UNIVERSITI PUTRA MALAYSIA

SENSITIVITY AND STABILITY OF CONDUCTING POLYMERS AND COPPER-BASED METAL ORGANIC FRAMEWORK FOR OPTICAL AMMONIA GAS SENSOR

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By

ABDUL HADI BIN ISMAIL

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the degree of Doctor of Philosophy

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SENSITIVITY AND STABILITY OF CONDUCTING POLYMERS AND COPPER-BASED METAL ORGANIC FRAMEWORK FOR OPTICAL AMMONIA GAS SENSOR

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Chairman : **Yusran Sulaiman, PhD**
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Optical approaches for ammonia (NH_3) gas sensing are contemplated as a reliable alternative to the conventional chemiresistive gas sensing techniques. Absorbance-based sensor by using white light were developed by using gasochromic materials, namely conducting polymers and copper-based metal-organic framework. Conducting polymers can be considered as the ideal material to be used as a single-component optical NH_3 gas sensor at room temperature. Recent interest in metal-organic frameworks has risen significantly, owing to their high surface area and porosity, as well as the inherent convenience of sculpting to design selected coordination sites for gas adsorption. Hence, a copper-based metal-organic framework, HKUST-1, has been chosen as a potential type of MOF for the intrinsic optical NH_3 gas sensor. The optical sensing performance of three different types of electropolymerised conducting polymers namely polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT) and polypyrrole (PPy), towards NH_3 gas were evaluated. On the basis of the former study, bilayers and copolymers containing electropolymerised PEDOT and PANI were further probed in order to attain the desired NH_3 sensing outputs from both materials. Characterisations of the samples were carried out using Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), and field emission scanning electron microscopy (FESEM) where functional group identifications of the corresponding samples and their morphological analysis were identified.. PEDOT exhibited the highest sensitivity (9.03/%) towards NH_3 gas comparing to PANI and PPy with the detection limit of 2.73 ppm, which is in agreement with their respective conductivity trends. The order of the bilayers and the presence of acid dopant on the fabrication of the sensing platform produced different absorbance responses upon exposure to NH_3 gas. The gasochromic behaviour of PANI and PEDOT during the adsorption of NH_3 gas was closely related to the changes in the oxidation state which have simultaneously altered the colour intensity of the respective sensing layer. Meanwhile, in contrast to the *in-situ* works, a long-term sensitivity performance of conducting polymers and metal-organic frameworks coated on side-polished plastic optical fibre (SP-POF) was presented. Long-term sensitivity of HKUST-1, PANI in protonated (emeraldine salt, ES) and deprotonated state (emeraldine base, EB) to the high concentration of NH_3 gas was performed. ES-EB composite has exhibited higher NH_3 sensitivity to the sole ES and ES-(HKUST-1) with minimal loss of sensitivity. ES-EB coated SP-POF has exhibited minimal sensitivity loss to NH_3 gas throughout the test duration with a 7.8% decrease followed by ES (28.1%) and ES-(HKUST-1) (50.86%). Of all developed samples in this work, PEDOT has exhibited the highest sensitivity to NH_3 gas(9.03/%) while PANI (EB) has exhibited shortest response and recovery time to 1% NH_3 gas, at room temperature. Also, incorporation of EB in the ES-coated SP-POF composite has significantly reduce the loss of sensitivity to NH_3 gas.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

SENSITIVITI DAN STABILITI POLIMER KONDUKTIF DAN KERANGKA LOGAM ORGANIK BERASASKAN KUPRUM UNTUK SENSOR OPTIKAL GAS AMMONIA

