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Detection of Amphetamine with Graphene Quantum Dots

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Abstract

Amphetamine abuse is an enduring problem in many developed nations, including Sweden. It causes lasting damage both to its users and in the form of increased strain on healthcare services. It is therefore critical that police be equipped with the tools necessary to rapidly and accurately identify any samples in order to combat this scourge. Current analysis methods rely on large complex machines such as gas-chromatographs. This causes a significant bottleneck as all samples must be sent to lab for analysis. In this report the potential application of graphene quantum dots(GQDs) as a sensor for amphetamine has been studied. These offer a potentially quick and cheap analysis method that could be integrated into an easily portable detector. It was found that GQDs synthesised by a simple method from citric acid shows increased photo-luminescence in the presence of amphetamine. The response is largely linear with increasing concentrations of amphetamine within an interval of 1mM-200mM. This indicates they may very well serve as a sensing element of an amphetamine detector.

Keywords

Graphene quantum Dots, Amphetamine, Sensor, GQD

Sammanfattning

Amfetaminmissbruk har länge varit ett problem i många industrialiserade länder, inklusive Sverige. Det skapar långvariga skador både på dess användare och i form av ökade kostnader för hälsovården. Det är därför kritiskt att polisen ges de verktyg som behövs för att snabbt och precist kunna analysera prov. Nuvarande analysmetoder använder sig av stora avancerade maskiner så som gas-kromatografer. Detta skapar en flaskhals då alla prov som tas måste skickas till labb för analys. I denna rapport har användningen av grafen kvantprickar (GQD) som en sensor för amfetamin studerats. Dessa har potentialen att ge en snabb och enkel analysmetod som skulle kunna integreras i portabel sensor. GQD:er syntetiserade med en simpel metod från citronsyra visas i dessa experiment ha ökad fotoluminiscens när de är lösta tillsammans med amfetamin. Denna respons är linjär relativt till koncentrationen av amfetamin inom intervallet 1mM-200mM. Detta indikerar att dessa GQD:er mycket väl kan användas som ett sensorelement i en amfetamindetektor.

Nyckelord

Grafen kvantprickar, Amfetamin, Sensor, GQD

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Acronyms

QDs	Quantum dots
GQDs	Graphene quantum dots
PL	Photoluminescence
NFC	Swedish National Forensic Centre

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Chapter 1

Introduction

Quantum dots have many potential applications. Among them is the ability to use them as a sensor element to detect various chemicals. The characteristic photoluminescence of the Quantum dots (QDs) may be altered due to an interaction with a particular chemical and so thus allowing the accurate detection of that chemical[17]. This report will be focusing entirely on so called Graphene quantum dots (GQDs). These are as the name implies quantum dots made of a single-layer pure carbon material, graphene. Specifically the use of GQDs have been investigated in detecting amphetamine. This project is part of a series of projects at RISE in collaboration with the Swedish National Forensic Centre (NFC). Previous projects include; a project to detect gunshot residue and explosives using both graphene oxide and GQDs[4] and, a project to detect amphetamine with a graphene based sensor[16].

1.1 Background

Amphetamine abuse has long been a relatively common problem in Sweden. Looking at the amount of seizures by customs agents and police the rate of growth for amphetamine has stagnated for the last couple of decades. It still significantly outstrips both heroin and cocaine however. The statistics include both amphetamine and methamphetamine but methamphetamine make up only a few percent of the seizures, though the exact percentage varies substantially. The only singular drug that has greater imported quantities is cannabis at roughly four times the number of seizures[1]. Of course the side-effects of amphetamine use are far more severe than those of cannabis and so possibly presents a greater societal issue. It is therefore important for

police to be given the tools necessary for identifying amphetamine in the field. While we will not be attempting to develop a functional field-kit for amphetamine detection in this project our aim is to ascertain whether GQDs could serve as a useful sensor element in such a device.

1.2 Problem

The problem with current methods of amphetamine detection such as mass spectrometry and gas-chromatography are that while they are accurate they typically also require large and expensive equipment. This means that they are limited to a few labs such as the ones at NFC. This in turn means that these labs become inundated with analysis requests for investigations and the queues only grow longer. If a simple method for analysis could be developed and put in the hands of police officers it would allow the labs at NFC to focus only on the more complex cases.

1.3 Purpose

The purpose of this thesis project is to synthesize GQDs and analyze their response to amphetamine. Specifically we will attempt to determine if the addition of amphetamine generates a reproducible response in the photoluminescence of the quantum dots. Success will ideally lead to such GQDs being incorporated into a "lab-on-a-chip" device that would allow police officers a simple way to test samples for amphetamine in the field.

1.4 Benefits, Ethics and Sustainability

If the research is successful and eventually leads to the development of the "lab-on-a-chip" devices suggested above the Swedish police force would of course be the first beneficiary.

Regarding sustainability GQDs have been shown to be environmentally friendly and even bio-compatible[2]. Indeed this is part of the reason GQDs were chosen rather than more traditional quantum dots that usually include heavy metals[17]. Furthermore the synthesis method used is both cheap and environmentally friendly as will be shown later in the report.

1.5 Delimitations

This project will be focusing entirely on amphetamine, specifically amphetamine sulphate, as the analyte. We will not be using other drugs or potential contaminants and so we will be unable to determine the selectivity of the GQDs towards amphetamine as compared to other analytes. We will also have a relatively small amount of amphetamine sulphate to work with limiting how many replication tests and different concentrations can be tested. This is also the reason we have chosen to focus on only one type of GQDs even though others could be synthesised.

1.6 Outline

In the next chapter will explain some of the theoretical background required to understand this project. This includes a short review of existing methods for amphetamine detection, an explanation of the properties and synthesis of GQDs, the theory of testing methods used, and some related work. Chapter 3 will explain in detail the synthesis procedure used as well as the experiments. Chapter 4 shows the results of the experiments with some discussion as well of these results. Finally in chapter 5 the conclusions that can be drawn are presented as well as some prospects for future work.

Chapter 2

Theoretical Background

This chapter will explain the theory necessary to understand the project as well as some of the related work.

2.1 Graphene Quantum Dots

This section will discuss Graphene quantum dots (GQDs). Both some basis for their properties and the experimentally confirmed Photoluminescence (PL) behavior will be explained.

2.1.1 Graphene

First an explanation of graphene itself. In the strictest definition graphene is a material consisting of a single layer of only carbon atoms arranged in an hexagonal honeycomb structure. It is the single layer version of graphite, which has many such layers stacked on top of each other and bonded together[15]. Commonly, however structures that contain a few stacked layers of graphene will also be called graphene. How many layers are considered graphene depends on context, but it is always less than 10. In fact it can be useful to have three categories of graphene, namely single-layer, double-layer, and multi-layer(3-9 layers) graphene. This is because each category will have its own electronic behavior. Notably both single-layer and double-layer graphene can be considered zero-bandgap semiconductors. For multi-layer graphene the behavior becomes more complex[7].

