Theoretical Study of Electronics: Properties of Single Wire

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Abstract:
The miniaturization process has now reached the nanoscale with valuable potential for the application of single-wire conductors in the development of various electronic systems. The investigation of molecular nanotechnology has lately garnered significant attention, particularly regarding their prospective use as practical molecules wire crossings. Aliphatic systems with -conjugated bonds in their chemical structures, like catechol, have garnered significant interest in this field. The following review focuses on theories and experimental work on the single-wire with properties of the emerging materials, integrated into future electronics. At the same time, significant theoretical advances have been realized in carbon-based materials including Carbon Nanotubes (CNTs) and graphene for enhanced electrical conductivity and mechanical strength, and important progress has been realized for electromagnetic and thermal behavior of single-wire systems through simulated techniques to provide optimization of energy transfer and conductivity in flexible electronics. But despite these theories' promises, still plenty of work is needed in order to translate them into practical reality. Challenges in scaling up the production processes, material stability improvement, and better integration of single-wire in large-scale systems like energy storage, power distribution, and wearable technologies will be addressed in future research.

Keywords: Nanotechnology, Single-Wire Conductors, Carbon Nanotubes, Graphene, Electrical property.

1. INTRODUCTION

Nowadays, electronics demand electronic equipment that is not only faster and smaller in size but also consumes lower power consumption than ever before. Although conductors such as copper and aluminum have extensive applications, they have limitations in scalability and efficiency while electronic components reach the level of nanoscale [1]. A new avenue is being presented by single-wire conductors employing nanotechnology-related nanomaterials like CNTs, graphene, and nanowires [2]. These materials have extremely high electrical conductivity, thermal stability, and mechanical strength; thus, they are very promising for next-generation electronics [3]. The specific properties of single-wire conductors have opened an avenue for high interest in their applications, considering them useful for high-speed data transmission lines to flexible and wearable electronics where traditional metallic conductors offer a lower efficiency.

In the last decades of the new century, the downsizing of electronic equipment achieved the nanoscale threshold [4], a domain generally referred to as nanoelectronics. Researchers have shown that size significantly improves efficiency and high-performance information processing, resulting in extensive consumption. Silicon is used as a semiconductor material because of its availability and superior performance in devices; nevertheless, the stringent purity requirements and superheating render its industrial application impractical due to charge losses, ecological toxicity, and expense [5]. Consequently, nanotechnology researchers are intensifying efforts to develop alternative materials to replace silicon for use in new electronic devices, including switches, diodes, rectifiers, solar cells, field-effect transistors, quantum wires, and applications in molecular electronics. Over the years, the literature has documented both experimental and theoretical methodologies in the quest for such devices [6].

As a consequence, among the initial systems with moderate thermal to electricity conversion efficiency was the linked “Polymer Poly (3,4-ethylenedioxythiophene) (PEDOT)” in 2011. Ever then, scientists have been hard at work developing novel organic thermoelectric materials in an attempt to improve this conversion efficiency. Highly modified molecules rods with intriguing electrical transport characteristics were constructed from 3, 6-disubstituted catechol. Based on scanning tunneling microscopy (STM) examination, another study found that long-carbon hemiquinones, which consist of catechol covalently connected to an ortho-benzoquinone, have polysubstituted catechol as their last arm. The catechol primarily works as a donor, while the ortho-quinone acts as a charge receiver [7]. Similarly, ring wires were created by covalently attaching alkyne groups to the two ends of aromatic rings and forming a catechol bridge between the backbones. As a chemical switch in the STM installation, the catechol/quinone redox number proved that the oxidation state greatly affects its electrical transport characteristics. This, in turn, can be controlled by adjusting the degree of electrical decentralization and, consequently, the electric conductivity of the structures. Nicolas Weibel et al. laid the groundwork for future electrochemical energy storage (EES) devices that are both cost-effective and environmentally friendly by designing and fabricating advanced active polymer compounds, including organic sensors based on catechol that have reversible oxidative sites [8].

The optical behavior of many organic dyes, especially big organic compounds, is dependent on the 1,2-dihydroxybenzene backbone. So, although there is scientific evidence that catechol is important for these big molecules' intramolecular electronic characteristics, very little is known about its electrical structural characteristics and the way electrical transportation works in these systems. Theoretically, in 1974, Aviram and Ratner published influential work on the electric characteristics of organic compounds. Their study of the thermal and electrical transport processes in individual molecules proved that aromatic systems play a crucial role in the semiconducting properties of these molecules. However, the exact nature of these properties can vary according to the arrangements of the molecules when held among their metal contacts or the tips, whether they are symmetrical or unsymmetrical [9].

