

## 单晶钙钛矿的制备及应用研究进展

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摘要: 近年来, 钙钛矿材料由于其带隙可调、吸收系数高、成本低等优势在国际上备受瞩目。其中, 单晶钙钛矿具有优于多晶钙钛矿的光学、电学特性, 成为制备高性能光电器件的理想材料。从钙钛矿的基本分子组成和化学结构出发, 介绍了单晶钙钛矿的基本光学和电学特性, 指出了块状、薄片/薄膜和纳米结构有机-无机杂化单晶钙钛矿的制备方法, 总结了它们在光电探测器、太阳电池、光泵浦激光和辐射探测中的应用。最后, 对单晶钙钛矿当前研究中所面临的挑战及未来的发展进行展望, 指出开发低成本、高稳定性、无毒的单晶钙钛矿光电器件有望加速其商业化进程。

关键词: 钙钛矿; 单晶; 光电探测器; 太阳电池; 激光; 辐射探测

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Research Progress of Preparation and Application of  
Single Crystal Perovskites

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Abstract: In recent years, perovskite materials have attracted much attention in the world due to their adjustable band gap, high absorption coefficient and low cost. Compared with polycrystalline perovskites, single crystal perovskites have better optical and electrical properties, which act as an ideal material for preparing optoelectronic devices with high performances. Based on the basic molecular composition and chemical structure of perovskites, the fundamental optical and electrical properties of single crystal perovskites are firstly introduced, and then the preparation methods of bulk, wafer/film and nanostructured organic || inorganic hybrid single crystal perovskites are presented. The research progress in applications of single crystal perovskites in the areas of photodetectors, solar cells, optical pump lasers and radiation detection is reviewed. Finally, the challenges in the current research and future development of single crystal perovskites are prospected, pointing out that developing low || cost, highly stable and non || toxic single crystal perovskite optoelectronic devices can promote its commercialization process.

Key words: perovskite; single crystal; photodetector; solar cell; laser; radiation detection

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抗磁悬浮原理在执行与传感方面的  
应用研究及发展

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摘要: 抗磁悬浮是利用物质对磁场的排斥力实现磁悬浮, 作为磁悬浮技术的一个分支, 是一种真正意义上的无接触悬浮。按照不同的应用领域, 从传感器、执行器、能量采集器、生物科学以及自组装等方面对抗磁悬浮结构进行了具体的介绍, 概述了抗磁悬浮在各个领域的工作原理、结构组成以及适用范围, 分析了抗磁悬浮发展现状及应用前景。研究得出抗磁悬浮具有室温下无源工作、自主稳定悬浮以及适宜在微器件尺度下使用等优点, 其系统简单、可靠性高、系统体积小且质量轻, 在工程技术上有重大的意义。

关键词: 抗磁悬浮; 磁悬浮; 微器件; 传感; 微电子机械系统 (MEMS)

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Application Research and Development of Diamagnetic Levitation

Principle in Actuation and Sensing

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Abstract:Diamagnetic levitation is achieved by using the repulsive force of materials on the magnetic field. As a branch of magnetic levitation technology, the diamagnetic levitation is a real contactless suspension. According to different application fields, the diamagnetic levitation structures are introduced in terms of sensors, actuators, energy harvesters, biological science, self assembly and so on. The working principle, structure composition and application range of the diamagnetic levitation in various fields are summarized. The development status and application prospect of the diamagnetic levitation are analyzed. It is concluded that the diamagnetic levitation has the advantages of passive operating at room temperature, autonomous and stable suspension, and suitable for use at the micro device scale. It has many good qualities such as simple system, high reliability, small volume and light weight. Therefore, it has a great significance in the engineering technology.

Key words:diamagnetic levitation; magnetic levitation; micro device; sensing; micro electromechanical system (MEMS)

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## Effect of the Surface Porous Silicon Layer on Performances of Monocrystalline Silicon Solar Cells