The hexagonal structure of graphene is held together by sp^2 -hybridized bonds. As is

well known carbon has four valence electrons, despite the fact that its ground state is $2s^2 2p^2$. This is due to hybridization. Commonly the electrons of the $2s$ shell hybridize with the $2p$ orbitals to form a tetrahedral structure. This is called sp^3 hybridization and is present in all molecules where carbon bonds to four different atoms. In graphene, and other flat carbon structures, however the $2s$ shell electrons instead hybridize to form a planar set of three orbitals in a triangle shape leaving one p orbital that is perpendicular to the other three, usually referred to as the p_z orbital. This is sp^2 hybridization. These free p_z orbitals will then normally form so called π -bonds. These are weaker than the σ -bonds formed between the sp^2 orbitals. The π -bonds are what creates the second bond in double bond between atoms, with σ -bonds forming the first[7]. π -bonds are significantly weaker than σ -bonds and so it requires less energy to break them or excite them into their antibonding state called π^* . An antibonding state is where the electron density is shifted away from the bond, even more so than if the atoms were not bonded. This causes repulsion between the atoms and so is a higher energy state than even simple non-bonding. While the transition from bonding to antibonding is possible for σ -bonds as well it requires substantially more energy. The transition from π -bonds to their antibonding orbitals, usually written $\pi \rightarrow \pi^*$, however often corresponds in energy to that of visible or ultra-violet light and so can be a cause of PL as will be discussed in section 2.1.3.

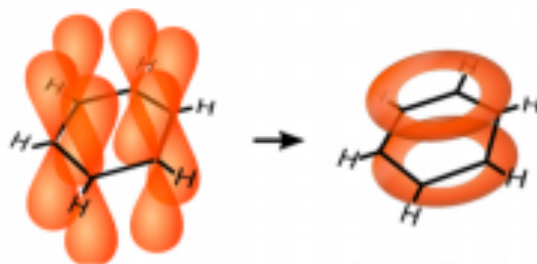


Figure 2.1.1: Formation of π -bonds in a carbon ring. Image by Vladsinger, CC-BY-SA 3.0.

2.1.2 Quantum dots

Before looking at GQDs it is helpful to have an understanding of the more traditional QDs. These QDs are made from semiconducting materials. A semiconductor has a valence and a conduction band, separated in energy by a bandgap. These bands refer to bands of energy levels that an electron can occupy. In their ground state the electrons will occupy the valence band, which is lower in energy. The electrons can however be

excited to the conduction band either by heat or by absorbing a photon with energy equal to or greater than the bandgap. When this happens it leaves behind a hole in the valance band. These holes can be considered positively charged particles capable of moving in the valance band. The reason we call such materials semiconducting is that they will only conduct electricity once electrons have been excited from their ground state in the valance band to the conduction band, at which point both the electrons and holes will contribute to conductivity[8].

When an electron is excited and leaves behind a hole these two particles will be attracted to each other as they have opposite charges. This electron-hole pair is called an exciton. The electron-hole pair will maintain an average distance to each other called the Bohr exciton radius, which depends on the material. When the size of the semiconductor crystal is reduced such that its radius is close to the Bohr exciton radius the exciton will start to experience quantum confinement. Quantum confinement means that the wavefunction of the exciton starts to significantly overlap with the edge of the crystal. This creates a situation that can be closely approximated by a particle in an infinite spherical well. This is well known system and has the energy levels given by $\epsilon_{n,l} = \hbar^2 \beta_{n,l}^2 / (2m_e^* R^2)$, where $\beta_{n,l}$ is the n th zero of the l th spherical Bessel function, m_e^* is the effective mass of the electron and R is the radius of the crystal. The critical thing to note here is that energy levels of the electron are inversely proportional to the square of the radius of the particle. Of course similar energy levels exist for the holes[8]. Combining this equation of the energy levels for both holes and electrons for the lowest energy level $\beta_{0,0} = \pi$, gives the confinement energy $E_{confinement} = \frac{\hbar^2 \pi^2}{2R^2} (1/m_e^* + 1/m_h^*)$. The confinement energy describes how much the bandgap is increased due to quantum confinement. We can see that as the radius of the quantum dot is decreased the size of the bandgap is increased.

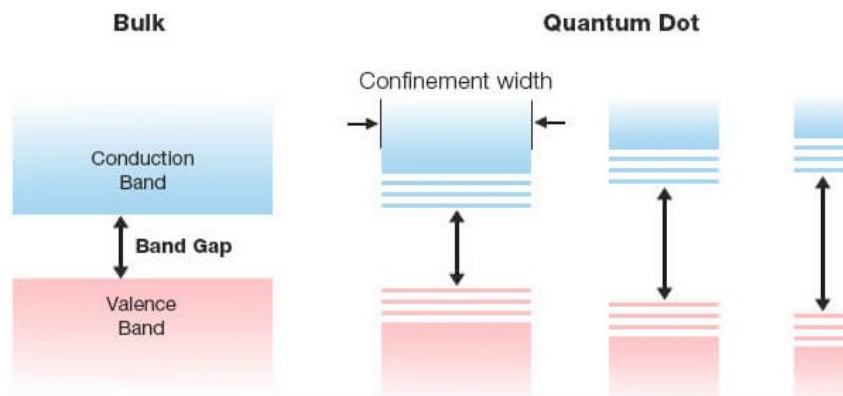


Figure 2.1.2: Illustration of quantum confinement with decreasing size of the quantum dot.

This bandgap dependence on the size of the particle is the most important feature of quantum dots. When a QD absorbs a photon with an energy greater than the bandgap it will create an exciton. The electron and hole will both then approach the lowest energy state of the conduction band and the highest energy state of the valence band respectively, through non-radiative means. They will then recombine and consequently emit a photon with energy equal to the bandgap. The difference between the wavelength of the absorbed photon and the emitted photon is called the Stokes shift. Since the bandgap is dependant on the size of the particle it allows us to tune the emitted light by changing the size[17].

2.1.3 GQD properties

As has been mentioned in the graphene section a large section of graphene will have zero band-gap. This means that graphene has no PL. However when we shrink the size of the graphene layer the band-gap opens up, due to quantum confinement. This band-gap also gives rise to PL. Similar to classical quantum dots as their size is reduced the band-gap is increased and the emitted wavelength becomes correspondingly shorter. It is therefore reasonable to refer to these flakes of graphene as graphene quantum dots. Most GQDs are around 5-20nm in size, but some have been reported as large as 60nm in diameter[10].

In difference to traditional QDs though it has been found that the PL properties of GQDs are not simply a function of their size. The exact mechanism of GQD PL remains unclear. However several explanations have been proposed, including excitons of carbon, emissive traps, quantum confinement effect, aromatic structures, oxygen-

containing groups, free zigzag sites and edge defects. Broadly they can be categorized as either intrinsic state emission or defect state emission. What is known is that multiple factors are significant in determining both the emitted colour and the intensity for GQDs. Indeed based on these factors light emitted by GQDs may run over the entire visible spectrum and beyond[10].

Two GQDs with different synthesis methods can have very different properties since edge structure and surface defects are known to have a significant effect on the GQDs, even if the size is similar. In particular there are strong indications that the free edge sites of the GQDs can have a sometimes dominant effect on the luminescence. Free in this case refers to that no additional atoms are attached to the edges and so the carbon atoms are left with unpaired valance electrons. There are two types of edges in graphene, arm-chair and zigzag. Arm-chair edges are more smooth and have a carbyne-like orbital structure. Zigzag edges are more sharp with carbon atoms only bonded with two atoms in the inner lattice and so creating carbene-like structures with two free electrons. It has been found that these carbene structures often take the triplet state with the two electrons having the same spin. This makes these sites paramagnetic and gives rise to some of the unexpected electro-magnetic properties of GQDs. It also creates emission sites for PL as it creates an intermediate energy level for the excitation and de-excitation of the electrons[10, 13].

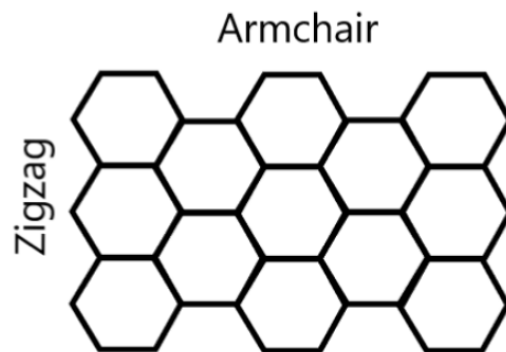


Figure 2.1.3: Armchair and zigzag edges of GQDs.

