Abstract

There are a wide range of applications for micro-electro-mechanical systems (MEMS). The automotive and consumer market is the strongest driver for the growing MEMS industry. A 100 % test of MEMS is particularly necessary since these are often used for safety-related purposes such as the ESP (Electronic Stability Program) system. The production of MEMS is a fully automated process that generates 90 % of the costs during the packaging and dicing steps. Nowadays, an electrical test is carried out on each individual MEMS component before these steps. However, after encapsulation, MEMS are opaque to visible light and other defects cannot be detected. Therefore, we apply an infrared low-coherence interferometer for the topography measurement of those hidden structures. A lock-in algorithm-based method is shown to calculate the object height and to reduce ghost steps due to the $2\pi$-unambiguity. Finally, measurements of different MEMS-based sensors are presented.

1. Introduction

Since the realization of the first micro-electro-mechanical systems (MEMS) in the 1970s, the MEMS market has grown continuously [1, 2]. The versatility of MEMS applications is mainly employed by the automotive, the medical and the consumer industries. At present, the annual growth of the market is around 6.6 % with an estimated volume of about 12 billion dollars in 2018 [3]. In addition to MEMS-based airbag and ESP sensors, the trend in automotive applications is towards MEMS sensor fusion. In smartphones a lot of different MEMS, e.g. acceleration sensors, gyroscopes or auto-focus systems are used. MEMS are also extensively used for the projection of information [4]. The comfort and high functionality of hearing aids has increased with simultaneous reduction in size by the use of MEMS [5].

Repetitive processes of deposition, patterning and etching are the basic steps of MEMS production [6]. The structures can then be examined for defects by various optical inspection techniques [7] [8, chapter 5]. In a final step, the MEMS structures are covered by a silicon cap wafer under vacuum or inert gas inclusion. The MEMS performance can then be inspected only by electronic tests because the structures are opaque to visible light. However, this encapsulation may cause additional defects in the wafer stack. In the case of a failed electronic test, the problem cannot be located on the MEMS wafer. An electronic test often does not reveal enough information for a thorough characterization [9]. A new inspection technique would be desirable to get a 100 % test before 90 % of the production costs occur during the following dicing and packaging steps of the entire MEMS device. Removing the silicon cap again for state-of-the-art optical metrology techniques might change the wafer stack and MEMS structures again.

Figure 1(a) shows a schematic cross-section of a typical wafer stack. The thickness of the silicon cap varies in the range 80–250 $\mu$m depending on the application and type of the MEMS. The wafer can have a crossbar for greater stability, the distance to the MEMS surface is reduced to a few micrometers from about 25–150 $\mu$m to the MEMS surface. The thickness of the MEMS structures is in the range of 10–20 $\mu$m. Typical defects in the wafer stack are shown in figures 1(b)–(d). Individual MEMS fingers can stick to each other or to other wafers. Due to tension in the stack, MEMS fingers may also be bent.

This paper discusses the feasibility of optical metrology techniques that work without removing or breaking the cap. An exemplary measurement is used to describe the signal processing and a possibil-
ity for the reduction of $2\pi$-unambiguity ghost steps in the object profile for a low-coherence interferometer (LCI) measurement technique. Finally, measurements of capped MEMS structures of different sensor types are presented.

2. Feasibility

The general requirements are high accuracy in the axial and lateral direction. Confocal microscopy (CM) is suitable for multilayer objects because the layers are separated by confocal filtering [12]. The accuracy is typically in the micrometer range and is limited by the numerical aperture (NA) in both the axial and lateral directions. In addition, spherical aberration occurs by imaging through a plane-parallel slab of dielectric material, such as the cap wafer. With CM, this has to be taken into account or corrected, since the CM signal is strongly deformed by spherical aberration and thus influences the measurement result [13]. In the case of interferometric measurement techniques, the axial resolution is decoupled from the NA and the resolution is in the nanometer range. In interferometric surface metrology, phase-shifting interferometry (PSI) [14, chapter 7] is a gold standard, but due to the known phase ambiguity problem, it requires very smooth surfaces with less than a quarter wavelength of discontinuities. Scanning white-light interferometry (SWLI) [15–22] has been established as the state-of-the-art technique for complex or rough surfaces because it overcomes this ambiguity problem. However, if noise is considered, SWLI seems to be more precise [23]. SWLI can also be used in a parallel arrangement for massive parallel inspection of MEMS, as presented in [24, 25]. Optical coherence tomography (OCT) is very suitable for multilayer and scattering objects, which makes it very attractive in the field of biomedicine [26–28]. A swept-source OCT technique is preferable to spectral-domain OCT, especially in the infrared, as technologically it leads to more sampling wavelengths and thus to a deeper imaging depth [29]. Digital holography [30, 31] or vibrometry [32, 33] are optical technologies for the inspection of the dynamic properties of MEMS.

