

面向航天领域极端环境应用的金刚石材料及其器件

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摘 要: 随着世界主要国家航天工程从近地轨道向深空环境推进, 航天器要实现在极端环境下可靠工作面临许多新问题。从太空辐照环境恶化到可持续能源问题掣肘, 从高集成、高热流器件散热困难到航天器健康监测传感器向高灵敏方向发展, 上述问题都亟需发展新一代航天器技术。金刚石独特的晶体结构使其具有“硬、高、透、宽、快”5 大特性, 决定了其在极端环境下表现出耐高温、耐高压、抗辐照等性能。本文主要总结了金刚石在深空探测、便携电源、智能热控、量子传感和光学窗口等航天领域的应用现状, 并展望了发展前景。

关键词: 金刚石; 航天领域; 极端环境; 深空探测; 量子传感

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金刚石被称作“终极半导体”和电子材料的“珠穆朗玛峰”, 被工业界寄予厚望^[1-3]。从基本的晶体结构来看, 金刚石具有典型的面心立方结构, 属于 $Fd\bar{3}m$ (227 号) 空间群, 其晶格常数为 0.356 nm。每个金刚石晶胞是由 2 个原胞构成, 含有 8 个碳原子。碳原子之间成 sp^3 键, 键长为 0.154 nm, 键角为 $109^\circ28'$ 。金刚石的堆积率约为 0.34, 同时具有较大的原子密度, 是原子排列最紧密的物质^[2, 4]。从能带理论出发, 金刚石的价带顶和导带底具有不同的 k 值, 是一种间接带隙半导体, 间接带隙约为 5.45 eV^[4]。得益于其独特的结构, 金刚石具有优异的力、热、光、电等物理性质, 具体可以总结为“硬、高、透、宽、快”5 大特性。“硬”指其表现为自然界硬度最大的材料 (1.0×10^4 kg/mm²); “高”是指高热导率 (室温下为 2 200 W/(m·K)); “透”是指在较宽的波段具有高的透过率 (从 0.23 μm 到微波波段除了在 3~5 μm 范围内有本征吸收峰以外完全透明); “宽”是指具有半导体最宽的禁带宽度 (带隙为 5.5 eV), “快”是指电子与空穴迁移速率快

(电子与空穴迁移率最高分别是 $4\,500\text{ cm}^2/(\text{V}\cdot\text{s})$ 和 $3\,800\text{ cm}^2/(\text{V}\cdot\text{s})$)^[4-8]。

与线缺陷和面缺陷一样, 点缺陷是金刚石晶体中普遍存在的一种晶体学特征, 包括空位、间隙原子和替代原子。具有光学特征的点缺陷被称作色心, 金刚石中的空位和间隙碳原子都是色心。如图 1 所示, 金刚石中色心根据掺杂原子种类的不同常分为 NV 色心、SiV 色心、NE8 色心、GeV 色心等, 且以前两者更为常见^[9-11]。N 原子的共价半径接近 C 原子的共价半径, 因此容易与金刚石中的 C 原子发生取代反应, 随后取代 N 原子再与周围空位结合形成色心。NV 色心具有中性 NV^0 及负电 NV^- 2 种电荷状态; SiV 色心同样存在形成 SiV^0 及 SiV^- 2 种电荷状态^[12-13]。NV⁻、NV⁰、SiV⁰、SiV⁻ 从基态跃迁到激发态吸收的能量分别是 1.9、2.2、1.6、1.3 eV^[13]。

基于上述特性, 面向航天极端环境条件, 金刚石在航天器深空探测、便携电源、智能热控、量子传感和光学窗口等领域具有较大应用前景, 故本文对上述 5 个方面的应用研究进展进行总结。

