

Light-Driven Actuators

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And

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Abstract

Light is a clean form of energy. The ability to use light to cause mechanical motion is relatively a new area of research that can bring benefits such as remote control of actuators and micro-machines. Graphene is a 2D nanomaterial that has high mechanical strength, thermal conductivity, and broad optical absorption. Graphene nanoplatelets (GNPs) dispersed into a polymer not only improves mechanical strength and thermal conductivity but also enables high-performance photomechanical actuators.

In this project, we dispersed (GNPs) into a Polydimethylsiloxane (PDMS) elastomer matrix to test the nanocomposite's mechanical responses after being exposed to near-infrared light (NIR) in timed illumination cycles of on for 90 seconds and off for 50 seconds. Different concentration levels of GNP to PDMS (0.1-2 wt%) nanocomposites were made, and varying levels of pre-strain (3%-40%) were applied to each test sample before it underwent the illumination cycle. Highly stretched test samples showed reversible contraction while lowly stretched test samples showed reversible expansion.

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1. Introduction and Background

According to the U.S. Energy Information Administration, in 2016 only 10% of the U.S. energy consumption came from renewable energy [1]. The remainder of that energy is coming from fossil fuels such as natural gas and coal. The widespread use of these non-renewable energy sources is a major contributor to the declination of the earth's environment. With a continuous push to conserve the environment, renewable energy sources are as important as ever. Light is a universal clean form of energy, meaning it will not harm or pollute the environment. Light energy provides advantages that other forms of energy cannot provide; it allows us to control devices remotely and wirelessly. The use of light as input energy to cause direct mechanical work is a relatively new field of study but has many potential applications. [2, 3]

Light-driven actuators are materials and devices that can produce a mechanical response from light. [4] As the study of nanomaterials that have photomechanical actuation increases, the potential applications for light energy increases too. The properties and advantages of light energy could lead to different applications in micromechanics, sensors, and the biomedical field. Within the past 20 years, nanotechnology has grown exponentially and will continue to grow as the popularity of miniaturization grows. [6]

Graphene is one of the world's first 2D materials that have unique mechanical, electrical, optical, and thermal properties. [5, 6] Graphene or "2D graphite" is a relatively new material, discovered in 2004. [5] It is one atom thick and made of carbon atoms arranged in a honeycomb lattice. [7] Graphene nanoplatelets (GNPs) are stacks of graphene sheets usually 5-15 nm thick and have been on an upward trend to create polymer composites because of the advantages they provide in a host material. [10] Graphene's ability to absorb large amounts of light is also a unique and interesting property, especially considering that it is only one atom thick. This is due

to its electrical properties. The electrons act like massless charge carriers with very high mobility. Adding another layer of graphene increases the amount of light absorbed. [11, 12] They are a great addition to polymer composites because of graphene's high tensile strength, high modulus of elasticity, and Quantum Hall Effect at room temperature. [8, 9] Smart materials like graphene and carbon nanotubes can undergo actuation in a nanocomposite when triggered by light as the external stimuli. [8, 13]

By dispersing GNPs into a host elastomer such as PDMS (polydimethylsiloxane), a polymer-graphene nanocomposite results. [14] Nanocomposites are great for many applications since the filler improves the host matrices' properties including thermal, electrical or mechanical properties enabling the composite to be used in high-performance applications. [6] The properties of the nanocomposite depend strongly on the dispersion of GNPs.

In this project, GNPs were dispersed into PDMS by wt% ranging from 0.1 to 2wt% GNP-to-PDMS, to test the nanocomposite's mechanical actuation after undergoing five cycles of illumination from the near-infrared light of on for the 90s and off for 50s. Each test strip underwent a pre-strain before it was subject to the illumination cycle which ranged from 3-40% strain of its original length. Lastly, the change in temperature of each test strip was measured using a thermocouple to see the thermal effects that resulted from absorption of light.

