CONJUGATE ANALYSIS OF THIN FILM HEAT SPREADERS TO REDUCE TEMPERATURE AT HOT SPOTS

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ABSTRACT

The effects of thin film coating on maximum temperature of integrated electric circuits are investigated. A fully three-dimensional conjugate heat transfer analysis was performed to investigate the effects of thin film material and thickness on the temperature of a hot spot. Two different materials, diamond and graphene nano-platelets simulated as materials for thin films. The thin film heat spreaders were applied to the top wall of the three optimized arrays of micro pin-fins having circular, airfoil and convex cross sections. The integrated circuit with a 4 x 3 mm footprint featured a 0.5 x 0.5 mm hot spot located on the top wall which was also exposed to a uniform background heat flux. The effective area of coverage of the thin films was also investigated computationally. It was found that thin film heat spreaders significantly reduce the hot spot temperature, allowing for increased thermal loads and therefore increased performance. Furthermore, it was found that thickness of the thin film heat spreader does not have to be greater than a few tens of microns.

1. INTRODUCTION

Next generation electronic chips are predicted to reach heat flux of at least 500 W cm$^{-2}$ at the background and significantly in excess of 1000 W cm$^{-2}$ at hot spots [1]. It is the soaring temperatures at the hot spots that have been creating a major challenge in the field of high power micro-electronics cooling. Various methods have been investigated that are capable of handling such high heat fluxes, including optimized microchannels [2], optimized arrays of micro pin-fins [3,4], micro-jet cooling [5] and thermo-electric cooling [6].

One technique successfully used for thermal management of electronic chips is implementation of thin film heat spreaders [7,8]. They are used to spread the thermal energy away from the hot spot, thereby reducing the maximum temperature at the hot spot. Fukutani and Shakouri [7] investigated Si and SiGe superlattice thin film micro-cooler and found that the hot spot temperature can be lowered by 10 to 30°C at a heat flux of 1000 W cm$^{-2}$. They also discovered there is an optimum film thickness and current that provides the highest cooling density at the hot spots. Wang, McCluskey and Bar-Cohen [8] performed a thorough study of the effectiveness of thin film heat spreaders in conjunction with a micro-channel cooling configuration. Mayer and Ram [9] performed optimization of heat sinks coupled with thin films. Much like the work done by Singh et al. [10] and Labounty et al. [11], this work investigated the use of diamond thin films applied to micro pin-fin cooling scheme. Smalc et al. [12] investigated the use of natural graphite as heat spreaders with much higher thermal conductivity.

The thin film heat spreaders analyzed in the study presented here were computationally simulated as applied to micro pin-fin geometries having three cross-sections: circular, symmetric airfoil and symmetric convex. The micro pin-fin geometries used in this work are defined in the same manner as presented by Reddy et al. [3,4] and are shown in Fig. 1. The effects of thin film thickness, material and effective area were investigated for each of the three pin-fin geometries.
Figure 1: Forced cooling via arrays of micro pin-fins having: a) circular, b) symmetric airfoil and c) symmetric convex cross sections. Only half of the configuration is shown and analyzed due to symmetry. Top, bottom and side walls are indicated. They are 30 µm thick.

2. 3D CONJUGATE HEAT TRANSFER ANALYSIS

Table 1 shows the parameters and the boundary conditions that define each of the three cooling configurations. The thermal boundary conditions were arrived at using the inverse design approach proposed by Reddy and Dulikravich [4], and were kept constant throughout the analysis. Shapes and sizes of the pin-fins were optimized a priori [3]. The entire top surface of the top wall was exposed to a uniform background heat flux. A much higher heat flux was enforced over one hot spot on the top surface of the top wall. The bottom surface and all sidewalls were thermally insulated and the outlet was pressurized at a gauge pressure of 20 kPa. Liquid water at 30°C inlet temperature was the cooling fluid.

Table 1: Geometric parameters and boundary conditions used for each analysis.

<table>
<thead>
<tr>
<th>Pin-fin cross section</th>
<th>Circular</th>
<th>Airfoil</th>
<th>Convex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin-fin diameter (µm)</td>
<td>120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pin-fin chord length (µm)</td>
<td>-</td>
<td>280</td>
<td>220</td>
</tr>
<tr>
<td>Pin-fin thickness (µm)</td>
<td>-</td>
<td>120</td>
<td>130</td>
</tr>
<tr>
<td>Pin-fin height (µm)</td>
<td>250</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>Coolant inlet speed (m s⁻¹)</td>
<td>5.1</td>
<td>5.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Background heat flux (W cm⁻²)</td>
<td>705</td>
<td>875</td>
<td>665</td>
</tr>
<tr>
<td>Hot spot heat flux (W cm⁻²)</td>
<td>2200</td>
<td>2200</td>
<td>2280</td>
</tr>
</tbody>
</table>

