BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Chemistry

DOCTORAL THESIS

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ABSTRAKT

Ve všech oblastech současného průmyslu zažívají pokročilé materiály extrémní romzmach, a to díky neustálé miniaturizaci součástek a elektroniky, vytváření chytrých a funkčních materiálů, vývoji nových terapeutických a diagnostických metod a v neposlední řadě zdokonalování a zefektivňování výrobních procesů. Významné postavení v tomto systému má sektor organické elektroniky, ve kterém řada technologických firem a investorů vidí velkou budoucnost.

K prokázání flexibility, všestrannosti a škálovatelnosti pokročilých materiálů byly syntetizované a zkumané zcela nové adamantanem substituované polythiofeny. Tyto polymery jako silné konkurenty komerčně využívaných materiálů ukazují, že oblast organické elektroniky dosud nedosáhla svých hranic. Byla provedena rozsáhlá charakterizace a studium nových polymerů. Pro rozšíření záběru výzkumu byla navržena, připravena a zkoumána řada zcela nových fotospfotospínačů na bázi para-bis(2-thienyl)fenylenu jako dalšího typu pokročilých organických materiálů.

Podle aktuálních trendů byly zkoumány i perovskitové materiály. Byla vyvinuta a optimalizována zcela nová, k životnímu prostředí šetrná, nízkonákladová a snadno do velkovýroby tranformovatelná metoda pro přípravu čtyř nejčastěji používaných hybridních perovskitových makrokrystalů. Tato metoda by mohla být odpovědí pro průmyslovou výrobu vysoce kvalitních, bezchybných a symetrických perovskitových krystalů a zařízení. Na druhou stranu byly zkoumány různé druhy perovskitových nanočástic za účelem zlepšení stability a vlastností. Byla zkoumána základní stabilizace za pomocí ligandů se zaměřením na ligandy na bázi adamantanu a pro zlepšení vlastností byla navržena stabilizace za pomocí polymerní matrice. Jako vodivá matrice pro perovskitové nanočástice byly použity adamantylem substituované polythiofeny ve formě tenkých vrstev.

ABSTRACT

Advanced materials in all areas of industry have experienced an extreme boom in recent years due to the constant miniaturization of components and electronics, the creation of smart and functional materials, the development of new therapeutic and diagnostic methods, and finally, the improvement and streamlining of production processes. An important position in this system is in the sector of organic electronics, in which many technological companies and investors see a great future.

To prove the flexibility, versatility, and scalability of the advanced materials, completely new adamantyl-substituted polythiophenes were prepared and investigated. As a strong competitors to commercially used materials, the novel polymers show that the field of organic electronics has not reached its borders until now. The wide characterisation and study of the new polymers was provided. To extend the research area, a series of completely new photoswitching molecules based on para-bis(2-thienyl)phenylene were designed, prepared, and investigated as another type of advanced organic materials.

Following the actual trends, even perovskite materials were investigated. A completely new, environmentally friendly, low cost, and ease-of-use scalable method was invented and optimized for four mostly used hybrid lead-halide perovskites macro crystals preparation. This method could be the answer for the industrial production of high-quality, defect-free, and symmetrical perovskite macrocrystals. On the other hand, different kinds of perovskite nanoparticles were investigated to improve stability and properties. The basic ligand stabilisation was examined, focusing on adamantyl-based ligands and for improving properties, the stabilisation by polymeric matrix was designed. Adamantyl substituted polythiophenes were used as conductive matrix for perovskite nanoparticles in the form of thin layer stabilisation.

KLÍČOVÁ SLOVA:

adamantan, polymer, thiofen, polythiofen, poly(3-hexyl)thiofen, fotospínače, perovskity, nanokrystaly perovskitů, nanočástice, polovodiče, ligandy, mikrovlnná syntéza, organická elektronika, optoelektrické vlastnosti, optoelektronika

KEY WORDS

adamantane, polymer, thiophene, polythiophene, poly(3-hexyl)thiophene, photoswitches, perovskites, perovskite nanocrystals, nanoparticles, semiconductors, ligands, microwave synthesis, organic electronics, optoelectric properties, optoelectronics

CONTENT

Aim of the dissertation thesis

The dissertation thesis aims could be divide into two areas. Firstly, design, synthesis, and characterisation of advanced organic materials with implemented adamantane skeleton suitable for use in the field of organic electronics. The first goal is to design the structures according to the source of the literature sources and the next step is to prepare several synthetic pathways for the preparation of materials. The new materials need to be characterised and the possibility of use for the field of organic electronics needs to be proved. Thiophene-based materials were chosen for this part of the research and two very interesting fields of application were chosen, organic conductive polymers and organic photoswitching materials.

The second aim is preparation and characterisation of hybrid perovskite structures. This part consists of preparation of perovskite macrocrystal and synthesis of perovskite nanoparticles. For the perovskite single crystals, the suitable method is necessary to discover and optimise the symmetricity, shape, and properties of the crystals. In the field of nanoparticles, research on preparation and stabilisation techniques should led to most suitable technique and stabilisation ligand.