2. Methodology

2.1 Preparing the Samples

The first step was to prepare samples of the GNP and PDMS nanocomposites at different GNP concentrations for testing. Wt% is the ratio of GNP to PDMS in the mixture. Below is an example calculation of 5wt%.

$$\text{wt\%} = \frac{\text{weight of nanoparticles}}{\text{weight of PDMS base}}$$

$$\text{Total Mass of base + GNP} = (\text{Mass of base}) * (1 + 0.05)$$

$$\text{GNP} = 0.05(\text{Mass of base} + \text{GNP})$$

We first measured out ~15g of PDMS Sylgard 184 silicone elastomer from Dow Corning, USA. The GNPs were weighed and added to the composite based on the desired wt% of the graphene to PDMS base. This was then shear mixed for at least 24 hours depending on the wt% to ensure a homogeneous mixture. Then we added a curing agent, hydrosiloxane, at a weight ratio of 1:10 as the crosslinker. We mixed this for another 10 minutes then degassed it to remove air pockets. This degassing process was repeated until no bubbles resided on the top of the mixture. The polymer mixture was dispersed onto glass slides and then spin coated at 750rpm for 150s to produce nominally thick films of 60 micrometers. It was then cured at 125C for 20 minutes to finish the curing process. We then cut the samples to approximately 30mm long test strips to put into the test set-up. A plain PDMS polymer composite was also prepared and tested to have a comparison.

2.2 Stress Testing

A previously designed test set-up dynamometer as shown in Figure 1b was used to test the photomechanical actuation responses of the sample. The 30mm long sample was placed vertically between two clamps. [15] The bottom clamp was weighed down by a 100g mass which sat on top of a highly accurate and precise scale. This scale was used to measure the force experienced by the test sample. The height of the top clamp was adjustable so that different restraints could be set. An 808nm 500mW laser was placed roughly 75mm from the sample. The laser pointed directly in the middle of the vertical test strip sample. Figure 1a) shows a picture of the strip between the two clamps and on the scale. Figure 1b) shows a 3D model of the test dynamometer.



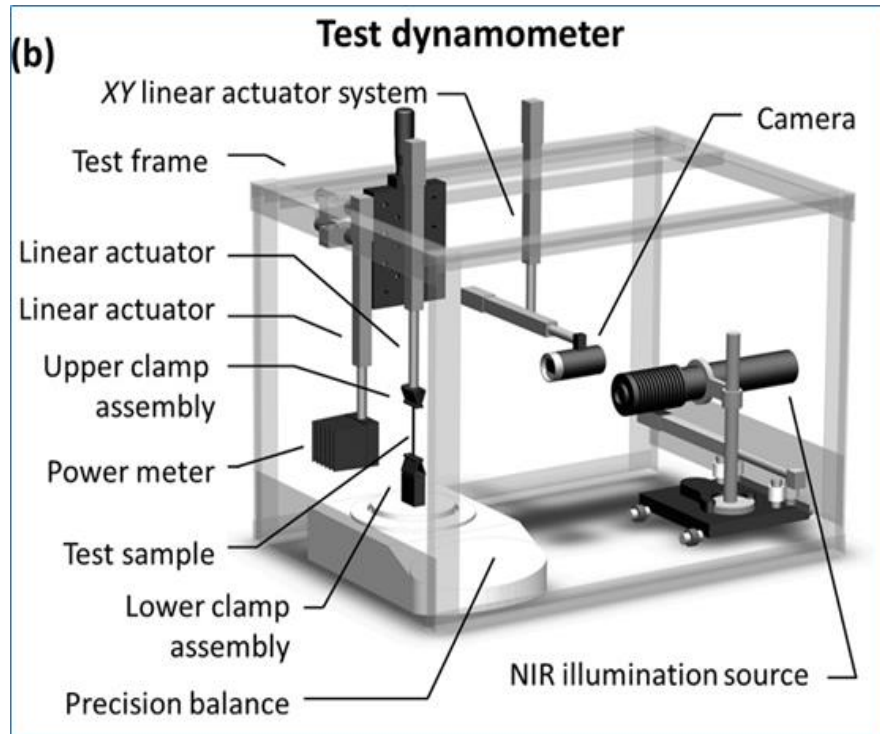


Figure 1: a) Picture of the test-setup shown with the sample between the two clamps and b) 3D Model of Test Dynamometer

An illumination process of the laser on for 90 seconds and off for 50 seconds was conducted for each wt% sample and for every strain percentage. When the laser was on, the deformation of the test strip caused a change in the scale reading. The data was collected via a previously coded LabVIEW program. The program logged the power (recorded by the power meter) and the force (recorded by the scale) into an excel sheet for further analysis. This data was then used to make the stress calculations. There was a camera inside the test setup which allowed us to monitor the whole experiment. Overall for each sample, we tested pre-strains from 3%-40%. The test sample underwent strain by manually twisting a knob in the test set up which pulled the upper clamp up and thus stretched the sample. We knew how far we were stretching it based on how many times we turned the knob. We used the engineering strain formula shown in equation [1] below to calculate how much we wanted to stretch the sample based on the strain we desired for that experiment.

