

# Thermal Radiation Research of Silicon Carbide with Periodic Structure

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Received: Apr. 30<sup>th</sup>, 2018; accepted: May 15<sup>th</sup>, 2018; published: May 22<sup>nd</sup>, 2018

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## Abstract

The silicon carbide with periodic structures shows good thermal radiation performance in the infrared band, and has important applications in thermal radiation source. This paper reviews the research status of one-dimensional and two-dimensional SiC thermal radiation structures and discusses the development trend based on SiC periodic structures.

## Keywords

Silicon Carbide, Thermal Radiation, Coherence

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# 周期SiC结构的热辐射研究进展

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收稿日期: 2018年4月30日; 录用日期: 2018年5月15日; 发布日期: 2018年5月22日

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## 摘要

具有周期结构排列的SiC在红外波段表现出良好的热辐射性能, 在热辐射源方面有重要的应用价值。本文综述了一维和二维SiC热辐射结构的研究现状, 并探讨了SiC周期结构在热辐射源方面的发展趋势。

## 关键词

SiC, 热辐射, 相干性

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## 1. 引言

由于电子的热运动而产生的辐射称为热辐射, 只要物体的温度高于“绝对零度”, 热能总是不断地转变为辐射能, 向外发出热辐射。理论上说, 物体热辐射的电磁波波长可以从零变化到正无穷, 在实际应用中, 把波长位于 0.38~100 mm 之间的电磁波辐射称为热辐射[1]。碳化硅(SiC)材料是自第 1 代元素半导体材料(Si)和第 2 代化合物半导体材料(GaAs, GaP, InP 等)之后发展起来的第 3 代半导体材料。SiC 材料具有带隙宽度可调、高硬度、高临界击穿电场、高热导率及化学稳定性好等特点[2] [3] [4] [5] [6]。1997 年法国学者 Greffet 在对由极性材料 SiC 制成的微光栅热辐射特性进行研究时, 发现热辐射呈现明显的干涉特征[7]。2000 年, Shchegrov 在离开表面不同的高度下对 SiC 样品的热辐射进行了实验测量, 由于倏逝波的存在, 在离表面 0.1 mm 处热辐射急剧增强[8]。Biels 等人[9] [10]考虑了基于 SiC-SiO<sub>2</sub> 多层膜的 HMM 最上层 SiC 薄膜支持的表面声子极化波的贡献。SiC 周期性结构能在窄带的红外波段范围内产生相干热辐射, 形成目前比较紧缺的红外热辐射源。因此, 基于 SiC 周期结构的热辐射特性的研究, 具有重要的理论价值和应用前景。

## 2. SiC 的热辐射

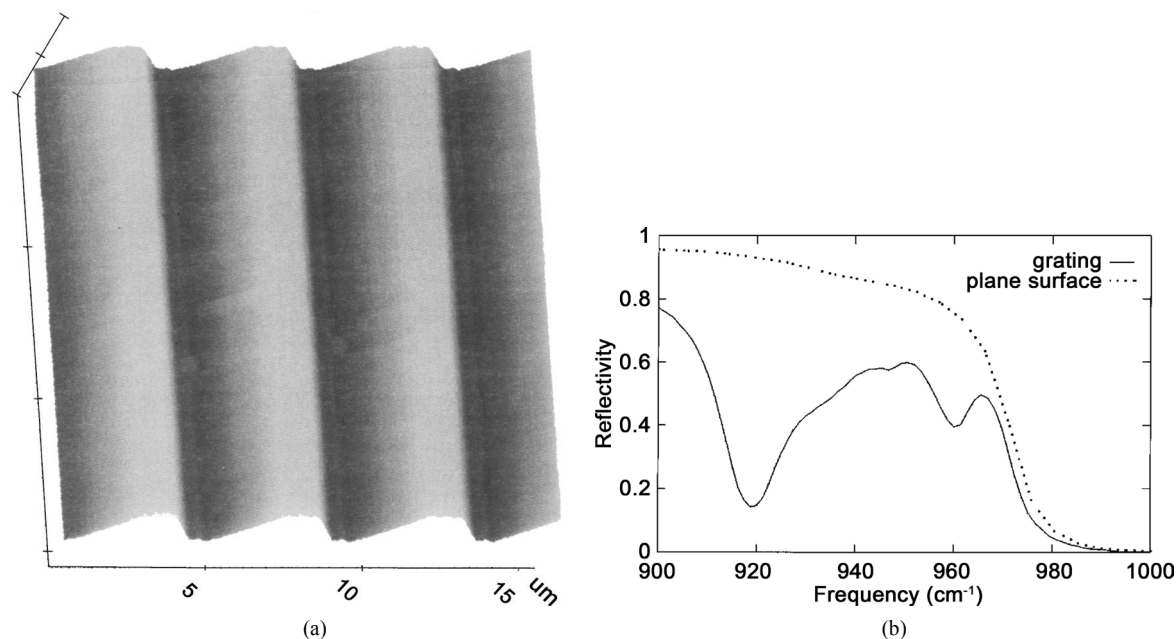
### 2.1. 一维结构的热辐射研究现状

1997 年, Gall J. L.等[7]研究了 SiC 一维光栅在偏振方向上的反射率, 通过实际测量发现, SiC 光栅结构与平面结构相比在反射率上有显著变化, 如图 1(a)和图 1(b)所示, 并得到了 SiC 光栅结构 P 偏振和 S 偏振的反射率, 实验与理论结果相差不大。