Finally, the connection of the previous two parts closed the circle and the work by applying the perovskite nanoparticles to the organic conductive matrix, to stabilise the nanoparticles and improve the properties of the advanced functional materials.

1 Introduction

In all fields of industry, there has been a technological boom of advanced materials in recent years, because of significant miniaturisation of devices, smart and functional materials development, research in a field of new diagnostic and therapeutic methods, and availability of new advanced production processes. Almost 7.26 billion smart phones are active at the moment, and average lifetime of people is the highest in history thanks to modern therapeutic procedures and materials [1,2]. The high importance of the field of organic electronics shows the interest of the biggest technological companies and investors. According to IDTechEx, infestations of technological giants in this field will be over 7 billion dollars for each company per year in production of Organic Light-Emitting Diode (OLED) devices, printed devices, organic photovoltaics, flexible organic electronics, modern diagnostic devices, etc. [3].

There are materials available in the industry which are based on complicated complex organometal compounds and have problems with low efficiency, poor stability, or poor quantum yields of solid-state fluorescence. Therefore, there is an effort to eliminate these downgrades at the molecular level, by modifying parameters such as rotation angles, rigidity, planarity and π- interactions among molecules [4]. That is the point when modern organic materials come on stage and take advantage of individual properties of organic molecules and their ability to interact with electromagnetic radiation, electromagnetic field, or electric current. Thanks to molecular tuning of properties, it is possible to miniaturize functional devices like in photovoltaic panels, OLEDs, or organic thin-layers transistors. Organic compounds with an appropriate structure and organization can transport electrons and behave as semiconductors. With their electrical properties, in the right application they can compete with inorganic materials [5].

One of the most used modifications is the side chain design, which can be made at the molecular level, or at the macromolecular level as well. For example, the implementation of bulky side chains like adamantane in organic molecules may have a strong impact for application in organic electronics. Adamantane is known as a highly symmetric molecule with an inert and extremely stable skeleton [6]. Over the last period, it has been widely used in different fields, from pharmacy to organic electronics. In the area of organic electronics, it is used for improving the stability of molecules or polymers and tuning their electrical and optical properties [7]. Generally, it is known that, in the case of optoelectric devices, it is possible to modify the wavelength of photoemission by substitution on the main chain and produce multicolor diodes [8,9,10]. Therefore, the side-chain modification is so important parameter in this field not only from the point of stability or solubility but also from the point of optical properties. Moreover, the hydrophobicity of

adamantane is very important to adjust the polymer properties and processability. As a pending group, it can improve solubility in organic solvents, and in addition, the adamantane skeleton can protect molecules against oxidizing agents or against elimination reactions [4]. As mentioned above, adamantane is a highly thermally stable molecule and it may pass on thermal stability as the pending group to molecules or polymers [11,4]. However, there are polymers with high thermal stability like polythiophenes and polyphenols moreover with perfect electrical properties, but the huge limitation is their poor solubility, processability, devices fabrication and with it connected problematic synthesis. Therefore, thanks to side chain engineering, there is a possibility of providing many types of materials directly modified for further application [10,12].

However, apart from polymers, there is a significant and completely different group of novel materials called perovskites, which is getting to the front of interest nowadays. Research groups from all over the world focused their aim on this perspective type of material with unique properties. Moreover, the combination of perovskites with other functional materials promises huge leap in the field of organic electronics and solar cells [13]. Metal halide perovskite-based materials have emerged as a promising future in the form of semiconducting nanoparticles (NP) and nanostructures due to their electrical and optical properties [14]. It is possible to prepare various low-dimensional halide perovskite nanostructures including quantum dots (QD) [15], nanocrystals (NC) [16], nanowires [17], or nanocrystalline thin films [18] to bring fruitful progress in optical and electronic applications, due to their unique quantum confinement effect, a high photoluminescence quantum yield (PLQY), large surface-to-volume ratio, and optical tenability [19]. Another highly important form of perovskite materials are single crystals, applicable for solar cells or detectors, but in the case of macro crystals there is a significant problem with preparation and processability, resulting in troubles during device fabrication [20].

2   Molecular photoswitches

There is a great area of application of advanced organic materials, connected to the field of biomedicine, and recently research in this area has focused, apart from others, on photoswitching molecules [21]. The term molecular photoswitch contains a group of chromophores with the ability to reversibly switch between two or more isomer forms induced by absorption of light with specific wavelength. Many physiological processes in living organisms, such as organisms like sight or photosynthesis, are based on photon absorption by the chromophore in the protein structure, resulting in a change in the protein conformation [22]. Based on these physiologically natural photoswithes, it is possible to design

artificial functional molecules sensitive to light to control or moderate a wide range of biological mechanisms like transcription, translation, protein quarter conformation, enzymatic activity, or membrane transport. The majority of photoswithes are based on UV excitation mechanism, but the research lately has focused on higher wavelengths of electromagnetic field because of better biocompatibility. Moreover, it is necessary to provide good solubility in water systems, non-toxicity and endurance against hydrolysis, oxidation, reduction, and photobleaching [23, 24].

