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Internal profile reconstruction of microstructures based on near-infrared light transmission reflection interferometry with optical path compensation

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Abstract: The bottom and sidewall profile reconstruction of microstructures with a high aspect ratio is a problem that urgently needs to be solved in the field of MEMS(Micro-Electro-Mechanical system). Microstructures profile reconstruction method is presented based on near-infrared light transmission reflection interferometry with optical path compensation(OPC), which is extended from white light to near-infrared light and from reflection interference to transmission interference. The near-infrared light transmission interferometry system is composed of a near-infrared light source, an interference microscope, an infrared light CCD, piezoelectric ceramics with high accuracy and a data acquisition system. A GaAs sample microstructure with two steps was designed and the method of vertical scanning interference of near-infrared light with OPC was adopted to reconstruct the internal profile of a microstructure, which was then compared with the results of scanning electron microscopy(SEM). Test results show that the relative heights of the measured microstructure steps using near-infrared light transmission reflection interferometry were 2.132 μm and 0.766 μm with 2.16% and 2.68% relative errors, respectively, which agree with the results of SEM and that of the near-infrared light reflection interferometer. The measurement system has the ability to reconstruct the bottom and sidewall profile of microstructures with a high aspect ratio.

Key words: near-infrared light transmission reflection interference; microstructures; internal profile reconstruction

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光程补偿近红外光透射反射干涉重构微结构内部形貌

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摘要:高深宽比微结构的底部及侧壁形貌重构是微机电系统领域亟待解决的一个问题。本文提出光程补偿近红外光透射反射干涉技术重构微结构内部形貌的方法,所采用的近红外光干涉技术将白光干涉系统中的光源扩展至近红外光源,将反射干涉技术扩展至透射反射干涉技术,近红外光干涉测量系统由近红外光光源、干涉显微镜、红外光 CCD、高精度压电陶瓷和数据采集系统组成。设计了具有两个台阶的 GaAs 半导体微结构待测样品,采用近红外光垂直扫描干涉法并通过光程补偿,重构了微结构的内部三维形貌,并与扫描电镜结果进行对比。光程补偿近红外光透射反射干涉技术测量的台阶相对高度分别为 2.132 μm 和 0.766 μm,与扫描电镜和近红外光反射干涉测量结果基本一致,分别对应 2.16% 和 2.68% 的相对误差。测量结果表明,该测量系统能够测量高深宽比微结构底部及侧壁形貌。

关 键 词:近红外光透射反射干涉;微结构;重构内部形貌
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1 Introduction

In recent years, high aspect ratio microstructures have been widely used in the field of MEMS due to their high sensitivity and large displacement[1]. While due to their small widths (about 1 – 10 μm), high depth (about 10 – 500 μm) and high aspect ratio (10:1 to 100:1), real-time online reconstruction of the bottom and sidewall features has become an urgent problem that needs to be solved[2]. At present, there are three main instruments for measuring the 3D shape of a microstructure: the scanning electron microscope[3] (SEM: Scanning Electron Microscope), the atomic force microscope[4-5] (AFM: Atomic Force Microscope) and the white light interferometer[6]. The SEM is a device that scans the sample with a very narrow electron beam. When measuring high aspect ratio structures, it is necessary to cut the microstructure sample to scan the profile. It is a destructive method of measurement with a high time requirement and a high cost. AFMs directly calculate the height of the sample surface using the force of a microprobe. Due to the particularity of high aspect ratio structures, it is necessary to change the tip structure to measure the inside of a structure during measurement. This is very difficult. White light interferometers are more suitable for measuring the surface topography of microstructures. There are many commercial devices, such as Polytec, Talysurf, Veeco, Zygo, *etc.*, but for high aspect ratio microstructures, white light diffraction is more severe. Furthermore, since the light hits the object to be tested at an angle during measurement, it cannot pass through a narrow slit completely. It is therefore difficult to measure a structure's bottom and sidewall topography[7-8]. In summary, based on the white light interference principle, semiconductor material (gallium arsenide GaAs or silicon Si) can be transmitted in the infrared light band. If infrared light is used instead of the white light in white light interference, an infrared light interference system could be constructed and a certain optical path compensation could be implemented.