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**Abstract:** Reflectivity plays an important role to the performances of solar cells. The porous silicon was prepared on the monocrystalline silicon substrates by the electrochemical method to reduce the reflectivity of the devices. Then the phosphorous diffusion was obtained by the rapid thermal annealing method to fabricate monocrystalline silicon solar cells. The images of the scanning electron microscopy(SEM) show that the porous silicon layer with an uniform pore size is formed on the surface of monocrystalline silicon, and the pore size increases with the increase of the etching time. The spectra measured from the ultraviolet-visible spectrophotometer indicate that the reflectivity of the porous silicon layer reaches 12% within the spectral range of 400-1100 nm. The sheet resistance decreases as the thickness of porous silicon increases, and reaches  $42 \Omega/\square$ , which proves that the porous silicon layer promotes the phosphorus diffusion. After rapid thermal phosphorus diffusion at  $850^\circ\text{C}$  for 40 s, the porous silicon solar cell was achieved with an efficiency of  $12 \sim 32\%$ , a short circuit current density of  $27 \sim 99 \text{ mA/cm}^2$ , an open circuit voltage of  $0 \sim 49 \text{ V}$  and a filling factor of 71%.

**Key words:** solar cell; porous silicon; reflectivity; rapid thermal process; phosphorus diffusion

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表面多孔硅层对单晶硅太阳能电池性能的影响

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**摘要:**反射率对太阳能电池的性能至关重要。采用电化学法在单晶硅衬底上制备多孔硅来降低器件的反射率,并采用快速热退火法对多孔硅层进行磷扩散处理,进而制备了单晶硅太阳能电池。扫描电子显微镜(SEM)显示出单晶硅表面形成了孔径均匀的多孔硅层,且孔径随着刻蚀时间的增加而增大;紫外-可见光分光光度计表明,该多孔硅层的反射率在 $400 \sim 1100 \text{ nm}$ 的光谱范围达到12%;磷扩散后薄层方块电阻达到 $42 \Omega/\square$ ,证明多孔硅层促进了磷扩散。最终在 $850^\circ\text{C}$ 、40 s快速热退火扩散条件下,成功制备出了效率为 $12 \sim 32\%$ 、短路电流密度为 $27 \sim 99 \text{ mA/cm}^2$ 、开路电压为 $0 \sim 49 \text{ V}$ 以及填充因子达到71%的太阳能电池。

**关键词:**太阳能电池;多孔硅;反射率;快速热处理;磷扩散

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共价有机框架/多壁碳纳米管复合材料  
及其双电层电容器性能

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摘要: 共价有机框架(COF)材料是一种特殊的结晶性有机多孔材料, 具有多种有机官能团结构, 同时有着非常低的骨架密度以及较高的比表面积。通过熔融热法制备TpPa Ⅱ COF材料并与导电性能优异的多壁碳纳米管(MWCNT)复合制得TpPa Ⅱ COF@MWCNT纳米复合材料, 复合材料的微观形貌通过扫描电子显微镜(SEM)和透射电子显微镜(TEM)进行表征, 通过循环伏安法对用于超级电容器的TpPa Ⅱ COF@MWCNT纳米复合材料的电化学性能进行研究。实验验证了该复合材料在不同扫描速度下的循环伏安曲线均呈现优异的双电层电容特性。当电流密度高达 $1 \text{ A} \cdot \text{g}^{-1}$ 时, 该复合材料的比电容仍达到 $25 \text{ F} \cdot \text{g}^{-1}$ , 在 $2 \text{ A} \cdot \text{g}^{-1}$ 的电流密度下测得5 000次循环后比电容的保持率略高于100%, 表现出良好的大电流充放电性能和应用前景。

关键词: 共价有机框架; 多壁碳纳米管; 双电层电容器; 大电流充放电性能; 稳定性

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Covalent Organic Frameworks/Multi Ⅱ Walled Carbon Nanotubes

Composite and Its Electric Double Ⅱ Layer Capacitor Properties

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Abstract: Covalent organic framework (COF) is a special crystalline organic porous material, and has a variety of organic functional groups, a very low skeletal density and higher specific surface area. By compounding the TpPa Ⅱ COF and multi Ⅱ walled carbon nanotube (MWCNT) with excellent conductivity, the TpPa Ⅱ COF@MWCNT nano composites were prepared using the thermal method. The micro Ⅱ morphology of the composites was characterized by the scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The electrochemical performances of the TpPa Ⅱ COF@MWCNT nano composites used for supercapacitor were studied by the cyclic voltammetric method. The experimental result shows that the cyclic voltammetry curves exhibit excellent electric double layer capacitance characteristics at various scanning rates. The specific capacitance of the composites reaches  $25 \text{ F} \cdot \text{g}^{-1}$  at the current density of  $1 \text{ A} \cdot \text{g}^{-1}$ , and the retention rate of the specific capacitance slightly exceeds 100% measured at the current density of  $2 \text{ A} \cdot \text{g}^{-1}$  after 5 000 cycles, showing good high current charge and discharge characteristic and good application prospects.