$$\text{Strain} = \frac{\Delta L}{L_0} \quad [1]$$

2.3 Optical to Mechanical Energy Conversion Calculation

The optical to mechanical energy conversion factor was calculated to see the relationship of the input light absorption to the output mechanical work. Equations [2] and [3] below were used to find the energy conversion factor ultimately η_M

$$P_{effective} = \left(\frac{P_{laser}}{A_{spot}}\right) * A_{incident} \quad [2]$$

$$\eta_M = \frac{\Delta\sigma_{total}}{P_{effective}} \quad [3]$$

Where:

$P_{effective}$ = effective laser power

P_{laser} = amount of power absorbed in the sample

A_{spot} = area of spot size

$A_{incident}$ = area for absorption within the film

$\Delta\sigma_{total}$ = total change in engineering stress from max expansion to max contraction

2.4 Thermal Response Testing

A thermocouple (Omega, K-type) was used to analyze the temperature changes of the strip while being exposed to NIR. The thermocouple was placed against the test strip between the two clamps in the test dynamometer. The illumination cycle was then run on each test strip, 0.5wt%, 1wt%, and 2wt% GNP/PDMS and the data of temperature vs. time was plotted.

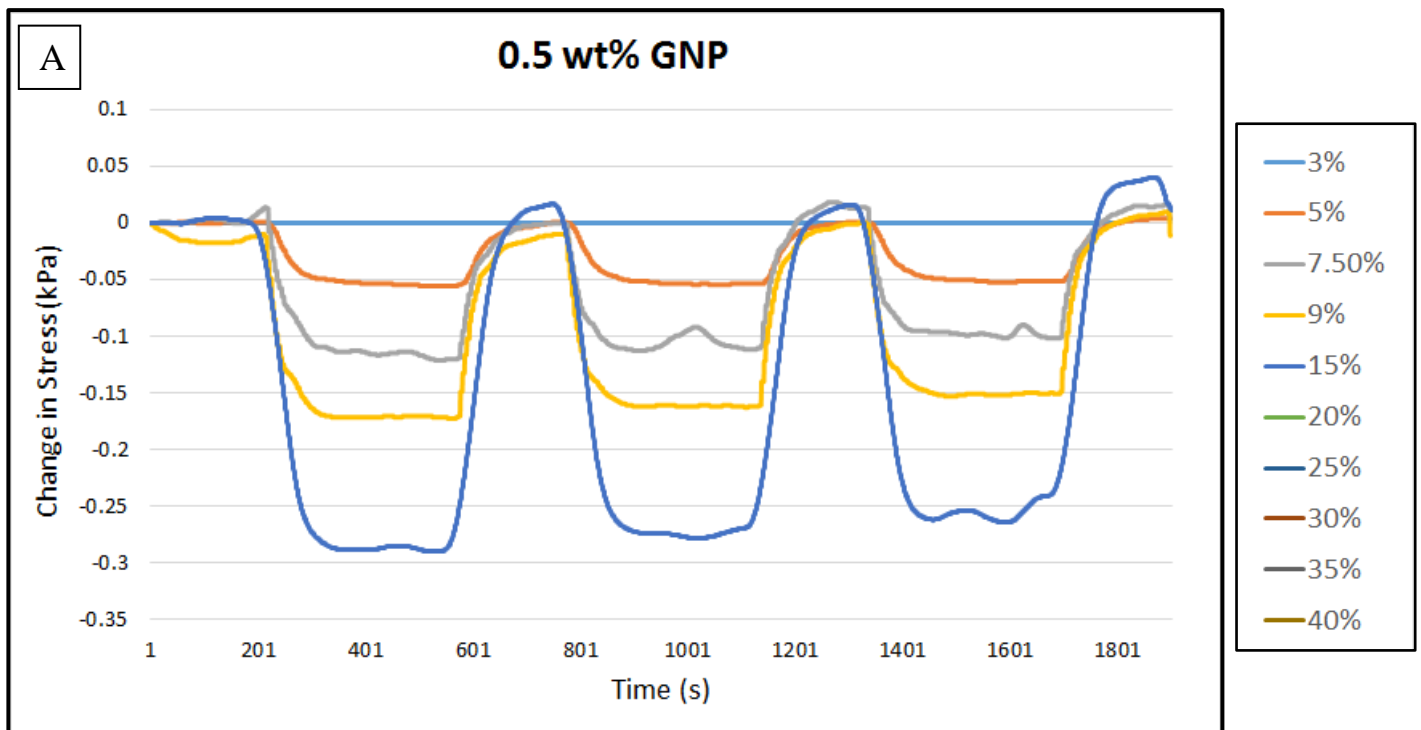
3. Results and Discussion

3.1 Change in stress vs. time for the three samples at various pre-strains

The photomechanical induced stress changes for the three samples were calculated by using the engineering stress shown in equation [4]. The force was found by multiplying the change in mass on the scale reading by $g = 9.81 \text{ m/s}$. The cross-sectional area was calculated using the width and thickness of the samples. The width was found by using a pair of calipers, and the thickness was found using a micrometer.

