金属泡沫复合微肋微通道热沉的流动传热特性分析

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摘要 构建了一种金属泡沫和固体微肋相结合的复合微肋微通道热沉(combined fin heat sink, CFHS), 采用扩展型达西模型和局部非热平衡传热模型数值研究了复合微肋微通道热沉的流动与传热特性, 结合热阻网络分析了复合微肋结构的传热规律, 并对复合微肋热沉的综合换热能效进行了评价. 结果表明, 与传统固体微肋结构相比, 复合微肋结构可显著提升微通道热沉的换热性能; 金属泡沫厚度和孔隙率是影响换热性能的主要因素, 存在最佳金属泡沫临界填充厚度以及最佳孔隙率参数设置. 相对于传统固体微肋热沉, 本文研究的复合微肋热沉热阻降低了约56%, 综合换热能效提升了约1.32倍, 金属泡沫最佳孔隙率及临界无量纲厚度分别为0.9和0.3. 本文相关研究成果可为开发高效的电子设备冷却装置提供理论指导.

关键词 金属泡沫, 微通道热沉, 对流传热, 数值模拟

随着微纳米材料及微机电加工技术的日臻成熟, 以及微电子设备集成化、微型化及高性能的不断发展, 电子设备内热功率负荷不断攀升, 导致器件热可靠性及热应力引发的结构安全性等问题突出, 严重制约了微电子技术的发展^[1,2]. 据国际半导体蓝图(international technology road map for semiconductors, ITRS)报道, 高性能单芯片微处理器的功率密度未来可高达500 W/cm², 如何对高功率密度电子设备进行有效热管理是亟待解决的关键问题^[3]. 主动式微通道液冷技术是高热流密度电子器件热管理的一种有效方案, 其中金属泡沫微通道热沉凭借优良的换热特性使其具有良好的应用前景^[4-7].

金属泡沫用于高热流密度电子器件热管理得到了广泛关注, 文献[8~13]采用数值和实验方法对完全填充金属泡沫热沉的冷却性能及流动传热特性进行了研究, 发现金属泡沫可有效降低器件表面温度, 强化热沉的冷却性能, 对高功率密度电子器件的散热

效果十分显著. 纪献兵和徐进良^[12]指出通道内填充金属泡沫后换热能力可提升约13倍; 但与此同时, 也发现冷却工质在金属泡沫热沉内的流动阻力显著增加; 万忠民等人^[13]实验测量了一款金属泡沫热沉的流动换热特性, 该系统压降高达17.7 kPa. 为了强化传热的同时降低金属泡沫热沉的流动阻力, Jeng等人^[14]实验研究了金属泡沫布置方式对流动传热的影响, 发现交错阶梯布置不仅可以有效地强化热沉的换热性能亦可以在一定程度上降低流动压降; Chen和Wang^[15]研究了孔密度非均匀布置金属泡沫热沉的传热性能, 结果表明, 沿流动方向孔密度逐渐递减的布置方案, 可使热沉热阻降低约62%, 同时可降低流动阻力. 综上所述, 金属泡沫热沉具有优良的散热性能, 但流动阻力却相对较大, 仅仅通过优化金属泡沫的布置形态, 在一定程度上可以协调传热与流阻间的矛盾, 但强化换热效果有限. 为了更好地协调金属泡沫热沉强化传热与流动减阻特性, 提升金属泡沫

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热沉的冷却性能,文献[16~18]开展了板翅式金属泡沫热沉的换热性能研究,研究表明,金属泡沫热沉添加板翅可使热沉的换热性能大幅提升,且存在最佳的板翅布置间距;此外,亦发现孔密度是影响流动传热的一个主要因素.在此基础上,Hung等人^[19]数值研究了平直微肋金属泡沫微通道热沉内的换热性能,并探究了金属泡沫填充形态对流动传热的影响,发现金属泡沫微肋夹层布置与完全填充的换热性能相当,但流动阻力却相对较低;此外,本课题组^[20]针对金属泡沫微通道热沉的泡沫填充方式也做了相关研究,发现梯形填充的换热性能与完全填充相当,流阻可降低约10%.金属泡沫热沉中添加板翅或平直微肋微通道热沉中填充金属泡沫可有效提升热沉的换热性能,但由于金属泡沫填充区域较大,导致流动阻力依旧较大.因此,如何在强化金属泡沫热沉换热性能的同时保持较低的流动阻力,即实现金属泡沫微通道热沉的强化传热与流动减阻的协同性还有待进一步研究.

