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Optical Diffraction Strain Sensor Prepared by Interference Lithography

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An optical strain sensor was developed for use in stretchable electronics. It consists of a diffraction grating formed directly on the examined surface illuminated by a laser beam which creates interference pattern. This pattern can then be used to determine axial and lateral strains for a uniaxial stress states. Direct laser interference patterning was employed as a fast processing tool for the preparation of micro- and sub-microgratings. Two coherent beams of Nd:YAG laser with 532 nm wavelength and pulse duration of 10 ns were used to selectively remove material from the irradiated sample surface. This technique creates periodic pattern on the metallized surface of polymeric substrates. New sensors formed by direct laser interference patterning method were able to resolve higher order diffraction maxima, which would be of benefit for strain measurement application. Experimental setup for tensile tests was composed of laser probe, the sensor element, and CCD camera. To extract strain values, we analysed acquired interference pattern images in real time software, developed with LabVIEW environment. This kind of contactless strain sensor is suitable for examination of stretchable electronics component for which conventional tensile tests are either not acceptable or can interfere with its normal operation.

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PACS/topics: Strain, direct laser interference patterning, optical strain sensor, diffraction grating, Poisson ratio, Kapton, flexible, optical strain gauge

1. Introduction

Measurements of deformation and mechanical properties of solids are important in many aspects of materials and life sciences. The determination of strength limits and elasticity of material which is compressed, stretched, or twisted, allows to design robust, reliable, and safe constructions. This type of measurements has so far been performed using the resistance strain gauges, which are used to record the resistance changes resulting from the deformation, based on which the applied force is determined with high accuracy [1, 2]. Among the most commonly used in mechanical engineering field are foil strain gauges with the strain sensitive pattern applied to a flexible polymer foil. These gauges can be fixed either outside or inside of the studied element with a special glue [3]. The alternative to these sensors are stretchable optical sensors which involve a simple waveguide installed on the housing made of silicon elastomer [4]. The waveguide coated with a thin gold reflective layer consist of a light-emitting diode (LED) and a photodiode embedded at the other end. Light propagates inside the waveguide, and if the mechanical deformation is present, the microcracks appear in the gold layer and allow the transmission of some of the light through waveguide walls. This results in the decrease of the registered light intensity.

For the small objects of the size comparable with the sensor dimensions, such measuring techniques are not effective but mechanical stress can be measured in microscale using X-ray diffraction, electron microscopy, and scanning probe microscopy. These techniques can determine the deformation in atomic scale from interatomic distances in crystallographic lattice. However, these methods cannot be applied in all cases and they require large size instruments. The measurement of deformation and monitoring of strain integrated with electronic elements are important in particular for systems such as flexible electronics [5–7], because in comparison to classical silicon electronics the stretchable elements are deformed to a larger degree. For such applications, the suitable method of strain measurement can be the use of light diffraction. In those cases, the surface of investigated object has to be covered with a periodic two-dimensional diffraction grating.

In this paper we demonstrate the method of deformation detection, which we applied to thin Bi films covered with a diffraction grating fabricated with laser interference lithography and deposited on a flexible polymer substrate. An important feature of this system is contactless sensing without any electronic interface: the system does not require attachment to the surface. This in turn allows purely optical measurement without perturbation of the object mechanical properties. Additionally, it allows measurements of the local strain and strain gradients, which is not possible using common methods.

2. Experimental

A 100 nm thick film of Bi was evaporated in high vaccum ($p = 10^{-7}$ mbar) on polyimide foil (DuPont, Kapton® type: 50HN, thickness 12.7 μm). At this Bi

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thickness the metallic film is not transparent in visible range, and therefore there is no transmission of light to the polymer substrate [8].

The two-dimensional diffraction grating on the Bi film was prepared by direct laser interference patterning (DLIP) method described elsewhere [9–11]. A pulsed Q-switched Nd:YAG laser (Quantel YAG980) operating at 532 nm with pulse duration of 10 ns and 10 Hz repetition rate was used as a light source. In order to produce stripe surface pattern, the samples were irradiated with two beam laser interference image at an angle of incidence of 1.3° or 2.4° with respect to the surface normal. Next, the sample was rotated at 90 degrees and irradiation was repeated in the same conditions. All structures were produced in a single pulse experiment with a primary beam pulse energy density of 34 $\mathrm{mJ/cm^2}$. For these conditions the ablation threshold is reached at interference maxima which results in selective local removal of Bi from the polymer substrate. A characterization of surface morphological changes of laser modified areas was done with scanning electron microscopy (SEM). The deformation measurements using the prepared diffraction gratings were performed with the home-made setup shown in Fig. 1. The geometry of the experimental setup and the measurement principle are demonstrated in Fig. 2. The sample, placed in tensile device and stretched with micrometer screw in the vertical direction, was illuminated by a laser diode with the wavelength of 658 nm. The transmission diffraction pattern was obtained on the semitransparent screen, behind which the CCD camera (Basler acA2500-60um, 5MP resolution) was placed and attached to PC by USB3.0 port.