$$\sigma = \frac{F}{A} \quad [4]$$

Figure 2 below shows the photomechanical induced stress for the three samples. To the right of the graph shows the color-coded pre-strain values.



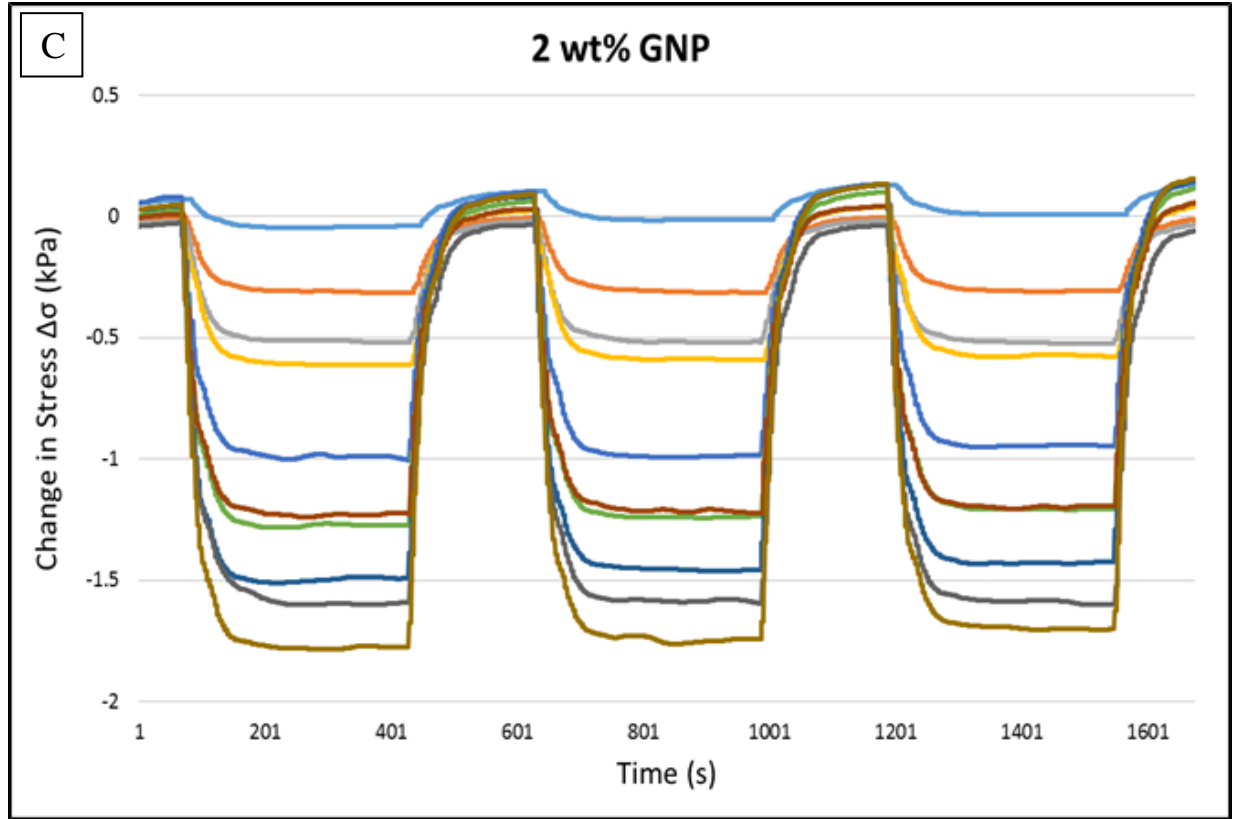
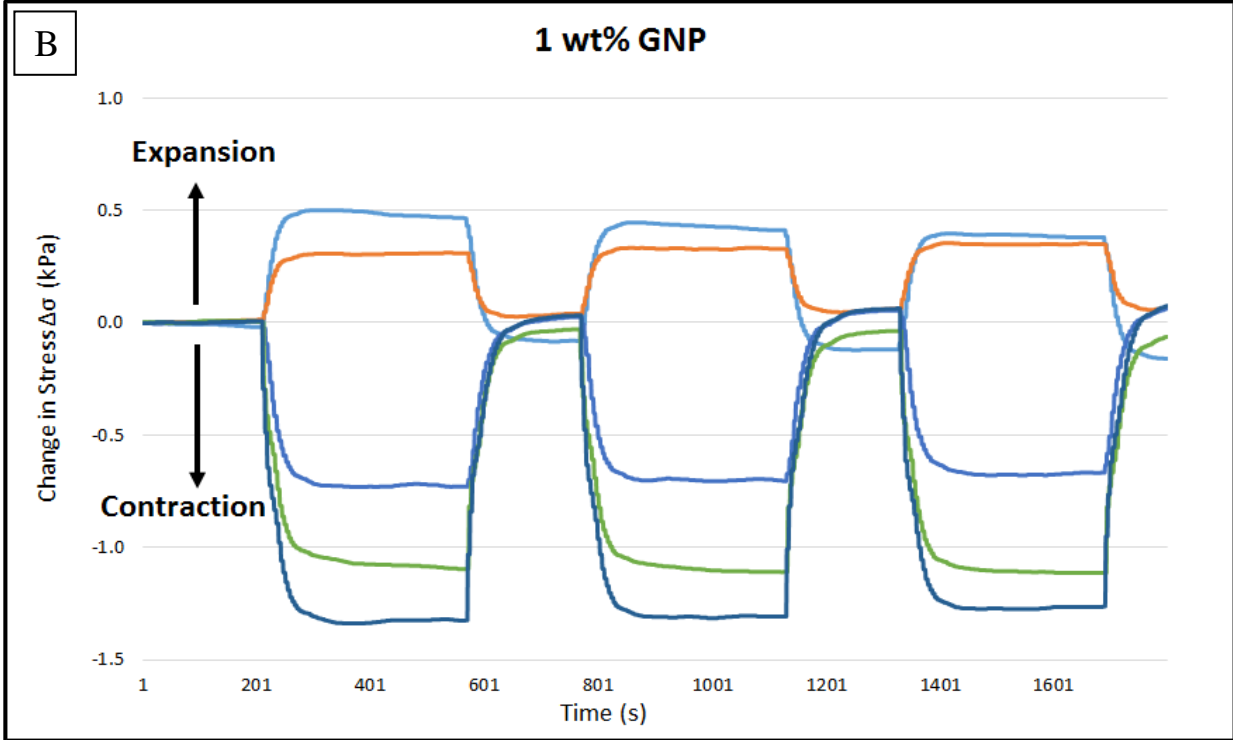