为此,本文构建了一种新型的金属泡沫复合微肋微通道热沉(复合微肋热沉)(combined fin heat sink, CFHS),采用扩展型达西模型和局部非热平衡传热模型对其耦合传热及流动特性进行了数值研究,分析了金属泡沫填充厚度、孔隙参数等对热沉换热性能的影响;在此基础上,结合简化热阻网络分析法对该热沉的传热热阻进行了分析,并采用能效因子对其综合换热能效给出了评价.

1 物理模型

本文所构建的金属泡沫复合微肋微通道热沉的整体示意图如图1(a)所示.与传统平直微通道热沉相

比,复合微肋热沉是将金属泡沫均匀地布置在传统微通道热沉流道固体微肋两侧,形成金属泡沫与固体微肋的复合微肋结构.为简化数值计算,选取其中的一个通道作为计算单元,如图1(b)所示.所选取计算单元的长、宽和高分别为20、2.4和6 mm,通道底部基板与顶部盖板厚度为 $\delta_1=\delta_2=0.5$ mm,通道的高度为 $H_c=5$ mm,宽度为 $W_c=2$ mm,肋片厚度为 $W_r=0.2$ mm,金属泡沫层厚度为 δ_p .热沉底面的热负荷为 100 W/cm^2 ,金属泡沫采用铜质,冷却工质为去离子水.

2 数学模型

为简化数值计算,数值研究中采用如下假设:(1)流体不可压缩;(2)金属泡沫各向同性;(3)各物性参数为常数;(4)忽略金属泡沫与微肋间的接触热阻.基于以上假设,可得描述上述模型流动与传热过程的控制方程如下:

质量守恒方程:

$$\nabla \cdot V = 0. \quad (1)$$

考虑到微肋两侧金属泡沫中流体流速相对较低,忽略惯性效应的影响,金属泡沫区域的动量方程采用扩展型达西模型(Brinkman-Darcy model);纯流体区域采用传统的N-S方程.

金属泡沫区域:

$$\frac{\rho_f}{\epsilon^2} (V \cdot \nabla) V = -\nabla P + \mu_{\text{eff}} \nabla^2 V - \frac{\mu_f}{K} V. \quad (2-1)$$

纯流体区域:

$$\rho_f (V \cdot \nabla) V = -\nabla P + \mu_f \nabla^2 V. \quad (2-2)$$

金属泡沫区域的能量方程采用考虑局部非热平衡效应的局部非热平衡传热模型(local thermal non-equilibrium model);纯流体区域则采用传统的对流

图1 (网络版彩色)物理模型.(a) 金属泡沫复合微肋热沉示意图;(b) 计算单元

Figure 1 (Color online) Physical model of CFHS. (a) Schematic diagram of CFHS; (b) computational domain

扩散能量方程.

金属泡沫区域:

(a) 流体相能量方程:

$$(\rho c_p)_f (V \cdot \nabla T) = \nabla \cdot (\varepsilon k_f \nabla T) + h_{sf} a_{sf} (T_s - T_f), \quad (3-1)$$

(b) 固体相能量方程:

$$(1 - \varepsilon) \nabla \cdot (k_s \nabla T_s) - h_{sf} a_{sf} (T_s - T_f) = 0, \quad (3-2)$$

纯流体区域:

$$\rho c_p (V \cdot \nabla T) = k_f \cdot \nabla^2 T, \quad (4)$$

其中, V 为流体的速度; P 为压力; T_f 为流体温度; T_s 为金属泡沫骨架温度; ρ , μ_f , c_p 和 k_f 分别为流体的密度、黏度、比热和导热系数, k_s 为固体的导热系数; ε 和 K 分别为金属泡沫的孔隙率和渗透率; a_{sf} 和 h_{sf} 分别为金属泡沫的比表面积和局部对流换热系数. 相关参数的计算式参见文献[21].

