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Review

A review study of (bio)sensor systems based on conducting polymers

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ABSTRACT

This review article concentrates on the electrochemical biosensor systems with conducting polymers. The area of electro-active polymers confined to different electrode surfaces has attracted great attention. Polymer modified carbon substrate electrodes can be designed through polymer screening to provide tremendous improvements in sensitivity, selectivity, stability and reproducibility of the electrode response to detect a variety of analytes. The electro-active films have been used to entrap different enzymes and/or proteins at the electrode surface, but without obvious loss of their bioactivity for the development of biosensors. Electropolymerization is a well-known technique used to immobilize biomaterials to the modified electrode surface. Polymers might be covalently bonding to enzymes or proteins; therefore, thickness, permeation and charge transport characteristics of the polymeric films can be easily and precisely controlled by modulating the electrochemical parameters for various electrochemical techniques, such as chronoamperometry, chronopotentiometry, cyclic voltammetry, and differential pulse voltammetry. This review article is divided into three main parts as given in the table of contents related to the immobilization process of some important conducting polymers, polypyrrole, polythiophene, poly(3,4-ethylenedioxythiophene), polycarbazole, polyaniline, polyphenol, poly(o-phenylenediamine), polyacetylene, polyfuran and their derivatives. A total of 216 references are cited in this review article. The literature reviewed covers a 7 year period beginning from 2005.

Contents

1. Introduction

1.1. Conducting polymers

Conducting polymers are named as “synthetic metals” due to their electric, electronic, magnetic and optical properties inherent to

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metals or semiconductors [1–3]. The conductivity of conducting polymers assigned to the delocalization of π-bonded electrons over the polymeric backbone, shows electronic properties, such as low ionization potentials and high electron affinities [4,5]. Use of conducting polymers gives us impedance type gas sensors [6,7] for low cost, highly sensitive and selective room temperature [8].

Conducting polymers have been widely used in the areas of bioanalytical science [9] due to their inherent charge transport properties and biocompatibility [10,11]. Recently, conducting polymer nano-materials have offered a great possibility for novel applications in synthesis and characterization techniques [12–16]. Conducting polymers have been reviewed by many scientists especially in biosensor evaluations [17,18]. Some conducting polymers are doped and/or covalently or physically modified by bionano-materials [19–22], especially proteins [23], neurotransmitters [24–26] and nucleic acids [27,28], which exhibit unique catalytic [29] properties that can be easily employed in the design of biosensors [30]. The sensitivity and selectivity of conducting polymer based biosensors are primarily determined by the difference in specific property before and after exposure to a test target molecule [31]. The test target molecules can change the number and mobility of charge carriers, which results in the overall change in conductivity, current, impedance data, etc. For biosensor system design, the response time is of crucial importance. A faster response time is supplied by nano-fibers [32,33] and nanotubes [34,35] due to its porous structures of used materials [36,37]. Carbon nanotube (CNT) and carbon nanofiber (CNF) have more advantages in their lower cost mass production, better mechanical stability, easier surface functionalization, and more edge sites on the outer wall compared with metal electrodes [38–40].

1.2. Conducting polymers in biosensor applications

Conducting polymers are sensitive to very minor perturbations due to the amplification by a total system response and offer an advantage over small-molecule [41,42]. Recent progresses in the controlled synthesis of these polymeric materials allow the rational design and preparation of new chemical and biological biosensor systems. In order to obtain a long operational life of the bio-molecules, the technique of the enzyme-immobilization onto the transducer is a key process to develop a good biosensor design. Generally, the enzyme-immobilization methods [43,44] include adsorption [45,46], covalent attachment [47,48], cross-linking [49] and entrapment [50]. As for the adsorption method [51], it utilizes the hydrophilic or hydrophobic properties of the material, such as ion exchange resin and nylon [52] to construct the enzyme electrode. The method of covalent attachment uses the functional group in the bio-molecules, such as $-NH_2$, $-COOH$, and $-SH$, for binding with transducer chemically [53,54]. On the other hand, cross-linking method [55] uses crosslinking agent, such as glutaral, to combine the bio-molecules and polymer. However, the adsorption method cannot grasp enzyme easily because of the weak attraction to electrode; besides, the covalent attachment and cross-linking methods may be difficult to retain the enzyme activity. In contrast, the approach of enzyme-immobilization, or enzyme entrapment, is attractive in recent years due to the stronger adhesion between enzyme and matrix. For example, the material, such as carbon gel [56] and polyvinyl chloride [57,58], is used to immobilize the enzyme onto the electrode. Moreover, a number of techniques for modifying proteins or synthesizing bioconjugates have been reported, including more sophisticated chemical modification methods, utilization of noncovalent affinity, and protein splicing [59]. Besides, the immobilization method, which entraps bio-molecules on the electrode surface electrochemically, has been extensively investigated recently [60–65]. Conducting polymers have been used in the production of biosensors in various fields, such as health care, immunosensors, DNA sensors [66], environmental monitoring and food analysis [67].