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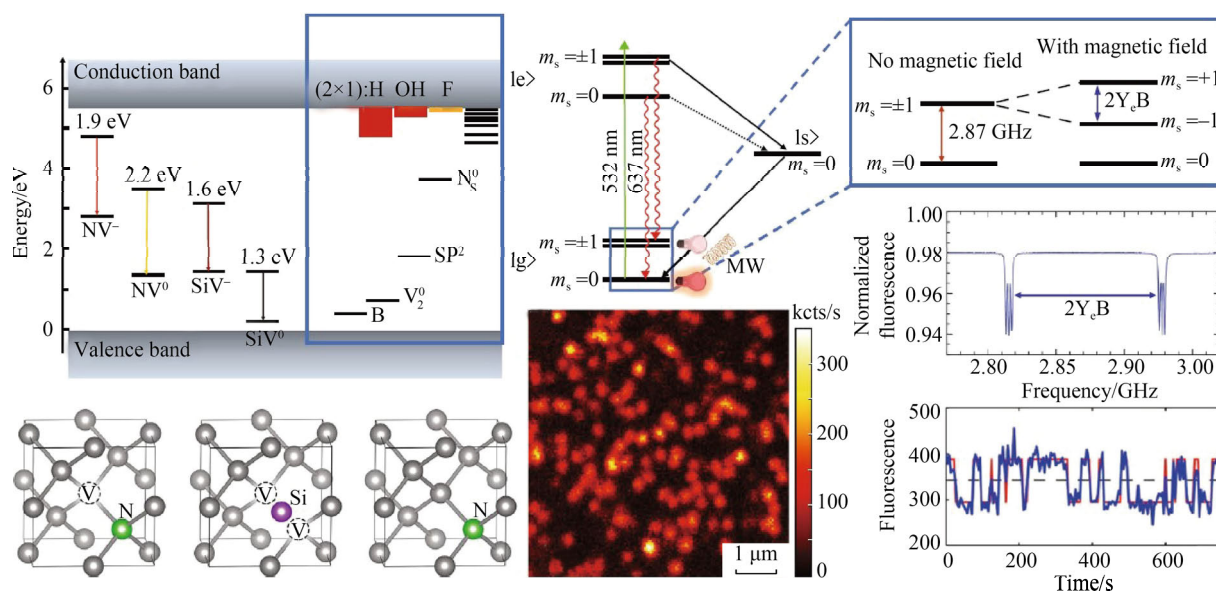
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1 深空探测

脉冲星导航是以自身辐射电磁波作为导航信息来源, 不同于卫星导航方式。脉冲星 2 个磁极各有一个辐射波束, 一般在 X 射线等多个波段辐射电磁信号, 而 X 射线频段辐射信号强度大, 易被小型探测器接收到, 故选用脉冲星辐射的 X 射线波段电磁信号进行导航式——脉冲星导航是目前最具有发展潜力的导航方式, 它可以解决以人造地球卫星为基础的高精度无线电导航的定位系统在深空探测中对地球依赖性大的问题, 因此深入研究适用于深空探测及星际间飞行的脉冲星导航系统具有重要的战略意义与应用前景^[14]。另一方面, 空间环境中的紫外

线波长为 1~400 nm^[15], 虽然其辐照能量在整个太阳辐照中所占比例很小, 但在行星大气观测、太阳观测、行星紫外散射等辐射特征探测上具有优势^[16]。

除了太阳辐射外, 空间中的宇宙射线辐射环境还包括银河宇宙射线和太阳质子事件^[17]。银河宇宙射线主要包括质子和少量的 He 粒子、重粒子; 而太阳质子事件主要由质子和 α 粒子组成^[17]。宇宙射线辐射可能会导致航天器主要元器件失效, 因此从维持航天器可靠工作的角度, 探测深空环境中航天器周围的粒子辐照环境具有重要的应用需求。苛刻的深空环境要求探测器具有较高的辐照硬度, 辐照硬度与探测器用半导体材料的结合能与声子速度具有相关关系^[18-19]。



cts is counts. Fluorescence value is counts per 4.4 s.

图 1 金刚石色心的能级结构^[13]

Fig. 1 Energy level of color center in diamond^[13]

金刚石探测器可以探测质子、电子、中子等高能粒子束流, 并且在极端环境中具有良好的稳定性^[20-22], 且其性能主要与材料结晶质量、表面改性、器件结构和外部偏压有关^[23-24]。目前的金刚石探测器中根据材料来源分为天然金刚石^[25]、高温高压金刚石^[26]、同质外延金刚石^[27]、异质外延金刚石^[28-29]、多晶金刚石^[30-33]等。根据器件结构, 金刚石探测器还可分为金属-半导体-金属结构(包含共面电极^[34]和异面电极结构^[18])、P-i-N 结构^[35]、三维结构^[36-38]、堆叠结构^[39]、薄膜结构^[20, 40]、阵列结构^[30]等。根据所探测的电磁信号, 金刚石探测器也可分为光电探测器(以紫外探测器为代表)和粒子探测器等。

Liu 等^[33]制备了接近 2 英寸大小的大面积多晶金刚石探测器, 电学性能显示其具有快速响应和

高灵敏度, 优于同尺度的 Si-PIN 型探测器。Zhang 等^[30]制备了 2 英寸多晶金刚石探测器阵列, 在 228 nm 处响应度为 45 mA/W, 截止波长为 240 nm, 响应时间约为 20 μ s。Liu 等^[34]构建了基于金属-高温高压金刚石 Schottky 结的高透过率、强抗辐照损伤的金刚石位置灵敏探测器, 在 220 nm 波段、0.624 μ W 光强的紫外光照下响应度为 13.37 mA/W, 可实现束流位置变化时对紫外光的快速响应。为提高紫外金刚石探测器响应度, Zhang 等^[41]设计了厚度不对称的叉指电极结构, 并观察到了由于光调控势垒而出现的整流特性。与非光调控的探测器件结构相比, 光调控探测器在 220 nm 处、100 V 偏压下表现出更优异的探测能力, 其响应度和可探测度均提高了 128%。

