Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL27835

Silver Nanowire Flexible Film-Based Extracorporeal Monitoring Sensor

Huiying Cong

Institute of Malvern College Qingdao, Qingdao, China
2020lydia.cong@malverncollege.cn

Abstract. This review comprehensively examines the application of silver nanowires in flexible sensors for extracorporeal health monitoring. Silver nanowire is a new type of nanomaterials which is a one-dimensional structure nanostructure composed of elemental silver. They provide high flexibility, excellent conductivity, high sensitivity and good biocompatibility, outperforming rigid battery. It may be developed in three main applications which are motion monitoring, temperature monitoring as well as ECG monitoring. Different fields have their own preparing processes. While the silver nanowires show a range of advantages to meet the flexible wearable sensors, the key challenges include the silver nanowires oxidation, silver ion toxicity, high-temperature instability, and poor skin contact stability. Overall, silver nanowires show great potential for wearable extracorporeal monitoring. With targeted optimization, they can balance performance, safety, and comfort, serving as a core material for next-generation flexible sensors. The study concludes that silver nanowire-based sensors hold significant potential for wearable healthcare applications, though further refinement is needed for long-term clinical use.

Keywords: silver nanowire, wearable, monitoring sensor

1. Introduction

The rapid advancement in electronic technology has had non-negligible impact on applications in many fields, including enhanced reality devices, human-computer interaction, electronic skins and sensing devices [1]. Sensing technologies are diffusely applied to the domain of manufacturing, consumer electronics, and healthcare due to their diverse advantages. With the boost of sensing technique, extracorporeal monitoring sensors has experienced a great achievement and become an indispensable section in the market. For examples, electrocardiography patches and pulse wave analysis are widely used. Nowadays, driving by aging population and technological progress, global health monitoring markets have undergone a comprehensive expand which hugely increased the demand of health monitoring sensors. However, the extracorporeal monitoring sensors require flexible sense, but traditional sensors are ordinarily constructed from rigid and fragile materials like indium-tin-oxide (ITO), which are susceptible to internal fractures when compelling bending or sustaining rapid and intensive movement, making them unsuitable to meet the demands of flexible or wearable sensors [1]. Recent years, nanostructures have been developed to overcome the weakness of flexible. This has raised the sensing flexibility and stability to a new level.

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.GL27835

In recent years, while wearable electronic devices become an essential aspect, there is a greater requirement for flexible sensors in the market. Characteristics such as high flexibility, stable conductivity, biocompatibility and high sensitivity have all become necessary parts to fit the demands. While tow-dimensional(2D) films like transition metals are usually brittle and may fracture easily which cannot satisfy a large number of demands. One-dimensional (1D) thin -film structures have been deeply researched as initiative channels in flexible sensing applications [2]. Comparing with the organic film with low electron mobility which determine the response time; ITO with low stretchability that cause it difficult to improve flexibility as well as metal film with relatively poor optical transparency, nanowire-based two-dimensional flexible thin film by dint of an excellent stretchability and bendability, tunable optically transparent, a unique electrical conductivity and a high stability commendably satisfy nearly every requirement of flexible sensors [3].

Silver Nanowires have been identified as the most suitable next-generation thin film ingredients for flexible sensors. Silver nanowires express a variety of benefits, such as strong conductivity high reliability as well as durability making them an ideal choice for high-performance electrode [4]. Meanwhile, an excellent biocompatible property and a superior durability allows extensive deformation to fit human bodies and continue a long-term signal monitoring. For example, electrocardiograph monitoring (ECG monitoring) adopted silver nanowires technology and synthesized flexible thin film and its performance enables 1200 cycles with 1 mm compression [5]. Another project using this material is motion monitoring. It has five cycles of loading and unloading [6]. This extremely advantageous data reflects that silver nanowire-based flexible thin film has tremendous potential in the future applications.

Herein, this article takes silver nanowires as flexible monitoring sensors for the Extracorpereal monitoring application. The content including emphatical discuss around the existent case of silver nanowire-based flexible thin film and the analysis of its practical application in various kinds of in vitro monitoring. The application potential as well as shortcomings were proposed and analysis. This article is divided into the following sections. The introduction given in section 1 introduced background of flexible sensor and advantages of silver nanowire, the case as section 2, typical case study of silver nanowires including the definition, fabrication process and synthetic methods, their transition into flexible thin film and the benefits were shown. Then, in section 3, various flexible sensors made by silver nanowire were proposed and their advantages and disadvantaged were analysis, and potential defects were indicated as well. Finally, in summary of section 4, solutions according to the challenges faced by current technologies and the future expectations were given.