Optical path compensation using infrared light transmission and reflection interference technology could achieve bottom and sidewall shape reconstruction for high aspect ratio microstructure.

In this paper, the near-infrared optical band is used as an example and a near-infrared light transmission reflection interference technology is proposed. The corresponding interferometric system consists of a near-infrared light source, an interference microscope, an infrared CCD, high-precision piezoelectric ceramic and a data acquisition system. In the beginning, the near-infrared optical interference topography reconstruction technology based on vertical scanning interferometry and the basic principle of GaAs material transmission in the infrared light band are studied. Secondly, a typical double-step GaAs material microstructure sample is designed and its internal shape of the measurements are performed. Comparing with the results obtained from SEM and the near-infrared light reflection interferometer, it shows that the optical path compensation near-infrared light transmission reflection interference system is effective. It was also found that the measured morphology is consistent with that measured by SEM method and near-infrared light reflection interference method. The results indicate that the internal shape of a high aspect ratio microstructure can be measured by proposed method.

2 Rationale

Fig. 1 shows the near-infrared light transmission reflection interference measurement of bottom and sidewall topography of microstructure with high aspect ratio. It can be seen that the bottom and sidewall topography can be reconstructed by an optical path compensation method.

2.1 Near-infrared Light Interferometer

We use near-infrared light interference microscopy to generate interference fringes (Fig. 2 shows the schematic of near-infrared light interferometer). This interference system is an improvement on the Linnik optical interferometer with 168 × measurement area magnification. The near-infrared light emitted by the near-infrared light source is split into two beams using a beam splitter. One is reflected by the reference mirror and the other meets the object to be tested whereupon it is reflected or transmitted. The interference fringes generated by the two beams are obtained by infrared CCD (pixel 320 × 256)[9]. High-precision piezoceramics is allowed for vertical movement in a range of 400 μm. Data acquisition

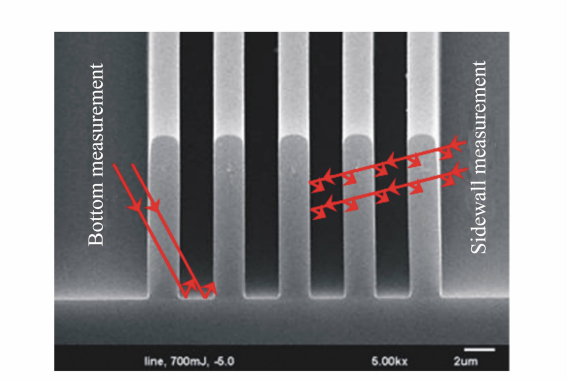


Fig. 1 Bottom and side wall profile reconstruction of the microstructure with high aspect ratio measured by the near-Infrared light transmission reflection interferometer

图 1 近红外光透射反射干涉仪测量高深宽比微结构底部及侧壁形貌

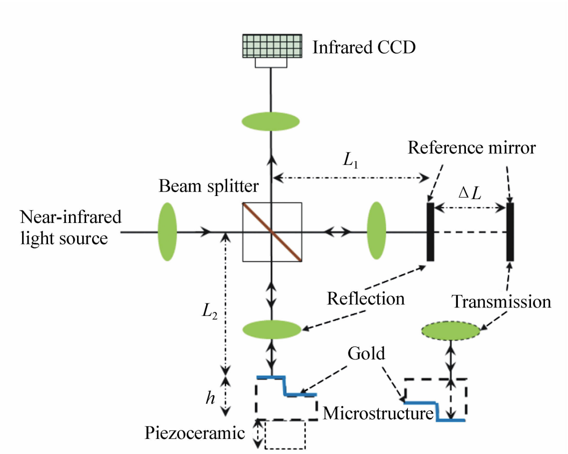


Fig. 2 Schematic of near-infrared light interferometer

图 2 近红外光干涉系统示意图

and topographic reconstruction are completed by self-developed dedicated software. To avoid error in results, measurements are taken in a quiet and dark environment.

