Silicon Micromachined Device Testing by Infrared Low-Coherence Reflectometry
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Abstract—With the development of silicon micromachining technologies, non-contact measurement techniques for in-depth non-destructive inspection of layered and microstructured samples are becoming increasingly relevant. In this paper, we apply optical low-coherence reflectometry (OLCR) to detect the optical path between the interfaces of several silicon devices with characteristic distance in the range 3–17 µm. The implemented configuration is based on a fiberoptic Michelson interferometer that exploits infrared broadband radiation in the wavelength range of 1.2–1.7 µm, with coherence length shorter than 2 µm, for performing spot tomographic measurements. OLCR enabled out-of-plane measurements on a MEMS linear accelerometer and in-plane measurements on vertical periodic silicon/air microstructures. The optical distance between hidden interfaces was found well in agreement with the design parameters.

Index Terms—Optical low-coherence reflectometry, distance measurements, time-domain analysis, non-destructive testing, infrared sensor, silicon micromachined device.

I. INTRODUCTION

Optical low-coherence reflectometry (OLCR) is a powerful diagnostic tool for characterizing optical components [1]–[8] and, in particular, for detecting the relative position of interfaces in the device under test (DUT), e.g., due to the presence of layers with different refractive indexes. OLCR is usually based on a Michelson interferometer with readout optical radiation characterized by short temporal coherence but high spatial coherence: groups of interferometric fringes are then originated only when the optical path-length difference between the interferometer arms is shorter than the coherence length of the readout radiation. In time domain OLCR, the DUT replaces a mirror of the Michelson scheme: as the other mirror is displaced, the length of the reference arm is changed and fringes are developed when the time delay to the mirror matches the time delay to a reflection site within the DUT.

Recently, OLCR schemes in the Fourier domain were investigated to replace the mirror mechanical scanning with the analyses of the interference spectrum for rapidly forming 3D images of the material or device under test, such as in optical coherence tomography [3], [4], [9].

With the development of silicon micromachined devices (e.g., MEMS), non-contact measurement techniques are often required for in-depth non-destructive inspection of multilayered microstructures in order to detect the layer thickness and the optical distance between interfaces. Application of OLCR for testing silicon (Si) miniaturized components requires a specific configuration ensuring very high longitudinal resolution obtained with light sources emitting radiation at wavelengths longer than 1.1 µm, since silicon is not transparent at shorter wavelengths. Moreover, a simple, compact and flexible optical setup based on optical fiber paths is preferred, for instance, for performing remote measurements.

In this work, we demonstrate the functionality of a compact fiberoptic (FO) Michelson interferometer for time-domain OLCR that exploits infrared (IR) broadband radiation provided by a fiber-coupled tungsten lamp. It enables inspection of microstructured silicon devices featuring layers with different refractive indexes with longitudinal (or axial) resolution better than a few µm [10]. Similar performances in the IR were previously demonstrated by other authors with more expensive and complex light sources or with free-space optical setups [5], [11]–[15]. More specifically, by performing out-of-plane measurements we were able to successfully detect with good accuracy the optical path between the different layers of a MEMS accelerometer, which integrates a suspended polysilicon inertial mass separated from the silicon substrate by a 4-µm-wide air-gap. Moreover, we successfully performed an in-plane characterization of vertical periodic microstructures, consisting of a one-dimensional array of silicon walls separated by deeply etched trenches [16], [17], by measuring the optical path among several silicon/air interfaces for arrays with different spatial periods, i.e., 8, 10, and 20 µm. We thus envision that a fiberoptic low coherence interferometer working in the near infrared may become a useful tool for in-depth non-destructive testing of silicon devices.

II. INSTRUMENTAL AND OPTICAL SCHEME FOR FO IR OLCR

The implemented instrumental and optical configuration for FO IR OLCR is shown in Fig. 1.

It was based on a Michelson interferometer that incorporated two bidirectional 2 × 2 FO couplers with flat spectral response and 50:50 splitting ratio so that interferometric signal detection could be performed with a balanced receiver [10]. By means of the FO splitters, broadband radiation was partly
coupled along the “measuring arm” to the DUT and along the “reference arm” to the translating reference-mirror. Back-reflected radiation, by the mirror and the DUT, was coupled to the InGaAs photodiodes (PhD1 and PhD2 in Fig. 1) incorporated into a custom-designed balanced receiver; this solution enabled efficient detection of the interferogram (i.e., the interferometric fringes) by removing DC and common mode signal components [18].

The amplification of the signal photogenerated by PhD1 was twice as large as that of the signal generated by PhD2 in order to compensate for the different optical power reaching the photodiodes. The output voltage of the balanced receiver was connected to an analog to digital (A/D) conversion board for data acquisition with a personal computer (PC). Both interferometer arms incorporated the same fiber paths, matched in length within 1 mm, whereas the final sections were in open space. At the end of both arms, pigtail-style fiber optic couplers were in place. The length of the reference arm matched the optical path up to the reference mirror (DC compensation). Back-reflected radiation (from the DUT as well as from the air/Si interface at the substrate level) was coupled along the “measuring arm” to the DUT and along the optical path obtained through out-of-plane interferometry along the x-axis. The interference between arms are the main causes of the asymmetric shape of each fringe groups.