2. Methods

Silver nanowire is a new type of nanomaterials which is a one-dimensional nanostructure composed of elemental silver. It has a diameter of 10-200nm, and a length of several to tens of micrometers. Its structure is high-aspect-ratio linear morphology typically with polyvinylpyrrolidone (PVP) coated on its surface for stability.

For silver nanowires synthesis methods, the dominant process is polyol reduction. The fabrication process initiates by dissolving silver nitrate ($AgNO_3$) in ethylene glycol under continuous stirring. Polyvinylpyrrolidone (PVP) is then introduced as a critical capping agent, which selectively adsorbs onto specific crystal facets to promote anisotropic growth. The reduction reaction is subsequently carried out under precise temperature control (160±5°C). The resulting product undergoes centrifugal purification (typically at 8000-12000 rpm for 15 min), achieving a yield exceeding 85%.

DOI: 10.54254/2755-2721/2025.GL27835

This optimized protocol ensures reproducible production of high-quality silver nanowires with controlled morphological characteristics.

Silver nanowires have a range of synthesis methods including vacuum filtration method, drop-casting method, spin-coating method, spray-coating method, Meyer rod coating as well as roll-to-roll coating method. Vacuum filtration requires first filtering the nanowire solution into a film and then transferring it to the target substrate. This method produces uniform films but involves a two-step process and is not suitable for large-scale production. Drop-Casting involves depositing a silver nanowires suspension onto the substrate, but coffee-ring effects can compromise film uniformity. Spin-Coating and Meyer Rod Coating can all produce uniform films. However, Spin-coating requires a large amount of excess solution and is not scalable. Both spray-coating and Meyer rod coating allow for larger-scale fabrication, but Meyer rod coating offers a greater advantage due to its faster deposition speed. This comparison highlights the trade-offs between uniformity, scalability, and process efficiency in silver nanowires thin-film fabrication. After this, some optimization plans could be carried on including high-temperature annealing, mechanical pressing and laser welding to reduce contact resistance.

Solution-processed silver nanowires have emerged as the most promising ITO alternative, combining scalable roll-to-roll coating compatibility with optoelectronic performance rivaling ITO. Through optimized synthesis, purification and coating techniques, the transparent conductive films obtained achieved 95% transmittance at just 20 Ω/sq sheet resistance. The technology demonstrates unparalleled potential for next-generation flexible optoelectronics by simultaneously addressing the critical challenges of conductivity, transparency, flexibility and production scalability that constrain conventional ITO and other substitute materials.

3. Analysis & challenge

3.1. Motion monitoring sensor

Silver nanowires were synthesized followed the method of polyol reduction, with a diameter of 89.3 ± 17.5 nm and a length of 23.4 ± 5.7μm. They were scattered in ethanol with concentration of 5 mg/ml and coated on glass via Meyer rod and dried at 50°C on a hotplate. A Thermoplastic polyurethane (TPU)/dimethylformamide (DMF) solution with concentration of 0.25 g/ml was spin-coated over silver nanowires' networks at 250 rpm for 30s, then annealed at 120°C for 1 h to embed the nanowires into TPU. Then, Laser scribing (100% speed, 10% power) patterned the composite, which was heat-pressed at 140°C for 30 s onto textiles. Next, Cu wires were electrically connected with the silver nanowire/TPU patterns on both sides by drop-casting a small droplet of silver stretchable printing ink followed by thermal treatment at 100 °C for 5 min to remove the solvent in the ink and secure the bonding between Cu wires and silver nanowire/TPU patterns. The process was shown in Fig .1 [6].

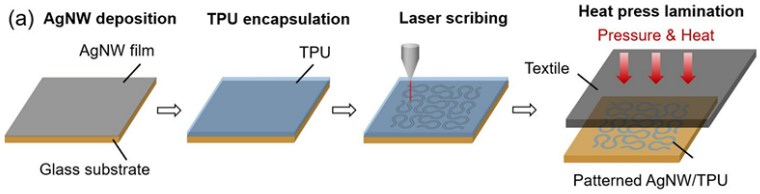


Figure 1. Fabrication of silver nanowire motion monitoring sensor [6]

DOI: 10.54254/2755-2721/2025.GL27835

The silver nanowire/TPU composite on textiles had 135 μm linewidth, 0.2 Ω/sq sheet resistance, and 5030 S/cm conductivity, maintaining stable electromechanical performance even under 50% strain with resistance slightly decreasing after heat pressing. After pre-strain treatment, under 30% strain, the resistance increased of straight-line, fractal, and coil patterns are 6%, 4%, and 2% respectively, showing excellent electromechanical stability. ~10% resistance increase after 100 washes, and 0.42 MPa Young's modulus. making them suitable for wearable applications [6].