Figure 2: Photomechanically induced stress changes in GNP/PDMS composites as a result of NIR illumination for increasing GNP concentrations with (a) 0.5wt% (b) 1wt% and (c) 2wt%

The results show how at high levels of pre-strain (15%-40%) the actuation response was reversible contraction while at low levels of pre-strain (3%-15%) the actuation response was reversible expansion.

As shown in Figure 2c), at 2wt% GNP-PDMS, the change in stress was the greatest while in Figure 2a) the 0.5wt% GNP-PDMS, the change in stress was the smallest. As the wt% of the graphene nanoplatelets increased, there was more of an actuation response since more energy was being converted due to the greater presence of the GNPs. This confirms how GNPs improve mechanical properties in the host elastomer matrix.

3.2 Change in stress vs. Prestrain

We also wanted to evaluate the effects pre-strain had on the actuation response. Figure 3 shows the change in stress vs. pre-strain % for the 2wt% sample. As the strain increased, the change in stress also increased. As the sample became more elongated from the increase in pre-strain, the GNPs became more aligned concerning one another thus increasing the change in stress and yielding a larger actuation response. Aligned nanoplatelets yield a stronger reinforcement of the GNPs in the matrix.

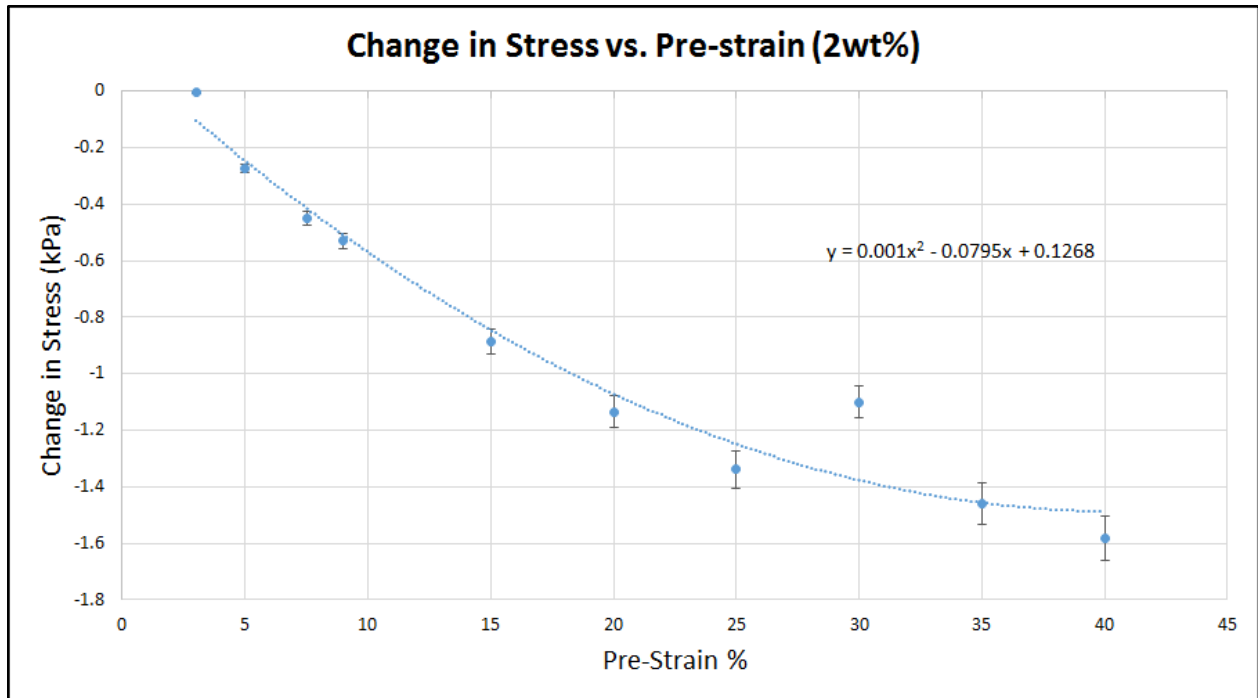


Figure 3: Average Actuation Response vs. Prestrain with ± 1 standard deviation error bars

The equation in figure 3 is the best-fit curve for the collected data points and could help predict the change in stress for different pre-strains.

3.3 Temperature vs. time

After running the illumination cycle again on the three test strips, it was found that the higher GNP wt% resulted in a higher temperature change. As shown in figure 4, there was a 1.74°C change in temperature for 2wt% whereas the 0.5wt% and 1wt% samples only changed the temperature by roughly 1°C. This proves how adding GNPs to an elastomer matrix also improves the thermal properties. As is the case with the stress response, more GNP means that more of the light will be converted to mechanical and thermal energy.

