An Outline of a Complementary Inspection System for Micro-Electro-Mechanical System (MEMS) Devices Based on Radiography and Plenoptic Camera

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Abstract. In the last decades, micro manufacturing was driven by micro-electro-mechanical systems (MEMS), where well-established manufacturing methods based on semiconductor technologies are able to produce structures in miniscule dimensions. Often, such modern electronic devices offer high level functionality in reduced space. However, such components may be impaired in several ways during fabrication and assembly stages resulting in damages or/and structural failures. To enable inspection of MEMS components, new technologies are needed to ensure reliable quality control in particular, in medical/aerospace industries where 100% quality inspection is required to achieve highest safety standards. In this paper, an outline of the inspection system architecture that can be applied to inspect MEMS component during the production phase using plenoptic camera and x-ray will be described. Preliminary test results demonstrate the system applicability. The inspection system aims to achieve an autonomous, reliable and accurate solution to reduce the production costs.

Keywords. X-ray, light field camera, robotic manipulation, image processing, MEMS, non-destructive testing (NDT).

1. Introduction

Traditionally, the term Micro-Electro-Mechanical Systems (MEMS) was used for microfabricated devices that integrates miniaturized mechanical and eletro-mechanical components such as accelerometers, gyroscopes, pressure sensors and microphones. MEMS devices are known to be highly attractive due to the high throughput, cost efficiency, small size and high integration capability with electric circuits which predominantly cover wide range of applications in automobile, aerospace and mobile communications. Lately, owing to the advancement of micro-fabrication material, tools and equipment, MEMS have extended into emerging devices and applications that are being manufactured for high value products in the medical field involving miniaturized medical systems, micro-fluidic systems, Organ-on-Chip devices and implantable systems [1]. Innovative material such as Cavity Silicon on Insulation (CSOI) produced through an advanced wafer fabrication process known as the Deep Reactive Ion-Etching (DRIE) process has enabled anisotropic etching in silicon wafer that can achieve a straight etch (i.e. vertical wall) which conventional wet etching cannot produce. Such

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CSOI material has gained wide attention in the industry as it offers a high performance MEMS device utilising less power [2].

Scanning Intravascular Ultrasound (IVUS) represents one of the most complex and highly integrated smart catheters used to aid angioplasty surgery (i.e. to measure the diameter of vessels), Figure 1. Capacitive Micro-machined Ultrasound Transducers (CMUTs) have gained increased popularity than the standard piezo transducer as they can be fabricated directly on top of the circuits that drive them which reduced the size and permit higher ultrasonic frequencies [3]. The CMUT is made by the deposition of three metal layers separated by dielectric layers. The electrodes are fixed to the substrate (bottom layer) and the top metal layer. The top metal electrode can move freely after the sacrificial centre metal layer has been etched. When voltage is applied between the two electrodes, they electrostatically attract each other thereby generating a pressure wave. By repeating this a few million times a second an ultrasonic wave is generated.

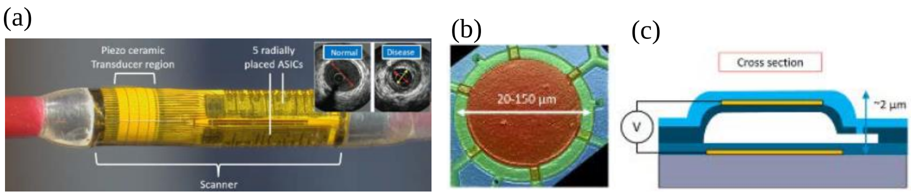

Figure 1. (a) IVUS scanning catheter and examples of images produced, (b) optical microphotographs of CMUT devices in top view, (c) Schematic cross-section of a CMUT.

The Flex-to-Rigid (F2R) technology such as flex-foil approach is employed to allow electronics to fold around or into the catheter tips as shown in Figure 2.

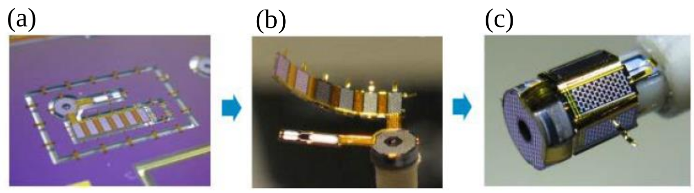

Figure 2. (a) F2R structures are fabricated wafer scale. (b) After fabrication the partly flexible structures are removed from the silicon wafer and assembled around a catheter tip. (c) Final 180° ultrasound microphone.

Standard assembly technologies that use high temperature soldering or wire bonding are becoming incompatible with advanced MEMS devices. Silver filled epoxies are being employed as an alternative which can cause quality issue as shown in Figure 3.

