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Every Carbon Conductor for Electrical and Electronic Wiring Use

Mr. Manjunath Raikar
Lecturer / Department of Electrical & Electronics
Sri Channakeshava Govt Polytechnic - Bankapur-581202, Dist Haveri
manjunathraikarn@gmail.com

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ABSTRACT

Recently, there has been an increasing interest in carbon-based electrical conductors since they may eventually replace metals. Without any metal, electrical conductors might be a step forward in the development of technology as well as a replacement for conventional wire. High electrical conductivity can be combined with other qualities, such as flexibility, dexterity, low weight, environmental stability, and high strength, to produce this effect. A special emphasis is placed on the empirical relationship between [3] morphology/structure/composition and the electrical properties, since the best mechanical properties and high electrical/thermal conductivity of the assembled fibers are all generally associated with low concentration of defects in the fiber backbone and in the individual carbon "building blocks".

This article discusses some of the most recent advancements in the field of "all-carbon" electrical conductors, starting at the beginning—the late 19th century, when carbon filaments were first used as streetlights in cities. By organizing nanoscale carbons (such as graphene and carbon nanotubes) into macroscopic threads, skeins, and ropes (referred to as fibers), such conductors may be created. This viewpoint emphasizes the significance that chemistry plays, especially about doping and molecular level control. This contribution explains the most current findings in the area and suggests further possible uses.

Keywords: Graphene, Carbon Nanotubes, Carbon Fibers, Graphene Fiber, CNT Fibers, Yarns, Doped Carbon, Electrical Conductivity

I. INTRODUCTION

A thorough understanding of the electrical properties of carbon-based materials is required due to the rising interest in novel electrically conductive materials that have better qualities than standard conductors. It goes without saying that other factors are taken into consideration when considering the potential usage of substitute electrical conductors. It is important to consider other features including mechanical and thermal qualities, chemical and thermal resistance, low weight and density, heat removal efficiency, connections with conventional wires, dependability, and durability [1].

Presently, a lot of carbon nanomaterials are either synthesized and used in their pure form or are combined with polymers to form multiphase materials (Haznedar et al., 2013; Cesano and Scarano, 2015; Cesano et al., 2016). In contrast to metal conductors, highly conductive carbon conductors may be found in assemblies that incorporate nanocarbons that are smaller in length and size (Fang et al., 2020). Building carbon-based macroscopic assemblies with improved electrical, mechanical, thermal, and electrochemical properties has been motivated by the lack of progress in the fabrication of "single domain" continuous carbon nanotubes and graphene fibers (Zhang et al., 2007; Lu et al., 2012, 2017, 2019; Miao, 2013; Mäder et al., 2015; Kou et al., 2017; Dhanabalan et al., 2019; Foroughi and Spinks, 2019; Yang et al., 2020; Yin et al., 2020) [2].

Comparing carbon nanotubes and graphene-based conductors to traditional metal wires, they have reached the electrical properties of their metal counterparts [4]. These materials have many benefits, including reduced weight, strong mechanical and electrical conductivities, sensing capabilities, resistance to harsh environments, and thermal and electrical conductivities (Cesano et al., 2013; Cravanzola et al., 2013; Cesano and Scarano, 2018; Chowdhury et al., 2019; Harun et al., 2019). However, as metals are only found in small quantities in nature, finding a beneficial substitute would be extremely important [6]. In light of these viewpoints, it is noteworthy that there are numerous reviews on the subject of carbon-based materials and properties, and that some of them (Lu et al., 2012; Cong et al., 2014; Lekawa-Raus et al., 2014b; Li and Pandey, 2015; Li et al., 2015; Xu and Gao, 2015; Kou et al., 2017; Yadav et al., 2017; Xu et al., 2019; Zhang et al., 2019; Zheng et al., 2020) should be considered highly significant. In addition to previous discoveries, Zheng et al. (2020) have recently shown that graphene fibers exhibit an ultrafast electro-thermal response (5943 K s−1), exceeding the record value of carbon nanotubes.