2.2 Principles of the Near-infrared Light Interference Three-dimensional Shape Reconstruction

Vertical scanning interferometry (VSI) is a typical algorithm for reconstructing the three-dimensional topography of a microstructure for its high precision and fast operation. It measures relative height by selecting fringes at zero phase[10-12]. The basic principle of near-infrared light interference is similar to that of white light interference. Therefore, a near-infrared light source with a center wavelength of 1 170 nm and a wavelength range from 1 000 nm to 1 400 nm is selected.

According to the principle of white light interference, the intensity of the near-infrared interferogram can be expressed using a standard relationship:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \ , \tag{1}$$

$$\delta = 2\pi\Delta/\lambda \ , \tag{2}$$

where I_1 and I_2 are the intensities of the two beams, δ is the phase difference between I_1 and I_2, λ is the wavelength of the near-infrared light, and Δ is the difference in the optical paths of I_1 and I_2. For the reflection interference $\Delta = L_1 - L_2$, and for the transmission reflection interference $\Delta = L_1 + \Delta L - (L_2 + nh)$, L_1 and L_2 are the reference optical path and the optical path of the object being tested in the reflection interference, ΔL is the reference optical path compensation in the transmission reflection interference, n is the refractive index of the transmission material (GaAs material has a refractive index of approximately 3.45 in the near-infrared band), and h is the thickness of the transmissive material. For the near-infrared broad-spectrum light source, the interference pattern obtained by the infrared light CCD can be regarded as the result of the interference superposition of different wavelengths. Therefore, the intensity distribution can also be expressed as[13]:

$$I(x,y,z) = I_0 + \int_{\lambda_c-\lambda_b}^{\lambda_c+\lambda_b} \psi(\lambda) \cos\frac{4\pi(z-z_p)}{\lambda}\mathrm{d}\lambda \ , \tag{3}$$

where I_0 is the intensity of the interferogram, λ_c is the center wavelength of the near-infrared light, $2\lambda_b$ is the bandwidth of the spectrum, $\psi(\lambda)$ is the energy distribution of the interference pattern near the wavelength λ, z is the relative position of PZT and z_p is the position corresponding to the zero optical path difference[10]. Since the selected near-infrared light source has a very short coherence length, when each pixel is at the zero position of the optical path difference ($z = z_p$), the intensity of the interference is at its highest and the three-dimensional topography of the microstructure can be reconstructed by recording the z_p[10] corresponding to each pixel.

Due to intrinsic absorption, the absorption process of electrons from the valence band to the conduction band gets excited. The intrinsic absorption wavelength of a semiconductor single crystal material is expressed by λ_g. When light illuminates the material, light with a wavelength greater than λ_g will penetrate, and light with a wavelength less than λ_g will be absorbed. As intrinsic absorption, the relationship between electron energy and the band gap is described as follows:

$$\frac{hc}{\lambda_g} \geqslant E_g , \tag{4}$$

where h is the Planck constant, c is the speed of light and E_g is the band gap width. For the gallium arsenide (GaAs) material used in this experiment, the E_g was 1.43 eV and the minimum transmission wavelength was 0.86 μm.

3 Results and Analysis

First, standard micro-structures were designed to verify the feasibility and accuracy of the system.

The standard samples were made of GaAs semiconductor materials with two different step heights (as shown in Fig. 3). In order to enhance the reflection effect, a layer of gold was plated on the surface of the GaAs and then polished. In order to verify the feasibility of the measurement system, the two steps were measured by SEM (step A and step B), producing measurements of 2.087 μm and 0.746 μm, respectively. As shown in Tab. 1, the SEM measurement results were used as a standard reference to verify the performance of the designed system.