One of the main mechanisms used for photoswitching is double-bond cis / trans isomerization, which can be observed at azobenzenes (Figure 1→4) or stilbenes (Figure 1→5) as the noticeable change of the molecule. The second mainly applied mechanism is based on 6π electrocyclization of trienes which leads to charge redistribution in molecules like spiro-pyrenes (Figure 1→6, 7) or fulgides [25,26].
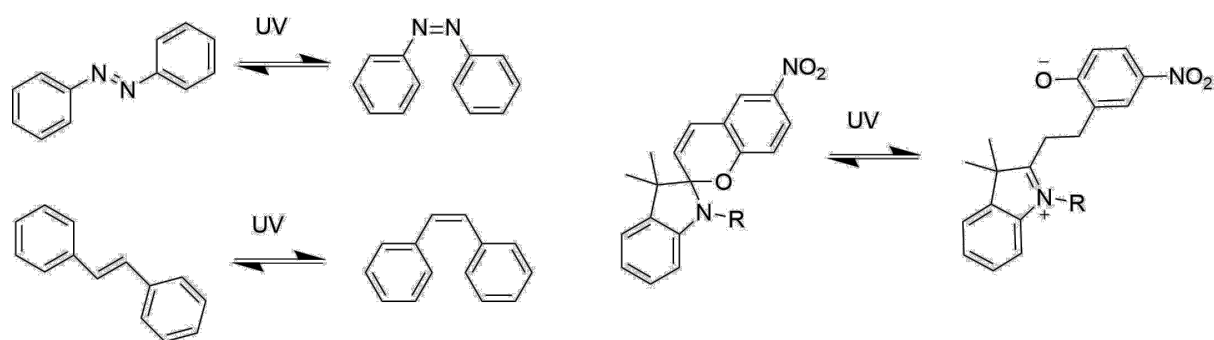
Figure 1: Main mechanisms used for photoswitching [26]

2.1 Condensation reactions

In case of every new material, there is the necessity of a good, reproducible and up-scalable synthetic or preparation method. For photoswitching molecules, it is possible to use condensation reactions [27]. This type of reaction is inspired by biological system because many biochemical reactions are basically the condensations, for example, condensation of two amino acids, or a huge amount of esterifications. Condensation reactions are generally described as the reaction where two molecules are combined to form one single molecule and a small molecule is produced such as water, ammonia, and others [28].

2.1.1 Imine preparation by condensation reactions

The imine preparation is a well-known reversible process initiated by nucleophilic addition of the primary amine to the carbon atom of the carbonyl group. Subsequently, the proton is transferred to carbonyl oxygen and the formation of carbinolamine, the neutral amino alcohol. The next step depends on used acid which protonate carbinolamine oxygen to create good leaving group which is eliminated as a water molecule. The last step consists of deprotonation of the nitrogen atom to produce a neutral imine product. The biggest problem of imine condensation is the reversibility of the reaction, which results in an equilibrium state and a low product yield. However, the reversibility and equilibrium state are dependent on the water present, so by constant water removal, the balance of the reaction can be moved to the product side [24].

The big improvement in reaction yields, time consumption, and up-scalability for mass production can be made by involving microwave irradiation. The research team of E.C.Border described a novel procedure for imine condensation in a microwave reactor for a wide range of functionalized and unfunctionalized imines and a whole series of imine derivatives with high yields was prepared [30]. This method provides fast conversion, no workup or purification, and quantitative conversion. The reaction kinetics was moved to the product by removing water using 3 Å molecular sieves and by microwave irradiation with high yields up to 100 % [30].

2.1.2 McMurry condensation reactions

The second condensation reaction with the ability to produce an unsaturated or conjugated system is the McMurry reaction. The reaction might be described as a reductive dimerization of carbonyl compounds that produce alkenes. The reaction is initiated by single electron transfer from the alkali metal atom to the carbonyl group of substrates, where the similarity to Pinacol coupling can be seen. In the second step, low-valent titanium reagents take part in oxygen removal, resulting in elimination and final alkene [31,32].

The McMurry reaction is widely used in the preparation of unsaturated photochromic derivatives such as dithienylethenes, *N* substituted dihydropyrroles or various advanced and complex molecules [33]. Moreover, it is possible to apply this reaction for polymerisation and produce homopolymers and copolymers from dialdehydes by McMurry polycondensation.

The main drawback of the reaction lay in low regioselectivity, mainly in mixed condensations [34]. In case when two different substrates are involved in reaction, there is the possibility of a mixture of coupled products, and it can be partially eliminated by excess of one substrate and change in reducing agent and temperature. On the other hand, if two substrates with sufficiently different reduction potentials are used, it is possible to provide condensation in an equimolar number of substrates [34,35].

3   Organic conducting polymers

Apart from biologically inspired products of condensation reaction, the conducting organic polymeric materials have received much attention over the past several decades because of their high potential for application as an alternative to their inorganic counterparts. Electrical, optical and electrochemical properties, such as those of inorganic semiconductors and conductive metals, predict a wide range of applications [36,37].