The authors have demonstrated the structural engineering of the graphene fiber assembly, wherein entanglements of individual graphene nanosheets are advantageous to achieve very low density (0.015–0.020 g/cm−3), along with high mechanical strength (c.a. 3.9 MPa), high specific electrical conductivity (SEC) (0.95–1.67 S m2 /g), and specific thermal conductivity (STC) (42.3–100 W cm2 K−1g−1) values, which are comparable to those of metals (SECCu: 6.61 S m2 g −1; STCCu: 0.45 W cm2 K−1g−1; SECAg: 5.98 S m2g−1; STCAg: 0.40 W cm2 K−1g−1). It has recently been shown by Hills et al. (2019) that microprocessors constructed of carbon nanotube FETs on Si wafers may be produced. These microprocessors are known as the 16-bit RV16X-NANO microprocessor, and they handle 32-bit instructions of the RISC-V architecture. In addition to verifying the microprocessor's functionality under operational settings, such as instruction retrieval, decoding, registration, execution units, and back writing to memory, the authors suggested a production process for carbon nanotube manipulation, doping, etching, and assembly. This process aims to overcome nanoscale flaws at larger scales and establish industry norms [5]. Simultaneously, Afroj et al. (2019) reported on the engineering of graphene oxide and graphene flakes for traditional textile coating using highspeed fiber dyeing process. Using currently available textile machinery, the approach can manufacture tons of conductive yarn based on graphene.

Scientists have further demonstrated that the resulting cloth retains its conductivity even after a few cycles of washing. Furthermore, several recent studies have shown that graphene and carbon nanotube-based yarns can be used for a variety of purposes, such as catalysis, energy harvesting and storage devices, sensors and biosensors, actuators, and Jang et al., 2019; Foroughi and Spinks, 2019; Panwar et al., 2019; Wang et al., 2019; Fang et al., 2020). These recent examples, along with a critical analysis of the literature, show that, despite the scientific background on this topic being vast and quickly expanding, it is incredibly diverse, making it nearly impossible to provide a comprehensive description of all the potential applications. Because of this, the current review's goal is to offer a range of perspectives on electrical characteristics [7].

II. THE FIRST CARBON CONDUCTIVE WIRES TO BE DEVELOPED

Marcellin Jobard was the first person to encounter a "glow lamp" made of carbon in 1838. It was a vacuum bulb with a tiny strip of carbon within that was used to carry electricity and generate a bright, steady light. Among the first scientists to pioneer electric lighting in the late century were Alessandro Cruto, Henry Woodward, Mathew Evans, Joseph W. Swan, and Thomas A. Edison. Following the initial methods involving metal filaments positioned either inside or outside of vacuum bulbs, they independently ascertained that low-cost, high-resistance filaments with a resistance of around a few hundred ohms were necessary to minimize the dimensions of the electric lights.

As a result, it was determined that pyrolyzed carbon filaments were the best potential candidate materials; some of them were even granted independent patents. Alessandro Cruto most likely got the most robust electric lamps, while Edison and Swan are perhaps the more well-known creators [9].

Aside from his greater number of patents in this case, Edison's contribution has been a set of specifications, traits, and techniques needed to create long-lasting electrical lighting. After around 20 years, a new revolution in light bulbs emerged in 1904: tungsten coiled coils in an inert gas-filled bulb quickly replaced carbon filaments because they produced a brighter light and were more durable.

III. CARBON FIBER

Joseph Swan is credited with creating carbon fibers for the first time in 1860 using cellulose filaments for light bulb applications. However, Union Carbide didn't make the first high-performance carbon fibers until 1958, which was a century later. These fibers were created by heating rayon fibers to a comparatively high temperature while they were exposed to an inert atmosphere until they carbonized [10].

