Chemical Engineering Journal
Volume 443, 1 September 2022, 136370

Ultra-sensitive pressure sensors based on large alveolar deep tooth electrode structures with greatly stretchable oriented fiber membrane

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https://doi.org/10.1016/j.cej.2022.136370

Abstract

Electrohydrodynamic (EHD) preparation of micro-nano fibers has significant advantages in the application of ultra-sensitive detection. However, far-field EHD always has the problem of jet instability, which limits its further application. In this study, we excellently realize the generated single jet deposition of aligned fibers by constructing auxiliary electric fields and creatively designed an ultra-sensitive structure based on large alveolar deep tooth electrodes with oriented TPU fiber membrane. As the isolation layer, the oriented fiber membrane controls the formation of the electric double layers by adjusting the contact area between the tooth-shaped electrodes and the polyelectrolyte membrane. Meanwhile, with increasing the pressure, the tooth-shaped electrodes with large alveolar depth bring more sidewall surfaces contact and expand the capacitance adjustment range. Therefore, we can continuously adjust the capacitance of the pressure sensor through the oriented fiber membrane to achieve an ultra-broad linear range (1.1–100 kPa) with ultra-high sensitivity of 230 kPa^{-1}.

Introduction

Electrohydrodynamic (EHD) technology has incomparable advantages in manufacturing micro-nano fibers, such as simple equipment, low processing cost and easy realization. It is widely used in biomedicine [1], [2], [3], filtration purification [4], [5], electronics [6], [7], [8], catalysis [9], [10], [11]. However, the instability [45], [46], [47] of the jet during the EHD process makes it difficult to program deposition, resulting in disorderly arranged fibers [48], [49], which greatly limits the development and application of this technology.

For a long time, many researches have been devoted to enhancing the stability of EHD jet deposition and different schemes have been proposed. Through the high-speed rotation of special shaped collecting devices such as drum [12], [13], disk [14] and cylinder grid [15], the oriented fibers could be obtained. In recent years, the near-field EHD technology becomes widely popular [16], [17], [18]. By reducing the distance between the nozzle and the collector, the stable movement area of the jet was used to avoid the instability area, and the controllable deposition of the jet was realized. Yang-Seok Park [8] exhibited a near-field EHD jet to achieve precise stack deposition of fibers by adding NaCl salt to the polymer solution. Although the near-field EHD avoids the jet unsteady motion zone, it loses the space between the nozzle and the collector and requires high-speed movement of the platform. Donghwi Cho [19] introduced insulating blocks between the nozzle and the collector to control the electric field distribution, realized the alignment of fibers, and prepared parallel, vertical and rhombic structures. Dan Li [20] used two parallel collectors with a certain distance to get aligned fibers. Another improved parallel electrode method [21] was proposed, which controlled the jet by placing a positively charged metal ring between the nozzle and the parallel collection electrodes to prepare aligned composite fibers. Controlled jet deposition can also be achieved by attaching a relatively hydrophobic and insulating substrate to an aluminum foil as a collector [22]. Jongwan Lee [23] placed the grounding pin under the glass collector and the cylindrical side wall electrode between the nozzle and the collector to suppress the instability of the jet and to produce nanofiber patterns. Xiaojie Cui [24] used a metal plate and a metal ring with voltage bias to restrict the diffusion motion of the jet in the EHD device to realize the controllable deposition of fibers. In addition, the electrodes were introduced into the EHD device to construct a variable electric field, and the jet deflected under the action of the electric field force to control the fibers deposition. Christian Grassl [25] proposed that when the voltage with a certain frequency change is applied to the parallel electrodes, the jet will deflect periodically between the electrodes under the action of the electric field force, and the unstable motion of the jet will be well restrained. Based on Christian Grassl's [25] research, Liashenko [26] successfully printed the 3D structures with submicron scale by placing electrodes perpendicular to each other combined with near-field EHD method. Rebrov [27] proposed to connect the high voltage pulse generator to the collector and realize the directional deposition of fibers by manipulating the electric field to prepare the oriented fibers in a large area. The previous works on EHD technology have made significant progress, which provides important reference values for this research. However, the instability and controllable deposition of far-field EHD jet has not been effectively solved. With the development of artificial intelligence, sensors are more and more widely used in tactile [50], [51] and proximity perception [52]. Improving the sensitivity of capacitive pressure sensors is mainly to make changes to the structure/material of the electrodes and the dielectric layers. Using materials with microstructural features as electrodes, such as metal nanowires [28], [29], carbon nanotubes [30], [50], and graphene [31], or construct microstructures [32] on the electrode surfaces to improve sensitivity, and ionic gel electrodes [33] are also used to improve sensitivity. It seems more popular to improve sensitivity by designing dielectric layer structure, pyramids [34], [44], micropillars [35], sphere microarray [43], porous structure [53] and nanofibrous membrane [36] dielectric layers are widely used.