2002 年, Greffet J. J. [5]发现一维 SiC 光栅结构形成的大距离(多个波长)上相干和定向辐射的热红外源, 与平坦表面的辐射率相比, 辐射源的辐射率增加了 20 倍。研究发现, 由于表面声子极化激元的激发, 在近红外波段实现全吸收特性[11] [12], 如图 2 所示, 为后来该方面的研究奠定了基础。2004 年, Marquier F. [13]等在 Greffet J. J.基础上研究了利用 SiC 表面波的热激发来提高模型在各个方向上的发射率, 实验和仿真结果表明热辐射现象只存在于 p 偏振。随后在 2009 年, Han S. E. [14]进一步研究了倾斜角对 s 偏振和 p 偏振的热辐射的影响, 如图 3 所示, 该热辐射只存在 p 极化波的某一特定角度, 并且发现与平坦表面的相干长度相比, 线性光栅和表面极化激元之间的动量交换可以明显减小热辐射的相干长度。

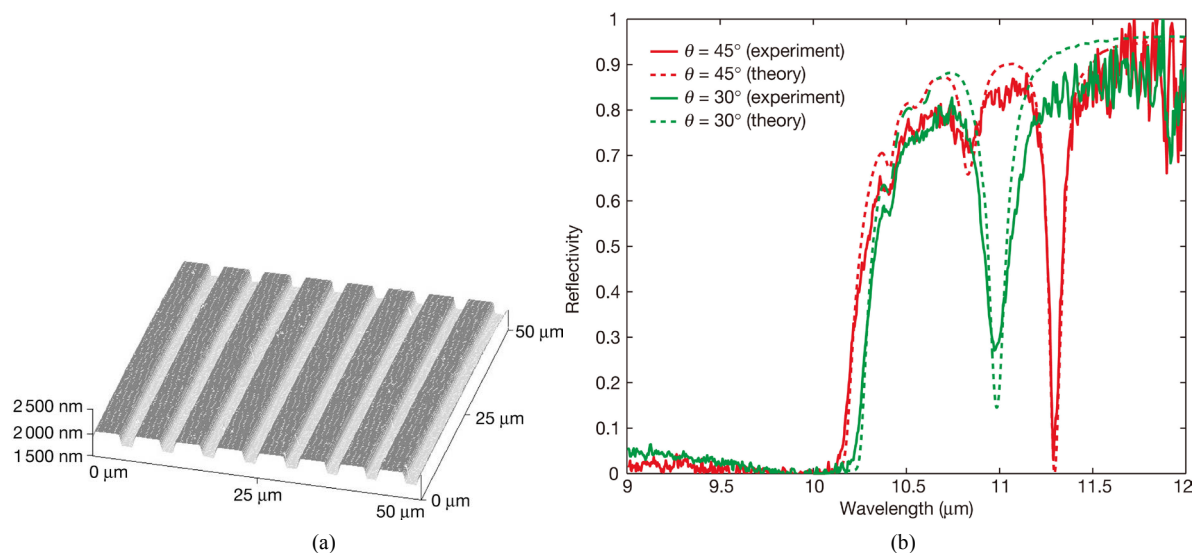
2005 年, Lee B. J.等[15]将 SiC 涂覆在一维光子晶体上表面来构建相干热源, 发现在横向电波(TE)和横向磁波(TM)的红外波段, 都表现出较强的热辐射现象, 热辐射位置随角度不断发生改变。对应的结构和热辐射随角度变化如图 4 所示, 说明 SiC 一维光子晶体热辐射具有角度敏感性。

2010 年, Jérémie Dré [16]设计出由 Ge 和 SiC 组成的双层结构(如图 5 所示), 发现当锗厚度为 700 nm, 碳化硅厚度为 200 nm 时, 该双层结构可在两个极化下同时实现窄带、不随入射角变化的热辐射现象。



**Figure 1.** (a) Surface profile of the SiC grating measured by atomic force microscopy; (b) spectral reflectivity of the grating and of the plane surface for p polarization at near normal incidence

**图 1.** (a) 原子力显微镜下 SiC 光栅的表面形状; (b) 垂直入射下平面表面和光栅表面 p 极化的反射率对比

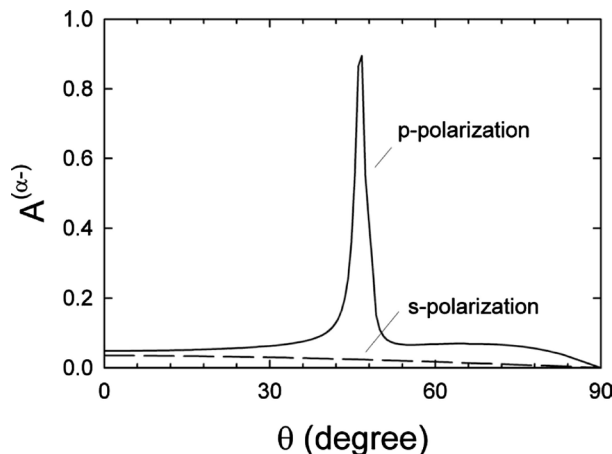


**Figure 2.** (a) Structure diagram of SiC grating; (b) comparison of theoretical and experimental absorption at 30° and 45° incident angles