Topographic and tomographic measurements of encapsulated MEMS have been shown by Saltmarsh [34], unfortunately without any further discussion of the results. Reference [35] mentioned that with a scanning interferometer it is possible to measure the object profile hidden by a silicon wafer. In [36] nondestructive inspection of buried cavities by a modified SWLI system has been presented. The same system was used to show the deformation of the top and bottom surfaces of a 4 $\mu$m thick silicon bridge [37]. In principle, the inspection of encapsulated MEMS would also be possible with x-ray-based methods, but would be very complex [38, 39]. High radiation energy makes it very unattractive as the entire measuring environment has to be shielded. A strongly limiting factor is also the measurement time of several hours. The momentum of x-ray photons is by a factor of $10^5$ higher than that of short-wave infrared light (SWIR) photons. This high radiation pressure could lead to an unwanted movement of the small silicon structures and thus could interfere with the measurement.

The success of the semiconductor industry is due to the good mechanical and electronic properties of silicon [40–42]. However, the feasibility of optical inspection techniques is limited by the optical properties of silicon. The material becomes only transparent for SWIR above a wavelength of 1.1 $\mu$m. The absorption coefficient decreases significantly, as it can be seen in figure 2 [43]. This refractive index curve has been calculated by the Sellmeier dispersion formula and fitted Sellmeier coefficients [44, 45]. At a wavelength of 1.55 $\mu$m, the refractive index is 3.485, which means that 30 % is reflected at each air–silicon transition. This high refractive index means also that through the cap only 7 % is reflected back at the interesting MEMS top surface.

3. Setup

An interferometric microscope is possible in various interferometer configurations. The Michelson con-
configuration [46] is limited to low NA due to the beamsplitter cube in front of the lens. Higher NA microscopic objective (MO) lenses are realized in the Mirau configuration [19, 47]. They have a more complex optical layout but are very robust against vibrations or temporal misalignment. These architectures can be used for multilayer objects as long as the optical path difference (OPD) within the depth of focus is within the coherence length (see e.g. [36]). High NA with a sufficient working distance can only be realized in the Linnik configuration [15, 23, 48–50] where two equal MOs are used.

Figure 3 shows the optical layout of the setup. An infrared light-emitting diode (LED) (Thorlabs M1550L3) with a center wavelength of 1.55 μm, a spectral full width at half maximum (FWHM) of 102 nm and an optical output power of 36 mW is coupled into a multi-mode fiber (MM) with a core-diameter of 1 mm and an NA of 0.39, which serves as a homogenizer. The condenser collimates the homogeneously luminous fiber end for a critical illumination of the object. A configuration with two beamsplitters matches the object and reference intensity to achieve a high interferometric contrast, despite the low reflectivity of the interesting surface. Two Olympus LCPLN50XIR MOs [51] with an NA of 0.65 and a magnification of 50 × are aligned in the Linnik configuration. A working distance of 4.5 mm is high enough to image the MEMS structures within the wafer stack. The theoretical lateral resolution of about 1.45 μm is sufficient to resolve most of the lateral structures. It was decided to implement the OPD scan in the reference arm, otherwise a scan of the very large 200 mm wafer would be necessary. The mirror was fixed in the focal position to the MO, which was mounted to a piezo actuator (PI PIFOC P-725.2 CD). The piezo scan range is 250 μm (closed loop) with a resolution of 0.75 nm [52]. As long as all MEMS structures are at the same height level, they are inspected by scanning the OPD in the reference arm. Finally, the object and reference are imaged by a 100 mm achromatic tube lens onto an indium gallium arsenide infrared (InGaAs) camera, which has a pixel pitch of 15 μm and 640 × 512 pixels [53]. With this small number of pixels, a trade-off of field of view (FOV) and sample points per Airy-disc in the image plane must be considered. The FOV is 280 μm × 350 μm.

