

Exploring Graphene to Enhance the Performance of Hybrid Solar Photovoltaic Thermal Collectors

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1 ABSTRACT

The capacity for heat transfer improvement through the inclusion of graphene and graphene oxide is explored in a hybrid system consisting of a photovoltaic (PV) panel and a fabricated heat extractor. The thermal properties of graphene are well-documented, and its innately high thermal conductivity makes it promising as a thermal interface material. Existing models of thermal interface materials and data from previous studies indicate that graphene is an appropriate candidate for hybrid systems. For the temperature cycles of a typical PV panel, thermal stability of graphene is also known to be sufficient, and graphene's negative thermal expansion coefficient represents a safe option. Graphene nanoparticles can also be added to the working fluid of the system, improving thermal conductivity directly.

Keywords: graphene, hybrid photovoltaic/thermal, thermal interface material, nanofluid

2 SUMMARY

A hybrid solar photovoltaic/thermal system allows for the capture of incident energy on a photovoltaic panel that would otherwise be lost as heat. The thermal component consists of a heat extractor mounted on the back of the PV panel. One face is aluminum, increasing the heat transfer from the PV panel backsheet, and the other is insulated to retain heat. The aluminum face is positioned in as close contact as practical with the back of the PV panel to maximize heat transfer to the cold water in the extractor. This serves the dual purpose of cooling the PV panel to increase performance and collecting heat. The firm contact between the metal and plastic, however, consists of less than 2% of the total surface area. A layer of graphene between the aluminum and the backsheet can serve as a thermal interface material (TIM), improving contact between the two by minimizing the presence of air and facilitating heat

transfer. Also, both graphene and graphene oxide show potential as nanoadditives to the working fluid in the heat extractor, improving heat transfer within the fluid. This paper explores various applications of graphene and graphene oxide to these hybrid systems.

3 MATERIAL PROPERTIES

Graphene is a recent material, quintessentially consisting of a single layer of carbon atoms arranged in a hexagonal lattice. Modern graphene has been explored in a variety of different forms, often relating to the number of carbon layers in the sample. These include monolayer graphene, with one layer, approximating a 2D material; bilayer graphene, with two; few-layer graphene (FLG), which typically has three to five; many-layer graphene, up to around ten; graphene nanoplatelets or graphene powder, which are thicker than layered sheets, but smaller in diameter; and graphene oxide, an altered lattice containing both carbon and oxygen. These 2D graphene forms can also be layered and compressed to reduce porosity and increase conductivity.

The form of graphene most suitable for TIM application is graphene powder. As the bare powder does not bond well to the surface, it can be placed into a polymer matrix such as silicone oil (noncured) or an epoxy resin (cured) with various weight percentages. Graphene powder is typically on the scale of microns per particle diameter, and nanometers in thickness.

3.1 Water Vapor Transmission Rate (WVTR)

The presence of water in a PV panel decreases the performance of the system, and materials with low WVTR are therefore desirable. Monolayer graphene has a low WVTR when layered on polymer such as polyethylene terephthalate, a

common material for PV panel backsheets [1], on the order of metals such as aluminum. It is expected that graphene powder within a polymer base would also decrease WVTR for the system, which increases long-term durability.

4 THERMAL INTERFACE MATERIALS

The unique structure of graphene allows for an extremely high thermal conductivity in-plane in samples of pristine 2D graphene (5000 W/m*K) due to phonon conducting behavior. For practical purposes, other forms of graphene are generally needed, which have reduced thermal conductivity. However, in these forms, graphene maintains a bulk thermal conductivity (~10 W/m*K) [2, 3] that is still several orders of magnitude higher than that of air (.024 W/m*K), making it a promising option for TIMs.

Research has been done on the thermal conductivity of larger 3D graphene structures approximately 10mm x 2mm x 50 μm [3]. Compression of these innately porous structures forms a “graphene paper” that demonstrated a thermal conductivity up to 50 W/m*K. While this is a possibility for future applications these samples are currently too small in scale.

Graphene powder has been studied by Zhang et al. [2] and displays a thermal conductivity of 13.5-23.8 W/m*K, below that of both pristine 2D graphene and the graphene paper. The reduction in thermal conductivity from the other graphene samples is attributed to thermal contact resistance as well as increased phonon scattering due to the uneven structure.

