博士学位论文

压阻式微加工碳化硅高温压力传感器关键技术研究

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学科名称：机械工程

2023 年 09 月

Research on Key Technologies of Piezoresistive Micromachined Silicon Carbide High Temperature Pressure Sensors

A dissertation submitted to

XXXXXXXXX University

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

By

XXXXX

Supervisor: XXXXXX

Mechanical Engineering

September 2023

摘　要

在航空航天、地热能源、汽车电子等领域，广泛存在高温恶劣环境下的压力测量需求，尤其是航空发动机、燃气轮机等国家重大战略发展领域。利用高温压力传感器监测燃烧室、压气机等关键部位气压，对发动机健康状态监测和燃烧效率提升有重要意义。上述高温恶劣环境工况复杂、空间狭小、失效因素多，导致高温压力传感器研制生产难度大，且国外就相关技术对我国实行长期封锁。因此，高温压力传感器自主研发和国产化迫在眉睫。作为第三代宽禁带半导体的典型代表，碳化硅（SiC）具有宽带隙、高导热性、高硬度、耐辐射和耐酸碱腐蚀等特性，具有极大的高温测试应用价值。基于全 SiC 衬底的高温压力传感器正逐步成为高温压力传感器的主要研究方向之一。综上，本文围绕全 SiC 高温压力传感器，研究了 SiC 压阻效应基础理论、传感器芯片设计、芯片制备、耐高温封装、静动态性能测试、工程化应用验证等关键技术，为高温恶劣环境压力原位测量提供理论和技术支持。论文主要研究工作如下：

（1）针对 SiC 压阻效应研究不充分，传感器芯片设计缺乏理论支撑的问题，开展 4H-SiC 压阻效应理论和实验研究。首先，采用张量分析和坐标变换法推导了六方 SiC 压阻矩阵的一般形式，研究了 4H-SiC（0001）晶面内不同晶向压阻系数；然后，基于密度泛函理论，采用量子力学第一性原理计算研究了单轴拉压应变下掺氮 4H-SiC 的电子结构响应及能带迁移规律，建立了拉压电导率变化的模型，揭示了半导体压阻效应的内在机制；随后，基于形变势理论，通过理论计算阐释了 4H-SiC（0001）晶面内不同晶向受到拉压应变后的各向同性载流子迁移率变化特征；最后，采用悬臂梁弯曲法实验验证了 4H-SiC 压阻效应的各向同性。基于以上研究结果，提出了一种 NPN 型压阻式 4H-SiC 压力传感器芯片结构，通过多参数优化设计，结合多物理场仿真，确定了 2MPa 和 5MPa 量程传感器芯片的结构和尺寸。

（2）针对金属 Ni 和 N 型 4H-SiC 欧姆接触形成及失效机理不明、芯片电极无法耐受高温的难题，开展金属和 N 型 4H-SiC 半导体接触理论和实验研究。首先，提出了金属和半导体接触界面多尺度分析方法，研究了 Ni 和 N 型 4H-SiC 界面宏观热应力和微观分子动力学扩散行为，实验测试了不同退火参数下 Ni 与 4H-SiC 的界面微观结构演化、接触电学特性、界面力学性能；其次，通过第一性原理计算了 Ni 和硅镍生成物的表面功函数及势垒高度，明确了 Ni 与 N 型 4H-SiC 欧姆接触的形成机理；最后，设计了基于矩形传输线法的欧姆接触制备工艺及力学-材料学-电学一体化表征体系，提出了能耐受 600℃高温的多层 SiC/Ni/TaN/Pt 高温欧姆接触金属体系，提升了传感器芯片的极限工作温度。

（3）针对 SiC 材料高硬度、耐腐蚀、难加工的制造难题，研究高效高质量的新型 SiC 微结构加工方法。首先，设计正交试验研究了掩蔽材料、干法刻蚀参数与 SiC 刻蚀