Significant added values of conducting polymers are mild synthetic conditions, excellent processability, chemical and structural diversity, structural flexibility, high-precision molecular design, and tuneable optical and electrical properties on the molecular level. Advances in manufacturing processes have allowed the preparation of versatile materials, layers, nanostructures, and nanomaterials with excellent performance and unique properties for various applications like organic electronics, optoelectronics, sensors, or energy storage devices [38].

Till now, polythiophenes are the most widely used conducting polymers, which exhibit remarkable and unique environmental and thermal stability, mechanical strength, magnetic, electrical, and optical properties, a wide range of application, and last but not least low-cost synthesis. The main disadvantage of unsubstituted polythiophene and generally unsubstituted conjugated polymer system is, as mentioned in the introduction, very poor solubility and processability because of strong interchain interactions. The unsubstituted polythiophene backbone is semi-flexible in solution, which results in strong aggregation of polymer chains leading to low solubility and processability problems, low mechanical flexibility, and poor optical and electrical properties. Due to the dependence of its conjugation length on intra- and interchain interactions, the conjugation length of unsubstituted polythiophene decreases with its aggregation [39,40].

Poly(3-hexylthiophene) (P3HT) prepared thanks to the functionalisation of the side chain in the β-carbons is the most important material in recent decades used for optoelectronic devices such as OFETs, OLEDs and organic photovoltaic solar

cells [41]. P3HT is till now unbeaten worldwide used conducting polymer; therefore, it is enormous challenge for many researchers to compete and overcome its electrical, optical properties, its stability and processability.

The shortcomings of the optical properties of polythiophene can be eliminated by incorporating specific bulky groups as pending substituents in the main polymer backbone. The bulky groups effectively increase the separation distances between individual polymer chains to restore optical properties as in solution even in solid-state, crystal structure, or polymer films. The photoluminescent properties of these modified compounds are independent of the environment. However, very large intermolecular separation of molecules is responsible for the drop or complete loss of electrical semiconducting properties. The use of adamantane in this type of chemical modification may represent a reasonable compromise between photoluminescence efficiency and electric semi-conductivity [42,43].

Adamantane as the smallest diamantoid lends exceptional properties to molecules. Adamantane itself is the most stable saturated molecule with such small molecular weight with one of the highest melting points of all known hydrocarbons and extreme mechanical, chemical stability, optical transparency, and biocompatibility. However, the most exceptional is the ability to self-organize into crystals with which was used to reinforce packing of p-conjugated systems in the solid state to improve optical and thermal properties [4]. The above-mentioned properties make adamantane an excellent side group to dramatically improve the properties, characteristics, and lifetime of polythiophene-based functional devices.

4 Microwave irradiation as the key to modern advanced materials

Microwave reactors allow extremely fast heating of the reaction mixture. The reactor makes it possible to achieve high pressures and temperatures that exceed the boiling point of the solvent used. The use of a closed system, high temperatures, and pressures dramatically reduces the reaction time, which can be reduced from tens of hours to several minutes. The acceleration of the reaction is based on Arrhenius' law, which states that the reaction rate doubles with each 10 °C increase in temperature. Performing reactions requires optimization, and for optimal reaction conditions, a series of experiments must be performed to achieve excellent yields, good selectivity, and purity. The advantage lies in the time saved when it is possible to perform a series of these experiments in one day. By achieving ideal conditions such as a suitable temperature gradient, a suitable length and sequence of heating and cooling steps, and the length of the whole

reaction, it is possible to obtain high yields and product purity, and the method can then be applied to other reactions of similar type [44].

The major advantage of microwave irradiation is undoubtedly that dielectric heating is electric energy converted into kinetic energy of particles, which is ultimately converted into heat. Against traditional heating mechanisms where reaction mixtures use a hot oil bath as a heat source and the transfer of heat is made by convection, which causes different temperature zones and very hardly controlled heating [44,45]. Microwave irradiation heats directly molecules and their dipoles/ions in the whole volume at the same temperature with no differences in temperature near the vessel wall and in the centre of reaction. In addition, it makes molecules oscillate and collision, which helps reaction kinetics [44,45].

5   Advanced hybrid organic-inorganic materials for organic electronic

The organic-inorganic hybrid perovskites seem to be a strong competitor for conventional silicon-based electronic devices. Halide-based perovskite materials are considered the most studied hybrid semiconductors and undoubtedly are the phenomenon of today's semiconductor period. The essence of its success comes from its original timeless properties that can be used in applications such as photovoltaic cells [46,47,48], light emitting diodes [46,49], lasers, ultraviolet-to-infrared photodetectors, X-ray and γ-ray detectors [50,51]. The wide range of possible applications is due to their superior properties, which are suitable band gaps, high absorption coefficient, tuneable optical properties, long and balanced electron–hole diffusion lengths, and low exciton binding energy [52].