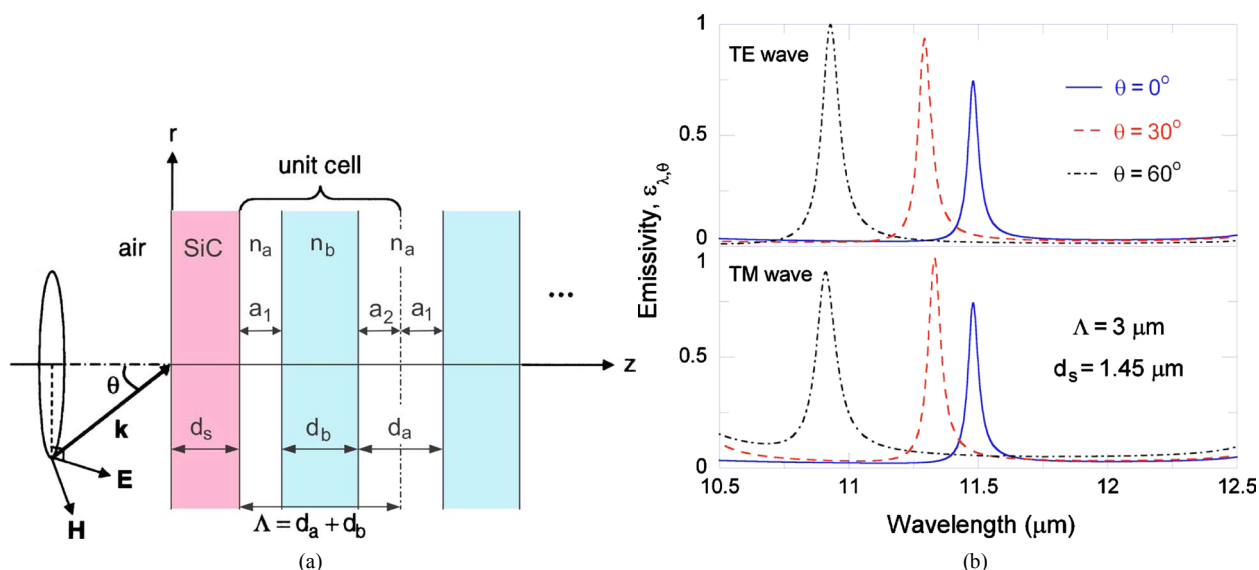
**图 2.** (a) SiC 光栅结构示意图; (b) 该结构在 30° 和 45° 入射角下理论与实验的吸收比较

2015 年, Giuseppe D'Aguzzo [17] 研究了嵌入在 ZnSe 主体介质中由 SiC 制成的亚波长颗粒周期性多层阵列的热发射特性, 如图 6 所示。由于单个粒子的固有声子极化激元共振与由不同粒子阵列热发射场之间的独特相互作用, 在 10.6~11  $\mu\text{m}$  之间产生多波峰的可干热辐射现象。

2015 年, Wang W. J. [18] 等提出了由碳化硅光栅和一维光子晶体结构构建的热辐射结构。如图 7 所示, 通过调整结构的几何参数可以有效地实现热发射/吸收的光谱和方向控制。若仅在模型顶部或底部加单层 SiC 薄膜, 将会在同一频率段出现单个吸收峰; 若在顶部和底部均加 SiC 薄膜形成三明治结构, 则

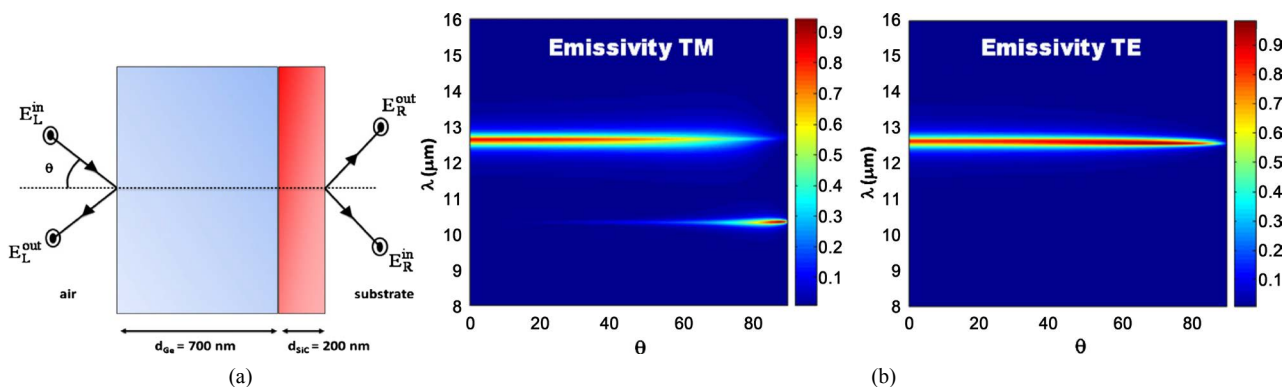


**Figure 3.** Angular dependence of the absorptance of a SiC linear grating for s and p polarizations  
**图 3.** 倾斜角对 p 偏振和 s 偏振吸收的影响