本文研究得到了 XXXXXXXXX 的项目资金支持。

表面粗糙度和刻蚀速率之间的关系，确定了适用于 4H-SiC 的最佳干法刻蚀工艺参数；然后，基于双温方程研究了超短脉冲飞秒激光烧蚀 4H-SiC 的材料去除机理，并通过正交试验研究了关键激光加工参数对 4H-SiC 膜片物性参数的影响规律；基于以上两种工艺研究，提出了飞秒激光辅助等离子体干法刻蚀 SiC 的复合加工方法，实现了 4H-SiC 传感器芯片敏感膜片的高表面质量且高速率加工；最后，设计了完整的芯片加工版图，制造了三种型号的 2MPa 和 5MPa 量程传感器芯片，验证了复合加工方法在 SiC 芯片微结构加工中的可行性和有效性，实现了飞秒激光加工与微纳制造工艺的融合。

（4）开展了传感器的耐高温封装、静动态性能测试和工程化应用验证。首先，提出了双层胶冗余芯片固定方案和热应力匹配封装结构，搭建了高温压力测试平台，静态测试表明 2MPa 传感器最高灵敏度为 3.78mV/V/MPa，精度为 0.24%FS，计量检定结果达 0.5 级。采用干法刻蚀膜片的 5MPa 传感器灵敏度为 1.81mV/V/MPa，精度为 0.47%FS，计量检定精度达 0.5 级。采用复合加工方法制备膜片的 5MPa 传感器灵敏度为 1.37mV/V/MPa，精度为 0.85%FS，计量等级为 1.0 级；然后，发明了面向发动机燃烧室高温恶劣工况、狭小空间压力监测的微型一体化传感器探针，其感压部直径≤8mm，小于传统水冷探针的封装尺寸（感压端直径 20mm），重量低于 1kg。使用该传感器参与 0.1 马赫数，600℃高温的航空发动机燃烧室模拟风洞试验，验证了传感器在高温恶劣工况下连续工作 5 小时的动态工程化服役性能。

通过以上研究工作，本文开发的基于 4H-SiC 压阻效应的高温压力传感器突破了传统压力监测技术瓶颈，为高温压力传感器的研制及其在重大装备和领域中的应用提供了理论依据与技术支持。

关 键 词：碳化硅（SiC）；高温压力传感器；微加工；压阻效应；欧姆接触

论文类型：应用基础研究

ABSTRACT

In aerospace, geothermal energy, automotive electronics and other fields, there is widespread demand for pressure measurement under high temperature and harsh environment, especially in major national strategic development fields such as aero-engine and gas turbine. The use of high temperature pressure sensor to monitor the pressure of key parts such as combustor and compressor is of great significance for the monitoring of engine health condition and the improvement of combustion efficiency. As a result, the development and production of high temperature pressure sensors are difficult due to the complex conditions, narrow space and many failure factors in the above high temperature and harsh environment, and foreign countries have imposed long-term blockades on related technologies. Therefore, independent research and development and localization of high-temperature pressure sensors are imminent. As a typical representative of the third generation of wide band gap semiconductors, silicon carbide (SiC) has wide band gap, high thermal conductivity, high hardness, radiation resistance and acid and alkali corrosion resistance, and has great value in high temperature testing applications. High-temperature pressure sensor based on all-sic substrate is becoming one of the main research directions of high-temperature pressure sensor. In summary, this paper focuses on the SiC high temperature and pressure sensor, the basic theory of SiC piezoresistive effect, sensor chip design, chip preparation, high temperature resistant packaging, static and dynamic performance testing, engineering application verification and other key technologies, to provide theoretical and technical support for the in-situ pressure measurement in high temperature and harsh environment. The main contents of this thesis are as follows:

1. In view of insufficient research on SiC piezoresistive effect and lack of theoretical support for sensor chip design, theoretical and experimental research of 4H-SiC piezoresistive effect were carried out. First, the general form of hexagonal SiC piezoresistive matrix is derived by tensor analysis and coordinate transformation method, and the piezoresistive coefficients of different crystal directions in 4H-SiC (0001) crystal plane are determined. Second, based on density functional theory and the first principles of quantum mechanics, the electronic structure response and energy band migration of nitrogen-doped 4H-SiC under uniaxial tension and compression strain were calculated and studied. A model of tension and compression induced conductivity change was established, and the internal mechanism of semiconductor piezoresistive effect was systematically clarified. Then, based on the deformation potential theory, through theoretical calculations, the isotropic carrier mobility change characteristics after straining in different crystal orientations in the 4H-SiC (0001) crystal plane were explained. Finally, the isotropy of piezoresistive effect of 4H-SiC was verified by cantilever bending method. Based on the above research results, a type of NPN piezoresistive 4H-SiC pressure sensor chip structure was proposed. Through multi-parameter optimization design, combined with multi-physical field simulation, the structure and size of

This work was supported by the XXXXXXX

2MPa and 5MPa range sensor chips were determined.

