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Soft, Lightweight, Multi-functional Conductors from Fullerene Carbon Nanotubes

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14. ABSTRACT
In an earlier AFOSR grant, we demonstrated that chlorosulfonic acid (CSA) can dissolve long carbon nanotubes (CNTs) and can be used as solvent for spinning CNT fibers and produce CNT films and coatings. However, since CNT length plays a crucial role in the electrical and mechanical properties of CNT fibers and films, it is fundamental importance to effectively determine the bulk length of the CNT source materials used for the CNT fiber/film manufacturing. Therefore, methods are needed for measuring CNT length accurately and easily. Under Grant FA9550-15-1-0370 in year 1, we developed a method to measure the CNT bulk average length from extensional viscosity measurements of semidilute CNT-CSA solutions. This technique improves upon methods available in the literature that rely on sonicating the CNTs, which is known to shorten their length. In addition, we developed a scalable method to produce a CNT electromagnetic shield for coaxial cables leading to the best data in the literature for CNT data cables in terms of losses per unit weight. Our cables have an electromagnetic shield that is 97% lighter than the commercial metal counterpart and an overall cable weight saving of ~ 50%. These achievements are critical for the aerospace industry where weight saving is a determinant factor. Finally, we used CNT fibers to fabricate a terahertz polarizer with an extinction ratio of 30 dB and a low insertion loss.

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Soft, lightweight, multifunctional conductors from fullerene carbon nanotubes

(AFOSR Grant FA9550-15-1-0370 WILLIAM MARSH RICE UNIVERSITY PASQUALI, MATTEO, 20 April 2020)

Final report

Accomplishments

Abstract

In an earlier AFOSR grant, we demonstrated that chlorosulfonic acid (CSA) can dissolve long carbon nanotubes (CNTs) and can be used as solvent for spinning CNT fibers and produce CNT films and coatings. However, since CNT length plays a crucial role in the electrical and mechanical properties of CNT fibers and films, it is fundamental importance to effectively determine the bulk length of the CNT source materials used for the CNT fiber/film manufacturing. Therefore, methods are needed for measuring CNT length accurately and easily. Under Grant FA9550-15-1-0370 in year 1, we developed a method to measure the CNT bulk average length from extensional viscosity measurements of semidilute CNT-CSA solutions. This technique improves upon methods available in the literature that rely on sonicating the CNTs, which is known to shorten their length. In addition, we developed a scalable method to produce a CNT electromagnetic shield for coaxial cables leading to the best data in the literature for CNT data cables in terms of losses per unit weight. Our cables have an electromagnetic shield that is 97% lighter than the commercial metal counterpart and an overall cable weight saving of ~ 50%. These achievements are critical for the aerospace industry where weight saving is a determinant factor. Finally, we used CNT fibers to fabricate a terahertz polarizer with an extinction ratio of 30 dB and a low insertion loss. The polarizer performance is shown to be comparable to commercial metallic wire-grid polarizers and can have important impacts in emerging THz technological applications, such as wireless communications, imaging, chemical detection, and astrophysics. Under Grant FA9550-15-1-0370 in year 2, we gained more insights on the CNT-CSA solution morphology: in particular, we studied how the nematic droplets, i.e. tactoids, in the biphasic regime (the regime where the isotropic phase is in equilibrium with the liquid crystalline phase) wet a surface and we calculated the line tension associated with it. This work is important for applications where a CNT-CSA solution in the biphasic regime is used to form coatings/films. In addition, we worked on understanding how CNT parameters like aspect ratio, diameter, and purity affect the CNT-CSA morphology at different concentrations via cryo-TEM (transmission electron microscopy) and cryo-SEM (scanning electron microscopy) by providing direct imaging on how the CNTs arrange in the solution. We found that nanometric resolution of cryo-EM reveals CNT self-assembly into liquid-crystalline domains of several nanometers in width at very early stages. Under Grant FA9550-15-1-0370 in year 3, we achieved significant progress in understanding how the properties of the CNTs used for fiber spinning scale to fiber properties. We demonstrated the importance of the aspect ratio of the CNTs for tensile strength and conductivity and have achieved the most conductive CNT fibers in current literature at 8.5 MS/m. We have also developed a method for making small fibrils of CNTs from microgram quantities. This work is important because we can quickly test the properties of CNTs fibers before the growth process is scaled up. Moreover, we developed a method to purify dry spun fibers made via a floating catalyst method to improve their properties. We also demonstrated the ability to spin fibers from high concentration aqueous dispersions. Lastly, we showed that CNT fibers perform well as flexible antennas. They perform on par

with copper monopole antennas, and, unlike metals, their radiation efficiency increases with increasing frequency. Under Grant FA9550-15-1-0370 in year 4, we made advancements in solution processing, fiber characterization, and applications of CNT materials. We improved our understanding of the morphology of CNT/CSA solutions through studies with small-angle neutron scattering and small-angle X-ray scattering. We also developed a new system of acids that individualize CNTs, but the acids are less corrosive than CSA. This allows for additional capabilities such as 3D printing neat CNT structures, screen printing, and direct coating of CNT films onto plastic sheets. Furthermore, we made progress on the properties of solution spun CNT fibers and have obtained an electrical conductivity of 10.9 MS/m and a tensile strength of 4.2 GPa. This continues our trend of over 20% improvement in properties each year, which is remarkable as it has consistently occurred over 15+ years and continues to occur for a material that is now competing with the best carbon fibers and electrical and thermal conductors. Additionally, we made new developments in characterizing and improving CNT fiber. We studied the bending stiffness of CNT fiber and determined relevant scaling laws so that we can engineer fibers for specific applications. We developed a new method for measuring the linear density of conductive fibers using a vibroscopic method. We evaluated the toxicity of CNT fibers for biocompatibility and found no signs of cellular, hematologic, immunologic, organ, and systemic toxicity. Finally, we developed a method to cross-link CNT fibers to improve their mechanical strength. Additionally, we studied the use of CNT fibers and films for several applications. We used highly aligned films to create thin patch antennas that performed on par with traditional copper antennas. Moreover, we demonstrated the use of CNT fibers as cardiac sutures. The CNT fibers can restore myocardial conduction which could be used as treatment for arrythmias. We also used CNT fibers as a backbone for creating fully solution processed light emitting fibers. Lastly, we used CNT fibers to create sewable EKG electrodes. The CNT based wearable electrodes are washable and obtain EKG signals that comparable to commercial (non-wearable) electrodes. Under the full term of this grant, we have made significant progress in our understanding of CNT solution processing, the development of CNT fibers, and the application of CNT based materials which has resulted in 36 published papers and 8 additional papers in progress.

Table 1 Summary of the accomplishments

CNT characterization	Developed a method to characterize CNT bulk length	Year 1
CNT coating fabrication and application	Use CNT films as outer conductor in coaxial cables: • Developed a continuous CNT coating method to produce the outer conductor of coaxial cables • Meet cable attenuation specs at high frequency • Decrease outer conductor weight of 97% (compared to commercial metal cables)	Year 1
CNT fiber application	Used CNT fibers as terahertz polarizer: • extinction ratio of 30 dB with a low insertion loss	Year 1
CNT-CSA solution morphology study	Determined the line tension of tactoids when wetting a surface	Year 2

CNT-CSA solution morphology study	Used cryo-TEM and cryo-SEM to understand phase behavior of CNT-CSA solutions depending on CNT aspect ratio, diameter, and purity	Year 2
CNT fiber spinning study	Determined how intrinsic CNT properties such as number of walls, aspect ratio, and Raman G/D ratio affect the properties of resulting CNT fibers	Year 3
CNT-CSA solution morphology study	Determined purification techniques and processing for CNTs produced from the floating catalyst method	Year 3
CNT fiber application	Demonstrated the use of CNT fibers as flexible antennas • Despite having lower conductivity, CNT fibers performed similarly to copper at a lower weight • Demonstrated better performance at high frequency compared to metal antennas	Year 3
CNT fiber spinning study	Demonstrated the ability to obtain lightweight conductors from aqueous solvents	Year 3
CNT fiber spinning study	Developed a method to use small (microgram) quantities of CNTs to form CNT fibers and studies the effects of packing density, twisting, and alignment on tensile strength	Year 3
CNT fiber property study	Determined the scaling laws for the bending behavior of CNTs fibers with CNT fiber diameter and the length of the constituent CNTs within the fiber	Year 4
CNT-CSA solution morphology study	Used small-angle neutron scattering to study the liquid crystalline behavior of long and short CNTs in CSA. The study confirmed CNTs are individualized in solution. Moreover, for the concentrations studied, the long CNTs formed a fully nematic and highly ordered phase, whereas the short CNTs remained in the biphasic regime.	Year 4
CNT fiber property study	Developed a method to accurately measure the linear density of CNT fibers and other electrically conductive fibers using a vibroscopic technique	Year 4
CNT fiber application	Demonstrated CNT thin patch antennas that have a radiation efficiency on par with copper antennas	Year 4
CNT fiber application	Demonstrated that CNT fiber can be used to improve conduction velocity over scare tissue in hearts to provide a restorative solution to cardiac arrythmias.	Year 4
CNT fiber application	Engineered a solution-based technique to create light emitting fibers	Year 4
CNT fiber property study	Evaluated the biocompatibility of CNT fibers by examining the cellular, hematologic, immunologic, organ, and systemic toxicity	Year 4
CNT fiber spinning study	Demonstrated advancements in CNT fiber spinning over the past 15 years and reported current state of the art properties	Year 4
CNT fiber application	Demonstrated the use of CNT thread as sewable, washable EKG electrodes for wearable electronics	Year 4

CNT superacid study	Developed new systems of superacids that individualize CNTs but have additional functionality such as 3D printable and improved material compatibility	Year 4
CNT-CSA solution morphology study	Used small-angle X-ray scattering to characterize the morphology of the liquid-crystalline phases formed in CNT solutions	Year 4
CNT fiber property study	Developed a method to vulcanize CNT fibers to improve CNT fiber tensile strength	Year 4

Year 1: Measuring the length and aspect ratio of CNTs in liquid phases

CNT length controls the properties of CNT fibers and films. Therefore, methods are needed for measuring CNT length accurately and easily. Methods available in the literature rely on sonicating the CNTs, which is known to shorten their length. We demonstrated that the length of carbon nanotubes (CNTs) can be determined simply and accurately from extensional viscosity measurements of semidilute CNT solutions. This new method is based on measuring the extensional viscosity of CNT solutions in chlorosulfonic acid with a customized capillary thinning rheometer and determining CNT aspect ratio from the theoretical relation between extensional viscosity and aspect ratio in semidilute solutions of rigid rods (Figure 1).

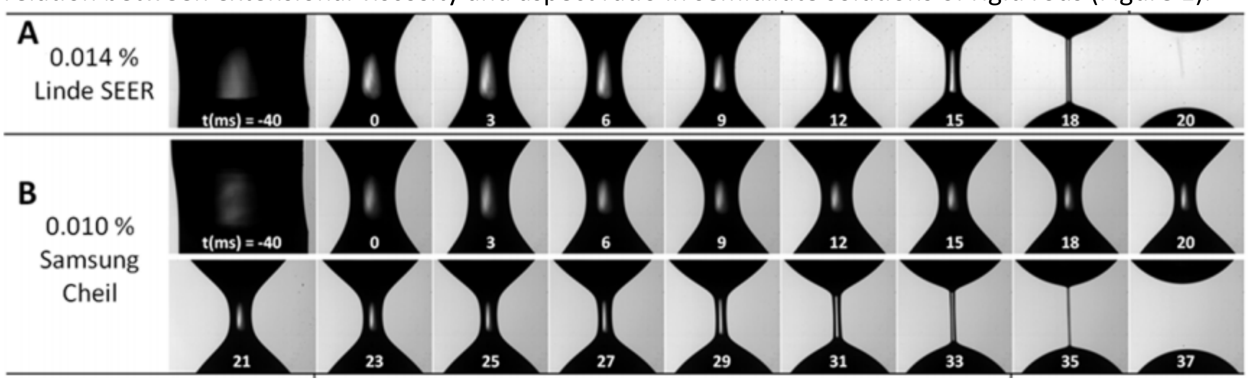

Figure 1 Filament profiles from capillary thinning experiments for (A) 0.014% Linde SEER and (B) 0.010% Samsung Cheil CNTs.

In this setup, a cylindrical droplet of CNT solution is placed between two pistons. At the beginning of the experiments, the pistons are separated rapidly by a prescribed distance. The filament thins under the action of surface tension, which drives fluid from the capillary center towards the ends (Figure 9, above). The viscosity of the liquid slows down the thinning and breakup process. Because the surface tension can be measured independently, this method can be used to measure the extensional viscosity of a CNT-laden fluid. We measure CNT diameter d by transmission electron microscopy (TEM) and arrive at CNT length L using the aspect ratio values obtained by extensional rheology. By studying samples grown by different methods, we show that the method works well for CNT lengths ranging from 0.4 to at least 20 µm, a wider range than for previous techniques. Moreover, we measure the isotropic-to-nematic transition concentration (i.e., isotropic cloud point) φ_{iso} of CNT solutions and show that this transition follows Onsager-like scaling $\varphi_{iso} \sim d/L$ (Figure 2). We characterize the length distributions of CNT samples by combining the measurements of extensional viscosity and transition concentration and show that the resulting length distributions closely match distributions obtained by cryo-TEM measurements. Interestingly, CNTs appear to have relatively low polydispersity compared to polymers and high polydispersity compared to colloidal particles.