III. IR OLCR FOR OUT-OF-PLANE MEASUREMENTS ON MEMS ACCELEROMETERS

As a benchmark for out-of-plane characterization (along the x-axis) of silicon microstructures by infrared low-coherence reflectometry, we tested a MEMS linear accelerometer (Fig. 2a) fabricated by STMicroelectronics using the ThELMA (Thick Epitaxial Layer for Micro-gyroscopes and Accelerometer) process [19]–[22]. The suspended inertial mass (epitaxial polysilicon) features a regular pattern of square holes (4 µm × 4 µm) required for the complete removal of the underlying sacrificial oxide layer and the release of the movable parts suspended above the substrate (Fig. 2b). If compared to the beam spot size (50-µm diameter), the inertial mass is thus a layer of non-homogeneous material.

Aim of the out-of-plane measurement was to detect hidden interfaces (i.e., polysilicon/air and air/silicon-substrate interfaces) and, thus, to measure in a non-destructive way the geometrical features of the accelerometer along the x-axis. The multilayer structure of the accelerometer was characterized by IR OLCR, as shown in the schematic view of the MEMS cross-section reported in Fig. 2b. The normalized interferometric signal as a function of the optical path obtained through out-of-plane OLCR, performed on the inertial mass of the accelerometer, is shown in Fig. 3. The fringe groups originated from the air/PolySi and PolySi/air interfaces of the suspended mass as well as from the air/Si interface at the substrate level are easily recognized in Fig. 3 and exhibit an asymmetric shape. The envelope of each fringe group, the so called fringe visibility function, is determined by the spectral distribution of the readout radiation, at least in an ideal optical setup. For example, a Gaussian spectral distribution provides a Gaussian (and thus symmetric) fringe visibility function. The tungsten lamp, used in our configuration, does not exhibit a symmetric spectrum around a central wavelength. Moreover, a dispersion difference exists between the interferometer arms because of the different length (1 mm) of their fiber optic paths and the difference increases as light penetrates the DUT. Asymmetric light spectrum and dispersion difference between arms are the main causes of the asymmetric shape of each fringe groups.
Additional groups of fringes, with significantly lower amplitude with respect to the main peaks, can be attributed to multiple round trips as well as to back-scattering contributions due to surface roughness of the lateral wall.

The interface position was deduced from the axial coordinate where the maximum intensity of the corresponding fringe, due to surface roughness of the lateral wall, can be attributed to the substrate was whereas the width of the air-gap between the mass and

IV. IR OLCR for In-Plane Measurements on Vertical Periodic Microstructures

As a benchmark for in-plane characterization (along the z-axis) of silicon microstructures, we tested vertical Si-air periodic microstructures, fabricated by electrochemical micromachining technology [16], [24]. They consist in one-dimensional (1D) arrays of silicon walls (of width $d_w$) separated by deeply ($h = 50 \mu m$) etched gaps (of width $d_g$) [25], [26]. In this work, IR OLCR was applied to detect the optical path distance between Si/air interfaces of 1D periodic microstructures with spatial period $p$ ranging from 8 to 20 $\mu m$, in particular with $p = 8 \mu m$ and $d_g \approx 5 \mu m$, $p = 10 \mu m$ and $d_g \approx 7 \mu m$, $p = 20 \mu m$ and $d_g \approx 17 \mu m$, as illustrated in Fig. 4. For in-plane, in-depth testing of the array, the read-out beam was shone perpendicularly to the Si walls, along the z-axis (see Fig. 4).

Fig. 5 shows the normalized interferometric signal obtained by in-plane IR OLCR measurements on the silicon microstructure with $p = 8 \mu m$, which is the most challenging in terms of axial resolution.

The depicted black trace clearly shows the interferometric fringes. Contributions due to Si/air interfaces of the first two spatial periods (indicated by the subscript 1 and 2 in Fig. 5) facing the input readout beam were easily recognized and marked on the graph. $OP_w$, $OP_g$ and $OP$ indicate, respectively, the optical path length of a Si wall, an air-gap, and a whole spatial period; for this structure we detected $OP_w \approx 9.4 \mu m$, $OP_g \approx 5.4 \mu m$ and $OP \approx 14.8 \mu m$. Assuming $n_{Si} = 3.59$ RIU for the group refractive index (in the IR) of Si [23], we obtain $d_{PolySi} = OP_{PolySi}/n_{PolySi} \approx 15 \mu m$ as expected by design [19]–[22]. As the presence of the etching holes does not affect the measurement of the optical path, the technique is suitable for non-destructive in-depth testing of micromachined silicon devices, e.g., for the evaluation of the etching phase result.

