is a thermal sensor, transducing absorbed IR radiation in a change of resistivity. The micro-structure has a form of a bridge, where two thermal isolation legs separate an absorbing plate, which is free standing with a 2.5 µm gap above the substrate forming an optical cavity. This technology has been developed initially for defense applications and today's IR cameras offer high performance in thermal imaging. Despite its market dominance for commercial applications this technology is extremely complex and hence expensive. The IR community is constantly on the search for a low-cost bolometer alternative. One potential candidate is a thermo-mechanical transducer type sensor. Absorbed IR radiation is converted into a mechanical deflection via the bi-material effect (mismatch of coefficients of thermal expansion of a two-material compound) of a free standing structure. This sensor-type, also called micro-mirror or micro-cantilever sensor, has several advantages over current competitive technology. This article focuses on the development of a strategy in order to understand and to implement micro-machining processes for a functional thermo-mechanical IR sensor. This methodology can be implemented in a number of research and development strategies of free standing micro-sensors –actuators and systems (further on called devices).

Methodology: Overview

The methodology for realizing a micro-device can be described as followed:

1. Fundamental consideration of the designated activity, definition of purpose and generating a concept.
2. Definition of aim and objectives – definition of target parameters and specifications.
3. Understand key correlation and physical background.
4. Theoretical (analytical / numerical) calculations if target specifications can be met, with choosing and defining micro-fabrication materials.

5. Definition of manufacturing technique with simultaneous
6. Definition of process flow.
7. Eventual examination and test of unknown material parameters.
8. Micro-fabrication of device.
9. Evaluation of micro-fabrication process if defined objectives were met.
10. If yes, characterization of micro-fabricated device with designated experimental setup.
11. Evaluation of results in correspondence to defined objectives. Eventual optimization.

Summarized these are the major sequences of the methodology work process. With the realization of a new type of micro-device there most likely will be a number of unforeseen difficulties occurring throughout almost each step of the undertakings. Depending on the situation, appropriate measures need to be implemented, which in most cases is returning to previous sequence(s) in the methodology plan.

In the following text the most important sequences will be described using the example of micro-fabricating a thermo-mechanical IR imager.

Purpose, Consideration and Concept

The purpose of realizing a novel-type IR sensor is to develop a low-cost alternative to current technology. The main objective is to use standard and cost-efficient micro-technology processes for micro-fabricating such sensor. The sensor exhibits a mechanical deflection, proportional to incident IR radiation. Each structure’s (pixel) deflection needs to be converted into an electrical signal. Previous work on this field has demonstrated capacitive [2], piezoresistive [3,4] and optical [5-7] readout techniques. In the case of using electronic readout techniques or using a ROIC substrate, such as in bolometer technology, the incident IR radiation is directed by the IR optics directly on the (top side of the) structure. There are three major mechanisms for IR absorption: *(i)* optical cavity using a metal thin-film of free space impedance and a λ/4-gap, *(ii)* bulk material absorption, such as nitrides, oxides or polymers in the long wave IR (LWIR: 7-14 µm wavelength) region, or *(iii)* geometric effects, such as black-Si, black-gold, micro-needles, etc. The thermo-mechanical sensor is based on bulk absorption since its base material is a dielectric or polymer. In the case of optical readout the operation mode differs to the case described above. Since the deflection is captured by reflected visual light at the front (top) side of the sensor, the IR radiation falls in at the back side, penetrating first the IR transparent Si-substrate. Fig. 1 demonstrates schematically the two operating modes for a thermo-mechanical IR sensor.

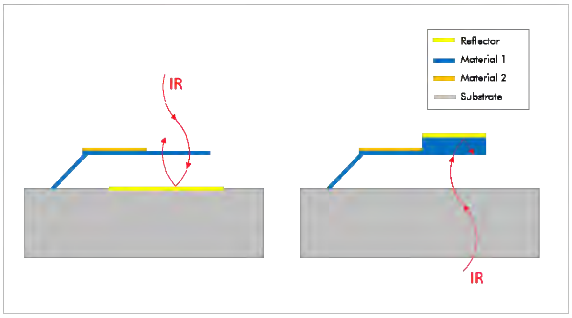

Fig. 1. Schematics of operating modes of a thermo-mechanical IR sensor: front side (left) or back side (right) IR irradiation.