While silver nanowires offer excellent conductivity and stretchability, they still need some improvement. They lack long-term skin scrubbing stability due to their reaction with oxygen. The resistance would increase 4% after 1000 cycles. Also, laser scribing limits linewidth below 135 μm, which may restrict high-density device integration. Biologically, long-term exposure may accumulate silver ions which are harmful to organs, and skin allergies occur.

3.2. Temperature monitoring sensor

The example for temperature monitoring sensor based on silver nanowires was shown in Fig. 2 and described as following: silver nanowires were synthesized via the polyol method, with an average diameter of 120 nm and length of ~25 μm. They were diluted in ethanol with concentration of 1 mg/ml and spray-coated onto pre-cleaned glass slides using an airbrush (10 psi back pressure, ~15 cm nozzle-substrate distance) with the glass on a hot plate. The silver nanowire network was thermally annealed at 150 °C and 200 °C for 30 min each, then spin-coated with colorless PI resin at 500 rpm for 30 s and cured at 60 °C for 3 h. The silver nanowires/polyimide film was laser-cut into a Kirigami pattern (0.8% power, 50% speed) and peeled off via water soaking. Copper wires were bonded with silver paste as leads [7].

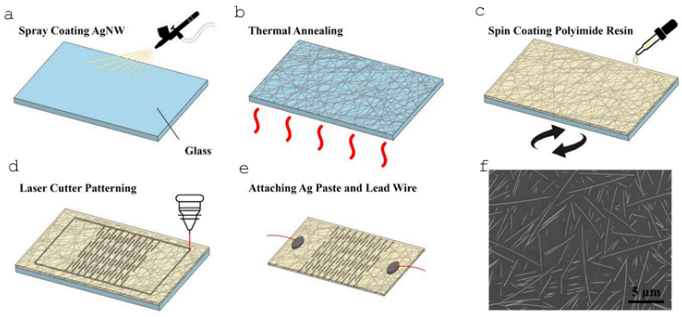


Figure 2. Fabrication of silver nanowire temperature monitoring sensor [7]

The silver nanowire network's Temperature coefficient of resistance increased with density and annealing temperature. At 2.053 nanowire/μm², Temperature coefficient of resistance rose from an as-prepared 2.94×10^{-3}/°C to 3.32×10^{-3}/°C after 200 °C annealing, close to bulk Ag's 3.8×10^{-3}/°C. For silver nanowires with a density of 0.26 nanowire/μm², the sheet resistance decreased from an as-prepared 23.73 $\Omega\cdot sq^{-1}$ to 3.73 $\Omega\cdot sq^{-1}$ after 200 °C annealing. As for the silver nanowire network with a density of 2.053 nanowire/μm², its sheet resistance dropped from an as-prepared 0.73 $\Omega\cdot sq^{-1}$ to 0.55 $\Omega\cdot sq^{-1}$ following 200 °C thermal annealing. The Kirigami sensor showed less than 0.05% resistance change at 100% strain, remained stable over 1000 cycles and had 0.47 Ω/°C sensitivity in the 25–60 °C range. It accurately monitored biceps temperatures from 35.3 °C to 36.8 °C and knee temperatures during motion, with readings matching infrared thermometer data [7].

DOI: 10.54254/2755-2721/2025.GL27835

The silver nanowire temperature sensor faces several defects and challenges. While the silver nanowire/polyimide sensor excels in stretchability and strain insensitivity, its sensitivity is lower than some alternatives. Also, spray-coating may cause uneven silver nanowire distribution, affecting consistency. Additionally, the laser-cutting process and silver paste wiring steps add complexity to large-scale manufacturing. Future work could optimize ink formulation for higher sensitivity and adopt precision deposition for uniform networks.