The driving force for exploring single-wire conductors relies on their possible revolution for electronic device designs and performances. Single-wire systems could potentially significantly improve energy transfer, cut down signal loss, and reduce heat generation by utilizing the specific quantum mechanical properties of nanoscale materials. Such properties are of upmost importance in addressing some of the challenges such as the ones generated by modern electronics - power dissipation and limited device miniaturization [10]. Theoretical and experimental research efforts focus on understanding their behavior, optimizing performance, and exploring integration into a wide range of electronic applications.

1.1 The Fundamental Properties of Single cable Wire

There are a number of basic properties governing its performance in electronic applications for any one wire. The first property is *electrical conductivity*, dependent upon the material, either copper or aluminum, and therefore directly linked to the effectiveness of current flow [11]. The other considerable factor is *resistance*, which varies directly with the length, cross-sectional area, and the intrinsic resistivity in the material of the wire, thus affecting the dissipation of energy *inductance*. The wire also contains an inductance that opposes any change in current, especially more obvious at higher frequencies. For values of frequency higher than the audio range, the *skin effect* forces the current to concentrate near the surface of the wire, thus increasing its resistance. Finally, *thermal properties* are also vital; a change in temperature affects the resistance of the wire; this is important for both power and signal transmission in a wire.

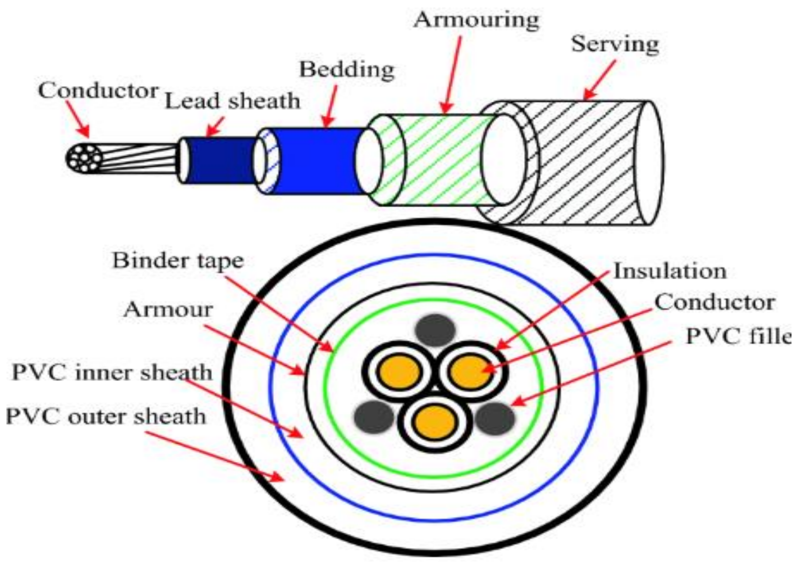

Figure 2: Electrical representation of the cable [12]

In contrast, the physical and chemical characteristics of cable wires work together to define their use and purpose. Among these characteristics are the following: *capacity, insulation, resistance, and conductance.* Copper, for instance, has a lot of uses in the telecom industry and in cables for Ethernet due to its low cost and high permeability [13]. Since it must be able to withstand the circumstances under which the cable will be utilized, the insulating material choice is crucial. One example is the need that cable wires used outside be able to withstand water and high temperatures. I thought you may be interested to hear that even a little rise in resistance to electricity can cause huge energy losses in the hefty power line that carries power across towns. This exemplifies the tremendous impact that resistance has on the effectiveness of cables [14].

1.2 Properties of individual conductors

To transmit electrical or telecommunications signals, one uses cables, which are large wires or bundles of wires often insulated. A cable's principal use is to transmit electrical current. Metal, with its exceptional conductivity, is by far the most frequent material for this purpose, but there are others [15]. An insulating layer is often used to protect cables so that charges cannot escape. How much insulation a cable needs is dictated by the maximum current it can carry [16]. Different kinds of cables are available to accommodate the vast array of modern technologies and gadgets. You may find some examples here.