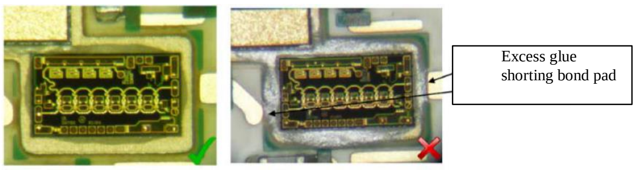

Figure 3. Example of failure mode as a results of incorrect adhesive dispensing.

In view of the total manufacturing cycle, the failure modes developed during the microfabrication process and assembly of these MEMS devices into packages and

Printed Circuit Boards (PCBs) cannot be undermined. One common feature for these MEMS devices are that they are all highly three-dimensional (3D). Although there are planar inspection tools utilised for such MEMS devices quality assessment, most of the inspection is based on electrical parameters. This potentially poses a problem from the manufacturing point of view where critical defect go un-noticed. especially for transport and medical applications, as the reliability is paramount. Another important factor to consider is the presence of subjective error dues to the use of manual or semi-autonomous inspection tool. Typically in a semi-autonomous inspection, operator have to manually orientate the MEMS devices and define the test points which could be randomly selected. The likelihood of missing critical defects can be high in such testing approach and inevitably adds cost to the production. The proposed system aims to tackle the reliability issues for MEMS devices (potential test cases identified above) by offering an automated 3D structural inspection system applied to inspect high value component production at both in-line and near-line processes which is reliable, accurate and cost-effective.

2. System overview

The system consists of two independent sub-systems based on (i) optical 3D inspection using plenoptic camera and (ii) Nano-focused X-ray imaging system. The decoupling of these sub-systems enables their efficient implementation at different test locations for varying application scenarios and consequently, reduced potential design intricacies for a one-size-fits-all system in this early development phase. However, a common Automated Defect Recognition (ADR) module will be implemented for both sub-systems employing initially the classical image processing approach as shown in Figures 4 and 5 for the optical and x-ray systems respectively.

2.1. Plenoptic camera subsystem

Plenoptic camera or light field camera enable a standard image to be captured with the depth information by employing a microlens array in front of the image sensor [4]. The user can interactively change the focus, the point of view and the perceived depth of field [5]. This subsystem integrates the camera, all optical and opto-mechanical components, an x-y translational stages, a z-stage for focus adjustment and the bespoke control software.

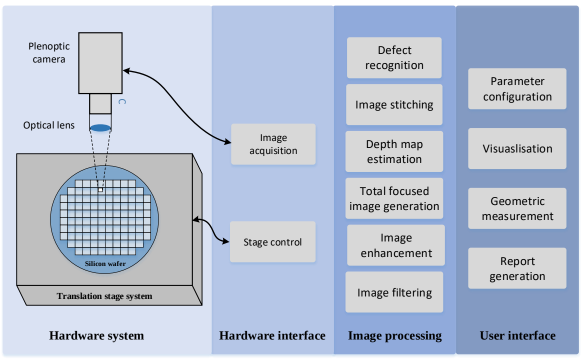

Figure 4. Schematic overview of plenoptic camera inspection sub-system.

2.2. Nano-focused X-ray subsystem

The hardware of the X-ray subsystem comprises a source, a detector, a z-stage for adjustment of the system magnification and a radiation shielding. The system source currently uses the Excillum "NanoTube N1 60 kV" [6] which the current design uses a transmissive Tungsten-diamond target and a long-life LaB6 cathode. The minimal distance between focus and object is 100 µm. The images created from the X-ray system need to achieve accuracies in the sub-micrometer scale. Therefore, the choice of detector is a critical part of the design. Preliminary investigations showed that the most likely detector type to be used for this subsystem will be a pixel based photon counting CMOS detector due to its superior image sharpness, absorption efficiency and Signal-Noise-Ratio.

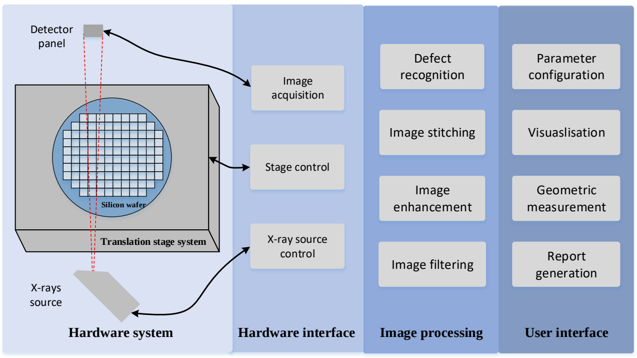

Figure 5. Schematic overview of X-ray inspection sub-system.