Organo-lead halide perovskites are hybrid materials with the general formula $APbX_3$, where A is a monovalent organic cation (for example methylammonium = MA or formamidinium = FA) and X is a halide anion. The most discussed application for halide-based perovskites is their use for solar cells [46]. The very first attempt to use halide-based perovskites as dye-sensitized solar cells came from Kojima *et al.* in 2009. Nowadays, the power conversion efficiency of fabricated devices reaches up to 30 % and exceeds the efficiency of solar cells used today in polycrystalline silicon films [53].

5.1   Organic lead halide perovskite macrocrystals

In recent years, there has been enormous progress in perovskite chemistry and in the production of functional devices based on hybrid perovskites. The main problem remains the production of large single crystals, low stability, and the

effect of many external factors during preparations, which caused the incomparability and irreproducibility of the results. Although these hybrid systems are subject to intense research and the clarification of the underlying principles of their behavior, continual industrial methods for the synthesis of these materials are needed. Furthermore, an early broad-spectrum technological application for various types of components can be expected, so the simplicity of its preparation will play a crucial role [48].

There are several approaches to how a single perovskite crystal can be growth; the possibilities were summarized by R. Babu *et al.* in a review [54]. The ITC method presented by Saidaminov *et al.* [48] uses bad solubility of perovskite precursors and the halide anion, both in the form of their salts in a precisely defined molar ratio with increasing temperature. This method is the most convenient because it is not as time-consuming as other techniques. Crystal growth is provided in higher temperatures and temperature graduation must be regulated very precisely, and conventional forms of heating have very unreproducible experimental data and are very rarely applicable in an industrial field. Crystal growth quality depends on the temperature rising speed, number of heating steps, the used heating medium, and many other external factors and cannot be completely controlled and monitored. The effects of external factors mostly led to production of fusion crystals, crystal clusters, or crystal fields completely inappropriate for application in electronic devices. Another very successful method is preparation via seed crystals, where selected seed (small single crystal) is placed at the bottom of the precursor solution of a second bottle, followed by heating. The main disadvantage of this method is the presence of defects and time consumption [54].

5.2 Organic lead halide perovskite nanoparticles

Over the last decade, organic lead halide perovskite nanoparticles have gained considerable attention because of their unique semiconducting and optical properties. Current synthetic strategies allow the preparation of a wide range of low-dimensional organic lead halide perovskite nanostructures including quantum dots, nanocrystals, nanowires, or nanocrystalline thin films. Nanostructures provide a unique quantum confinement effect, high photoluminescence quantum yield, a large surface-to-volume ratio, and optical tenability applicable in the field of LEDs, lasers, solar cells, photodetectors, and resistive switching memory devices [55].

The essential role in the synthesis of colloidal perovskite nanoparticles is stabilizing the crystal growth by ligands and surfactants. The oldest and most researched area is ligand-assisted precipitation, which uses precise ligand

engineering to tune the properties of a specific application. This method is cost-effective, wide-spread, and easy to scale up. The method was first reported in 2014 by Schmidt *et al.* on methylammonium lead bromide nanoparticles using long chain carboxylic acids and long chain primary amines. Since then, huge amount of different caping agents and different applications have been published. The main objective is to study the influence of the choice of solvent system, capping agents, precipitation temperature, and the ratio of precursors on colloidal stability and physical properties [56].

5.3 The smart use of host matrices for organic lead halide perovskite nanoparticles stabilisation

According to the above-mentioned and in correspondence with the information from the introduction, the preparation of materials with homogenous morphology and distribution resulting in reproducible properties is a big challenge. Moreover, nanoparticles have a tendency to aggregate leading to the loss of their optoelectrical properties. The traditional stabilisation methods for colloidal solutions by caping agents suffer from the use of long-chain insulating ligands and low concentration, which is unsuitable for film creation. The solution brings about the use of functionalised materials such as organic polymer matrixes or hybrid inorganic porous materials, which will not only prevent aggregation, but will also add functionality, stability against humidity, air, light, or heat and bring better properties for specific applications [57].

6 Results and discussion

6.1 Condensation reactions

The main para-bis(2-thienyl)phenylene backbone for formylations with "in" substituted alkyl chain at the thiophene ß position was prepared with modified synthetic steps inspired by our published procedure [4,58,59].

There are several approaches for aromatic compound formylation, and the most used approach is Vilsmeier-Haack formylation. This direct formylation was provided on alkylated para-bis(2-thienyl)phenylene by the mechanism of electrophilic aromatic substitution on a position of thiophene ring. The disadvantage of the reaction was the poor selectivity when the formylation on the a position of second thiophene ring provided a biformylated product. It was found out that the use of more concentrated mixtures of Vilsmeier-Haack reagent makes

