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Dielectrophoretic Trapping of Carbon Nanotubes for Temperature Sensing

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DIELECTROPHORETIC TRAPPING OF CARBON NANOTUBES FOR TEMPERATURE SENSING

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Approved by
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APPROVAL OF THESIS

We, the faculty supervising the work of Kaylee Burdette, affirm that the thesis meets the high academic standards for original scholarship and creative work established by the M.S.E in Electrical and Computer Engineering and the Department of Computer Sciences and Electrical Engineering. This work also conforms to the editorial standards of our discipline and the Graduate College of Marshall University. With our signatures, we approve the manuscript for publication.

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ABSTRACT

Conventional sensors are rapidly approaching efficiency limitations at their current size. In designing more efficient sensors, low dimensional materials such as carbon nanotubes (CNTs), quantum dots, and DNA origami can be used to enable higher degrees of sensitivity. Because of the high atomic surface to core ratio, these materials can be used to detect slight changes in chemical composition, strain, and temperature. CNTs offer unique advantages in different types of sensors due to their electromechanical properties. In temperature sensing, the high responsiveness to temperature and durability can be used to produce an accurate, reliable sensor in even extreme temperatures. This study aimed to utilize CNTs to reliably produce a temperature sensor in an easily reproducible method. CNTs were trapped and immobilized using dielectrophoresis to bridge two gold nanoelectrodes on a sapphire substrate. The fabricated device showed high sensitivity to temperature variation, with a measured resistive sensitivity of 2.96 E-3/K, a higher sensitivity than similar thin film sensors. This study will help further development of CNT-based temperature sensors.

CHAPTER 1

INTRODUCTION

As technology advances, the use of more sensitive sensors for gas, temperature, and even pressure and strain sensing are in more demand. Sensors can be used in food and agriculture for detecting food spoilage [1], in labs to detect vapor levels [2], and even used to detect explosives via vapor [3].

Temperature sensors make up a large portion of the global sensor market [4]. They are used in a wide variety of fields, from commercial use in appliances to more demanding industrial and lab environments. Some applications, especially those used in controlling an environment, require high accuracy and fast response times. In cryogenic settings, it is especially vital that the temperature sensor is extremely accurate [4, 5].

Good temperature sensors must be reliable with fast responses, low power draw, low heat dissipation, and specific point accuracy [4]. Many require low costs and stability over time and in a range of environments. Miniaturization is a solution to some of these constraints, but it is difficult to remain within all acceptable limits [6].

Nanomaterials are one way to achieve accurate, reliable sensors. Cost with a lot of nanomaterials is low, and the extremely small dimensions lead to very fast response rates [6]. In addition to enhancing the sensor properties, nanomaterials in sensors can be incorporated into a variety of materials including wearable strain sensors or energy harvesters [7-10]. The variability of some nanomaterials means that they are tunable to a specific application. In photovoltaics, quantum dots can be tuned to specific wavelengths of light based on their size [10]. Carbon nanotubes, another type of nanomaterial, have tunable electrical and mechanical properties ideal for a range of different sensor types [11, 12].

Carbon nanotubes have other properties that make them ideal as temperature sensors. They are able to remain operable in extreme temperatures [4, 5, 13]. They're also fairly low cost and are very sensitive to temperature change [14].

Carbon nanotube-based sensors can be fabricated a few different ways. Thin films utilize a large number of nanotubes by spraying, gluing, or even printing an extremely thin layer of nanotubes onto a surface. These sensors can be carbon nanotube-based composites or pure carbon nanotubes. More precise amounts of nanotubes require a form of nanoparticle manipulation. These involve utilizing forces to move and trap the nanoparticles to incorporate them into the sensor.

In this study, different numbers of carbon nanotubes were incorporated into a temperature sensor by using dielectrophoretic force.

Motivation

The sensor industry is rapidly approaching conventional sensor efficiency limits. One solution to this is the miniaturization of sensors. Nanoparticles in circuitry is the next big step towards more efficient sensors. Low dimensional materials such as DNA origami, thin films, and quantum dots have been used in sensors.

This study will focus on the specific benefits of carbon nanotubes as a sensor medium for temperature sensing, including their unique electrical properties. The tunability of carbon nanotubes and subsequent sensor properties is another draw for their use. By changing the type and/or number of carbon nanotubes on a sensor, the effectiveness for a certain application can be altered.

Objectives

The objectives of this study were to develop a sensitive carbon nanotube-based temperature sensor with comparable sensitivity to other nanosensors using dielectrophoretic trapping. Since lower dimensional materials lead to greater sensitivity, a carbon nanotube-based temperature sensor should have a higher sensitivity than similar thin film sensors. This study also investigates the properties of carbon nanotubes as used in a temperature sensor, and the effect of the number of nanotubes used.

CHAPTER 2

LITERATURE REVIEW

Introduction

This study investigates the use of carbon nanotubes (CNTs) in a temperature sensor. This chapter covers some of the background necessary to understand the current state of nanomaterials in sensors and the methods used.

First, the benefits of nanoparticles in sensors are explored. Using nanoparticles (decreasing the 'dimensionality') ensures a sensor that is extremely sensitive to environmental changes. Next, we delve into the electromechanical properties of carbon nanotubes (CNTs) and what makes them particularly viable for temperature sensors. Finally, we cover sensor fabrication methods via nanoparticle manipulation.

Nanoparticle-Based Sensors

Sensors used in industry and elsewhere have a few metrics commonly used to determine their relative efficacy. Sensitivity, selectivity, stability, drift, and response time are all consideration factors for a sensor's performance [4, 15, 16]. Sensors require an external stimulus to trigger a measurable change in the sensor's output. For this review, only sensors whose resistance and bandgap changes with stimuli will be covered in any detail. These include conductance, capacitance, and resistance changes in the output signal as a response to stimuli. The sensitivity of a sensor and the limit of detection are closely related. The limit of detection is the minimum value of an analyte required for detection. Lower limits of detection mean higher sensor sensitivity. Selectivity is the ability for a sensor to distinguish between a target stimulus and interference [15]. In a chemical sensor, a sensor would need to detect only the target analyte while being unaffected by other chemicals, which becomes harder with very similar molecules

[1]. Sensor drift is a change in the sensor's output over time, with no corresponding change in the environment [17]. This can lead to false responses or lack of response, and lead to unreliable results and frequent recalibration. Sensors need to remain accurate to be reliable. Finally, sensors need to respond quickly to a change in environment. This is especially vital for sensors involved in safety and regulation, as often they are used in part of a feedback system [18].