The MO position in the object arm can be varied in the axial direction by a microscrew to match the path lengths. This variable path length compensation is needed because different MEMS types have a different cap thickness. It follows strongly that different spherical aberrations are introduced since they depend on the NA, slab thickness and refractive index. A correction collar of the Olympus MO displaces a lens triplet inside the MO to vary the spherical aberration [54]. A glass or silicon thickness of 0–1.2 mm can be compensated.

4. Signal processing

In the following we first describe the determination of the object position by means of the lock-in algorithm. Then, the extension of this algorithm is presented, which leads to a reduction of occurring 2π ghost steps.

4.1. Lock-in evaluation

In an LCI setup the interference signal is mainly defined by the light source spectrum. An LED typically has a Gaussian-shaped spectral distribution. The incoherent superposition of all single interferences for each wavelength of the light source results again in a Gaussian-shaped correlogram [55]. The FWHM is then defined by the spectral bandwidth of the light source. The LCI signal as a function of the OPD $\Delta z = 2(z_R - z_O)$ can be estimated by [19]:

$$I_{LCI}(\Delta z) = I_0 \left[1 + e^{-\frac{\Delta k^2 \Delta z^2}{4 \ln(2) k_0}} \cos(k_0 \Delta z + \varphi_0)\right],$$

where $z_R$ is scanned by the piezo actuator. The normalized intensity $I_0$ is the maximum of the correlogram at the object position $z_O$. $\Delta k$ is the spectral...
bandwidth (FWHM) in wavenumbers, \( k_0 \) is the center wavenumber and \( \varphi_0 \) is an additional phase. This phase \( \varphi_0 \) is a combination of a material-dependent phase change on reflection [56–58] and dispersion effects [59, 60]. A phase inconsistency between the envelope and the interference may also arise due to highly curved or tilted surfaces [61, 62]. Various signal processing techniques of the LCI correlogram have been developed to determine the object’s height position [17, 63–75].

In the following, the lock-in technique is described briefly [76, 77]. The algorithm uses a synthetically generated complex harmonic wave signal \( f_{\text{lock-in}} (\Delta z) \) with the same wavenumber \( k_0 \) as the LCI correlogram \( I_{\text{LCI}} (\Delta z) \) of (1). The starting phase of the lock-in function is equal to zero. First, the DC offset \( I_{\text{DC}} \) is subtracted from the signal, then it is multiplied by the lock-in function:

\[
I_{\text{temp}} (\Delta z) = \left[ I_{\text{LCI}} (\Delta z) - I_{\text{DC}} \right] \cdot f_{\text{lock-in}} (\Delta z).
\]

After a low-pass filter of \( I_{\text{temp}} (\Delta z) \), the absolute value is the correlogram envelope \( I_{\text{corr}} (\Delta z) \). The filtering must be phase-stable, such as the Butterworth filter [78] or the Fourier-transform method [79]. This Gaussian-shaped envelope is used to calculate the center of gravity (COG) position \( z_{\text{COG}} \). By using the \( \arctan2 \) function the constant phase difference between the signal \( I_{\text{LCI}} (\Delta z) \) and the lock-in function \( f_{\text{lock-in}} (\Delta z) \) is calculated:

\[
\varphi = \arctan2 \left[ \sum \Im (I_{\text{temp}}), \sum \Re (I_{\text{temp}}) \right].
\]