The different factors that are significant in GQD luminescence will here be briefly explained. The first is of course size. As mentioned above GQDs have been shown to have quantum confinement that increases the band-gap, thus blue shifting the emissions as the GQDs become smaller. However for some GQDs prepared by different synthesis methods their luminescence is almost size independent. It is clear that for

these GQDs other factors must be dominant, presumably defect states that would not scale with the size of the GQDs[10].

The GQD luminescence is also usually dependant on the excitation wavelength used. Both intensity and emission wavelength can vary. It is believed that this is due to optical selection of differently sized GQDs and emission sites. The absorption of GQDs comes primarily from the excitation of the carbon π -bonds to their anti-bonding state $\pi \rightarrow \pi^*$. However the absorption peak for this process can vary between ca 200nm and 270nm for GQDs based on their size due to quantum confinement[10]. Therefore different GQDs in a sample can be favored based on their size when using different emission wavelengths. Other emission sites created by surface functional groups, edge sites, or defects can also create different pathways for absorption and emission as they can have energy states in between the π and π^* states. It is however possible for the emission wavelength to be mostly independent from the excitation wavelength if the GQDs are monodisperse and have consistent surface states. Indeed this is shown by Yongqiang Dong et al.[6] for their GQDs synthesized by citric acid pyrolysis, which is the method that will be used in this project.

The pH value of the GQD solution can also have a significant impact on the luminescence. It is suggested that for GQDs with emission that comes from zigzag edge sites these sites will become protonated in acidic conditions. This disrupts the carbene structure that causes emission from these sites and so limits or prevents the emission in more acidic environments. This behavior has been experimentally confirmed[12]. For some other GQDs however the behavior may be different, including for example reduced luminescence for both alkaline and acidic solutions. In these cases it is likely that pH interaction with various surface groups and defects are what determines the change. In the report by Shoujun Zhu et al.[18] they show that the luminescence decreases for both high and low pH while stable in the region of pH 4-8. It is notable that at pH over 12 the peak blue-shifts and narrows. This certainly indicates a different mechanism than for the zigzag sites, in particular since it is known that the GQDs have several surface groups in this case. The relationship between pH and the fluorescence properties of GQDs remains complex and highly synthesis dependant.

2.2 Instrumentation

2.2.1 Photoluminescence

The main analysis method used in this project is PL measurements. This is a simple method for measuring how a fluorescent sample, such as QDs, react to being excited by a particular wavelength. PL typically uses light in the ultraviolet to visible region of the spectrum as the exciting light. The energy of these photons corresponds to electronic transitions and electron-hole pair generation in QDs. It can therefore be used to find changes in the emitted spectrum of light as a result of the interaction between the QDs and amphetamine, if there is an interaction between the two.

The structure of a general spectrofluorometer is fairly simple, though details can be changed depending on the needs of the experiments performed. A source, commonly a xenon lamp, emits a spectrum of white light. This passes through a monochromator that selects a specific wavelength. This light is focused onto the sample which is typically held in a quartz or plastic cuvette. This exciting light causes the sample to fluoresce. Orthogonal to the incoming beam of light is a detector aperture that collects the emitted light. This light is passed through another monochromator and finally its intensity is measured by a photo-multiplier tube. The two monochromators allows us to measure the emitted intensity either as a function of excitation wavelength or as a function of emission wavelength, keeping the other at a fixed value. For this project we will be using the emission wavelength as our variable, using the same excitation wavelength, 335nm, for all measurements[9].

2.2.2 FT-IR Spectroscopy

Fourier-transform infrared(FT-IR) spectroscopy is a method that as the name implies uses infrared light to analyse a sample. Specifically its purpose is to find the absorbance of a sample at each wavelength, usually in a spectrum from 4000cm^{-1} to 400cm^{-1} (from $2.5\mu\text{m}$ to $25\mu\text{m}$ in wavelength). The reason we are interested in analysing this region of light is that the energy corresponds to the vibrational modes of many common chemical bonds. When light strikes the molecules in the sample if it has energy similar to that of one of the vibrational modes it may be absorbed. A particular bond will have characteristic energy levels for both its stretching and bending modes, with stretching having higher energy. The absorbance peaks in the FT-IR spectrum can

therefore show the presence of the various kinds of bonds in the sample. Such analysis can however be complicated by the fact that peaks may overlap and so having some knowledge about the chemical composition of the sample is usually necessary to be able to rule out unlikely bonds. An alternate use is to compare the acquired spectrum with one from literature.

The most immediately obvious way to acquire this data would be to use a single wavelength of light and measure its absorbance. Then continue incrementing the wavelength over the spectrum. Indeed this is how the measurements in UV-vis are usually done. In FT-IR however multiple wavelengths are measured at once. This is achieved through an interferometer. An interferometer can be schematically described as follows. Light from a full spectrum source, similar to a black-body, strikes a beam-splitter at a 45° angle. This will ideally cause 50% of the beam to be reflected and 50% to be transmitted. The reflected beam is then reflected back to the beam-splitter by a stationary mirror. The transmitted beam is also reflected back, but with a moving mirror. The transmitted beam therefore has to travel an extra variable distance called the optical path difference(OPD) compared with the reflected beam. When the two beams are recombined at the beam-splitter this OPD will cause them to be out of phase. Depending on the phase-shift they will have constructive and destructive interference at various wavelengths. This beam that is passed through the sample will therefore contain the wavelengths that have constructive interference. This produces data in the form of absorbance as a function of OPD (in cm). The Fourier-transform allows us to convert this into absorbance as a function of wavenumber (in cm^{-1}).

2.3 Related Work

The main piece of related work to this project is the article by Majid Masteri-Farahani et al.[11]. Their work uses GQDs synthesized by the same method as the one we used, though it should be noted that they used phosphate buffered saline solution(PBS) rather than de-ionized water as the solvent. In it they demonstrate that it is possible to detect both methamphetamine and morphine with these GQDs due to a change in their PL. Both of these analytes are related to amphetamine, especially methamphetamine which has the same structure except for one extra methyl group. They found that adding methamphetamine decreased the luminescence of the GQDs and morphine increased the luminescence. In both cases there was a linear response with a detection

limit of ca $1.5\mu\text{g}/\text{ml}$ for methamphetamine and $0.5\mu\text{g}/\text{ml}$ for morphine. These results are a large part of the inspiration to investigate whether a similar response might be found for amphetamine.

Chapter 3

Experimental

In this chapter will be described how the quantum dots were synthesised, as well as the methods used to test their PL behavior and interactions.

3.1 Chemicals

We used citric acid monohydrate, sodium hydroxide, Amphetamine sulfate provided by NFC, and 2-phenylethylamine hydrochloride with $\geq 98\%$ purity.