As technology advances, traditional sensors are approaching their limits [16]. Newer sensors are compatible with miniaturization and the significant advances that follow this development step [4]. The dimensionality of sensors is now being lowered to increase efficacy by improving the surface area in contact with the environment for sensing [11]. 2-dimensional (2D) thin films and nanosheets made from carbon nanotubes and metal oxides have been used for chemical sensing [18, 19], 1-dimensional (1D) nanotubes and nanorods for vapor and temperature detecting [20-22], and 0-dimensional (0D) quantum dots for pH sensing [23], among other uses. Low power, cost, and space are often necessary for space technologies and biosensors that can be placed on or in the body [24, 25]. Using lower dimensional materials requires less power draw and takes up significantly less space than conventional sensor materials [6]. DNA origami, graphene-based thin films, and carbon nanotubes (CNTs) are all used in the new wave of miniaturized sensors [6, 26, 27].

Structure and Properties of Carbon Nanotubes

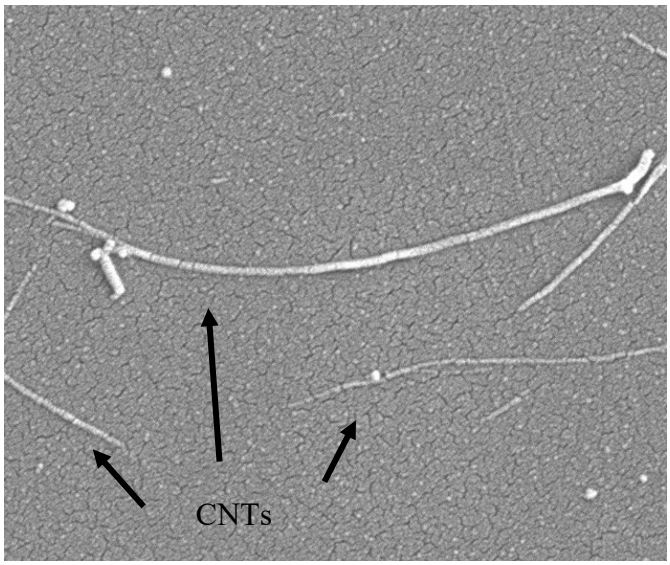


Fig. 1. Carbon nanotubes
An SEM image of carbon nanotubes.

Carbon nanotubes are made up of tubes of carbon rings (Fig.1). Nanotubes can be thought of as a monolayer of carbon atoms rolled along an axis. When the nanotube consists of only one graphene sheet rolled, it is referred to as a single walled carbon nanotube (SWCNT). A nanotube with two or more graphene sheets stacked and rolled is referred to as a multi walled carbon nanotube (MWCNT).

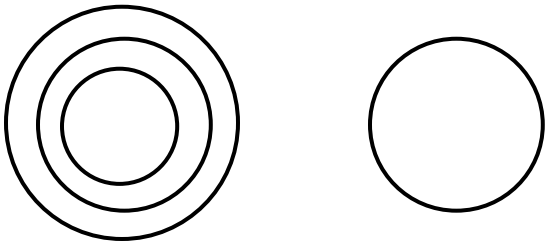


Fig. 2. Cross section of multi walled versus single walled nanotubes
A representation of MWCNTs vs SWCNTs. A MWCNT, pictured left, is made up of multiple concentric layers of rolled carbon atoms, while a SWCNT is a single layer.

The number of 'walls' has interesting implications on the electric and sensing properties of the CNT itself. MWCNTs are generally less sensitive than their single walled counterparts [28] since not all of the atoms are exposed to the 'outside' of the structure, meaning there is less surface area for an analyte to interact with.

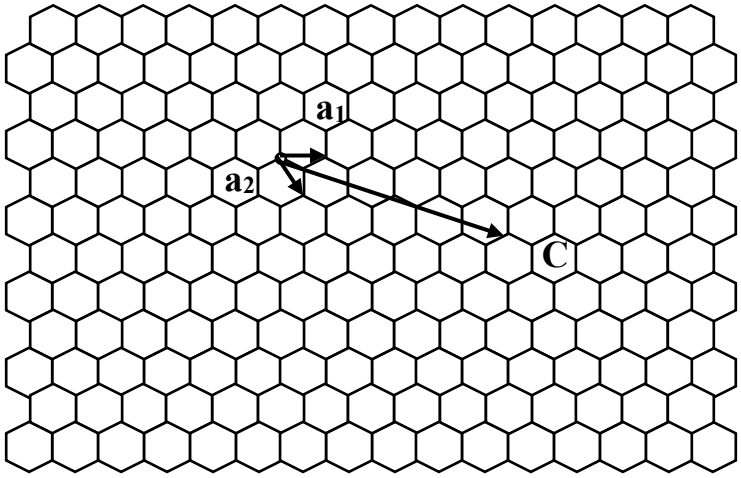


Fig. 3. Nanotube wrapping on a graphene sheet
C is the chiral wrapping vector, while a_1 and a_2 are lattice vectors.

Another major player in the mechanical, optical, and electronic properties of a given CNT is the chirality, or the asymmetry of the nanotube [12, 29, 30]. As shown in Fig. 3, a

nanotube is rolled along some vector C, defined as the chiral wrapping vector. The angle of this vector in relation to the two unit vectors a_1 and a_2 gives the equation

$$C=n\mathbf{a_1}+m\mathbf{a_2} \quad (1)$$

where (n,m) are indices that indicate the wrapping sites in relation to the origin. If n = m, the nanotube is metallic. Likewise, any combination of n and m such that n – m = 3N where N is some integer also produces metallic nanotubes [31, 32]. All other chiralities produce semiconducting nanotubes [31]. A majority of nanotubes are semiconducting [33]. These nanotube types can be used for different purposes, including in the use of integrated circuits, where semiconducting nanotubes can be used as transistors and metallic nanotubes can work as connectors [26].