Then the phase \( \varphi_0 \) of (1) is calculated by:

\[
\varphi_0 = (\varphi - 2 k_0 z_{\text{COG}}) \mod 2 \pi,
\]

where \( 2 k_0 z_{\text{COG}} \) is the phase at the COG position \( z_{\text{COG}} \). With the phase \( \varphi_0 \) and the interference period \( \pi/k_0 \), the distance to the next zero-phase position of the correlogram is:

\[
\Delta z_d = \begin{cases} 
\frac{\varphi_0}{2 k_0} - \frac{\pi}{2 k_0} & \text{if } \varphi_0 > \pi \\
\frac{\varphi_0}{2 k_0} + \frac{\pi}{2 k_0} & \text{if } \varphi_0 < -\pi \\
\varphi_0 & \text{if } -\pi \leq \varphi_0 \leq \pi.
\end{cases}
\]

Thus, the final object position corresponding to the next zero-phase position of the signal \( I_{\text{LCI}} (\Delta z) \) next to \( z_{\text{COG}} \):

\[
z_0 = z_{\text{COG}} + \Delta z_d.
\]

The combination of the envelope and the phase information improves the sensitivity to the surface height and reduces the measurement uncertainty. However, the inconsistency between the phase and coherence information often leads to a mis-recognized interference peak with a \( 2 \pi \) difference in the OPD, which corresponds to a height of \( \lambda_0/2 \) in the measurement result.

4.2. Lock-in evaluation with \( 2 \pi \) ghost steps reduction

In the following, an extension of the lock-in algorithm is described that reduces the number of \( 2 \pi \) ghost steps. The lock-in function \( f_{\text{lock-in}} (\Delta z) \) is modified by a known starting phase offset \( \varphi_{\text{lock-in}} \):

\[
f_{\text{lock-in}} (\Delta z) = \exp \left[ i \left( k_0 \Delta z + \varphi_{\text{lock-in}} \right) \right].
\]

The lock-in phase \( \varphi_{\text{lock-in}} \) has to be considered in (4):

\[
\varphi_0 = \left[ \varphi - 2 k_0 z_{\text{COG}} + \varphi_{\text{lock-in}} \right] \mod 2 \pi.
\]

After the calculations as described in section 4.1, the object position has to be corrected by the introduced phase offset \( \varphi_{\text{lock-in}} \):

\[
z_0 = z_0 + \frac{\varphi_{\text{lock-in}}}{2 k_0}.
\]

This known phase offset \( \varphi_{\text{lock-in}} \) leads to a shift in the \([−\pi; \pi]\) unambiguity interval, as shown in figure 4.
COG position \( z_{\text{COG}} \) and object position \( z_O \) is depicted in figure 4(a). The phase \( \varphi_{\text{lock-in}} \) is equal to zero and thus the unambiguity of the \( [-\pi; \pi] \) interval is symmetrical around the COG position \( z_{\text{COG}} \) (range filled in grey). Here the calculated next zero phase position of the signal \( I_{\text{LCI}} \) is on the left side of \( z_{\text{COG}} \). In the result in figure 4(b) the phase offset \( \varphi_{\text{lock-in}} \) is \( \pi \). The unambiguity interval is shifted to the right side and therefore the right zero phase position of the signal \( I_{\text{LCI}} \) is detected.

A measurement of the case of occurred \( 2\pi \) ghost steps is shown in figure 5. In the height profile in figure 5(a) of a mirror measurement, many \( \lambda_0/2 \) steps along with a rising profile line can be seen. The distance between the calculated object position \( z_O \) and the \( z_{\text{COG}} \) is depicted in figure 5(b) in phase values \( \varphi_O \):

\[
\varphi_O = \frac{z_O - z_{\text{COG}}}{2k_0}.
\]  

(10)

The distance to the next zero-phase position is not constant because the phase values \( \varphi_O \) are completely arbitrary distributed within \( \pm \pi \).

In figure 6 the evaluation of the same measurement data and a phase \( \varphi_{\text{lock-in}} \) of \( \pi \) is shown. Here a straight object line can be seen because the ghost steps are almost completely removed. The standard deviation of a line fit here is 2.6 nm. The phase \( \varphi_O \) in figure 6(b) is within the \( [-\pi; \pi] \) interval.