Berdermann 等^[28]基于 Ir/YSZ/Si(001)衬底上生长的异质外延金刚石样品,制备了粒子探测器,然后在 α 粒子、 β 粒子、质子等一系列粒子辐照环境下,研究了探测器的电学性能,发现基于异质外延金刚石的粒子探测器在性能上与基于同质外延单晶金刚石的探测器性能相近,且优于基于多晶金刚石探测器的性能。Liu 等^[42–43]基于金属-金刚石-金属探测器结构,研制了面向带电粒子探测的 α 粒子单晶金刚石探测器,暗电流密度为 $9.2 (\text{pA}\cdot\text{mm}^{-2})/(\text{V}\cdot\mu\text{m}^{-1})$ 。在 10 keV 和 40 keV 的 X 射线管电压下,单晶探测器的信噪比分别达到约 2 000 和 7 000,明显高于同等条件下多晶探测器的信噪比(分别达到约 550 和 2 000),这再次表明单晶材料相比多晶材料具有更优的电学性能。

近年来,随着异质外延单晶金刚石尺寸已经扩大到 1.0~3.5 英寸^[44–46],因此未来应该开展更多大面阵金刚石探测器相关的研究。

2 便携电源

深空环境由于远离太阳辐照且航天器飞行时间漫长,基于太阳能转化为电能的能源获取方式将面临重大挑战,如何长时间有效地获取能源并供给航天器直接影响其能否长时间、可靠工作,而放射线同位素提供了一种崭新的实现方案。同位素电池^[47]主要是一种将放射性同位素在衰变过程中的能量转化为电能的装置,其优点是在无外部动力源的条件下可自行发电。

同位素电池根据工作原理主要分为热电效应同位素电池(包含静态型和动态型)、辐射伏特效应同位素电池和其他新型机制同位素电池(包含新型复合式,新型压电式,特殊换能方式)^[48]。热电效应同位素电池是基于热电效应将同位素衰变过程中释放的热量转换为电能。辐射伏特效应同位素电池主要是利用半导体换能结在同位素衰变过程中释放的高能粒子射线辐照下的光伏效应产生输出电流。同位素电池的性能参数包括能量转换效率、开路电压、短路电流、填充因子等。通常,开路电压越大、短路电流越大、填充因子越大,能量转换效率越高^[47, 49]。换能结作为同位素电池的核心部件,很长一段时间是基于第一代半导体 Si 材料制备的,目前以金刚石、SiC、GaN 和 AlGaAs 等宽禁带半导体制备的器件不断涌现^[47, 49]。

金刚石的平均电离能为 12.4 eV,禁带宽度为 5.5 eV,电子-空穴对产生效率为 44.2%,明显优于

Si、SiC 和 GaN 等材料^[47]。目前金刚石同位素电池的研究从结构上分为 3 类,分别是 Schottky 结器件、其它 N 型半导体/P 型金刚石异质结器件、金刚石 PN 结器件。Schottky 结换能器件研究最早可以追溯到 2006 年 Trucchi 等^[50]的论文报道,但该团队制作的器件短路电流只有 0.15 nA、开路电压只有 4.8 V,能量转换效率小于 0.4%。为了提升电池性能,研究者近年来又开展了系列研究。Liu 等^[51]在金刚石衬底上沉积了约 10 nm 厚的 ZnO 薄膜充当电子传输层后又沉积了金属电极,最终获得了开路电压高达 1.43 V 的 Schottky 同位素电池器件。该器件 ZnO 层与金刚石之间高度差为 355 nm,功函数差为 240 mV。

由于金刚石 N 型掺杂的难题尚未克服,基于金刚石 PN 结换能结器件的研究停留在初级阶段。Liu 等^[52]从理论上预测了该类型器件的电池性能,发现开路电压为 4.8 V,但转换效率高达 26.8%的金刚石同位素电池器件。

为了绕过金刚石 N 型掺杂效率较低无法满足应用需求的问题,搭建其他 N 型半导体-P 型金刚石异质结结构引起了研究者的关注。现已开发出 ZnO^[53]、AlN^[54]、Ga₂O₃^[55]和 WO₃^[56]等 N 型掺杂半导体材料,但器件性能大都不及预期。2020 年,Kim 等^[55]制备了金刚石/ β -Ga₂O₃ 异质结器件,获得了高达 5 V 的开路电压和一千万的整流比。