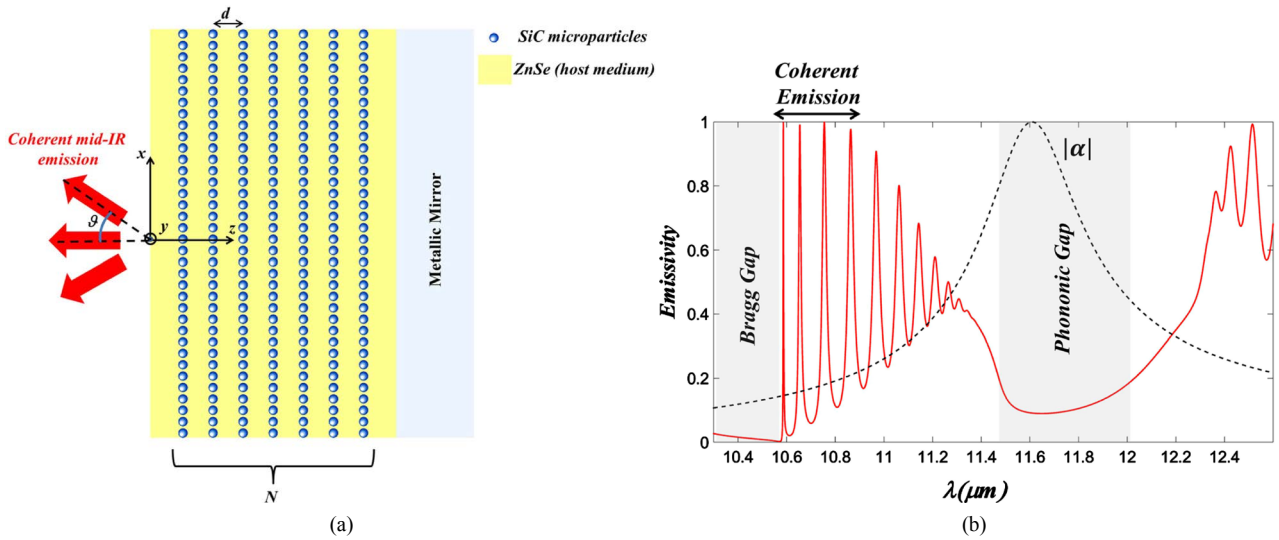
**Figure 4.** (a) a layer of SiC structure coated on the ZnSe and KBr one-dimensional periodic structures; (b) the emissivity of the TE wave and the TM wave at different angles

**图 4.** (a) 在 ZnSe 和 KBr 一维周期结构上涂覆一层 SiC 的结构示意图; (b) 该结构 TE 波和 TM 波在不同角度下的辐射率

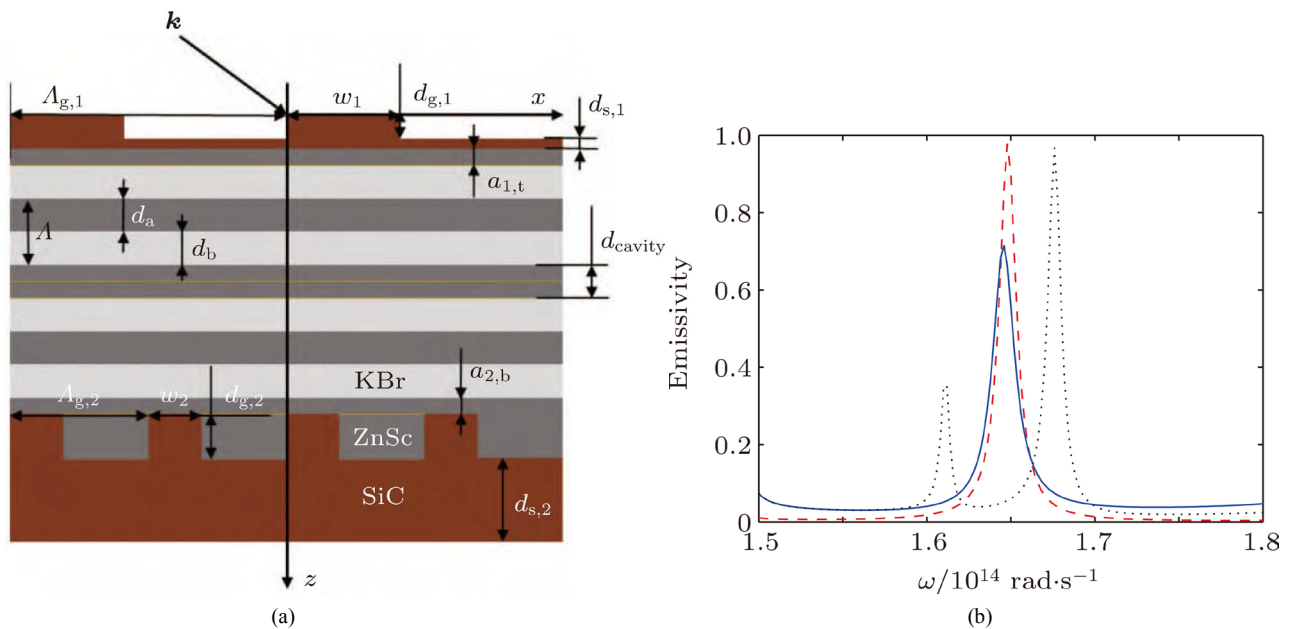


**Figure 5.** (a) two-layer structure of one dimension; (b) emissivity spectrum of TE and TM wave

**图 5.** (a) 一维双层结构; (b) TE、TM 光谱图



**Figure 6.** (a) Finite multilayer structure made of  $N$  layers of SiC microparticles separated by a distance of  $d$  and embedded in a ZnSe background medium; (b) comparison of spectral emissivity at different layers wavelengths  
**图 6.** (a) 嵌入在 ZnSe 主介质中间距为  $d$  的碳化硅亚波长粒子的周期性多层阵列; (b) 此结构在不同层数的波长下光谱发射功率对比