2. Some conducting polymers used in biosensor applications

2.1. Polypyrrole and its derivatives

Among other conducting polymers, polyaniline and polythiophene are often used as immobilizing substrates for bio-molecules [68,69] and as efficient electro-catalysts [70]. However, to detect bio-analytes at a physiological pH, biosensing materials must be electro-active in neutral environments. Polypyrrole (PPy) is very attractive because it is more easily deposited than neutral pH aqueous solutions of pyrrole monomers [71]. PPys have been a subject of extensive investigation during the last four decades due to their outstanding electronic and optical properties [72,73]. Because of high electrical conductivity, long term environmental stability and ease of synthesis by chemical or electrochemical means, PPy has been used to construct chemical sensors [74,75], photovoltaic cells, actuators, electrochemical cells, and so on [76,77].

PPy is also a promising material for some other technological and biomedical applications due to its stability under environmental conditions [78], thermal stability [79], biocompatibility [80,81], and biodegradation in composition with biodegradable polymers [82,83]. PPy is often applied in the design of biosensors based on immobilized enzymes [84,85], antibodies [86] or single stranded DNA [87]. To enhance its functions PPy can be easily modified by covalently attached redox groups [88] and proteins [89,90] or molecular imprinted by low [91] and high [92] molecular weight molecular imprints.

Liu and co-workers have proposed over-oxidized PPy films as a substitute for Nafion films [93–95]. In its oxidized form, PPy is a positively charged conducting polymer [96]. Upon over-oxidation, PPy loses its conductivity and charge [97]. Characterization of these films by X-ray photoelectron spectroscopy (XPS) [98,99] and Fourier transform infrared (FT-IR) [100] revealed that over-oxidation results in addition of carbonyl and carboxylic groups, which attract dopamine cations and reject ascorbate and 3,4-dihydroxy-phenylacetic acid (DOPAC) anions. DOPAC is a metabolite of the neurotransmitter dopamine. DOPAC can be oxidized by hydrogen peroxide that causes the formation of toxic metabolites which destroy dopamine storage vesicles in the substantia nigra. The carbonyl groups create a high electron density that is also diffuse. Therefore, they may not cause strong electrostatic interactions with dopamine and other cations, such as those found with the negatively charged sulfonate groups in Nafion. Voltammetric studies of over-oxidized PPy-coated electrodes exist at relatively slow scan rates (<50 mV s^{-1}) in a few articles [101].

Phosphate ion determination methods are time-consuming and laborious for conducting polymer biosensor. As a result, they are able to measure the substrate directly in the sample [102,103] to prevent low sensitivity and poor stability [104]. With the advent of enzyme-based biosensors, several approaches have been investigated to detect phosphate [105]. Most of the early works were based on alkaline or acid phosphates with glucose [106], but further approaches that used the bienzyme system, which includes purine nucleoside phosphorylase (PNP) [107] and xanthine oxidase (XOD) [108] gained more interest.

Metal nano-particles into the sensing interface to facilitate electron transfer can significantly improve the sensitivity [109,110]. Among the metal nano-particles, Au–Pt hybrid nano-particles (NPs) have received considerable attention. They exhibit good catalysis and resistance to deactivation due to the highly synergistic action between gold and platinum [111]. It has been widely applied in analytical chemistry because of its high environmental stability, electronic conductivity and biocompatibility [112,113]. Che et al. [114] fabricated a third-generation mediator-free hydrogen peroxide biosensor by combining electrodeposition and self-assembly techniques. Immobilized DNA on the surface of a substrate electrode increases greatly the coverage of bio-molecules on the electrode surface and provides a pathway of electron transfer

between enzyme and electrode surface [115]. The effective enzyme immobilization on the electrode surface and keeping its activity are other significant elements to construct a sensitive biosensor [116]. The application of PPy derivatives in biosensors and bioelectronics has been investigated by the different immobilization mechanism of biomolecules [117].