Unfortunately, it was shown that the process was ineffectual because of the stiffness, poor strength, and comparatively low carbon content (20%) of the fibers. In the early 1960s, new methods based on polyacrylonitrile (PAN) were developed to produce carbon fibers that contained more than 99% carbon. By experimenting with process parameters (such as a very high temperature) and precursor types (such as rayon, PAN, and pitch), new generation carbon fibers with a high tensile modulus and mechanical strength were obtained in the following years. To produce a graphitic structure and remove heteroatoms (N, S, O, and H), high temperature carbonization was optimized. The most common precursor for carbon fibers used today is PAN, which is produced via several processes including thermal oxidation, carbonization, graphitization, and surface treatments [12].

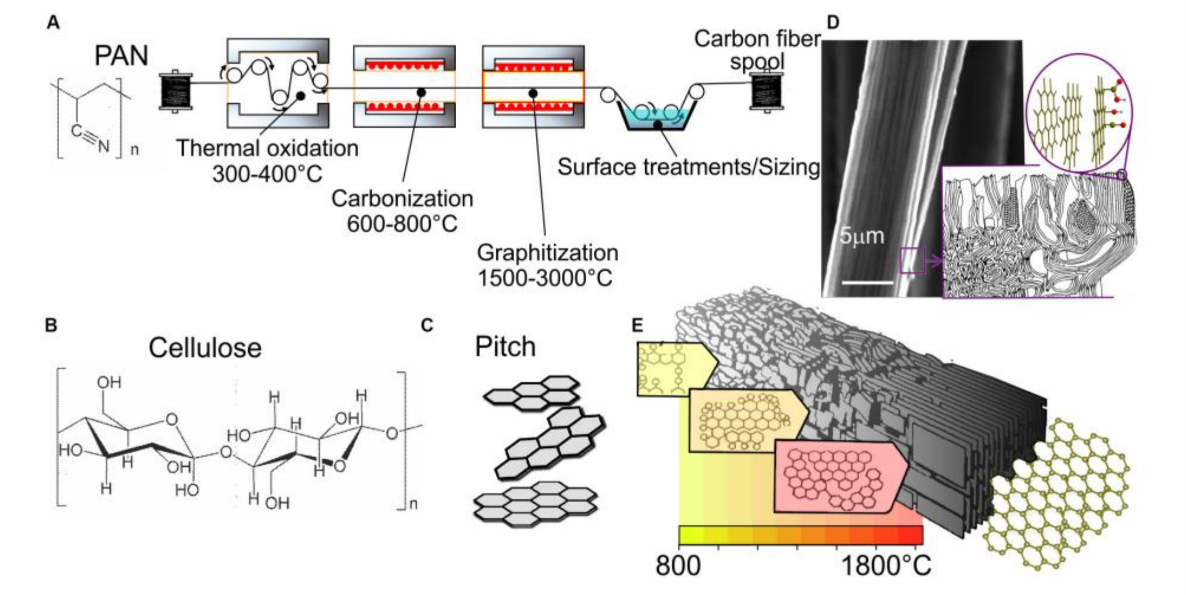

FIGURE 1 | Fabrication steps of carbon fibers from **(A)** polyacrylonitrile (the most used precursor): oxidation and crosslinking of the PAN fibers, pyrolysis and possibly, the graphitization step occurring at the higher temperatures under inert atmosphere or vacuum conditions; two other conventional precursors of carbon fibers: **(B)** cellulose and **(C)** pitch; **(D)** morphology, structure and surface chemistry of PAN-derived carbon fibers; and **(E)** evolution of the carbon structure with the increasing temperature from amorphous to crystalline structure (i.e., hexagonal graphite).

Figure 1 shows a SEM picture of the morphology of a carbon fiber that was produced from PAN along with a few models of surface chemistry and crystalline domain configurations. Moreover, carbon fibers can be produced with a wide range of properties, contingent on the type of precursor and production process. For example, when thermally treated above 1500–2000◦C, they display a more ordered arrangement (Figure 1E), have higher thermal and electrical conductivities, a very high elastic modulus, and a carbon content greater than 99%. They go by the name "graphitic fibers" sometimes. Lower temperatures result in fibers with lower C contents (93–95%) as well as poorer mechanical and conductivity values. Carbon fibers are employed in electrode/microelectrodes (a single carbon fiber), flexible heating applications, and whenever a low wear friction on the contact surface is required (e.g., brush contact), in addition to its primary use in fiber-reinforced composites [13].