- High-Definition Multimedia Interface (HDMI) cables.
- Universal Serial Bus (USB) cables

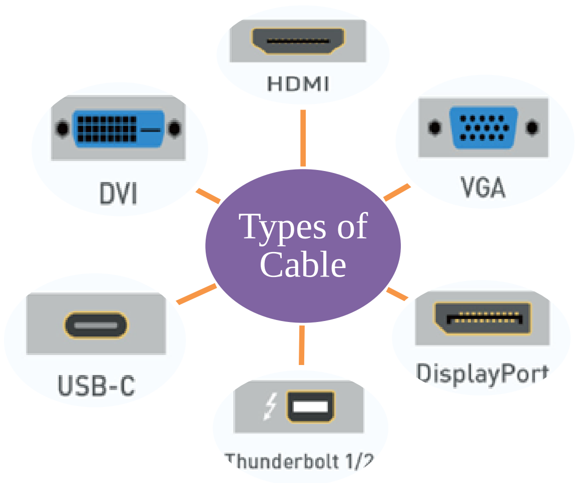

Figure 1: various types of cables

- Video Graphics Array (VGA) cables
- Thunderbolt cable

- Ethernet cables for computer networking

1.3 Emerging trends in Single wire conductors

Single-wire conductor emerging trends are caused by improvements in material science, which can be seen as improved insulations and the creation of multifunctional applications. The use of various material combinations has affected single-wire conductor designs to up to 20% to 30% increase in conductivity per unit volume; it cuts down on the material and the weight, which comes very useful, especially for the aerospace and automotive industries [17]. Advanced insulation techniques, including polyimide coatings, possess superior resistance to thermal insulation, operate within up to 250°C dielectric loss reduction by about 15%, and improve safety and reliability.

Miniaturization is also another trend that represents further development of single-wire conductors based on compact devices demanded to be able to perform enhanced operational performance. These modern designs are provided with ultra-slim wires; their diameter can reach as low as 0.05 mm [18]. They can function adequately even at frequencies greater than 1 GHz, thereby finding applications in high-speed data transfer, Internet of Things, and wearable technology that are primary concerning both space and performance factors Power-over-Single-Wire (PoSW) is another kind of single-wire systems, which happens to be very effective for simultaneous combining power and signal transmission. For instance, the efficiency level in single-wire system can go up to 95%. In addition, they can transfer data at any speed more than 1 Gbps together with the supply of up to 5W of power [19]. This type of integration into designs saves the need for multiple cables and connectors within a system.

Another recent advancement is the incorporation of energy-harvesting features within single-wire conductors, which is quite useful for low-power applications such as sensors at remote locations [20]. Besides retinal systems, the conductors are able to demonstrate efficiencies between 30 and 40% for energy conversion and, thus, provide a promising renewable energy resource. In essence, these advancements exhibit significant numerical improvements based on conductivity, frequency capabilities, and efficiency, while satisfying the new demands of high-performance electronic systems for compact, reliable, and multifunctional conductors.

2. REVIEW OF LITERATURE

2.1 Fundamental Theories on Electronic Properties of Single Wire

There has been a recent uptick in interest in carbon-based conductive materials as a possible metal-free alternative. The researchers at **Song et al., (2020) [21]** created a novel carbon black-carbon nanotubes hybrid filler by first preparing conducting carbon black and then using polymerization of free radicals to graft a silicone coupling agent onto it. They combined this with carbon nanotubes. Therefore, the tensile strength (4.5 MPa) and extension at break (211%) of silicone rubber composites with 5.56 vol% hybrids filler were both strong. The composite exhibited an optimal conductance of 248.7 S/m and a minimal conducting percolation threshold of 0.24 vol. Rubber-based polymers made from "Ethylene Propylene Diene Monomer (EPDM)" were favored by **Zhang et al. (2024) [22]** for their outstanding irregular conductivity as enhanced insulation in wire devices. It became possible to considerably reduce the decrease amount of breaking strength, which equated to 19.94 percent in neat EPDM, by adding 10 % h-BN to the composites. With the CNT/h-BN/EPDM combined, the COMSOL Multiphysics simulations showed that the cable accessory's electrical field intensity could be eliminated. A novel idea for a single cell electrons collection was proposed by **Yu et al., (2020) [23]**. This collector was constructed in-situ using a linked unbroken conductive layer that spanned the cell membrane. With its record-high interface exchange efficiency and BES efficiency, the single cell electron collectors achieved close proximity to the cellular electron transmission machinery while optimizing the interfacial area. Similarly, **Hazrol et al. (2020) [24]** investigated how the resistance to electricity, resistivity, and conductance of SPS/SPNCC (SPS - sugar palm starch) film composites were affected by loadings of sugarcane palm cellulose nanocrystalline (0.00-0.10 wt %). Findings indicated that SPS/SPNCC films exhibited resistance values ranging from 3.1 • 102 to 1.5 • 104 (Ω • cm).