This work is published as: **Relationship of Extensional Viscosity and Liquid Crystalline Transition to Length Distribution in Carbon Nanotube Solutions**, Dmitri E. Tsentalovich, Anson W. K. Ma, J. Alex Lee, Natnael Behabtu, E. Amram Bengio, April Choi, Junli Hao, Yimin Luo, Robert J. Headrick, Micah J. Green, Yeshayahu Talmon, and Matteo Pasquali, *Macromolecules*, 2016, 49, 681−689

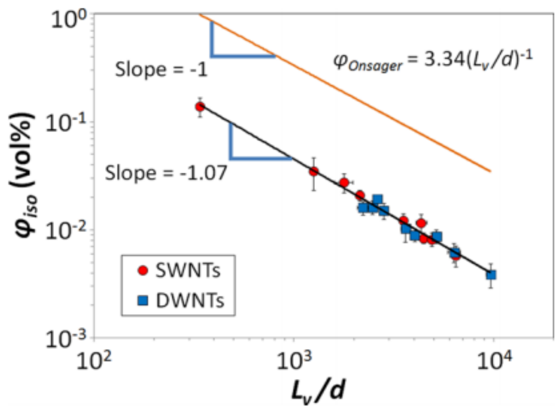

Figure 2 Isotropic cloud point as a function of CNT aspect ratio for all the SWNT (red) and DWNT (blue) samples tested in this work. The black line is a power law fit to the experimental data. The orange line shows Onsager's prediction for solutions of monodisperse rigid rods.

Year 1: Lightweight, Flexible, High-Performance Carbon Nanotube Cables Made by Scalable Flow Coating

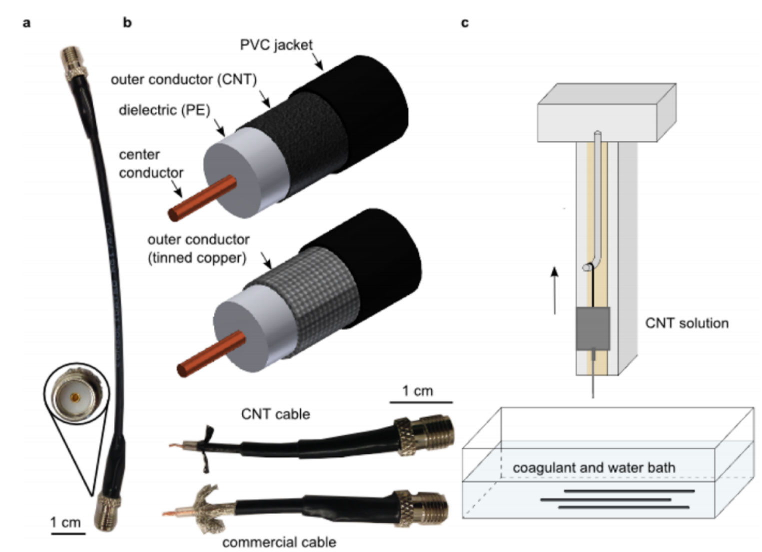

Figure 3 (a) Photograph of a CNT coaxial cable with SubMiniature version A (SMA) connectors and (inset) SMA connector at an auxiliary view. (b, top) Schematics of a CNT coaxial cable compared to a conventional commercial cable and (bottom) photographs of the CNT coaxial cables and the conventional commercial cable with the different coatings revealed. (c) Laboratory-based dip coating process used to coat the coaxial cables.

Making films from CNT solutions is a viable technique for many applications in which scalability, film electrical conductivity, and low weight are determinant factors. One interesting application for lightweight conductive films is in cables. Coaxial cables for data transmission are ubiquitous in telecommunications, aerospace, automotive, and robotics industries. Yet, the metals used to make commercial cables are unsuitably heavy and stiff. These undesirable traits are particularly problematic in aerospace applications, where weight is at a premium and flexibility is necessary to conform with the distributed layout of electronic components in satellites and aircraft. The cable outer conductor (OC) (Figure 3b) is usually the heaviest component of modern data cables; therefore, exchanging the conventional metallic OC for lower weight materials with comparable transmission characteristics is highly desirable. Carbon nanotubes (CNTs) have recently been proposed to replace the metal components in coaxial cables; however, signal attenuation was too high in prototypes produced so far. In this work, we fabricate the OC of coaxial data cables by directly coating a solution of CNTs in chlorosulfonic acid (CSA) onto the cable inner dielectric as shown in the Figure 3c and removing the acid by subsequent coagulation. This coating has an electrical conductivity that is approximately 2 orders of magnitude greater than the best CNT OC reported in the literature to date. Also, as shown in Figure 4 (left) our CNT cables met the military standard MIL-C-17 at 1 GHz (a reference frequency for military specifications) and was only 30 % higher in attenuation at 400 MHz and about two-fold higher below 100 MHz. This high performance led to the best data in the literature for CNT cables in terms of losses per unit weight (Figure 4 (right)). Our CNT coaxial cables are an attractive alternative to commercial cables with a metal (tin-coated copper) OC, since they provide a comparable cable attenuation and mechanical durability with a 97% lower component mass.

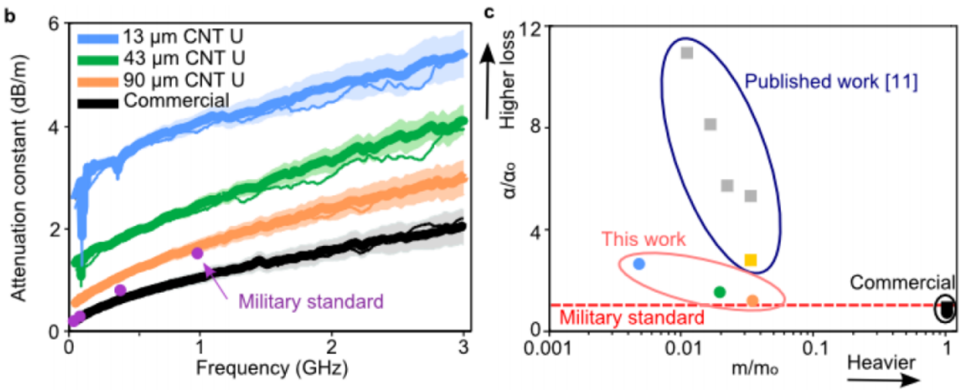

Figure 4 (left) The attenuation constant versus frequency for the different Unidym (U) CNT coaxial cables and the commercial cables. The multiline algorithm (solid lines) and least-squares fit (thinner lines) were used to extract the attenuation constant. The uncertainty (shaded regions) was computed by error propagation. The purple dots represent the military standard for attenuation at 0.05, 0.1, 0.4, and 1 GHz for RG-174/U (1.5 dB/m or 45 dB/100ft). (right) Normalized attenuation (α/α_o) versus normalized mass (m/m_o) for the Unidym CNT coaxial cables and commercial cable. Attenuation (α) was normalized by military standard attenuation (α_o) at 1 GHz for the RG-174/U cable type (1.5 dB/m, dashed line). Squares are published work on RG-58/U cables.

This work is published as: **Lightweight, Flexible, High-Performance Carbon Nanotube Cables Made by Scalable Flow Coating** Francesca Mirri, Nathan D. Orloff, Aaron M. Forster, Rana Ashkar, Robert J. Headrick, E. Amram Bengio, Christian J. Long, April Choi, Yimin Luo, Angela R. Hight Walker, Paul Butler, Kalman B. Migler, and Matteo Pasquali, *ACS Appl. Mater. Interfaces*, 2016, **8**, 4903−4910. In the paper acknowledgements, we acknowledged grant FA9550-09-01-0370 instead of FA9550-15-1-0370 by mistake: we apologize for it. This work has also led to a patent (M. Pasquali, F. Mirri, T.T. Hsu, "Fabrication of carbon nanotube coatings for electromagnetic shielding", 2014, USPTO Patent Application 61/931,097 (filed on Jan 24, 2014) WO 2015/156894 filed 1/26/2015) that was awarded the *Hershel M. Rich Invention Award* for the best invention in 2016 at Rice University. Also, a company (DexMat, Inc., www.dexmat.com) was founded in 2015 to focus on the scale up and commercialization of the CNT fibers and cables developed at Rice University under grant FA9550-15-1-0370. Dexmat has already been awarded two SBIR phase I grants from AFRL, one of which has resulted in a Phase II award.

Year 1: Carbon nanotube fiber terahertz polarizer

Unique properties of electromagnetic waves in the terahertz (THz) frequency range are expected to lead to new applications in diverse areas, including wireless communications, chemical detection, and medical imaging. Recent advances in the generation, manipulation, and detection of THz waves have brought these anticipated applications closer to realization. Conventional, commercially available terahertz (THz) polarizers are made of uniformly and precisely spaced metallic wires. They are fragile and expensive, with performance characteristics of highly reliant on wire diameters and spacings. Carbon nanotubes (CNTs)

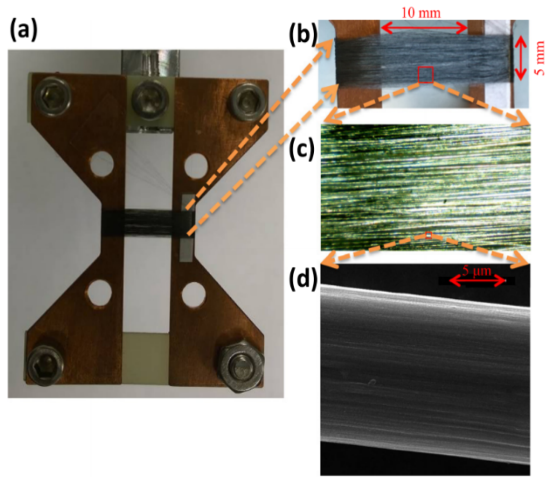

Figure 4 Optical and scanning electron microscopy images of CNT-fiber THz.

are emerging optoelectronic materials that have unique ultrabroadband anisotropic optical absorption properties. In particular, they exhibit essentially perfect polarization anisotropy in the THz frequency range, ideally suited for polarizer applications. In this work, we reported a simple and highly error-tolerant method for fabricating a freestanding THz polarizer with nearly ideal performance, reliant on the intrinsically one-dimensional character of conduction electrons in well-aligned fibers of carbon nanotubes (CNTs). The polarizer was constructed on a mechanical frame over which we manually wound acid-doped CNT fibers with ultrahigh electrical conductivity (Figure 5). We demonstrated that the polarizer has an extinction ratio of 30 dB with a low insertion loss. The polarizer performance was fully characterized through measurement of salient Muller matrix elements and shown to be comparable to commercial metallic wire-grid polarizers. Its performance characteristics are tolerant to structure imperfections introduced in the hand-winding process, making this a robust method for producing high-quality THz polarizers in a cost-effective manner. The intrinsic anisotropic optical properties of aligned CNTs are the reason for this ideal performance. This CNT-fiber polarizer will have important impacts in emerging THz technological applications, such as wireless communications, imaging, chemical detection, and astrophysics.

This work is published as: **Carbon nanotube fiber terahertz polarizer**, Ahmed Zubair, Dmitri E. Tsentalovich, Colin C. Young, Martin S. Heimbeck, Henry O. Everitt, Matteo Pasquali, and Junichiro Kono, 2016, *Applied Physics Letters,* **108**, 141107.

Year 2: Line Tension of Twist-Free Carbon Nanotube Lyotropic Liquid Crystal Microdroplets on Solid Surfaces

In order to optimally make CNT coatings from CNT-CSA solutions, a deep knowledge on CNT-CSA solution behavior as well as on how the solution will behave in contact with surfaces is needed. CNTs form liquid crystals in CSA when a certain CNT concentration (that depends on the CNT aspect ratio) is reached. Specifically, at high concentrations, the solution is characterized by a fully liquid crystalline phase (nematic), whereas at low concentrations the solution appears isotropic, i.e., the CNTs are randomly oriented with respect to each other. At intermediate concentrations, the nematic liquid crystalline phase is in equilibrium with an isotropic phase forming the so called biphasic regime. In this regime, the nematic phase appears as elongated, spindlelike droplets, called tactoids. Nematic tactoids in equilibrium with the isotropic phase and in contact with a flat solid surface (sessile tactoids) have a flattened elongated shape, characterized by noncircular contact lines (Figure 6).

Characterizing the line tension in liquid crystal systems requires an appropriate model that can capture the elongated shape and nonconstant contact angle of nematic tactoids. Line tension, i.e., the force on a three-phase contact line, has been a subject of extensive research due to its impact on technological applications including nanolithography and nanofluidics. However, there is no consensus on the sign and magnitude of the line tension, mainly because it only affects the shape of small droplets, below the length scale dictated by the ratio of line tension to surface tension σ/τ. This ratio is related to the size of constitutive molecules in the system, which translates to a nanometer for conventional fluids. We show that this ratio is orders of magnitude larger in lyotropic liquid crystal systems comprising micrometer-long CNTs. We propose a method to characterize the line tension by fitting measured tactoid shape to a macroscopic theoretical model that incorporates interfacial forces and elastic deformation of the nematic phase. By applying this method to hundreds of droplets of CNT dissolved in CSA, we find that $\sigma/\tau \sim -0.84 \pm 0.06$ µm. This ratio is 2 orders of magnitude larger than what has been reported for conventional fluids, in agreement with theoretical scaling arguments.

This work is published as: **Line Tension of Twist-Free Carbon Nanotube Lyotropic Liquid Crystal Microdroplets on Solid Surfaces**, Vida Jamali, Evan G. Biggers, Paul van der Schoot, and Matteo Pasquali, 2017, *Langmuir,* **33**, 9115−9121.

