

基于 CVD 单层 MoS₂ FET 的光电探测器

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摘要: 通过化学气相沉积(CVD)工艺在 SiO₂/Si 衬底生长出 MoS₂ 材料, 对材料进行喇曼光谱表征, 验证了单层 MoS₂ 的存在; 基于 CVD 生长的单层 MoS₂ 完成了晶圆级背栅场效应晶体管(FET)光电探测器的工艺研发; 对 MoS₂ FET 器件进行了电学特性表征, 开关比可达到 10⁵ 数量级, 场效应迁移率约为 1 cm² · V⁻¹ · s⁻¹, 栅极漏电流为 10⁻¹⁰ A 数量级; 对 MoS₂ FET 器件的光电特性进行了表征, 该光电探测器具有普通光电导探测器的基本光电特性, 其光电流随光照强度的增强以及源漏电压的增加而增加, 同时由于栅极的调制提高了光电探测器的灵活性。通过控制栅极电压能够控制 MoS₂ FET 光电探测器的暗电流大小, 实现对探测器 η 参数的有效调制。最后通过器件能带图对 MoS₂ FET 光电探测器的光电特性进行了阐释, 为其走向实际应用奠定了理论基础。

关键词: 二硫化钼(MoS₂); 场效应晶体管(FET); 二维(2D)半导体材料; 光电探测器; 过渡金属硫属化合物(TMD)

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A Photodetector Based on CVD Monolayer MoS₂ FETs

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Abstract:The MoS₂ material was successfully synthesized by the chemical vapor deposition (CVD) process on the SiO₂/Si substrate. The existence of a monolayer MoS₂ was validated by Raman spectrum characterization. Based on the CVD monolayer MoS₂, the wafer scale fabrication process of a back gate field effect transistor (FET) photodetector was successfully developed. The electrical properties of the MoS₂ FET were characterized. The on/off ratio of the obtained device reaches the order of magnitude of 10⁵, the field effect mobility is about 1 cm²·V⁻¹·s⁻¹, and the gate leakage current is 10⁻¹⁰ A order of magnitude. The photoelectric properties of the MoS₂ FET were also characterized. The photodetector has the basic photoelectric properties of a common photoconductive detector, its photocurrent increases with the increase of the illumination intensity and the voltage between the drain and source. In addition, the flexibility of the photodetector is enhanced as a result of the modulation of the gate electrode. The magnitude of the dark current of the MoS₂ FET photodetector can be changed by controlling the gate voltage, then the parameter η can be effectively modulated. Finally, the photoelectric properties of the MoS₂ FET photodetector was illustrated by the device band diagram, providing a theoretical foundation for the practical applications.

Key words:molybdenum disulfide(MoS₂); field effect transistor (FET); two dimensional (2D) semiconductor material; photodetector; transition metal dichalcogenide (TMD)

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Fe₂O₃ /rGO/MoS₂ 复合材料的制备及其电化学特性

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摘要: 采用水热法合成氧化铁-石墨烯/二硫化钼(Fe₂O₃ /rGO/MoS₂)复合材料。使用 X 射线衍射 (XRD) 和扫描电子显微镜 (SEM) 分别对复合材料的晶体结构和微观形貌进行分析和表征。测试结果表明 Fe₂O₃ 均匀掺杂在 rGO/MoS₂ 复合材料中。同时, 利用循环伏安法和安培滴定法对制备的 Fe₂O₃ /rGO/MoS₂ 电化学传感器的电化学性能进行测试。实验结果表明: 制备的 Fe₂O₃ /rGO/MoS₂ 电化学传感器, 在对亚硝酸盐检测时, 其灵敏度可达 $0.378 \mu\text{A} \cdot \mu\text{M}^{-1} \cdot \text{cm}^{-2}$ ($1 \text{ M}=1 \text{ mol/L}$), 检出限为 $0.2 \mu\text{mol/L}$ (信噪比为 3) 且具有较宽的检测范围($1.0 \sim 9.830 \mu\text{mol/L}$)和较强的抗干扰性。