In this study, we propose the method of constructing auxiliary electric fields to control the generated single jet deposition. By introducing an auxiliary electrode near the nozzle of EHD equipment, the focused electric field was constructed between the nozzle and the collector. It was easy to achieve a single stable jet with a collection distance of 10 cm, which effectively solved the problem of instability of far-field EHD jet. Then, we designed deflection electric field in the device, controlled the single stable charged jet to deflect rapidly under the action of electric field force, deposited regular patterns and prepared oriented fiber membrane. Innovatively, using the controllable far-field EHD technology, we demonstrate an ultra-sensitive structure based on large alveolar deep tooth electrodes with oriented TPU fiber membrane. The oriented fibers were placed between the electrodes and the polyelectrolyte membrane as isolation layers, so that the sensor obtained a small initial capacitance value. The formation of the electric double layers were adjusted through the oriented fiber membrane to control the change of capacitance in a wide range. With the combination of oriented fiber membrane, polyelectrolyte membrane and tooth-shaped electrodes, the pressure sensor shows great advantages in linearity and sensitivity, achieving an ultra-broad linear range (1.1–100 kPa) with ultra-high sensitivity of 230 kPa^{-1}, providing a new idea for ultra-sensitive detection.

Section snippets

Materials

Polyvinylpyrrolidone (PVP, K90) was purchased from Shanghai Aladdin Biochemical Technology Co, Ltd. Thermoplastic polyurethane(TPU-1065A), purchased from DaDong Resin Chemical Co, Ltd. N. N-dimethylformamide (DMF, reagent pure), purchased from Shanghai Macklin Biochemical Technology Co. Ltd. Acetone (Chromatographic reagent) was purchased from XiLong Chemical Co, Ltd. PVDF-HFP was purchased from Sigma Aldrich (Shanghai) Trading Co, Ltd. Lithium bis(trifluoromethanesulfonimide) (LiTFSI), Mw…

Jet focusing

In order to solve the problem of EHD jet instability, we have made a lot of efforts. Initially, we set the distance between the nozzle and the collector (collection distance) to 7 cm and the voltage of the nozzle to 5 kV. It can be seen (Fig. S1, Supporting Information) that compared with no negative high voltage, applying −6 kV high voltage can increase the length of the jet stabilization zone. Before jetting, the fluid contacts with the metal nozzle with 5 kV high voltage, the charge transfer …

Conclusions

In summary, we excellently realized the controllable deflection deposition of single stable jet in the far field EHD. By constructing auxiliary electric fields to constrain the jet movement, the problem of far-field EHD jet instability was solved, and the deposition of single stable jet with a collection distance of 10 cm could be easily realized. The jet motion could be controlled by adjusting the auxiliary electric fields to control the deposition of the jet. Through this method, we…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

Acknowledgements

Q. Y, S. X. contributed equally to this work. This work was financially supported by the Guangdong Major Scientific Research Project (2018KZDXM061).…

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