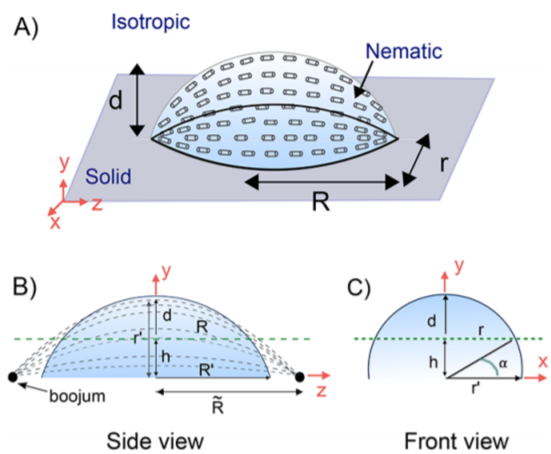

Figure 6 (A) Schematic of a sessile nematic liquid crystal droplet (tactoid) of depth d, minor axis r, and major axis R, in equilibrium with the isotropic phase and in contact with a solid surface. (B) Side view of an asymmetric sessile tactoid with the depth d and the major axis R that can be assumed as a portion of a symmetric tactoid of minor axis r′ and major axis R′ that is cut by a solid surface at distance h from the axis of symmetry of the tactoid. The director field lines (dashed lines), showing the average orientation of the molecules, converge on two virtual point defects at vertical position h and horizontal position $\tilde{R}$. (C) Front view of an asymmetric tactoid showing the depth d, the minor axis length r, and the minor axis r′ of the original tactoid cut by a solid surface at distance h.

Year 2: Direct Imaging of Carbon nanotube Liquid-Crystalline Phase Development in True Solutions

In order to gain more insights about the CNT-CSA solution behavior, direct solution imaging is fundamental to understand CNT-CSA solution morphology. Using direct-imaging cryogenic transmission and scanning electron microscopy, we show different stages of liquid-crystalline phase development in progressively more concentrated solutions of CNTs in CSA: a dilute phase of individually dissolved CNTs, semidilute and concentrated isotropic phases, coexisting concentrated isotropic and nematic phases in local equilibrium with each other, and a fully liquid-crystalline phase (Figure 7). Nanometric resolution of cryogenic electron microscopy reveals CNT self-assembly into liquid-crystalline domains of several nanometers in width at very early stages. We find significant differences in CNT liquid-crystalline domain morphology as a function of the CNT aspect ratio, diameter, and degree of purity.

This work is published as: **Direct Imaging of Carbon nanotube Liquid-Crystalline Phase Development in True Solutions**, Olga Kleinerman, Lucy Liberman, Natnael Behabtu, Matteo Pasquali, Yachin Cohen, Yeshayahu Talmon, 2017, *Langmuir* **33**, 4011-4018.

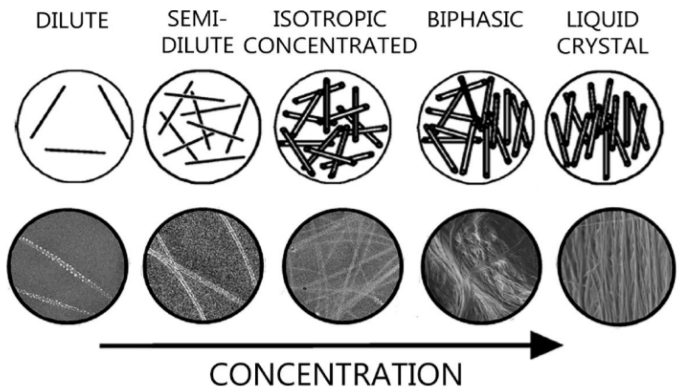

Figure 7 (Upper panel) Model of aligned phase development in an athermal rigid-rod polymer solution. The concentration of solute is increased from left to right. (Lower panel) Cryo-EM micrographs, showing liquid-crystalline phase development in CNT/CSA solution as a function of nanotube concentration (this work). Dilute, semidilute, and isotropic phases are cryo-TEM micrographs. Biphasic and fully liquid-crystalline phases are cryo-SEM images.

Year 3: Influence on Carbon Nanotube Characteristics on Macroscopic Fiber Properties

To understand how to develop the best performing CNT conductors, we study how intrinsic parameters of carbon nanotube (CNT) samples affect the properties of macroscopic CNT fibers with optimized structure. We measure CNT diameter, number of walls, aspect ratio, graphitic character, and purity (residual catalyst and non-CNT carbon) in samples from 19 suppliers; we process the highest quality CNT samples into aligned, densely packed fibers, by using an established wet-spinning solution process. We find that fiber properties are primarily controlled by CNT aspect ratio; sample purity is important for effective spinning. Properties appear largely unaffected by CNT diameter, number of walls, and graphitic character (determined by Raman G/D ratio) as long as the fibers comprise thin few-walled CNTs with high G/D ratio (above 20). We show that both strength and conductivity can be improved simultaneously by assembling high aspect ratio CNTs, producing continuous CNT fibers with an average tensile strength of 2.4 GPa and a room temperature electrical conductivity of 8.5 MS/m, about 2 times higher than the highest reported literature value (about 15% of copper's value), obtained without post-spinning doping.

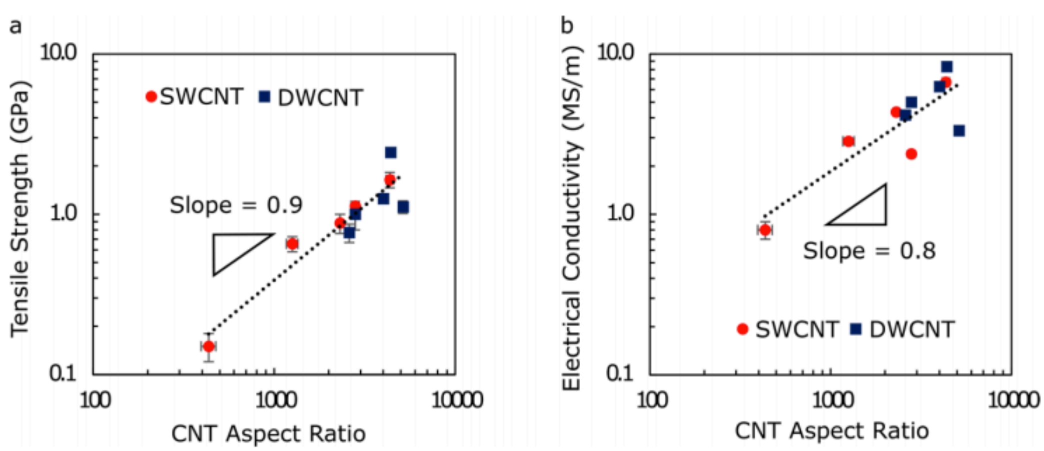

Figure 8 (a) CNT fiber tensile strength versus aspect ratio and (b) CNT fiber conductivity versus aspect ratio for fibers made from SWCNTs and DWCNTs from different manufacturers. Error bars are the standard deviation from five or more measurements, and on average we obtain 4%, 11%, and 4% error for aspect ratio, tensile strength, and electrical conductivity, respectively.

This understanding of the relationship of intrinsic CNT parameters to macroscopic fiber properties is key to guiding CNT synthesis and continued improvement of fiber properties, paving the way for CNT fiber introduction in large-scale aerospace, consumer electronics, and textile applications.

This work is published as: **Influence of Carbon Nanotube Characteristics on Macroscopic Fiber Properties,** Dmitri E. Tsentalovich, Robert J. Headrick, Francesca Mirri, Junli Hao, Natnael Behabtu, Colin C. Young, and Matteo Pasquali, 2017, *ACS Applied Materials and Interfaces,* **9**, 36189-36198.

Year 3 Purification and Dissolution of Carbon Nanotube Fibers Spun from the Floating Catalyst Method

Because we understand the importance of aspect ratio in developing high performance CNT conductors, we aim to look at various CNT growth processes that produce long tubes. However, often the as-grown CNTs contain significant impurities and defective tubes. In this study, we apply a simple but effective oxidative purification method to purify CNT fibers synthesized via a floating catalyst technique. After the purification treatment, the resulting CNT fibers exhibited significant improvements in mechanical and electrical properties with an increase in strength, Young's modulus, and electrical conductivity by approximately 81, 230, and 100%, respectively. With the successful dissolution of the CNT fibers in superacid, an extensional viscosity method could be applied to measure the aspect ratio of the CNTs constituting the fibers, whereas high-purity CNT thin films could be produced with a low resistance of 720 Ω/sq at a transmittance of 85%. This work suggests that the oxidative purification approach and dissolution process are promising methods to improve the purity and performance of CNT macroscopic structures.

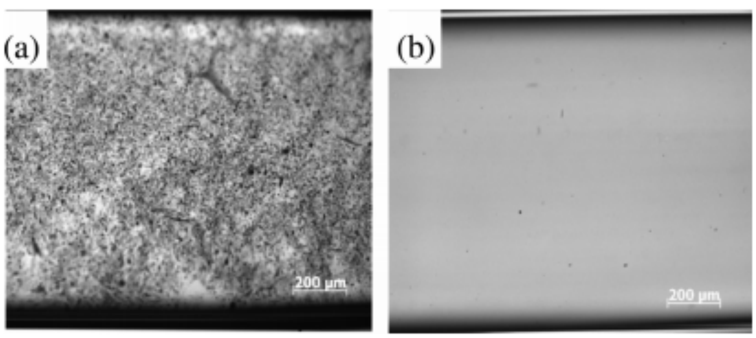

Figure 9 Transmission microscope images of (a) unpurified CNT material and (b) purified material in CSA. These images demonstrate that the purification technique was effective in removing materials that cannot be dissolved.

This work is published as: **Purification and Dissolution of Carbon Nanotube Fibers Spun from the Floating Catalyst Method**, Thang Q. Tran, Robert J. Headrick, E. Amram Bengio, Sandar Myo Myint, Hamed Khoshnevis, Vida Jamali, Hai M. Duong, and Matteo Pasquali, 2017, *ACS Applied Materials and Interfaces*, **9**, 37112-37119.

Year 3: High Efficiency Carbon Nanotube Thread Antennas

Although previous research has explored the underlying theory of high-frequency behavior of carbon nanotubes (CNTs) and CNT bundles for antennas, there is a gap in the literature for direct experimental measurements of radiation efficiency. These measurements are crucial for any practical application of CNT materials in wireless communication. In this study, we report a measurement technique to accurately characterize the radiation efficiency of k/4 monopole antennas made from the CNT thread. We measure the highest absolute values of radiation efficiency for CNT antennas of any type, matching that of copper wire. To capture the weight savings, we propose a specific radiation efficiency metric and show that these CNT antennas exceed copper's performance by over an order of magnitude at 1 GHz and 2.4 GHz. We also report direct experimental observation that, contrary to metals, the radiation efficiency of the CNT thread improves significantly at higher frequencies. These results pave the way for practical applications of CNT thread antennas, particularly in the aerospace and wearable electronics industries where weight saving is a priority.

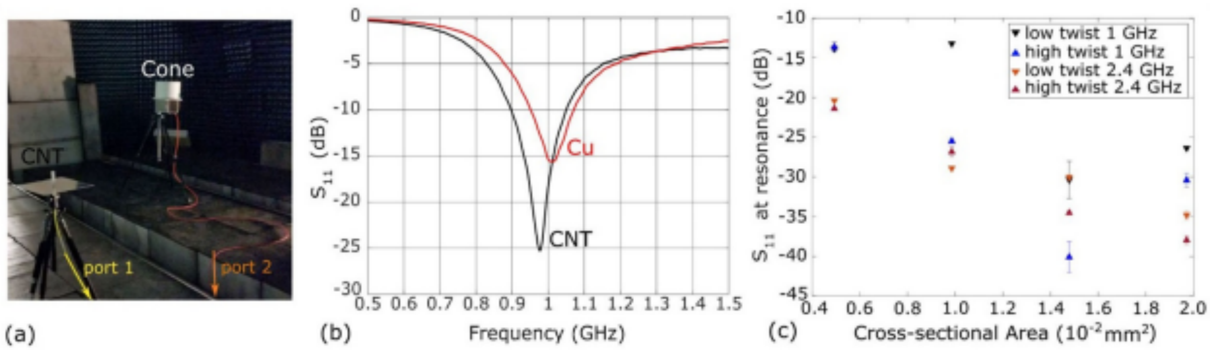

Figure 10 Validation of the reproducibility of the CNT thread monopole antenna configuration (a) experimental set-up inside the anechoic chamber, (b) representative S11 plot of 16 filament low twist CNT thread and 30 AWG Cu wire, and (c) S11 values at resonance for all four thinnest CNT thread antennas for three consecutive plugging and un-plugging into the test ground plane.

This work is published as: **High Efficiency Carbon Nanotube Thread Antennas**, E. Amram Bengio, Damir Senic, Lauren W. Taylor, Dmitri E. Tsentalovich, Peiyu Chen, Christopher L. Holloway, Aydin Babakhani, Christian J. Long, David R. Novotny, James C. Booth, Nathan D. Orloff, and Matteo Pasquali, 2017, *Physical Review Letters*, **111**, 163109.