3 智能热控

星载有源相控阵天线具有性能优异、器件集成度高等特点,但在狭小的空间内密集布置了大量的发射/接收(T/R)组件将会导致局部高热流密度,因此很难实现有效散热。T/R 组件作为有源相控阵天线的重要组成部分,是促进相控阵波束电子扫描的关键部件,一般采用低温共烧陶瓷内部结构,高度集成了多种高性能、高增益芯片。卫星相控阵天线中微米级芯片内的热流密度可达 $50 \text{ W}/\text{cm}^2$,远超一般热管传热极限,但芯片底部陶瓷材料的热导率仅约为 $2 \text{ W}/(\text{m}\cdot\text{K})$,明显无法满足散热要求。同时,紧凑的排布结构使得传统的热控方式难以适应特殊天线结构要求,而 90%的天线热量集中在相对较小的天线正面区域为热控增加了难度。综上分析,卫星有源相控阵天线的散热问题已成为阻碍其工程应用的短板和瓶颈^[57–59]。

金刚石具有热导率高、对空间环境适应性强等优点,在散热问题的解决上潜力巨大。Lu 等^[7]采用直流等离子体喷射法制备的多晶金刚石作为热沉材

料,在天线 T/R 组件铝合金框架中嵌入了 48 片高热金刚石片,可将天线 T/R 组件遥测温度范围控制在 6.2~17.2 °C, T/R 组件的最大温度梯度为 2.2 °C;当天线在全传输模式下工作 20 min 后,天线 T/R 组件仅升温 2.3 °C。

除了基于促进热传导增强散热的金刚石热沉器件以外,本文发现近年来基于近场热辐射原理提高热控器件内部热流进而实现智能热控的研究引起了研究者的注意^[60-63],故予以阐述。所谓近场热辐射是指当发射端(热端)与接收端(冷端)之间的距离小于发射端温度下黑体辐射波长时所发生的辐射热流超过黑体极限的一种现象。热流调控结果与间隙、材料性质有关,甚至可以通过施加电场来实现控制^[61, 64-65]。电场调控热流和发射率,通常是基于金属-氧化物-半导体结^[60-61, 65]和 P 型半导体-N 型半导体结^[64],通过电场改变半导体结或表面附近的载流子分布^[64, 66],进而调控材料的电学性质而导致发射率改变。Papadakis 等^[61]发现了一种通过施加偏压调控器件中载流子累积与耗尽过程的热开关机制。Thomas 等^[67]报道了一种采用石墨烯场效应异质结构门开关对热辐射调控的器件,发现当真空间隙距离为 1~3 μm 时,热流调控幅度为(24±7) mW/(m²·V),为采用二维半导体材料实现近场热辐射调节奠定了基础。Shi 等^[68]设计了石墨烯/SU8 5 层异质结构,利用石墨烯的 Fermi 能级随外电场的可调性,在期望的中远红外波段内构造多重表面等离激元耦合,使得 2 个 5 层异质结构在间距 55 nm 处,产生巨大的近场热辐射能量,突破黑体辐射极限约 1 129 倍,将现有的国际最佳水平提升约 1 个数量级。后来^[65],又制备了 2 个相同的石墨烯/SU8/SiO₂ 异质结构,利用 2 个背栅调压装置,分别调控辐射体和接收体端石墨烯的 Fermi 能级高度,使得两物体在模式匹配与模式失配的 2 个状态下切换,最终在两热源间距约 80 nm 的条件下,实现近场辐射换热的调制深度高达 32.2%,远高于已报道的石墨烯基调控(约 2%)。该调制深度也是目前已知的两体系统中实验观测到的最大的调制深度。Xu 等^[64, 66]提出了可利用电压调控近场辐射热流的新型光电子元件:“光子 p-n 结”以及基于 MIS 结的智能热控皮肤。图 2 为基于 MIS 结的“热控皮肤”示意图。由图 2 可见,该结构包括 6 层复合结构,通过调控 MIS 结之间的电压,半导体中的载流子会重新分布进而影响真空层的近场热辐射热流,最终会导致整个器件的发射率发生变化(有效发射率调节范围 0.2~0.8)。随着金刚石场效应

晶体管和二极管器件的发展^[69-71],基于金刚石的近场热辐射器件在未来可能会在该领域大有可为。

4 量子传感

航天器在太空环境中工作除了面对太阳辐照和宇宙射线外,还面临着空间碎片、高低温交变环境等多方面的威胁,这些因素都可能导致航天器结构失效、给航天飞行带来较大隐患,故对航天器温度、压力/应变、加速度等参数进行实时监测提出了迫切需求^[72-73]。传统的传感器往往是基于光纤传感技术,利用外界条件(比如温度,压力/应变,加速度,电磁场)对光纤中光波传输特性的影响,将光波信号的变化解调后推演测量出外界条件的变化^[74],但该技术总是面临安装困难等问题,不利于未来航天器质轻、灵活的发展趋势。除了光纤传感器外,基于压电效应、压阻效应测量压力/应变^[75-76]、基于热敏电阻效应测量温度^[77]、基于内光电效应测量电磁波^[78-79]等其他类型传感器层出不穷。