The diameter of the CNT also plays a role in the electric and mechanical properties. Strain sensors rely on the Young's modulus of the material, a number that has to do with how well a material handles inelastic strain. A smaller diameter increases the Young's modulus of the CNT, meaning SWCNTs have superior flexibility and strength [11]. In general, CNTs have extremely high flexibility along with high strength and stiffness, making them ideal candidates for flexible sensors. Sibinski *et al.* covered the use of CNT fibers in yarn for sensors integrated into clothing and Yamada *et al.* covered the use of nanotubes for bandages and other biosensors [7, 25]. The diameter also plays a role on the bandgap of CNTs. The bandgap, or energy gap, refers to the amount of energy required to pass from the valence to conduction band of a material. Fig. 4 shows the bandgap for a conductive material versus a semiconductive material. For metallic nanotubes, bandgaps are negligibly small. Bandgaps of semiconducting nanotubes, however, change inversely with diameter, from 0.18 eV of a very large SWCNT to 1.8 eV for small diameter nanotubes [34].

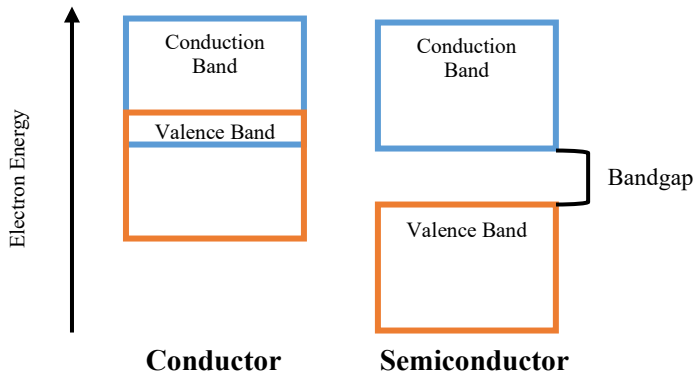


Fig. 4. Bandgap energy
A chart of the bandgap for various materials. Less conductive materials have a higher bandgap. Conductors have negligibly small or even overlapping conduction and valence bands.

The unique mechanical and electrical properties of carbon nanotubes make them an extremely viable candidate for nanosensors [35]. Carbon nanotubes can be incorporated into sensors as individual tubes, bundles of nanotube fibers, or as part of a polymer nanocomposite [4]. In addition, carbon nanotube based sensors can work under extreme temperatures, including cryogenic environments [5].

The overall properties of a given batch of carbon nanotubes and the subsequent "purity" of their formation depend largely on synthesis [32, 36]. Firstly, the size of the nanotubes themselves are determined in most synthetization by the size of the catalyst [37]. This means to tune the diameter (and therefore the electrical and mechanical properties) the method of synthesis needs to be tuned as well. The purity of the resultant nanotubes is also a concern. Certain applications require semiconductor nanotubes rather than metallic, and vice versa, but there is currently no process that will selectively produce only one type of nanotube [37]. Recent studies have attempted to control the chirality output of synthesized nanotubes with one study

achieving 97% purity, which is still below the required threshold for high-end electronics applications [38, 39]. These impurities must be considered for the experiment.

Carbon Nanotubes for Temperature Sensing

Using carbon nanotubes for temperature sensing relies on the inherent properties of the CNTs and their reaction to temperature change [19]. There are a couple of different methods that can be used with CNTs to detect change in temperature. One of these is Raman band shifting, which can be observed with CNTs embedded in polymer matrices [40]. Unfortunately, inconsistencies in the embedded nanotubes (including chirality, size, and type disparities) have a significant effect on the efficacy of this method [40]. Due to the unpredictable and inconsistent nature of synthesized nanotubes, this study will be focusing on the second method for temperature sensing, which is monitoring electrical changes.

CNTs have a strong temperature dependence on conductivity [14, 19]. The resistivity of CNTs decreases with temperature and the conductance increases [24]. This means that these properties can be exploited to detect temperature change.

Sensor Type	Deposition Method	Description
Thin Film	Printing, Spraying, Gluing, CVD	Involve a thin coating of CNTs or a CNT-based composite material. Considered 2D.
CNTs or CNT bundles	DEP, drop deposition, or other nanomanipulation	Involve individual or bundles of carbon nanotubes. Considered 1D. Generally more sensitive than thin films [4].

Table 1. Sensor Types
A table comparing sensor types. DEP = dielectrophoresis, CVD = chemical vapor deposition.

CNTs can be incorporated into sensors in a few different ways, as shown in Table 1. Thin films, used for some resistance-based sensors, involve depositing a thin layer of CNTs or a CNT-based composite onto a surface for use [6, 19]. Thin-film based sensors utilize methods such as chemical vapor deposition and spray coating to completely coat an area of interest [4]. More sensitive 1-D sensor technologies rely on other methods for the precise manipulation of much smaller amounts of CNTs.

Trapping of Nanoparticles

One concern with using nanoparticles in sensors is getting consistent and repeatable results. As stated, there is not much control over the types of nanotubes in each batch once synthesized. 2D thin films use methods such as printing or gluing to coat an area in a layer of carbon nanotubes. These methods are not useful for small numbers of nanotubes as used in this study. To make a reliable 1D sensor, the nanotubes must be correctly aligned using a consistent and reproducible method. Given the scale of nanoparticles, physical manipulation is not an option, so other methods of manipulation must be employed.

These methods often involve using outside forces such as electric and magnetic fields to arrange particles. Optical trapping relies on the scattering and gradient forces of focused light to manipulate particles [41]. This method is more dynamic and unable to be set permanently, however, so it is not ideal for this experiment.

Dielectrophoresis is the method of exerting force on a dielectric particle when exposed to a nonuniform electric field. It differs from electrophoresis with its ability to manipulate neutral particles as well as charged particles.