**Figure 7.** (a) Schematic representation of the geometry considered; (b) spectral-normal emissivity with a SiC film of thickness  $d = 1.25 \mu\text{m}$  on the top (solid), a SiC film of thickness  $d = 7 \mu\text{m}$  at the bottom (dash), and two SiC films on both sides simultaneously (dot)  
**图 7.** (a) 结构示意图; (b) 实线为模型顶部加厚度  $d$  为 1.25 微米的 SiC 薄膜的辐射率, 虚线为模型底部加厚度  $d$  为 7 微米的 SiC 薄膜的辐射率, 点线为顶部和底部都加上 SiC 薄膜的辐射率

会出现双峰吸收, 从而理论上验证了双峰存在的可能性。

2016 年, Chalabi H.等[19]提出在 SiC 表面构造一定的纳米结构可以把预先选定的光谱范围的热辐射聚焦到离表面一个明确的高度上, 非周期对称模式的结构如图 8 所示。

2012 年和 2013 年, Biehs S. A.等[9]考虑了基于 SiC-SiO<sub>2</sub> 多层膜的热辐射现象, Guo Y.等[20]提出具

有双曲线色散的超一维结构可形成宽带热辐射现象。Biehs S. A.等[9]考虑了基于 SiC-SiO<sub>2</sub> 多层膜的 HMM 最上层 SiC 薄膜支持的表面声子极化波的贡献(如图 9 所示), 并分析了布洛赫模式和表面声子极化子对近场热传输的贡献。

2014 年, Ito K. [21] 等通过谐振光栅和 SiC 板之间的消逝波的耦合方案来获得强烈的光谱和角度辐射。如图 10 所示, 指出当光栅波导模式的横向波束与 SiC 板的表面声子极化的横向波束一致时, 入射光通过消逝波的耦合被 SiC 平板吸收。

### 2.2. 二维结构的热辐射研究现状

2008 年, Dahan N.等[22]提出了 SiC 谐振腔耦合结构的热辐射相干控制, 如图 11 所示, 介绍了基于 SiC 的各向异性结构的相干热辐射, 由于耦合谐振腔表面声子极化激元的激励使得相干性得到增强。实验证明通过利用周期性耦合的谐振腔, 可以在激发源不可用的光谱频带中设计出非常高的相干热源, 而且不受离域表面波强加的相干性的限制。

2012 年, Arnold C.等[23]实验证实了二维 SiC 光栅的相干红外热辐射。其结构和对应的相关曲线如图 12 所示, 由于二维 SiC 光栅表面上的表面声子极化激元的热激发, 可在 p 偏振和 s 偏振同时获得高的热辐射。研究发现只要满足相位和极化匹配条件, 二维光栅的表面波与传播波之间的耦合是有效的。大波矢的表面波的热激发以及它们与二维光栅的耦合能够获得发射率接近于 1 的高度各向同性的热源[24]。