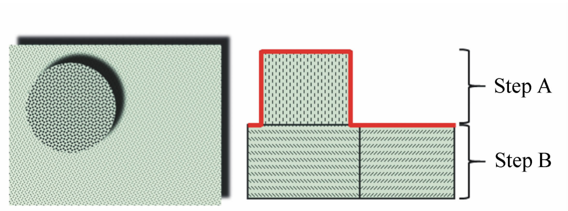


Fig. 3 Structure of the test object: the top view and the cross-section

图 3 测量样品结构图:俯视图和剖面图

Next, the microstructure morphology was reconstructed by near-infrared light reflection interference technique. At this time, the optical path difference between the two paths was $\Delta = L_1 - L$. Five phase-shifting interferograms were recorded to have a scatter stripe pattern. The piezoelectric ceramic stepping was 0.01 μm, corresponding to a phase step of 0.061 rad. The interferogram was shown in Fig. 4 (a) and the three-dimensional shape obtained after the solution was calculated. The results were very consistent with the actual topography shown in Fig. 3. The accuracy of the measurement results is proven by the diagonal appearance of extracted pixels from (0,256) to (256,0), as shown in Fig. 4 (b). The measurement results show that the relative heights of the two steps are 2.107 μm and 0.759 μm, which is close to the measurement results from the SEM, with relative errors of 0.96% and 1.74%, respectively. Due to the influence of the diffraction effect, the measured shape of the edge of the step is distorted, which is a common problem in interferometers[14-15].