边界条件如下: 假设冷却工质以均匀且恒定的速度 u_{in} 和温度 T_{in} 进入通道; 通道的流、固交界面速度无滑移; 流体与金属泡沫交界面上速度相等、热流连续; 底面热负荷恒定; 通道出口采用局部单向化; 其余固体边界为绝热边界条件.

为综合分析金属泡沫复合微肋热沉的强化换热性能, 采用综合考虑传热及流阻的能效因子对其综合换热能效进行评价. 综合换热能效因子的定义, 如式(5)所示^[19]:

$$pf = \frac{Nu_m / Nu_0}{(f_m / f_0)^{1/3}}, \quad (5)$$

其中, Nu_m , f_0 和 Nu_0 , f_0 分别为复合微肋热沉和传统热沉的平均努赛尔系数和摩擦阻力系数.

3 数值计算方法及程序的验证

本文采用SIMPLER算法求解压力和速度的耦合问题, 对流项采用QUICK格式进行离散. 为提高数值计算精度, 在金属泡沫与固体、流体的交界面处进行局部网格加密处理. 同时, 为验证数值结果的可靠性, 将完全填充金属泡沫通道内的速度和无量纲温度分布与Xu等人^[22]给出的解析解做了对比(图2), 图中 θ 为无量纲温度, 详见文献[22]所示), 本文数值解与文献中的解析解吻合良好, 验证了数值计算的可靠性.

4 结果与分析

对金属泡沫复合微肋热沉的流动换热特性进行了数值研究, 结合热阻网络分析法和综合能效因子对复合微肋热沉进行热阻分析及评价. 此外, 探究了金属泡沫孔隙率及填充厚度对复合热沉流动传热的影响规律, 确定最佳的几何结构参数.

4.1 与传统热沉流动与换热特性的对比

为分析本文所构建的金属泡沫复合微肋热沉的换热特性, 图3给出了复合微肋热沉和传统热沉平均 Nu 数的对比(图中 $\alpha = 2\delta_p / W_c$ 为金属泡沫无量纲填充厚度). 由图可知, 复合微肋热沉较传统热沉换热性能明显提高, 当 Re 数为1000时, 复合热沉的平均 Nu 数可达传统热沉的2.53倍. 图4所示的两类热沉加热底面无量纲温度分布对比更清晰直观地反映出了复合微肋热沉的优良冷却性能. 可见, 复合微肋结构可显著地强化微通道热沉的换热特性.

为进一步分析复合微肋热沉的传热特性, 如图5

图2 数值计算的验证. (a) 速度分布的对比; (b) 无量纲温度分布的对比

Figure 2 Validation of numerical simulation. (a) Comparison of velocity profile; (b) comparison of dimensionless temperature

图3 平均Nu数的对比

Figure 3 Comparison of average Nusselt number

图4 加热底面无量纲温度分布的对比。(a) 传统热沉; (b) 金属泡沫复合微肋热沉

Figure 4 Comparison of dimensionless temperature distribution of (a) traditional heat sink; (b) combined fin heat sink

图5 金属泡沫复合微肋热沉传热过程示意图。(a) 热传递示意图; (b) 简化热阻网络图

Figure 5 Schematic of heat transfer in CFHS. (a) Heat transfer process; (b) simplified thermal resistance network

所示为复合微肋热沉传热过程示意图及简化热阻网络图,采用热阻网络分析法对复合微肋热沉的整体热阻进行计算(如式(6)所示)并与传统微通道热沉进行了对比,如图6所示。随 Re 数的增加,两类热沉的热阻均不断降低;但复合微肋热沉的整体热阻明显低于

传统微通道热沉。当 Re 数为1000时,复合微肋结构可使热沉整体热阻降低约56%。这是由于复合微肋中的金属泡沫区域增加了对流传热面积,降低了流体与微肋间对流传热热阻,强化了流体与微肋间的对流传热,进而显著增强了复合微肋热沉的整体换热性能。

$$R_T = 1 / \left(1 / (R_{cd,fin} + R_{cv,fin}) + 1 / (R_{cd,mf} + R_{cv,mf}) + R_{cv,f} \right) + R_{cd,w}$$

$$= 1 / \left(1 / \left(\frac{H_c}{k_s A_s} + \frac{1}{\varepsilon h_f A_{sf}} \right) + 1 / \left(\frac{H_c}{k_s (1-\varepsilon) A_{ps}} + \frac{1}{h_{sf} A_{mf}} \right) + \frac{1}{h_f A_f} \right) + \frac{\delta_l}{k_s A_w}, \quad (6)$$