Oleh

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Pendekatan optik untuk penderiaan gas ammonia boleh dianggap sebagai satu alternatif yang bagus selain pendekatan penderiaan elektrik. Penderia gas berasaskan penyerapan yang menggunakan cahaya putih telah dihasilkan dengan menggunakan bahan-bahan gasokromik, termasuklah polimer konduktif dan kerangka logam-organik berasaskan kuprum. Sejak kebelakangan ini, banyak kajian terhadap pembangunan dan penambahbaikan penderia gas NH_3 telah dilaporkan seiring dengan jumlah penggunaan NH_3 dalam kepelbagaian sektor di peringkat global. Polimer konduktif telah dianggap sebagai bahan yang unggul untuk digunakan sebagai sensor optikal gas NH_3 pada suhu bilik. Kecenderungan kajian terkini terhadap kerangka logam-organik (MOF) telah melonjak dengan ketara, disebabkan oleh luas permukaan yang tinggi, permukaan berliang dan sintesis tapak penjerapan gas boleh direka bentuk dengan mampan. Oleh itu, sejenis kerangka logam-organik berasaskan kuprum, HKUST-1 telah dipilih sebagai MOF yang berpotensi untuk penderia optik intrinsik gas NH_3. Prestasi penderiaan optikal bagi tiga jenis polimer konduktif terenap iaitu polianilina (PANI), poli(3,4-etildioksitiofena) (PEDOT) dan polipirol (PPy) terhadap gas NH_3 telah dinilaikan. Berdasarkan perolehan data kajian tersebut, polimer dwilapisan dan kopolimer berdasarkan PEDOT dan PANI terelektroenap seterusnya diuji dengan tujuan untuk mendapatkan hasil penderiaan NH_3 daripada kedua-dua bahan ini. Pencirian sampel telah disempurnakan dengan menggunakan kaedah spektroskopi Raman, spektroskopi transformasi inframerah Fourier (FTIR) dan pengimbasan pancaran medan mikroskopi elektron (FESEM) di mana kumpulan berfungsi dan analisis morfologi untuk setiap sampel telah dikenalpasti. PEDOT menghasilkan kadar tindakbalas yang tertinggi (9.03/%) terhadap NH_3 berbanding PANI dan PPy dengan had pengesanan 2.73 ppm, selari dengan aliran kekonduksian polimer-polimer tersebut. Cara susun atur bahan untuk sistem sensor dwilapisan dan pengaruh dopan asid dalam penghasilan pelantar penderia didapati telah menghasilkan tindakbalas penyerapan yang berbeza terhadap gas NH_3. Tindakbalas gasokromik PANI dan PEDOT semasa penjerapan gas NH_3 berkait rapat dengan perubahan keadaan pengoksidaan yang akan mengubah keamatan warna lapisan sensor tersebut. Berbeza dengan kajian sebelumnya, yang menggunakan pendekatan *in-*

situ, prestasi penderiaan jangka panjang gentian optik plastik sisi digilap (SP-POF) bersalut polimer konduktif dan kerangka logam-organik juga telah dibentangkan. Penderiaan jangka panjang HKUST-1, PANI (garam zamrud, ES) dan PANI (bes zamrud, ES) terhadap gas NH_3 berkepekatan tinggi juga telah disempurnakan dengan jayanya. Komposit ES-EB meghasilkan kepekaan yang lebih tinggi berbanding ES tunggal dan komposit ES-(HKUST-1) dengan kadar pengurangan penderiaan yang amat rendah. SP-POF bersalut ES-EB menunjukkan kadar pengurangan kepekaan gas NH_3 yang rendah (7.8%) berbanding ES (28.1%) dan ES-(HKUST-1) (50.86%). Daripada semua sampel yang ditelah dibangunkan dalam kajian ini, PEDOT telah menunjukkan kadar penderiaan tertinggi (9.03/%) manakala PANI (EB) mempunyai kadar waktu tindak balas dan pemulihan yang paling singkat terhadap 1% gas NH_3. Di samping itu, penggabungan EB ke dalam SP-POF bersalut ES telah mengurangkan kadar pengurangan penderiaan gas NH_3 dengan ketara.

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I certify that a Thesis Examinations Committee has met on 27 January 2022 to conduct the final examination of Abdul Hadi Bin Ismail on his thesis entitled "Sensitivity and Stability of Conducting Polymers and Copper-based Metal Organic Framework for Optical Ammonia Gas Sensor" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1988. The committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

Ag/AgCl	Silver/Silver chloride
ANI	Aniline
APS	Ammonium peroxodisulfate
BCG	Bromocresol green
BCP	Bromocresol purple
BPB	Bromophenol blue
BTB	Bromothymol blue
BTC	Benzene-1,3,5-tricarboxylate ligand
CNT	Carbon nanotubes
CPR	Chlorophenol red
CSA	Camphorsulphonic acid
CUSs	Coordinatively unsaturated sites
DFT	Density functional theory
DOAS	Differential optical absorption spectroscopy
EB	Emeraldine base
EDOT	3,4-ethylenedioxythiophene
EIS	Electrochemical impedance spectroscopy
ES	Emeraldine salt
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier transform infrared
GO	Graphene oxide
GQD	Graphene quantum dots
H_2DHBDC	2,5-dihydroxybenzene-1,4-dicarboxylate
IR	Infra-red