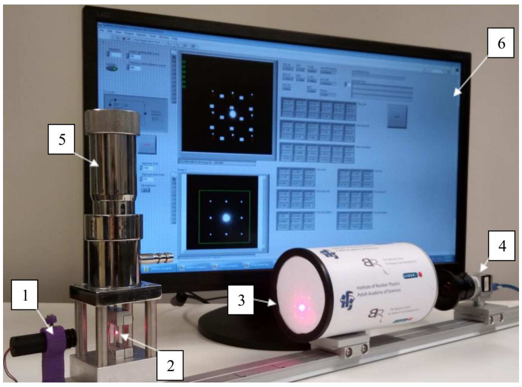

Fig. 1. The experimental setup for optical measurements of deformation: 1 — laser, 2 — diffraction grating, 3 — semitransparent screen, 4 — CCD camera, 5 — tensile test device, 6 — software interface.

Data acquisition and analysis were carried out using vision acquisition system (VAS) and vision development module (VDM) of the LabVIEW software application program.

3. Results

3.1. Determination of the grating constant

In order to obtain a good accuracy of deformation measurement the grating constant has to be carefully determined. Figure 3 shows SEM images obtained for patterns generated on Bi films on the polyimide substrate by two interfering coherent beams at incident angle of 1.3° with respect to the surface normal. The grating constants were calculated from cross-section profiles along the x and y lines marked in Fig. 3 and are equal to 12 μm.

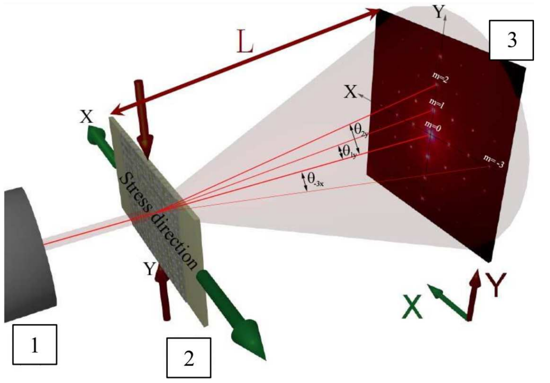

Fig. 2. The schematic presentation of the measurement principle.

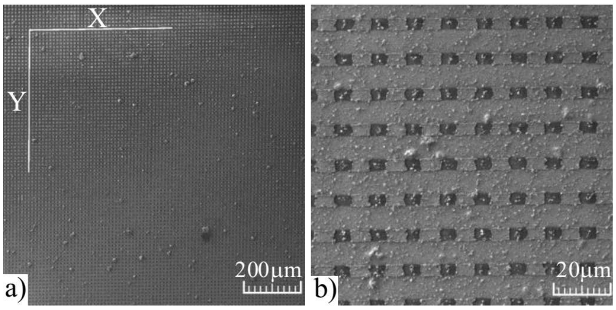

Fig. 3. SEM images of diffraction gratings prepared by DLIP method at incident angle 1.3 degree with respect to the surface normal. The x and y lines indicate the area used for the estimation of grating constants.

We also performed the Fourier analysis of periodical grating structure to precisely determine the quality of the grating structures. The results are shown in Fig. 4. The signal intensity profiles, shown in Fig. 4a and c were collected along the x and y lines marked in Fig. 3. The results of the Fourier transformation of these signals are presented in Fig. 4b and d, respectively, showing the same quality and period regardless of the direction.

The most intensive peak of the first order seen in Fig. 4b and d, corresponding to the diffraction grating constant in each direction, equals to 12.05 ± 0.01 μm. The same procedure was executed for diffraction grating obtained by sample illumination at 2.4°, and the grating constant obtained in this case was 6.3 μm.

3.2. Strain measurements

The strain measurement with the described diffraction grating is based on the recording of the change of the diffraction spot position. Using the following formulae:

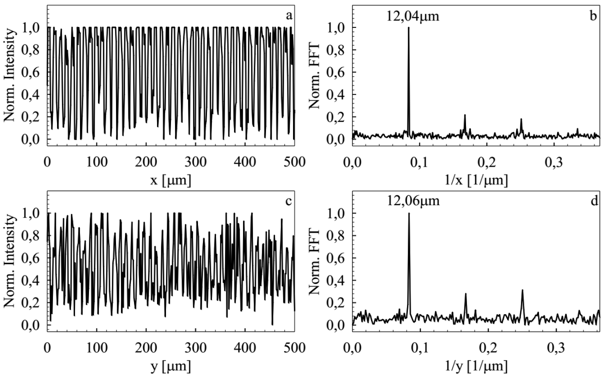

Fig. 4. Signal intensity profiles (a,c) of diffraction grating shown in Fig. 2 along the x and y lines and the corresponding Fourier transformation (b,d).

$$\varepsilon_x = \ln\left(\sqrt{\frac{(L/x_\varepsilon)^2+1}{(L/x_{\varepsilon=0})^2+1}}\right),$$
$$\varepsilon_y = \ln\left(\sqrt{\frac{(L/y_\varepsilon)^2+1}{(L/y_{\varepsilon=0})^2+1}}\right) \qquad (1)$$

derived from the grating Eq. [12, 13] and the definition of true strain ε_{xy} [14], we can determine ε_x and ε_y values of strain tensor in the x and y direction from the change of the spot position of undeformed $x_{\varepsilon=0}$ and deformed x_ε film. The value L is a distance between the grating and the screen.