Carbon fibers do not signal the end of fibers; rather, they are the beginning of new classes due to their excellent mechanical properties and a few peculiarities (PAN-based fibers have a turbotrain structure: contain basal planes slipped out of their alignment, thus exhibiting high tensile strength, while pitch-derived fibers show higher Young's modulus, high stiffness) and peculiar thermal/electrical conductivities (Chung, 2017). As schematized in the insets of Figure 1D, carbon fibers really exhibit a polycrystalline nature with many grain boundaries/defects, near voids, and a rough morphology. As a result, their characteristics are limited in comparison to their graphite equivalent. This might be viewed as an obvious result of the direct pyrolysis of organic precursors [14].

IV. CARBON NANOTUBES WITH VAPOR GROWTH (VGCFS), AS WELL AS SINGLE- AND MULTI-WALLED CARBON NANOTUBES (MWCNTS AND SWCNTS)

Since the 1950s, graphitic filaments made of hydrocarbons or CO have been seen to develop as deposits on a variety of substrates within the 350–2500°C furnace tube, frequently unintentionally (Bacon, 1959). However, because of the lower deposition temperature (350–800◦C), the production of carbon fibers and nanofibers became more appealing with the catalytic breakdown of hydrocarbons aided by metal (i.e., Fe, Ni, Co, alloys) and metal oxide nanoparticles (Tibbetts, 1985). Numerous books, book chapters, and scientific papers have been written about this subject. The reader might consult the specialized literature (Iijima and Ichihashi, 1993; Rodriguez et al., 1995; Ajayan, 1999) for a thorough analysis of this topic. In summary, it's critical to keep in mind that three distinct categories of precursors—solid, liquid, and gas—are relevant. The low cost and wide availability of solid and liquid carbon precursors are drawing attention; however, hydrocarbons are the most often used because of their purity, which makes them suitable for use as model systems [15].

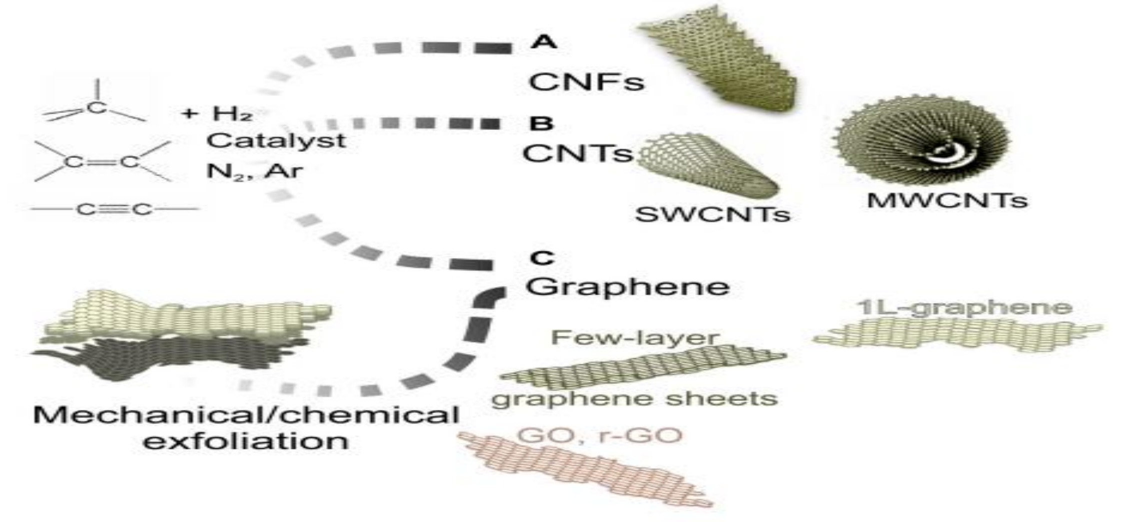

FIGURE 2 | Fabrication scheme of 1D and 2D carbons from molecular precursors (or pre-constituted CNT/graphene structures): **(A)** carbon nanofibers (CNFs), **(B)** single-walled and multi-walled carbon nanotubes (SWCNTs, MWCNTs); and **(C)** 2D carbons obtained from "*bottom-up*" and "*top-down*" approaches: graphene, graphene oxide (GO) and reduced graphene oxide (r-GO).