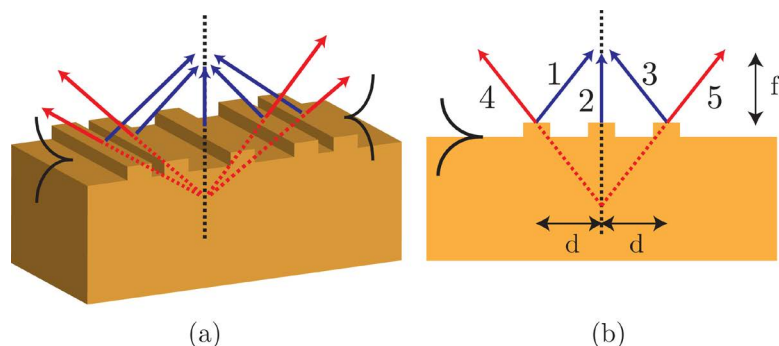


Figure 8. Schematic representation of the geometry considered  
图 8. 几何结构示意图

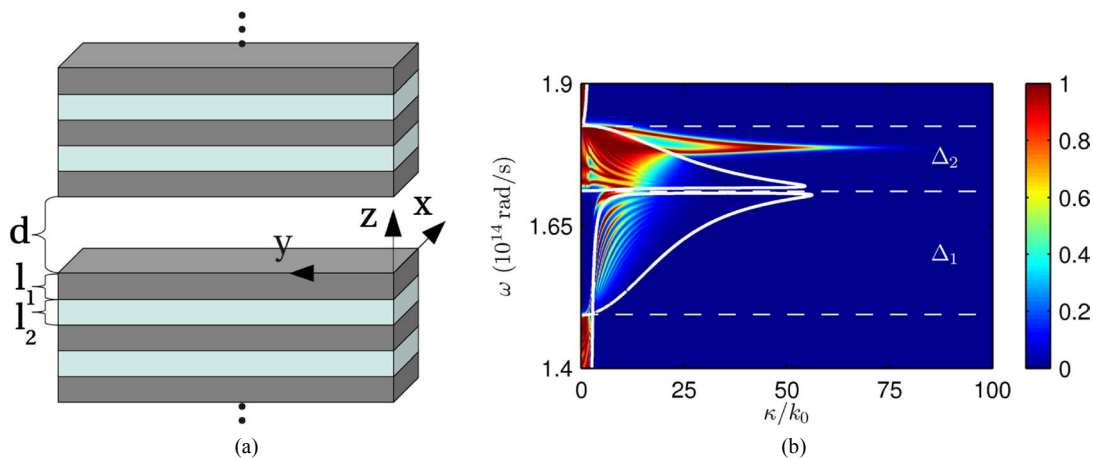
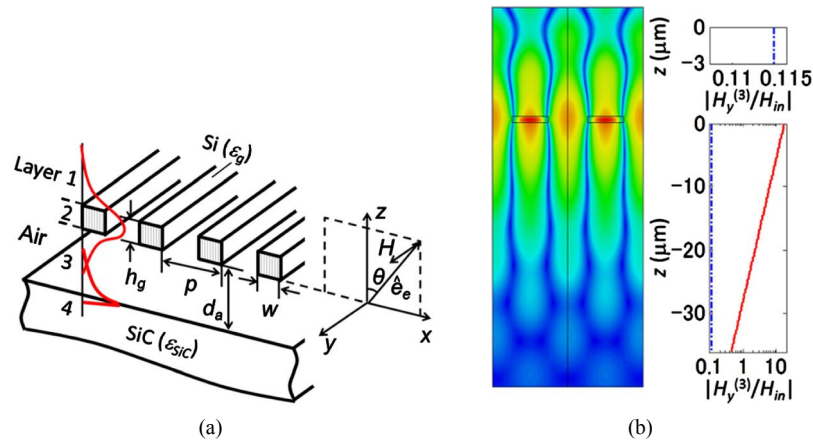
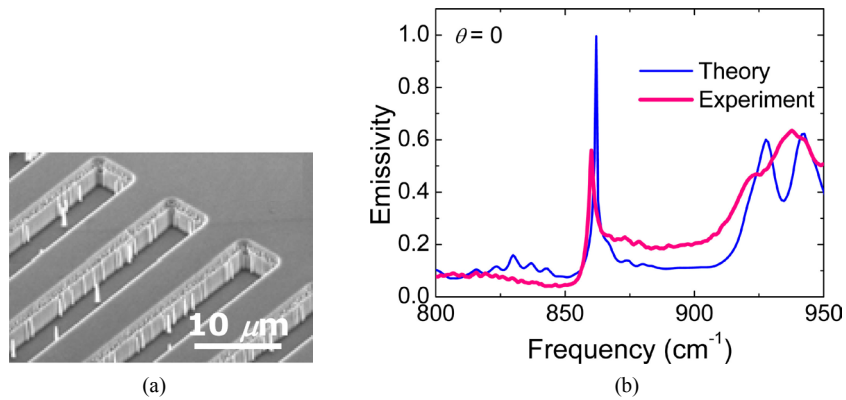


Figure 9. (a) Sketch of the geometry of two SiC-SiO<sub>2</sub> multilayer structures separated by a separation distance  $d$ ; (b) distribution of transmission coefficient between SiC-SiO<sub>2</sub> multilayer structures at  $d = 100$  nm

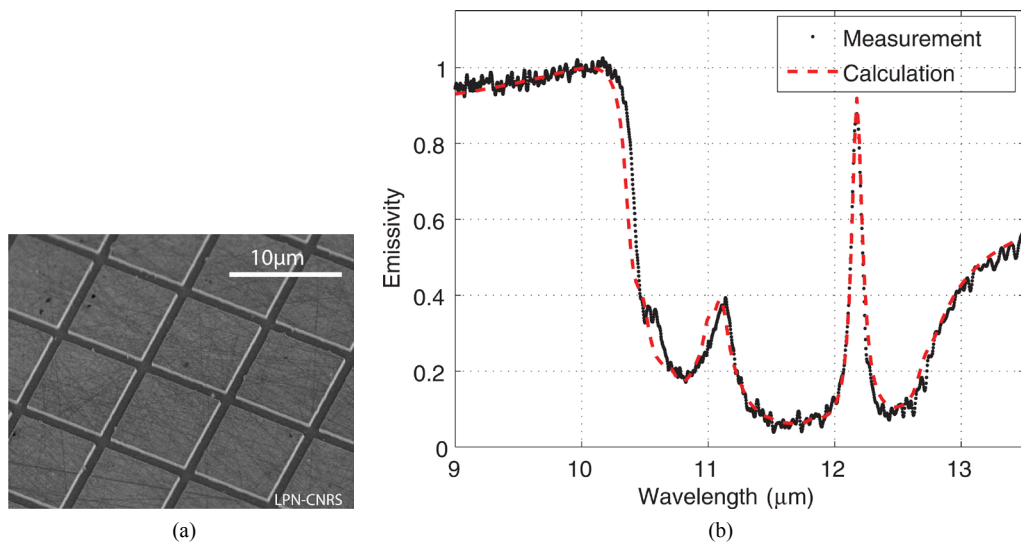
图 9. 相距为  $d$  的两 SiC-SiO<sub>2</sub> 多层膜结构的(a)结构示意图和(b)能量传输系数的模式分布,  $d = 100$  nm



**Figure 10.** (a) Resonance grating and SiC plate structure; (b) absorption spectrum  
**图 10.** (a) 谐振光栅和 SiC 板结构; (b) 吸收光谱图



**Figure 11.** (a) SEM image of CRC structure upon SiC; (b) calculated and experimental directional emissivity at the peak frequency  
**图 11.** (a) SiC 结构的 SEM 图; (b) 理论和实验得到的在峰值频率处的定向发射率