The definition of operation mode is crucial since it has an effect on the process flow of the micro-fabrication. Within our research and development activities the focus has been set at a sensor in back side IR irradiation mode with optical readout. This configuration offers following distinctive advantages in comparison to other readout techniques and to current bolometer technology:

I. The sensor fabrication has the least possible number of lithography steps and processes. Hence it is least complex and inexpensive to fabricate.
II. The sensor does not need power for operation. It is electronically absolutely passive.
III. Self-heating and electrical noise are not present.
IV. Pixel formats are easily scalable. ROIC architecture is limited to a certain numbers of pixels (current bolometer technology to XGA resolution).
V. Maximum pixel density possible due to non-existing circuits.
VI. The amount of thermal conductance through thermal isolation legs is easily adjustable due to single material use and non-existing metallic circuit paths.
VII. Temperature and stress compensated design possible and therefore no need for thermo electric sensor stabilization or main requirements on thin film stress engineering.
VIII. Optical readout consists of standard low-cost optical components such as laser

diode and CCD imager, contributing to an affordable IR camera.

IX. Systems responsivity is adjustable on a great number of properties on sensor-, module- or system-level.

X. Possibility of multi-band, short and mid wavelength IR detection, due to very high transduction linearity and possibility to induce high temperature gradients in the structure without losing functionality.

Definition of Objectives, Working Principle

The working principle and the physical correlation of a thermo-mechanical IR sensor can be found in [8]. At this point of the methodology it is crucial to define target parameters. Important merits on the detector-level are:

1. Operating spectral band (e.g. LWIR for thermal imagery of living environment).
2. Format size (e.g. 320 x 240 Pixel) in order to have spatial resolution of the imaged thermal scenery.
3. Pixel-pitch for reducing size, weight and cost of detector and IR optics (for thermo-mechanical sensor e.g. ~50 µm smallest limit).
4. Imaging rate (e.g. 30 frames/second for continuous imagery).
5. Structure's resonant frequency (e.g. >5 kHz to enable usage in mobile devices).
6. Temperature measurement range to define target temperature operation span (e.g. 300K).
7. System's sensitivity expressed as noise equivalent temperature difference (NETD) (e.g. <500 mK).

Calculations and Definition of Design and Materials

After the definition of the target parameters theoretical calculations are crucial to determine the geometry and materials. Some commonly used bi-material compounds for the thermo-mechanical acting region of the structure are dielectric-metals, such as nitride-aluminium. The sensor design is most critical for the detectors sensitivity. A study of different designs is given in [8].

Selection of Micro-fabrication Technique

In order to realize free standing micro-structures generally two fabrication techniques can be implemented: surface micromachining with the usage of sacrificial layers, or bulk Si micromachining realizing free standing structures through back-side dry or wet etch.

In recent research activities deep reactive ion etching (DRIE), also known as deep silicon etching has been used for removing the substrate underneath the structure [5]. The removal of several 100 microns of Si-substrate with a relative high aspect ratio is technological demanding. The other method includes standard Si wet etching with KOH [4,6]. With last method a high density focal plane array (including a high resonant frequency of the array) is barely possible to realize. For better control of the DRIE process, the substrate can be thinned with wet etch to ≤100 µm thickness and finally plasma etched.

A great number of micro-devices are produced by using sacrificial layers. This technique uses modular stack processing with a final sacrificial layer removal step. The most common sacrificial materials are oxides and polyimides. The greatest tradeoff of the usage of sacrificial materials is compatibility restrictions with other processes and materials.