Suhindra et al. [4] describe a mechanism for applying a non-curing graphene filler TIM to a metallic surface, using silicone oil as a base polymer matrix for the graphene. This system forms a particle-laden polymeric (PLP) TIM that behaves as a Herschel-Bulkley fluid [5]. PLPTIMs can be produced more easily at the required scales, making them an attractive candidate. The thermal resistance of this system is given by Equation 1:

$$R = \frac{BLT}{k_{TIM}} + R_{c_1} + R_{c_2} \quad (1)$$

where BLT is the bond line thickness of the TIM, k_{TIM} is the bulk thermal conductivity of the TIM, and R_{c_1} and R_{c_2} are the contact resistances of each side of the TIM [5]. BLT for a typical system should be around 25-100 μm [4].

The silicone oil used in the study has a thermal conductivity of .18 W/m*K, but this rapidly increases with the loading fraction of graphene filler, as shown in Figure 1. Goyal et al obtained a similar thermal conductivity using FLG graphene sheets in an electrically conductive silver epoxy [6]. At a graphene volume fraction of 50%, the researchers found a thermal conductivity around 10 W/m*K.

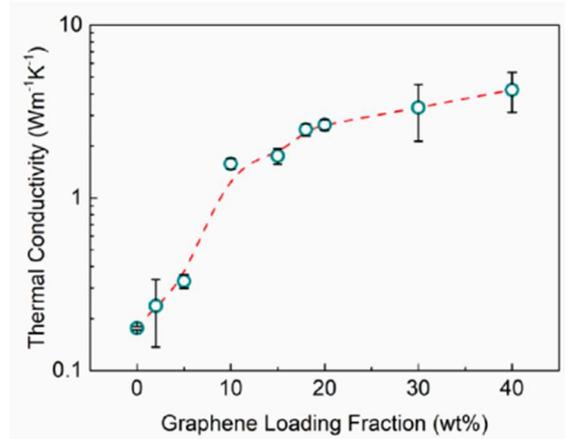


Figure 1: Thermal conductivity of graphene fillers in silicone oil base by percentage [4]

Also of interest are the thermal contact resistances between the TIM and the outer surfaces, as the total thermal resistance and therefore total conductivity depend on them. Although the internal thermal conductivity appears to increase with the loading fraction of graphene filler, the contact resistance on a metallic surface reaches a minimum at approximately 15% loading fraction as shown in Figure 2, so that there is a non-monotonic relationship between the graphene loading and the contact resistance. After the minimum is reached, it is followed by a slight increase in the contact resistance.

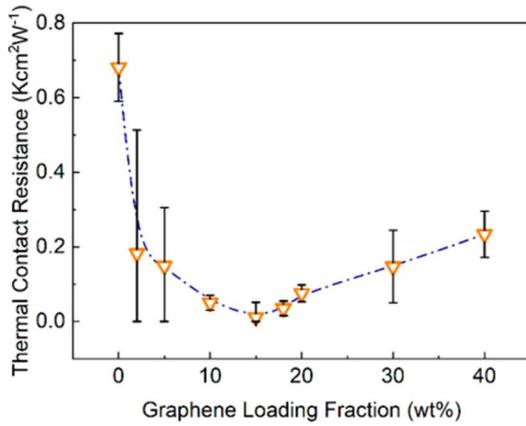


Figure 2: Thermal contact resistance of graphene fillers in silicone oil base by percentage [4]

This minimum is hypothesized to result from the dependence of thermal contact resistance on both bulk thermal conductivity and shear modulus, according to Equation 2 [4]:

$$R_{c_1+c_2} = c \left(\frac{S_q}{K_{TIM}} \right) \left(\frac{G}{P} \right)^n \quad (2)$$

where G contains both the storage modulus and the shear modulus, S_q is the surface roughness, P represents the pressure on the TIM, n and c are empirical constants, and K_{TIM} is the bulk thermal conductivity. After the minimum, the loading fraction is sufficient to alter the shear modulus of the TIM and begins to prevent effective contact with the surface, despite the overall increase in thermal conductivity from the increased graphene. Shahil et al. state that the overall thermal conductivity of an MLG-modified TIM matrix is described through Equation 3 [7]:

$$K = K_p \left(\frac{2f(K_p - K_m) + 3K_m}{(3-f)K_p + K_m f + \frac{R_B K_p K_m f}{H}} \right) \quad (3)$$

where K_p and K_m describe the thermal conductivities of the filler and matrix materials, f is the volumetric loading fraction, H represents the thickness, and R_B is the thermal boundary resistance at the graphene-matrix interface.