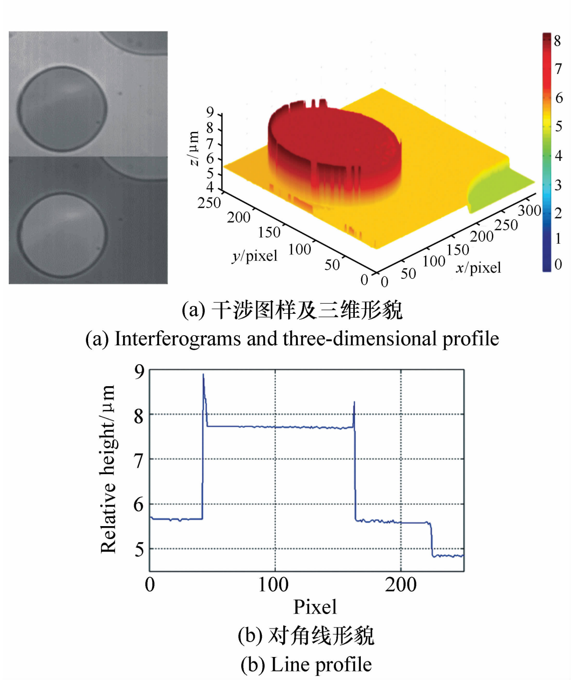


Fig. 4 Measurement results with near-infrared light reflection interference

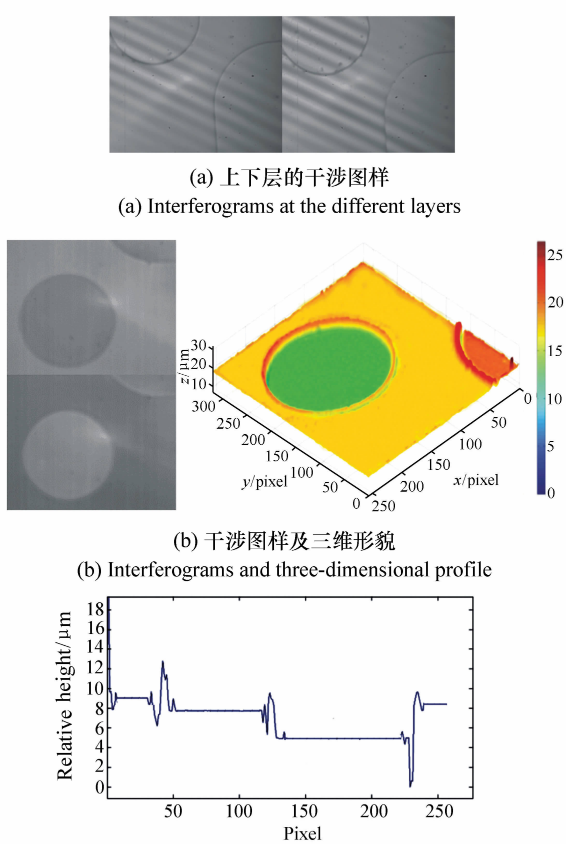
图 4 近红外光反射干涉测量结果

Under the same interference microscope, the near-infrared light transmission reflection interference technology replaces the near-infrared light reflection interference. At the same time, the optical path of the object to be tested increases by nh. Because of this, optical path compensation is performed on the reference path, and $\Delta L = nh$. In order to verify whether the near-infrared light is transmitted through the GaAs material, the interferogram of the different layers is obtained by adjusting the PZT position. As seen in Fig. 5 (a), the upper interference fringes have no change at the position of the step and the interference fringes in the lower layer have changed. This proves that the infrared light has passed through the GaAs material. By adjusting the position of the reference mirror and controlling the piezoelectric ceramics using a computer with a scanning interval of 0.01 μm the interferogram was obtained. At the same time, the results were corrected due to the uneven upper surface of the transmitted layer. As shown in Fig. 5(a), the calculated three-dimensional topography is largely identical to the topography shown in Fig. 4(a). Also, to describe the experimental results, the diagonal topography from pixels (0,256) to (256,0) were extracted, as shown in Fig. 5(b). As shown in Tab. 1, the relative heights of the two steps are 2.132 μm and 0.766 μm, respectively, which are fundamentally consistent with the results of the SEM and the near-infrared light reflection interference, with relative errors of 2.16% and 2.68%, respectively. Due to the diffraction effect, the topography on the edge of the step is similarly distorted.

Tab. 1 Comparison of relative step heights for different measurement methods

表1 不同测量方法台阶相对高度对比

Measurement method	Step A/μm	Error/%	Step B/μm	Error/%
SEM	2.087		0.746	
Near-infrared light reflection interference	2.107	0.96	0.759	1.74
Near-infrared transmission interference	2.132	2.16	0.766	2.68



(a) 上下层的干涉图样
(a) Interferograms at the different layers

(b) 干涉图样及三维形貌
(b) Interferograms and three-dimensional profile

(c) 对角线形貌
(c) Line profile

Fig. 5 Measurement results using near-infrared light transmission reflection interference with optical path compensation

图5 光程补偿近红外透射反射干涉测量结果

4 Conclusion

A near-infrared light interference measurement system was built and the relative heights of steps were obtained using the near-infrared light transmission reflection interference technology. The internal three-dimensional shape reconstruction of a micro-structure was achieved. The morphological measurement results of the standard sample were consistent with the SEM measurement results. When the near-infrared light transmission interference technology was used instead of the near-infrared light reflection interference technology, the system could be measured normally. The optical path compensation near-infrared light transmission reflection interference measurement results were 2.132 μm and 0.766 μm, respectively, corresponding to a 2.16% and 2.68% relative error, which is good enough to measure the height and high-aspect ratio microstructure. At present, the measurement error is large and there are two main reasons for this. The first is that the big difference between the near-infrared light and the white light spectrum introduces chromatic aberration. The second is that the reconstruction algorithm requires further improvement.

——中文对照版——

1　引　言

近年来,高深宽比的微结构以其灵敏度高、位移大等优点在微机电系统领域得到了广泛的应用[1],而其宽度小(约 1 ~10 μm)深度大(约 10 ~500 μm)高深宽比(10:1 至 100:1)的特点,使如何实时在线重构高深宽比底部及侧壁三维形貌成为一个亟待解决的问题[2]。目前,测量微结构三维形貌的仪器主要有 3 种:扫描电子显微镜[3](Scanning Electron Microscope,SEM)、原子力显微镜[4-5](Atomic Force Microscope,AFM)、白光干涉仪[6]。SEM 是用极狭窄的电子束去扫描样品,在测量高深宽比结构时,需要切开微结构制成剖面样品,本身就是一种破坏、损伤性的测量方法,而且测量时间长成本高;AFM 是通过显微探针受力的大小直接换算出样品表面的高度,由于高深宽比结构的特殊性,测量时,需要改进针尖结构使其深入到结构内部进行测量,但针尖的改进面临很大的困难;相比于其它两种仪器,白光干涉仪更适合用于测量微结构的表面形貌,而且已经有很多商用设备,如 Polytec、Talysurf、Veeco、Zygo 等,但对于高深宽比微结构形貌测量,白光干涉仪也有其局限性:一方面白光衍射比较严重,另一方面由于测量时光线与待测物品有一定角度,光线无法完全通过窄狭缝,因此很难测量此结构的底部及侧壁形貌[7-8]。综上所述,基于白光干涉原理,利用半导体材料(砷化镓 GaAs 或硅 Si)在红外光波段可以透射的特性,如果将红外光代替白光干涉的白光光源,构建红外光干涉系统并实施一定的光程补偿,采用红外光透射反射干涉技术,即可实现高深宽比微结构的底部及侧壁形貌重构。