关键词: 石墨烯; 二硫化钼; 氧化铁; 亚硝酸盐; 电化学传感器

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Fabrication of a Fe₂O₃ /rGO/MoS₂ Composite Material and Its Electrochemical Properties

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Abstract: The ferric oxide /reduced graphene oxide/molybdenum sulfide (Fe₂O₃ /rGO/MoS₂) composite material was synthesized using the hydrothermal method. By the X ray diffraction (XRD) and scanning electron microscope (SEM), the crystal structure and micromorphology of the as prepared composite material were analyzed and characterized. The test results show that the Fe₂O₃ nanoparticles are doped uniformly in the rGO/MoS₂ composite material. Meanwhile, with the cyclic voltammetry and amperometry, the electrochemical properties of the as prepared Fe₂O₃ /rGO/MoS₂ electrochemical sensor were measured. The experimental results show that during the detection of the nitrite, the as prepared Fe₂O₃ /rGO/MoS₂ electrochemical sensor shows a high sensitivity of $0.378 \mu\text{A} \cdot \mu\text{M}^{-1} \cdot \text{cm}^{-2}$ ($1 \text{ M}=1 \text{ mol/L}$), a low detection limit of $0.2 \mu\text{mol/L}$ (signal noise ratio is 3), a large detection range ($1.0 \sim 9.830 \mu\text{mol/L}$) and good anti interference ability.

Key words: graphene; molybdenum sulfide; ferric oxide; nitrite; electrochemical sensor

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富勒烯纳米流体在石墨烯纳米孔隙中的
边界滑移特性

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摘要: 采用经典分子动力学方法探索了电场强度和富勒烯纳米颗粒浓度对水-富勒烯纳米流体在石墨烯纳米孔隙中 Couette 剪切流动特性的影响机理。结果表明: 当剪切应变率超过临界剪切应变率时, 边界滑移速率迅速增加, 且临界剪切应变率随着电场强度的增强而增大; 边界滑移速率和流体黏性值都随着富勒烯体积分数的增加而增大。当电场强度较小时, 流体的流动表现为边界正滑移, 但当电场强度达到临界值时, 流体的流动存在边界负滑移; 边界滑移速率先随着电场强度的增强而减小, 直至电场强度达到临界值后, 边界滑移速率随着电场强度的增强先减小后增大。富勒烯纳米流体的黏性值先随着电场强度的增强而增大, 而当电场强度达到临界值后, 纳米流体的黏性值则随电场强度的增强呈现先减小而后增大的趋势。

关键词: 富勒烯纳米流体; 石墨烯; Couette 流; 边界滑移; 分子动力学

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Boundary Slip Property of Fullerene Nanofluids in
Graphene Nanochannels

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Abstract: The effect mechanisms of the electric field intensity and fullerene nanoparticle concentration on the Couette flow motion behaviors of water fullerene nanofluids in graphene nanochannels were investigated by using classical molecular dynamics simulations. The results indicate that the boundary slip velocity increases abruptly when the shear strain rate is above a threshold, and the critical shear strain rate increases with the increase of the electric field intensity. Both the boundary slip velocity and the fluid viscosity increase with the increase of the fullerene volume fraction. There exists the positive slippage at the boundaries when the electric field intensity is relatively weaker, while the negative slippage appears as the electric field intensity reaches the critical value. The boundary slip velocity decreases with the increase of the electric field intensity, but with the increase of the electric field intensity, the boundary slip velocity decreases first until the electric field intensity is above a threshold, and then increases. The viscosity of the fullerene nanofluid increases with the increase of the electric field intensity. However, when the electric field intensity increases above a threshold, the viscosity of the nanofluid decreases first and then increases with the increase of the electric field intensity.