3.2 Synthesis of Graphene Quantum Dots

For the synthesis of the Graphene Quantum Dots (GQDs) a slightly modified version of the process reported by Yongqiang Dong et al.[6] was used. The idea of this synthesis method is to use pyrolysis, the elimination of water from a substance, to create GQDs from citric acid ($C_6H_8O_7$). The structure of citric acid is shown below. The theory is that when sufficiently heated the pyrolysis of citric acid occurs through a hydrogen group of one citric acid molecule interacting with a hydroxide ($-OH$) group of another citric acid molecule. They then form a water molecule and in so doing allow the carbon atoms to bond together. The structure of citric acid is such that these carbon bonds will form hexagonal carbon rings, the fundamental structure of graphene. After the right amount of carbonization, increase in carbon content, these structures will form into nanometer-sized "flakes" of graphene. These "flakes" are the graphene quantum dots that were sought. The formation of these nanoparticles can be visually

confirmed by the citric acid liquid turning orange. The GQDs will be left with many carboxyl($-COOH$) and hydroxide groups on the surface. These surface groups will allow the graphene quantum dots to be stable and dissolve in water. If the pyrolysis process is carried on too far however more of these groups will be eliminated and the the small graphene "flakes" will form into larger sheets of graphene oxide (GO). This change can also be easily seen since the liquid will at this point turn black.

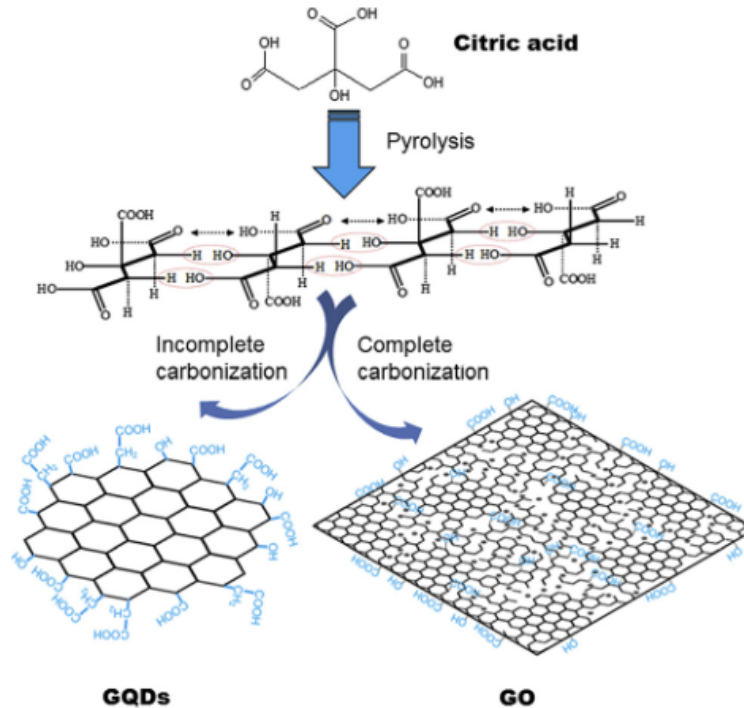
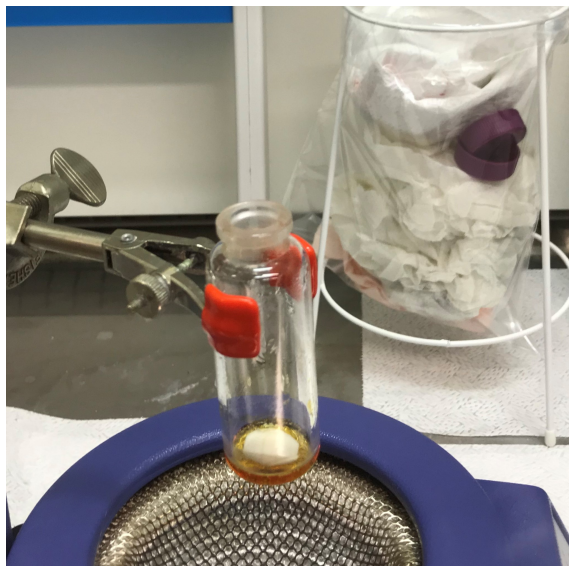


Figure 3.2.1: Synthesis process from citric acid to GQDs or GO depending on the degree of carbonization. Image sourced from [6].

The specific synthesis procedure used to produce **GQD!** (**GQD!**) for these experiments. 2g of crystalline citric acid monohydrate($C_6H_8O_7 * H_2O$) were put into a beaker. This beaker was placed in a mantle heater and heated to $200^{\circ}C$. The beaker was left open to the air in a fume hood to allow evaporation. After approximately 15min the powder had fully liquefied, forming a transparent liquid. After 20min the liquid had become a pale yellow. After 25min the liquid had reached a darker yellow. At 35min it had finally turned orange. The beaker was removed from the heating mantle after 40min, to ensure that the carbonization was sufficiently complete. 10mg/ml sodium hydroxide($NaOH$) was then slowly added to the liquid to neutralize it. The pH of the citric acid liquid is of course inherently low since it is made from a pure acid. The sodium hydroxide was added while the solution was being constantly stirred by a

magnetic stirrer and while checking the pH regularly. After adding 50ml of the sodium hydroxide the solution had reached the desired pH of ca 7. Finally a yellow solution of GQDs in water was obtained.



(a) After 40min

(b) After neutralizing with $NaOH$

Figure 3.2.2: Pictures of the citric acid liquid after 40min and after neutralizing it with $NaOH$, respectively.

The GQD solution was put in a bottle and stored in a cupboard until it was used. As will be shown in the results section this has little adverse effect on the quality of the GQDs.

3.3 Photoluminescence Measurements

The main part of this project has been to determine the change in the photoluminescence (PL) of the quantum dots as a response to the presence of amphetamine. First a model chemical was used in place of amphetamine to prove the concept, since acquiring amphetamine was somewhat problematic. The model chemical was 2-phenylethylamine hydrochloride ($C_6H_5CH_2CH_2NH_2 \cdot HCl$). This chemical is identical to amphetamine except for a single methyl side chain. It is therefore reasonable to assume it should have similar bonding and electrochemical properties. The experimental procedure is the same for both chemicals.

Firstly stock solutions of the analyte were prepared at double the concentrations that would be measured. It was decided that a broad range of concentrations should be

used to get an overview of the behavior. The highest concentration stock solution was prepared first by dissolving the powder form of the chemical in Milli-Q water. Once the powder was fully dissolved the solution was further diluted to make the lower concentration stock solutions. This procedure avoids remeasuring that may introduce errors, particularly when weighing the powder. Stock solutions of the QDs were also prepared. While the QDs are already suspended in their own aqueous solutions it was found that diluting them gave better results. For the **GQD!** a 1:3 dilution using Milli-Q water was used.

From these stock solutions was then prepared the samples that the measurements would actually be performed on. These were all prepared and stored in plastic cuvettes. The samples were made by taking 0.5ml of the QD stock solution and mixing it with 0.5ml of the relevant analyte stock solution in the cuvette. Controls were also prepared by taking 0.5ml of the QD solution and mixing it with 0.5ml of Milli-Q water. Each solution was thoroughly mixed. The samples were always left for at least one hour after mixing to ensure that they had sufficient time to interact and stabilize.

The measurements were made with a Jasco Spectrofluorometer FP-8300. This was done by taking 0.995ml of the sample solution and putting it into a quartz cuvette. Leaving a small amount of the solution allows more accurate measurements as there is no risk of sucking up air with the pipette. The quartz cuvette was carefully placed into the spectrometer. An excitation wavelength of 335nm was used, as this yielded a reliable signal for the **GQD!**. After the measurement was complete the solution was extracted from the quartz cuvette and returned to the plastic cuvette. The quartz cuvette was then thoroughly rinsed out, twice with DI-water and once with Milli-Q water. Finally it was dried with compressed air. The same quartz cuvette was then reused for all experiments.