Year 3: Highly Concentrated Aqueous Dispersions of Carbon Nanotubes for Flexible and Conductive Fibers
Dispersing carbon nanotubes (CNTs) using surfactants into water requires ultrasonication that supplies mechanical energy to debundle and exfoliate CNTs. However, sonication is known to damage CNTs and to cut them into short fragments. Also, the CNT concentration in water dispersion is typically limited to up to 1.0 wt %. Here, we show that by using a sulfuric acid pretreatment, we can enhance the debundling of CNTs and reduce subsequent sonication to achieve homogeneous dispersions without damaging CNTs. Additionally, using a progressive and controlled dialysis, we are able to increase the CNT concentration up to 1.8 wt %. We demonstrate that such highly concentrated dispersions can be used as spin dopes to fabricate continuous fibers. Our fibers have an electrical conductivity up to 580 kS/m, a tensile strength of about 1 GPa, and a Young's modulus of 123 GPa, exceeding the mechanical properties of related fibers made from conventional surfactant-stabilized dispersions of sonicated CNTs.
This work is published as: **Highly Concentrated Aqueous Dispersions of Carbon Nanotubes for Flexible and Conductive Fibers,** Laurent Maillaud, Robert J. Headrick, Vida Jamali, Julien Maillaud, Dmitri E. Tsentalovich, Wilfrid Neri, E. Amram Bengio, Francesca Mirri, Olga Kleinerman, Yeshayahu Talmon, Philippe Poulin, and Matteo Pasquali, *2018, Industrial & Engineering Chemistry Research,* **57**, 3554-3560.

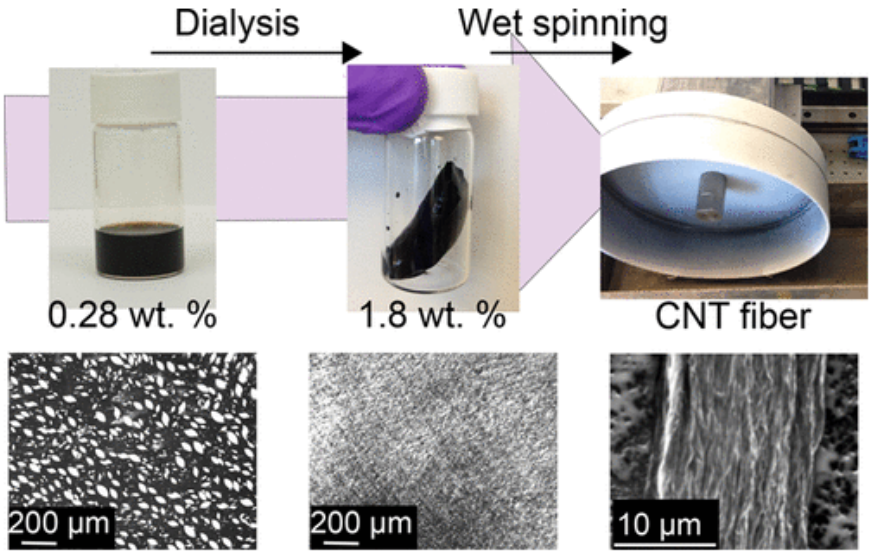

Figure 11 Top: Photographs of solutions of CNTs in aqueous dispersions before and after dialysis demonstrating the ability to obtain high concentration solutions and a photograph of CNT fiber spun from the high concentration solution. Bottom left: Polarized optical micrographs of the CNT solutions show the liquid crystalline domains. Bottom Right: SEM image of the resulting CNT fiber.

Year 3: Structure–Property Relations in Carbon Nanotube Fibers by Downscaling Solution Processing

At the microscopic scale, carbon nanotubes (CNTs) combine impressive tensile strength and electrical conductivity; however, their macroscopic counterparts have not met expectations. The reasons are variously attributed to inherent CNT sample properties (diameter and helicity polydispersity, high defect density, insufficient length) and manufacturing shortcomings (inadequate ordering and packing), which can lead to poor transmission of stress and current. To efficiently investigate the disparity between microscopic and macroscopic properties, a new method is introduced for processing microgram quantities of CNTs into highly oriented and well-packed fibers. CNTs are dissolved into chlorosulfonic acid and processed into aligned films; each film can be peeled and twisted into multiple discrete fibers. Fibers fabricated by this method and solution spinning are directly compared to determine the impact of

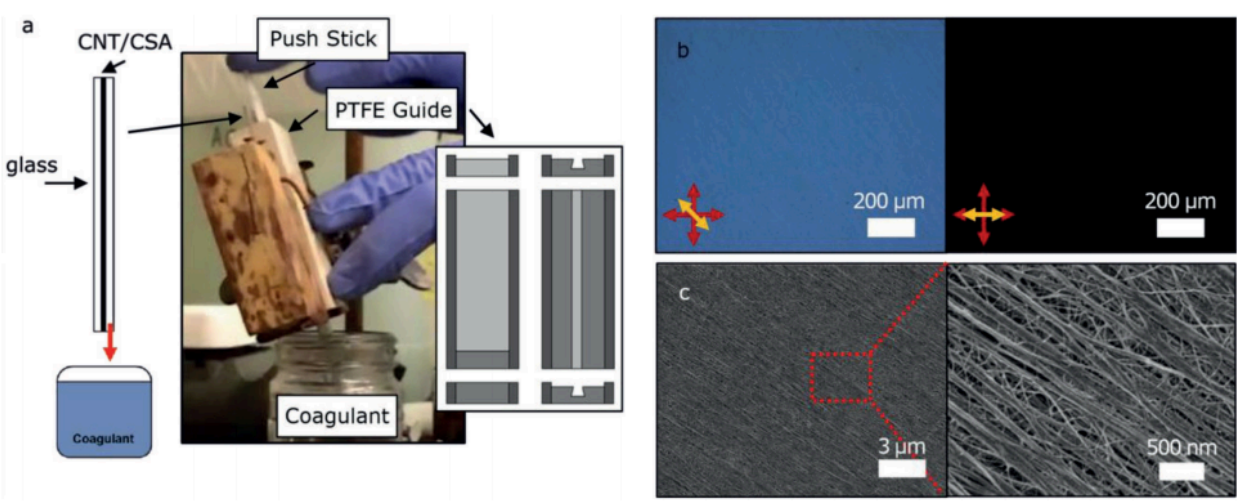

Figure 12 a) Diagram of process to shear align CNTs dissolved in CSA on glass microscope slides with picture and diagram of the PTFE holder. b) Birefringence from placing a film between crossed polarizer and analyzer (red arrows) when the alignment direction is at 45° and 0° (yellow arrows). c) HR-SEM images of the aligned CNT film alignment, twist, packing density, and length. Surprisingly, these discrete fibers can be twice as strong as their solution-spun counterparts despite a lower degree of alignment. Strength appears to be more sensitive to internal twist and packing density, while fiber conductivity is essentially equivalent among the two sets of samples. Importantly, this rapid fiber manufacturing method uses three orders of magnitude less material than solution spinning, expanding the experimental parameter space and enabling the exploration of unique CNT sources.

This work is published as: **Structure–Property Relations in Carbon Nanotube Fibers by Downscaling Solution Processing,** Robert J. Headrick, Dmitri E. Tsentalovich, Julián Berdegué, Elie Amram Bengio, Lucy Liberman, Olga Kleinerman, Matthew S. Lucas, Yeshayahu Talmon, and Matteo Pasquali, 2018, *Advanced Materials*, **30**, 1704482.

Year 4: Bending Behavior of CNT Fibers and Their Scaling Laws

Due to their excellent conductivity, mechanical strength, and flexibility, CNT fibers are a promising material for many applications including cardiac sutures, electrocardiogram electrodes, and wearable antennas. To engineer CNT fiber for these specific applications, it is important to understand the bending behavior of the fiber with key parameters such as fiber diameter and the length of the constituent CNTs. Here, we use a cantilever testing setup to indirectly measure the bending stiffness of CNT fibers and interpret the results using Euler Elastica theory. When varying the length of the constituent CNTs, we find that the bending stiffness scales with a power law of 1.6. When varying the diameter of the CNT fiber, we find that the bending stiffness scales with a power law of 1.9. We also develop an elementary model that agrees with the experimentally obtained data. Finally, these results suggest that the bending stiffness of CNT fiber is largely governed by constituent CNTs sliding along the fiber axis.

This work is published as: **Bending Behavior of CNT Fibers and Their Scaling Laws**, Mohammed Adnan, Robert A Pinnick, Zhao Tang, Lauren W Taylor, Sushma Sri Pamulapati, Gianni Royer Carfagni, and Matteo Pasquali, 2018, *Soft Matter*, **14**, 8284-8292.

Year 4: Quantification of Carbon Nanotube Liquid Crystal Morphology via Neutron Scattering

Solution processing is an industrially viable technique for producing CNT fiber and films on a large scale. However, true solutions of rigid rods such as CNTs in CSA have a complex phase behavior that must be well understood to optimize solution processing techniques. Here, small angle neutron scattering was performed on "short" (L/D~440) and "long" (L/D~4300) CNTs dissolved in CSA at various concentrations. The scattering results demonstrate that for both lengths of CNTs, the CNTs are individualized in solution. At the highest concentration tested (10 mg CNTs/g CSA), the long CNTs form a fully nematic phase with

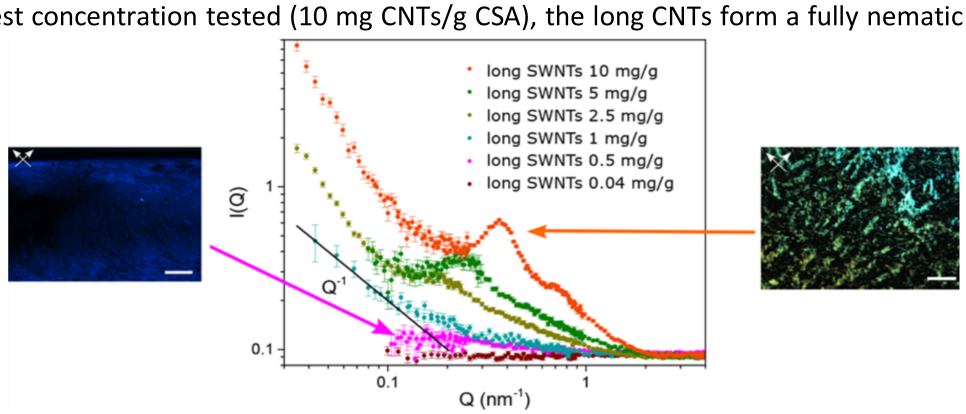

Figure 13 SANS data for solutions of long SWCNT show a correlation peak at high concentrations, indicative of ordered SWNT structures in the samples. The polarized light images show (left) a low concentration solution in the biphasic regime under polarized light, and (right) a high concentration solution in the nematic regime.

strong local positional order in the plane perpendicular to the CNT axis, whereas the short CNTs are still within the biphasic regime. Furthermore, when diluting the CNT solutions, the scattering data indicates a 2D relaxation of the long CNTs and an intermediate expansion between 2D and 3D for the short CNTs. This difference can be attributed to the biphasic nature of the short CNT solutions.

This work is published as: **Quantification of Carbon Nanotube Liquid Crystal Morphology via Neutron Scattering**, Francesca Mirri, Rana Ashkar, Vida Jamali, Lucy Liberman, Robert A. Pinnick, Paul van der Schoot, Yeshayahu Talmon, Paul D. Butler, and Matteo Pasquali, 2018, *Macromolecules*, **51**, 6892-6900.

Year 4: Electrical and Acoustic Vibroscopic Measurements for Determining Carbon Nanotube Fiber Linear Density

CNT fibers and other high-performance fibers are essential for reducing the weight of aircraft, satellites, and ground transportation. However, to assess CNT fibers and other new materials for application, it is necessary to accurately measure the linear density to determine their possible weight savings. The current technique for measuring linear density requires complex mechanical equipment to vibrate the fiber and record the fiber's resonate frequency. Here, we introduce a new technique for measuring linear density that utilizes the electrical conductivity of CNT fiber to produce mechanical vibrations. An AC current is passed through a short length of CNT fiber (20 mm) in the presence of a strong magnetic field. The fiber then undergoes a tensile test. As the fiber is held under varying tension, the resonant frequencies can be recorded through a microphone. These data can then be used to easily and accurately determine the linear density on short pieces of fiber without the need for expensive equipment. Using short pieces allows the measurement of multiple fiber sections along a continuous length (tens of meters).

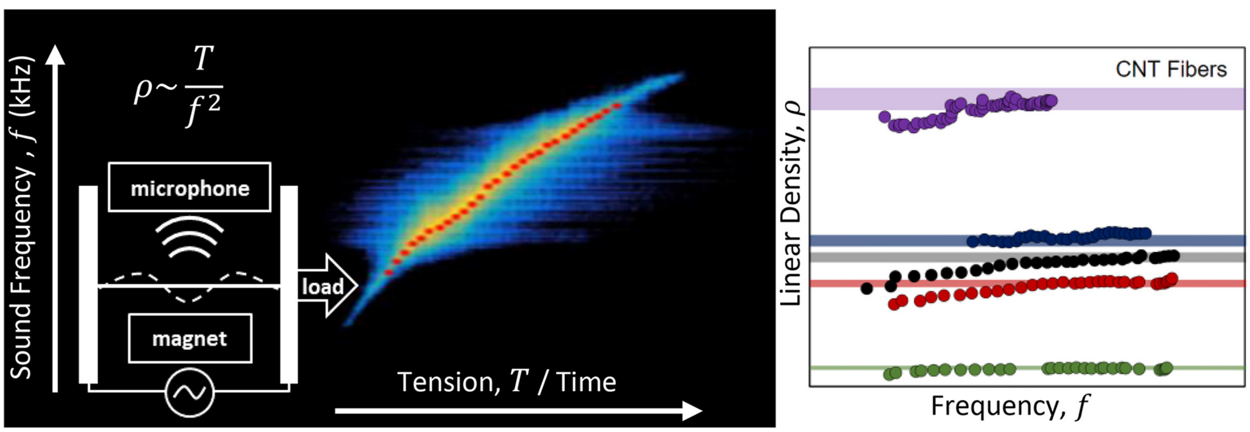

Figure 14 Left: the measured frequency of the sound produced by the CNT fiber under tension during a tensile test. The inset shows a schematic of the testing setup. In short, a CNT fiber is tensile tested in the presence of a magnetic field and AC current. A microphone is used to record the sound produced by the fiber. Right: The calculated linear density at various resonate frequencies (circles) compared to the linear density measured by weighing meters of fiber on a microbalance. The two measurement techniques are in good agreement.