Li et al. (2022) [25] presented a new framework for one-way single-wire power transmission. Determining the effects of its length and forms on transfer effectiveness, we conducted an in-depth study of the framework of one-way single-wire energy transfer. Research suggested that the receiving structure's length was more important than the sending structure's length for increasing the system's efficiency. Theoretical derivation of the expression of the spatial distribution of electromagnetic radiation was followed by empirical and computer validation of the proposed framework. In their study, **Tehrani et al. (2021) [26]** proposed that graphene and carbon nanotubes, two types of tiny carbons, offered a promising avenue for the creation of superior electrical conductors for use in electric devices, interactions, electronics, and power generation in the energy, military, and transportation sectors. This research compiled the most important findings from the area of novel nanocarbon-based and metal-nanocarbon circuits. The binding forces of many 1D material types fell within the usual exfoliating ranges for 2D substances, according to **Zhu et al. (2021) [27]**, who used density-functional-theory-based approaches. Researchers calculated electrical characteristics as well. The findings indicated that some 1D vdW materials, such as the HfI_3 and PNF_2 structure families, were able to maintain their bulk characteristics even at film diameters close to that of one atomic unit.

Table 1: research on emerging single-wire conductor technologies with methods and key findings

Sr. no.	**Authors name**	**Year**	**Method Used**	**Findings**
1	Zhang	2024	EPDM	The breakdown strength was considerably reduced, constituting 19.95% of pure EPDM.
2	Li	2022	one-way single-wire power transfer	The coiled constructions exhibited superior power transfer efficiency compared to the linear configurations.
3	Tehrani	2021	nanocarbons	Processing Cu-CVD graphene sheets at high temperatures and pressures achieved conductivity of 116% IACS at ambient temperatures.
4	Zhu	2021	Density-functional-theory-based method.	The findings indicated that some 1D van der Waals materials preserved their bulk characteristics even at practically molecular film thicknesses.
5	Song	2020	Free radical polymerization.	A silicone-based composite with 5.76 vol% hybrid filler exhibited elevated tensile strength (4.6 MPa) and flexibility at break (213%).
6	Yu	2020	Single cell electron collector.	The SCEC established close interaction with the intracellular electron transfer apparatus and optimized the interfacial area, resulting in unprecedented interfacial electron transfer effectiveness and BES capability.
7	Hazrol	2020	SPNCC	The findings indicated that the resistance values of SPS/SPNCC films ranged from 3.1.

2.2 Advancement in Analytical and Simulation Technique for Single Wire Electronics

Luo et al. (2023) [28] developed a conducting film to maintain the Li/LATP contact. This study demonstrated that an electronic conductor interlayer (Al or Ag) significantly improved the interfacial equilibrium of Li/LATP. Furthermore, when combined with solid polymer electrolyte (SPE) to create an Al-SPE bilayer, it efficiently safeguarded LATP against electron assault and interphase development. Notably, Li symmetrical cells using an Al-SPE bilayer demonstrated exceptional stability that exceeded 5000 hours at a current density of 0.2 mA cm^{-2}. **Salomez et al. (2022) [29]** provided a modeling technique for this capacitance and strategies to mitigate it. The examined parts were ring core inductors that used magnetic substances regarded as ideal conductors or possessing high permittivity, including nanocrystalline materials and various Mn-Zn ferrite materials. The developed model allowed for precise assessment of the influence of turn-core space on parasitic capacitance, while permitting a reduction in its value with little effect on the volume of the magnetized element. In this framework, Maxwell's equations for two distinct media were formulated. Based on these equations and the boundary conditions at the medium interface, **Jin et al. (2022) [30]** investigated the transmission law of the magnetic energy in the SWPT system. Transmitted power attained 300 W at a distance of 100 m and 136 W at a separation of 201 m. **Pei et al. (2022) [31]** introduced a novel "Odd-Mode Metachannel (OMM)" capable of "Supporting odd-mode surface Plasmon Polaritons (SSPPs)" to serve as the primary transmitting route for single-conductor devices. Simultaneously, the advantages of OMM, such as crosstalk reduction, minimal "Radar Cross Section (RCS)", and adaptability, are thoroughly shown. Consequently, the suggested OMM and its ability to interface with active semiconductor parts may provide a novel pathway for future single-conductor conforming devices and intelligent skins. Conversely, **Henke et al. (2021) [32]** introduced a novel analytical method for calculating the fluctuating axial distribution of temperatures along an isolated double wire wiring, taking into account the irregular heat dependency of the cable characteristics. It facilitates accurate and rapid computation of cable temperatures. Cable protection may function nearer to its limits while still ensuring overload safety.