Key words: fullerene nanofluid; graphene; Couette flow; boundary slip; molecular dynamics

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ZnO 修饰多针-板结构负电晕放电气体传感器

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摘要: 基于负电晕放电原理的气体传感器利用局部高压电场将目标气体电离, 根据电离特性对气体进行识别。采用 MEMS 技术制备硅尖阵列电极, 利用电喷 ZnO 纳米颗粒对电极表面进行修饰, 结合金平板正电极构建了多针-板结构电晕放电气体传感器。研究了电极间距对传感器负电晕放电特性的影响, 综合考虑起晕电压、信号输出范围及稳定放电范围, 优化电极间距为 100 μm 。测试了在 -0.70 kV 放电电压下传感器对乙酸气体的敏感特性。该传感器对乙酸气体的响应灵敏度约为 1.05 mV/10⁻⁶, 理论检测限(三倍噪声)约为 8.6 $\times 10^{-6}$, 测试范围内传感器响应同乙酸气体体积分数近似呈线性关系。实验结果表明, ZnO 纳米颗粒修饰减小了放电尖端曲率半径, 增加了放电尖端个数, 消除了硅尖阵列之间高度和顶端曲率半径的差异, 从而有效降低了起晕电压, 提高了传感器对乙酸气体响应灵敏度及电晕放电的稳定性。

关键词: 负电晕放电; 微电子机械系统 (MEMS); 硅尖阵列; ZnO 修饰; 气体传感器

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A ZnO Modified Multi Needle to Plate Gas Sensor Based on Negative Corona Discharge

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Abstract: The gas sensor based on negative corona discharge identifies the gases according to their ionization properties by ionizing the target gas with local high voltage electric field. The silicon tips array as a negative electrode was fabricated with the MEMS technology and the electrode surface was modified with the electrosprayed ZnO nanoparticles. A multi needle to plate gas sensor based on corona discharge was designed and fabricated with the gold sputtered plate as a positive electrode. The effect of the electrode spacing on the negative corona discharge characteristics of the sensor was investigated. Considering the onset voltage, output signal and stable discharge range, the electrode spacing was optimized to 100 μm . The sensing properties of the sensor to acetic acid gas were investigated with the applied discharging voltage of -0.7 kV. The response sensitivity of the sensor to acetic acid gas is about 1.05 mV/10⁻⁶, and the theoretical detection limit based on three times the base line noise is about 8.6 $\times 10^{-6}$. The sensor response and acetic acid gas volume fraction exhibit an approximately linear relationship within the test range. The experimental results show that ZnO nanoparticle modification effectively reduces the curvature radius of the discharge tip, increases the number of discharge tip, and eliminates the differences of the height and top curvature radius of the silicon tip arrays. Then the corona onset voltage decreases effectively, and the sensitivity of the sensor to acetic acid gas and stability of corona discharge increase.

Key words: negative corona discharge; micro electromechanical system (MEMS); silicon tip array; ZnO modification; gas sensor

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基于 MEMS 技术的光泵原子磁力仪发展与应用

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摘要: 综述了光泵原子磁力仪的发展过程及技术指标, 介绍了基于 MEMS 的光泵原子磁力仪的现状, 总结了光泵原子磁力仪的主要应用。对基于 MEMS 技术的光泵原子磁力仪的发展应用前景提出了建议, 基于 MEMS 技术的光泵原子磁力仪在未来也会成为空间磁场分布测量的重要手段, 为航空、船舶、医疗诊断等领域提供重要支撑。微型化的原子磁力仪甚至有望集成到家用医疗设备或嵌入到可穿戴设备中去, 这将成为原子磁力仪进入消费电子领域的突破口, 基于 MEMS 技术的光泵原子磁力仪会成为新一代磁测量产品的标志, 成为磁测量民用市场不可替代的产品。

关键词: 原子磁力仪; 磁传感器; MEMS 集成; 灵敏度; 碱金属原子气室; 光泵浦; 拉莫尔频率

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Development and Application of Optical Pump Atomic