LMR	Lossy mode resonance
LOD	Detection limit
MKR	Microfibre knot resonator
MMF	Multi-mode optical fibre
MOFs	Metal-organic frameworks
MPD	Modal power distribution
MR	Methyl red
MWCNTs	Multi-walled carbon nanotubes
NIR	Near infra-red
PANI	Polyaniline
PANI-EB	Polyaniline in emeraldine base oxidation state
PANI-ES	Protonated polyaniline (Emeraldine salt)
PEDOT	Poly(3,4-ethylenedioxythiophene)
PMMA	Poly(methyl methacrylate)
POF	Plastic optical fibre
PPy	Polypyrrole
Pt	Platinum
Py	Pyrrole
RE-MOF	Rare-earth-based MOFs
SP-POF	Side-polished plastic optical fibre
SPR	Surface plasmon resonance
SWCNTs	Single-walled carbon nanotubes
TCPE	Tetrakis(4-carboxyphenyl)ethylene)
TDLAS	Tunable diode laser absorption spectroscopy
TLV	Threshold limit value
TM-MOF	Transition metal-based MOFs

TMA	Trimesic acid
UATR	Attenuated total reflectance
UV	Ultra-violet
VOC	Volatile organic compounds

CHAPTER 1

INTRODUCTION

1.1 Research background

Ammonia gas (NH_3) is the most abundant alkaline gas in the atmosphere, accounting for a significant portion of reactive nitrogen. As one of the integral constituents of the atmospheric environment, NH_3 is produced either by decomposition of organic wastes or from anthropogenic activities. It is a highly toxic, colourless gas that can cause health issues in humans. Human exposure to NH_3 gas occurs as a result of unexpected extrication at manufacturing and industrial facilities, as well as agricultural casualties. In a surrounding where the concentration of ammonia exceeds its respective threshold limit value (TLV) of 25 ppm for 8 hours individual average weighted time, inhalation of ammonia can cause respiratory problems and mortality, be conditional on the exposure period (Pyatt, 2003). Prior to the present time, numerous researches on the development and improvisation of NH_3 gas sensors have been reported which is coherent to the manifold applications of NH_3 in multifarious sectors and areas globally. These works are commonly prompted by the need for reliable detection of NH_3 which can cause potential hazardous effects to human health due to its toxic and corrosive nature (National Research Council Committee on Acute Exposure Guideline, 2008).

An exceptional amount of works has been reported regarding the development and improvements of NH_3 gas sensors. Presently, NH_3 gas sensors which can be utilised at room temperature and fabricated by simple methods are still on insistence and enticing new works and approaches. Further, experiments on the applicability of optical gas sensors are continuing with more extents for improvisations. Undeterred by the setbacks, optical gas sensors offer some advantages, such as flexibility, immunity from magnetic and electrical noise, and protection from the possibility of combustion and explosion (Eguchi, 1992). Hence, polymeric materials, especially conducting polymers can meet these criteria because of the ease of preparation and their viability to be coalesced with supplementary materials such as inorganic compounds or carbon-based materials. The utilisation of conducting polymers for ammonia (NH_3) gas sensing by various types of optical means is well-known. Absorbance (Gribkova *et al.*, 2020, Jin *et al.*, 2001b), reflectance (Ai *et al.*, 2007), transmittance (Nicho *et al.*, 2001) and surface plasmon resonance-based (Mishra *et al.*, 2012) sensors are several instances of optical principles which have been exploited for this purpose. All of these works were critically scrutinised and we can infer that the majority of optical sensing principles using conducting polymers generally exhibit superior sensitivity and selectivity to NH_3 gas on a par with the conventional chemiresistive sensor.