This work is published as: **Electrical and Acoustic Vibroscopic Measurements for Determining Carbon Nanotube Fiber Linear Density**, Robert J. Headrick, Mitchell A. Trafford, Lauren W. Taylor, Oliver S. Dewey, Russell A. Wincheski, Matteo Pasquali, 2019, *Carbon*, **144**, 417-422.

Year 4: Carbon Nanotube Thin Film Patch Antennas for Wireless Communications

Early work on carbon nanotube (CNT) antennas indicated that their performance could not match that of metals such as copper. However, improvements in CNT quality (CNT purity and length) and CNT processing have developed macroscale materials with improved electrical and mechanical properties. Here, we demonstrate CNT thin film patch antennas that have a radiation efficiency (94%) on par with copper patch antennas at frequencies from 10-14 GHz. These results demonstrated a promising technology for antennas in extreme environments where temperature, corrosion, mechanical strength, or weight consideration is important.

This work is published as: **Carbon Nanotube Thin Film Patch Antennas for Wireless Communications**, E. Amram Bengio, Damir Senic, Lauren W. Taylor, Robert J. Headrick, Michael King, Peiyu Chen, Charles A. Little, John Ladbury, Christian J. Long, Christopher L. Holloway, Aydin Babakhani, James C. Booth, Nathan D. Orloff, and Matteo Pasquali, 2019, *Applied Physics Letters*, **114**, 203102.

Year 4: In Vivo Restoration of Myocardial Conduction with Carbon Nanotube Fibers

Re-entrant arrhythmias are caused by impaired myocardial conduction. Current surgical treatments for arrythmias often use an ablation technique that irreversibly scars portions of the cardiac tissue. Often, extensive ablation and further follow-up procedures must often be performed before arrhythmia noninducibility is achieved which increases the risk of complications. Here, we demonstrate a material-based approach that uses strong, soft, and highly conductive CNTs to restore conductivity to cardiac scare tissue. This technique improved conduction velocity within the heart for all animal model studied. Furthermore, there was no evidence of gross or histopathologic toxicity.

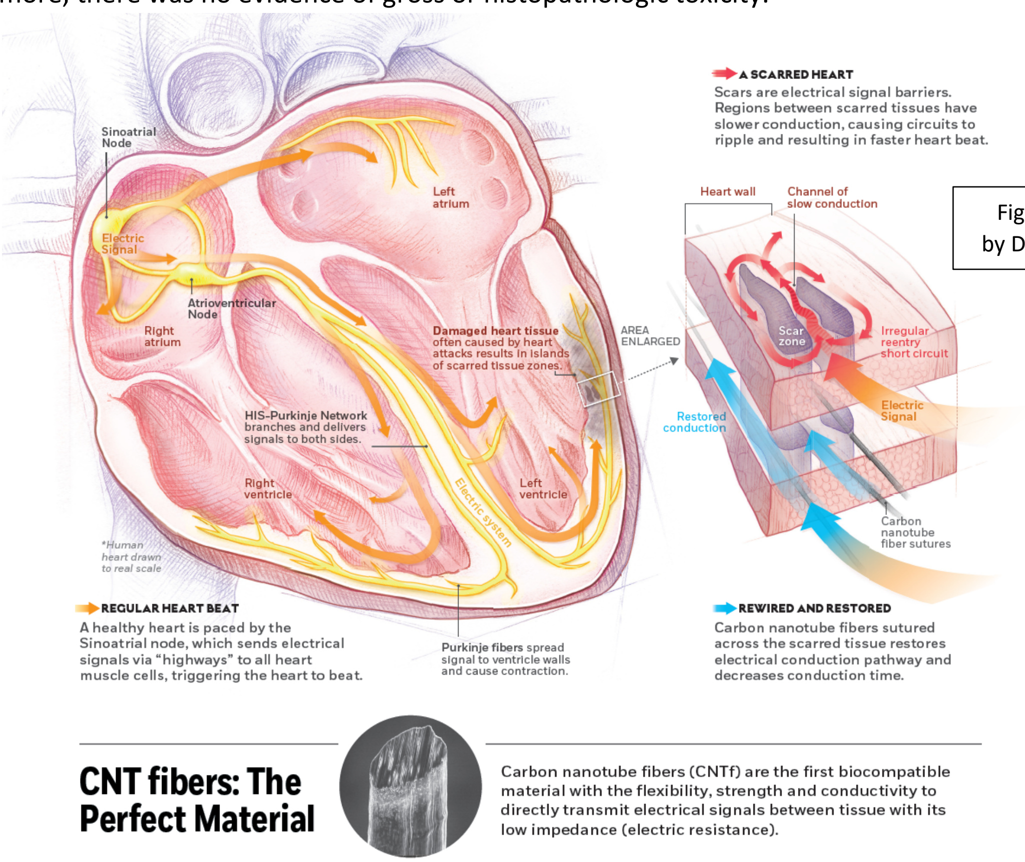

Figure 15: Art by Daisy Chung

This work is published as: **In Vivo Restoration of Myocardial Conduction with Carbon Nanotube Fibers**, Mark D. McCauley, Flavia Vitale, J. Stephen Yan, Colin C. Young, Brian Greet, Marco Orecchioni, Srikanth Perike, Abdelmotagaly Elgalad, Julia A. Coco, Mathews John, Doris A. Taylor, Luiz C. Sampaio, Lucia G. Delogu, Mehdi Razavi, Matteo Pasquali, 2019, *Circulation: Arrhythmia and Electrophysiology*, **12**, e007256. It was also featured in the Rice Magazine (magazine.rice.edu) Winter 2020 issue (Fig. 15 above).

Year 4: Perovskite-Carbon Nanotube Light Emitting Fibers

In the emerging field of wearable electronics and functional textiles, fibers with opto-electronic properties are in imporant building block for more intricate systems. Current fabrication techniques are ineffective at obtaining uniform devices in the fiber-shapred form factor. Here, we develop a solution processing based fabrication technique to produce a three-layer light emitting fiber. This process is shown in Figure 16. The resulting devices are robust, small in diameter, and lightweight due to the high quality CNT fiber backbone. The versitility and success of the work demonstarted here offers a platform for the development of additional functional fibers for wearable devices. This work has been submitted as: Perovskite-**Carbon Nanotube Light Emitting Fibers**, Vida Jamali, Farnaz Niroui, Lauren W. Taylor, Oliver S. Dewey, Brent Koscher, Matteo Pasquali, A. Paul Alivisatos, under review.

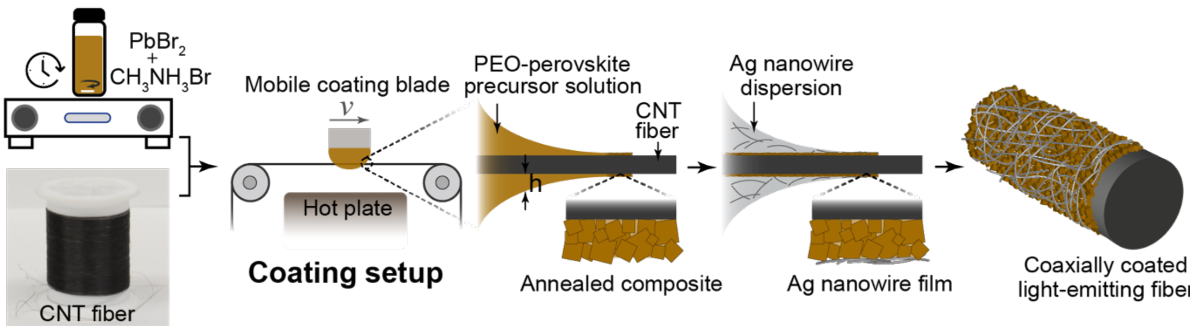

Figure 16 Schematic of the fabrication process for the coaxially-coated light-emitting carbon nanotube fiber. A layer-by-layer solution coating procedure is implemented to apply a PEO-MAPbBr3 precursor solution over the CNT fiber and annealed to form the emissive layer followed by a silver nanowire dispersion, coated to form the top contact.

Year 4: Macroscopic Fibers Made from Carbon Nanotubes are Bio- and Immune-compatible: Implications for Carbon Nanotube Macrostructures in Biomedical Applications

We systematically evaluated carbon nanotube fiber (CNTF) biocompatibility profile by assessing its cellular, hematologic, immunologic, organ, and systemic toxicities. We found that: 1) CNT fibers exhibit no cytotoxicity on different cell lines and a variety of primary cells, including cardiomyocytes, macrophages, T cells, B cells, NK cells, and monocytes; 2) CNT fiberss do not induce any hemotoxic responses in human blood cells and are immune-compatible with key blood immune cells; 3) there is no evidence of organ toxicity induced by CNTF leachates or CNTF implants. Together, these results show that CNTFs are biocompatible as implantable interfaces at multiple scales, exposure conditions, and timepoints.

This work has been submitted as: **Macroscopic Fibers Made from Carbon Nanotubes are Bio- and Immune-compatible: Implications for Carbon Nanotube Macrostructures in Biomedical Applications** J. Stephen Yan, Flavia Vitale, Marco Orecchioni, Julia A. Coco, Guillaume Duret, Salvatore Antonucci, Sushma Sri Pamulapati, Lauren W. Taylor, Oliver S. Dewey, Moises Di Sante, Anna Maria Segura, Ley, Fabio Di Lisa, Mark D. McCauley, Jacob T. Robinson, Mehdi Razavi, Lucia G. Delogu, Matteo Pasquali, under review.

Year 4: Improved Properties, Increased Production, and the Path to Broad Adoption of Carbon Nanotube Fibers

Carbon Nanotube Fibers have been the Holy Grail of nanotechnology research since their first demonstration by Poulin and collaborators in 2000. Our research group has been at the forefront of this research since 2004, with the development of a solution spinning manufacturing method; we have demonstrated (under earlier AFOSR support) that CNT properties can indeed be translated to macroscale fibers. We report the latest property improvements of solution spun CNT fibers. By using high aspect ratio and high purity CNTs, we can produce fibers with an electrical conductivity of 10.9 MS/m, a thermal conductivity of 390 W/m K, and a tensile strength of 4.2 GPa. We show that, when put into historical context, this progress continues the trend of a doubling in properties every three years since the first production of CNT fibers in the early 2000's (Figure 17). With continued efforts by academic institutions and industrial partners, CNT fibers could see broad adoption in many sectors such as aerospace composites, motor vehicles structural, electrical, and thermal components, and power transmission lines.

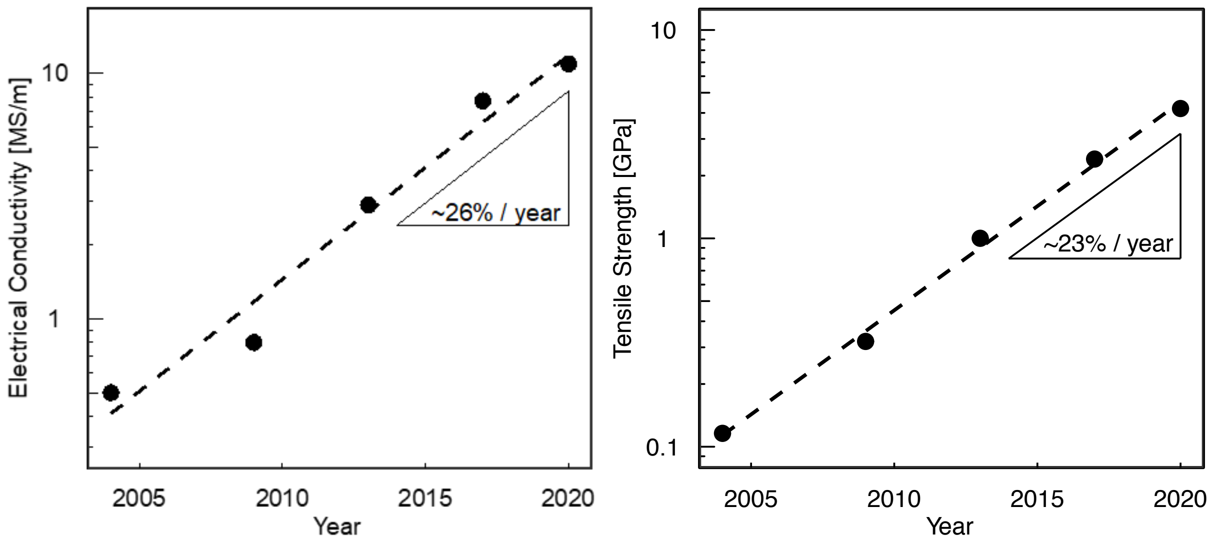

Figure 17 The improvement in electrical conductivity and tensile strength of solution spun CNT fibers at Rice University over time. The properties have been improving on average over 20% per year, equivalent to a doubling every 3 years.

This work has been submitted as: **Improved Properties, Increased Production, and the Path to Broad Adoption of Carbon Nanotube Fibers,** Oliver S. Dewey, Lauren W. Taylor, Robert J. Headrick, Natsumi Komatsu, Nicolas Marquez Peraca, Geoff Wehmeyer, Junichiro Kono, and Matteo Pasquali, submitted.