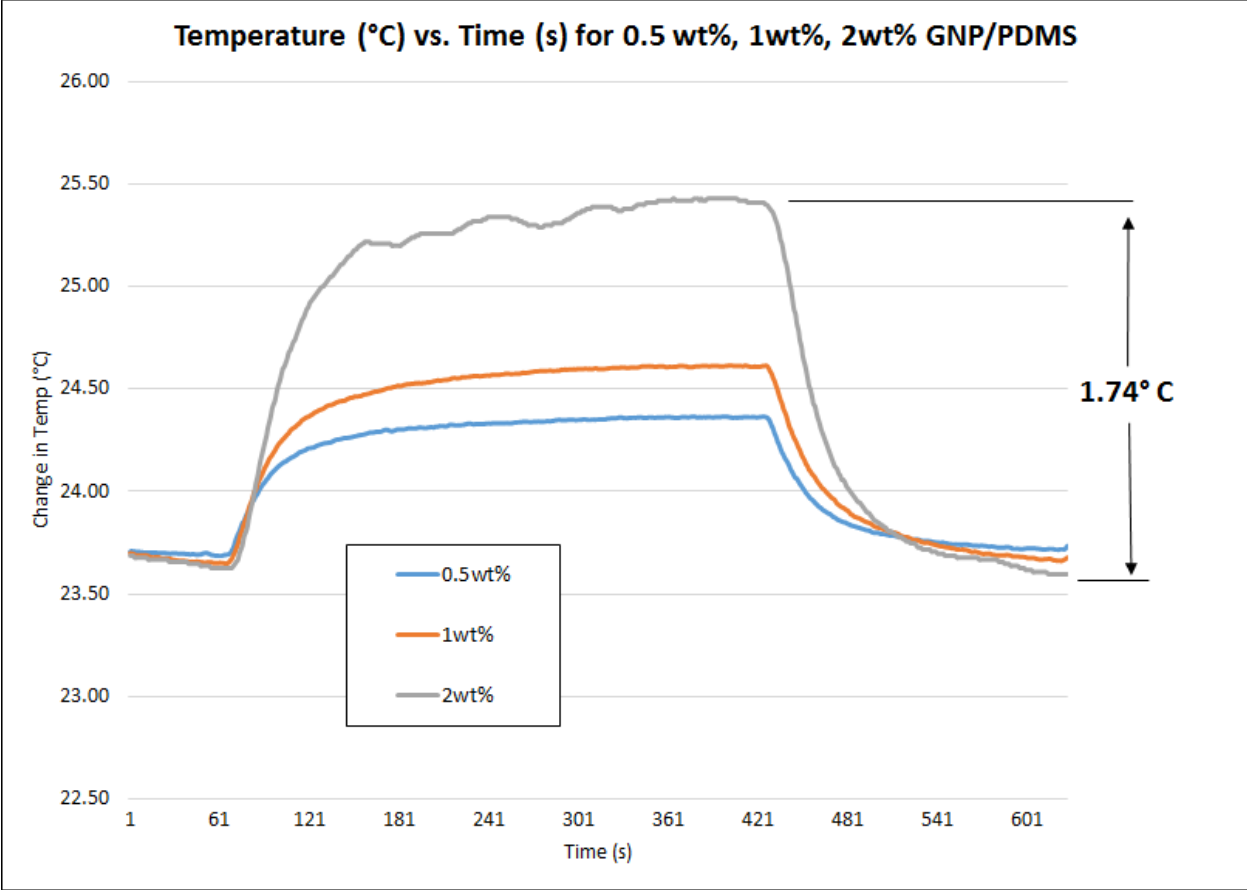


Figure 4: Temperature vs. Time Measurements for 0.5 wt%, 1 wt%, and 2 wt% GNP/PDMS