Conducting polymers are known for their electrochromic and gasochromic properties (Hu *et al.*, 2017). The electrochromism of polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT) and polypyrrole (PPy) used in various applications were reported elsewhere (Camurlu, 2014). The electrochromic behaviour is due to their continuous π–π conjugated structure and low band gap (PANI: ~3 eV, PEDOT : ~1.65

eV, PPy : ~1.73 eV), enabling it to absorb electromagnetic radiation in ultra-violet (UV), visible light and near infra-red (NIR) regions. Light absorption bands of conducting polymers strongly depending on the density of the delocalised electrons, together with other facets. As a matter of interest, the electron density of the conducting polymers can be affected by the interaction with electron-donating or electron-accepting type of analytes (Neo *et al.*, 2016). Adsorption of gaseous analytes on conducting polymers will induce gasochromic behaviour of these materials. Particularly, effective adsorption of NH_3 gas on protonated PANI (emeraldine salt, ES) will deprotonate it to the emeraldine base (EB) state. This condition is associated with colour change from green to blue (gasochromism) respective to the PANI oxidation states. This phenomenon can be substantiated by using a wide range of optical measuring techniques, exemplifying their potential for use in optical gas sensors.

Gas sensing using metal-organic frameworks (MOFs) has emerged as a reliable alternative to conventional materials, such as conducting polymers and metal oxides. Gas storage, gas separation, and gas removal (Li *et al.*, 2018, Wang *et al.*, 2018) are some of the potential applications of MOFs; thus, the use of MOFs for gas sensing is conceivable considering their current advancements. Chemiresistive NH_3 gas sensors based on ZIF-8 composite (Wang *et al.*, 2020a) and trimesic acid (TMA)-based MOFs with different types of metal nodes (Sel *et al.*, 2015) are few instances of their relevance in this area. Despite its suitability for gas sensing application based on several factors (e.g; (i) high surface area, high porosity and durability for gas sorption and (ii) ease of sculpting to build selective coordination sites for gas adsorption (Chae *et al.*, 2004, Eddaoudi *et al.*, 2001, Kitagawa, 2015, Li *et al.*, 1999, Yaghi *et al.*, 2003), the applicability of MOFs for NH_3 gas sensing is still developing judging from scarcity of related works in the literature. Additionally, the poor conductivity of the latter MOFs has led to inadequate sensitivity and selectivity that restricted their utilisation for chemiresistive gas sensing (Li *et al.*, 2020). Of all types of optical principles for gas adsorption, luminescence quenching of MOFs remains the most reported (Kreno *et al.*, 2012, Lin *et al.*, 2016). Another ideal optical principle for gas sensing is gasochromism as experimentally revealed by Lee *et al.* (Lee *et al.*, 2011) and Britt *et al.* (Britt *et al.*, 2008). Nonetheless, reports on gasochromic gas sensors based on MOFs are still anomalous (Lee *et al.*, 2011).

1.2 Problem statement

Until recently, conducting polymer-based electrical transducers for NH_3 gas sensing has been extensively assessed as they purvey high sensitivity and are cost-effective. Rather, compared to the electrical transducing platforms, the optical gas sensor offers several advantages such as resistance to electromagnetic interferences and temperature. In addition, the investigation of optical NH_3 gas sensors based on conducting polymers is still in the stage of development which extends new research and findings. Therefore, in this work, the optical response of PANI, PPy and PEDOT towards NH_3 gas has been scrutinised. The evaluation of response and recovery time, as well as their sensitivity towards NH_3 gas has been contrasted accordingly.

Thus, in this thesis, improvisation on the optical sensitivity and LOD of PANI/PEDOT bilayers and PANI–PEDOT copolymers upon exposure to NH_3 gas at room temperature has been analysed. Additionally, a plausible gasochromic phenomenon that is imputable to changes in the oxidation states of PANI and PEDOT during exposure of NH_3 gas was also described.

Inspired by the excellent gasochromic behaviour of MOFs, good optical sensing performances can be achieved using side-polished plastic optical fibre (SP-POF) as the optical transducer. A common type of copper-based MOF which is HKUST-1 (Cu-BTC/MOF-199) was used as the sensing material and its optical sensing performance was evaluated. The optical sensitivity, response time, and recovery time were described accordingly.

Until recently, the establishment of novel MOFs are still progressing thus adjudication of ideal MOFs for optical NH_3 gas sensitive layer is still inconclusive. HKUST-1 (Cu-BTC, MOF-199) is a prevalent MOF that has been communicated in various niches. Both the copper metal clusters and the trimesic acid organic linker will serve as either Brønsted acidic or Lewis acid sites for deprotonation or to be reduced upon adsorption of NH_3 gas, resulting in a change in the optical properties. According to a number of recent reviews (Petit and Bandosz, 2010, Rieth *et al.*, 2019), HKUST-1 has been postulated to suffer degraded crystallinity due to the high basicity of NH_3. This condition might affect its NH_3 gas sensing performance, especially on long time period. However, credible scientific evidence and contributions are also needed to flesh out these hypothetical notions which in this case, our inclusion of HKUST-1 in the ES-based composite for optical NH_3 gas sensing will give experimental evidence to support or dismiss it.