This method of manipulation has been used for DNA origami and other nanoparticles (including CNTs) for sensor applications [4, 27, 42]. Nanoparticles are dispersed in a medium

and then directly deposited onto the area of interest, where an electric field is then applied. The particle then moves along the electric field gradient. If the particle moves towards the area of increasing electric field, this is referred to as positive DEP, or pDEP. Likewise, attraction toward the lower electric field strength is referred to as negative DEP (nDEP). The magnitude and direction of the dielectrophoretic force exerted on a carbon nanotube is defined by the equations

$$F_{DEP}(t)=2\pi ab^2\varepsilon_m Re(K)\nabla|E_{rms}|^2 \quad (2)$$

$$K=\frac{\epsilon_p-\epsilon_m}{3\left[\epsilon_m+\left(\epsilon_p-\epsilon_m\right)L\right]} \quad (3)$$

where a and b are the half the length and the radius of the CNTs respectively. ϵ_m and ϵ_p are the permittivity of the environment and the particle respectively. $\nabla|E_{rms}|^2$ is the gradient of the root mean square of the electric field. K is the complex polarizability, or the Clausius-Mossotti factor. If $Re(K) > 0$, the DEP force is positive. If Re(K) is negative, so is the DEP force. Fig. 5 shows positive dielectric forces acting on a particle.

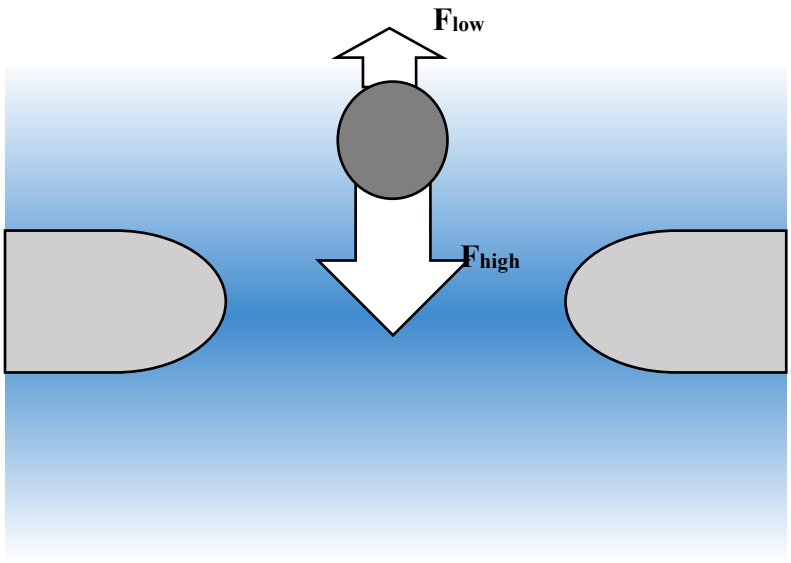


Fig. 5. Dielectrophoretic force on a particle
A representation of a particle being subjected to positive dielectrophoretic force. The particle is pushed along the electric field gradient formed by two nanoelectrodes to the high density area at the center.

When using this method of alignment, there are a few factors to take into consideration. Firstly, the size of the nanoparticle, in this case CNTs, must be considered. The tubules must be long enough to span the electrode gap. Conversely, tubules significantly longer than the electrode gap can lead to additional alignment issues. In *Chung et al.*, this issue was solved by using a combination of alternating and direct current applied to the electrodes [43]. Timing of the dielectrophoresis can also affect the final number of aligned nanoparticles [44].

To effectively trap and align an ideal number of nanoparticles, the voltage and frequency of the applied signal need to be tuned in. The DEP force is partially determined by the frequency-dependent polarization of the particles [45]. Increasing the voltage decreases overall trapping time but can have negative effects as well. The voltage needs to be high enough to overcome Brownian motion, but low enough to not overload the system, attract too many CNTs

to the site of interest, or cause adverse chemical reactions. Improper tuning can lead to no particles aligning, misalignment, or aggregation in the trapping site [27].

Summary

Low dimensional nanomaterials are the next step for sensors, due to fast response, low power draw, and high sensitivities [6]. CNTs are a particularly viable 1D nanoparticle, due to their strength, flexibility, and electrical characteristics. Current synthesis for nanotubes does not allow for total selection of electromechanical characteristics, so these impurities must be accounted for in an experiment [37].

Due to the nature of nanoparticles, special methods must be used for alignment. Dielectrophoretic force relies on the electric field gradient to move a particle into a position. This method is useful because it can permanently align particles onto nanoelectrodes.

CHAPTER 3

TEMPERATURE SENSOR USING CARBON NANOTUBES

Introduction

The previous chapter briefly showed the advantages of CNTs for sensors as well as the properties of CNTs. We also went over considerations for nanoparticle alignment.

This chapter will explain the fabrication and characterization of a temperature sensor using SWCNTs, including the process used for alignment and measurements. CNTs in solution were deposited on a specially designed dielectrophoretic chip, and then aligned on nanoelectrodes via dielectrophoresis. The individual chip devices were then tested at different temperatures from 23°C to 40 °C and the corresponding electrical responses recorded and compared. Viable devices were then imaged with an SEM.

This chapter goes over the fabrication of the dielectrophoretic chip, the DEP trapping process, and device testing and imaging.

Device Structure

Special dielectrophoretic chips were fabricated for use in this research using photolithography. The fabrication process of the chip is explained elsewhere [42]. The chips were made with a crystalline sapphire substrate that was layered with gold and silicon nitride. First the chip was coated with a high-resolution positive photoresist coating before being exposed to UV light through a mask in the shape of the chip structure. An electron-beam evaporator was then used to deposit a 5/60 nm thick chromium/gold layer followed by a lift off to remove unwanted metal and photoresist. A 100 nm silicon nitride layer was deposited using plasma-enhanced chemical vapor deposition before being etched at the nanoelectrode sites.

The final chips consisted of gold nanoelectrodes and structure coated in silicon nitride, with only the very tips of the nanoelectrodes and the pads exposed.