2.3. Inspection procedure and Automated Defect Recognition (ADR)

As an illustration, one substrate usually contains hundreds or thousands of MEMS/micro devices and more than one image might be needed to fully cover a single device. A suitable number of acquired images will be stitched and subsequently segmented to obtain a group of small images, each of which contains just one MEMS/micro device for further processing. An illustration of the image stitching and segmentation process is shown in Figure 6. Note that an overlap between adjacent scans is required to guarantee the image quality in the combined/re-segmented image.

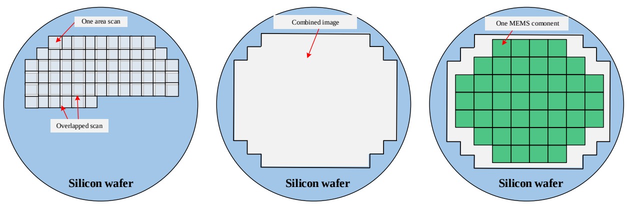

Figure 6. Illustration of image combination and segmentation.

After segmentation, the images are fed into defect recognition algorithm to identify defective components and also defect types. Various features and machine learning algorithms will be studied to get a satisfactory defect recognition ratio.

3. Preliminary results and discussion

To verify the effectiveness of the two inspection methods for MEMS inspection and also assist the system development, a preliminary study is conducted to inspect a CMUT sample from one end user.

3.1. Inspection results from plenoptic camera

A plenoptic camera, R12μ, is employed for the optical inspection [4]. The camera has a sensor size of 13.09 x 8.80 mm^2 and an effective resolution of about 3 MP. With a 10X optical lens equipped, its key specifications are listed in Table 1.

Table 1 Key specification of the plenoptic camera equipped with a 10x optical lens.

Field of view	Lateral resolution	Depth of field	Depth resolution
1.31 x 0.88 mm^2	0.62 μm	0.24mm	1.3-1.6 μm

The acquired image by plenoptic camera can be calculated to obtain a total focused image and a depth map, as shown in Figure 7(a) and (b), respectively. A bright object can be clearly observed in the total focused image, as highlighted by the red rectangle for the Region of Interest (ROI) in Figure 7(a). Also, in the depth map, the bright area shows a high depth value. These two information indicate the bright object can be a foreign particle defect on the MEMS component. Combining the total focused image and depth map, a 3D point cloud view can be generated, as presented in Figure 7(c).

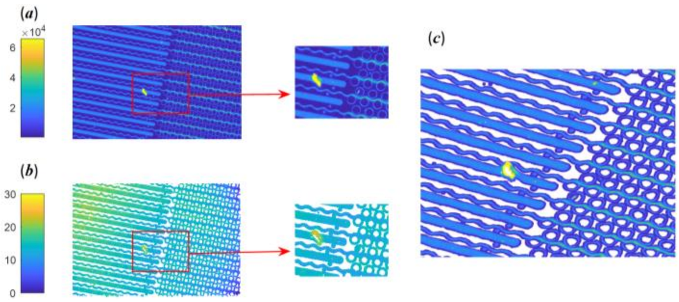

Figure 7. (a) Total focused image and its ROI, (b) Estimated depth map and its ROI and (c) 3D view.

3.2. Inspection results from X-ray system

The CMUT sample is also subjected to inspection by an Xradia 520 Versa machine [7] and the results are presented in Figure 8. The inspection is performed under excitation voltage of 30 kV, current of 67 μA and exposure time of 160 s. The pixel size in the image is 0.1 μm. The edges of the CMUT elements show clear intensity value changes, which can be used to segment CMUT elements and thereafter to check if there is any missing CMUT on a die. Note that the interior and exterior of CMUT element does not show obvious contrast difference, which increased the difficulty of extracting CMUT elements. In the system design, lower excitation voltage and various detector panels will be explored to check if the contrast can be enhanced. As highlighted in the red circles, some CMUT elements contain dark areas in comparison with a normal CMUT element. As these dark areas are all within enclosed CMUT element, they are less likely to be dust articles. After discussion with the end user, these dark areas are suspected to be caused by the incomplete etching of sacrificial aluminum layer, which is an internal defect and cannot be observed through optical inspection.

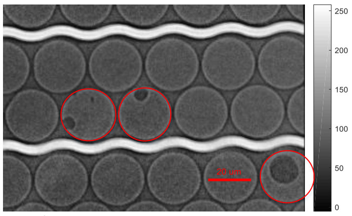

Figure 8. X-ray projection image.

4. Conclusions

The outline of the proposed CITCOM inspection system based on plenoptic camera and X-ray is described. Preliminary tests conducted on CMUT have shown the applicability of both plenoptic cameras and X-ray as complementary techniques for the inspection of 3D MEMS components. Further development work will focus on optimising the hardware for better resolution and developing bespoke image processing and machine learning defect detection algorithms to meet in- or near-line production inspection.

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Project website: https://citcom.eu/

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