Sensing stability is an important criterion for assessing a gas sensor's reliability and long-term efficiency. Conducting polymers and MOFs can be considered to be less chemically stable than metal oxides but they can exhibit higher selectivity to a particular gas. Degradation of conducting polymers was anthologised by Korotchenkov (Korotcenkov, 2014) which has asserted thermal, oxidative, hydrolytic and photodegradation. Apart from these factors, NH_3 gas may also cause conducting polymers to degrade, resulting in decreased sensing performance. Prolonged adsorption of NH_3 on conducting polymers causes NH_3 gas poisoning and accelerates the ageing process. A majority of works in the literature were focalised on sensitivity and selectivity improvisation, a concise study on long-term conducting polymers and MOFs stability to several cycles of NH_3 gas exposure is much needed. With that being the case, the long-term stability of an ES-based composite coated on SP-POF that was subjected to a high NH_3 gas concentration was assessed. In addition, the influence of EB and HKUST-1 on the developed ES-based optical NH_3 gas sensor were discussed and illustrated.

1.3 Research objectives

The following are the objectives of this study:

1. To investigate the optical NH_3 gas sensitivity of electropolymerised PEDOT, PANI (EB) and PPy.

2. To assess the optical NH_3 gas sensitivity of electropolymerised PEDOT and PANI (EB) in the form of bilayers and copolymers.
3. To evaluate the influence of emeraldine base (EB) and HKUST-1 on long-term optical NH_3 gas sensitivity of emeraldine salt (ES)-based composites coated on side-polished plastic optical-fibre (SP-POF).

1.4 Significance of study

In general, the primary contribution of this research is to demonstrate the usability of conducting polymers and MOFs for optical NH_3 gas detection at ambient temperature. Particularly, four non-conventional materials, namely PEDOT, PANI in ES and EB states, PPy, and a type of well-established MOF, the HKUST-1 (Cu-BTC, MOF-199) will be used due to their affinity to adsorb NH_3 gas molecules. Empirical and comparative study of the optical properties of these materials which are mainly based on their gasochromic behaviour is crucial to the development of intrinsic optical NH_3 gas sensors. Several influencing parameters were initially used to determine the optical NH_3 sensitivity of electropolymerised PEDOT, PANI-EB, and PPy on an indium tin oxide (ITO) glass substrate. Consequently, with the intention of developing bilayer and copolymers as the sensing layer, the desired traits from the sole materials such as strong sensitivity, fast response and recovery times will be assessed in order to develop a composite with synergistic efficacy. The optical sensitivity of conducting polymers and MOFs to NH_3 gas over a long-term period was investigated by utilising SP-POF as the optical transducer. The aptitude of the ES to adapt to high NH_3 gas concentrations for 70 days was monitored. The effect of EB and HKUST-1 on the NH_3 sensitivity of ES was further investigated by developing ES-EB and ES-(HKUST-1) composite coated on the SP-POF.

Several limitations of the study can be listed as following :

1. Due to the high target gas concentrations (up to 10,000 ppm) provided in the gas lab facility, the empirical data used to derive the detection limit is restricted. Hence , the detection limit in this investigation was theoretically determined.

2. Selectivity study was also limited as the gas sensing setup does not allow simultaneous mixing of multiple target gases. Availability of gases are currently limited only to NH_3, H_2 and CH_4 gas which has limited the extent of selectivity and interference studies. Additionally, these issues have also restricted field test to be done on any particular sensor.