Table 2: summary of advanced methods and key findings in single-wire conductor research

Sr. no.	**Authors name**	**Year**	**Method Used**	**Findings**
1	Luo	2023	Kelvin Probe Force Microscopy	Li symmetric cells that utilized an Al-SPE bilayer exhibited exceptional stability, exceeding 5000 hours at a current density of 0.1 mA cm^{-2}.
2	Salomez	2022	2-D finite element method	The developed model enabled precise assessment of the impact of the turn-core area on parasitic capacitance.
3	Jin	2022	SWPT method	The propagation power attained 301 W at a distance of 100 m and 136 W at a distance of 200 m.
4	Pei	2022	OMM	The suggested OMM eliminated significant barriers to the implementation of conformal single-conductor systems and facilitated the development of potential smart skins.
5	Henke	2021	Crank-Nicholson-method	It facilitated accurate and rapid computation of cable temperatures.

Despite the development of bulk and multi-wire systems, the cultivation of single-wire electronics from a theoretical perspective still lacks adequate research. Previous efforts have mainly focused on conventional conductivity and failed to take into account quantum phenomena relevant for single-wire systems. In addition, there is no common approach to analyze the electronic properties for single wires from many new materials. Some lights have to be shed over the influence of quantum confinement along with interactions with external fields. Further, the discussion of single-wire properties also reveals that there remains numerous more limitations unexplored in the realm of quantum computing, nanoelectronics, and flexible electronics.

3. RESEARCH QUESTIONS

i. What are emerging trends in enhanced single-wire conductor's conductivity and mechanical properties by using modern advanced material compositions and hybrid fillers?
ii. How can novel simulation techniques and analytical models be enhanced by prediction and understanding of electromagnetic and thermal behavior in single-wire electronics?
iii. What potential do growing one-way single-wire power transfer system, one-cell electron collectors, and potential applications for next-generation flexible electronics and energy-efficient systems?

4. DISCUSSION

The review gives an overview of outstanding development, theoretically as well as practically, in knowledge concerning single-wire conductors with new material and better composite structures. There is a quick growing theoretical investigation into single-wire electronics regarding the production of advanced materials that can enhance electrical and mechanical properties in conductors. Super electrical conductivity and strength have made carbon-based materials, carbon nanotubes (CNTs), and graphene central to this work. For instance, in 2020, Song et al. proved the viability of hybrid composites of carbon black-CNT in enhancing electrical conductivity and mechanical strength in silicone rubber. Zhang et al. also demonstrated that incorporation of CNTs into EPDM composites offers a good means of enhancing the conductivity as well as tensile strength of such composites. These new discoveries proved that the advanced composites would probably replace the conventional metal wires, which are relatively more efficient and durable. In addition, Tehrani et al. (2021) discussed how high-performance applications could be carried out using nanocarbon conductors, which has greater conductivity even at extreme conditions. While, for example, the theoretical models proposed in previous theories are still not enough to describe the nanoscale behavior of those materials and especially when the quantum effect starts to dominate in single-wire systems, as also indicated by Yu et al. (2020) and Zhu et al. (2021).

Moreover, simulation and modeling methods assist in understanding better the behaviors of electromagnetic and thermal behaviors of a single-wire system. The predictions of temperature distributions and the assessment of parasitic capacitance that are crucial for optimizing a single-wire system in practical applications have been done by using the Crank-Nicholson method and finite element simulations as illustrated by Henke et al. Salomez et al. in 2022. New systems include one-way single-wire power transfer structures studied by Li et al. in 2022 and odd-mode metachannels proposed by Pei et al. in 2022. These show that theoretically, energy transmission may be enhanced and applied in flexible, conformal electronic systems. The progresses call for not-so-good news aspect-theory models predict all the performance improvements but in practice, practical validation has to be taken in order to satisfy the promises of the systems. More research is needed to connect theoretical models to real-world applications in large-scale applications such as power distribution, energy storage, and wearable electronics. Although the theoretical research into single-wire electronics is growing steadily, further research is required on more comprehensive models taking into account both material- and system-level challenges.

5. CONCLUSION

This review tends to focus on the ongoing advancement of the theoretical and practical understanding of single-wire conductors with emphasis on advanced materials like CNTs and graphene. The prospects of using such materials to hopefully revolutionize electronics not only because conductivity, strength, and efficiency in energy transference will be exponentially improved but will hopefully revolutionize electronics. However, although simulation techniques and theoretical models show so much promise for optimization in system behaviors the practical validation of the models remains to be the core of the ongoing challenge. This future work should bridge the gap between theory and application by addressing material-level as well as system-level obstacles in the development of valid performance in real-world conditions. Such further advancements of these systems are critical for the next-generation electronics-development, involving energy-efficient power systems and flexible, wearable technologies.

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