Field-effect transistors (FETs) have attracted increasing interest as primary candidates to fabricate state-of-the art sensor platforms because they are capable of achieving high current amplification and sustaining an enhanced signal-to-noise (S/N) ratio [118–120]. Organic field effect transistors (OFET) are important to study for charge transport in organic semiconductor investigation of many parameters, such as temperature, electric field, and charge carrier density [121,122]. The integration of a single carbon nanotube (CNT) with an FET has opened up new routes toward the development of highly efficient sensor research [123]. In particular, conducting polymer nano-materials have attracted much attention as promising building blocks for FET sensor applications [124,125]. Compared with conventional films, 1D conducting polymer nano-materials have remarkable characteristics derived from anisotropic electronic properties, high surface area, and small dimensions [126,127]. Yoon et al. [128] reported the detection of glucose based on a liquid-ion gated field-effect transistor configuration in which enzyme-functionalized PPy nanotubes are employed as the conductive channel.

Kros et al. [129] have reported the detailed results on the stability of PPy and PEDOT-coated track-etch membranes under physiological relevant conditions by means of amperometric and resistance measurements. The experiments showed that PPy could only be used as an electro-active component in biosensing for a very short period of time. An ammonia sensor based on conducting PPy was of the early practical realizations of π-conjugated sensors [130].

2.2. Polythiophene and its derivatives

Polythiophenes (PThs) are an important representative class of conjugated polymers that form some of the most environmentally and thermally stable materials. PThs can be used in many areas, such as electrical conductors, non-linear optical devices, LEDs, transistors, electrochromic or smart windows, photo-resists, antistatic coatings, sensors, batteries, electromagnetic shielding materials, artificial noses and muscles, solar cells, microwave absorbing materials, new types of memory devices, nano-switches, imaging materials and polymer electronic interconnects [131].

The entrapment process by electropolymerization in one-step, using conducting polymers, is a fast, convenient and popular method. During the entrapment process, the enzyme is entrapped inside the polymer and the thickness can be arbitrarily controlled by changing the polymerization time. An amperometric biosensor with poly(3-thiopheneacetic acid) as a matrix has been fabricated by Nien et al. [132] for linking cholesterol oxidase, in order to carry out the detection of cholesterol.

The determination of the glucose concentration is important in several aspects for food, microorganism, and medicine, especially for diabetes. The normal concentration range of blood glucose in the human body varies from 4 to 8 mM, and the concentration may be up to 10 mM for diabetes. Nien et al. [133] used PEDOT from conducting polymer, which served as the matrix to fabricate an amperometric glucose biosensor. PEDOT has a very stable and highly conductive cationic 'doped' state. The low HOMO–LUMO band gap of conductive PEDOT allowed the formation of a tremendously stable, highly conductive state [134]. In the aspect of sensors, the applications of PEDOT include a DNA sensor based on conducting PEDOT for direct detection that quantifies the targeted single strand DNA [135], and was served as a self-absorbing piezoelectric sensor consisting of conductive PEDOT [136]. Besides, an enzyme modified biosensor entrapped by PEDOT for the detection of phenolic compound and an amperometric sensor coating of PEDOT for the measurement of chromate have been reported [137].

There is a great interest in the development of easy-to-use DNA sensors. Detection of specific DNA sequences is of great importance in numerous applications, such as medical research and clinical diagnosis. Although fluorescent label and surface plasmon resonance have been widely used as hybridization transduction systems, these methods may be lengthy and costly [138,139]. Polythiophene also may be used as active substrates. It can sensitively report a biological recognition event, such as DNA hybridization immobilization of oligonucleotide (ODN) probes onto conducting polymer [140]. Uygun [141] prepared a simple and label-free electrochemical sensor for recognition of the DNA sensor event by electrochemical polymerization of 4-hydroxyphenyl thiophene-3-carboxylate. It was synthesized and characterized electrochemically on glassy carbon electrode.

C-rich DNA sequences with the potential to form closely packed i-motifs based on intercalated $C{\cdot}C^{+}$ base pairs are frequent in the human genome, especially the human telomere DNA [142,143]. These unique structures often participate in important biological processes and even have close relationship with diseases, such as cancer [144]. Obviously, it becomes very important to detect the presence and conformational conversion of i-motif structures. Wang et al. [145,146] have developed a new method to detect the conformational conversion of i-motif using new material, the water soluble conjugated polymer, and cationic polythiophene as a sensing probe.