It is well acknowledged on this topic that when hydrocarbons are utilized, the reactions occur at the exposed surfaces of the metal catalyst and the metal nanoparticles shape the carbon nanostructures that are forming (Cesano et al., 2005; Li and Pandey, 2015). Accordingly, bulk diffusion, carbon concentration gradients, and reaction temperature control the development process of carbon nanostructures (Derbyshire et al., 1975; Iijima et al., 1992; Rodriguez et al., 1995; De Jong and Geus, 2000; Kharlamova, 2017). Different forms of structures may be seen depending on the kind of catalyst, reaction temperature, metal particle sizes, and growth techniques (Li and Pandey, 2015; Kharlamova, 2017) (Figures 2A, B). According to De Jong and Geus (2000), carbon nanotubes (SWCNTs and MWCNTs) can be identified from nanofibers based on how the carbon layers are stacked. Smaller metal nanoparticles are removed during the synthesis of SWCNTs, whereas larger catalyst particles encourage the formation of MWCNTs and nanofibers. Similarly, large area graphene sheets may be produced by a bottom-up method that involves a metal catalyst (mostly Cu, Pt, Co, but also Ni and other metals) and a carbon feedstock. The hydrocarbon content and cooling rate during graphene formation can also be controlled [6].

V. FIBER INTERCONNECTS: COVALENT BONDING AND VAN DER WAALS INTERACTIONS

It is well known that defects and the weak contacts between neighboring fibers restrict the mechanical, thermal, and electrical conductivities of carbon fibers (LekawaRaus et al., 2014b; Fang et al., 2020; Wang et al., 2020). The connecting of fibers through catalytically generated nanofilaments (carbon nanofibers and carbon nanotubes) by employing C2H4 or xylene at 700 and 800◦C has been demonstrated by Cesano et al. (2005), Veedu et al. (2006), and Anthony et al. (2018) .

According to the authors' findings, metal nanoparticles (Fe, Ni) travel from their original location on the fiber surface to the tip of the filaments that are still forming, where they function as separate catalytic centers (Cesano et al., 2005). A more compact CNT/CFs composite can eventually be densified thanks to the catalytic nanoparticles that are transferred into the structure of the growing nanofilaments and contribute significantly to the ongoing formation of interconnected CNF entanglement that links the neighboring CFs.

Zheng et al. (2019) recently demonstrated the 3D assembly of graphene sheets generated directly on carbon fibers by thermal CVD [7]. PAN fibers were carbonized at 1100°C (under NH3) after being stabilized (in air). For extended reactions (10h), the scientists saw a striking densification of the graphene nanosheets, along with the growth time and filling of the gaps between composite fibers (Figures 3E–H). In a recent paper, Karakassides et al. (2020) reported using a microwave plasma-enhanced chemical vapor deposition (PECVD) process with a CH4 and N2 gas mixture under vacuum conditions (total pressure = 15 Torr) to grow radially aligned graphene nanoflakes on carbon fibers without the need for a catalyst.

The authors noted that in addition to a notable increase in the mechanical properties, the reduction of contact resistance between graphene flakes and carbon fibers improved both specific capacitance (CSP) and electrical conductivity (from ca. 160 S/cm to ca. 257 S/cm and from ca. 0.27 mF/cm2 to ca. 0.65 mF/cm2, respectively).