3.3. ECG monitoring sensor

Silver nanowires of diameter 50 nm and concentration of 20 mg/ml in ethanol were mixed with polyvinyl butyral (PVB) solution (0.1 g PVB in 10 ml ethanol) and stirred for 1 h to form silver nanowires/PVB/ethanol dispersion. The dispersion was dripped onto a mold holding mechanically cut hydrophilic polyurethane sponge, left for 20 s natural deposition, then solidified at room temperature for 0.5 h to get AgPHPUS electrodes. Additionally, the conductive silver paste was used to connect the conducting wire with the end of the fractal pattern which consisted of a series of arc parts with center angles of 90,180 and 270°. This design described was shown in Fig.3 and it has an extraordinary significance in the application of stretchable devices [5].

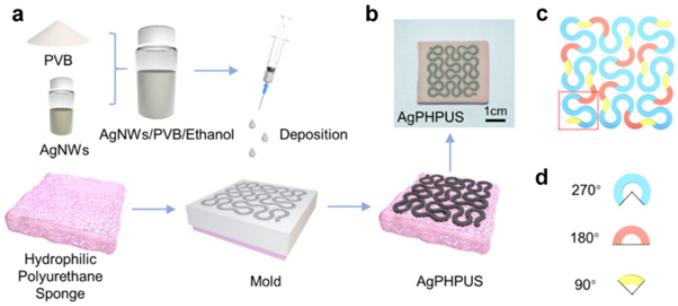


Figure 3. Fabrication of silver nanowire ECG monitoring sensor [5]

Silver nanowires enabled the AgPHPUS electrode to have stable electrical performance. Resistance that lower than 5% changed after 10 Scotch-tape tests, <7% resistance increased in 10% NaCl solution (15 days), and <4% resistance changed after 1200 compression cycles (25.4 mm curvature radius). Its ECG signals (instant and 12-h wear) matched commercial Ag/AgCl electrodes, with clear P/QRS/T waves. PVB protected silver nanowires from oxidation, keeping resistance stable [5].

Silver nanowires have some drawbacks as ECG monitoring sensors. Its sensitivity relies on sweat as electrolyte, sweat or skin layers can mess up weak ECG signals, and body movements like bending arms can also distort signals which makes it unreliable. They also might peel off due to friction or sweat, breaking the conductive path. Biologically, some patients might be allergic to silver ions and sometimes the sensor were not breathable which would cause discomfort. Also, 50 nm silver nanowires may have uneven dispersion in polyurethane pores. Future work could modify silver nanowires surface for better dispersion and add hydrogel layers for dry-skin adaptability.

DOI: 10.54254/2755-2721/2025.GL27835

4. Summary & suggestion

Table 1. Comparison of various silver nanowire sensor application

Type	advantages	disadvantages
Motion Monitoring Sensor	-high conductivity -high flexibility	-long-term instability -harmful to skin
Temperature Monitoring Sensor	-high temperature sensitivity -fast response time	-high-temperature instability -limited detect range
ECG monitoring Sensor	-high stretchability -biocompatible-sensing capability	- Poor skin contact stability -discomfort to patients

The application of silver nanowires sensors are concluded and showed in Table. 1 For motion monitoring sensors, they have high conductivity for quick and exact response. The nanowires overlap to form a continuous conductive pathway, enabling accurate capture of weak deformations or bioelectrical signals generated during movement. Another benefit is high flexibility to be as different shape to fit our body skin and can bend and stretch with the limbs. They are suitable for dynamic situation during various exercises and the signal is not easy to be interrupted. However, silver may interact with oxygen when exposing in the air for a long time and form silver oxide which will make the sensor not functional. In addition, silver itself in certain degree is toxic, when it has a long-term or large-scale contact with human's skin, it may trigger allergic reactions such as redness. If the sensors get damaged and go into human's bodies, it may pose even more biosafety problems. Although there are some drawbacks, silver nanowires are still a considerable material for the applications in many fields. To improve stability, coating with polymers such as PVB can reduce detachment. To prevent silver nanowires from irritating the skin, the core strategy is to use biocompatible polymers to block direct contact between the sensor and to prevent the migration of silver ions to our skins.

For temperature monitoring sensors, silver nanowires can provide a large foundation of sensitivity of high temperature due to their excellent electrical conductivity. Their temperature coefficient of resistance can approach that of bulk silver. This allows them to accurately capture tiny temperature fluctuations like 0.1°C. Also, their thermal response speed far exceed traditional rigid sensor level. However, they have short comings. For instance, high-temperature instability (above 150 °C) may cause nanowires fuse together and degree rapidly. This will break the conductive network and no longer make accurate temperature detection. Their stable temperature coefficient of resistance is typically suitable for human body (-20℃~100℃) but not for factory use. To address the insufficient during high temperature, anti-sintering materials such as a small amount of metal or non-metal droplets with high melting points can be introduced during the preparation of silver nanowires. Overall, silver nanowires are suitable for temperature monitoring sensors.