Magnetometers Based on MEMS Technology

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Abstract:The development process and technical indexes of optical pump atomic magnetometers are reviewed. The current status of the optical pump atomic magnetometer based on MEMS is introduced, and the main applications of the optical pump atomic magnetometer are summarized. The suggestions of the development and application prospect for the optical pump atomic magnetometer based on MEMS technology are proposed.The optical pump atomic magnetometer based on MEMS technology will become an important mean for the measurement of spatial magnetic field distribution in the future, and provides an important support for aviation, ship and medical diagnosis. The miniature atomic magnetometers are even expected to be integrated into home medical devices or embedded in wearable devices, which will become a breakthrough in the field of atomic magnetometers into the consumer electronics field.The optical pump atomic magnetometers based on MEMS technology will be a symbol of the new generation of magnetic measurement products as the magnetic measurement irreplaceable products in the civilian market.

Key words:atomic magnetometer; magnetic sensor; MEMS integration; sensitivity; alkali metal vapor cell; optical pump; Larmor frequency

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电容式加速度传感器设计及工艺加工

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摘要: 针对精确制导的应用需求, 设计了一种量程为 100g “三明治” 电容式加速度传感器, 通过 ANSYS 仿真软件在 100g 及 10 000g 高过载条件下进行应力分析和模态分析, 并通过 Matlab 分析、优化结构参数从而确定传感器敏感结构的具体尺寸。利用阻抗分析仪分析得到了传感器的静态电容为 14 09 pF, 结构输出灵敏度为 0 281 8 pF/g, 传感器的输出灵敏度为 13 5 μ V/g。根据结构特性设计工艺流程并进行关键工艺加工: 硅基质量块双面湿法腐蚀、ICP 干法刻蚀及玻璃通孔电镀工艺。最终, 通过实验验证电容式加速度传感器设计的可行性。

关键词: 电容式加速度传感器; 高过载; 湿法腐蚀; 电镀工艺; 灵敏度

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Design and Process of a Capacitive Accelerometer Sensor

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Abstract:According to the application requirements of precision guidance, a "sandwich" capacitive accelerometer sensor with the range of 100g was designed. Using the ANSYS simulation software, the stress analysis and modal analysis were carried out under high overload conditions of 100g and 10 000g.The size of the sensitive structure of the accelerometer sensor was obtained by the MATLAB analysis and optimal structure parameters.The analysis results of the impedance analyzer show that the static capacitance of the sensor is 14 09 pF, the output sensitivity of the structure is 0 281 8 pF/g,the sensitivity of the sensor is 13 5 μ V/g.According to the structural characteristics of the accelerometer sensor, the process flow was designed and the key processes were carried out,including the double sided wet etching based on silicon,ICP dry etching and glass through hole electroplating. Finally, the design feasibility of the capacitive accelerometer sensor was verified by experiments.

Key words:capacitive accelerometer sensor;high overload;wet etching;electroplating;sensitivity

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MEMS 环形振动陀螺结构与仿真分析

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摘要: 针对轴对称壳形振动陀螺的工作机理与振动特性, 提出了一种新颖的全对称 U 型梁 MEMS 环形波动陀螺, 并分析了其工作原理、振动特性与敏感工作方式。在此基础上应用 ANSYS 有限元分析软件建立了该环形振动陀螺谐振结构的有限元模型, 分别进行了模态分析、谐响应分析、瞬态冲击响应分析与静力分析。仿真分析结果显示该环形陀螺驱动与敏感模态固有频率的频差为 33 Hz, 工作模态的频率匹配性较好; 工作模态与其他振动模态的最小频差为 1 032 Hz, 能够有效抵抗环境振动的干扰; 谐振结构在 10 000g 的瞬态冲击作用下最大应力为 39.5 MPa, 可以正常稳定工作。

关键词: 微电子机械系统 (MEMS); 环形振动陀螺; 振动特性; 有限元分析; 工作模态; 模态分析

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Structure Design and Simulation Analysis of a MEMS