其中, $R_{cd,fin}$, $R_{cv,fin}$ 为固体微肋的导热热阻、对流热阻; $R_{cd,mf}$, $R_{cv,mf}$ 为金属泡沫的导热热阻、对流热阻; $R_{cd,w}$ 为基底的导热热阻; A_s 为固体微肋的导热面积; A_{sf} 为固体微肋的对流换热面积; A_{ps} 为金属泡沫与基底的

接触面积; A_{mf} 为金属泡沫的表面积; A_f 为流体对流传热面积; h_f 为平均对流换热系数; A_w 为底面面积。

复合微肋结构不仅能显著强化换热,同时亦会对热沉内的流动状态产生重要的影响。图7给出了流

图6 (网络版彩色)热阻的对比

Figure 6 (Color online) Comparison of thermal resistance

体在复合微肋热沉和传统热沉内流动压降的对比。由图可知,传统热沉微肋两侧复合金属泡沫可导致流动压降显著增加,随 Re 数的增大,二者之间的流动压降差距逐渐增大。在低流速情况下,由于流体主要从未填充金属泡沫的流体通道中流过,与传统热沉相比,二者之间压降差距较小;随着流速不断增加,大量的流体从微肋两侧的金属泡沫层中高速渗流通过,但由于金属泡沫层增加了流体流动的迂曲度和表面黏滞阻力,金属泡沫骨架对流体的黏性滞止作用逐渐增强,导致流动压降急剧增加。

由上述分析可知,虽然复合微肋结构可显著地强化换热,但亦会引起流动阻力大幅增加。为综合考虑流动压降与强化传热的影响,图8给出了复合微肋热沉的综合换热能效分析。由图可知,金属泡沫复合微肋热沉的综合换热能效明显优于传统微通道热沉,当 Re 数为1000时,综合能效可提升约1.32倍。同时随 Re 数的增大优势越来越明显。可见,金属泡沫复合微肋热沉是高热流密度电子设备冷却的一种有效方案。

4.2 金属泡沫几何参数对复合热沉换热性能的影响

由于复合微肋热沉的换热性能受金属泡沫几何参数影响较大,其中金属泡沫孔隙率及填充厚度是两个重要的几何结构参数。因此,为了有效地强化复合微肋热沉的换热性能,提升热沉的冷却能力,对金属泡沫孔隙率及填充厚度进行了参数化优化分析。

当金属泡沫的孔径恒定为100 PPI(pores per inch)时,图9给出了金属泡沫孔隙率对复合微肋热沉流动及换热的影响规律。随孔隙率的增加,热沉冷却能力

图7 (网络版彩色)流动压降的对比

Figure 7 (Color online) Comparison of pressure drop

图8 (网络版彩色)综合换热能效因子随 Re 数的变化

Figure 8 (Color online) Variation of thermal performance factor with Re

呈现出先增加后降低的变化趋势,当孔隙率约为0.85时,平均 Nu 数达到最大值,热沉冷却能力最佳。由于随孔隙率的增加,金属泡沫骨架对流体的阻碍作用减弱,微肋两侧金属泡沫中流体速度增加,对流换热效果增强;但当孔隙率增加到一定程度,金属泡沫的有效导热系数和对流换热比表面积不断减小,对流换热效果逐渐恶化。与此同时,随着孔隙率的增加,金属泡沫对流动的阻碍作用不断减弱,进而导致流体在复合微肋热沉中的流动阻力逐渐降低。综合换热及流阻两方面的影响,当孔隙率约为0.9时,热沉的综合换热能效达到最优,这点与热沉冷却能力有所不同。

金属泡沫填充厚度对复合微肋热沉流动换热的影响规律如图10所示。与传统微通道热沉($\alpha=0$)相比,随着金属泡沫填充厚度的逐渐增大,流阻不断增加;然而,热沉的换热特性在金属泡沫无量纲填充厚度小