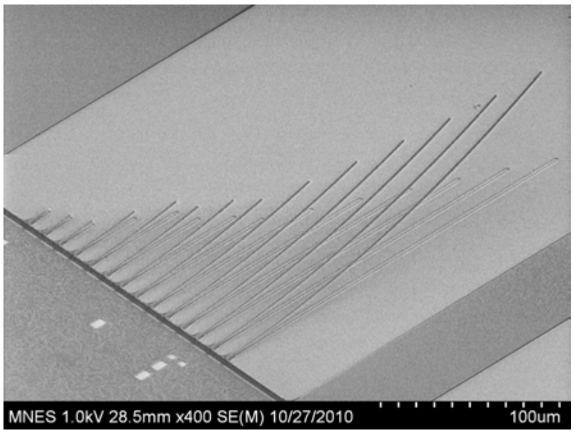

Fig. 2. SEM capture of 150 nm LPCVD Si_3N_4 test structures with excellent mechanical properties and acceptable residual stress. Sacrificial layer material: TEOS.

Oxide sacrificial layers can be deposited either in PECVD or as TEOS in LPCVD processes. Thermal oxide is not recommended since its etch-rate is too small for removal. Most common removal techniques include (wet) buffered oxide etch (BOE) with supercritical CO_2 dry, or hexafluoride (HF) vapour etch. One great problem occurring with wet etch removal is sticking of the structure to the substrate if adhesion forces are present due to remaining fluids in the etched gap between. Hence the removal step is most critical. Another problem with oxide sacrificial layers is the restrictive usage of metals, in particular aluminium due to the HF process step. We have found that Al in fact is compatible with HF vapour etch, however not with BOE. One of the greatest benefits of this sacrificial material is its highly cost-effective deposition using LPCVD where up to 25 wafers can be processed simultaneously per run. Furthermore LPCVD nitrides can be implemented in the process plan. Our development work shows excellent thin-film quality and stress control of Si_3N_4 LPCVD films (see Fig. 2).

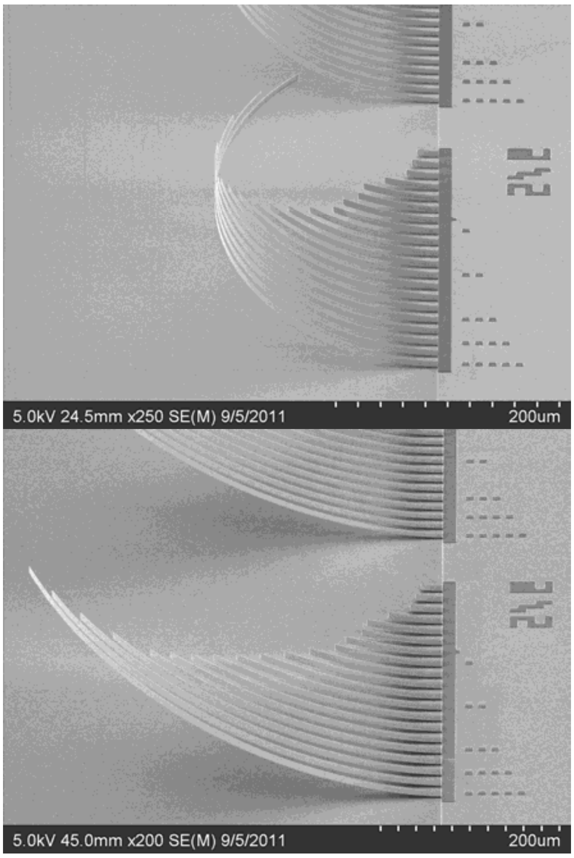

Fig. 3. 500 nm PECVD Si_xN_y deposited on polyimide sacrificial layer which has been structured in previous process step with an Al mask (top) and a resist mask (bottom). In both cases masking materials were fully removed. Demonstration of complexity on PECVD films residual stress control in combination with polyimide.

Polyimide sacrificial layers are structured and removed by O_2 plasma etching. Sticking of the released structures is generally not occurring due to the dry etch process step. This technique's tradeoff is the temperature limitation to the polyimide's hard bake temperature which is typically around 350°C. Therefore plasma enhanced deposition processes for oxides, nitrides and amorphous silicon are used within the process plan. There are different kinds of polyimides with specific properties available, such as for low-stress or photosensitive applications. In general there are no material restrictions except of the usage of polymers since O_2 plasma removes a majority of organic compounds. The greatest problem of this method is thin film stress and quality issues of plasma enhanced deposited films. Our experimental investigations have shown that even the sacrificial layer's masking material effects thin film stress of the successional layer (see Fig. 3).