Ring Vibration Gyroscope

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Abstract: According to the operating mechanism and vibration characteristics of the axially symmetric thin shell vibrating gyroscope, a novel MEMS ring vibration gyroscope with holosymmetric U springs was proposed, and its operating principle, vibration characteristics and sensitive operating mode were analyzed. On the basis of this, the finite element model of the ring vibration gyroscope resonant structure was established by using ANSYS finite element analysis software. Furthermore, the modal analysis, harmonic response analysis, transient impact response analysis and static analysis were performed. The results of the simulations and analyses show that the natural frequency difference between the driving mode and sensing mode of the ring gyroscope is 33 Hz, and the frequency matching of operating modes is better. The minimum frequency difference between the operating mode and other vibration modes is 1 032 Hz, which can effectively resist the interference of environmental vibration. The maximum stress of the resonant structure is 39.5 MPa under the transient impact of 10 000g, in which case the MEMS ring vibration gyroscope can work stably.

Key words: micro electromechanical system (MEMS); ring vibration gyroscope; vibration characteristic; finite element analysis; operating mode; modal analysis

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水平固体表面温度梯度下硅油液滴运动

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摘要: 液滴的操控技术成为当今微流体技术的重要发展方向, 气-液、气-固、固-液等界面问题日益突出。首先通过实验方法, 研究了在水平固体表面液滴由温度梯度引起的热毛细迁移行为, 从理论方面分析了温度梯度、接触角滞后作用对液滴迁移速度的影响。然后通过数值模拟方法求解 N-S 方程耦合能量方程, 获得硅油液滴运动过程内部温度场和流场的变化过程。结果表明: 当基底存在温度梯度时, 液滴在基底表面会向冷端迁移, 并伴随着接触角滞后现象, 表面张力梯度作用使液滴内部产生两个涡胞, 涡胞的发展影响液滴的迁移过程, 两个涡胞发展为单个涡胞, 液滴迁移速度趋于稳定。

关键词: 微流体; 液滴水平运动; 温度梯度; 表面张力; 接触角

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A Silicone Oil Droplet Motion Under Temperature Gradient on
Horizontal Solid Surface

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Abstract:The droplet control technique has become an important development direction in microfluidics technology, gas liquid, gas solid and solid liquid interface effect problems have become increasingly prominent. Firstly, the experimental method was used to research the droplet thermocapillary migration induced by the temperature gradient in the horizontal solid surface. The influences of the temperature gradient and the contact angle hysteresis on the droplet migration velocity were analyzed theoretically. Then, the numerical simulation method was used to solve the N-S equation coupled the energy equation, the change processes of the internal temperature and flow fields during the silicone oil droplet motion process were obtained. The results show that when there is a temperature gradient in the substrate, the droplet will migrate to the cold end on the substrate surface with the contact angle hysteresis phenomenon. A surface tension gradient of a droplet creates two vortex cells inside the droplet, and the development of the vortex cells affects the migration of droplet. Two vortex cells gradually develop into a single vortex cell, and the droplet migration velocity tends to be stable.

Key words:microfluidics; droplet horizontal motion; temperature gradient; surface tension; contact angle

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阻挡层 CMP 中铜钴电偶腐蚀的影响因素

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摘要: 在 Co 化学机械抛光 (CMP) 过程中, Co 的化学反应活性强于 Cu, Co/Cu 界面存在较大的电化学腐蚀电位差。采用动电位扫描电化学技术, 表征金属铜钴表面的电化学反应。采用降低 Cu/Co 接触腐蚀电位差的方法, 表征铜钴电偶腐蚀。研究了阻挡层 CMP 中影响铜钴电偶腐蚀的几个因素: pH 值、H₂O₂ 和 FA/O 螯合剂; 并对其控制机理进行了深入的研究。实验结果表明: pH 值对钴的腐蚀电位影响较大, 对铜的腐蚀电位影响不大, 随着 pH 值的增加降低了铜和钴的腐蚀电位差; 在碱性环境下, H₂O₂ 可降低 Cu 和 Co 的腐蚀电位差 (最小可降到 3 mV), 可有效抑制 Cu 和 Co 之间电偶腐蚀现象的产生; 在 H₂O₂ 基电解液中添加适量的 FA/O 螯合剂有助于降低 Cu 和 Co 的腐蚀电位差, 对抑制 Cu 和 Co 电偶腐蚀现象的产生具有重大的作用。