Year 4: Washable Electrocardiogram Textile Electrodes from Sewn High Performance Carbon Nanotube Fibers

Wearable electronics have become increasingly important to monitor first responders, track workouts, or track day to day wellness. However, progress in wearable electronics has been slow to due material limitations; metal materials are not soft and suffer from poor flex fatigue, and polymers tend to have insufficient conductivity. Here, we demonstrate the use of CNT thread as electrocardiogram (EKG) electrodes and demonstrate the potential of the material for wearable electronics due to the resistance to flex fatigue and high conductivity. CNT thread can be sewn into textiles and obtain EKG signals that are not significantly different from commercial 3M EKG electrodes (Figure 18). Furthermore, the device was washed repeated and did not show degradation in signal quality. Finally, the CNT thread can be used as transmission wires to carry the EKG signal to other parts of the body, allowing the placement of batteries and transmitters away from the detection point, and thus demonstrating the practicality of CNT based thread for other wearable systems.

This work will be published as: **Washable Electrocardiogram Textile Electrodes from Sewn High Performance Carbon Nanotube Fibers**, Lauren W. Taylor, Steven M. Williams, J. Stephen Yan, E. Amram Bengio, Oliver S. Dewey, Flavia Vitale, and Matteo Pasquali, In Preparation.

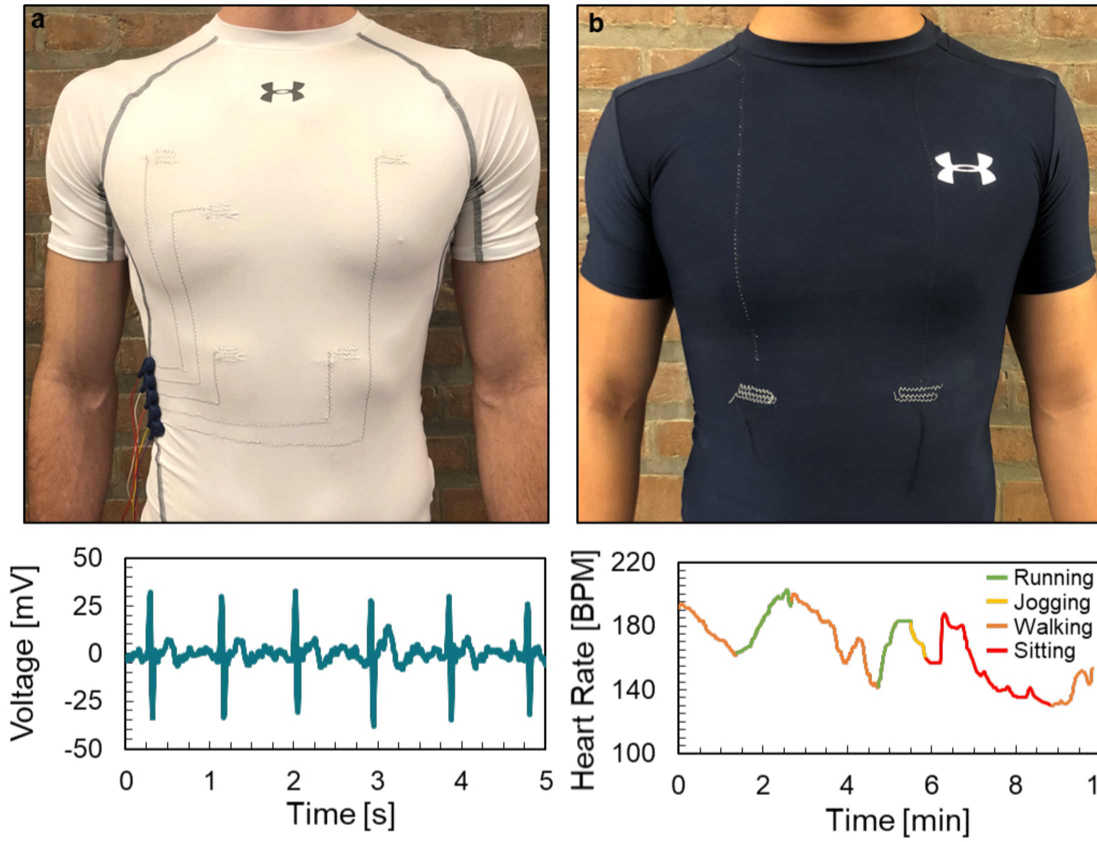

Figure 18 a) An athletic shirt sewn with 5 CNT thread electrodes. The electrodes are connected to standard clips to measure an EKG signal (shown below). The electrodes can acquire a quality signal with all of the features easily discernable. b) An athletic shirt sewn with 2 CNT thread electrodes. The electrodes are connected to a commercial wireless hear rate monitor using CNTT transmission wires. The shirt was worn by an author, and the heart rate while running, jogging, walking, and sitting was recorded overtime and transmitted to a cell phone.

Year 4: Versatile Acid Solvents for Pristine Carbon Nanotube Assembly

We developed a new acid solvent system for processing high quality CNTs into one-, two-, and three-dimensional structures using standard commercial coating and printing equipment. CNTs are spontaneously dissolved at concentrations as high as 10 mg/mL and form bulk a liquid crystalline solution. The unique properties of this CNT ink enable the 3D printing of neat CNT aerogels for the first time, which have specific electrical conductivities as high as 55 S m^2/kg. Moreover, the mild nature of the solvent system provides chemical compatibility with common materials such as polypropylene and polyethylene terephthalate, allowing for ambient processing and water coagulation. We demonstrate continuous production of transparent electrodes with state-of-the-art optoelectronic performance (89.9 %T and 43.3 Ω/sq) and CNT fibers with excellent electrical and mechanical properties (1.11 GPa, 5.2 MS/m).

This work will be published as: **Versatile Acid Solvents for Pristine Carbon Nanotube Assembly**, Robert J. Headrick, Steven M. Williams, Crystal E. Owens, Lauren W. Taylor, Oliver S. Dewey, Cedric J. Ginestra, Lucy Liberman, Asia Mati, Yeshayahu Talmon, Benji Maruyama, Gareth H. McKinley, A. John Hart, and Matteo Pasquali, In Preparation.

Year 4: Self-assembly of Carbon Nanotubes into a Columnar Phase at Low Concentrations Revealed by Small Angle X-ray Scattering

Highly defective CNTs (low crystallinity) behave as colloids and do not form self-supporting macroscale materials, whereas fullerene CNTs behave as polymers, both in fluid phases as well as solid macro-materials. Solutions of fullerene CNTs in chlorosulfonic acid (CSA) follow the phase behavior of rigid rod polymers interacting via a repulsive potential and display a liquid-crystalline phase at sufficiently high concentration. Here, we show that small-angle X-ray scattering can be paired with polarized optical microscopy, to characterize the morphology of the liquid-crystalline phases formed in CNT solutions at concentrations from 3 to 6.5 % by volume. We find that upon increasing concentration, CNTs self-assemble into liquid crystalline phase with pleated texture, resembling that of the hexagonal columnar phase with a large inter-particle spacing. We then explain how thermal undulations of CNTs can enhance their electrostatic repulsion and increase the effective diameter of the CNTs in solution by an order of magnitude. By calculating the critical concentration where the mean amplitude of undulation of an unconstrained rod becomes comparable to the rod spacing, we find that thermal undulations start to affect steric forces at concentrations as low as the isotropic cloud point in CNT solutions.

This work will be published as: **Self-assembly of Carbon Nanotubes into a Columnar Phase at Low Concentrations Revealed by Small Angle X-ray Scattering**, Vida Jamali, Francesca Mirri, Evan G. Biggers, Robert A. Pinnick, Lucy Liberman, Yeshayahu Talmon, Fred C. MacKintosh, Paul van der Schoot, Matteo Pasquali, In Preparation.

Year 4: Efficient Vulcanization for Improving Mechanical Properties of Solution Spun CNT Fiber

The ultimate tensile strength of CNT fibers is well below that of individual CNTs. One of the main reasons for this shortfall is weak lateral interactions (and hence stress transmission) between individual CNTs, which are only held together by weak van der Waals forces. Load transfer between individual CNTs can be improved by increasing the load transfer area, such as by increasing packing density or length (aspect ratio) of individual CNTs, or by increasing the lateral interactions between adjacent CNTs. We demonstrate the use of a vulcanization process that induces sulfur-based crosslinks between individual CNTs within the fiber. We report an increase in tensile strength of 15-55%, where fibers with a lower starting tensile strength show a larger improvement. Moreover, we do not observe any degradation in electrical conductivity of the fiber despite inducing defects into the sidewalls of the CNTs. This is a promising technique to enhance the tensile strength of CNT fibers in a cost-effective manner when ultra-high strength is important such as in aerospace composites or light-weighting car chassis.

This work will be published as: **Efficient Vulcanization for Improving Mechanical Properties of Solution Spun CNT Fiber**, Steven M. Williams, Lauren W. Taylor, Oliver S. Dewey, David Zhou, Katherine R. Gehring, Bryan Whiting, and Matteo Pasquali, In Preparation.

Under Grant FA9550-15-1-0370 in years 1 to 4 we published several additional collaborative papers (listed below):

- **Enlightening the ultrahigh electrical conductivities of doped double-wall carbon nanotube fibers by Raman spectroscopy and first-principles calculations**, Damien Tristant, Ahmed Zubair, Pascal Puech, Frédéric Neumayer, Sébastien Moyano, Robert J. Headrick, Dmitri E. Tsentalovich, Colin C. Young, Iann C. Gerber, Matteo Pasquali, Junichiro Kono, and Jean Leotin, *Nanoscale*, 2016, **8**, 19668-19676.
- **Increased solubility and fiber spinning of graphenide dispersions aided by crown-ethers,** Chengmin Jiang, Zhiwei Peng, Carlos de los Reyes, Colin C. Young, Dmitri E. Tsentalovich, Vida

Jamali, Pulickel M. Ajayan, James M. Tour, Matteo Pasquali, and Angel A. Martí, *Chemical Communications*, 2017, **53**, 1498-1501.

- **Eco-friendly process toward collector- and binder-free, high-energy density electrodes for lithium-ion batteries**, Thomas Bibienne, Laurent Maillaud, Steeve Rousselot, Lauren W. Taylor, Matteo Pasquali, Mickaël Dollé, *Journal of Solid State Electrochemistry*, 2017, **21**, 1407–1416
- **A micro-scale printable nanoclip for electrical stimulation and recording in small nerves**, Charles A Lissandrello, Winthrop F Gillis, Jun Shen, Ben W Pearre, Flavia Vitale, Matteo Pasquali, Bradley J Holinski, Daniel J Chew, Alice E White, Timothy J Gardner, *Journal of Neural Engineering*, 2017, **14**, 036006.
- **Charged Iodide in Chains Behind the Highly Efficient Iodine Doping in Carbon Nanotubes,** Ahmed Zubair, Damien Tristant, Chunyang Nie, Dmitri E. Tsentalovich, Robert J. Headrick, Matteo Pasquali, Junichiro Kono, Vincent Meunier, Emmanuel Flahaut, Marc Monthioux, Iann C. Gerber, and Pascal Puech, 2017, *Physical Review Materials*, **1**, 1064002.
- **Fluidic Microactuation of Flexible Electrodes for Neural Recording,** Flavia Vitale, Daniel G. Vercosa, Alexander V. Rodriguez, Sushma Sri Pamulapati, Frederik Seibt, Eric Lewis, J. Stephen Yan, Krishna Badhiwala, Mohammed Adnan, Gianni Royer-Carfagni, Michael Beierlein, Caleb Kemere, Matteo Pasquali, and Jacob T. Robinson, 2018, *Nano Letters*, **18**, 326-335.
- **Carbon Nanotube Woven Textile Photodetector,** Ahmed Zubair, Xuan Wang, Francesca Mirri, Dmitri E. Tsentalovich, Naoki Fujimura, Daichi Suzuki, Karuppasamy P. Soundarapandian, Yukio Kawano, Matteo Pasquali, and Junichiro Kono, 2018, *Physical Review Materials*, **2**, 015201.
- **Extraction of Boron Nitride Nanotubes and Fabrication of Macroscopic Articles Using Chlorosulfonic Acid**, Mohammed Adnan, Daniel M. Marincel, Olga Kleinerman, Sang-Hyon Chu, Cheol Park, Samuel J.A. Hocker, Catharine Fay, Sivaram Arepalli, Yeshayahu Talmon, and Matteo Pasquali, 2018, *Nano Letters*, **18**, 1615-1619.
- **Directional Sensing Based on Flexible Aligned Carbon Nanotube Film Nanocomposites**, Chao Sui, Yingchao Yang, Robert J. Headrick, Zixuan Pan, Jianyang Wu, Jing Zhang, Shuai Jia, Xinwei Li, Weilu Gao, Oliver S. Dewey, Chao Wang, Xiaodong He, Junichiro Kono, Matteo Pasquali and Jun Lou, **2018**, *Nanoscale*, Advanced Issue.
- **Aligned-SWCNT Film Laminated Nanocomposites: Role of the Film on Mechanical and Electrical Properties,** Chao Sui, Zixuan Pan, Robert J. Headrick, Yingchao Yang, Chao Wang, Jiangtan Yuan, Xiaodong He, Matteo Pasquali, and Jun Lou, 2018*, Carbon,* **139**, 680-687.
- **Bright and Ultrafast Photoelectron Emission from Aligned Single-Wall Carbon Nanotubes through Multiphoton Exciton Resonance**, Mark E. Green, Derek A. Bas, Hsin-Yu Yao, Jamie J. Gengler, Robert J. Headrick, Tyson C. Back, Augustine M. Urbas, Matteo Pasquali, Junichiro Kono, and Tsing-Hua Her, 2018, *Nano Letters*, **19**, 158-164.
- **Scalable Purification of Boron Nitride Nanotubes via Wet Thermal Etching**, Daniel M. Marincel, Mohammed Adnan, Junchi Ma, E. Amram Bengio, Mitchell A. Trafford, Olga Kleinerman, Dmitry V. Kosynkin, Sang-Hyon Chu, Cheol Park, Samuel J.A. Hocker, Catharine C. Fay, Sivaram Arepalli, Angel A. Martí, Yeshayahu Talmon, and Matteo Pasquali, 2019, *Chemistry of Materials*, **31**,1520-1527.
- **All-Solid-State Cells with Li4Ti5O12/Carbon Nanotube Composite Electrodes Prepared by Infiltration with Argyrodite Sulfide-Based Solid Electrolytes via Liquid-Phase Processing**, So Yubuchi, Wataru Nakamura, Thomas Bibienne, Steeve Rousselot, Lauren W Taylor, Matteo Pasquali, Mickaël Dollé, Atsushi Sakuda, Akitoshi Hayashi, Masahiro Tatsumisago, 2019, *Journal of Power Sources*, **417**, 125-131.