VI. CNTS AND GRAPHENE ASSEMBLED TO FORM FIBERS

While carbon nanotubes (CNTs) and graphene are widely recognized for their usage in polymer matrix composite materials

(i.e., bulk materials or films), carbon-based polymer fibers have unique uses in select application domains. The potentialities (and limits) of CNT/polymer and graphene/polymer fibers were examined in recent studies by Salavagione et al. (2018) and Lu et al. (2019), respectively. In summary, the current level of polymer-based fiber technology indicates promise for use as electrodes, wearable and smart textiles, and electromagnetic shielding. However, the thermal and electrical conductivities of metals are not nearly as high as those of these composite fibers [11].

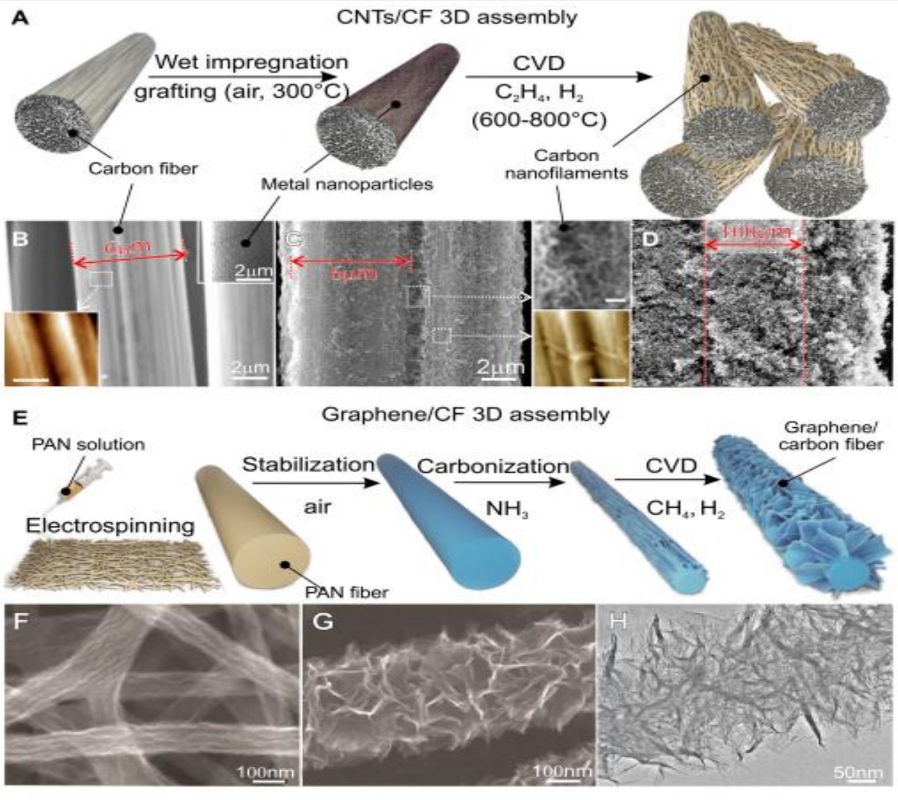

FIGURE 3 | (A) Schematic representation of carbon nanofilaments-interconnected carbon fiber assemblies as obtained by C_2H_4 catalytic decomposition at 700°C; SEM and AFM images of: **(B)** the native carbon fibers used as support; In the top and bottom insets of **(B)** the morphologies of a nickel catalyst nanoparticles supported on carbon fiber and of the wrinkled surface of the native carbon fibres; **(C)** interconnection and **(D)** densification of the carbon fiber support by carbon nanofilaments as obtained under static (700 Torr) and dynamic conditions (100 ml/min) after 1h of reaction time; **(E)** schematic representation of carbon fiber-graphene assemblies as obtained by CH_4 thermal decomposition at 700°C; **(F)** SEM images of the native PAN nanofibers; and **(G,H)** SEM and TEM images of the graphene-coated carbon fibers. AFM image scalebars are 300 nm. Panels **(B–D)** adapted from Cesano et al. (2005) with permission from American Chemistry Society. Panels **(E–H)** adapted from Zeng et al. (2018) with permission from Wiley-VCH.

