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Review

Colorimetric sensors for rapid detection of various analytes

Ajay Piriya V.S [a], Printo Joseph [a], Kiruba Daniel S.C.G. [b], Susithra Lakshmanan [c], Takatoshi Kinoshita [d,*], Sivakumar Muthusamy [a,*]

[a] Division of Nanoscience and Technology, BIT Campus, Anna University, Tiruchirappalli 620024, India
[b] Department of Instrumentation and Applied Physics, Indian Institute of Science, Bangalore 560012, India
[c] Department of Chemical Engineering & Biotechnology, University of Cambridge, West Cambridge Site Philippa Fawcett Drive Cambridge CB3 0AS, United Kingdom
[d] Department of Materials Science and Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 4668555, Japan

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ABSTRACT

Sensor technology for the rapid detection of the analytes with high sensitivity and selectivity has several challenges. Despite the challenges, colorimetric sensors have been widely accepted for its high sensitive and selective response towards various analytes. In this review, colorimetric sensors for the detection of biomolecules like protein, DNA, pathogen and chemical compounds like heavy metal ions, toxic gases and organic compounds have been elaborately discussed. The visible sensing mechanism based on Surface Plasmon Resonance (SPR) using metal nanoparticles like Au, Ag, thin film interference using SiO_2 and colorimetric array-based technique have been highlighted. The optical property of metal nanoparticles enables a visual color change during its interaction with the analytes owing to the dispersion and aggregation of nanoparticles. Recently, colorimetric changes using silica substrate for detection of protein and small molecules by thin film interference as a visible sensing mechanism has been developed without the usage of fluorescent or radioisotopes labels. Multilayer of biomaterials were used as a platform where reflection and interference of scattering light occur due to which color change happens leading to rapid sensing. Colorimetric array-based technique for the detection of organic compounds using chemoresponsive dyes has also been focused wherein the interaction of the analytes with the substrate coated with chemoresponsive dyes gives colorimetric change.

Contents

1. Introduction

Future of sensing is based on the key factors of simplicity, cost-effectiveness and rapid response. Sensors based on colorimetric approach are significant while analyzing its ideal characteristics. Earlier sensors

* Corresponding authors.
E-mail addresses: kinoshita.takatoshi@nitech.ac.jp (T. Kinoshita), muthusiva@gmail.com (S. Muthusamy).

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are mean to be a bulk and complex one, requiring different functional blocks such as transducer, processing unit, a detection unit etc. leading to a delayed sensor response. Current technology based on colorimetry is all about the miniaturization of size, cost, in-situ and without any additional instruments. A calorimetric sensor is used for instantaneous detection of analyte and shows a color change, which can be detected visually. Nanotechnology plays an important role in current sensor technology. For example, nanoparticles like Au, Ag, Cu are extensively used in visual detection owing to its optical property known as Surface Plasmon Resonance (SPR). SPR is the phenomenon where collective oscillation of free electrons occurs due to resonance with incident light in visible region [1]. Plasmon resonance scattering (PRS) of Au and Ag nanoparticles have been utilized for bio-affinity sensing [2]. Generally, the detection mechanism is based on molecular interaction on the surface of the substrate which is modified or functionalized with certain functional groups or nanoparticles [1,2,3]. The role of nanoparticles in colorimetric sensing is reported and their results have shown that label-free assay is also possible with nanoparticles [4].

There are many challenges involved in developing an effective sensor, an ideal sensor should satisfy certain characteristics like selectivity, sensitivity, robustness, accuracy, precision, minimal error, reproducibility, linearity etc. Selectivity of a sensor is mean to be the characteristics to recognize the analyte of interest from many other interfering compounds/samples. The characteristic of a sensor to detect the analyte even at very low concentration is termed as sensitivity. It is a fact that cost may not tally with sensor characteristics. But the current technology satisfies the above-mentioned challenges. Lab-on-chip (LOC) is one among the prominent platforms on which the sensor technology is implied with high level of success [5]. It involves simple and portable devices made of polydimethylsiloxane (PDMS) being used for analyte detection by flowing liquid samples within a microchannel [5]. Microfluidics has gained wide acceptance in sensor technologies due to its low footprint and lesser user of analyte-containing reagents. Lab-on-chip technology using paper, i.e. lab-on-paper (LOP) became prominence for its low cost, rapid detection and self-sustainability. Sensor platform based on LOP for the detection of different biomolecules has already been reported by Whitesides [6]. LOP is simple, cheap and easily disposable. LOP uses cellulose paper for entrapping the molecules in a targeted site and the detection is based on the colorimetric approach. Microarray using LOP can detect different samples simultaneously.

Basically, colorimetric sensors can be classified according to the type of interaction of molecules, either chemical or biomolecules and are classified as chemical sensors and biosensors respectively. Table 1 shows a list of sensor analytes and their respective probes. In the following sections, detailed studies of different sensor systems were discussed.

Table 1
A list of sensor analytes and their respective probes.