本文以近红外光波段为例,提出光程补偿近红外光透射反射干涉技术,对应的干涉测量系统由近红外光源、干涉显微镜、红外 CCD、高精度压电陶瓷和数据采集系统组成。首先研究了基于垂直扫描干涉技术的近红外光干涉形貌重构技术,以及 GaAs 材料在红外光波段透射的基本原理,其次设计了具有两个台阶的典型 GaAs 材料微结构样品,并对其内部形貌进行测量,最后通过与 SEM 和近红外光反射干涉的测量结果比较,证明光程补偿近红外光透射反射干涉系统能够测量高深宽比微结构内部形貌。

2　基本原理

图 1 所示为近红外光透射反射干涉测量高深宽比微结构底部及侧壁形貌示意图,可知通过一定的光程补偿方法,即可实现底部及侧壁形貌的重构。

2.1　近红外光干涉系统

利用近红外光干涉显微仪产生干涉条纹,图 2 为近红外光干涉系统装置图及原理示意图。此干涉系统是基于 168 倍测量区域放大率的 Linnik 光学干涉仪进行改进的。近红外光源发射的近红外光通过分束器分成两束,一路经参考镜后反射,另一路经待测物品后反射或透射反射,两束光产生的干涉条纹由红外光 CCD(像素320 ×256)获取[9],高精度压电陶瓷允许在400 μm的垂直范围内移动,数据采集和形貌重建由自行编制的专用软件完成。为了避免将误差导入到结果中,测量是在安静和阴暗的环境中进行的。

2.2　近红外光干涉重构三维形貌原理

垂直扫描干涉法(VSI)由于精度高、操作速度快,是一种典型的微结构三维形貌重建算法,其通过选择在零相位处的条纹测量其相对高度[10-12]。近红外光干涉基本原理与白光干涉的原理相似,因此光源选择了中心波长为 1 170 nm,波长范围从 1 000 nm 到 1 400 nm 的近红外光光源。

根据白光干涉原理,可以用标准关系表示近红外光干涉图的强度:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta , \quad (1)$$

$$\delta = 2\pi\Delta / \lambda , \quad (2)$$

其中，I_1和I_2是两光束的光强，δ是I_1和I_2的相位差，λ是近红外光波长，Δ是I_1和I_2的光程差，对于反射干涉情况$\Delta = L_1 - L_2$，对于透射反射干涉情况$\Delta = L_1 + \Delta L - (L_2 + nh)$，其中，$L_1$和$L_2$是反射干涉情况下参考路光程和待测物光程，$\Delta L$为透射反射干涉情况下参考路补偿的光程，$n$为透射材料的折射率（GaAs 材料在近红外光波段折射率约为3.45），h为透射材料的厚度。对于近红外光宽谱光源，由红外光 CCD 获取的干涉图样可以看做是不同波长干涉叠加的结果，因此强度分布也可以表示为[13]：

$$I(x,y,z) = I_0 + \int_{\lambda_c-\lambda_b}^{\lambda_c+\lambda_b} \psi(\lambda) \cos\frac{4\pi(z - z_p)}{\lambda} d\lambda \quad (3)$$