As a benchmark for in-plane characterization (along the z-axis) of silicon microstructures, we tested vertical Si-air periodic microstructures, fabricated by electrochemical micromachining technology [16], [24]. They consist in one-dimensional (1D) arrays of silicon walls (of width $d_w$) separated by deeply ($h = 50 \mu m$) etched gaps (of width $d_g$) [25], [26]. In this work, IR OLCR was applied to detect the optical path distance between Si/air interfaces of 1D periodic microstructures with spatial period $p$ ranging from 8 to 20 $\mu m$, in particular with $p = 8 \mu m$ and $d_g \approx 5 \mu m$, $p = 10 \mu m$ and $d_g \approx 7 \mu m$, $p = 20 \mu m$ and $d_g \approx 17 \mu m$, as illustrated in Fig. 4. For in-plane, in-depth testing of the array, the read-out beam was shone perpendicularly to the Si walls, along the z-axis (see Fig. 4).

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Fig. 6. Normalized interferometric signal acquired on a silicon microstructure with $p = 10 \, \mu m$. $OP_w$: optical path of the silicon wall; $OP_d$: optical path of the air-gap; $OP$: optical path of a spatial period of the microstructure. Typical values for a 10-µm structure: $OP_w \approx 10.1 \, \mu m$, $OP_d \approx 7.2 \, \mu m$ and $OP \approx 17.3 \, \mu m$.

In Fig. 6 we report the normalized interferometric signal acquired on the silicon microstructure with $p = 10 \, \mu m$, which yields as typical values $OP_w \approx 10.1 \, \mu m$, $OP_d \approx 7.2 \, \mu m$ and $OP \approx 17.3 \, \mu m$.

The normalized interferometric signal obtained on a silicon microstructure with $p = 20 \, \mu m$ is shown in Fig. 7. Contributions due to the Si/air interfaces of the first three spatial periods were easily recognized yielding $OP_w \approx 11.8 \, \mu m$, $OP_d \approx 16.7 \, \mu m$ and $OP \approx 28.5 \, \mu m$, in good agreement with the design parameters.

Since the time-varying photodetected signal is due to the interference of the reflected fields from the device under test and the reference mirror, the relative peak intensities of the fringe groups depend on the field reflection and transmission coefficients. These coefficients could be calculated using Fresnel relationships, assuming a plane wave crossing ideal interfaces due to refractive index steps, with orthogonal incidence, and thus neglecting losses. Under this assumption, for the air/Si array we obtain that the maximum intensity of the second group (due to the 2nd Si/air interface of the 1st wall) should be approximately 70% of the first maximum (due to the 1st crossed air/Si interface) whereas the maximum intensity of the third group (due to the 1st Si/air interface of the 2nd wall) should be approximately 50% of the first. However, we are working with a Gaussian beam and, more important, the reflection and transmission coefficients are affected by the optical quality of the interfaces; thus, optical losses could be induced by light scattering. Our results show that the relative peak intensities of the first three groups experimentally recorded on the structure with $p = 20 \, \mu m$ (Fig. 7) are in agreement with the estimated values. For other structures, the detected intensity peaks are lower than expected and we hypothesize that the additional losses could be due to greater surface roughness.

The interferometric signal measured on micromachined structures featuring $p = 20 \, \mu m$ displayed also groups of fringes relative to radiation performing double round trips inside the air-gaps, and thus located at an optical distance equal to twice the optical path of the air-gap ($2 \times OP_d$). In the case of unknown structures, fringe groups due to real interfaces could be distinguished from artifacts by defining a “threshold intensity curve”. For example, with specific reference to Si/air multi-layers with unknown distribution, the peak intensity of the fringe groups versus the position of the nth interface should be a decreasing function proportional to the quantity $(t_{air/Si} \cdot t_{Si/air})^n$ being $t$ the field transmission coefficient at the interface (including losses) and $n$ the number of crossed interfaces. Thus, fringe groups with a peak amplitude much different from the expected theoretical threshold should be considered artifacts and, thus, neglected.

V. Conclusion

We have demonstrated the functionality of a compact, all-fiber setup for IR OLCR that enables optical distance measurements between in-depth, hidden interfaces of silicon microstructures (due to refractive index variations) with good accuracy and high longitudinal resolution. The all-fiber setup for IR OLCR was benchmarked for both out-of-plane and in-plane characterization of silicon microstructures, and experimental results clearly indicate that a broadband light source is suitable for high-resolution IR OLCR in micromachined devices testing. Thanks to these properties, our fiber-optic IR OLCR setup may become a powerful and highly versatile diagnostic tool for testing silicon devices (such as MEMS) integrating different type of three-dimensional microstructures (e.g., free-standing microstructures, deeply etched microstructures).
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[19] Dr. Merlo is a member of the Associazione Italiana di Elettrotecnica, Elettronica, Automazione, Informatica e Telecomunicazioni (AIEET), and a Senior Member of the IEEE Photonics Society.

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