2. Aiming at the problems that the metal Ni and N-type 4H-SiC ohmic contact formation and failure mechanism are unknown, and the chip electrode cannot withstand high temperature, the theoretical and experimental research of the metal and N-type 4H-SiC semiconductor contact is carried out. First, a multi-scale method for metal and semiconductor contact interface was proposed. The macroscopic thermal stress and microscopic molecular dynamics diffusion behavior of Ni and N-type 4H-SiC interface were studied. The microstructure evolution, contact electrical properties and mechanical properties of Ni and 4H-SiC interface under different annealing parameters were tested experimentally. Second, the surface work functions and barrier heights of Ni and nickel silicide were calculated by first principles, and the formation mechanism of ohmic contact between Ni and N-type 4H-SiC was confirmed. Finally, an ohmic contact preparation process based on rectangular transmission line method and an integrated characterization system of mechanics, materials science and electricity were designed. A multi-layer SiC/Ni/TaN/Pt high temperature ohmic contact metal system was proposed, which could withstand 600℃, and the limit working temperature of the sensor chip was improved.

3. To solve the manufacturing problem of SiC materials, a new SiC microstructure processing method with high efficiency and high quality was studied. First, orthogonal experiments were designed to study the relationship between masking material, dry etching parameters, surface roughness and etching rate of SiC, and to determine the best dry etching parameters suitable for 4H-SiC. Second, based on the Two-Temperature-Equation, the material removal mechanism of ultra-short pulse femtosecond laser ablation of 4H-SiC was studied, and the influence of key laser processing parameters on the physical properties of 4H-SiC diaphragm was studied by orthogonal test. Based on the above two technologies, an integrated processing method of SiC dry etching by femtosecond laser assisted plasma was proposed, which realized high surface quality and high-speed machining of 4H-SiC sensor chip diaphragm. Finally, a complete chip fabrication process and layout were designed, and three types of 2MPa and 5MPa range sensor chips were fabricated. The feasibility and effectiveness of the composite processing method were verified, and the fusion of femtosecond laser machining and micro-nano manufacturing process was realized.

4. The high temperature encapsulation, static and dynamic performance test and engineering application verification of the sensor are carried out. First, a double-layer adhesive redundant chip fixing scheme and thermal stress matching packaging structure was proposed, and a high temperature pressure test platform was built. The static test showed that the maximum sensitivity of the 2MPa sensor was 3.78 mV/V/MPa, the accuracy was 0.24%FS, and the measurement verification results reached 0.5 level. The sensitivity of the 5MPa sensor using dry etching method is 1.81 mV/V/MPa, the accuracy is 0.47%FS, and the measurement and verification accuracy is up to 0.5 level. The sensitivity of the 5MPa sensor prepared by composite processing method is 1.37 mV/V/MPa, the accuracy is 0.85%FS, and the

measurement accuracy is 1.0 level. Then, an integrated sensor probe for pressure monitoring in the narrow space of engine combustion chamber was designed and manufactured. The diameter of the pressure sensing part is less than 8mm, it is smaller than the package size of the traditional water-cooled probe (the diameter of the pressure-sensing end is 20mm), and the weight is less than 1kg, which breaks through the conventional package specifications of pressure sensors. The sensor probe was used in the simulation wind tunnel test of aero-engine combustion chamber at 0.1 Mach number and 600℃, which verified the dynamic engineering service performance of the sensor under high temperature air flow for 5 hours.

Through the above research, the high temperature pressure sensor based on the piezoresistive effect of 4H-SiC developed in this thesis breaks through the bottleneck of traditional pressure monitoring technology. It provides theoretical basis and technical support for the development of high temperature pressure sensor and its application in major equipment and fields.

KEY WORDS: Silicon carbide (SiC); High temperature pressure sensor; Micromachining; Piezoresistive effect; Ohmic contact

TYPE OF DISSERTATION: Application Fundamental Research