2.3. Poly(3,4-ethylenedioxythiophene) and its derivatives

Vasantha and Chen [147] used PEDOT-modified glassy carbon electrodes for the detection of dopamine and ascorbic acid. In addition, Manisankar et al. [148] used poly(3,4-ethylenedioxythiophene) (PEDOT)-modified electrodes for the determination of pesticides. A PEDOT modified electrode has been studied as a potentially useful amperometric sensor to use either alone or in the frame of a set of sensors, i.e. within on electronic tongue [149]. Yan et al. [150] have studied organic electrochemical transistors (OECTs) based on PEDOT: poly(styrene sulfonic acid) with various gate electrodes, including graphite, Au and Pt electrode etc. The modified electrode has been used as dopamine sensor and the detection limit of the device to dopamine is lower than 5 nm. Khudaish et al. [151] have stated that the modified electrode showed a substantial reactivity and high sensitivity in the oxidation of dopamine (DA) and ascorbic acid (AA). A simple and fundamental approach for the simultaneous and selective determination of DA and AA with a detection limit brought down to 142 nM and 331 nM, respectively.

2.4. Polycarbazole

Homopolymers of carbazole and copolymer with *p*-tolylsulfonyl pyrrole (*p*-Tsp) films were electrochemically deposited on single carbon fiber microelectrodes in 0.1 M $LiClO_4$/acetonitrile (ACN) by Ates et al. [152]. In this study, sensors show an amperometric response to dopamine concentrations with a detection limit of 0.27 μM dopamine for the polycarbazole (PCz) and 0.5 μM dopamine for P(Cz-co-*p*-Tsp). An efficient protection was obtained against ascorbic acid interference at physiological concentration value of 500 μM. In another work, electropolymerization of *N*-vinylcarbazole with various electrochemical techniques on carbon fiber microelectrode (CFME) has been investigated for tailoring CFME polymer interphases to promote fiber-matrix adhesion [153].

Pernites et al. [154] have developed a novel chemo-sensitive ultra-thin film with high selectivity for the detection of naproxen, paracetamol, and theophylline. Ultra-thin films have been used in a series of nonfunctional and bifunctional H-bonding terthiophene and carbazole monomers.

They showed the feasibility of using a series of electropolymerizable terthiophene and carbazole monomers for the imprinting of drug molecules. The bifunctional monomers of –COOH and –OH functional groups were found to be most effective for imprinting than their nonfunctional counterparts and the bifunctional NH_2, but they resulted in a longer time to reach saturation [155,156]. A possible compromise was the use of thinner films. Wang et al. [157] have studied poly(9-vinylcarbazole)/silver composite nanotubes and networks formed at the air–water interface. The material was prepared via the reduction of Ag(+) ions and the self-assembly of poly(vinylcarbazole) on $AgNO_3$ aqueous solution surfaces. In this study, the formed composite nanostructures depended strongly on the experimental temperature.