For a successful micro-fabrication of a "sandwich-type" thermo-mechanical IR-sensor using a dielectric-metal bi-material compound following process plan can be implemented: Polyimide spin on, hard-bake and structuring with a standard photoresist mask using O_2/CF_4 reactive ion etching (RIE). Deposition of 700 nm SiN_x in ICP-CVD at 300 °C, deposition and lift-off of e-beam evaporated 400 nm Al. Defining structures geometry by RIE standard nitride etch. Sacrificial layer removal in barrel O_2 plasma at 400 W for 20 min. this straightforward process plan implies only three photolithographic steps. Fig. 4 demonstrates an example of a free-standing fully functional thermo-mechanical micro-mirror IR sensor, micro-fabricated using polyimide sacrificial layer.

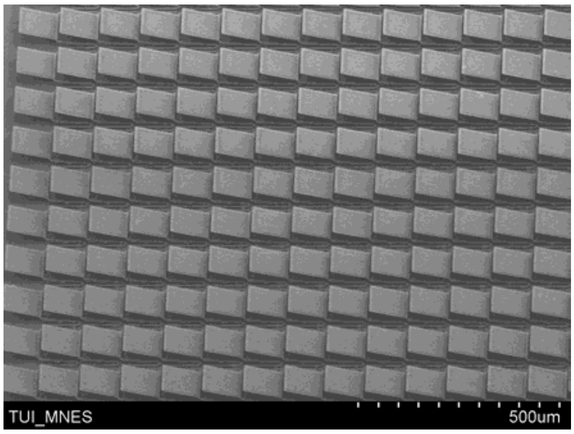

Fig. 4. SEM detail of a 320 x 240 micro-mirror array.

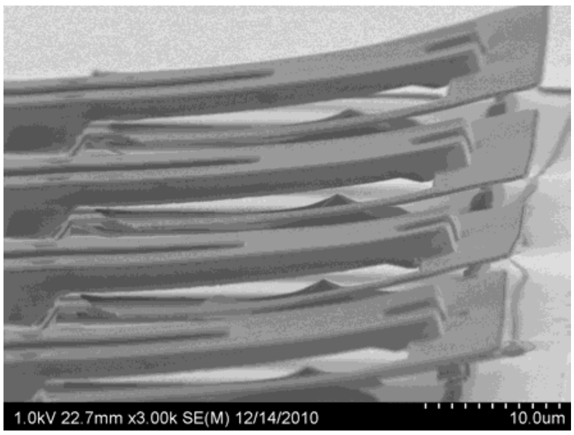

Fig. 5. SEM detail of free-standing arch-type design IR sensors using LPCVD processes.

For the realization of a so-called "arch-type" IR sensor design [4,8] following processes were used: LPCVD 700 nm TEOS deposition and

BOE structuring followed by LPCVD 150 nm nitride deposition. Both LPCVD processes implement 25 wafers per run. The nitride is structured by standard nitride RIE etch. The third and final lithographic process defines a modified SU-8 layer serving as second bi-material of the structure's polymer-dielectric bi-material compound. The oxide is removed by BOE with supercritical drying. Additionally some absorbing layer can be deposited on the free standing structures to increase sensor's responsivity to IR irradiation. In Fig. 5 functional and free-standing arch-type IR cantilevers are shown.

Conclusion

Within our research and development activities in developing a low-cost thermo-mechanical IR sensor we have established a methodology to realize a functional device. This methodology can be implemented in a number of novel-type device development plans. The most difficult part of the methodology plan is to implement a process plan in order to micro-fabricate a function device meeting its target specifications. In many cases the method of choice is trial-and-error to investigate process compatibility and control. Since thin-film parameters can different greatly from their bulk values, new micro-fabrication developments will remain challenging.

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