A hybrid computational grid of approximately 40 million hexahedral cells was created using ANSYS Meshing® for each 2D conjugate analysis performed in this work. A comparison of the results obtained using a computational grid of 50 million cells showed that the results deviated by less than 1%, thereby assuring grid convergence. Five layers of structured grid were placed on each solid-fluid interface with the minimum allowable length scale being one micron. This allows for continuum to be satisfied so that the Reynolds Averaged Navier-Stokes (RANS) [13] equations can be solved for the fluid domain. The mass, momentum and energy conservation equations for an incompressible fluid flow are given as

\[ \nabla \cdot \vec{V} = 0 \]  
\[ \rho \left( \vec{V} \cdot \nabla \right) \vec{V} = \nabla \cdot \left( \rho \vec{V} \right) \]  
\[ \rho \left( \vec{V} \cdot \nabla \right) \vec{V} = \nabla \cdot \left( \rho \vec{V} \right) \rho_0 + \nabla \cdot (k \nabla T) \]

The steady-state heat conduction equation was solved for the solid domain.

\[ \nabla \cdot (k \nabla T) = 0 \]

where \( k \) is the thermal conductivity and \( T \) is the absolute temperature.

Although the Reynolds number in this study ranged from 80 - 180, Alfieri et al. [14] have shown that it can still lead to vortex shedding from the micro pin-fins. The standard k-ε turbulence model was used to simulate the turbulent flow in all cases due to its stability and good convergence rate.

For comparison purposes the three micro-pin fin configurations were analyzed without the heat spreader under the thermal conditions specified in Table 1. The temperature distributions on the top surface are shown in Fig. 2. In each 3D conjugate analysis, two sample lines (streamwise and cross-stream) will be used to show the variation of temperature on the top surface along those sample lines.
3D CONJUGATE ANALYSIS OF AN ARRAY OF MICRO PIN-FINS WITH A DIAMOND THIN FILM ON THE TOP (HOT) SURFACE

The effects of diamond thin film heat spreaders on maximum temperature were analyzed in detail. Films of three different thicknesses (5, 10 and 15 µm) were applied to each configuration as the top layer of the overall 30 µm thick top wall which is exposed to the uniform background heat flux and a much higher heat flux over the hot spot area. Thermal conductivity of diamond film heat spreader in this work was taken as 1700 Wm⁻¹K⁻¹.

3.1 CIRCULAR CROSS SECTION PIN-FINS

Figure 3 shows the temperature distribution on the top surface of the chip with circular cross-section pin-fins when thin heat spreader films of various thicknesses were applied.

It can be seen that maximum temperature has significantly decreased. Figure 3 (in comparison to Fig. 2) also demonstrates that the diamond film is very effectively spreading the heat over a larger area even in the upstream direction.

Figure 4 shows the temperature variation along the two sample lines. It can be seen that diamond thin film greatly reduces maximum temperature. It also suggests that a thickness exists beyond which improvements are not significant.

Figure 4 also suggests that the diamond thin film has an effective area, outside of which the temperature is unaffected. It should be mentioned that the oscillations in temperature are caused by the presence of pin fins along the sample lines below the top wall. These pin fins increase heat conduction in this area, thereby leading to reduced temperatures.
3.2 SYMMETRIC AIRFOIL CROSS SECTION PIN-FINS

Figure 5 shows temperature distribution on the top surface of the top wall of the micro pin-fin array with symmetric airfoil micro-pin fin cross sections. The temperature distribution suggests that the diamond thin film is spreading heat more in the cross-stream direction than in the streamwise direction. This aids in reducing temperature non-uniformity, which in turn reduces thermal stresses.

Figure 5: Temperature distribution on the top surface of the top wall in case of an array of micro pin-fins with symmetric airfoil cross sections with: a) 5 µm, b) 10 µm and c) 15 µm thick diamond film heat spreader on the top (hot) surface.

Figure 6 shows that the diamond thin film in this configuration of micro pin-fins reduces temperature oscillations, which suggests improved temperature uniformity. Figure 6 also suggests that the thin films have a limited area of effectiveness.

3.3 SYMMETRIC CONVEX CROSS SECTION PIN-FINS

Figure 7 shows the temperature on the upper surface of the top wall of the array of micro pin-fins having convex cross sections. Again, increasing thin film thickness has shown to dissipate heat away from the hot spot. Consequently, more of the heat is being removed by the fluid away from the hot spot in the cross-stream direction, as can be seen in the elevated temperatures towards the outlet.