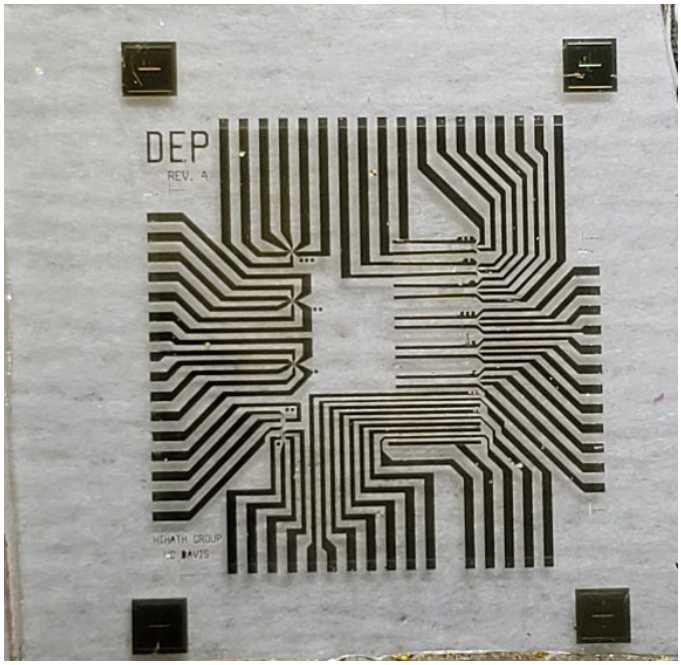


Fig. 6. Dielectrophoretic chip structure
An image of one of the dielectrophoretic chips used. The working area of the chip was 1 cm^2. The exposed gold pads are on the outer edge of the working area.

The overall chip structure, shown in Fig. 6, consisted of different types of nanoelectrodes. Fig. 7 shows an example of the nanoelectrodes. Each pair of nanoelectrodes and corresponding trapping site are referred to in this paper as devices.

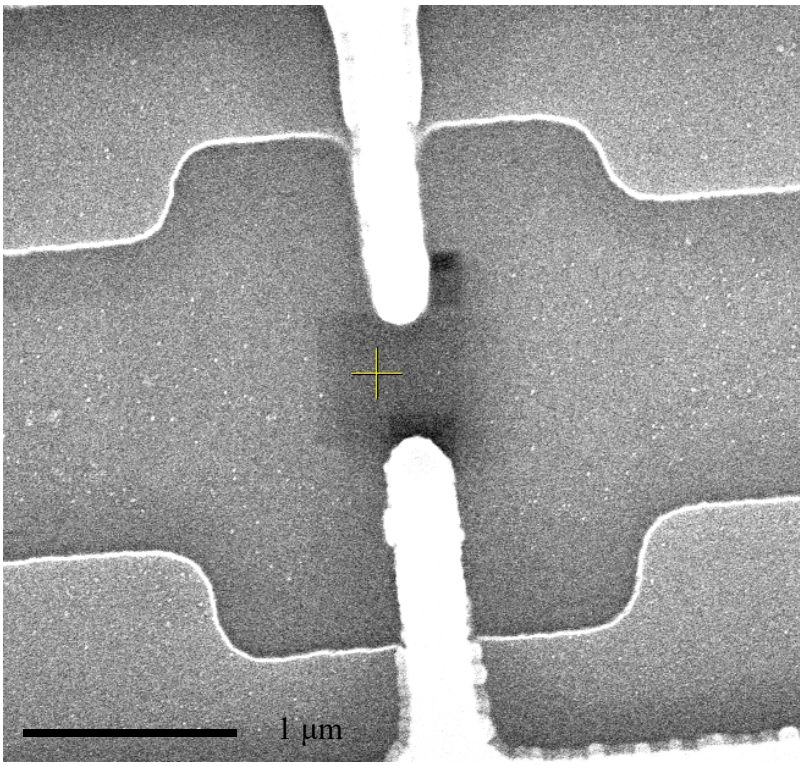


Fig. 7. Nanoelectrodes
An SEM image of one of the nanoelectrode configurations.

Experimental Method

To prepare the dielectrophoretic chips, ethanedithiol (EDT) was deposited on the surface of the chip by deep coating it in a solution of EDT (1% by volume in acetonitrile) overnight, shown in Fig. 8. The EDT helps to protect from the possible formation of Schottky barriers at the junction of the gold nanoelectrodes and the carbon nanotubes, which would impede proper electrical readings. After sitting overnight in the solution, the chips were removed, rinsed with additional acetonitrile, and dried. Once dry, deposition could begin.

Fig. 8. DEP chip in solution
A DEP chip in ethanedithiol solution. The chips were left to sit overnight in the solution.

The nanotubes used for this experiment were high purity (> 90%) SWCNTs from Carbon Solutions. The CNTs were put into a stock solution to be diluted later. Fig. 9 shows the stock solution versus a working solution diluted with high purity DI water.

Fig. 9. Carbon nanotube solution versus the working solution
Stock solution is pictured on the left. The working solution pictured on the right is a 1:2 dilution with DI water.

Due to their tendency to aggregate, the CNTs were sonicated before being deposited onto the trapping area of the chip via a micropipette. To create the dielectrophoretic force, a frequency generator ran through the transimpedance amplifier circuit shown in Fig. 10 also attached to the probes. The frequency was set to 33 kHz and the peak-to-peak voltage was set between 1.6 and 2.0 V during the deposition process.

Output from this setup was monitored on an oscilloscope for overall voltage change. A 30% or greater increase in the peak-to-peak voltage of the circuit output implied successful alignment of CNTs at the nanoelectrode site. Deposition at each device typically lasted a duration of 10 – 20 minutes. Excess solution was suctioned off the chip and gently rinsed with DI water using a micropipette to remove excess CNTs, then gently blown with an air pump to remove excess water. The chips were left to completely dry before testing.

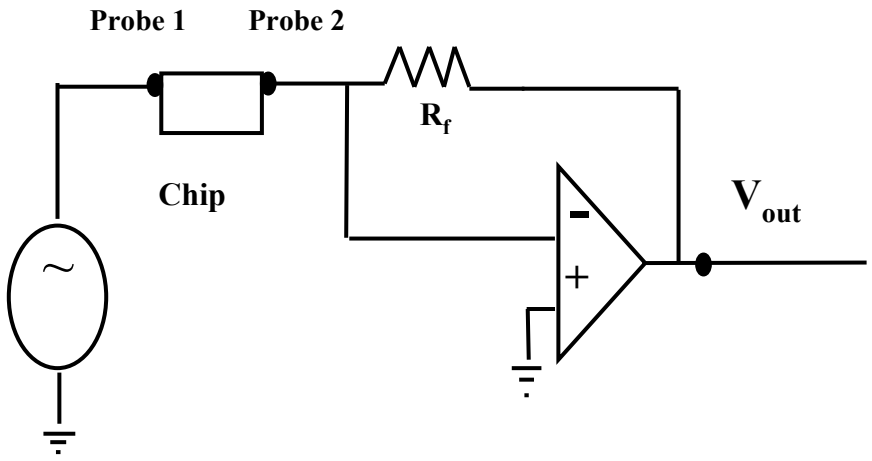


Fig. 10. Transimpedance amplifier circuit
A schematic structure of the circuit used in the setup. An AC power source leads directly to the probes and through the nanoelectrodes before connecting the transimpedance amplifier, including a changeable feedback resistor R_f. R_f was kept at 1 MΩ for trapping.