3.4 FT-IR

To perform the FT-IR analysis first two samples that had been prepared earlier according to the Photoluminescence measurements section were dried. One of the samples was a pure GQD control sample and the other a 200mM amphetamine and GQD sample. These were placed on two glass disks to dry. They were dried in a vacuum overnight ca 50°C overnight. This produced a viscous residue from the GQDs as well as powder form amphetamine sulphate from the mixed sample. The two residues and

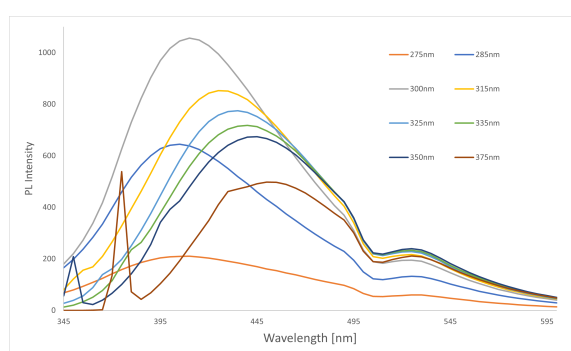
the amphetamine powder were each ground together with potassium bromide (*KBr*) powder. These powders were then pressed with 1.1 tons of force into pellets. These pellets were then placed in turn into the FT-IR spectrometer to be measured. Each pellet was measured several times after being rotated to ensure that the results were accurate.

Chapter 4

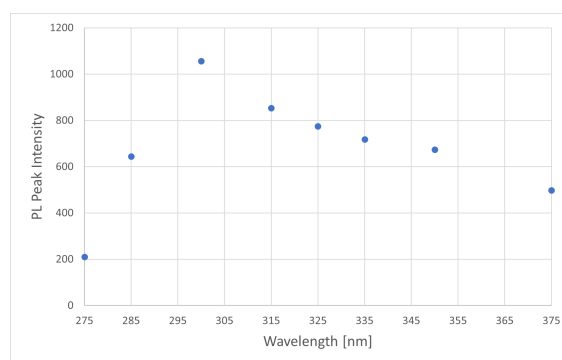
Results and Discussion

4.1 Wavelength response

In this section are the results of the PL response measurements of the citric acid GQDs using different excitation wavelengths. The graphs presented below show the emitted signals as well as their peak intensities for clarity. Note that the sharp peaks seen in the 350nm and 375nm measurements are simply reflections of the exciting laser itself, as they are at that same wavelength.



(a) GQD response to different excitation wavelengths



(b) PL peak maxima for different excitation wavelengths

Figure 4.1.1: Citric acid GQD response to different excitation wavelengths.

A shift in the peak wavelength of the GQDs can be seen as well as changes in intensity. While the response for a 300nm excitation wavelength gives the highest intensity it should also be noted that the intensities drop off sharply at lower wavelengths. A longer wavelength in the seemingly more stable region at 335nm was therefore chosen

to avoid any significant shifts in emission intensity. It is also not always desirable to have the greatest intensity possible especially since it will be shown that the intensity is increased by the presence of amphetamine. For these experiments and setup it was found that 335nm gave an adequate luminescence emission.

4.2 Photoluminescence

In this section are the first measurements of the PL with the chemical 2-phenylethylamine hydrochloride, which is similar to amphetamine in structure and so should give similar results.

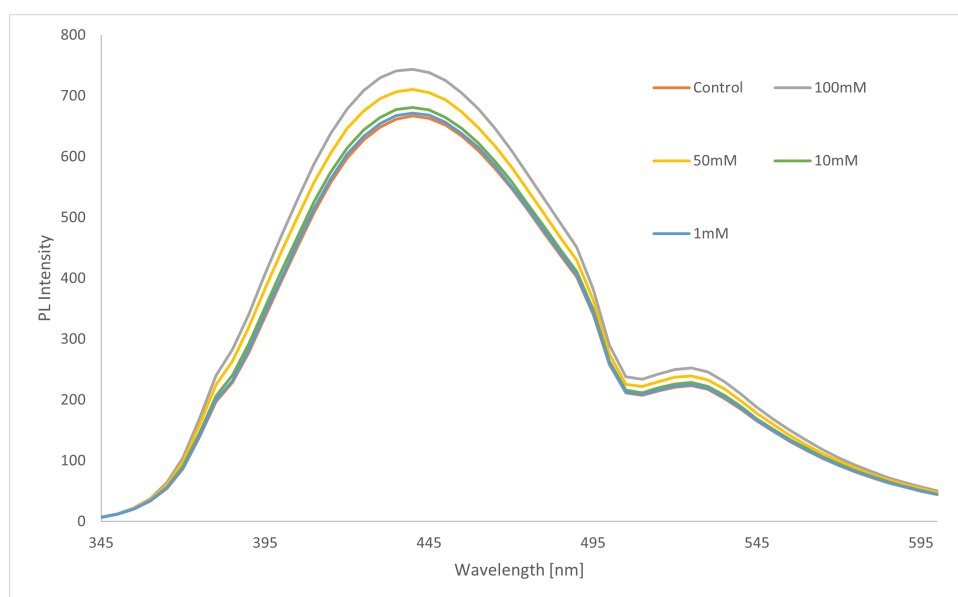


Figure 4.2.1: PL response of citric acid GQDs with 2-phenylethylamine hydrochloride.

IT can clearly be seen that as the concentration of 2-phenylethylamine hydrochloride is increased the PL intensity is also increased. The luminescence is increased across the entire spectrum but the most significant increase is around the maximum at 440nm. The response at the maxima therefore gives the clearest signal for detection. As they are of particular interest they are shown below, using the luminescence increase relative to the control.

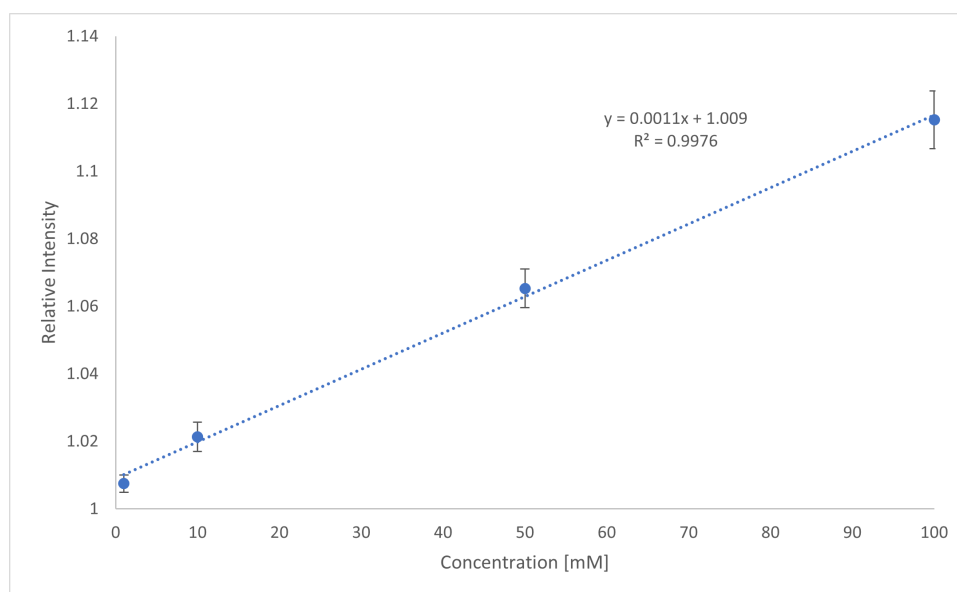
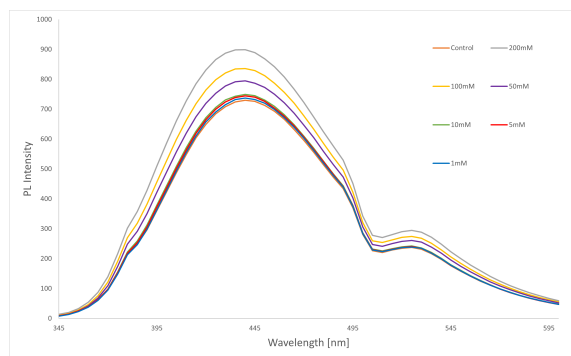