Figure 5 shows the evolution of the diffraction pattern with the applied force. Stretching the grating in the y direction results in the decrease of the distance between the spots with respect to central spot along y direction, while the distance along the x direction increases. This means that elongation of grating in the y direction causes the reduction of its size in x direction. The values of deformation components in the x and y direction, ε_x and ε_y calculated from the positions of diffraction spots and formula (1), are given below Fig. 5.

The accuracy of the strain measurement depends on the accuracy of position determination for the individual spots shown in Fig. 5. The simplest way to determine spot positions is to use an image recognition algorithm with an assumption that each spot is represented as an elliptical object with specific dimensions. In such case the position of a center of such object defines the location of its center of mass, which can then be established. This can be done with VDM tools available in the LabVIEW package. However, such solution requires high contrast of the diffraction pattern, hampered by ambient conditions. Additionally, spot smearing appears and is related to inhomogeneous laser beam intensity profile and imperfections of the diffraction grating structure. These factors decrease the precision of spot position determination. We therefore applied another algorithm based on beam intensity profiles. Around each spot we defined circular region of interest (ROI) with a diameter chosen in such a way that at the edges of the circle the intensity dropped to the level of background. For each region we calculated centroid [15], and its maximum was a measure of spot position.

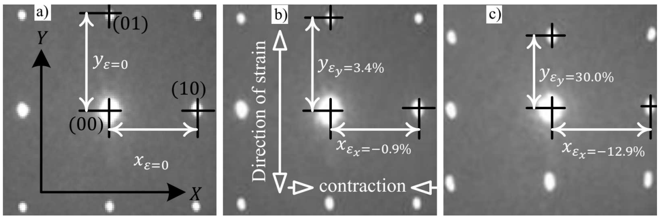

Fig. 5. The evolution of the diffraction pattern of grating with constant equal to 6.3 μm stretched in the y direction taken in the transmission mode. The distance between sample and screen was 10 cm. (a) $\varepsilon_x = 0, \varepsilon_y = 0$, $x = 305$ pix, $y = 305$ pix, (b) $\varepsilon_x = 3.4\%$, $\varepsilon_y = 0.9\%$, $x = 308$ pix, $y = 295$ pix, (c) $\varepsilon_x = 30\%$, $\varepsilon_y = 12.9\%$, $x = 351$ pix, $y = 234$ pix.

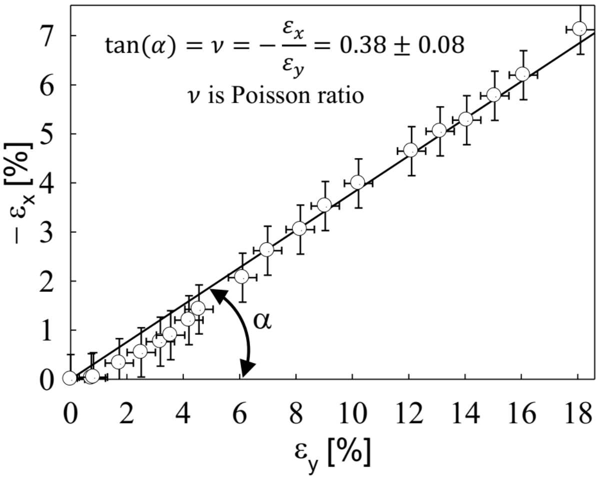

Fig. 6. The dependence of ε_x on ε_y for the diffraction grating with the diffraction constant equal to 6.3 μm.

The results of purely optical strain measurement are illustrated in Fig. 6. In this experiment elongation of the sample in the y direction was also verified with a micrometric screw (5) which was a part of the tensile test device shown in Fig. 1.

The linear dependence between deformation components in the x and y direction, ε_x and ε_y is shown in Fig. 6. The Poisson ratio equal to 0.38 ± 0.08 was determined as a slope of this dependence, and this value is in a good agreement with published data for the polyimide material [16, 17].

4. Conclusions

We described the method of mechanical deformation measurement with the use of two-dimensional optical diffraction gratings. Gratings were prepared by DLIP of a Bi thin film deposited in vacuum on polyimide foil. We constructed a simple setup for test measurements controlled by software written in LabVIEW. We demonstrated the results of optical measurements of ε_x and ε_y components of the strain tensor for uniaxial deformation of polyimide foil. From the dependence between deformation components in the x and y direction ε_x and ε_y we deduced the Poisson ratio which is in a good agreement with published data. In the future we will be able to use these mechanical characteristics of the prepared gratings for measurements of deformation on curved surfaces.

Acknowledgments

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