4.1 Graphene Oxide

Graphene oxide (GO) is the result of oxidizing regular graphene, a matrix of carbon, hydrogen, and oxygen. GO can be treated further to

form reduced graphene oxide (RGO). Two-dimensional GO loses some conductivity compared to pristine 2D graphene due to phonon scattering; the loss varies with oxidation degree. At .35 oxidation level (i.e., a GO matrix comprised of 35% oxygen) the thermal conductivity is around 72 W/m*K [8]. Tang et al. [9] found that a cured epoxy resin TIM using RGO fillers improved the thermal conductivity substantially when compared to the pure epoxy. This system continued to improve with the introduction of 3D graphene networks (3DGN) produced through chemical vapor deposition, with the RGO serving as a “bridge” to connect the graphene and the epoxy resin. The results of RGO with different functionalized groups and 3DGN as a function of loading fraction are displayed in Figure 3.

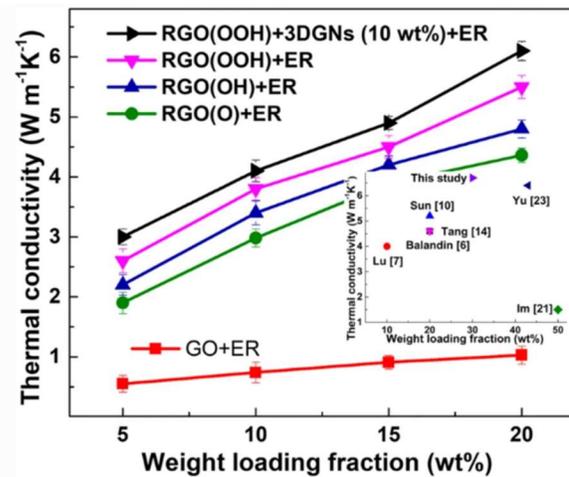


Figure 3: Thermal conductivity of reduced graphene oxide fillers in epoxy resin base by percentage [9]

5 GRAPHENE NANOFLUID

Nanoparticles of graphene can also be added directly to the water of the hybrid PV/thermal system, creating a graphene nanofluid. The suspended nanoparticles augment the thermal properties of the original fluid, improving the heat transfer capabilities. At the same Reynolds numbers, nanofluids demonstrated an increase in heat transfer performance compared to the original working fluid [10]. Das et al. [11] found that a .1 weight percent of graphene in water was sufficient to increase thermal conductivity in the fluid by 29% at 45 °C. Importantly, the viscosity of the fluid is also altered by the presence of the nanoparticles, but this is highly temperature dependent. At 20°C the nanofluid viscosity is

increased by 175% compared to water, but at 50 °C the viscosity is 25% lower than that of water. The resulting nanofluid is Newtonian [11]. Torii [10] obtained data for a graphene oxide nanofluid, increasing the heat transfer coefficient by up to 62% for a .2% volume concentration of GO. The results indicate that both graphene and graphene oxide nanofluids are candidates for efficient working fluids.

6 CONCLUSIONS

This paper explored various means by which graphene could improve the operation of a hybrid solar PV/thermal system. Further analysis and experimentation are needed to identify which of the options are most suitable for the specific system of interest, but a TIM consisting of graphene filler in a polymer base represents one of the most promising candidates. This TIM will need to be evaluated in a real system to evaluate the effects of possible degradation or contamination on the thermal properties. The possibility of water's enhancement with a graphene-based nanofluid is likewise attractive. A combination of several potential improvements is of interest since there is no mutual exclusivity. Stability of the proposed improvements is crucial to longevity, and of course cost will be a major factor. An economic analysis of the most viable options is therefore a key next step. Refining this hybrid system will provide a straightforward means to increase the efficiency of ever more ubiquitous PV panels, lessening the impact of human energy consumption on the environment.

7 REFERENCES

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