

学校编码: 10384

分类号_____密级_____

学号: 18120051403026

UDC_____

厦 门 大 学

博 士 学 位 论 文

**4H-SiC 基紫外探测器减反射膜
的设计、制备及应用**

**Design, Fabrication and Application of 4H-SiC Based Ultraviolet
Antireflection Coatings for Photodetectors**

张 峰

指导教师姓名: 吴正云 教授

专业名称: 凝聚态物理

论文提交日期: 2008 年 9 月

论文答辩时间: 2008 年 9 月

学位授予日期:

答辩委员会主席: _____

评 阅 人: _____

2008 年 9 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果,均在文中以适当方式明确标明,并符合法律规范和《厦门大学研究生学术活动规范(试行)》。

另外,该学位论文为()课题(组)的研究成果,获得()课题(组)经费或实验室的资助,在()实验室完成。(请在以上括号内填写课题或课题组负责人或实验室名称,未有此项声明内容的,可以不作特别声明。)

声明人(签名):

年 月 日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

1. 经厦门大学保密委员会审查核定的保密学位论文，于 年 月 日解密，解密后适用上述授权。

2. 不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年 月 日

厦门大学博硕士学位论文摘要库

摘 要

碳化硅 (SiC) 材料由于具有宽禁带 (4H-SiC 为 3.26eV)、高击穿电场、高热稳定性等优点, 在紫外光电探测领域展现出了极大的潜力。各种结构的 4H-SiC 基紫外探测器 (如肖特基、金属-半导体-金属 (MSM)、p-i-n 以及雪崩探测器等) 在尾焰探测、臭氧层检测、短波通讯等方面展现出了良好的应用前景。

为了提高探测器对入射光线的吸收效果, 一般采用热氧化的方法在 4H-SiC 紫外探测器的入射表面上生长一层 SiO_2 薄膜, 作为探测器的减反射膜和钝化层, 以提高器件的量子效率和响应度。这层 SiO_2 薄膜虽然在抑制器件暗电流方面起到了良好的作用, 但是在消除光学损耗方面却具有一些不可避免的缺点, 主要是: 对紫外线的反射率较高、薄膜和界面吸收较大和厚度不能精确控制。因此, 为了消除这些缺陷, 进一步提高 4H-SiC 基紫外探测器的量子效率, 本文主要开展了 4H-SiC 基紫外探测器减反射膜的设计、制备以及应用工作, 并取得了以下重要结果:

1. 根据薄膜的透明波段、消光系数、折射率、机械性能和化学稳定性, 从几十种光学薄膜材料中挑选了 Al_2O_3 和 SiO_2 , 作为 4H-SiC 基紫外探测器的减反射膜材料。考虑到薄膜的稳定性, 设计将 SiO_2 膜置于 Al_2O_3 膜与 4H-SiC 基底之间, Al_2O_3 作为外层膜淀积在 SiO_2 薄膜之上。应用矢量法和导纳匹配技术, 对薄膜的厚度进行设计。考虑到薄膜实际制备中的误差, 模拟了折射率、厚度等变化对薄膜反射率的影响。结果发现: 厚度变化对薄膜反射率的影响最大, 但折射率、消光系数和表面粗糙度等因素的影响也不能忽视。

2. 根据减反射膜的设计, 应用电子束蒸发工艺在 4H-SiC 基底上淀积了总厚度为 138nm 的 $\text{Al}_2\text{O}_3/\text{SiO}_2$ 薄膜。通过反射率测试发现, 该薄膜在 276nm 具有 0.25% 的反射率极小值, 是目前在 4H-SiC 基底上所能得到的最小值。由于有些 4H-SiC 探测器的制备需要高温退火, 所以将制备好的 $\text{Al}_2\text{O}_3/\text{SiO}_2$ 薄膜分别在 550、950 及 1100 $^\circ\text{C}$ 的氮气中退火来检验薄膜特性。测试结果发现: 反射率极小值随退火温度的升高有蓝移的趋势, 反射率最小值有轻微的波动, 但仍然保持在 0.4% 左右。检测发现这是由于薄膜厚度降低造成的。薄膜表面的粗糙度和颗粒均会随退火温度升高而增加, 但退火后的薄膜粗糙度比退火前的小。尽管 $\text{Al}_2\text{O}_3/\text{SiO}_2$ 薄膜在退火前后始终保持在无定形状态, 但是薄膜和基底界面随退火温度的升高有互扩散现象, 并且有铝硅酸盐和低值 Si 氧化物的生成。