- **Carbon Nanotube Fiber Field Emission Array Cathodes**, Steven B. Fairchild, Peng Zhang, Jeongho Park, Tyson C. Back, Daniel Marincel, Zizhuo Huang, and Matteo Pasquali, 2019, *IEEE Transactions on Plasma Science*, **47**, 2032-2038.
- **Polyimide Aerogels as Lightweight Dielectric Insulators for Carbon Nanotube Cables**, Haiquan Guo, Oliver S. Dewey, Linda S. McCorkle, Mary Ann B. Meador, and Matteo Pasquali, 2019, *ACS Applied Polymer Materials*, **1**, 1680-1688.
- **Transport and Photo-Conduction in Carbon Nanotube Fibers**, Oliver S. Dewey, Robert J. Headrick, Lauren W. Taylor, Matteo Pasquali, Giuseppe Prestopino, Gianluca Verona Rinati, Massimiliano Lucci, Matteo Cirillo, 2019, *Applied Physics Letters*, **115**, 023101.
- **Stability of Chemically Doped Nanotube–Silicon Heterojunction Solar Cells: Role of Oxides at the Carbon–Silicon Interface**, Daniel D. Tune, Hiroyuki Shirae, Vincent Lami, Robert J. Headrick, Matteo Pasquali, Yana Vaynzof, Suguru Noda, Erik K. Hobbie, and Benjamin S. Flavel, 2019, *ACS Applied Energy Materials*, **2**, 5925-2932.
- **Self-Sorting of 10-µm-Long Single-Walled Carbon Nanotubes in Aqueous Solution**, Peng Wang, Benjamin Barnes, Xiaojian Wu, Haoran Qu, Chiyu Zhang, Yang Shi, Robert J. Headrick, Matteo Pasquali, YuHuang Wang, 2019, *Advanced Materials*, **31**, 1901641.
- **Macroscopically Aligned Carbon Nanotubes for Flexible and High-Temperature Electronics, Optoelectronics, and Thermoelectrics**, Weilu Gao, Natsumi Komatsu, Lauren W. Taylor, Gururaj V. Naik, Kazuhiro Yanagi, Matteo Pasquali, Junichiro Kono, 2019, *Journal of Physics D: Applied Physics*, **53**, 063001.
- **The Effect of Carbon Nanotube Diameter and Stiffness on their Phase Behavior in Crowded Solutions**, Lucy Liberman, Vida Jamali, Matteo Pasquali, Yeshayahu Talmon, 2019, *Langmuir*, **36**, 242-249.
- **PEDOT Assisted CNT Self-Supported Electrodes for High Energy and Power Density**, Steeve Rousselot, Philippe Antitomaso, Laurence Savignac, Simon Généreux, Lauren W. Taylor, Thomas Bibienne, Matteo Pasquali, Steen B. Schougaard, Mickaël Dollé, Submitted.

Program statistics

PI: Dr. Matteo Pasquali

Graduate Students supported by this grant:

- 2015-2016: Dmitri E. Tsentalovich, Francesca Mirri, Vida Jamali, E. Amram Bengio, Stephen Yan, Mitchell Trafford, Lauren W. Taylor, Robert Pinnick
- 2016-2017: Vida Jamali, E. Amram Bengio, Stephen Yan, Mitchell Trafford, Lauren W. Taylor, Robert Pinnick
- 2017-2018: E. Amram Bengio, Oliver Dewey, Robert Pinnick, Lauren W. Taylor, Mitchell Trafford, Stephen Yan
- 2018-2019: Oliver Dewey, Sushma Sri Pamulapati, Mitchell Trafford, Steven Yan

1. Number of PI and Co-PI involved in the research project: 1
2. Number of Post Doc Supported under AFOSR: Dr. Francesca Mirri (until December 2017)
3. Number of graduate students supported by AFOSR: 5 (final grant installment).
4. Other researchers supported by AFOSR: none
5. Number of publications by PI's in the last 12-month period in refereed journals: 19 (Sept 2018 - September 2019)
6. Publications (in refereed journals only) and theses that acknowledge AFOSR supports (this grant only): 36 published. 3 submitted. 5 in preparation.

1. **Relationship of Extensional Viscosity and Liquid Crystalline Transition to Length Distribution in Carbon Nanotube Solutions**, Dmitri E. Tsentalovich, Anson W. K. Ma, J. Alex Lee, Natnael Behabtu, E. Amram Bengio, April Choi, Junli Hao, Yimin Luo, Robert J. Headrick, Micah J. Green, Yeshayahu Talmon, and Matteo Pasquali, *Macromolecules*, 2016, 49, 681−689.
2. **Carbon nanotube Fiber Terahertz Polarizer**, Ahmed Zubair, Dmitri E. Tsentalovich, Colin C. Young, Martin S. Heimbeck, Henry O. Everitt, Matteo Pasquali, and Junichiro Kono, 2016, *Applied Physics Letters,* 108, 141107.
3. **Lightweight, Flexible, High-Performance Carbon Nanotube Cables Made by Scalable Flow Coating** Francesca Mirri, Nathan D. Orloff, Aaron M. Forster, Rana Ashkar, Robert J. Headrick, E. Amram Bengio, Christian J. Long, April Choi, Yimin Luo, Angela R. Hight Walker, Paul Butler, Kalman B. Migler, and Matteo Pasquali, *ACS Applied Materials and Interfaces*, 2016, 8, 4903−4910.
4. **Enlightening The Ultrahigh Electrical Conductivities of Doped Double-Wall Carbon Nanotube Fibers by Raman Spectroscopy and First-Principles Calculations**, Damien Tristant, Ahmed Zubair, Pascal Puech, Frédéric Neumayer, Sébastien Moyano, Robert J. Headrick, Dmitri E. Tsentalovich, Colin C. Young, Iann C. Gerber, Matteo Pasquali, Junichiro Kono, and Jean Leotin, *Nanoscale*, 2016, **8**, 19668-19676.
5. **Increased Solubility and Fiber Spinning of Graphenide Dispersions Aided by Crown-Ethers,** Chengmin Jiang, Zhiwei Peng, Carlos de los Reyes, Colin C. Young, Dmitri E. Tsentalovich, Vida Jamali, Pulickel M. Ajayan, James M. Tour, Matteo Pasquali, and Angel A. Martí, *Chemical Communications*, 2017, **53**, 1498-1501.
6. **Eco-Friendly Process Toward Collector- and Binder-Free, High-Energy Density Electrodes for Lithium-Ion Batteries**, Thomas Bibienne, Laurent Maillaud, Steeve Rousselot, Lauren W. Taylor, Matteo Pasquali, Mickaël Dollé, *Journal of Solid State Electrochemistry*, 2017, **21**, 1407–1416
7. **A Micro-Scale Printable Nanoclip for Electrical Stimulation and Recording in Small Nerves**, Charles A Lissandrello, Winthrop F Gillis, Jun Shen, Ben W Pearre, Flavia Vitale, Matteo Pasquali, Bradley J Holinski, Daniel J Chew, Alice E White, Timothy J Gardner, *Journal of Neural Engineering*, 2017, **14**, 036006.
8. **Direct Imaging of Carbon Nanotube Liquid-Crystalline Phase Development in True Solutions**, Olga Kleinerman, Lucy Liberman, Natnael Behabtu, Matteo Pasquali, Yachin Cohen, Yeshayahu Talmon, 2017, *Langmuir* **33**, 4011-4018.
9. **Line Tension of Twist-Free Carbon Nanotube Lyotropic Liquid Crystal Microdroplets on Solid Surfaces**, Vida Jamali, Evan G. Biggers, Paul van der Schoot, and Matteo Pasquali, 2017, *Langmuir,* **33**, 9115−9121.
10. **Influence of Carbon Nanotube Characteristics on Macroscopic Fiber Properties,** Dmitri E. Tsentalovich, Robert J. Headrick, Francesca Mirri, Junli Hao, Natnael Behabtu, Colin C. Young, and Matteo Pasquali, 2017, *ACS Applied Materials and Interfaces,* **9**, 36189-36198.
11. **Purification and Dissolution of Carbon Nanotube Fibers Spun from the Floating Catalyst Method**, Thang Q. Tran, Robert J. Headrick, E. Amram Bengio, Sandar Myo Myint, Hamed Khoshnevis, Vida Jamali, Hai M. Duong, and Matteo Pasquali, 2017, *ACS Applied Materials and Interfaces*, **9**, 37112-37119.
12. **High Efficiency Carbon Nanotube Thread Antennas**, E. Amram Bengio, Damir Senic, Lauren W. Taylor, Dmitri E. Tsentalovich, Peiyu Chen, Christopher L. Holloway, Aydin Babakhani, Christian J. Long, David R. Novotny, James C. Booth, Nathan D. Orloff, and Matteo Pasquali, 2017, *Physical Review Letters*, **111**, 163109.
13. **Charged Iodide in Chains Behind the Highly Efficient Iodine Doping in Carbon Nanotubes,** Ahmed Zubair, Damien Tristant, Chunyang Nie, Dmitri E. Tsentalovich, Robert J. Headrick, Matteo Pasquali, Junichiro Kono, Vincent Meunier, Emmanuel Flahaut, Marc Monthioux, Iann C. Gerber, and Pascal Puech, 2017, *Physical Review Materials*, **1**, 1064002.

14. **Dissolution and Characterization of Boron Nitride Nanotubes in Superacid,** Olga Kleinerman, Mohammed Adnan, Daniel M. Marincel, Anson W. K. Ma, E. Amram Bengio, Cheol Park, Sang-Hyon Chu, Matteo Pasquali, and Yeshayahu Talmon, 2017, *Langmuir*, **33**, 14340-14346.
15. **Fluidic Microactuation of Flexible Electrodes for Neural Recording,** Flavia Vitale, Daniel G. Vercosa, Alexander V. Rodriguez, Sushma Sri Pamulapati, Frederik Seibt, Eric Lewis, J. Stephen Yan, Krishna Badhiwala, Mohammed Adnan, Gianni Royer-Carfagni, Michael Beierlein, Caleb Kemere, Matteo Pasquali, and Jacob T. Robinson, 2018, *Nano Letters*, **18**, 326-335.
16. **Carbon Nanotube Woven Textile Photodetector,** Ahmed Zubair, Xuan Wang, Francesca Mirri, Dmitri E. Tsentalovich, Naoki Fujimura, Daichi Suzuki, Karuppasamy P. Soundarapandian, Yukio Kawano, Matteo Pasquali, and Junichiro Kono, 2018, *Physical Review Materials*, **2**, 015201.
17. **Extraction of Boron Nitride Nanotubes and Fabrication of Macroscopic Articles Using Chlorosulfonic Acid**, Mohammed Adnan, Daniel M. Marincel, Olga Kleinerman, Sang-Hyon Chu, Cheol Park, Samuel J.A. Hocker, Catharine Fay, Sivaram Arepalli, Yeshayahu Talmon, and Matteo Pasquali, 2018, *Nano Letters*, **18**, 1615-1619.
18. **Directional Sensing Based on Flexible Aligned Carbon Nanotube Film Nanocomposites**, Chao Sui, Yingchao Yang, Robert J. Headrick, Zixuan Pan, Jianyang Wu, Jing Zhang, Shuai Jia, Xinwei Li, Weilu Gao, Oliver S. Dewey, Chao Wang, Xiaodong He, Junichiro Kono, Matteo Pasquali, and Jun Lou, **2018**, *Nanoscale*, Advanced Issue.
19. **Highly Concentrated Aqueous Dispersions of Carbon Nanotubes for Flexible and Conductive Fibers,** Laurent Maillaud, Robert J. Headrick, Vida Jamali, Julien Maillaud, Dmitri E. Tsentalovich, Wilfrid Neri, E. Amram Bengio, Francesca Mirri, Olga Kleinerman, Yeshayahu Talmon, Philippe Poulin, and Matteo Pasquali, *2018, Industrial & Engineering Chemistry Research,* **57**, 3554-3560.
20. **Structure–Property Relations in Carbon Nanotube Fibers by Downscaling Solution Processing**, Robert J. Headrick, Dmitri E. Tsentalovich, Julián Berdegué, Elie Amram Bengio, Lucy Liberman, Olga Kleinerman, Matthew S. Lucas, Yeshayahu Talmon, and Matteo Pasquali, 2018, *Advanced Materials*, **30**, 1704482.
21. **Aligned-SWCNT Film Laminated Nanocomposites: Role of the Film on Mechanical and Electrical Properties**, Chao Sui, Zixuan Pan, Robert J. Headrick, Yingchao Yang, Chao Wang, Jiangtan Yuan, Xiaodong He, Matteo Pasquali, and Jun Lou, 2018*, Carbon,* **139**, 680-687.
22. **Bending Behavior of CNT Fibers and Their Scaling Laws**, Mohammed Adnan, Robert A Pinnick, Zhao Tang, Lauren W Taylor, Sushma Sri Pamulapati, Gianni Royer Carfagni, and Matteo Pasquali, 2018, *Soft Matter*, **14**, 8284-8292.
23. **Bright and Ultrafast Photoelectron Emission from Aligned Single-Wall Carbon Nanotubes through Multiphoton Exciton Resonance**, Mark E. Green, Derek A. Bas, Hsin-Yu Yao, Jamie J. Gengler, Robert J. Headrick, Tyson C. Back, Augustine M. Urbas, Matteo Pasquali, Junichiro Kono, and Tsing-Hua Her, 2018, *Nano Letters*, **19**, 158-164.
24. **Quantification of Carbon Nanotube Liquid Crystal Morphology via Neutron Scattering**, Francesca Mirri, Rana Ashkar, Vida Jamali, Lucy Liberman, Robert A. Pinnick, Paul van der Schoot, Yeshayahu Talmon, Paul D. Butler, and Matteo Pasquali, 2018, *Macromolecules*, **51**, 6892-6900.
25. **Scalable Purification of Boron Nitride Nanotubes via Wet Thermal Etching**, Daniel M. Marincel, Mohammed Adnan, Junchi Ma, E. Amram Bengio, Mitchell A. Trafford, Olga Kleinerman, Dmitry V. Kosynkin, Sang-Hyon Chu, Cheol Park, Samuel J.A. Hocker, Catharine C. Fay, Sivaram Arepalli, Angel A. Martí, Yeshayahu Talmon, and Matteo Pasquali, 2019, *Chemistry of Materials*, **31**,1520-1527.
26. **All-Solid-State Cells with Li4Ti5O12/Carbon Nanotube Composite Electrodes Prepared by Infiltration with Argyrodite Sulfide-Based Solid Electrolytes via Liquid-Phase Processing**, So Yubuchi, Wataru Nakamura, Thomas Bibienne, Steeve Rousselot, Lauren W Taylor, Matteo