Device Characterization

After the trapping process, the chip devices were tested both for viability and temperature sensing capabilities. The circuit and nanoelectrodes were attached via probe to a data acquisition system. The data collection program was run in intervals at different temperatures achieved by warming a thermoelectric generator located under the sensor, shown in Fig. 11. Each tested device was subjected to 3 separate trials from room temperature (approximately 23 °C) to around 40 °C.

Fig. 11. Thermoelectric device
The thermoelectric device used for temperature trials. A DC power source heated the plate. The probe on the left was for temperature readings.

A small amount of voltage was applied as a triangle waveform with an amplitude of 0.5 V and a frequency of 0.1 Hz, as shown in Fig. 12 for each temperature trial. The program measured current output and produced an I-V curve for each trial. This data was used to monitor electrical characteristic changes over the trials.

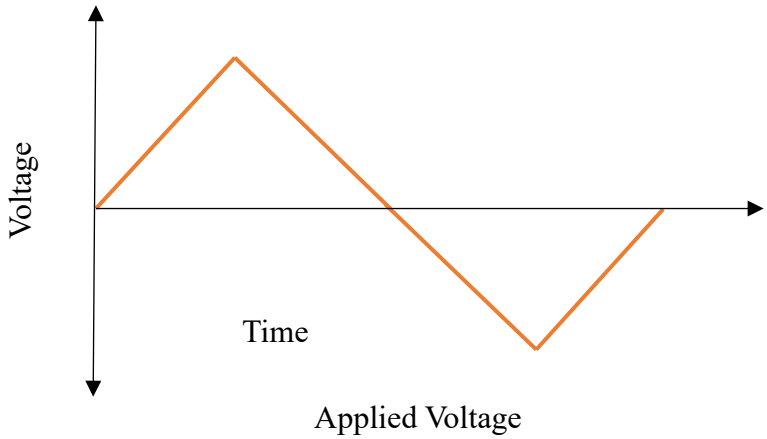
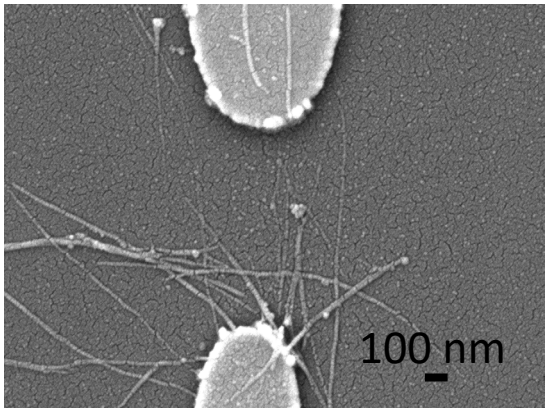


Fig. 12. Applied voltage over time for temperature trials
A graph of the applied voltage over the course of one temperature trial.

SEM Imaging

Devices that remained viable throughout the trials were then imaged using a JEOL scanning electron microscope (SEM). Images were taken both with the bare chips and once chips were coated with a sputter coater, at varying magnifications.. Fig. 13 shows a comparison of two nanoelectrodes with trapped nanotubes. There are much more CNTs on the lower resistance device.

a. 

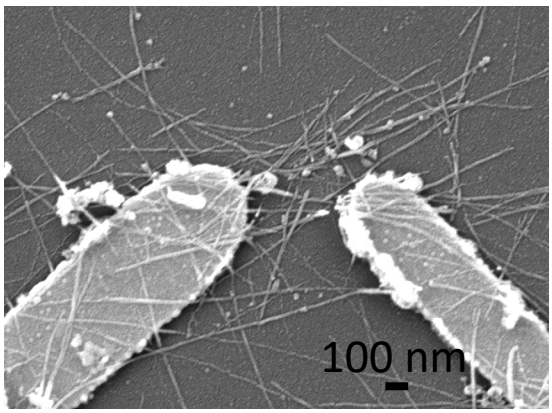
b. 

Fig. 13. SEM images of trapped CNTs
Images of trapped CNTs on different devices. (a) high impedance device (a few CNT crossed the nanoelectrodes). (b) low impedance device (multiples CNTs crossed the nanoelectrodes).

Results and Discussion

Since the number of trapped nanotubes can affect sensor performance [4, 12], only devices with a set range of trapped nanotubes were considered viable. Too many nanotubes on a device lead to decreased sensitivity. Devices with too many carbon nanotubes attached to the nanoelectrodes were dismissed. The amount of CNTs trapped determined overall device resistance, so the viable devices had measured average resistances from 200 kΩ to 20 MΩ, with higher resistances correlating to fewer nanotubes. Devices over 20 MΩ were less likely to give good data, and could potentially be dust or other interference instead of properly trapped nanotubes.

Collected data from the temperature trials was compiled via a MATLAB program to produce an average I-V curve over all trials for a given device, as shown in Fig. 14. The slope of this graph was used to calculate the average resistance using Ohm's Law (V = IR).