2.5. Polyaniline and its derivatives

Although many papers have been devoted to the electropolymerization of aniline and the characterization of the polyaniline-modified electrodes, there is not much information on the properties of the polymeric films formed by the electro-oxidation of the aniline derivatives [158]. Among those derivatives, ortho-phenylenediamine and its polymer poly(o-phenylenediamine) (POPD) have shown interesting properties and thus promising application in various aspects. POPD can be obtained as a thin layer or self-limiting thickness on different conducting substrates by anodic electropolymerization processes. Aussawasathien et al. [159] reported the preparation of electrically conductive polyaniline–polystyrene composites by using an emulsion pathway. In this study, they have prepared lithium perchlorate doped-polyethylene oxide (PEO) electrospun nanofibers for humidity sensing and camphorsulfonic acid doped-polyaniline/polystyrene electrospun nanofibers for sensing hydrogen peroxide and glucose. Gok et al. [160] reported the conducting polyaniline (PANI) sensors for some organic and inorganic solvents. In this work, PANI emaraldine salts (PANI-Cl, PANI-Br, PANI-ClO_4) were synthesized by the electrochemical method using different acids (HCl, HBr, $HClO_4$). The sensor properties of PANI have been changed depending on the nature of dopant anions. Sayyah et al. [161] investigated the electro-copolymerization of pyrrole and aniline in organic acid medium. They found that the IR spectrum of the copolymer was not a simple differentiation of the spectrum of each individual polymer. This means that the resulting polymer is a copolymer instead of being a mixture of PPy and polyaniline. Kong et al. [162] reported the electrochemical copolymerization of aniline and m-aminophenol in the presence of L-glutamic acid (L-Glu) as template molecules. As a result, enantioselective recognition of Glu enantiomers was performed on the electrode column by applying different potentials on copolymers in the ceramic column. Recently, Kan et al. [163] investigated the copolymerization of aniline and o-chloroaniline by using cyclic voltammetry. Their copolymerization is different from the polymerization of aniline or- o-chloroaniline in terms of growth rate, redox potentials, and charge transport mechanisms. Polyaniline (PANI) was found to be a better choice for gases, such as ammonia, due to its higher sensitivity, reversible response and shorter response time. The effect of ammonia and water on the conductivity of polyaniline has been investigated along with the polymer adsorption capacity. The transduction behavior of polyaniline has been exploited in thin film sensors for several gas molecules as well as volatile organic compounds. Ammonia sensors based on doped polyaniline films have been extensively studied [164] due to its higher sensitivity, reversible response and shorter response time [165,166]. The effects of ammonia and water on the conductivity of PANI have been investigated along with the polymer adsorption capacity [167–169]. Ammonia sensors based on doped PANI films have been extensively studied [170–173].

Sheng and Zheng [174] have covalently immobilized two enzymes: horseradish peroxidase and glucose oxidase (GOD) on carboxylic MWNTs. Then, the deposition of PANI on the MWNTs surface occurred after the addition of glucose into the system. Glucose acts as the substrate and reacts with GOD in the presence of the natural co-substrate O_2, to produce H_2O_2. Then, H_2O_2 serves as a substrate and reacts with horseradish peroxidase for the deposition of PANI in the presence of aniline.

2.5.1. Poly(o-phenylenediamine)

Poly(o-phenylenediamine) (PPD) derivative is achieved through substituting hydrogen by an amino group in aniline [175]. PPD is an interesting conducting polymer due to its conductance [176], electrochromic [177] and photoelectronic [178] properties, and especially the permselectivity [179]. These properties provide favorable conditions for its applications in electrochromic display [180], biosensors [181], and corrosion prevention [182]. PPD was used as an enzyme-entrapping membrane and the most common electroactive interference in biosensor applications [183].

The important factor for improving the stability, reproducibility and sensitivity of the biosensors is the immobilization of biomolecules on different kinds of transducer surfaces [184]. The polymer film modified electrode has stable performance and the ability to link biomolecules in terms of their functional groups [185]. The advantages of sensor application of polymeric materials are combined with different transduction mechanisms [186]. Incorporation of enzyme in the polymer film has been obtained either by introducing enzyme directly in the polymerization solution or by other means, such as electrostatic interactions with film components, such as cross-linking onto films and casting [187,188]. In all cases, there is no control of the amount of immobilized enzyme. The PPD could form an electrically insulating film through its oxidized state in a slightly acid or neutral solution. Thus, thin layer of self-limiting thickness could easily be obtained by anodic electropolymerization on the different conducting substrates [189]. The PPD film was electropolymerized in the design of the dielectric layer of capacitive biosensor [190–193].

Chirizzi and Malitesta [194] studied a potentiometric urea biosensor obtained by electrochemical entrapment of urease PPD matrix on carbon substrate. PPD matrix elucidate the original application of an electrosynthesized as buffer medium for enzyme other than as immobilization matrix. Zain et al. [195] fabricated a biosensor for monitoring of d-serine by using mammalian d-amino acid oxidase (DAAO) immobilized on a Nafion coated PPD modified electrode. They reported the combined layers of PPD in a Nafion enhanced the enzyme activity and biosensor efficiency. It was about two times greater than compared with each individual layer. Feng et al. [196] have developed a biosensor based on bovine serum albumin (BSA) and PPD. They reported BSA, due to the strong electrostatic affinity, was easily bound with the positively charged amino groups of PPD films. Windmiller et al. [197] fabricated a biosensor system by immobilization of glucose oxidase PPD. PPD film was obtained by simple one-step electropolymerization procedure.

