

激光差动共焦显微振动-动态拉曼光谱原位探测技术研究

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**Research on In-Situ Detection Technology
of Laser Differential Confocal
Microscopic Vibration-Dynamic Raman Spectroscopy**

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摘要

微机电系统（Micro-Electro-Mechanical Systems, MEMS）作为高性能传感器系统的核心感知单元，具有体积小、响应快、灵敏高等显著优点，在航空、航天、兵器等国家重大战略装备中具有不可替代的作用。随着微纳加工及制造技术的革新，利用高频动态响应实现传感性能跨越已成为新一代 MEMS 器件发展的关键所在。在高频动态过程中，器件性能通常由几何结构与动态特性共同决定。因此，如何实现微纳器件几何参数与动态特性的高分辨原位表征，已成为当前微纳器件表征领域中亟待解决的重要课题。

然而，现有微纳器件表征技术面临诸多瓶颈，传统的静态表征手段无法捕捉动态演变过程，单一参数的离散检测亦难以揭示多参数耦合下的动态响应本质，严重阻碍了对微纳器件性能的准确评估与深入理解。

针对上述问题，本论文“激光差动共焦显微振动-动态拉曼光谱原位探测技术研究”，在激光差动共焦显微拉曼光谱探测技术基础上，提出了激光差动共焦显微振动-动态拉曼光谱原位探测新方法，构建了激光差动共焦显微振动-动态拉曼光谱原位探测系统，首次实现几何形貌、振动参数及动态应力的多参数原位探测与融合成像。

本论文研究内容来源于 XXX。

本论文的主要研究工作如下：

1) 针对微纳器件表征领域中几何、振动、应力等多参数难以原位检测的问题，提出了激光差动共焦显微振动-动态拉曼光谱原位探测新方法。该方法利用激光差动共焦探测系统实现显微成像与振动参数探测，结合频闪照明的拉曼光谱探测系统实现动态拉曼光谱探测，首次实现了动态微纳器件的几何、振动、应力等多参数原位探测，突破了传统表征技术在多维信息原位融合表征方面的瓶颈。

2) 针对共焦显微振动参数测量振幅分辨率不足的问题，提出了自适应差动共焦显微振动传感模型映射方法，开发了基于数字滤波和基于深度学习的两种振动传感模型，均可直接从振动耦合的差动共焦轴向强度响应曲线建立位移-电压映射关系，实现无需预扫描的原位振动测量，其中深度学习模型相比数字滤波模型具有更强的非线性拟合能力。在此基础上，进一步结合加窗快速傅里叶变换技术，实现了亚纳米级的振动振幅参数解调。

3) 针对动态拉曼光谱探测中光谱空间分辨力不足的问题, 提出了焦点跟踪的相位分辨动态拉曼光谱探测方法。该方法利用短脉冲频闪照明技术实现对动态拉曼光谱的相位分辨探测功能, 并进一步结合差动共焦技术, 确保拉曼光谱激发始终精确定位于光斑焦点位置, 解决了振动样品动态拉曼光谱的高空间分辨探测难题。

基于上述研究, 构建了激光差动共焦显微振动-动态拉曼光谱原位探测系统, 并开展了系统性能测试和实验验证研究。实验结果表明: 系统几何空间分辨力横向达 320 nm, 轴向达 11 nm; 光谱空间分辨力横向达 320 nm, 轴向达 1 μm ; 时域解调位移分辨力优于 1.8 nm ($k=3$), 1-dB 动态测量范围为 180 nm; 频域解调振幅分辨率达 0.09 nm/Hz^{1/2} @ 1 kHz~100 kHz 和 0.02 nm/Hz^{1/2} @ 100 kHz~93 MHz, 振动检测带宽达 93 MHz; 可探测 360 kHz 的动态应力, 拉曼光谱分辨力优于 0.6 cm⁻¹, 光谱频移测量重复性为 ± 0.02 cm⁻¹, 对应应力分辨力达 10 MPa @Si<100>。实验结果表明, 本论文研究的“激光差动共焦显微振动-动态拉曼光谱原位探测技术”具有高空间分辨、高振幅分辨、多参数原位测量等显著优势, 为微纳器件性能表征提供了全新的技术方案。

关键词: 微机电系统; 多参数原位探测; 差动共焦; 动态拉曼光谱; 高空间分辨

Abstract

As the core sensing units of high-performance sensor systems, Micro-Electro-Mechanical Systems (MEMS) possess significant advantages such as small volume, fast response, and high sensitivity, playing an irreplaceable role in major national strategic equipment in aviation, aerospace, and weaponry. With the continuous innovation of micro/nano processing and manufacturing technologies, utilizing high-frequency dynamic response to achieve a leap in sensing performance has become the key to the development of a new generation of MEMS devices. During the high-frequency dynamic process, device performance is usually jointly determined by the geometric structure and dynamic characteristics. Therefore, how to achieve high-resolution in-situ characterization of the geometric parameters and dynamic characteristics of micro/nano devices has become an important and urgent topic in the current field of micro/nano device characterization.