Figure 7: Temperature distribution on the upper surface of the top wall of the array of micro pin-fins having convex cross sections. Again, increasing thin film thickness has shown to dissipate heat away from the hot spot. Consequently, more of the heat is being removed by the fluid away from the hot spot in the cross-stream direction, as can be seen in the elevated temperatures towards the outlet.
4. 3D CONJUGATE ANALYSIS OF AN ARRAY OF MICRO PIN-FINS WITH A GRAPHENE NANO-PLATELETS THIN FILM ON THE TOP SURFACE

This study also investigates graphene nano-platelets as a material for thin films. Graphene nano-platelets (GNPs) are a viable alternative not only because they are less expensive than diamonds, but also because they possess a much higher thermal conductivity \( (k = 5000 \text{ Wm}^{-1}\text{K}^{-1}) \). However, this high value of thermal conductivity is only experienced for a single “sheet” or atomic plane of GNP with an approximate thickness of 1nm. Balandin [15] reported that the thermal conductivity drastically decreases with additional layers of GNP. He stated that for a thin film consisting of more than four atomic planes, the thermal conductivity drops below that of the bulk graphite, but with sufficient number of layers it recovers. Due to the sufficiently thick layers of GNP used in this work, it can be assumed that the thermal conductivity of GNP recovers to values of bulk graphite \( (k = 1400 \text{ Wm}^{-1}\text{K}^{-1}) \) [15]. The thermal conductivity of GNP was assumed to be isotropic because of the random orientation of the GNPs arising when creating films of large thicknesses.

4.1 CIRCULAR CROSS SECTION PIN-FINS

Figure 9 shows the temperature distribution on the upper surface of the top wall in case of an array of circular pin-fins coated with GNP thin films indicating that for a thicker coating of GNP, the temperature decreases significantly. In the case of circular pin-fin, a thin coating does not have a significant effect on either the maximum temperature or its distribution.
In Fig. 10 the large difference between performance due to 5µm and 10µm thick films of graphene nano-platelets is evident. This suggests that a thin film thickness of greater than 5µm is needed to achieve any measurable performance. A thin coating of the top (hot) surface also has very little effect on overall and local temperature uniformity as can be seen from the temperature oscillations. This is also the case for the diamond thin film.

**4.2 SYMMETRIC AIRFOIL CROSS SECTION PIN-FINS**

The temperature distribution on the top surface of the airfoil pin fins coated with GNP is shown in Fig. 11. It can be seen that even the 5µm film offers significant improvement for the airfoil shape over the circular pin fins. It can also be seen that the GNP performs similar to the diamond thin films in dissipating heat away from the hot spot. This is evident in the similar temperature distribution away from the hot spot in the cross-stream direction.

**Figure 11: Temperature distribution on the top surface of the top wall in case of an array of micro pin-fins having symmetric airfoil cross sections with: a) 5 µm, b) 10 µm and c) 15 µm thick heat spreader film made of graphene nano-platelets on the top (hot) surface.**
Figure 12: Temperature variation along: a) sample line 1, and b) sample line 2 for graphene nano-platelets coated top surface of the top wall of an array of micro pin-fins having airfoil cross section.

The temperature variations along the sample lines, shown in Fig. 12, demonstrate that even the thinnest film of GNP effectively reduces maximum temperature in case of pin-fins having airfoil cross sections. Thin film of GNPs also appears to improve overall and local temperature uniformity. As in the case of the diamond thin film, the performance gains of the GNP thin film quickly reduces as the film thickness increases. This is in contrast with the case of pin-fins having circular cross sections (Fig. 10) which suggests the existence of an optimal film thickness in terms of the rate of its effectiveness as a function of the film thickness. This confirms the general conclusions of the excellent paper by Fukutani and Shakouri [7] who used a simpler analysis.

4.3 SYMMETRIC CONVEX CROSS SECTION PIN-FINS

It can be seen from Fig. 13 that the airfoil and convex cross section pin fin geometries have similar temperature distribution. It can also be seen that a 5 µm thick GNP heat spreader is not able to dissipate the heat away from the hot spot as effectively as it is for the airfoil cross section pin fins or a thicker film.

Figure 14 shows the temperature variation along the two sample lines. Both figures suggest that even in the case of the GNP heat spreader there is an effective area outside of which the performance gains are insignificant. It can also be seen that even the thinnest coating with GNP improves local temperature uniformity.
It was previously shown that all thin films have an effective area outside of which the thin films have very little effect. This section investigates the effect when the thin film is spread on the hot spot and only slightly beyond the hot spot. The boundaries of the diamond thin films were simulated as extending 0.25mm from the boundaries of the hot spot (Fig. 15). The thickness of the diamond thin film was kept constant at 15\(\mu\)m.

When compared to the results obtained when fully coating the top surface of the top wall, it can be seen (Fig. 16) that the segmented thin film has very little effect on the maximum temperature. It, however, does influence the temperature distribution. It is not able to dissipate the thermal energy as effectively as in the case where the entire upper surface was coated with either diamond film or a graphene nano-platelets film.