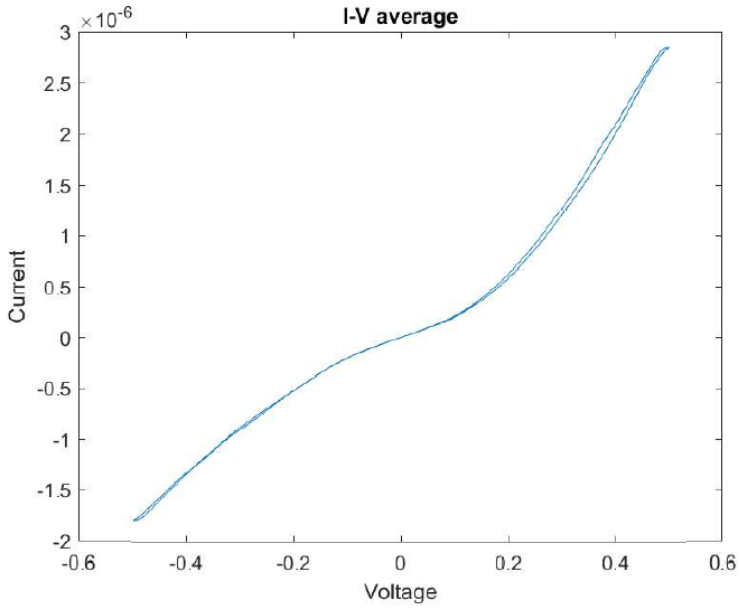


Fig. 14. I-V curve average
Measured average I-V curve over all temperature trials on a single device. This graph is representative of an average output I-V curve for a properly trapped device.

A graph of the normalized resistances of a device as a response to temperature is shown in Fig. 15. This graph took the normalized resistance at specific temperatures to calculate the temperature based resistive sensitivity. The equation

$$R=R_{ref}\left(1+\alpha(T-T_{ref})\right) \quad (4)$$

gives resistance as a function of temperature. R_{ref} is the resistance at some reference temperature T_{ref}. α is the temperature coefficient of resistance of the material. The sensitivity as a function of temperature was calculated to be 2.96 E-3/K. Similar thin film CNT-based temperature sensors at room temperature had lower measured resistive sensitivities of 1.436 E-3/K and 1.3 E-3/K [25, 46]. Both sensors were assembled by printing MWCNTs with organic resin and PMMA (acrylic) onto flexible polymer substrates.

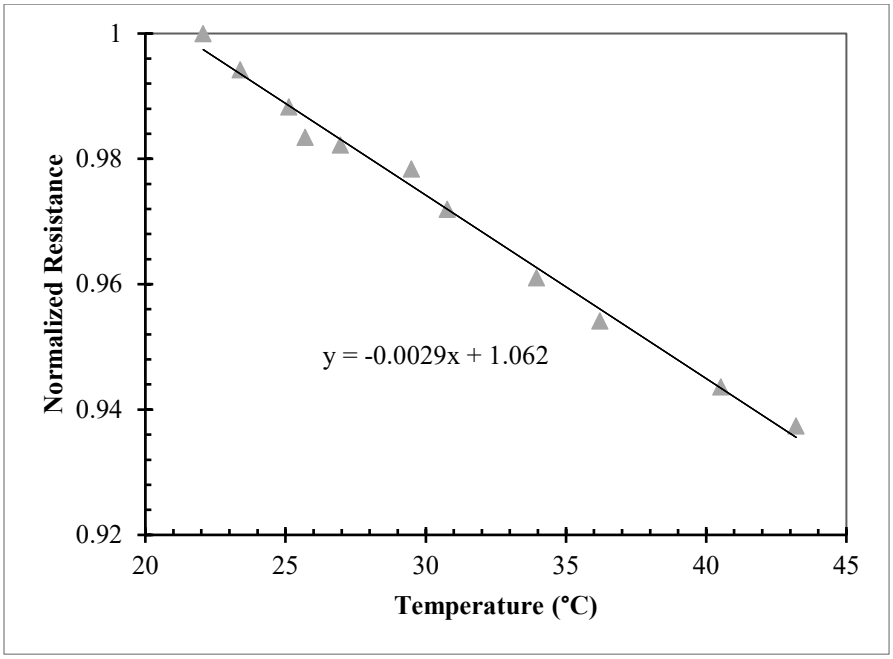
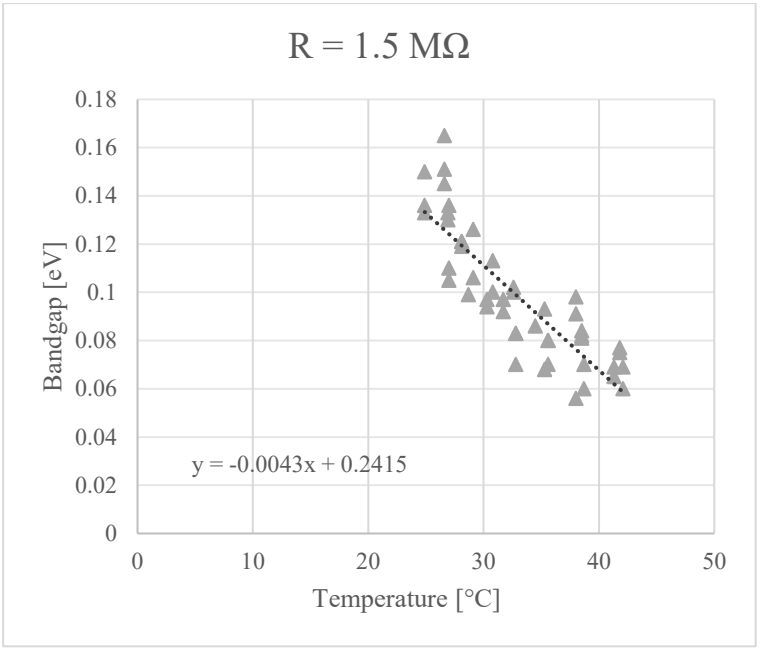


Fig. 15. Resistance as a function of temperature
This graph gives the normalized resistance as a function of temperature. The measured sensitivity was 2.9 E-3.