Silver nanowires have distinct advantages for ECG monitoring sensors: They are highly stretchable—they can stretch over 50% without breaking their conductive structure, so they move with the body during daily activities. Their good conductivity lets them pick up tiny ECG signals clearly, showing important waves as well as commercial silver electrodes. But they have two big problems. Their contact with skin isn't stable: sweat or small moves make their resistance increases, messing up ECG signals. Also, they can discomfort patients, stiff bases make skin feel stuffy or itchy after long wear. To fix these, use a double coating and tiny bumps design. Use a thin Al_2O_3 layer to block sweat, plus a hydrogel to stick better to skin and add 10μm tiny bumps to boost skin attachment by 40%. For comfort, use flexible TPU bases instead of stiff ones, cut the nanowires'

DOI: 10.54254/2755-2721/2025.GL27835

density, and add small holes for breathability. Overall, silver nanowires are suitable for ECG sensors, especially wearable ones. Optimized sensors work for daily and sports use. They just need better sweat resistance for long medical use (over 7 days), and with tweaks, they could be a top choice for flexible ECG sensors.

5. Conclusion

In brief, the article systematically explored the silver nanowires in the field of flexible monitoring sensors. Over the past decades, many researches and reports have focused on the structure and the use of silver nanowires. As a 1D material, silver nanowires have high flexibility to fit the skin, high conductivity, biocompatibility and high sensitivity outperforming traditional rigid materials like ITO to enable them to be suitable in a number of applications and meet flexible sensing demands. This paper studied in three typical fields: motion monitoring, temperature monitoring and ECG monitoring. In specific scenarios, silver nanowires sensors show strong performance:

1. motion sensors maintain stability under 50% strain and 100 washes.
2. temperature sensors achieve TCR close to bulk silver (3.32×10^{-3}/°C) with 0.47 Ω/°C sensitivity.
3. ECG sensors match commercial silver electrodes in signal quality.

These confirm their broad application potential. However, some key challenges exit:

1. Silver oxidation and silver ion release cause resistance drift and toxicity which can be dealt with coating.
2. High-temperature instability and limited monitoring range which can be improved by introducing new material droplets.
3. Poor skin contact stability and high susceptibility to sweat interference that may be enhanced by double-coating

References

[1] E. Liu, Z. Cai, Y. Ye, M. Zhou, H. Liao, and Y. Yi, “An Overview of Flexible Sensors: Development, Application, and Challenges, ” Sensors 23, no. 2 (2023): 817,
[2] J. C. Costa, F. Spina, P. Lugoda, L. Garcia-Garcia, D. Roggen, and N. Münzenrieder, “Flexible Sensors—From Materials to Applications, ” Technologies 7, no. 2 (2019): 35,
[3] X. Song, Y. Gu, S. Wang, J. Wang, L. Yu, “Nanowire-based Flexible Sensors for Wearable Electronics, Brain-Computer Interfaces, and Artificial Skins” Electron (2025): e77.
[4] J. Shi, L. Wang, Z. Dai, et al., “Multiscale Hierarchical Design of a Flexible Piezoresistive Pressure Sensor With High Sensitivity and Wide Linearity Range, ” Small 14, no. 27 (2018): e1800819, K. Huang, J. Liu, S. Lin, et al., “Flexible Silver Nanowire Dry Electrodes for Long-Term Electrocardiographic Monitoring, ” Advanced Composites and Hybrid Material 5, no. 1 (2021): 220–228.
[5] K. Huang, J. Liu, S. Lin, et al., “Flexible Silver Nanowire Dry Electrodes for Long-Term Electrocardiographic Monitoring, ” Advanced Composites and Hybrid Material 5, no. 1 (2021): 220–228, https: //doi. org/10.1007/s42114-021-00322-0.
[6] S. Yao, J. Yang, F. R. Poblete, X. Hu, and Y. Zhu, “Multifunctional Electronic Textiles Using Silver Nanowire Composites, ” ACS Applied Materials and Interfaces 11, no. 34 (2019): 31028–31037.
[7] Z. Cui, F. R. Poblete, and Y. Zhu, “Tailoring the Temperature Coefficient of Resistance of Silver Nanowire Nanocomposites and Their Application as Stretchable Temperature Sensors, ” ACS Applied Mate rials and Interfaces 11, no. 19 (2019): 17836–17842.