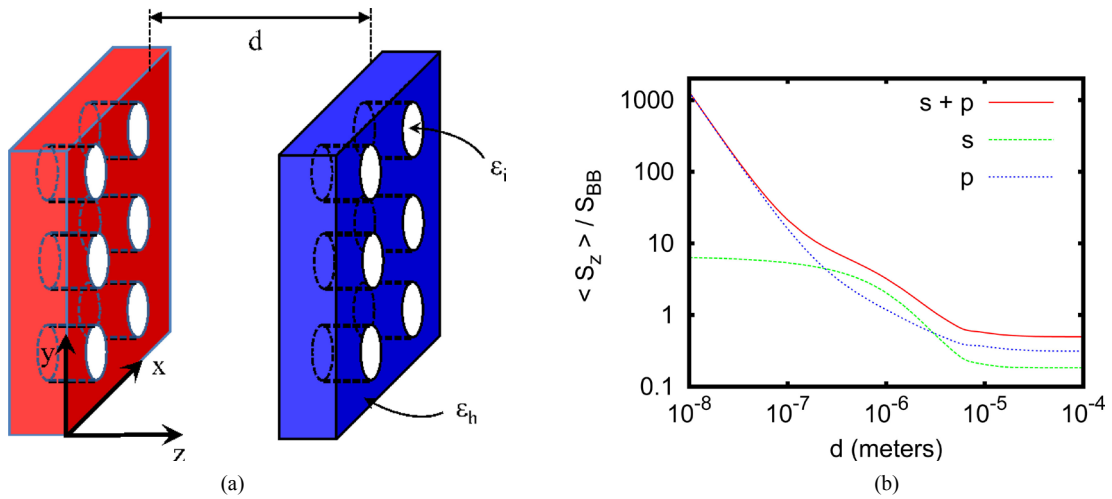


**Figure 12.** (a) SEM image of CRC structure upon SiC; (b) measurement (dots) and calculation (dashed line) of the emissivity spectrum in the direction normal to the surface  
**图 12.** (a) SiC 结构的 SEM 图; (b) 该二维结构在垂直于表面的方向上实验和理论计算发射率谱

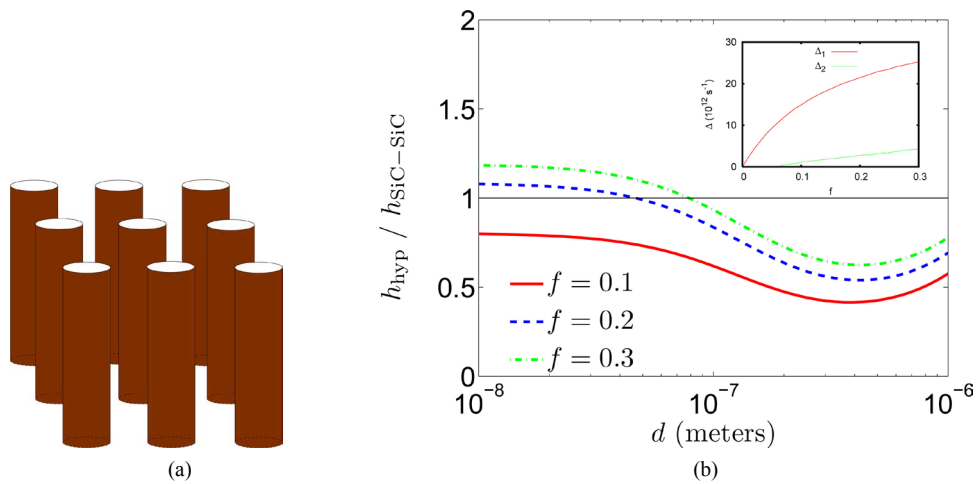
2011年, Biels S. A. [25]等人通过利用有效介质理论表征二维孔状阵列结构的等效介电函数, 并给出了具有孔状阵列两 SiC 介质平板之间的近场热传输增强特性, 其系统结构如图 13 所示。由图可见, 在间距为 10 nm 时, 两个 SiC 体的热通量是两个黑体热通量的大约 1000 倍, 这是因为内部全反射受挫以及表面声子极化子的耦合, 大于  $\lambda$  的距离后, 热通量由基尔霍夫-普朗克定律决定, 并受黑体值的限制。对于小于 100 nm 或大于 10  $\mu\text{m}$  的间距, 热通量由 p 偏振决定, 而距离在两者之间的由 s 偏振来决定。

2012年, Biels S. A. [26]等人运用有效介质理论描述了基于 SiC 纳米线阵列的近场热传输特性, 如图 14 所示。研究表明, 材料中双曲模式的贡献使得近场热传输得到增强, 在特定的 SiC 材料的填充因子下, 近场传热系数要高于体块的 SiC 材料, 从而说明在 SiC 内添加其他材料能有效改变传热系数。

2016年, Christopher R. [27]构造了一个二维 SiC 柱状结构, 如图 15 所示。作者研究了其表面等离子激元和本征模特性, 分析了观察到的局部和表面声子极化激元之间明显的光谱, 证明它们之间可能存在相干的可逆能量交换。