the reaction much faster and much more selective, because the electrophilic substitution on the second thiophene ring runs much slower, which is caused by the deactivation of the conjugated system by the first formyl group. Very important is controlling the pH of the water phase during the workup to complete the hydrolysis of the complex to aldehyde (Figure 2).
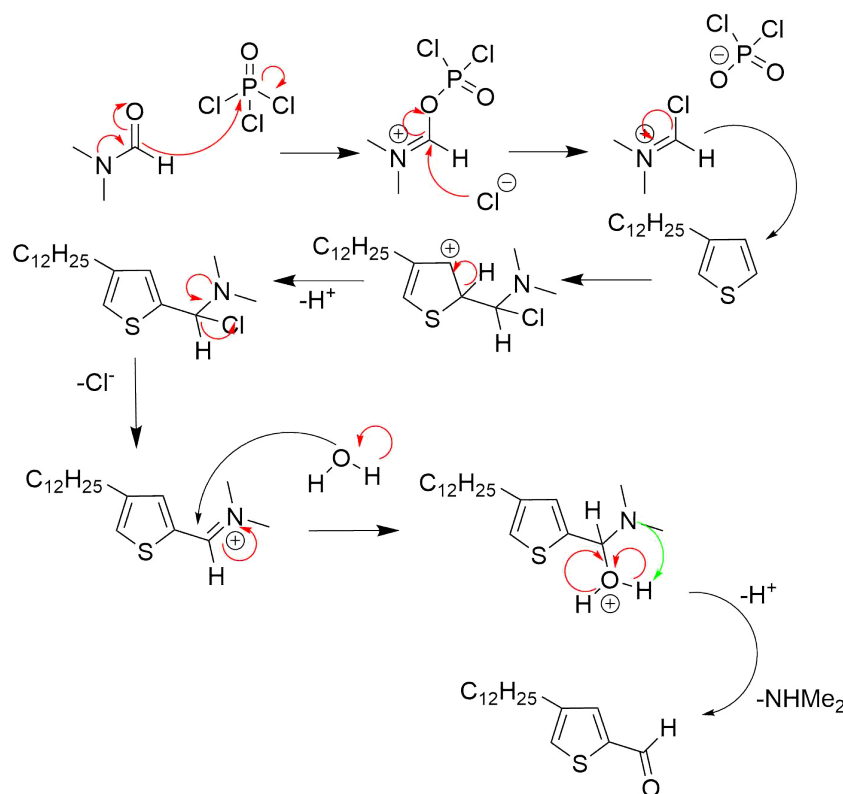

Figure 2: Mechanism of Vilsmeier Haack reaction

The derivatives with the adamantyl-ethyl side chain were prepared by the same procedures described in the diploma work [59]. The formylation of adamantane derivatives was provided according to previous results mainly by Vilsmeier-Haack formylation, but the yield was much lower around 50 % in comparison with dodecyl derivatives. The lover results could be caused by strong steric hindering around a position of the thiophene. Moreover, the reaction mixtures were more diluted because of the lower solubility of adamantane derivatives.

6.1.1 Imine derivatives preparation

The imine condensation was provided by two different approaches, the conventional solution-based method and the alternative microwave-assisted method in the form of melt. The microwave-assisted method provided much higher yields in extremely short reaction times. Higher yields are in good correlation with the reaction mechanism. During the reaction, the equilibrium

between starting material and products forms, and to move equilibrium to the product it is necessary to eliminate produced water. In the classical solvent-based approach it is done by Dean-Stark apparatus, but in the microwave approach using melt without solvents, the water generally evaporates and condenses on the reactor cap, where it can be easily removed. The reaction time was 1 hour only, but for using the Dean-Stark apparatus and solvent-based approach it was more than 24 hours. Generally, it can be said that this microwave assisted melt-based condensation provides a very economic, environmentally friendly, fast, and reproducible synthetic way. It was possible to use this method for a wide range of imine condensation with good results.

The main difference between prepared derivatives with different alkyl chains was thermal stability. Generally, molecules with adamantane side chain were over 180 °C however in the case of dodecyl substituted molecules, only around 50 °C. This corresponds to the generally known ability of adamantane incorporation to boost the thermal stability of the molecules. In the case of the aminobenzothiazole derivatives there was a huge lack of stability, and it was impossible to purify a suitable amount for further optical study or to provide optical study without decomposition.

6.1.2 Imine derivatives characterisation

The prepared imine derivatives, as mentioned in the beginning, were focused on the field of photoswitches. To confirm their ability to photoswitching, the photoinduced isomerisation was performed in solution at 365 nm irradiation by dynamic absorption spectroscopy. It was shown that molecules possess fast E/Z photoisomerization conversion, and it was proved that molecules are T-type photochromic switches due to fast thermal Z/E relaxation in the dark phase.
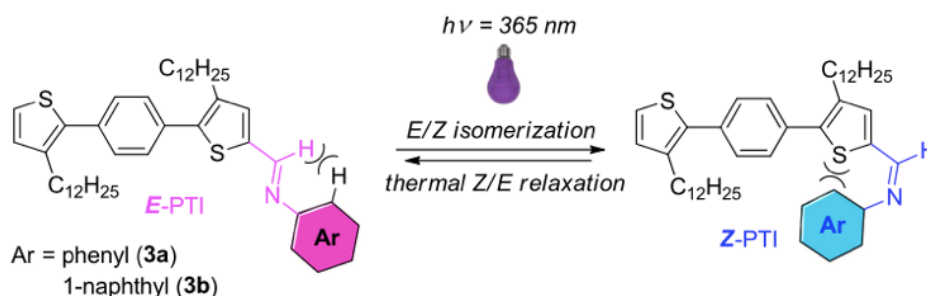

Figure 3: Presentation of E/Z switching of molecular photoswitches under UV irradiation

6.1.3 Imine derivatives conclusion

The prepared imine derivatives have promising results in the field of photoswitching materials. The major advantage is simple, high yield, and solvent-free synthesis using microwave irradiation. The optical study and DFT calculations were provided at the prepared molecules. The series of photoswitchers, were prepared and published according to the positive results of the first measurements.