其中，I_0是干涉图的强度，λ_c是近红外光中心波长，$2\lambda_b$是光谱的带宽，$\psi(\lambda)$为在波长λ附近干涉图样的能量分布，z为 PZT 的相对位置，z_p为零光程差对应的位置[10]。由于所选择的近红外光源相干长度很短，当每个像素点在零光程差位置($z = z_p$)时，干涉强度最大，通过记录每个像素点对应的z_p[10]，即可重构微结构的三维形貌。

由于本征吸收，电子从价带到导带的吸收过程被激发。半导体单晶材料的本征吸收波长用λ_g表示。当光照射材料时，波长大于λ_g的部分光会穿透，波长小于λ_g的光将被吸收。作为本征吸收，电子能和能带隙的关系描述如下：

$$\frac{hc}{\lambda_g} \geq E_g, \quad (4)$$

其中，h是普朗克常数，c是光速，E_g是带隙宽度。对于本实验所用的砷化镓（GaAs）材料，E_g为1.43 eV，最小的透射波长为0.86 μm。

3 结果与分析

首先，设计了一个标准待测样本（Micro-structures），以验证系统的可行性和准确性，标准样品由 GaAs 半导体材料制作，其有两个不同高度的台阶（如图3所示）。为了增强反射效果，在 GaAs 表面镀了一层金并进行了抛光处理。为了验证该测量系统的可行性，利用 SEM 对两个台阶进行了测量（台阶 A 和台阶 B），其结果分别为2.087 μm 和0.746 μm，如表1所示。其中，SEM 测量结果做为一个参考标准来验证所设计系统的性能。

其次，利用近红外光反射干涉技术重构了微结构形貌，此时两路光的光程差为$\Delta = L_1 - L$。用分散条纹图案记录了5个相移干涉图，压电陶瓷步进为0.01 μm，对应0.061 rad 的相位步进，干涉图如图4(a)所示。解算后所得的三维形貌与图3所示的实际形貌非常一致，提取从像素(0,256)到像素(256,0)的对角线形貌以来证明测量结果的准确性，如图4(b)所示。测量结果显示，这两个台阶的相对高度是2.107 μm 和0.759 μm，接近于 SEM 测量结果，分别对应0.96%和1.74%的相对误差。由于衍射效应的影响，台阶边缘所测量形貌发生了失真，这个是干涉仪常见的问题[14-15]。

最后，在同样的干涉显微镜下，用近红外光透射反射干涉技术代替近红外光反射干涉技术，同时由于待测物品光程增加了nh，因此在参考路进行光程补偿ΔL，且$\Delta L = nh$。为了验证近红外光是否透过 GaAs 材料，通过调整 PZT 位置获得了不同层的干涉图样，如图5(a)所示。由图5可以看出，上层干涉条纹在台阶边缘位置没有任何变化，而下层的干涉条纹发生了变化，证明红外光已经透过 GaAs 材料，调整参考镜的位置并通过计算机控制压电陶瓷以0.01 μm 的扫描间隔获取干涉图样，同时由于透射的上层表面不均匀，对结果进行了矫正，如图5(a)所示。所解算的三维形貌与图4(a)中所示的形貌基本一致。为了清晰地描述实验结果，提取从像素(0,256)到像素(256,0)的对角线形貌，如图5(b)所示。表1表明这两个台阶的相对高度分别为2.132 μm 和0.766 μm，这与扫描电镜和近红外光反射干涉测量结果基本一致，分别对应2.16%和2.68%的相对误差。同样地，由于衍射效应，在台阶边缘上的形貌有失真现象。

4 结 论

本文搭建了近红外光干涉的测量系统，利用

光程补偿近红外光透射反射干涉技术获得了台阶的相对高度,实现了微结构的内部三维形貌重构。标准样品的形貌测量结果与 SEM 测量结果一致,当用光程补偿近红外光透射反射干涉技术代替近红外光反射干涉技术时,该系统可以正常测量。光程补偿近红外光透射反射干涉技术测量结果分别为 2.132 μm 和 0.766 μm,分别对应 2.16% 和 2.68% 相对误差,结果表明其能够测量高深宽比微结构底部及侧壁形貌。目前测量误差较大,主要原因有两方面,一方面近红外光和白光光谱相差大引入了色差,另一方面是重构算法需要改进。

References:

[1] TOTSU K, FUJISHIRO K, TANAKA S, *et al.*. Fabrication of three-dimensional microstructure using maskless gray-scale lithography[J]. *Sensors and Actuators A: Physical*, 2006, 130-131: 387-392.