Key words: covalent organic framework; multi Ⅱ walled carbon nanotube(MWCNT); electric double Ⅱ layer capacitor; high current charge and discharge characteristic; stability

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## Electrical and Photoelectric Properties of NiO/SiC Heterojunction

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**Abstract:** NiO is a natural p-type direct band gap semiconductor material. A p-NiO/n-4H-SiC heterojunction was fabricated with NiO films deposited on 4H-SiC (0001) substrate by the magnetron sputtering method. The effects of the oxygen volume flow and argon volume flow on the NiO film properties were studied, and the photoelectric properties of the NiO/SiC heterojunction were studied. The results show that the prepared NiO films are polycrystalline structure, when oxygen volume flow and argon volume flow are both 30 cm<sup>3</sup>/min, the NiO films appear [200] crystal orientation, the grain size of the smooth and compact p-type films is about 15 nm. Ni was used as the electrode metal. The J-V measurement result indicates that the heterojunction has good rectifying behaviour with a turn-on voltage of about 1.4 V. Under a UV light illumination of 13.5 mW, the heterojunction exhibits good photo response with the open circuit voltage Voc of about 30 mV and photocurrent density Jph of 0.89 mA/cm<sup>2</sup>.

**Key words:** NiO; heterojunction; magnetron sputtering; rectifying behaviour; photo response

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NiO/SiC 异质结的光电特性

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**摘要:** NiO 是一种天然 p 型直接带隙半导体材料, 首次采用磁控溅射的方法在 n 型 4H-SiC (0001) 衬底上淀积 NiO 薄膜, 制作 p-NiO/n-4H-SiC 异质结。研究了氧气和氩气体积流量对 NiO 薄膜特性的影响, 并研究了 NiO/SiC 异质结的光电特性。结果表明: 所制备的 NiO 薄膜为多晶结构, 当氧气和氩气体积流量均为 30 cm<sup>3</sup>/min 时, NiO 薄膜出现 [200] 晶向的择优生长, 呈现 p 型导电, 薄膜平整致密, 粒径约为 15 nm。采用 Ni 作为金属电极, J-V 测试结果表明异质结具有较好的整流特性, 开启电压约为 1.4 V, 在 13.5 mW 的紫外灯照射下, 异质结出现了光响应, 开路电压 Voc 约为 30 mV, 光电流密度 Jph 为 0.89 mA/cm<sup>2</sup>。

**关键词:** 氧化镍 (NiO); 异质结; 磁控溅射; 整流特性; 光响应

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基于石墨烯复合薄膜的平面微电感

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摘要: 石墨烯由于其独特的组成结构, 具有极其优异的电学性能, 基于石墨烯薄膜的电子器件越来越受到研究者的关注。通过将石墨烯与微型导电线圈结合, 探究石墨烯对线圈微电感性能的影响。滴涂石墨烯并通过三组对比实验确定石墨烯薄膜的干燥方式(-5 °C 冷干干燥、室温真空干燥和室温自然干燥)。结果显示, 室温真空干燥形成的石墨烯薄膜更为连续均匀、薄膜厚度小且电阻率更低。进一步实验得到, 45 °C 为室温真空干燥方式的较佳干燥温度。采用微电子机械系统 (MEMS) 工艺制备三种不同材料的微型导电线圈(铜导线、石墨烯/铜复合导线、石墨烯导线)。对三种线圈的电学参数进行测试, 发现石墨烯/铜复合导电线圈的电感性能有较大提高。

关键词: 微电子机械系统 (MEMS); 石墨烯薄膜; 微电感; 真空干燥; 平面线圈; 石墨烯/铜复合导线

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Planar Micro  $\Pi$  Inductance Based on the Graphene Composite Film

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Abstract:The graphene has extremely excellent electrical properties because of its unique composite structure. Electronic devices based on graphene films are taken more and more attention by researchers. The effect of the graphene on the micro  $\Pi$  inductance of the coil was explored by combining the graphene with the micro  $\Pi$  conducting coil. The graphene solution was dropletly coated and three sets of experiments were designed to determine a better drying method of graphene films (cold drying at -5 °C, vacuum drying at room temperature and natural drying at room temperature). The results show that the graphene film of vacuum drying at room temperature is more continuous and uniform, and has thinner thickness and lower resistance. Further experiment shows that 45 °C is the preferred drying temperature of vacuum drying at room temperature. By the micro  $\Pi$  electromechanical system (MEMS) technology, three kinds of micro  $\Pi$  conducting coils with different materials were fabricated (copper wire, graphene/copper composite wire and graphene wire). The electrical parameters of the three coils were tested. The results show that the inductance performance of the graphene/copper composite conductive coil is improved.