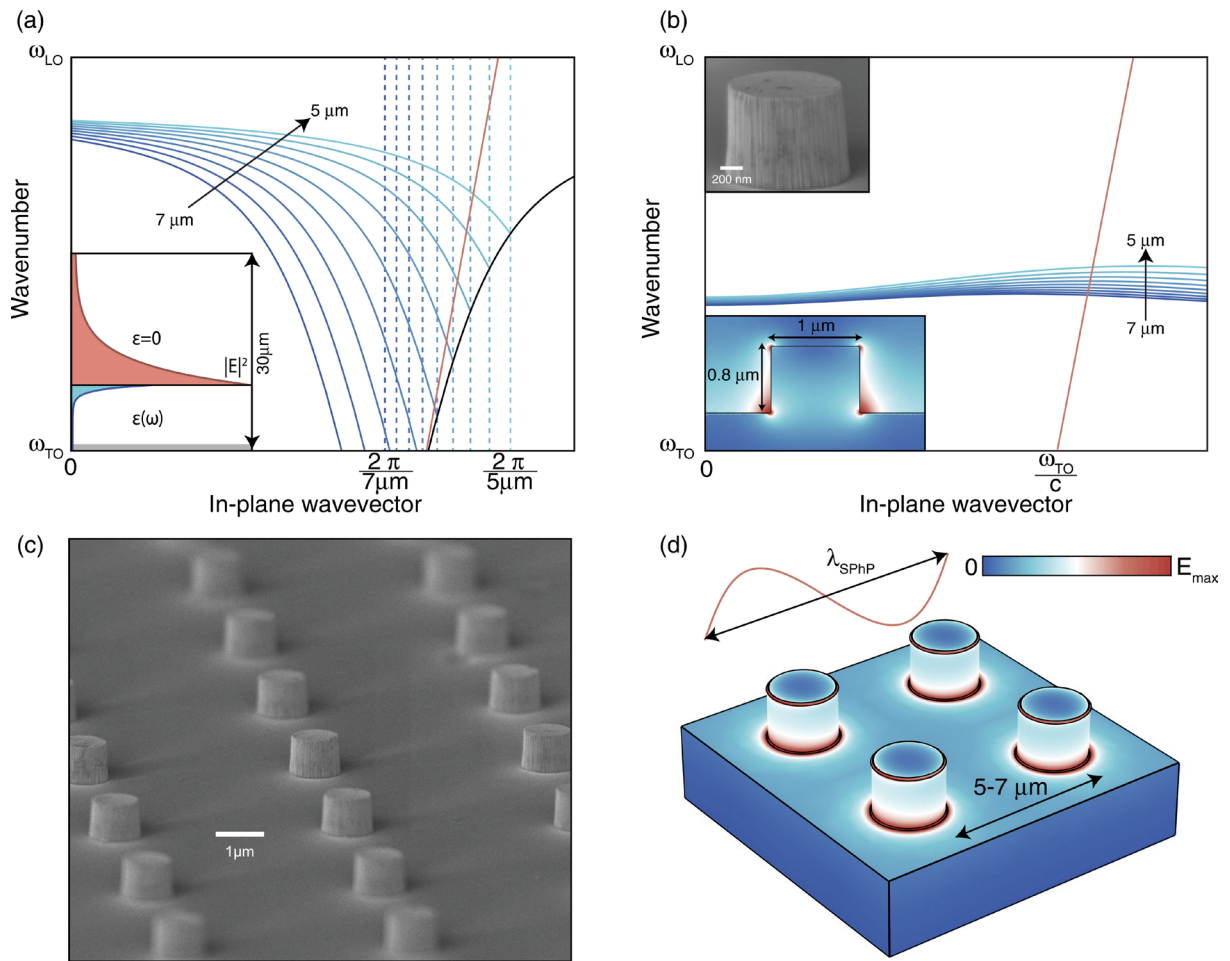


**Figure 13.** (a) Sketch of two porous SiC slabs with different temperatures separated by a vacuum gap, (b) heat flux between two porous SiC slabs over distance normalized black bodies  
**图 13.** 具有孔状阵列的两 SiC 介质平板(a)结构示意图和(b)黑体辐射归一化的热传输通量随间距的变化



**Figure 14.** (a) Sketch of a hyperbolic material consisting of a periodical array of nanowires; (b) heat transfer coefficient varies with separation distance d for two hyperbolic materials normalized to the value for two bulk SiC media  
**图 14.** 基于纳米线阵列的 HMM 的(a)结构示意图和(b)采用体块 SiC 材料情况归一化传热系数随间距 d 的变化





**Figure 15.** Schematic diagram and emissivity spectrum  
**图 15.** 结构和光谱示意图

### 3. 总结与展望

热辐射源于局部热平衡中物体自发发射的完全不相关进程，一些热源可以在近场中表现出较高的空间相干性。这些空间相干性可以用来设计在相同波长上与激光器相当的具有角度发散的高定向源，也可以用来显著增强或抑制热辐射。现代热辐射器可以获得不同于传统热源广谱发射的窄带热发射[28]-[40]。

利用周期结构控制热辐射是近年的研究热点，且碳化硅(SiC)材料是自第 1 代元素半导体材料(Si)和第 2 代化合物半导体材料(GaAs, GaP, InP 等)之后发展起来的第 3 代半导体材料。SiC 材料具有带隙宽度可调、高硬度、高临界击穿电场、高热导率及化学稳定性好等特点。SiC 薄膜的热辐射又具有很好的干涉特征，并且 SiC 在修改材料表面辐射特性，近场辐射强化换热以及红外光电器件的开发等方面获得较好应用[41]-[49]。

综上所述，由于 SiC 周期性结构能在窄带范围内产生相干热辐射现象，从而引起了人们的广泛关注，并从实验均证实了一维和二维结构的热辐射现象。

目前为满足需求，设计多边带和定向角度热辐射是未来发展的两个主要发展方向。设计多边带 SiC 热辐射结构，在一种极化方式下可以出现多个辐射峰值，能够满足多波源热辐射源需求；设计定向辐射的 SiC 热辐射结构，使其仅在某个角度有一个热辐射峰，而在其他角度不存在辐射峰，能够确保得到的热辐射源能量集中，辐射功率更高。

SiC 一维和二维除了在光子晶体结构上有差异外, 其热辐射也表现出了不同的吸收特性, 随着 SiC 热辐射研究深入和 3D 打印技术的不断成熟, 对于 SiC 三维周期结构的理论和实验的研究也将成为可能。

## 基金项目

国家自然科学基金(No 61107030), 毫米波国家重点实验室(No. K201703)和中央高校基本科研业务费专项资金项目。

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