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Thermo-optic switching properties of paraffin-wax hosting carbon fillers

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ABSTRACT

Enhancing the thermal- optical properties of phase change materials (PCMs) is the major issue to be addressed when designing thermo optic switch. Paraffin waxes have high thermal energy storage density but low thermal conductivity and, hence, require large surface area. In this paper, we examine the thermal-optical behavior of paraffin wax hosting several concentrations of graphite or graphene, aiming to provide an emerging class of PCMs. Scanning electron microscope SEM were used to characterize the microstructure of the so-formed composite. Heat transfer rates of paraffin wax composites were investigated during heating and cooling phases. The thermal properties were measured using a differential scanning calorimeter DSC). Thermo-optic switching (TOS) based on transmission versus time and temperature under electric heating was analyzed. Results show that both graphite and graphene accelerate melting and solidification heat transfer rate of the paraffin composites. It was observed that, although both graphite and graphene promote decreasing of switching and saturation times, paraffin wax-graphene composite samples cause up to 54% reduction in thermo optical switching time when increasing graphene concentration. These findings have important implication for understanding paraffin-graphene reactivity and surface area modification. These experiments showed a route for paraffin wax hosting carbon fillers as thermo optical sensing materials to be used in TOS device applications.

1. Introduction

Optical switches have potential applications in optical communications. Among different types, thermo-optical switches are very attractive due to small size and integration with wave guide multiplexers. Their tunability are based on the change in the materials refractive index with temperature [1].

Switchable thermo-chromic materials as inorganic solids, polymers and small organic molecules operate in temperature response based stimuli. i.e. a switching between two states (clear at low temperature and dark at high temperature). Vanadium oxide is the well known inorganic solid, it transforms from insulating monoclinic phase at low temperature to metallic phase at high temperature. It has promising applications in optoelectronic switches, phase change memory and spectrally selective smart windows [2]. A reversible thermal induced optical switching is observed by light transmission measurement in alkali germinate glass hosting bismuth nanoparticles (Bi NPs) [3]. Based on the optical contrast between the solid and liquid phases of materials, the use of low melting point materials with plasmonic properties such as Ga, Pb, Bi, Sn is promising to design spectral thermo-optical switches. Bi NPs containing glassmatrices show excellent stability and reliability for thermal optical switches candidates [3].

Thermal energy is stored in the Phase Change Materials (PCMs) through the phase transition, Solid-liquid transition is the most popular phase transition form used for thermal energy storage, due to the large enthalpy involved in the process [4,5]. The light transmission techniques on PCM are based on the variation of the transmitted intensity by different phases such as liquid or solid phase [6–9], Jana [10] did transmission measurements of bees wax of different vegetable oils to follow the crystallization behavior of wax. The transmissions were investigated for melted sample during the cooling phase. Light transmission techniques can be used to imply determination of wax appearance temperature [11].

We aim to study the thermo- optical properties of PCMs via simple light transmission techniques under the heating effect [12], Among PCMs, paraffin wax has many promising advantages such as its low vapor pressure, which facilitates controlling the reaction rate; its chemical inertness and low cost. paraffin wax composites are in solid state at room temperature, the so-formed material is opaque to light transmission. Therefore, by rising the temperature the composites acquire some transparency which allows the light to be transmitted under heating conditions. The switching temperature is the key factor for evaluating the thermo-optical switching performance. However, paraffin wax displays an unacceptable low thermal conductivity ~0.24 W/

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Nomenclature

G	Graphite
Gn	Graphene
G/wax	Paraffin wax hosting graphite
Gn/wax	Paraffin wax hosting Gn
T_{ON}	The switching on temperature during the heating phase
T_s	The saturation intensity during the heating phase
t_{ON}	The switching time during heating phase
t_s	The saturation time during heating phase
ηT_{ON}	The enhancement percent of the switching temperature
ηT_S.	The enhancement percent of the saturation temperature.
ηt_{ON}	The enhancement percent of the switching time
ηt_s.	The enhancement percent of the saturation time
S-S	Solid-solid transition
S-L	Solid-liquid transition

m K [5,13,14], which results in a limitation in enhancing the performance and energy storage devices. the use of carbon fillers inserted in the PCM matrix has proven to be successful, as their presence accelerates melting and solidification heat transfer rates [15–18]. Graphite (G)and graphene (Gn) exhibit a remarkably high thermal conductivities, thermal stabilities, carbon fillers have been the topic of many reports due to the significant improvement in thermal conductivity of PCMs obtained by adding a certain percentage of this carbon fillers [19–25].