图9 (网络版彩色)孔隙率对流动与换热的影响

Figure 9 (Color online) Effects of porosity on flow and heat transfer characteristics

于0.1时有所恶化。此外,当金属泡沫无量纲填充厚度小于0.3时,综合换热能效因子小于1。这说明只有当金属泡沫具有一定厚度后,才能强化热沉的综合换热能效,即存在金属泡沫临界厚度尺寸。针对本文所研究的复合微肋热沉而言,无量纲临界厚度约为0.3。

5 结论

为解决高热流密度电子器件的散热问题,本文提出了一种金属泡沫复合微肋微通道热沉结构,分析了该复合微肋热沉的流动换热特性,并就金属泡

图10 (网络版彩色)金属泡沫无量纲填充厚度对流动与换热特性的影响

Figure 10 (Color online) Effects of dimensionless metal foam layer thickness on flow and heat transfer characteristics

沫孔隙率及填充厚度进行了参数化优化分析。主要结论如下: (1) 金属泡沫复合微肋结构可显著地强化微通道热沉的冷却能力及综合换热能效,在所研究的最高流速下,与传统热沉相比,复合微肋热沉的热阻降低了约56%,综合换热能效提升了约1.32倍; (2) 金属泡沫孔隙率和填充厚度是影响金属泡沫复合微肋热沉换热性能的重要几何参数,研究发现存在最佳孔隙率及临界厚度参数;本文所研究的复合微肋热沉,最佳孔隙率约为0.9,无量纲临界厚度约为0.3。

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Summary for “金属泡沫复合微肋微通道热沉的流动传热特性分析”

Thermal hydraulic performance of micro-channel heat sink with composite metal foam-solid fin design

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Three-dimensional (3D) interconnect technology promises significant performance advantages for the next generation of high speed and multi-functional electronic devices, however, the large-scale integration of electronic circuit and vertical stacking of multi-functional dice have been demonstrated to result in substantially increased waste-heat generation rates and localized hotspots. Efficient thermal management solutions are imperative to ensure the operating temperature of components below a reasonable level. Among various cooling techniques, metal foam heat sink has been identified as a promising alternative for electronic cooling, because of the large specific surface area, high effective thermal conductivity and intensive fluid mixing capability that foam material provided.

In this study, a novel micro-channel heat sink with combined metal foam-solid fin, namely combined fin heat sink (CFHS), was established for electronics cooling. Numerical simulations based on Brinkman-Darcy extended momentum equation and local thermal non-equilibrium energy equations were carried out to investigate the fluid flow and heat transfer characteristics. To simplify the computations, a single channel was used as the computational domain with a dimension of 20 mm×2.4 mm×6 mm. The constant heat flux of 100 W/cm² was supplied at the bottom wall to simulate the high-powered electronic device. Metal foam and fin were made of high thermal conductivity copper, and pure water was used as the working coolant. It was assumed that the metal foam was fully saturated with fluid in laminar flow state and the thermal resistance between the metal foam and fin was neglected. Effects of combined fin configuration on the flow and heat transfer performances were studied to determine the optimal porosity and dimensionless metal foam layer thickness for designing the CFHS. The thermal performance of the novel heat sink was compared to that of the conventional heat sink, and the total thermal resistance was analyzed based on the simplified thermal resistance network.

The results indicate that the CFHS is more favorable in promoting thermal performance than the average Nusselt number of CFHS is 2.53 times higher than that of the conventional heat sink, while accompanied by the high pressure drop as a penalty. The flow resistance and specific area are two conflicting parameters that affect the thermal and hydraulic performances of the CFHS, our results show that there exists a critical dimensionless metal foam thickness and optimal porosity, which are 0.9 and 0.3, respectively. Compared with the conventional heat sink, the total thermal resistance of CFHS is significantly reduced by 56%, and the thermal performance factor of CFHS performs 1.32 times higher. The presented CFHS thus provides a feasible solution for thermal management of electronic devices with high-powered density.

metal foam, micro-channel heat sink, convective heat transfer, numerical simulation

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