Pasquali, Mickaël Dollé, Atsushi Sakuda, Akitoshi Hayashi, Masahiro Tatsumisago, 2019, *Journal of Power Sources*, **417**, 125-131.

27. **Electrical and Acoustic Vibroscopic Measurements for Determining Carbon Nanotube Fiber Linear Density**, Robert J. Headrick, Mitchell A. Trafford, Lauren W. Taylor, Oliver S. Dewey, Russell A. Wincheski, Matteo Pasquali, 2019, *Carbon*, **144**, 417-422.
28. **Carbon Nanotube Fiber Field Emission Array Cathodes**, Steven B. Fairchild, Peng Zhang, Jeongho Park, Tyson C. Back, Daniel Marincel, Zizhuo Huang, and Matteo Pasquali, 2019, *IEEE Transactions on Plasma Science*, **47**, 2032-2038.
29. **Carbon Nanotube Thin Film Patch Antennas for Wireless Communications**, E. Amram Bengio, Damir Senic, Lauren W. Taylor, Robert J. Headrick, Michael King, Peiyu Chen, Charles A. Little, John Ladbury, Christian J. Long, Christopher L. Holloway, Aydin Babakhani, James C. Booth, Nathan D. Orloff, and Matteo Pasquali, 2019, *Applied Physics Letters*, **114**, 203102.
30. **Polyimide Aerogels as Lightweight Dielectric Insulators for Carbon Nanotube Cables**, Haiquan Guo, Oliver S. Dewey, Linda S. McCorkle, Mary Ann B. Meador, and Matteo Pasquali, 2019, *ACS Applied Polymer Materials*, **1**, 1680-1688.
31. **Transport and Photo-Conduction in Carbon Nanotube Fibers**, Oliver S. Dewey, Robert J. Headrick, Lauren W. Taylor, Matteo Pasquali, Giuseppe Prestopino, Gianluca Verona Rinati, Massimiliano Lucci, Matteo Cirillo, 2019, *Applied Physics Letters*, **115**, 023101.
32. **Stability of Chemically Doped Nanotube–Silicon Heterojunction Solar Cells: Role of Oxides at the Carbon–Silicon Interface**, Daniel D. Tune, Hiroyuki Shirae, Vincent Lami, Robert J. Headrick, Matteo Pasquali, Yana Vaynzof, Suguru Noda, Erik K. Hobbie, and Benjamin S. Flavel, 2019, *ACS Applied Energy Materials*, **2**, 5925-2932.
33. **Self-Sorting of 10-µm-Long Single-Walled Carbon Nanotubes in Aqueous Solution**, Peng Wang, Benjamin Barnes, Xiaojian Wu, Haoran Qu, Chiyu Zhang, Yang Shi, Robert J. Headrick, Matteo Pasquali, YuHuang Wang, 2019, *Advanced Materials*, **31**, 1901641.
34. **In Vivo Restoration of Myocardial Conduction with Carbon Nanotube Fibers**, Mark D. McCauley, Flavia Vitale, J. Stephen Yan, Colin C. Young, Brian Greet, Marco Orecchioni, Srikanth Perike, Abdelmotagaly Elgalad, Julia A. Coco, Mathews John, Doris A. Taylor, Luiz C. Sampaio, Lucia G. Delogu, Mehdi Razavi, Matteo Pasquali, 2019, *Circulation: Arrhythmia and Electrophysiology*, **12**, e007256.
35. **Macroscopically Aligned Carbon Nanotubes for Flexible and High-Temperature Electronics, Optoelectronics, and Thermoelectrics**, Weilu Gao, Natsumi Komatsu, Lauren W. Taylor, Gururaj V. Naik, Kazuhiro Yanagi, Matteo Pasquali, Junichiro Kono, 2019, *Journal of Physics D: Applied Physics*, **53**, 063001.
36. **The Effect of Carbon Nanotube Diameter and Stiffness on their Phase Behavior in Crowded Solutions**, Lucy Liberman, Vida Jamali, Matteo Pasquali, Yeshayahu Talmon, 2019, *Langmuir*, **36**, 242-249.
37. **Perovskite-Carbon Nanotube Light Emitting Fibers**, Vida Jamali, Farnaz Niroui, Lauren W. Taylor, Oliver S. Dewey, Brent Koscher, Matteo Pasquali, A. Paul Alivisatos, Submitted.
38. **PEDOT Assisted CNT Self-Supported Electrodes for High Energy and Power Density**, Steeve Rousselot, Philippe Antitomaso, Laurence Savignac, Simon Généreux, Lauren W. Taylor, Thomas Bibienne, Matteo Pasquali, Steen B. Schougaard, Mickaël Dollé, Submitted.
39. **Macroscopic Fibers Made from Carbon Nanotubes are Bio- and Immune-compatible: Implications for Carbon Nanotube Macrostructures in Biomedical Applications** J. Stephen Yan, Flavia Vitale, Marco Orecchioni, Julia A. Coco, Guillaume Duret, Salvatore Antonucci, Sushma Sri Pamulapati, Lauren W. Taylor, Oliver S. Dewey, Moises Di Sante, Anna Maria Segura, Ley, Fabio Di Lisa, Mark D. McCauley, Jacob T. Robinson, Mehdi Razavi, Lucia G. Delogu, Matteo Pasquali, Submitted.

40. **Improved Properties, Increased Production, and the Path to Broad Adoption of Carbon Nanotube Fibers,** Oliver S. Dewey, Lauren W. Taylor, Robert J. Headrick, Natsumi Komatsu, Nicolas Marquez Peraca, Geoff Wehmeyer, Junichiro Kono, and Matteo Pasquali, In Preparation.
41. **Washable Electrocardiogram Textile Electrodes from Sewn High Performance Carbon Nanotube Fibers**, Lauren W. Taylor, Steven M. Williams, J. Stephen Yan, E. Amram Bengio, Oliver S. Dewey, Flavia Vitale, and Matteo Pasquali, In Preparation.
42. **Versatile Acid Solvents for Pristine Carbon Nanotube Assembly**, Robert J. Headrick, Steven M. Williams, Crystal E. Owens, Lauren W. Taylor, Oliver S. Dewey, Cedric J. Ginestra, Lucy Liberman, Asia Mati, Yeshayahu Talmon, Benji Maruyama, Gareth H. McKinley, A. John Hart, and Matteo Pasquali, In Preparation.
43. **Self-assembly of Carbon Nanotubes into a Columnar Phase at Low Concentrations Revealed by Small Angle X-ray Scattering**, Vida Jamali, Francesca Mirri, Evan G. Biggers, Robert A. Pinnick, Lucy Liberman, Yeshayahu Talmon, Fred C. MacKintosh, Paul van der Schoot, Matteo Pasquali, In Preparation.
44. **Efficient Vulcanization for Improving Mechanical Properties of Solution Spun CNT Fiber**, Steven M. Williams, Lauren W. Taylor, Oliver S. Dewey, David Zhou, Katherine R. Gehring, Bryan Whiting, and Matteo Pasquali, In Preparation.

Theses:

1. Dmitri Tsentalovich, Ph.D. thesis, Rice University, 2015
2. Francesca Mirri, Ph.D. thesis, Rice University, 2016
3. Mohammed Adnan, Ph. D. thesis, Rice University, 2016
4. Colin Young, Ph. D. thesis, Rice University, 2016
5. Vida Jamali, Ph. D. thesis, Rice University, 2017
6. E. Amram Bengio, Ph.D. thesis, Rice University, 2017
7. Robert Headrick, Ph.D. thesis, Rice University, 2018
8. Robert Pinnick, M.S. thesis, Rice University, 2019
9. J. Stephen Yan, Ph.D. thesis, Rice University, 2020
10. Lauren Taylor, Ph.D. Thesis, Rice University, 2020 (expected)
11. Steven Williams, Ph.D. Thesis, Rice University, 2020 (expected)

Awards and Honors received by the PI (life-time received):

- U. Bologna, ENICHEM prize (top 3 Chemical Engineering students) (1989, 1991, 1992)
- U. Bologna Ciba-Geigy award for best Chemical Engineering dissertation (1993)
- U. Bologna fellowship for graduate studies abroad (1994-1995)
- NSF-CAREER award (2001)
- AIChE S.TX Best Applied Paper Award (2008)
- Rice University Faculty Teaching & Mentoring Award (2009)
- AIChE S.TX Best Applied Paper Award (2009)
- AIChE S.TX Best Fundamental Paper Award (2010)
- NASA Tech Brief Award (2011)
- AIChE S.TX Best Applied Paper Award (2013)
- Paul Schlack Honorary Prize for Man-Made Fibers (2014)
- Goradia Prize (2014)
- Herschel M. Rich Award, Best Invention Award (invention supported by grant FA9550-15-1-0370), Rice University (2016)

- Elected APS Fellow (2016)
- Elected AAAS Fellow (2018)
- Rice University Presidential Mentoring Award (2020)

Visits by Pasquali group members to AFRL (all to WPAFB, Dayton)

- 14 July, 2019 to 27 July, 2019
  - Arthur Sloan (PhD Student)
- 10 February 2019 to 9 March 2019
  - Arthur Sloan (PhD Student)
  - Emily Yedinak (PhD Student)
- 17 October 2018 to 24 October 2018
  - Arthur Sloan (PhD Student)
- 10 August 2017 to 11 August 2017
  - Dan Marincel (Postdoctoral Researcher)
- 27 February 2017 to 2 March 2017
  - Matteo Pasquali (PI)
- 24 October 2016 to 4 November 2016
  - Robert Headrick (PhD student)
  - Steven Williams (PhD student)
- 9 May 2016 to 25 June 2016
  - Robert Headrick (PhD student)
- 19 to 23 October 2015
  - Robert Headrick (PhD student)
- 26 to 27 April 2015
  - Matteo Pasquali (PI)
  - Alberto Goenaga (Rice consultant and CEO of DexMat, Rice spinoff company)
- 13-14 October 2014
  - Matteo Pasquali (PI)
  - Dmitri Tsentalovich (PhD student)
- 24 to 26 March 2014
  - Matteo Pasquali (PI)

Visit by AFRL personnel to Pasquali laboratory at Rice University

- 12 October 2017
  - Dr. Steven Fairchild (AFRL WPAFB, Dayton)
  - Dr. Kent Averett (AFRL WPAFB, Dayton)
  - Dr. Timothy Haugan (AFRL WPAFB, Dayton)
- 27 January 2017
  - Dr. Steven Fairchild (AFRL WPAFB, Dayton)
  - Dr. John Boeckl (AFRL WPAFB, Dayton)
  - Dr. Nate Lockwood (AFRL Kirtland AFB, Albuquerque)
- 22 to 24 August 2016
  - Dr. Benji Maruyama (AFRL)
  - Dr. Kerry Bennington (AFRL)

- 29 March 2016
    - Dr. Steven Fairchild (AFRL WPAFB, Dayton)
    - Dr. Matthew Lange (AFRL WPAFB, Dayton)
- 7 January 2016 (the team visited Rice; including the Pasquali lab; Pasquali gave an overview presentation)
    - Dr. Laura Barnes (AFRL)
    - Dr. Timothy Bunning (AFRL/RX)
    - Dr. Jose Camberos (AFRL)
    - Dr. Thomas Christian (AFOSR)
    - Chief Ray Devite (AFRL)
    - Dr. Kenneth Goretta (AFOSR)
    - Dr. Ajit Roy (AFRL)
    - Dr. Amanda Schrand (AFRL)
    - Dr. Morley Stone (AFRL)
    - Capt. Dave Wirth (AFRL)
- 17 November 2015
    - Diana Carlin (AFRL)
    - Joycelyn Harrison (AFOSR)
- 8 to 10 April 2015
    - Benji Maruyama (AFRL)