3.4 Pre-strain vs energy conversion factor

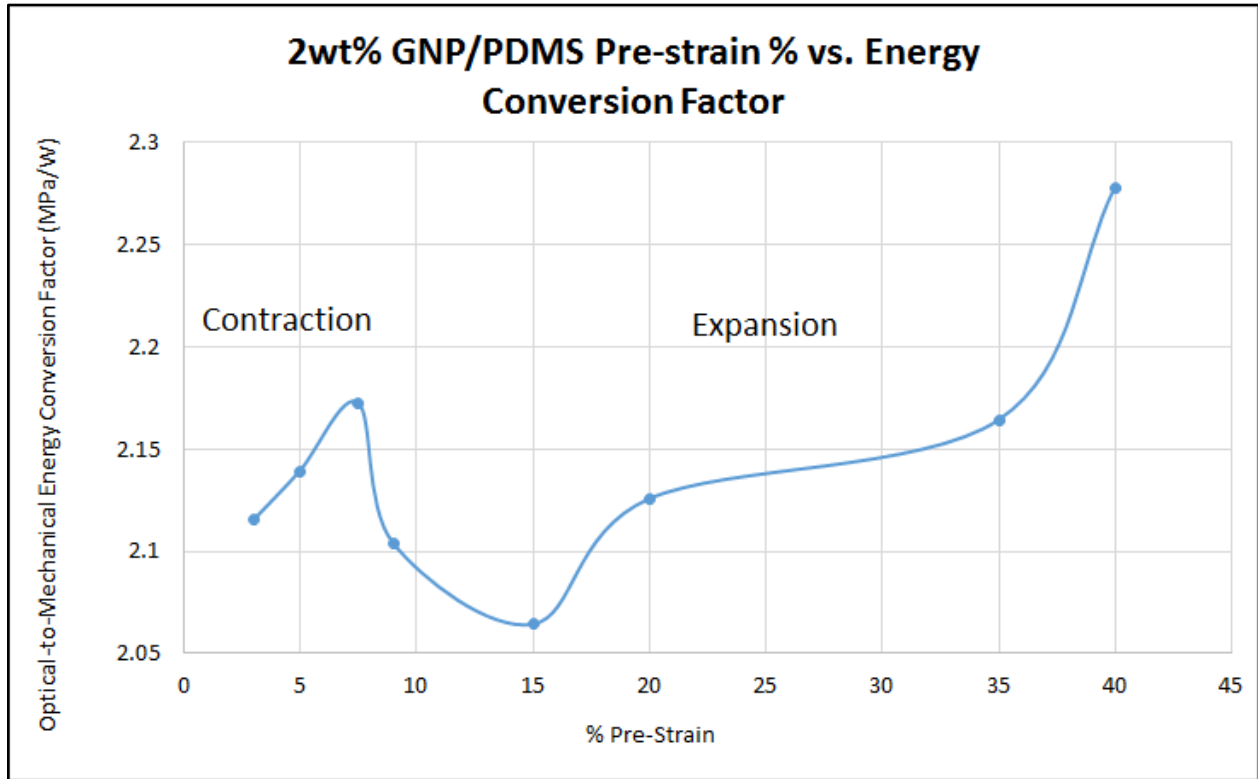


Figure 5: Optical-to-Mechanical Energy Conversion Factor vs. % Prestrain for the 2wt% sample

By using Equations [2] and [3], the effective laser power was determined. The total change in engineering stress divided by the effective laser power was calculated to find the optical-to-mechanical energy conversion factor.

We did this for each pre-strain of the 2wt% test sample to show how at lower levels of pre-strain (3~9%) there was a relatively medium energy conversion factor and how at mid-levels (9-15%) the factor decreased. This corresponds with the stress - wt% graphs since there was a minimal change in stress at these medium levels. At high levels of pre-strain the energy conversion factor increased significantly, especially at the highest pre-strain of 40%. This too

agrees since the maximum change in stress happened at the highest pre-strains. Figure 5 shows the conversion factor for each pre-strain.

4. Conclusions and Future Work

In this study, our test results display that dispersion of GNPs into a PDMS silicone elastomer matrix triggers a photomechanical actuation response. The polymer actuator showed reversible light-induced elastic expansion and contraction. For a one wt% sample, a photomechanically induced change in stress of 0.5 kPa at low pre-strains and -1.25 kPa at high pre-strains was successfully demonstrated. Our samples exhibited an optical-to-mechanical energy conversion factor of $\eta_M \sim 2.15 \text{ MPa W}^{-1}$.

There are few materials that exist that can convert photons of different wavelengths into mechanical motion that is large enough for practical purposes. [16] There is still need for a material design that is simple, versatile, reversible, wavelength selective, scalable and encompasses large optical to mechanical stress response that is based on their unique structure based tunability in optical absorption at different wavelengths.

GNP/PDMS composites have a variety of possible future technological applications as photomechanical actuators; one can develop soft robots or surfaces that can undergo simultaneous expansion and contraction. [17, 18, 8] On a small scale, this could be used for assembling surfaces to study mechanical forces on soft matter, such as biological materials like cells. By delivering forces to cells directly, one could risk damaging them or introducing foreign materials or bacteria to the system which could prove harmful to the study. By using a GNP-polymer surface, the forces could be delivered in a non-contact manner using photomechanical actuation.