3. The use of optical fibre has made the electrodeposition technique of fabricating sensing materials unfeasible. Because electrodeposition can only be done on a conducting surface (the ITO glass substrate), it is only suitable for in-situ applications. Therefore, preparation of sensing layer coating on the non-conducting optical fibre can only be done by other types of synthesis procedures (e.g; chemical or hydrothermal approaches) followed by relevant coating methods on the optical fibre (e.g; drop-casting, dip-coating or spray-coating).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Summary and conclusion

PEDOT which has been synthesised by electropolymerisation technique can be utilised for NH_3 sensing application at room temperature based on the reported results. Notwithstanding, PEDOT has exhibited the highest sensitivity towards NH_3 gas (9.03/%) with the detection limit of 2.73 ppm while PANI in emeraldine base form exhibits better response and recovery time (1.01 min, 4.26 min) although PANI has been electropolymerised without the presence of acid dopant. The detection limit of PEDOT is highly comparable with the literature which is mainly focused on electrical sensing. The influence of the electrical nature on the optical sensing performance of PANI, PEDOT and PPy is significant indicating adequate information to showcase good agreement in the conductivity of conducting polymers and their respective optical sensing performance.

The effect of combining PEDOT and PANI (emeraldine base) in the form of bilayers and copolymers as the sensing layer on the optical NH_3 gas sensing performance has been presented in this study. The possible optical mechanism involved, including the gasochromic behaviour of the respective conducting polymers during the adsorption of NH3 gas has been proposed. Apart from the chemical or physical interaction between the sensing layer and the target gas, the morphological condition of the sensing layer can also influence the sensing performance, predominantly in the desorption process of gas molecules and the baseline drift. The sensitivity of both bilayers are 8.17/% and 3.35/% for PEDOT(aq)/PANI(aq) and PANI(aq)/PEDOT(aq), respectively while the LOD of PANI(aq)/PEDOT(aq) (7.86 ppm) is below the threshold limit value (TLV) of NH3 gas which is 25 ppm permissible exposure limit as established by the Occupational Safety and Health Administration.

The long-term sensitivity of SP-POF coated ES-based composites to high NH_3 gas concentration was evaluated. The inclusion of EB and HKUST-1 in the optical sensing composite has resulted in significant output over 70 days of the test period. ES-EB composite has exhibited minimal sensitivity loss to NH3 gas followed by sole ES and ES-(HKUST-1) (ES-EB < ES < ES-(HKUST-1)). Sensitivity deterioration of sole ES to NH3 gas was due to (i) slower NH_3 gas desorption rate and (ii) its high affinity to water molecules (hydrophilicity). A similar problem was suffered by the ES-(HKUST-1) composite which has suffered the highest sensitivity loss of all tested samples. Minimal sensitivity loss of the ES-EB coated SP-POF in contrast to the sole ES and ES-(HKUST-1) composite were majorly contributed by (i) higher desorption of NH_3 gas and (ii) lower affinity of the composite to atmospheric vapour in a humid environment. The incorporation of EB was considered to facilitate the desorption rate, thus averting the NH_3 poisoning that would occur from prolonged adsorption. The hydrophobic nature of EB has reduced the interference of atmospheric water vapour which tends to be adsorbed on the hydrophilic ES.

5.2 Recommendations

Further optimisation of the ES:EB ratio can be expected as well as method development on acquiring improved SP-POF coatings. A significant attribute of certain NH_3 sensing materials is their ability to withstand the ramifications of NH_3 gas poisoning and humidity (atmospheric vapour) over a period of time. Emerging from the analysed results from this work, further studies can be carried out as following:

i. The EB, both obtained from chemical polymerisation and electropolymerisation methods has exhibited the respective characteristic due to ease of NH_3 desorption and its hydrophobic properties. EB can be further applied either as a sole-component or in sensing composite on various types of optical transducers. Apart from HKUST-1 which suffers deteriorated NH_3 gas sensitivity over time, other wide range of MOFs possessing gasochromic properties and good NH_3 adsorption and desorption rate can also be further investigated.

ii. Sample deposition approach on the optical fibre is another important aspect to consider. The electrodeposition approach is an excellent method to efficiently coat the sensing platform. A well-coated sensing platform will definitely increase the effective adsorption during gas exposure. Based on this research, the optical NH_3 sensitivity of drop-casted materials on the SP-POF (section 4.3) was significantly weaker than the electrodeposited on the ITO glass (section 4.1 and 4.2). However, this method is practically impossible due to the fact that most of the optical transducers are nonconducting. Other promising sample coating alternatives would be spray coating or chemical bath deposition.

iii. Another intriguing attribute that may well be investigated is the interference test. By including other types of corrosive gases such as HCl, Cl_2 and NO_2 gas in the selectivity test (which is currently unavailable in the gas lab facility), more credible evidence for practical applications should be acquired.

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