金刚石 NV 色心不仅能以极高的分辨率对电磁场、压力/应变、温度等多种物理量在室温大气乃至极端环境下进行精密测量,还可建立多体量子纠缠、用于研究量子信息等基础问题,在前沿基础科学、高科技产业等领域有重大应用价值^[80]。金刚石量子传感^[81-84]的基本原理则是利用 NV 自旋能级对电磁场^[85-86]、应变^[87-89]、温度^[90-92]等物理信号敏感的特性,通过测量外场下 NV 变化所导致的输出荧光信号强度变化的情况来实现。温度、压力/应变、电磁场等参量对自旋能级以及电子顺磁共振谱频率的影响,可以通过 NV 色心的自旋哈密顿量来解释^[93],如式(1):

$$\frac{\mathcal{H}}{\hbar} = D \left(S_z^2 - \frac{2}{3} \right) + \gamma \mathbf{B} \cdot \mathbf{S} + \epsilon_z \mathbf{E}_z \left(S_z^2 - \frac{2}{3} \right) + \epsilon_{xy} \{ \mathbf{E}_x (S_x S_y + S_y S_x) + \mathbf{E}_y (S_x^2 + S_y^2) \} \quad (1)$$

式中: D 是零场分裂频率, 2.87 GHz(见图 1); $\mathbf{B}$ 为矢量磁场; $\mathbf{E}$ 为电场矢量; ϵ_{xy} 和 ϵ_z 为沿着 xy 平面与沿着 z 坐标轴的耦合常数; $\mathcal{H}$ 为哈密顿量; $\hbar$ 为十年与哈密顿特性函数同量纲的一比例函数; $\mathbf{S}$ 为曲面矢量; ϵ 为耦合常数; S 为有效面积; x 、 y 、 z 为沿着 x 、 y 、 z 3 个坐标轴方向,由式(1)可知, NV 色心的主轴沿着 z 轴或者是(111)晶面轴。磁场可以从与 Zeeman 分裂项相关的 ODMR 光谱的共振结果中获得,但这种方法只适用于磁场强度较高的情况,因为只有强磁场才能导致共振峰分裂。为了

能够实现色心对弱磁场的测量,开发了基于脉冲序列的测试方法,因为磁场影响布洛赫球体中自旋的进动,可以通过分析来自某些脉冲序列的信号来获得磁场。与磁场类似,NV色心对电场同样很敏感,因为电场也会改变ODMR光谱。为了提高电场感应灵敏度,可以应用某些协议来精确定局电场和/或外部电场^[85–86]。温度变化可导致ODMR谱图零场分裂常数显著变化,一般表现为:在室温附近随温度线性变化,在降温过程中随温度非线性变化,

但是在极低温度下随温度几乎没有变化^[91]。应力主要改变色心的频率及分布,通过比较施加应力前后ODMR谱的变化可以计算出应力的方向及大小。表1为Schirhagl等^[93]总结的面对不同物理场时量子传感耦合系数及灵敏度的理论或实验结果,可以发现量子传感的灵敏度较高。同时,图3为用于磁场探测的金刚石量子传感器与其他类型传感器的灵敏度比较,可以发现金刚石量子传感器的灵敏度还是比较高的。

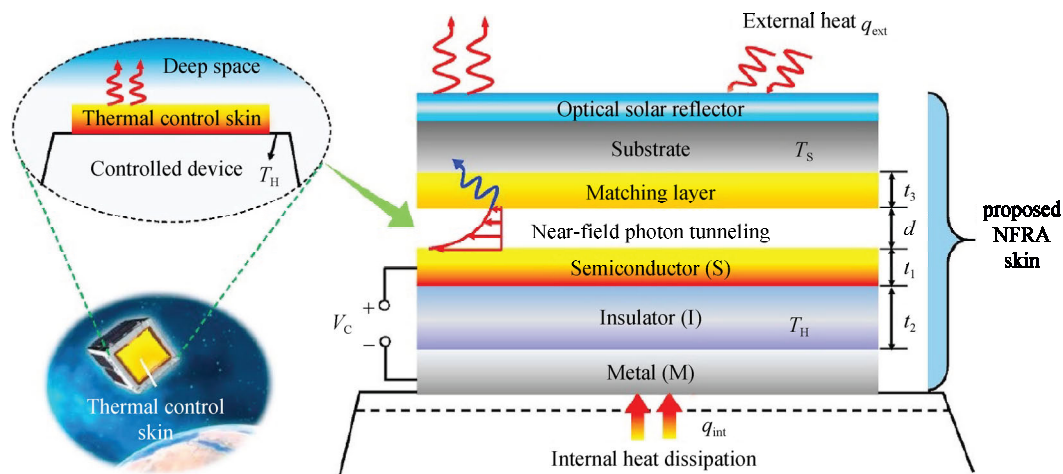


图2 基于近场热辐射原理制备的MIS器件结构^[66]