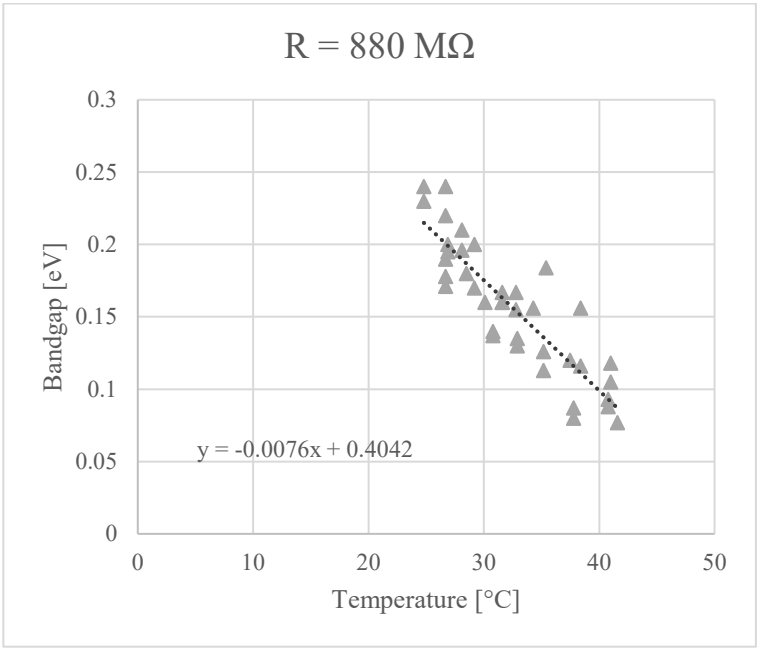
The bandgaps were also calculated via the I-V curves measured for each data set. That data was collected and formed into a graph of the measured average bandgap versus the temperature for each device which is shown in Fig. 16. Semiconductor bandgaps have a strong temperature dependence, so CNTs exhibit this property as well. The slope for the line of best fit for the data points gives the sensitivity of the bandgap to temperature change. The bandgap sensitivity decreased as the resistance increased, from 7 E-3 eV/°C at 630 kΩ to 4.3 E-3 eV/°C at 1.5MΩ resistance. Since higher numbers of CNTs corresponded to lower resistances, the sensitivity of the bandgap increased as the number of CNTs increased. One possible explanation

is that more nanotubes lead to more surface area to be affected by temperature changes. It could also be harder to detect changes with a very low number of nanotubes.

a.



b.



c.

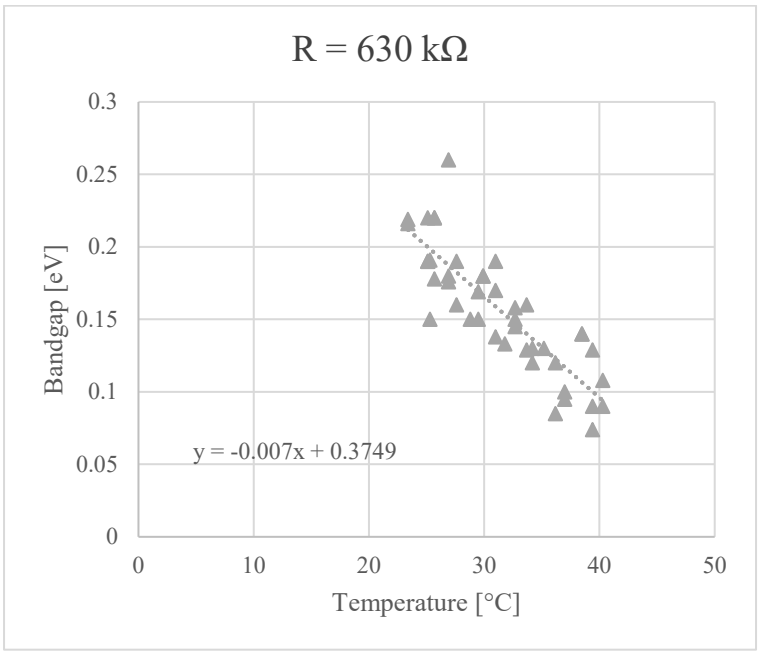


Fig. 16. Bandgap sensitivity as a function of temperature at different resistances
(a) This device was measured at approximately 1.5 MΩ resistance, and the corresponding sensitivity was 4.3 E-3 eV/°C. (b) This device was measured at approximately 880 kΩ, with the sensitivity measured at 7.6 E-3 eV/°C. (c) This graph was measured with a 630 kΩ resistance and the sensitivity measured 7 E-3 eV/°C.

CHAPTER 4

CONCLUSION AND FUTURE WORK

This study showed that the resistance of the nanotube device decreased as the temperature increased. The comparison of the results with the provided data in literatures shows that the sensitivity for the 1-dimensional CNT device measured was higher than that of similar 2-dimensional CNT temperature sensors made with films. For two room temperature thin-film based CNT sensors, resistive sensitivities measured 1.436 E-3/K and 1.3 E-3/K [25, 46]. The measured resistive sensitivity of our device measured almost double at 2.96 E-3/K. This supports prior statements that lower dimensional sensors are more sensitive. More comprehensive temperature measurements that cover a broader range of temperatures would be an additional useful comparison.

The sensitivity of the bandgap to temperature change decreased as resistance increased, making for greater variability in devices with more CNTs attached at the points of interest.

As a small, reactive sensor, the sensor fabricated in this study could have use in environmental controls or other purposes within a larger system. So far, the only measured temperatures tested have been room temperature ones, so lower temperature environmental controls with fast feedback necessary would be a great purpose for the sensor.

In the future, there is potential for a direct comparison of the impact of the type of nanotube on the sensing capabilities. As nanotube selectivity processes improve, a distinction between the chiral type and diameter of specific nanotubes can be tuned to the sensors. The impact of the number of nanotubes on the overall sensor could also be studied.

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APPENDIX A: APPROVAL LETTER

MARSHALL UNIVERSITY
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Office of Research Integrity

January 28, 2022

Kaylee Burdette
5525 Shenandoah Drive
Cross Lanes, WV 25313

Dear Ms. Burdette:

This letter is in response to the submitted thesis abstract entitled *"Dielectrophoretic Trapping of Carbon Nanotubes for Temperature Sensors."* After assessing the abstract, it has been deemed not to be human subject research and therefore exempt from oversight of the Marshall University Institutional Review Board (IRB). The Code of Federal Regulations (45CFR46) has set forth the criteria utilized in making this determination. Since the information in this study does not involve human subjects as defined in the above referenced instruction, it is not considered human subject research. If there are any changes to the abstract you provided then you would need to resubmit that information to the Office of Research Integrity for review and a determination.

I appreciate your willingness to submit the abstract for determination. Please feel free to contact the Office of Research Integrity if you have any questions regarding future protocols that may require IRB review.

Sincerely,

Bruce F. Day, ThD, CIP
Director