The thermal improvements graphene makes in a polymer can translate well into different applications. For example, being able to thermally control the nanocomposite based on dispersion could be used for the management of thermal properties for miniature electronic devices. [19] In miniature electronic devices, the power dissipation in the form of heat has a significant effect on the life span and total power output of the device. Thermal interface materials are used to connect different thermal elements. It is important to minimize the thermal contact resistance to have the most efficient power output. The thermal contact resistance mostly results from a mismatch of thermal expansion between two interfaces. Many of these interface materials are hybrids of polymers that have low thermal conductivity and will not be able to keep up with future technology. [20] Graphene is a potential applicant for a thermal interface material since it has a very high thermal conductivity. Furthermore, the expansion from heat in a GNP nanocomposite could help prevent gaps that form between thermal interface materials and thus improve the effective heat dissipation. [20] Another use is for thermal pastes. Thermal pastes are often applied between two interfaces to prevent gaps and enhance thermal contact. These thermal pastes must be thin, have high thermal conductivity, and be able to conform to the topology of the surfaces which would further prevent gaps. [20]

Graphene-polymer nanocomposites also have many potential applications in the biomedical field including drug delivery, biosensing, cancer therapy, and tissue engineering. [21, 16] Scientists are also researching their potential applications in energy technology. Graphene was only discovered in 2004, so it has not been investigated too much; there are still many qualities and features we do not know about it. Once more research is done on graphene-polymer nanocomposites, we believe there will be a plethora of applications in various fields of research.

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