However, existing micro/nano device characterization technologies face numerous bottlenecks. Traditional static characterization methods cannot capture the dynamic evolution process, and the discrete detection of a single parameter is also insufficient to reveal the essence of dynamic response under multi-parameter coupling, which severely hinders the accurate evaluation and in-depth understanding of the performance of micro/nano devices.

Aiming at the above problems, this thesis, titled "Research on Laser Differential Confocal Micro-vibration and Dynamic Raman Spectroscopy In-situ Detection Technology", proposes a novel in-situ detection method based on laser differential confocal micro-Raman spectroscopy detection technology. An in-situ detection system for laser differential confocal micro-vibration and dynamic Raman spectroscopy is constructed, realizing for the first time the multi-parameter in-situ detection and fusion imaging of geometric morphology, vibration parameters, and dynamic stress.

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The main research work of this thesis is as follows:

1) Aiming at the difficulty of in-situ detection of multiple parameters such as geometry, vibration, and stress in the field of micro/nano device characterization, a new in-situ detection

method using laser differential confocal micro-vibration and dynamic Raman spectroscopy is proposed. This method utilizes a laser differential confocal detection system to achieve micro-imaging and vibration parameter detection, and combines it with a stroboscopic illumination-based Raman spectroscopy detection system to achieve dynamic Raman spectroscopy detection. It achieves the multi-parameter in-situ detection of geometry, vibration, and stress of dynamic micro/nano devices for the first time, breaking through the bottleneck of traditional characterization technologies in the in-situ fusion characterization of multi-dimensional information.

2) Aiming at the problem of insufficient amplitude resolution in confocal micro-vibration parameter measurement, an adaptive differential confocal micro-vibration sensing model mapping method is proposed. Two vibration sensing models based on digital filtering and deep learning are developed. Both can directly establish a displacement-voltage mapping relationship from the vibration-coupled differential confocal axial intensity response curve, achieving in-situ vibration measurement without the need for pre-scanning. Among them, the deep learning model demonstrates stronger nonlinear fitting capabilities compared to the digital filtering model. On this basis, by further combining the windowed Fast Fourier Transform (FFT) technique, picometer-level vibration parameter demodulation is achieved.

3) Aiming at the problem of insufficient spectral spatial resolution in dynamic Raman spectroscopy detection, a phase-resolved dynamic Raman spectroscopy detection method with focus tracking is proposed. This method utilizes short-pulse stroboscopic illumination technology to achieve phase-resolved detection of dynamic Raman spectroscopy, and further integrates differential confocal technology to ensure that the Raman spectroscopy excitation is always precisely located at the spot focus, thereby solving the challenge of high spatial resolution detection of dynamic Raman spectroscopy for vibrating samples.

Based on the above research, the laser differential confocal micro-vibration and dynamic Raman spectroscopy in-situ detection system was constructed, and system performance testing as well as experimental verification were carried out. The experimental results show that the geometric spatial resolution of the system reaches 320 nm laterally and 11 nm axially; the spectral spatial resolution reaches 320 nm laterally and 1 μm axially. The time-domain demodulation displacement resolution is better than 1.8 nm ($k = 3$), and the 1-dB dynamic

measurement range is 180 nm. The frequency-domain demodulation amplitude resolution reaches $0.09 \text{ nm/Hz}^{1/2}$ @ 1 kHz~100 kHz and $0.02 \text{ nm/Hz}^{1/2}$ @ 100 kHz~93 MHz, with a vibration detection bandwidth reaching 93 MHz. It can detect dynamic stress at 360 kHz, the Raman spectral resolution is better than 0.6 cm^{-1} , and the repeatability of spectral shift measurement is $\pm 0.02 \text{ cm}^{-1}$, corresponding to a stress resolution of 10 MPa @Si<100>. The experimental results indicate that the “Laser Differential Confocal Micro-vibration and Dynamic Raman Spectroscopy In-situ Detection Technology” studied in this thesis has significant advantages such as high spatial resolution, high amplitude resolution, and multi-parameter in-situ measurement, providing a brand-new technical solution for the performance characterization of micro/nano devices.

Keywords: Micro-Electro-Mechanical Systems (MEMS); multi-parameter in-situ detection; differential confocal; dynamic Raman spectroscopy; high spatial resolution