Analyte	Probe	Reference
Chemical sensors		
Volatile organic compound	Dyes	Kenneth S. Suslick et al. [31]
Volatile organic compound	Dyes	Michael C. Janzen et al. [33]
Volatile primary amine	Inkjet printing	Tamaki Soga et al. [36]
Volatile organic compound	Colloidal crystal	Tatsaro Endo et al. [34]
Organic compound	Dye	Chen Zhang et al. [35]
Odour visualization	Dye	Neal A. Rakow et al. [32]
Trinitrotoluene(TNT)	Quantum dot	Kui Zhang et al. [64]
Hg^{2+} & Ag^{+}	AuNPs	Cheng-Yan Lin et al. [49]
Thiocyanate	AuNPs	Zhang Z et al. [66]
Cu^{2+}	Ag nanoparticles	Nalin Ratnararthorn et al. [55]
Cu^{2+}	Ag nanoparticles	Yu-rong Ma et al. [53]
Cu^{2+}	Ag coated Au nanoparticles	Tingting Lou et al. [54]
Cu^{2+}	Au nanoparticles	Ruili Liu et al. [52]
Cu^{2+}	Au nanoparticles	Xiaorong He et al. [51]
HCL gas	Nanofibrous membrane(polyimide)	Yuan–Yuan Lv et al. [60]
H_2S gas	Dye	Avijit sen et al. [61]
H_2O_2		Miao Xu t al [63]
Humidity	Copper nanoparticles	A. Luechinger et al. [58]
n-butyl phenol	Peptide coated SiO_2	T. Kinoshita et al. [8]
NH_3	Polymeric material	J. Courbat et al. [62]
Vapour sensing	Metalloporphyrin	Neal A. Rakow [32]
Biosensors		
Natural amino acid	Dyes	Huo Dan-Qun et al. [16]
Protein conformational change	AuNPs	Soon woo Chah et al. [10]
Avidin	Sio_2 thin film	R. Tominaga et al. [23]
Carcinoembryonic antigen	$ZnFe_2O_4$-MWCNT	Weiyan Liu et al. [24]
Antibody	Ag NP	Jian Ling et al. [25]
Heparin	TFP-Graphene oxide	Liping Cai et al. [43]
Heparin	Graphene oxide-Gold nanorods	Xiuli Fu et al. [40]
Protein		P-Phenyleneethynlylene
Oscar R. Miranda et al. [9]		
Bacteria(Sphingobium yanokuyai)	RNA probe	Sivakumar et al. [27]
Histidine	Ag Nps	Haibing Lai et al. [12]
Dopamine	AuNPs	Yuanfu Zhang et al. [41]
Dopamine	Au-Ag NPs	Sivakumar et al. [42]
Bacteria	Polymer	Liron Silbert et al. [26]
DNAse I	AuNps	Weian zhao et al. [28]
Enzymatic reaction	AgNPs	Hui Wei et al. [11]
Nucleic acids	Silicon substrate	Robert Jenison et al. [29]
Biomolecules	Aptamer & Au NPs	Wei Wang et al. [13]
Antibiotic protein(kanamycin)	Aptamer&AuNPs	Kyung Mi Song et al. [14]
DNA	Aptamer & AuNps	Min sik Eom et al. [30]
Protein	Aptamer &AuNps	Jwa-Min Nam et al. [15]
L-cystein& L-Homocystein	Flourescein	Oleksander et al. [17]

2. Biosensor

Nanotechnology has its own wide range of application in the medical diagnostics field, due to its specific property of Surface Plasmon Resonance possessed by metals like Au, Ag, Cu and Pt nanoparticles [1]. For sensitive sensing of biomolecules, SPR property of nanoparticles plays a crucial role. Biosensor utilizes SPR technology for many applications like an early diagnosis of diseases such as cancer, neural disorders like Alzheimer's, Parkinson diseases etc. [3,4]. Biosensor as the term implies that it senses biomolecules such as antigen or antibody, protein, DNA and also deals with interactions, enzyme detection, identification of microorganisms i.e., pathogen and DNA detection. The detection of analyte using colorimetric sensing is possible using surface modified nanoparticles, chemoresponsive dyes etc.

Biosensors focusing on biomimetics i.e., mimicking the nature and Pete Vukusic also studied iridescent color of butterfly wings [7]. Sensors based on biomimetics are fabricated due to the wide range acceptance of colorimetry interference. First of its kind has already been reported by Kinoshita et al. [8] using self-assembled monolayer (SAM) of polypeptides which is explained in detail in the following passages. Biosensors can be classified on the basis of detection phenomena as protein sensor, immuno sensor, pathogen sensor and DNA sensor.

2.1. Protein and amino acid sensors

Proteins are large biomolecules which are made up of amino acids. Sensing of protein molecules includes detection of amino acids, antigen-antibody interaction (immuno sensor) and also enzyme detection since all enzymes are proteins. Various amino acids or protein molecules like L-histidine, cysteine, lysozyme and methylases are detected using colorimetric approach. Few prominent examples of protein and amino acid sensors are explained below.

Vincent et al. [9] have been reported that the rapid and sensitive colorimetry sensing of bacteria using a supramolecular enzyme-nanoparticle assemblies. Protein conformational change is important in