Key words:micro  $\Pi$  electromechanical system (MEMS); graphene film; micro  $\Pi$  inductance; vacuum drying; planar coil; graphene/copper composite wire

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一种用于湿度监测的 LC 无线无源传感器的  
制备与测试

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摘要: 提出了一种采用丝网印刷和亚胺化工艺制备的 LC 无线无源技术的二硫化钼 (MoS<sub>2</sub>) /聚酰亚胺 (PI) 湿度传感器。对比了不同超声时间下的二硫化钼/聚酰亚胺复合材料的湿度敏感性能, 得出对湿度最灵敏的材料为超声 4 h 的二硫化钼/聚酰亚胺材料。测试结果表明, 制备的器件在量程 10%RH~95%RH 内具有较好的频率响应, 频率变化值为 6 || 205 MHz; 在高湿度范围内 (60%RH~95%RH), 传感器的灵敏度可达 153 || 59 kHz/%RH。此外, 该传感器的响应和恢复时间分别为 7 || 2 s 和 10 || 4 s, 迟滞性误差约为 5%RH 且具有较好的稳定性。该传感器可广泛应用于化学合成和矿井环境等领域的湿度监测。

关键词: 传感器; 无线无源; 二维材料; 湿度监控; 聚酰亚胺 (PI); 二硫化钼 (MoS<sub>2</sub>)

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Preparation and Measurement of a LC Wireless Passive  
Sensor for Humidity Monitoring

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Abstract: A molybdenum disulfide (MoS<sub>2</sub>)/polyimide (PI) humidity sensor was proposed using LC wireless passive technology prepared by the screen printing and imidization process. By comparing the humidity sensitivity of the molybdenum disulfide/polyimide composites for different ultrasonic time, it is found that the most sensitive material for humidity is the molybdenum disulfide/polyimide material with ultrasonic time of 4 h. The test results show that the prepared device has a good frequency response in the range of 10%RH-95%RH and the frequency change value is 6 || 205 MHz. The sensitivity of the sensor is up to 153 || 59 kHz/%RH in the high humidity range (60%RH-95%RH). In addition, the response time and recovery time of the sensor are 7 || 2 s and 10 || 4 s, respectively, the hysteresis error is about 5%RH, and the sensor has a good stability. The sensor has broad application prospects in the fields of chemical synthesis, mine environment and so on for humidity monitoring.

Key words: sensor; wireless passive; 2D material; humidity monitoring; polyimide (PI); molybdenum disulfide (MoS<sub>2</sub>)

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一种基于金刚石 NV 色心系综的磁力计

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摘要: 金刚石氮空位(NV)色心系综磁力计的灵敏度受激光激发效率的影响很大。对此通过增加激光与金刚石的接触面积来提高 NV 色心的激发效率, 搭建了共聚焦磁检测系统。建立了 NV 色心的原子模型, 根据其磁检测的原理, 可通过光探测磁共振 (ODMR) 技术来检测外部磁场。沿着金刚石 [111] 晶向施加静磁场, 四个共振峰所对应的微波频率与磁场强度呈现线性关系。因此, 可通过检测共振峰的漂移来解算出外部磁场强度。在激光功率 50 mW、微波功率 23 dBm 时, 计算得出室温下该磁力计的极限灵敏度达到  $0 \parallel 3 \text{ nT/Hz}^{1/2}$ , 实验测得系统的磁噪声灵敏度为  $0 \parallel 2 \text{ nT/Hz}^{1/2}$ 。通过提高金刚石 NV 色心激发效率可以进一步提高金刚石磁力计的灵敏度。

关键词: 磁力计; 金刚石系综; 氮空位色心; 光探测磁共振 (ODMR); 极限灵敏度

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A Magnetometer Based on NV Color Center Diamond Ensembles