3. 制备了具有 $\text{Al}_2\text{O}_3/\text{SiO}_2$ 减反射膜的 4H-SiC 基 MSM 紫外探测器, 以及具有热氧

化 SiO_2 薄膜的 4H-SiC 同类型器件。测试结果表明 $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ 器件的光电流是 $\text{SiO}_2/4\text{H-SiC}$ 器件的两倍，但前者的暗电流与后者相比较大，在 10V 偏压下分别为 7.5 和 0.5pA。 $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ 器件在 20V 偏压下的响应度峰值位于在 290nm 处，达到 0.12A/W，为 $\text{SiO}_2/4\text{H-SiC}$ 器件的两倍。经计算， $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ 器件的内外量子效率峰值均在 280nm 波长，分别为 50%和 77%，是目前量子效率最高的 4H-SiC 基 MSM 探测器。经过对比发现，在 240-300nm， $\text{Al}_2\text{O}_3/\text{SiO}_2$ 薄膜的反射率与器件的响应度吻合得很好。

4. 采用氧化和电子束蒸发两种淀积工艺制备的 $\text{Al}_2\text{O}_3/\text{SiO}_2$ 减反射膜，应用到了 4H-SiC 基 p-i-n 紫外光电二极管上。经测试发现，由于 $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ 器件钝化层的侧壁钻蚀，造成该器件的暗电流比热氧化的 $\text{SiO}_2/4\text{H-SiC}$ 同类型器件大，在 10V 偏压下分别为 3.9 和 0.1pA。不过，前者的在 280nm 光照下的电流却是后者的 2.8 倍，达到 2.8nA。两种器件的响应度随反偏电压的增加均有很小的增益。在 10V 的偏压下， $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ 和 $\text{SiO}_2/4\text{H-SiC}$ 器件的响应度峰值分别位于 270 和 260nm，大小为 49 和 32mA/W，对应外量子效率分别为 23%和 15%。经过分析发现：这两种器件的量子效率低是由于 i 层没有完全耗尽造成的。两种器件的响应度峰值与反射率最小值均吻合得很好。

关键词：4H-SiC； $\text{Al}_2\text{O}_3/\text{SiO}_2$ 薄膜；光电探测器

ABSTRACT

Silicon carbide (SiC) has been performing considerable potential for ultraviolet (UV) photodetectors due to its properties such as wide band gap (3.26 eV for 4H-SiC), high break down electric field and high thermal stability. 4H-SiC based UV photodetectors such as Schottky, metal–semiconductor–metal (MSM), p-i-n and avalanche have been presenting excellent performance for UV detection application in flame detection, ozone-hole sensing, short-range communication, etc.

Generally, the most widely used antireflection coating and passivation layer for 4H-SiC based photodetectors are native SiO₂ layer grown by heating 4H-SiC atmosphere in order to improve absorption of photodetectors. Nevertheless, the SiO₂ single layer suffers from high reflection, large absorption and inaccurate film thickness. Therefore, in this dissertation, UV antireflection coatings were designed, fabricated and applied in order to reduce optical losses and improve the quantum efficiency (QE) of 4H-SiC based photodetectors. The important results were obtained as follows:

1. According to transparent range, extinction coefficient, refractive index, mechanical properties and chemical reliability, Al₂O₃ and SiO₂ films were selected in tens of optical film materials as antireflection coatings on 4H-SiC based UV photodetectors. SiO₂ film was designed between Al₂O₃ film and 4H-SiC substrate and Al₂O₃ film was deposited on SiO₂ film according to its reliability. The optical thicknesses of Al₂O₃ and SiO₂ film were designed according to the vector method and admittance matching technology. Errors of refractive index, thickness, etc were simulated to evaluate error effects on reflectance of Al₂O₃/SiO₂ films. Thickness error was the main factor. However, the effects of refractive index, extinction coefficient and surface roughness could not be ignored.