Figure 15: View of the top (hot) surface (one-half because of symmetry) of the electronic chip showing partial coating using thin films.

Figure 16: Temperature distribution on the top surface of the top wall of the array of micro pin-fins with: a) circular, b) symmetric airfoil and c) symmetric convex cross sections and with segmented diamond film heat spreader.

Figure 17: Temperature distribution on the top surface of the top wall of the array of micro pin-fins with: a) circular, b) symmetric airfoil and c) symmetric convex cross sections and with segmented thin graphene nano-platelets film heat spreader.
Figure 17 shows the temperature distribution on the top surface of the chip partially coated with GNP. Again, it can be seen that the maximum temperature was not significantly affected. However, the temperature distribution has significantly changed. This suggests that although only coating a small region of the chip can reduce material cost, it can drastically increase the thermal stresses.

Figure 18 shows the temperature variation along the two sample lines for the airfoil configuration. It can be seen that for the diamond thin film the difference between the maximum temperature between the 15µm full coating and 15µm segmented coating is miniscule. It is also evident that a full coating significantly improves local temperature uniformity as can be seen from the absence of temperature oscillations. In the case of GNP heat spreader, the maximum temperature difference between fully and partially coated cases is also miniscule.

Figure 18b shows the temperature variation along the streamwise direction in case of the symmetric airfoil cross section pin-fins. It shows that a fully coated top surface effectively carries heat via conduction further upstream. This allows for the cooling process to begin further upstream, as can be seen by the lower temperature at the leading edge of the chip.

6. SUMMARY

Table 2 summarizes the maximum temperature for each of the three pin-fin configurations for each of the three thicknesses of diamond heat spreader.

Table 2: Maximum temperature (degrees Celsius) for the three pin-fin configurations with top surface of the top wall coated with diamond (k = 1700 Wm⁻¹K⁻¹) heat spreader for various film thicknesses.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Circular</th>
<th>Airfoil</th>
<th>Convex</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Film</td>
<td>91</td>
<td>82</td>
<td>84</td>
</tr>
<tr>
<td>5 µm</td>
<td>86</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>10 µm</td>
<td>73</td>
<td>70</td>
<td>68</td>
</tr>
<tr>
<td>15 µm</td>
<td>71</td>
<td>66</td>
<td>65</td>
</tr>
<tr>
<td>Segmented</td>
<td>71</td>
<td>66</td>
<td>65</td>
</tr>
</tbody>
</table>

It can be seen that the maximum temperature decreases as film thickness increases. This is true only up to a certain thickness, after which further increasing the thickness results in an insignificant decrease in maximum temperature.

Table 3 summarizes the maximum temperature for each of the three-pin fin configurations for each of the three thicknesses of GNP heat spreader.

Table 3: Maximum temperature (degrees Celsius) for the three pin-fin configurations with the top surface of the top wall coated with GNP (k = 1400 Wm⁻¹K⁻¹) heat spreader for various film thicknesses.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Circular</th>
<th>Airfoil</th>
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</tr>
</thead>
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<tr>
<td>No Film</td>
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</tr>
<tr>
<td>10 µm</td>
<td>75</td>
<td>69</td>
<td>70</td>
</tr>
<tr>
<td>15 µm</td>
<td>63</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>Segmented</td>
<td>63</td>
<td>67</td>
<td>67</td>
</tr>
</tbody>
</table>

It shows that the GNP heat spreader is just as effective in lowering the maximum temperature as the diamond heat spreader while greatly reducing material cost. The conclusions for diamond heat spreaders also applies to GNP heat spreaders.
CONCLUSIONS

This work investigated the effects of thin film heat spreaders on maximum temperature and temperature uniformity in the case of micro pin-fin arrays with a hot spot. The difference in performance between diamond and graphene nano-platelets was also investigated. It was shown that the graphene nano-platelets heat spreaders are just as effective as better diamond heat spreaders in spreading the heat away from the hot spot. When the effects of thin film thickness were studied, it was observed that further increasing the thickness beyond a certain value no longer improves performance. This was the case for both diamond and graphene nano-platelets heat spreader thin films. The effective coverage area for both diamond and nano-platelets thin films was also investigated. Rather than coating the entire top surface with either of the two materials, only a section at and around the hot spot was coated. It was observed that the sectional coating creates the same reduction of the maximum temperature as the full coating for either of the two materials for any of the three pin-fin configurations. It does, however, greatly deteriorate the local temperature uniformity. Thus, coating the entire top surface exposed to the heat flux with either of the two materials will significantly decrease the maximum temperature at the hot spot and increase the overall and local temperature uniformity.

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