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Abstract: The sensitivity of a magnetometer based on nitrogen vacancy (NV) color center ensembles in diamond is greatly affected by the laser excitation efficiency. The excitation efficiency of the NV color center was improved by increasing the contact area between laser and diamond, and a confocal magnetic detection system was built. An atomic model of the NV color center was established. According to the principle of magnetic detection, the external magnetic field could be detected by optical detection magnetic resonance (ODMR) technology. When a static magnetic field is applied along the diamond [111] crystal orientation, the microwave frequencies corresponding to the four resonance peaks have a linear relationship with the magnetic field strength. Therefore, the external magnetic field strength could be obtained by detecting the drift of the resonance peaks. When the laser power and microwave power are 50 mW and 23 dBm respectively, the limit sensitivity of the magnetometer is  $0 \parallel 3 \text{ nT/Hz}^{1/2}$  at room temperature, and the magnetic noise sensitivity of the system is  $0 \parallel 2 \text{ nT/Hz}^{1/2}$ . The sensitivity of the diamond magnetometer can be further improved by increasing the excitation efficiency of the diamond NV color center.

Key words: magnetometer; diamond ensemble; nitrogen vacancy color center; optical detection magnetic resonance (ODMR); limit sensitivity

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## 基于 PEDOT : PSS 与碳纳米管复合纳米材料的应变传感器

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摘要: 提出一种基于导电聚合物聚(3,4 亚乙二氧基噻吩)-聚(苯乙烯磺酸)(PEDOT : PSS)与碳纳米管 (CNT) 复合纳米材料的柔性应变传感器。介绍了复合纳米材料的制备、应变传感器的制备与封装以及传感器力学性能的测试。利用自制夹具对传感器进行了测试, 测试结果表明制备的传感器在不同拉伸下, 传感器 U 卩 I 曲线符合欧姆定律, 该传感器最大相对拉伸可达 100%, 应变灵敏度系数 (GF) 可达 301, 并且具有良好的重复性。该应变传感器在人类运动监测、个性化医疗以及心理健康监测等方面具有广阔的应用前景。

关键词: 柔性传感器; 应变传感器; 碳纳米管; 纳米材料; 聚(3, 4 亚乙二氧基噻吩)-聚(苯乙烯磺酸) (PEDOT : PSS); 运动监测

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Strain Sensor Based on PEDOT : PSS and Carbon

Nanotube Composite Nanomaterials

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Abstract: A flexible strain sensor based on conductive polymer poly(3,4 卩 ethylenedioxythiophene) : poly(styrenesulfonate) (PEDOT : PSS) and carbon nanotube (CNT) composite nanomaterials was presented. The preparation of composite nanomaterials, preparation and packaging of strain sensor and mechanical properties test of the sensor were introduced. The self 卩 made fixture was used to test the sensor. The test result shows that the U 卩 I curve of the sensor is in accordance with ohm's law under different tensile conditions. In addition, the maximum relative stretch of the sensor can reach 100%, and the gage factor (GF) can reach 301, and the sensor has excellent repeatability. The strain sensor has a broad application prospect in the fields of human movement monitoring, personalized medicine and psychological health monitoring.

Key words: flexible sensor; strain sensor; carbon nanotube (CNT); nanomaterial; poly(3,4 卩 ethylenedioxythiophene) : poly(styrenesulfonate) (PEDOT : PSS); motion monitoring

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基于纳米混悬液的摩擦起电运动平衡传感器

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摘要: 由于机器人、便携式设备的快速发展, 对传感器提出了小体积、高灵敏度的新要求。

基于固体柔性聚合物与液体之间的摩擦起电, 传感器在接触面积与摩擦两方面有优势, 使其具有很好的发展前景。提出一种基于聚四氟乙烯 (PTFE) 的液固接触摩擦起电的运动平衡传感器。利用金属混悬液可以输出-4~4 mV 的电压。在传感器左倾时输出正电压, 右倾时输出负电压, 使传感器在物体平衡监测方面有很大的优势。同时在物体进行加速或者减速运动时, 可以通过输出的电信号判断运动状态, 并进行分析。通过采集的电信号来反映加速度值, 为设计加速度传感阵列、全方位加速度传感提供了基础。