2. Al₂O₃/SiO₂ films were deposited on 4H-SiC substrates by using electron-beam evaporation according to above film design. The minimum reflectance of the films was 0.25% at 276nm, which is the minimum attained so far. The Al₂O₃/SiO₂ films were annealed in N₂ at 550, 950 and 1100 °C, respectively, to examine film performance. The minimum reflectance shifted to shorter wavelength with the increase of annealing temperature due to reduction of film thickness. The surface grains appeared to get larger in size and the root mean square

(RMS) roughness of the annealed films increased with the annealing temperature but was less than that of the as-deposited. Although the $\text{Al}_2\text{O}_3/\text{SiO}_2$ films kept amorphous, there were diffusion, Al-silicates and Si-suboxides at the interface between films and 4H-SiC substrate.

3. 4H-SiC based MSM UV photodetectors with $\text{Al}_2\text{O}_3/\text{SiO}_2$ films had been fabricated and compared with $\text{SiO}_2/4\text{H-SiC}$ MSM detectors. The photocurrent of former was twice as large as the latter, while the dark current was also larger. The $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ devices showed a peak responsivity of 0.12 A/W at 290 nm under 20 V, which was twice as much as that of MSM detectors. The internal and external QE of the $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ devices were 50% and 77% at 280 nm respectively, which are the highest attained so far for 4H-SiC based MSM photodetectors. The responsivity of the $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ devices agreed well with their surface reflectance in 240-300nm.

4. The $\text{Al}_2\text{O}_3/\text{SiO}_2$ films prepared by oxidation and electron-beam evaporation were applied on 4H-SiC based p-i-n photodiodes. The dark current of the devices was 1 pA, which was larger than that of $\text{SiO}_2/4\text{H-SiC}$ detectors due to undercut of mesa sidewall. But the photocurrent of the former was 2.8 nA, which 2.8 times as larger as that of the latter. There were slight gains in these two devices with the increase of backward bias voltage. The peak responsivities of $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ and $\text{SiO}_2/4\text{H-SiC}$ devices were 49 mA/W at 270 nm and 23 mA/W at 260 nm, respectively, corresponding to external QEs of 23% and 15%. The low external QEs were due to incomplete depletion in i layer. The peak responsivities of these two devices agreed well with their minimum surface reflectances.

Key words: 4H-SiC; $\text{Al}_2\text{O}_3/\text{SiO}_2$ films; photodetectors

目 录

第一章 绪论	1
§1.1 4H-SiC 基紫外光电探测器概述.....	1
§1.2 4H-SiC 基紫外减反射膜的研究现状.....	5
§1.3 本文工作与论文结构.....	7
参考文献.....	9
第二章 4H-SiC 材料的性质	12
§2.1 SiC 材料的基本性质.....	12
§2.1.1 SiC 材料的晶体结构.....	13
§2.1.2 SiC 材料的命名.....	14
§2.2 4H-SiC 材料的光学性质.....	15
§2.2.1 透射率和反射率.....	15
§2.2.2 折射率.....	17
§2.2.3 吸收系数.....	18
§2.3 4H-SiC 材料的电学性质.....	19
§2.3.1 本征载流子浓度.....	19
§2.3.2 迁移率与漂移速度.....	20
§2.3.3 电离率与临界击穿电场.....	22
§2.3.4 表面复合.....	23
参考文献.....	25
第三章 4H-SiC 基紫外减反射膜的设计	27
§3.1 紫外光学薄膜材料的选择.....	27
§3.1.1 透明波段.....	27
§3.1.2 消光系数.....	29
§3.1.3 折射率.....	29
§3.1.4 机械性能.....	30
§3.1.5 化学稳定性.....	32
§3.2 4H-SiC 基紫外减反射膜的设计.....	32

§3.2.1 矢量作图法.....	33
§3.2.2 导纳匹配技术.....	34
§3.3 薄膜参数误差对反射率的影响.....	37
§3.3.1 折射率误差的影响.....	37
§3.3.2 厚度误差的影响.....	38
§3.3.3 其他影响.....	40
§3.4 本章总结.....	41
参考文献.....	42
第四章 4H-SiC 基紫外减反射膜的制备与测试.....	43
§4.1 Al₂O₃/SiO₂ 薄膜的制备方法.....	43
§4.1.1 电子束蒸发.....	43
§4.1.2 磁控溅射.....	44
§4.2 Al₂O₃/SiO₂ 薄膜的制备及退火工艺.....	45
§4.2.1 制备工艺.....	45
§4.2.2 退火工艺.....	45
§4.3 Al₂O₃/SiO₂ 薄膜的测试与分析.....	46
§4.3.1 反射谱.....	46
§4.3.2 折射率与厚度.....	47
§4.3.3 表面与截面形貌.....	49
§4.3.4 X 射线衍射谱 (XRD).....	52
§4.3.5 X 射线光电子能谱 (XPS).....	53
§4.4 本章总结.....	57
参考文献.....	58
第五章 4H-SiC 基紫外减反射膜的应用之一.....	60
——具有 Al₂O₃/SiO₂ 减反射膜的 4H-SiC 基 MSM 紫外光电探测器.....	60
§5.1 MSM 紫外光电探测器的结构与工作原理.....	60
§5.2 MSM 紫外光电探测器性能参数的理论分析.....	63
§5.2.1 暗电流.....	63