关键词: 钴; 铜; 电化学; 电偶腐蚀; 化学机械抛光 (CMP); H₂O₂

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Influencing Factors of the Galvanic Corrosion Between Cu and Co in the Barrier Chemical Mechanical Polishing

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Abstract: During the Co chemical mechanical polishing (CMP) process, the chemical reactivity of Co is stronger than that of Cu, and a large electrochemical corrosion potential difference exists at the Co/Cu interface. The electrochemical reactions of the metal Cu and Co surfaces were characterized by the electrochemical potentiodynamic scanning technology. The galvanic corrosion between Cu and Co was characterized by the method for reducing Cu/Co contact corrosion potential difference. The several factors influencing the galvanic corrosion between Cu and Co in the barrier CMP were studied, such as the pH value, H₂O₂ and FA/O chelating agent, and the control mechanisms were researched. The experimental results show that the pH value has a great impact on the corrosion potential of Co, and has little impact on the corrosion potential of Cu. With the increase of pH value, the corrosion potential difference between Cu and Co decreases. In alkaline environments, the corrosion potential difference between Cu and Co decreases with the H₂O₂ (the minimum can be reduced to 3 mV), and the galvanic corrosion phenomenon between Cu and Co is effectively restrained. The corrosion potential difference between Cu and Co decreases in the H₂O₂ based electrolyte with additive of the FA/O chelating agent, and the galvanic corrosion phenomenon between Cu and Co is also effectively restrained.

Key words: Co; Cu; electrochemistry; galvanic corrosion; chemical mechanical polishing (CMP); H₂O₂

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碳化硅 ICP 刻蚀的掩膜材料

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摘要: SiC 材料由于具有非常强的化学稳定性与机械硬度, 不能用酸或碱性溶液对其进行腐蚀, 在 MEMS 制备工艺中, 通常采用干法刻蚀来制备 SiC 结构。针对干法刻蚀中遇到的问题, 比较了光刻胶、Al 和 Ni 等多种掩膜材料对 SiC 刻蚀的影响以及 SiC 与掩膜材料的选择比。实验证明, 光刻胶作为掩膜, 与 SiC 的选择比约为 1:67, 并且得到的台阶垂直度较差。Al 与 SiC 的选择比约为 7, 但是致密性差, 并且有微掩膜效应。金属 Ni 与 SiC 的选择比约为 20, 并且得到的台阶比较垂直且刻蚀形貌良好。最后, 使用 Ni 作为掩膜材料对 SiC 压阻式加速度传感器的背腔和压敏电阻进行了电感耦合等离子体 (ICP) 刻蚀。

关键词: 碳化硅 (SiC); 电感耦合等离子体 (ICP) 刻蚀; 掩膜图形化; 选择比; 刻蚀形貌

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A Mask Material for SiC ICP Etching

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Abstract: Due to very strong chemical stability and mechanical hardness, SiC materials can't be etched by acid or alkaline solution. In the MEMS fabrication process, the SiC structure is generally fabricated by dry etching method. The effects of the mask materials, including the photoresist, Al and Ni on the SiC etching and the selectivity of the SiC and mask materials were compared to solve the problems in the dry etching process. The experiment results show that with the photoresist as the mask, the selectivity between the photoresist and SiC is about 1:67, and the verticality of the step is low. The selectivity of Al and SiC is about 7, but the density is poor, and the micro mask effect exists. The selectivity of Ni and SiC is about 20, and the vertical step and good etching morphology are obtained. Finally, using Ni as the mask material, the back cavity and piezoresistor of the SiC piezoresistive accelerometer were etched by inductively coupled plasma (ICP) etching.

Key words: silicon carbide (SiC); inductively coupled plasma (ICP) etching; mask pattern; selectivity; etching morphology

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