关键词: 摩擦起电; 柔性聚合物; 金属混悬液; 平衡监测; 运动监测; 加速度传感

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Motion || Balanced Sensor Based on the Triboelectricity

from Nano Suspension Liquid

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Abstract:With the rapid development of robots and portable devices, the new demands of small size and high sensitivity for sensors are required. The sensor based on the triboelectricity between the solid flexible polymer and liquid has the advantages of contact area and friction, thus has a good development prospect. A PTFE || based liquid || solid contact triboelectric motion || balanced sensor was proposed. An output voltage of -4-4 mV can be measured using the metal suspension liquid. When the sensor tilted to the left, the output voltage was positive, and when the sensor tilted to the right, the output voltage was negative, thus the sensor has great advantages in object balance monitoring. At the same time, when the object was accelerating or decelerating, the movement state could be judged by the output electrical signal and was analyzed. The acceleration values were reflected by the collected electrical signal, providing a basis for accelerometer array design and comprehensive acceleration sensing.

Key words:triboelectricity; flexible polymer; metal suspension liquid; balance monitoring; movement monitoring; acceleration sensing

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基于可控剥离技术的柔性 PZT 薄膜的  
制备及其铁电性质

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摘要: 可控剥离技术 (CST) 作为一种薄膜制备方式已被广泛应用于柔性领域, 例如硅基柔性太阳能电池等。首先采用溶胶-凝胶法先后在普通硅基底上制备镍酸镧 (LaNiO<sub>3</sub>) 缓冲层和锆钛酸铅(PZT)薄膜。通过 X 射线衍射仪 (XRD) 和扫描电子显微镜 (SEM) 进行材料表征, 发现 PZT 薄膜结晶良好, 而且表面致密均匀, 表明 LaNiO<sub>3</sub> 缓冲层有利于 PZT 薄膜的成膜。之后通过基于电镀镍方法的可控剥离技术实现了硅基底柔性 PZT 薄膜的制备。PZT 薄膜弯曲之后, 采用铁电测试仪测试了电滞回线。电滞回线表明该 PZT 薄膜的极化强度随着施加电压的增加而增大, 而且随着电压的增加, 电滞回线逐渐趋于饱和, 饱和极化强度为 38  $\mu\text{C}/\text{cm}^2$ 。最终得出该柔性 PZT 薄膜不仅具有良好的机械性能, 而且具有很好的铁电性能。

关键词: 可控剥离技术 (CST); 电镀; 柔性 PZT 铁电薄膜; 溶胶-凝胶; 镍酸镧 (LaNiO<sub>3</sub>)

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Fabrication of the Flexible PZT Thin Film Based on the Controlled  
Spalling Technology and Its Ferroelectric Properties

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Abstract: As a thin film preparation method, the controlled spalling technology (CST) has been widely used in flexible fields, such as silicon  $\text{Si}$  based flexible solar cells and so on. The lanthanum nickel oxide (LaNiO<sub>3</sub>) buffer layer and  $\text{Pb}$   $\text{Zr}$  based lanthanum doped zirconate titanates (PZT) thin film were successively prepared on the common silicon substrate by the sol  $\text{gel}$  method. The X  $\text{ray}$  diffractometer (XRD) and scanning electron microscope (SEM) characterization results show that the PZT thin film has good crystallization behaviour and its surface is dense and uniform, indicating that the LaNiO<sub>3</sub> buffer layer is favorable for the growth of the PZT thin film. Then the flexible PZT thin films were fabricated on the silicon substrate by the CST with the electroplating nickel process. After the PZT film bending, the ferroelectric hysteresis loops were measured by the ferroelectric tester. The ferroelectric hysteresis loops indicate that the polarization of the PZT thin film increases with the increase of the applied voltage. And with the increase of the voltage, the ferroelectric hysteresis loops gradually become saturated, and the saturation polarization is 38  $\mu\text{C}/\text{cm}^2$ . Finally, it is concluded that the flexible PZT thin film has a good mechanical property and a good ferroelectric performance.