§5.2.2 光电流.....	63
§5.2.3 量子效率与响应度.....	64
§5.2.4 电容和截止频率.....	65
§5.3 Al₂O₃/SiO₂/4H-SiC MSM 紫外光电探测器的制备及关键工艺研究.....	66
§5.3.1 晶片材料参数.....	66
§5.3.2 器件制备流程.....	66
§5.3.3 关键工艺探究.....	68
§5.4 Al₂O₃/SiO₂/4H-SiC MSM 紫外光电探测器的性能测试与分析.....	71
§5.4.1 测试系统简介.....	71
§5.4.2 测试原理与方法.....	73
§5.4.3 测试结果与讨论.....	74
§5.5 本章总结.....	81
参考文献.....	82
第六章 4H-SiC 基紫外减反射膜的应用之二.....	84
——具有 Al₂O₃/SiO₂ 减反射膜的 4H-SiC 基 p-i-n 紫外光电二极管.....	84
§6.1 p-i-n 紫外光电二极管的工作原理与器件结构.....	84
§6.2 p-i-n 紫外光电二极管性能参数的理论分析.....	85
§6.2.1 暗电流.....	85
§6.2.2 光电流.....	87
§6.2.3 量子效率和响应度.....	89
§6.2.4 响应速度.....	90
§6.2.5 噪声等效功率 (NEP) 和归一化探测率 D*.....	91
§6.3 Al₂O₃/SiO₂/4H-SiC p-i-n 紫外光电二极管的制备及关键工艺.....	91
§6.3.1 晶片材料参数.....	91
§6.3.2 器件制备流程.....	92
§6.3.3 关键工艺探究.....	94
§6.4 Al₂O₃/SiO₂/4H-SiC p-i-n 紫外光电二极管的性能测试与分析.....	96
§6.4.1 测试原理与方法.....	96
§6.4.2 测试结果与讨论.....	96

§6.5 本章总结.....	103
参考文献.....	104
第七章 工作总结与展望.....	107
§7.1 工作总结.....	107
§7.2 今后研究工作计划.....	109
附录 博士期间发表论文及申请专利.....	111
致谢.....	112

厦门大学博硕士论文摘要库

CONTENTS

Chapter 1 Introduction	1
§1.1 An Overview of 4H-SiC Based Ultraviolet Photodetectors	1
§1.2 Research Progress of 4H-SiC Based Ultraviolet Antireflection Coatings	5
§1.3 Organization of the Dissertation	7
References	9
Chapter 2 Properties of 4H-SiC	12
§2.1 Basic Properties of SiC	12
§2.1.1 Crystal Structures of SiC	13
§2.1.2 Nomenclatures of SiC	14
§2.2 Optical Properties of 4H-SiC	15
§2.2.1 Transmittance and Reflectance	15
§2.2.2 Refractive Index	17
§2.2.3 Absorption Coefficient	18
§2.3 Electrical Properties of 4H-SiC	19
§2.3.1 Intrinsic Carrier Concentration	19
§2.3.2 Mobility and Drift Velocity	20
§2.3.3 Ionization Rate and Critical Electric Field	22
§2.3.4 Surface Recombination	23
References	25
Chapter 3 Design of 4H-SiC Based Ultraviolet Antireflection Coatings ...	27
§3.1 Selection of Ultraviolet Optical Film Materials	27
§3.1.1 Transparent Band	27
§3.1.2 Extinction Coefficient	29
§3.1.3 Refractive Index	29
§3.1.4 Mechanical Property	30
§3.1.5 Chemical Reliability	32
§3.2 Design Methods of 4H-SiC Based Ultraviolet Antireflection Coatings	32