Fig. 2 Near-field radiation device made of MIS structure^[66]

NV色心的制备有2种方法:一是先通过高能粒子辐射含氮金刚石产生空位,再在800℃的高真空环境中退火使得空位迁移到N原子附近,实现单色心的制备^[83];二是离子注入方法,但由于离子尺寸较大,得到的N空位色心通常只会停留在金刚石亚表面而不是注入到晶格内部^[94]。色心制备完成后,提高量子传感的性能还可以通过以下方式优化^[95]:色心定向排布和光学镀膜技术。实现色心的定向排列可以降低无效的荧光背景,提高矢量场探测时的信噪比与灵敏度;高压条件下退火或者控制生长取向^[96]可以实现这一目的。光学镀膜技术可以提高荧光收集效率而提高灵敏度。Wang等^[97]以N浓度约为 $2 \times 10^{-3}\%$ 的透明淡黄色CVD金刚石为研究对象,研究了电子辐照剂量与N₂保护气氛中退火时间对N_s⁰原子转化为NV色心速率和NV浓度的影响,实现了浓度最高为 $3.69 \times 10^{-4}\%$ 、转化率最大为18.45%的色心制备。Wang等^[80]发展了一种基于自对准策略的光子学器件加工技术,实现了高性能金刚石纳米柱传感阵列的制造。通过金刚石晶体取向进一步控制荧光发射偶极方向,最终实现单个NV色心饱和和光子计数率达到~4.34 Mcps、荧光强度提升大约

20倍的结果。为了进一步提高传感器灵敏度,Wang等^[98]另辟蹊径,以2.9 GHz微波磁场探测为例,引入稍强的辅助微波与待测微波干涉,使得微波磁场探测灵敏度提升了近 10^5 倍、达到 $8.9 \text{ pT}/\sqrt{\text{Hz}}$ 。

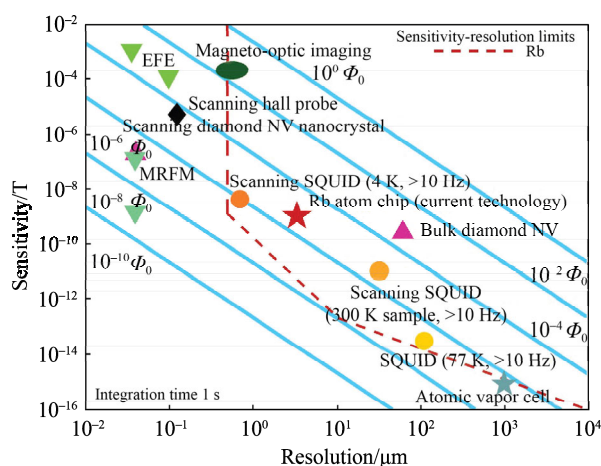


图3 用于磁场探测的金刚石量子传感器性能与其他类型传感器对比结果^[99]

Fig. 3 Field sensitivity and spatial resolution for different magnetometers^[99]

表 1 NV 色心探测不同的物理场时的理论或实验结果^[93]
Table 1 Performances of diamond quantum sensors when detecting different physical fields

Physical field	Coupling coefficient	Sensitivity
Magnetic field	28 GHz/T	0.01 $\mu\text{T}/\sqrt{\text{Hz}}$
Electric field	0.17 Hz/(V·m ⁻¹)	5.8 kV·cm ⁻¹ / $\sqrt{\text{Hz}}$
Stress	$\sim 10^{11}$ Hz/($\delta l \cdot l^{-1}$)	$\sim 10^{-7}$ / $\sqrt{\text{Hz}}$
Pressure	1.5 kHz/bar	6.8 bar/ $\sqrt{\text{Hz}}$
Temperature	74 kHz/K	0.13 K/ $\sqrt{\text{Hz}}$

5 光学窗口

光学窗口作为航天器光电系统的重要组成部分，一般用于隔绝外界空间环境与充当光学成像结构组件 2 方面的作用^[100]。1978 年，先驱号飞船采用天然金刚石研制了红外光学窗口，这是首次将金刚石用于光学窗口^[101]。除此之外，航天器的光学敏感器也是光学窗口应用的主要场合。空间光学敏感器是指在空间环境中基于光学探测原理获取航天器姿态或导航信息的敏感器，包括星敏感器、太阳敏感器等^[102]。空间光学敏感器被誉为航天器的“眼睛”，为深空探测、遥感测绘等空间任务提供定位信息^[102]。星敏感器是一种以恒星为参考源的姿态测量设备，主要由遮光罩、光电成像系统及驱动模块、信号处理模块等结构组成^[103]。