Key words: controlled spalling technology (CST); electroplating; flexible PZT ferroelectric thin film; sol  $\text{gel}$ ; lanthanum nickel oxide (LaNiO<sub>3</sub>)

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## PDMS 微流控芯片中的微通道加工技术

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摘要: 传统加工方法制作 PDMS 微流控芯片中的微通道存在诸多限制, 特别是难以实现复杂三维微通道的加工。首先介绍了微通道的传统加工方法, 接着简要介绍了不同 3D 打印技术的基本原理, 最后重点阐述了 3D 打印技术在 PDMS 微流控芯片微通道加工中的应用。未来, 微流控芯片中微通道的加工将会向着高通量、低成本、高精度、三维化、集成化、微型化的方向发展。3D 打印、以纳米压印为主要代表的微纳制造技术与传统微通道成型技术的不断融合, 为研究人员提供了更多的思路, 必将成为微通道加工中的重要技术手段, 推动微流控芯片在生物医学、检验检疫、分析化学等领域更广泛的应用。

关键词: 3D 打印; PDMS; 微流控芯片; 微纳制造; 电流体动力学 (EHD)

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Microchannel Processing Technology in PDMS Microfluidic Chips

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Abstract: Traditional processing methods have many limitations in the fabrication of microchannels in PDMS microfluidic chips, especially for the complex three dimensional micro channel. The traditional processing methods of microchannels are firstly introduced, and then the basic principles of different 3D printing technologies are briefly introduced. Finally, the applications of the 3D printing technology in the fabrication of PDMS microfluidic chip microchannels are emphatically expounded. In the future, the fabrication of microchannels in microfluidic chips will develop in the directions of high throughput, low cost, high precision, three dimensional, integrated and miniaturized. The continuous integration of the 3D printing and micro nano manufacturing technology with the nanoimprint as the main representative and traditional microchannel molding technology provides more ideas for researchers, and will become an important technical means in the microchannel processing, and promotes the wider application of microfluidic chips in fields of biomedicine, inspection and quarantine, and analytical chemistry.

Key words: 3D printing; PDMS; microfluidic chip; micro nano manufacturing; electrohydrodynamics (EHD)

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## 一种 MEMS 陀螺晶圆级真空封装工艺

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摘要: 为了提高 MEMS 陀螺的品质因数(Q 值), 提出了一种晶圆级真空封装工艺。先在陀螺盖帽晶圆上刻蚀出浅腔, 然后在浅腔结构上制备钨(W)金属引线, 再通过 PECVD 工艺淀积介质层, 在介质层上制备钛/金(Ti/Au)键合环, 最后将盖帽晶圆与制备好的结构晶圆完成金硅共晶键合, 并利用吸气剂实现晶圆的长久真空封装。经测试, 采用本方案的封装的气密性与金属层厚度紧密相关, 调整合适的金属层厚度后可使真空泄漏速率小于  $2 \times 10^{-12} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ 。此外, 设计了一种特殊的浅腔阵列结构, 该结构将金硅键合强度从小于 20 MPa 提升至大于 26 MPa, 同时可防止键合时液相合金向外溢流。对陀螺芯片的性能测试表明, 该真空封装工艺简单有效, 封装气密性良好, Q 值高达 168 540, 满足设计指标要求。

关键词: MEMS 陀螺; 晶圆级真空封装; 金硅共晶键合; 真空泄漏速率; 键合强度; Q 值

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Wafer Level Vacuum Packaging Process for a MEMS Gyro

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Abstract: In order to improve the quality factor (Q value) of the MEMS gyro, a wafer level vacuum packaging process was proposed. Firstly, the shallow cavities were etched on the gyro cap wafer. Then, tungsten (W) metal leads were fabricated on the shallow cavities, and a dielectric layer was deposited by the PECVD process. After that, the titanium/gold (Ti/Au) bonding rings were prepared on the dielectric layer. Finally, the cap wafer was bonded with the prepared structural wafer by the Au/Si eutectic bonding process, and the getters were used to realize the wafer long term vacuum packaging. The test results show that the hermeticity of the package is closely related to the thickness of the metal layer. By adjusting the appropriate thickness of the metal layer, the vacuum leak rate can be reduced to less than  $2 \times 10^{-12} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ . In addition, a special shallow cavity array structure was designed to increase the Au/Si bonding strength from less than 20 MPa to more than 26 MPa, preventing the overflowing of the liquid alloy during bonding process simultaneously. The performance test results of the gyro chip demonstrate that the vacuum packaging process is simple and effective, and an excellent hermetic sealing is obtained, the Q value is as high as 168 540, satisfying the design specifications.

Key words: MEMS gyro; wafer level vacuum packaging; Au/Si eutectic bonding; vacuum leak rate; bonding strength; Q value

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