6.1.4 McMurry condensation products

The McMurry reaction uses low-valent titanium species for the coupling of molecules. It is necessary to understand that, when using highly reactive reductant for creating the low-valent titanium reagents, the reagent must be generated before adding coupling substrates, as was done in above-mentioned experiments. There are a huge number of combinations of reagents that can be used to generate low-valent titanium compounds, which can be optimized directly to the used substrates. In our case, it was commonly used $TiCl_4$ and lithium. The reaction is usually provided in THF or another ethereal solvent, but solvent choice could dramatically affect reaction selectivity.

6.1.5 McMurry condensation products characterisation

The two new condensates were prepared according to the McMurry reaction procedure by using a widely used combination of reagents. Not all structures of the products were confirmed by NMR or GC/MS analysis. In the case of pentacene chinone it was impossible to prepare product in THF because the substrates begin to precipitate immediately; even at higher temperatures it was impossible to dissolve the pentacene chinone. The only product of the reaction was the homocoupled product of adamantanone and the starting material that did not react, pentacene chinone. It could be solved by solvent exchange or by modification of the pentacene structure by solubilising units like alkyl chains. The product of fluoenone and adamantanone coupling provided satisfactory results according to the GC/MS analysis. The product was confirmed and is supposed to be used as a monomer for further preparation of thiophene-based oligomers and polymers.

6.2 Thiophene based polymeric materials

6.2.1 Polymer synthesis

Due to unsatisfactory results with oxidative coupling polymerisation with iron (III) chloride, chemical polymerization based on cross-coupling reactions was used for all polymer preparation. Monomers were prepared by Kumada cross coupling according to the literature [4]. Adamantyl-substituted polythiophenes were prepared by two different approaches. The first approach used monobrominated monomers, for the polymerization reaction, the monobrominated monomers were converted to lithium salt on the opposite position of bromine. At very low temperatures were the monomer converted to magnesium salt and a chain cross-coupling polymer reaction was provided. The main disadvantage of this reaction was the preservation of very low temperatures and careful manipulation with lithium compounds. The regioregularity of the products was not good, according to NMR. In both cases, it was possible to follow unresolved wide multiplets in the aromatic region instead of a nicely resolved singlet of one proton bonded to every thiophene ring. Moreover, the molecular weights were low, too, so it can be told that the molecules were rather oligomers around 2 kDa.

On the other hand, second approach starts with dibrominated monomers, selectively converted to Grignard reagent at -5 °C and then the regioregular polymer was prepared at room temperature. Against the previous procedure, there were mild reaction conditions. From the point of view of products, the reaction with mild conditions surprisingly provides higher molecular weights and much more regioregularity.

6.2.2 Polymer characterisation

One of the most important features of polymeric materials is the molar mass. Using the GPC system, it was estimated that the molar mass of the prepared polymers in higher fractions was up to 15 kDa. The polydispersity of the prepared materials was around 6 which is in good agreement with the typical polydispersity range (1.5 – 20) for chemical chain reaction polymerisation.

The stability was investigated by DSC and TGA measurements. On the TGA data can be seen thermal stability up to 250 °C, and till 250 °C there is only insignificant weight loss of few % which could be caused by humidity or other volatile residue from synthesis. In the next part up to 400 °C can be recognised

for slow weight loss of about 10 %, which turn into fast weight loss after 400 °C pointing to material degradation. The material is depredated in two steps, first over 400 °C and second over 550 °C. To characterise new materials with precision, the DSC measurements were performed. On the basis of the results, it is clear that the sample exhibits high thermophysical stability up to 300 °C. There is no phase change in the measured range. The results are in accordance with the exceptional ability of adamantane to self-organise and its enormous durability [4].

Optical properties of novel adamantane substituted polythiophenes were investigated using ultraviolet/visible (UV/vis) spectroscopy and luminescence spectroscopy (Figure 4). The absorption spectra were measured in both solid-state/thin films and in solution. There is visible significant red shift in case of P3HT between the thin layer and the solution sample. For the adamantalymethyl sample there is no noticeable red shift, these results are in good agreement with predicted torsional deformation rigidity of used adamantalymethyl side chain.