以中国探月工程为例，紫外月球敏感器光电系

统研制需要解决 3 大问题^[104]：1) 光学材料选材；2) 像质；3) 重量。2007 年，嫦娥一号主要采用光学玻璃和光学晶体的配组代替蓝宝石，设计水平达到了中国国内先进水平。例如，可以将冕牌玻璃和火石玻璃搭配使用(可用 CaF₂ 或镧冕玻璃(LaK)和重火石玻璃(ZF)匹配^[105])。

金刚石在深紫外波段不仅具有较高的透过率、能很好地满足敏感器光学系统窗口的应用要求，还具有很强的抗辐照特性、在极端空间环境中具有良好的稳定性^[106]。随着大尺寸曲面金刚石制备技术的发展，金刚石在未来可能会是一个优异的光学替代材料。

6 总结与展望

本文面向航天极端环境应用，提出了金刚石材料在深空探测——探测器、便携电源——同位素电池、航天器热控——热传导及近场热辐射器件、航天器健康监测——量子传感器、光学窗口——星敏感器窗口等 5 个方面的应用研究现状，如表 2 所示。详细内容总结如下：

1) 针对空间辐射环境复杂苛刻的问题，金刚石探测器研究主要集中在通过优化探测器结构及材料结晶质量，发展高灵敏、快响应、高信噪比、大尺寸金刚石探测器及其阵列上。

表 2 金刚石材料及器件应用研究现状总结

Table 2 Summary for research application status of diamond materials and its devices

Field	Device	Property demand	Development stage
Deep-space exploration	Ultraviolet/X-ray/particle detectors	Excellent electrical properties	Device fabrication
Portable power supply	Isotope battery	Excellent electrical properties	Device fabrication
Thermal management	High thermal conductive materials/ Near-field thermal radiation device	Excellent electrical and thermal properties	Application verification/device fabrication
Quantum sensing	Quantum sensor	Color center property	Device fabrication
Optical window	Optical sensor	Excellent optical properties	Theoretical research

2) 针对深空探测航天器远离可持续太阳辐照面临能源短缺问题，金刚石同位素电池研究主要集中于 Schottky 结器件、其它 N 型半导体/P 型金刚石异质结器件、金刚石 PN 结器件等 3 种结构同位素电池的性能研究上。金刚石 PN 结换能结器件研究尚处于理论预测阶段，其它 N 型半导体/P 型金刚石异质结器件具有优于 Schottky 器件的性能。

3) 针对航天器主要元件高密度集成导致热流密度大及空间冷黑环境/太阳辐照交替导致冷热环境温度温差大等热控问题，金刚石不仅凭借超高的热导率在卫星天线 TR 组件散热上已经应用验证，同时

凭借其较高的载流子迁移率在基于 PN 结或者 MIS 结的近场热辐射器件研制领域具有应用潜力。

4) 针对航天器光电系统光学窗口既耐空间极端环境还能保持自身光学性能的需求，金刚石光学窗口可用于制备卫星红外窗口、星敏感器紫外窗口等，是一种性能优异的替代材料。

5) 针对航天器面对多源目标时亟需健康监测技术这一问题，金刚石量子传感技术在应对温度、压力/应变、电磁场等外部条件时具有灵敏度大、分辨率高等显著优势，是未来航天器传感器技术的发展方向。

为了更好地发挥金刚石在航天极端领域的应用优势,至少还需要在以下几个方面继续努力:

1) 2 英寸大面阵多晶金刚石阵列被报道具有良好的紫外探测性能,但基于大面积异质外延单晶金刚石的成功合成意味着具有更优异电学性能的金金刚石探测器将成为可能,因此要继续在更大尺寸金刚石晶圆合成及其探测器研制上加大力度。

2) 无论是金刚石同位素电池还是近场热辐射器件,都是基于构建金刚石半导体异质结来实现的,但有效的金刚石 N 型掺杂技术尚未得到突破,因此需要继续开展基于新原理的金刚石有效掺杂技术。

3) 金刚石量子传感技术具有多参数传感的优点,但在面对多源目标时如何将不同场信号激励下的输出信号予以区分、减少干扰则需要深入研究。

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Diamond Materials and Devices for Extreme Environment Applications in Aerospace

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Extended Abstract

As the world major national space projects advance from near-Earth orbit to the deep space, spacecraft have some challenges to operate reliably in extreme environments. It is thus necessary for the development of spacecraft to solve the problems (*i.e.*, From the deterioration of the space irradiated environment to the constraints of energy problems far from the sun, from the difficulties of high heat flow and heat dissipation of highly integrated devices to the development trend of highly sensitive sensors for spacecraft health monitoring). Diamond has five characteristics like "hard, high, transparent, wide and fast" due to its unique crystal structure, determining its high temperature resistance, high frequency resistance, high pressure resistance and irradiation resistance in extreme environments.