§3.2.1 Vector Mapping Method.....	33
§3.2.2 Admittance Matching Technology	34
§3.3 Film Parameter Error Effects on Reflectance	37
§3.3.1 Effects of Refractive Index Error	37
§3.3.2 Effects of Thickness Error.....	38
§3.3.3 Others	40
§3.4 Summary	41
References	42
Chapter 4 Fabrication and Measurement of 4H-SiC Based Ultraviolet	
Antireflection Coatings	43
§4.1 Fabrication Methods of Al₂O₃/SiO₂ films.....	43
§4.1.1 Electron-Beam Evaporation	43
§4.1.2 Magnetron Sputtering.....	44
§4.2 Fabrication and Annealing of Al₂O₃/SiO₂ films	45
§4.2.1 Fabrication.....	45
§4.2.2 Annealing	45
§4.3 Measurement and Analysis of Al₂O₃/SiO₂ films	46
§4.3.1 Reflectance.....	46
§4.3.2 Refractive Index and Thickness	47
§4.3.3 Morphologies of Surface and Interface.....	49
§4.3.4 X-ray Diffraction (XRD)	52
§4.3.5 X-ray Photoelectron Spectroscopy (XPS)	53
§4.4 Summary	57
References	58
Chapter 5 An Application of 4H-SiC Based Ultraviolet Antireflection	
Coatings: 4H-SiC Based Metal-Semiconductor-Metal Ultraviolet	
Photodetectors with Al₂O₃/SiO₂ films.....	60
§5.1 Structure and Principle of Metal-Semiconductor-Metal Ultraviolet	

Photodetectors	60
§5.2 Parameter Analysis of Metal-Semiconductor-Metal Ultraviolet Photodetectors	63
§5.2.1 Dark Current.....	63
§5.2.2 Photocurrent	63
§5.2.3 Quantum Efficiency and Responsivity.....	64
§5.2.4 Capacitance and Cutoff Frequency	65
§5.3 Device Fabrication and Key Technology Research of Al₂O₃/SiO₂/4H-SiC Metal-Semiconductor-Metal Ultraviolet Photodetectors	66
§5.3.1 Parameters of 4H-SiC Wafers	66
§5.3.2 Process of Device Fabrication.....	66
§5.3.3 Research of Key Technologies	68
§5.4 Measurement and Analysis of Al₂O₃/SiO₂/4H-SiC Metal-Semiconductor-Metal Ultraviolet Photodetectors	71
§5.4.1 Introduction of Measurement System	71
§5.4.2 Measurement Principle and Method	73
§5.4.3 Results and Discussion.....	74
§5.5 Summary	81
References	82
Chapter 6 An Application of 4H-SiC Based Ultraviolet Antireflection Coatings: 4H-SiC Based p-i-n Ultraviolet Photodiodes with Al₂O₃/SiO₂ films	84
§6.1 Structure and Principle of p-i-n Ultraviolet Photodetectors	84
§6.2 Parameter Analysis of Metal-Semiconductor-Metal Ultraviolet Photodetectors	85
§6.2.1 Dark Current.....	85
§6.2.2 Photocurrent	87
§6.2.3 Quantum Efficiency and Responsivity.....	89
§6.2.4 Responsivity Rate.....	90

§6.2.5 Noise Equivalent Power (NEP) and Specific Detectivity D^*	91
§6.3 Device Fabrication and Key Technology Research of $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ p-i-n ultraviolet photodiodes	91
§6.3.1 Parameters of 4H-SiC Wafers	91
§6.3.2 Process of Device Fabrication	92
§6.3.3 Research of Key Technologies	94
§6.4 Measurement and Analysis of $\text{Al}_2\text{O}_3/\text{SiO}_2/4\text{H-SiC}$ p-i-n ultraviolet photodiodes	96
§6.4.1 Measurement Principle and Method	96
§6.4.2 Results and Discussion	96
§6.5 Summary	103
References	104
Chapter 7 Summary and Future Work	107
§7.1 Summary	107
§7.2 Future Work	109
Appendix	111
Acknowledgements	112

Degree papers are in the "[Xiamen University Electronic Theses and Dissertations Database](#)". Full texts are available in the following ways:

1. If your library is a CALIS member libraries, please log on <http://etd.calis.edu.cn/> and submit requests online, or consult the interlibrary loan department in your library.
2. For users of non-CALIS member libraries, please mail to etd@xmu.edu.cn for delivery details.

厦门大学博硕士论文摘要库