The development of nanocarbons assembled into fibers has been sparked by the need to go beyond the limitations of polymer matrix composites. These fibers are of practical interest if they can provide thermal and electrical conductivities that are on par with or greater than those of metals (such as Cu, Ag). Though the topic of carbon-based yarn production is far more expansive than what is covered here, some recent specialized articles (Miao, 2013; Kou et al., 2017; Zhang et al., 2019; Yin et al., 2020) offer more analysis on the subject.

Whether solid-state or liquid spinning techniques are used throughout the production process has a significant impact on the quality of CNT and graphene fibers. The molecular level of polymer science is leveraged by spinning techniques (Cheng and Lee, 2016; Cecone et al., 2018; García-Mateos et al., 2019; Mohammad zadeh Moghadam and Dong, 2019).

The direct dry-spinning method (Figure 4A) or twisting while spinning, utilizing the van der Waals forces acting among the vertically grown SWCNTs and/or MWCNTs to arrange them into micro-sized ropes of infinite length, are two simple ways to obtain CNT yarns from vertically grown CNTs (Jiang et al., 2002; Li et al., 2004; Zhang et al., 2004, 2005). Depending on the twisting process (if used) and spinning settings, the final structure may change significantly [14]. If not, electrospinning or wet spinning methods can be used to produce CNT and graphene fibers (Figures 4E, F), which give the fiber a unique shape (Figure 4G). It has been discovered that post treatments improve the fibers' qualities and density [13].

A comparison of the various techniques used to produce CNT fibers may be made. The yarns can be made via the wet-spinning technique or fixed-catalyst CVD, which uses CNTs immediately spun from a floating-catalyst CVD reactor and is a comparatively easier and cleaner process (i.e., no solvents or acids are required). The last process, which involves a strong acid treatment in the coagulation bath, can provide fibers with the greatest conductivity (8.5 × 104 S/cm) for CNT fiber, most likely from a doping phase (Tsentalovich et al., 2017). In comparison to CNT arrays, the floating-catalyst CVD process offers superior conductivity below the electrical characteristics of fibers originating from the wet spinning approach (Dini et al., 2019).

Moreover, SWCNTs and DWCNTs are by far the greatest options to improve fiber performance. Better fibers are produced by aligning nanotubes into CNT arrays; more entangled arrays result in worse fiber qualities (Kou et al., 2017). Furthermore, it is well known that obtaining desirable qualities is significantly influenced by each individual nanotube's long length and big aspect ratio.
Remarkably, Behabtu et al. (2013) used the wet spinning method to create CNT yarns after dissolving CNTs in cloroqualone acid. This procedure is comparable to the one frequently employed to create high-performance industrial fibers. In addition to their electrical characteristics, which will be covered later, these fibers underwent mechanical and thermal testing. In summary, 1.4% elongation at break, modulus (120 GPa), and tensile strength (1 GPa) were measured. The thermal conductivity of the identical fibers was found to be around 380 W/m K−1. The impact of iodine doping was established by the same writers. Thus, even after thermal annealing at 600 C, the thermal conductivity rose by 100% (635 W/m K−1). These lead us to the conclusion that the ultimate characteristics of CNT fibers depend critically on their ideal shape and structure, which include CNT alignment, a high packing density, and the absence of impurities and defects [9].

VII. CONCLUSION

From the beginning to the most current discoveries, the article provides an overview of the scientific advances made in the field of carbon-based fibers intended for use as electrical conductors. The problem has been gradually reopened to transform the carbon properties into materials at the frontier, starting with graphite and the first created pyrolyzed fibers and continuing to carbon fibers and assembled nanocarbons (carbon nanotubes and graphene sheets) into fibers, yarns, and ropes. The primary topic of discussion is the most current advancements in the doping paradigm for all-carbon fibers, with an emphasis on the role that chemistry plays and on materials based on graphene and/or carbon nanotubes. Unprecedented electrical characteristics are observed when using metal and non-metal compound doping to get the metal counterpart values. In keeping with this, conductivity record values have been discovered to be significantly greater than those of metals, indicating the possibility of replacing them in some prototypes as documented in recent literature. Additionally, there are several other benefits that all carbon fibers offer over traditional metals.

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