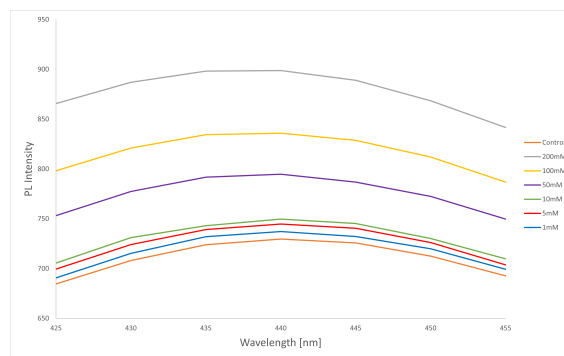
Figure 4.2.2: Relative increase in luminescence at the maxima for citric acid GQDs with 2-phenylethylamine hydrochloride.

It can now be seen that the maxima have a linear response with increasing concentration of 2-phenylethylamine hydrochloride. The error bars show two standard deviations. This response is very promising for the potential application of these GQDs as a sensor. Based on these results test of the GQDs with actual amphetamine were performed, specifically using amphetamine sulphate. Note that amphetamine sulphate has 2 units of amphetamine per unit of sulphate. All graphs below will use the concentration of amphetamine base.

When testing the citric acid GQDs with amphetamine test were run over two separate days. The first is a singular test with no replication that was meant as a proof of concept. The second was a test with triplicate replication as described in the experimental section. Both of the results will however be shown below as the first test is more illustrative of the results and some potential errors were found in the replication tests that will be discussed below.



(a) Overall PL response of citric acid GQDs with amphetamine sulphate.



(b) Expanded version of fig.(a) around the maxima.

Figure 4.2.3: PL response of citric acid GQDs with amphetamine sulphate.

As expected a very similar response to the one acquired with 2-phenylethylamine hydrochloride can be seen in these results. The overall curve, peak positions and increasing luminescence trend all follow the same behavior. This is further shown when plotting the maxima.

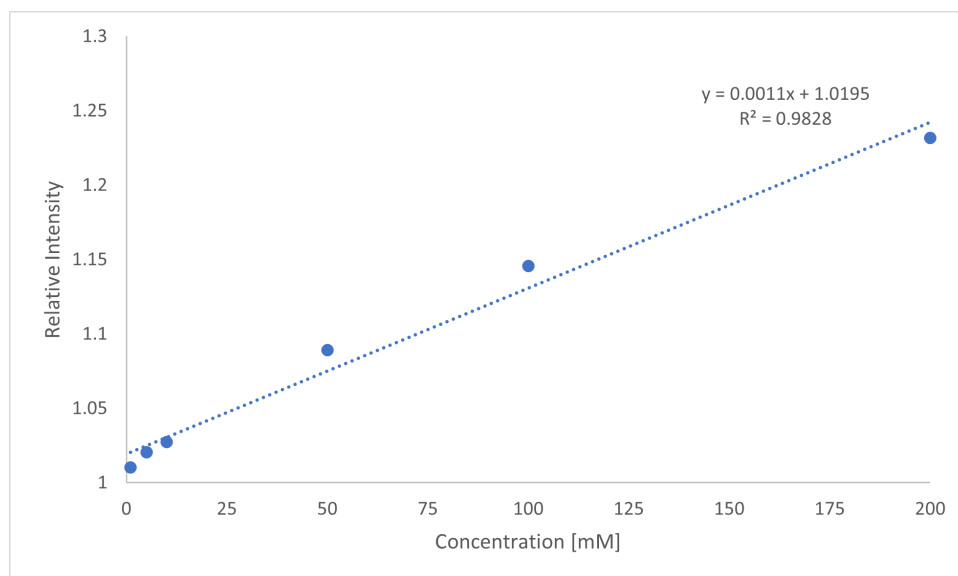
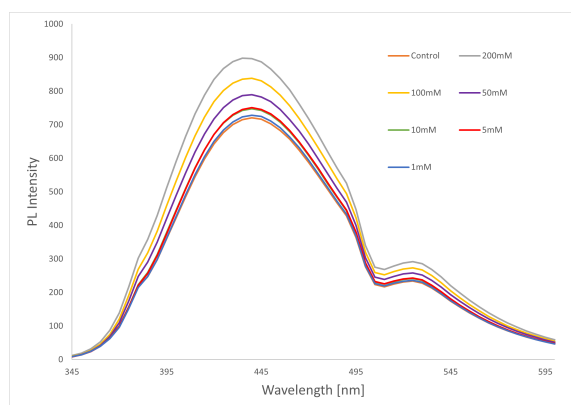


Figure 4.2.4: Relative increase in luminescence at the maxima for citric acid GQDs with amphetamine sulphate.

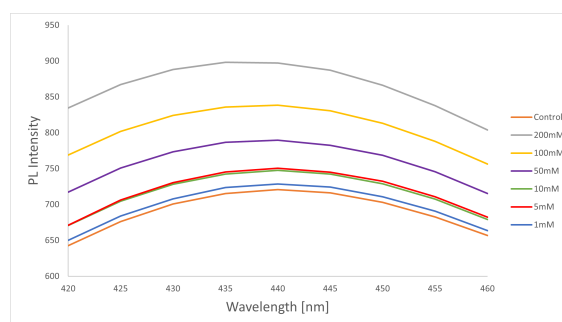
The two equations given by linear regression can be compared; $y = 0.0011x + 1.009$ for 2-phenylethylamine and $y = 0.0011x + 1.0195$ for amphetamine. They have the same rate of change as concentration of the analyte is increased. Knowing the equation of luminescence increase as a function of concentration is critical for any practical application of the GQDs as a sensor as this will allow the user to calculate the

concentration of the analyte from the luminescence increase. It should also be noted that the fact that these two curves are so similar would make it virtually impossible for a sensor based on these GQDs to distinguish between the analytes. Indeed it has been shown that this type of GQDs also have increased luminescence in the presence of morphine[14] as well. It is reasonable to believe that the GQDs would respond to most chemicals in the amphetamine family, though to what degree and in what manner (increased or decreased luminescence) would need further studies. Regardless these results show a clear response to amphetamine in the range 1mM-200mM.

In this section the results of the triplicate replication measurements will be shown. These results illustrate what some of the potential issues with using these **GQD!** as a sensor might be. The potential sources of error will be further discussed in the next section.



(a) Overall PL response of citric acid GQDs with amphetamine sulphate.



(b) Expanded version of fig.(a) around the maxima.

Figure 4.2.5: Averaged PL response of citric acid GQDs with amphetamine sulphate.

While the general shape of the response and the peak positions remain the same this graph has one very notable feature, the 5mM luminescence is higher than for the 10mM measurements. While this seems like a significant flaw in the functionality of the GQDs as a sensor it is most likely due to a change in temperature. It will be shown in the next section temperature can have a significant effect on the luminescence of the GQDs. As has been noted in the experimental section the samples were stored in a fridge. The measurements started with the lowest concentrations, but the the 1mM measurements were remeasured later in the day. It therefore seems probable that the 5mM result is colder than room temperature and so is higher than it would have been.

