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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

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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 Al_2O_3/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 Al_2O_3/SiO_2 薄膜分别在 550、950 及 1100℃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 Al_2O_3/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 Al_2O_3/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 Al_2O_3/SiO_2/4H-SiC 器件的光电流是 SiO_2/4H-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。Al_2O_3/SiO_2/4H-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 SiO_2/4H-SiC 器件的两倍。经计算，Al_2O_3/SiO_2/4H-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，Al_2O_3/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 Al_2O_3/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 Al_2O_3/SiO_2/4H-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 SiO_2/4H-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，Al_2O_3/SiO_2/4H-SiC 和 SiO_2/4H-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；Al_2O_3/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 SiO_2 layer grown by heating 4H-SiC atmosphere in order to improve absorption of photodetectors. Nevertheless, the SiO_2 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, Al_2O_3 and SiO_2 films were selected in tens of optical film materials as antireflection coatings on 4H-SiC based UV photodetectors. SiO_2 film was designed between Al_2O_3 film and 4H-SiC substrate and Al_2O_3 film was deposited on SiO_2 film according to its reliability. The optical thicknesses of Al_2O_3 and SiO_2 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 Al_2O_3/SiO_2 films. Thickness error was the main factor. However, the effects of refractive index, extinction coefficient and surface roughness could not be ignored.

2. Al_2O_3/SiO_2 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 Al_2O_3/SiO_2 films were annealed in N_2 at 550, 950 and 1100 ℃, 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 Al_2O_3/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 Al_2O_3/SiO_2 films had been fabricated and compared with SiO_2/4H-SiC MSM detectors. The photocurrent of former was twice as large as the latter, while the dark current was also larger. The Al_2O_3/SiO_2/4H-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 Al_2O_3/SiO_2/4H-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 Al_2O_3/SiO_2/4H-SiC devices agreed well with their surface reflectance in 240-300nm.

4. The Al_2O_3/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 SiO_2/4H-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 Al_2O_3/SiO_2/4H-SiC and SiO_2/4H-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; Al_2O_3/SiO_2 films; photodetectors

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