This lock-in phase offset \( \varphi_{\text{lock-in}} \) should be constant for each signal of the dataset, otherwise additional ghost steps may be introduced. The calculation of the object height position is not influenced by the shift of the \( 2\pi \) unambiguity since the position is corrected by the known phase value in (9). This algorithm can be used in particular for measurement data showing a systematic phase shift between the envelope and signal, as is the case with different metals [56]. The algorithm is implemented as a C++ plugin in the measurement software itom [80].

5. Measurements

First, we show SWIR measurements through the silicon cap wafer of various MEMS sensors before presenting measurements taken with a commercially available SWLI sensor after the cap has been destroyed and removed.

5.1. Measurements of encapsulated MEMS

The first MEMS object is an X-Fab inertial sensor. It was necessary to remove the metallic cover to get access through the silicon cap. As can be seen in figure 7, the individual fingers are resolved. Stuck fingers (compare figure 1) would become visible.

Figure 8 shows the height profile of a gyroscope sensor from the company Bosch, which was measured through the top cap wafer. This kind of MEMS has more complex structures but not all of them can be inspected. Some structures are hidden by the crossbar,
as drawn in figure 1(a). Here the distance between the crossbar and the structures is less than the axial resolution of the setup. A measurement through the bottom MEMS wafer is also, in principle, possible. Here electrical conductor tracks are placed on the wafer and again some structures are hidden as is visible beside the fingers in figure 9. Between those conductor tracks, the structures of a comb drive actuator are visible.

Some other structures of this MEMS are shown in figure 10. The outer structure (marked with ‘1’) has a higher strength and shows less deformation than the structures in the middle of the field. These structures are for motion detection (marked with ‘2’), which are more flexible and thus show more deformation.

Deflection of this platform is measured (figure 11). The deformation is in the range of 200–500 nm. Line 1 corresponds to the half-timbered structure and 2 to the motion structures.

5.2. Verification by SWLI

For a verification measurement, the cap wafer was destroyed and removed to get access for a commercial available SWLI sensor (Mahr Surf WS1, Leica N-Plan 50x/0.50 Mirau MO). The same structures as in figure 10 were measured and evaluated by the same algorithm as described in section 4. The height profile in figure 12 shows again some deflection of the inner platform but the half-timbered outer structures are almost flat, as expected.

The line height profile in figure 13 was extracted from the same structures as in figure 11. The half-timbered structure (1) shows only some tilt and the motion structures (2) show a height deviation of 230 nm.

The height profiles of the measurements in figures 10 and 12 show different results, especially for the half-timbered structures. It is obvious that the cap thickness varies and has a significant influence on the
height profile. The cap wafer is made of cheap wafer material because it has no function for the MEMS sensor itself. Due to the simple processing of the cap, the thickness varies. This variation cannot be compensated for because the cap cannot be removed from the stack in the production line.

The cross-section profiles in figure 14 were measured by the Mahr SWLI of the bottom and top surface of the cap. Both surfaces show completely different profiles. The variation of the top surface lies in the range of 100 nm. Through the etching process, the profile of the bottom surface looks like a bathtub. The borders of the bathtub reduce the usable window to about 150 μm. In addition, the etching process of the cap results in a roughness (Rq) of about 50 nm.

6. Conclusion

We presented a novel infrared interferometric sensor. It can be used to inspect the profile of encapsulated MEMS structures through the silicon cap wafer. These MEMS structures can be influenced by defects such as stuck or bent MEMS fingers, which are introduced during the encapsulation process. Such defects are hidden to common optical inspection systems. The setup is based on a Linnik interferometer. The spherical aberration caused by focusing through a plane–parallel slab of dielectric material is corrected by special microscopic objective lenses with correction collars. The signal processing is based on the lock-in technique of the low-coherence correlator. An extension of this algorithm is introduced to get rid of most of the 2π ghost steps. Measurements of different MEMS sensors show the feasibility of such inspection techniques. Unfortunately, the influence of the silicon cap thickness variation on the MEMS profile measurement cannot be compensated for because this cannot be removed, in particular, in the production line.

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