Deep space exploration plays a role in space environment sensing and pulsar-based navigation by detecting X-ray, ultraviolet and particles from solar radiation. Diamond detectors are fabricated based on photovoltaic effect and/or interaction between particle and diamond. Electrode structure, device structure, and diamond quality have an impact on the detector performance. The detector arrays with large area and excellent performance with the heteroepitaxial diamond size of 1.0–3.5 inches are developed. In addition, a portable power supply based on isotope batteries is also an effective option to solve the problem of insufficient solar radiation during deep space exploration. A radio-voltaic effect isotope battery mainly utilizes the photovoltaic effect generated by the high-energy particle radiation released during isotope decay inside the semiconductor energy transfer junction to generate output current. Compared with other wide-bandgap semiconductors including SiC, GaN, AlGaAs and diamond, diamond has a higher electron-hole pair generation efficiency of 44.2%. The existing transducer junction structure focuses on metal/diamond Schottky junction and diamond/other semiconductors P–N junction, on account of the lack of efficient N-doping. A open circuit voltage of 5 V and a rectification ratio of 10^7 are obtained for diamond/ β -Ga₂O₃ hetero-junction battery while a theoretical value of energy conversion efficiency of 26.8% is predicted for diamond P–N junction. As the thermal environment inside and outside the spacecraft changes, thermal management and control are crucial for the spacecraft *in-orbit* work. Diamond as a semiconductor with a high thermal conductivity can enhance the heat conduction as a heat spread or heat radiation as a near-field thermal radiation device. Space active phased array antenna typically features a high performance and a high heat flux due to the high device integration of transmit/receive (T/R) module. The T/R module generates a significant amount of heat in a very small space, leading to a challenge for the thermal management and dissipation from the "hotspot" of devices. When diamond is applied in four launched satellites, the temperature gradients of the T/R modules less than 2.2 °C is recorded from the flight data, further verifying the rationality and effectiveness of using high-thermal-conductivity diamonds in the thermal design and implementation of active phased array antenna. Near-field thermal radiation device can be used as the heat dissipation surface of a satellite or other spacecraft. As an intelligent thermal control method, the emissivity can be adjusted upon the application of the electric field in the P–N junction and MIS junction. This technology is in the theoretical research stage, but this device based on diamond heterojunction has prospects. In the bargain, in addition to solar irradiation and cosmic rays, spacecraft operating in the space environment also faces many threats such as space debris and high/low temperature alternating environment, leading to the failure of spacecraft structure and bring great hidden dangers

to space flight. It is thus important to monitor spacecraft temperature, pressure/strain, acceleration and other parameters in real time. The basic principle of diamond quantum sensing is to use the NV⁻ spin energy level to be sensitive to physical signals such as electromagnetic field, strain, temperature, *etc.*, via measuring the change in the intensity of the output fluorescence signal caused by the NV⁻ change in the external field. Comparing the sensitivity of diamond quantum sensors and other types of sensors in detecting magnetic fields indicates that the sensitivity of diamond quantum sensors is still relatively high. Space optical sensors are known as the "eyes" of spacecraft, providing the positioning information for space missions such as deep space exploration and remote sensing mapping. Diamond has a high transmittance in the deep ultraviolet band, which can well meet the application requirements of the sensor optical system window, and has intense anti-irradiation characteristics and good stability in extreme space environments. With the development of large-scale curved diamond preparation technology, diamond could be used as an excellent optical alternative material in the future.

Summary and prospects In this review, the application of diamond materials in deep space exploration (detectors), portable power supplies (isotope batteries), spacecraft thermal control (heat conduction and near-field thermal radiation devices), spacecraft health monitoring (quantum sensors), and optical windows (optical sensor windows were proposed). To represent the application advantages of diamond in the extreme field of aerospace, it is necessary to continue efforts in at least the following aspects. First, 2-inch large-area array polycrystalline diamond arrays are reported to have a good ultraviolet detection performance, and it is possible to effectively synthesize large-area heteroepitaxial single crystal diamond for diamond detectors with better electrical properties. Second, diamond isotope cells and near-field thermal radiation devices both are based on the construction of diamond semiconductor heterojunctions, but the effective diamond N-type doping technology has not yet been broken through. It is thus necessary to further develop the effective diamond doping technology based on new principles. Finally, diamond quantum sensing technology has the advantages of multi-parameter sensing, but how to distinguish the output signal under different field signal excitations and reduce the interference in the face of multi-source targets needs to be further investigated.

Keywords diamond; aerospace; extreme environment; deep space exploration; quantum sensing