Here follows the plot for the maxima of the replication measurements with two standard deviations.

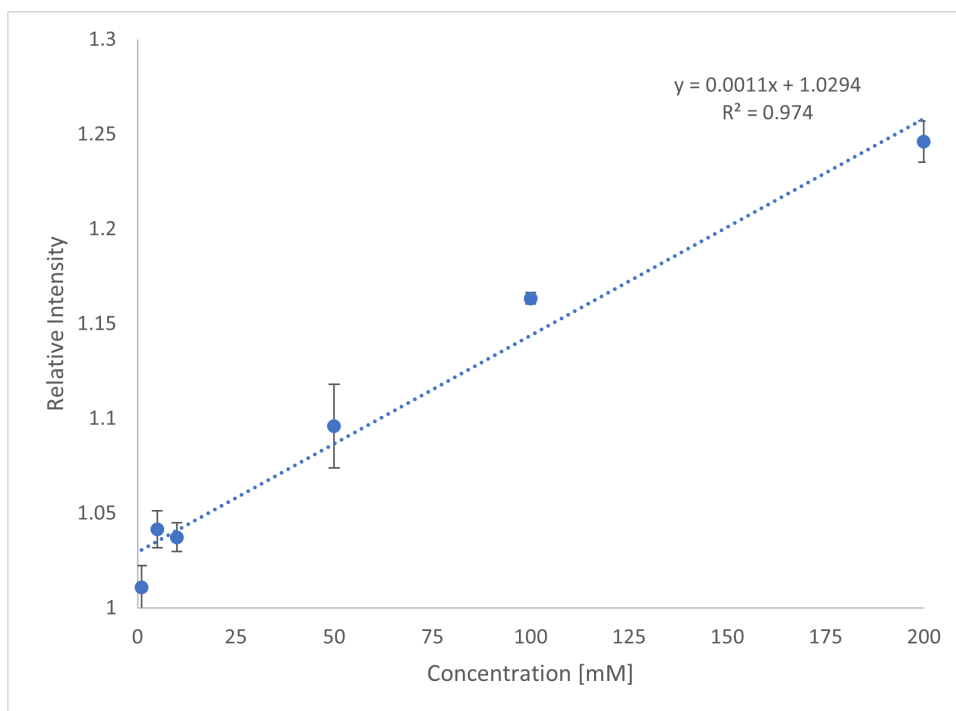


Figure 4.2.6: Average relative increase in luminescence at the maxima for citric acid GQDs with amphetamine sulphate.

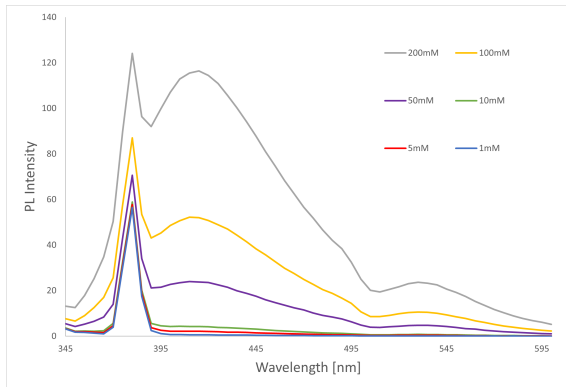
This shows a similar, but slightly different trend than the one presented in fig.4.2.4. Specifically the rate of change is the same but the intercept at zero is higher 1.0294 rather than 1.0195. It can also be seen more clearly that the values of the 1mM and the 200mM measurements lie noticeably below the trend line. This may be because at a concentration of 200mM the GQDs are reaching saturation, meaning that most of the GQDs are already bonded to amphetamine and so the probability of interaction goes down. This will cause the rate of change to decrease as well, until full saturation is reached. At 1mM the concentration may be near the detection limit of the GQDs. Indeed the standard deviation in relative intensity of the control is 0.01095. The 1mM measurement has an average of 1.01080 and a standard deviation of 0.00579. There is a large overlap of these two distributions and so it could be difficult to distinguish between control variation and a 1mM measurement. The measurements of 5mM however are well outside the range of the variation in control and so can be easily distinguished. It is thus reasonable to assume 5mM as a lower detection limit for the method of amphetamine detection presented in this report.

Furthermore it can be noted that the standard deviation in the 50mM measurement is far greater than for any other measurement. Since there is no particular reason for this measurement to deviate so much, this is most probably related to the practicalities

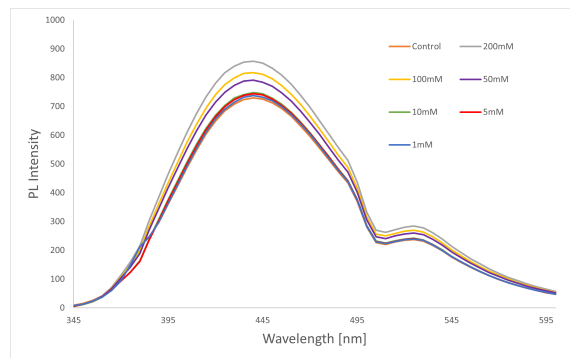
of pipetting and mixing of the samples in question. Many of the difficulties with acquiring accurate data for the GQD luminescence stem from the need for highly accurate measurements of the quantities of sample used. Even small deviations can cause inaccurate results since the change in relative intensity is rather small.

4.3 PL Error Sources

In this section the potential sources of error in the PL response of the GQDs as a sensor will be further investigated. The first of these is that amphetamine itself exhibits fluorescence. The PL response of just amphetamine sulphate in Milli-Q water at the same concentrations as those used in the GQD experiments was therefore measured.



(a) PL response of pure amphetamine in water.



(b) PL response of GQDs and amphetamine with the pure amphetamine response subtracted.

Figure 4.3.1: The effect of amphetamine fluorescence on the PL measurements.

As can be seen the amphetamine does indeed have a noticeable PL response to being excited by UV-light. The magnitude of this response however is clearly smaller than the change in luminescence that we have shown for the interaction between GQDs and amphetamine, as can be seen in fig.4.3.1b. Thus amphetamines own fluorescence can be eliminated as the primary cause of the luminescence increase.

The next error source is one that has been mentioned above, namely temperature. A simple measurement of the low concentration samples show that they can significantly change their luminescence in response to a change in temperature. The results below are from one measurement where the GQD and 1mM amphetamine sample had just been taken from the fridge at ca 4°C and the second measurement was taken later in the day when that same sample had reached room temperature at ca 20°C.

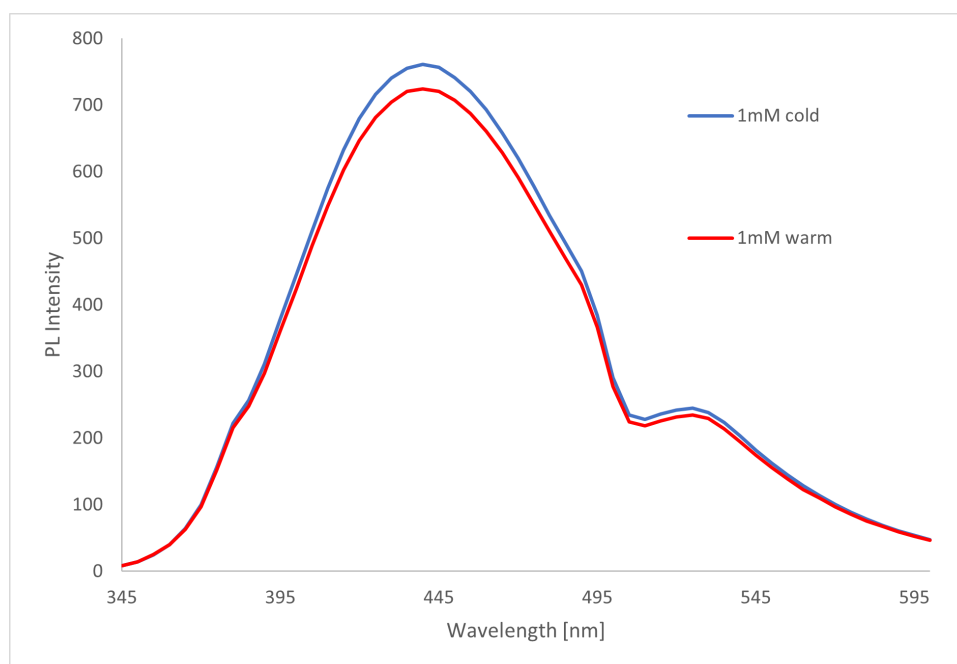


Figure 4.3.2: Comparison of the PL response for the 1mM sample for room temperature and near fridge temperature.