In this work, the thermo-optical properties of paraffin composites hosting graphite or graphene at different concentrations are studied. TOS setup has been established based on transmittance, according to [26]. In particular, this paper compares the thermo-optical switching properties of graphite (G) and graphene (Gn) as catalysts to enhance thermal properties of paraffin wax based PCMs. The experiment is easy in construction and low cost introducing the use of PCM to TOS technology.

2. Materials and methods

2.1. Sample preparation

Paraffin wax (C_nH_{2n+2}, $n = 26$) was used from DIFCO laboratories as received. Graphite was obtained from JOHNSON MATTHEY CATALOG Company. The commercial chemical displays carbon graphite rods with an average diameter of 6.15 mm and 150 mm length, with a purity of 99.9995%. A small amount of graphite powder was grinded from the graphite rods into a micron sized material to be used in this work. Graphene was purchased from Nanotech Egypt for Photoelectronics. Nano sized graphene powder was used in this work, The synthesis of graphene was achieved by chemical reduction of graphene oxide according to [27–30]. Basic chemical-physical properties of materials are in Table 1.

Paraffin wax-graphite composites were prepared by the following procedure as illustrated in Fig. 1a: first, the wax was annealed to be molten; a certain concentration of graphite or graphene was then incorporated in the paraffin matrix. In the case of graphite-paraffin composites, 2.5 mL toluene was added into the molten paraffin wax (1.3 g) to promote homogenous distribution of the filler within the matrix, while no solvent was used for graphene-paraffin composites preparation. The molten was then constantly stirred for 2 h under heating at 70 °C. Two series of samples were prepared: graphite-paraffin composites dispersed in toluene with a percent ratio of 0.007%, 0.03%, 0.07%, 0.3%, 0.7%, 3% and 7%. The second series included graphene-paraffin composites with 0, 0.001%, 0.005%, 0.007%, 0.03%, 0.07% and 0.3%. The differences in concentrations of the above series are due to the more opacity of Gn which limits light transmission with increasing Gn concentrations. The total volumes of mixtures (Gn/Wax & G/Wax) are constant throughout all experiments.

2.2. Thermo optical switching based on transmittance setup

The previously prepared paraffin-carbon filler samples were annealed in a test tube of cylindrical shape under electric helical heater. The tester tube had an inner and outer diameter of 10 and 11 mm respectively, the tube is surrounded by a helical of copper wire in order to distribute the heat homogenously through the tube walls. Glass tube is not thermally isolated from the surroundings; this means there may be an exchange of heat between the wax medium and the surroundings. A diode laser of 677 nm wavelength incident on the test tube (power 4 mW); while the test tube under electric heating via helical copper heater surrounding the tube with power 100 mW (the orange helix in Fig. 2). As the wax is in solid state at room temperature; no transmitted light is observed due to its opacity. When the wax temperature is raised under the effect of heating, it undergoes phase change and the transmittance is increased obviously. Light transmission is recorded via a power meter (Thorlabs S142C). A thermocouple is inserted inside the tube to analyze the temperature gradient during heating and cooling. Both transmittance and temperature were recorded every 1 s. The experimental setup is shown in Fig. 1b. no focusing unit is used in the setup to allow the laser transmission in a larger area in the material.

Differential Scanning Caliormetery (DSC) were investigated to determine melting temperature, solidifying temperature, latent heat capacity, heat gained, and heat lost of paraffin wax composites (DSC-50, Shimadzu, Coulombia, MA, USA). DSC measurements were performed at10 °C/min heating and cooling rates for temperature range from room temperature to 90 °C. Scanning electron microscopy (SEM) was carried out using QUANTA FEG250 SEM instrument (FEI, Hillsbor,OR, USA).

3. Results and discussions

3.1. Morphology

For graphite paraffin wax composite, some agglomerations of graphite particles were observed in some regions, revealing a non-homogenous distribution of graphite in paraffin wax (see Appendix A). Scanning Electron microscopy SEM of paraffin wax composites are shown in Fig. 1. When toluene was used as solvent, paraffin wax-graphite samples exhibited not only better homogeneity but also transparency was observed, which increased for lower graphite contents. Graphene-paraffin samples were not mixed with solvent, showing remarkable homogeneity and transparency, Graphene is well dispersed in the wax matrix as seen in Fig. 1.

Table 1
Thermo-physical properties of paraffin wax, graphite G and Graphene Gn, s solid, l liquid.

Material/Charecteristics	Paraffin wax	G	Gn
Density Kg/m^3	900 s 800 l	500	250–700
Spesific heat J/Kg·°C	800	700	
Latent heat J/Kg	173		
Thermal conductivity W/m K	0.167 l 0.346 s	150	2000–4000
melting temperature °C	64	3000	3852