2.6. Polyphenol

Amperometric biosensors have been used for in situ detection of phenolic compounds due to the high sensitivity, simplicity, and easy miniaturization [198]. Consumption of polyphenol-rich products with a reduction in the incidence of cardiovascular diseases causes certain cancers and other diseases related to aging [199,200]. Chemical structure of polyphenols acts as antioxidant and anti-inflammatory compounds, scavenging and neutralizing free radicals, and inhibiting lipoprotein oxidation [201–203]. Chawla et al. [204] have developed high-performance amperometric polyphenol biosensor, based on copper nanoparticles (CuNP)/chitosan (CHIT)/carboxylated multiwalled carbon nanotube (cMWCNT)/polyaniline modified electrode. They reported the CuNP's and cMWCNT had a synergistic electrocatalytic effect in the matrix of CHIT. PANI is a good thermal insulator for enzymes to protect the enzyme from environmental and thermal variations [205]. Tan et al. [206] described catechol biosensor, which was

selected as the model polyphenol, based on the immobilization of polyphenol oxidase (PPO) into polyaniline (PANI).

2.7. Polyacetylene

The other electrochemically prepared conducting polymer used for the bio-molecule immobilization is polyacetylene (PA). In literature, Kim et al. [207] have investigated the development of an enzyme-linked immunosorbent assay (ELISA) that uses electro-conductive polythiophene as a biosensor. The result of sensitivities for polythiophene biosensor was obtained as in the low parts per billion.

PA strongly resisted thermal decomposition and efficiently emitted blue light. However, poly(phenylacetylene) was degraded and emitted weakly [208]. Zeng et al. [209] have recently prepared disubstituted polyacetylenes bearing high polar side groups, such as azo moieties, indole groups, amine and pyridine ones, which were inaccessible from the direct polymerization of their corresponding monomers [210,211]. PA was studied the presence of α-amino acids by an indirect approach with the detection limit of histidine as ~2.7×10^{-5} M.

2.8. Polyfuran

Ali et al. [212] have studied polyfuran due to its possible technological application as a phenon dispersion and heat capacity. Polyfuran is very sensitive to humidity and its electrical resistivity decreases considerably and reversibly upon contact with moisture. Polyfuran also can be used as optoelectronic device, since upon doping the color changes from yellow-brown to black-brown [213–215]. Galal et al. [216] have studied electrodeposition of palladium nanoclusters on polyfuran film modified platinum electrode. These biosensor systems include some catecholamines, namely dopamine, epinephrine and norepinephrine, ascorbic acid and paracetamol.

3. Conclusion

Conducting polymers related to biosensor applications have recently become an important topic in Material Science and Chemistry. Some important conducting polymers, such as polypyrrole, polythiophene, polycarbazole and polyaniline, polyphenol, poly(o-phenylenediamine), polyacetylene, polyfuran and their copolymers have many advantages due to their charge transport properties and biosensor applications. Thus, the entrapments of bio-molecules (enzymes and proteins) in polymer matrix are of crucial importance especially in medicine and in the health sector. The immobilization of well-defined polymer–protein interactions opens new opportunities for the preparation of novel materials in which both macromolecular blocks combine to form structured and functional materials. Therefore, new techniques and new copolymer structures have been designed for various biosensor systems. In the future, it is possible to obtain development of a new type of enzyme-based bio-electronic devices by using conducting polymers.

Abbreviations

BSA	Bovine serum albumin
CNT	Carbon nanotube
CNF	Carbon nanofiber
CMWCNT	Carboxylated multiwalled carbon nanotube
CPNTs	Carboxylated polypyrrole nanotubes
CHIT	Chitosan
CuNP	Copper nanoparticles
DAAO	d-Amino acid oxidase
FETs	Field-effect transistors
FT-IR	Fourier transform infrared
GOD	Glucose oxidase
MWCNTs	Multiwalled carbon nanotubes
NPs	Nanoparticles
ODN	Oligonucleotide
OECTs	Organic electrochemical transistors
OFET	Organic field effect transistors
PPy	Polypyrrole
PThs	Polythiophenes
p-Tsp	*p*-Tolylsulfonyl pyrrole
PNVK	Poly-*N*-vinylcarbazole
POPD	Poly(o-phenylenediamine)
PPO	Polyphenol oxidase
PANI	Polyaniline
PPD	Poly(o-phenylenediamine)
PA	Polyacetylene
PNP	Purine nucleoside phosphorylase
SA	Stearic acid
XOD	Xanthine oxidase
XPS	X-ray photoelectron spectroscopy

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