The colder sample has a clearly higher response than the warm sample. There is an increase of ca 5% in the luminescence of the cold sample. This type of shift can account for the higher response of the 5mM sample in the replication tests. Regardless temperature is definitely an important factor to keep in mind when using the GQDs as a sensor.

Finally it is known that the pH of the solution can affect the luminescence of the GQDs. Therefore each concentration of amphetamine was measured with pH strips. The results for all of these were that pH was 6.5 – 7.0. There is no significant change that would be likely to cause the increased luminescence. To further ensure that these results were accurate two of the high concentration samples and the control were also measured with an electronic pH-meter.

Sample	pH
Control	7.15
200mM	6.78
100mM	6.89

Table 4.3.1: pH results for electronic measurement.

Indeed a minor shift towards the basic can be seen with addition of amphetamine

sulphate. However all values are exceeding close to neutral and so highly unlikely to be the cause of the increased PL response we see in our experiments.

4.4 FT-IR

Analysis with Fourier transform infra-red spectroscopy (FT-IR) has also been performed. This technique shows absorbance peaks corresponding to chemical bonds and so it should be possible to find an interaction between the GQDs and the amphetamine. The results for the FT-IR measurements are shown below.

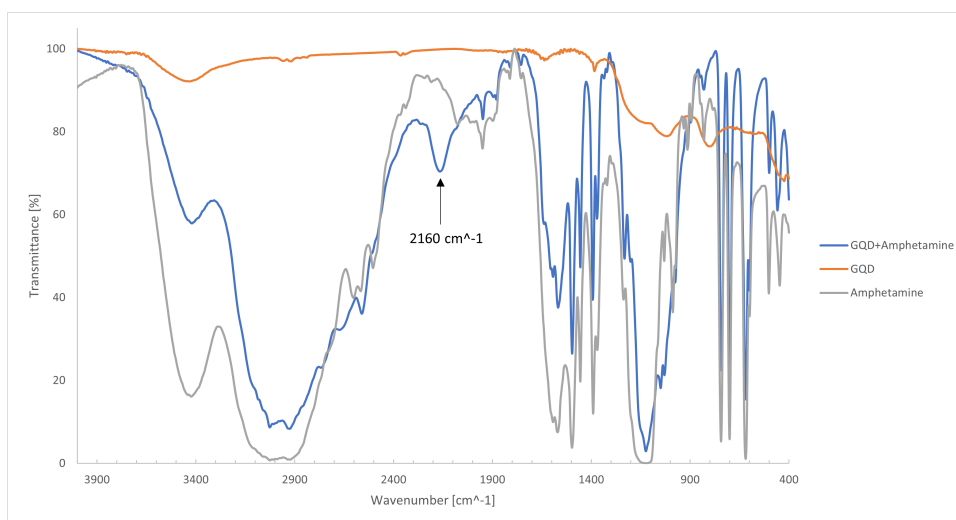


Figure 4.4.1: FTIR transmission for the individual samples of GQDs and amphetamine, as well as the mixed sample.

The amphetamine FT-IR curve is very similar to the one measured in [5]. It expresses all the expected peaks for amphetamine sulphate. The curve of the GQDs also shows peaks that correspond to expected bonds in GQDs, notably O-H stretching, C=C cyclic alkene stretching and C-H stretching and bending. These are all bonds should be present in the GQDs, in particular the significant peak from the C=C bonds of the hexagonal carbon rings that comprise the bulk of the graphene.

When looking at the result of the mixed sample it can be seen that it is very similar to that of the pure amphetamine sample. This is in part due to the high concentration of amphetamine in the sample. Also it is worth noting that the FT-IR curve of the amphetamine contains most of the peaks present in the GQD curve. This is because the amphetamine molecules contain most of the same chemical bonds including the cyclic alkene structure in its benzene ring. There is however one deviation that is only

present in the mixed sample, a peak at ca 2160cm^{-1} . This new peak could potentially indicate that some type of bond had formed between the molecules. This result is sadly not as clear as one might wish. Some other sources do show a small peak at 2150cm^{-1} for pure amphetamine sulphate[3]. Additionally when our colleges at RISE attempted to replicate our results they found the same peak in the pure sample. Both of these measurements were performed using attenuated total reflection(ATR) as opposed to measuring through a solid KBr wafer. This change in method should not affect the results, but the preparation method might. Determining whether the peak is caused by a genuine interaction between the molecules or is created by some part of the preparation method is however beyond the scope of this project.

Chapter 5

Conclusion

5.1 Summary

In this project it has been shown that GQDs synthesised by a simple and cheap process can be used to detect amphetamine. This is due to an increase in luminescence of the GQDs in presence of amphetamine. The detection limit found for this process is around 5mM or ca $920\mu\text{g}/\text{ml}$ of amphetamine sulphate. This limit is far higher than the one that Majid Masteri-Farahani et al.[11] found for methamphetamine, $1.5\mu\text{g}/\text{ml}$. This could be due to the GQDs having a much stronger response to methamphetamine than amphetamine and therefore being highly selective. Due to the similarity of the two substances however and the lack of an obvious mechanism that would generate such a vast change in behavior perhaps a more plausible explanation is a change in the medium of the solution. It is known that the solution that the GQDs are dispersed in can have a significant impact on their PL[10]. The experiments in this report were all done using pure de-ionized water as the solvent, where as the experiments performed by Majid Masteri-Farahani et al.[11] used phosphate buffered saline as the solution. It is possible that the buffer solution helped in limiting some reaction that in turn limits the interaction between the amphetamine or methamphetamine with the GQDs. Regardless the work in this project shows that there is a clear interaction between GQDs synthesised by citric-acid pyrolysis and amphetamine to a sufficient degree that they could with some further refinement be used as a sensing element.

5.2 Future Work

One clearly important and relatively simple experiment that should be done is whether a different solvent changes the results of these experiments. If such experiments are carried out it may also be possible to find a more exact detection limit as well as a more exact relationship between the concentration of analyte and the luminescence shift. It should also be tested with other drug analytes and contaminants to determine the selectivity. This will be critical to find if the GQDs can be used in real life applications. It may also be interesting to investigate microwave based techniques for synthesis. While the process presented in this project is simple, green and cheap a microwave assisted synthesis may be more scalable. Further it was found in our limited tests with such GQDs that they offered far greater luminescence and potentially sensitivity. They do however seem to be quite sensitive to light, in difference to the extremely stable thermally synthesised GQDs, which is why their use was abandoned in this project. The long term goal stated in the introduction remains of also integrating the GQDs as a sensor element in a micro-fluidic "device-on-a-chip".

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