[2] ZHANG T, GAO F, JIANG X Q. Surface topography acquisition method for double-sided near-right-angle structured surfaces based on dual-probe wavelength scanning interferometry[J]. *Optics Express*, 2017, 25(20): 24148-24156.

[3] HOU P X, LIU C, CHENG H M. *Field Emission from Carbon Nanotubes*[M]. Nanomaterials Handbook. 2nd Ed. CRC Press, 2017: 255-272.

[4] MORITA S, GIESSIBL F J, MEYER E, *et al.*. *Noncontact Atomic Force Microscopy*[M]. Berlin: Springer, 2015.

[5] 董恺琛,娄帅,姚杰,等. 脉冲激光沉积薄膜的残余应力测量[J]. 光学 精密工程, 2018, 26(1): 70-76.
DONG K CH, LOU SH, YAO J, *et al.*. Measurement of residual stresses in pulsed laser deposited thin films[J]. *Opt. Precision Eng.*, 2018, 26(1): 70-76. (in Chinese)

[6] TSUDA Y, KITASAKO Y, SADR A, *et al.*. Effects of brushing timing after erosive challenge on enamel loss in situ: White light interferometer and nanoindentation study[J]. *Dental Materials Journal*, 2016, 35(4) 613-620.

[7] DAO T, THOMAS T, MARX D, *et al.*. Evaluation of non-destructive etch depth measurement for through silicon vias[C]. 2012 IEEE International Conference on IC Design & Technology, IEEE, 2012: 1-4.

[8] ZHOU Y F, CAI H ZH, ZHONG L Y, *et al.*. Eliminating the influence of source spectrum of white light scanning interferometry through time-delay estimation algorithm[J]. *Optics Communications*, 2017, 391: 1-8.

[9] XUE CH Y, LIU J, CHOU X J, *et al.*. White-light transmission reflection interference technology application in three-dimensional reconstruction method validation for microstructures[C]. Proceedings of the 3rd International Congress on Image and Signal Processing, IEEE, 2010, 2: 867-870.

[10] 刘燕德,万常斓. 芝麻油掺伪的近红外透射光谱检测技术[J]. 农业机械学报, 2012, 43(7): 136-140.
LIU Y D, WAN CH L. Analysis of sesame oil adulteration using near infrared transmission spectroscopy[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2012, 43(7): 136-140. (in Chinese)

[11] 秦五昌,汤修映,彭彦昆,等. 基于可见/近红外透射光谱的孵化早期受精鸡蛋的判别[J]. 光谱学与光谱分析, 2017, 37(1): 200-204.
QIN W CH, TANG X Y, PENG Y K, *et al.*. Identification of fertilized chicken eggs based on visible/near-infrared spectrum during early stage of incubation[J]. *Spectroscopy and Spectral Analysis*, 2017, 37(1): 200-204. (in Chinese)

[12] THOMAS D J. 3D white light interferometry assessment of robotic laser scalpel assisted surgery to minimise scar tissue formation[J]. *International Journal of Surgery*, 2017, 38: 117-118.

[13] XIAO Y, QIU L R, ZHAO W Q. Laser confocal cylindrical radius measurement method and its system[J]. *Applied Optics*, 2017, 56(23): 6596-6602.

[14] TAPILOUW A M, CHANG Y W, YU L Y, *et al.*. Reduction of batwing effect in white light interferometry for measurement of patterned sapphire substrates (PSS) wafer[J]. *Proceedings of SPIE*, 2016, 9960: 996006.

[15] TERESCHENKO S, LEHMANN P, GOLLOR P, *et al.*. Vibration compensated high-resolution scanning white-light Linnik-interferometer[J]. *Proceedings of SPIE*, 2017, 10329: 1032940.

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