The adamantalyethyl sample red shift is more noticeable and this is again in accordance with predicted properties, when ethyl group offers more free space for torsional deformations and rotations. For comparison, the optical spectra of reference P3HT sample were measured where the big difference in the absorption spectra of solution and thin layer is present, and the width and shape of the peak have also changed. There are almost no noticeable changes for novel studied polymers between thin layer and solution spectra, which corresponds to the idea of the same interactions of the adamantane side chains in the thin layer and in solution.
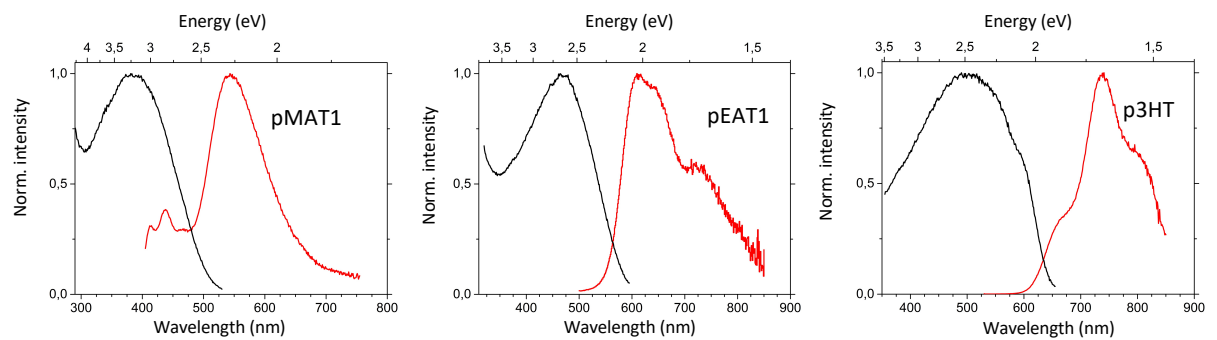
A: The absorption spektra in solution; thin layer; thin layer after thermal purification
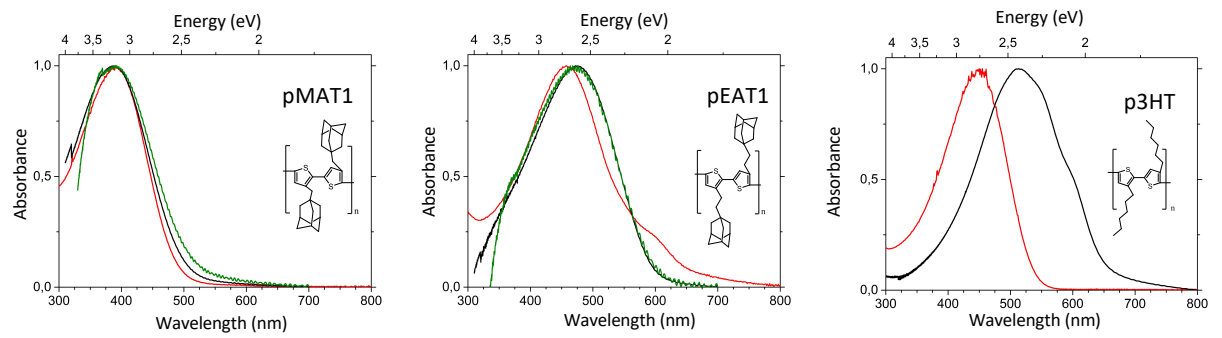
B: The solution emission spektra; excitation spectra
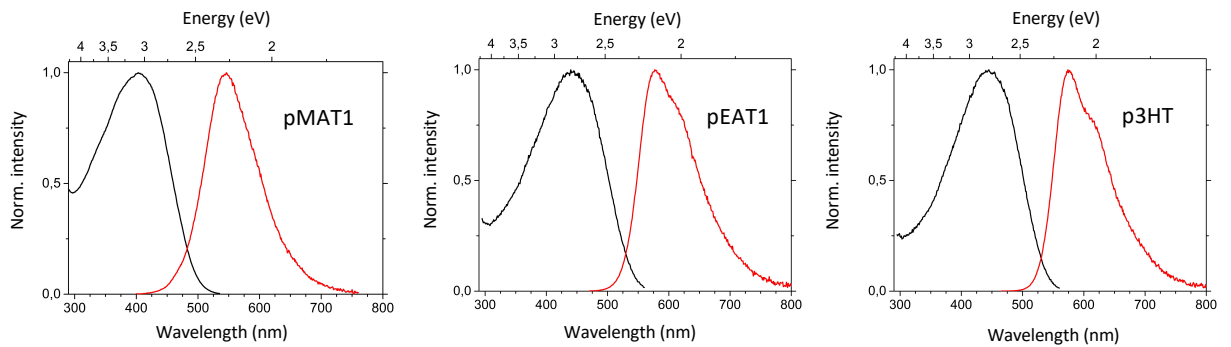
C: The thin layers emission spektra; excitation spectra

Figure 4: The absorption (a), excitation and emission spectra of polymers in solution (b) and thin layer (c)

To study the effect of bulky admantane substituent on the optical behavior of novel materials, the emission and excitation spectra were measured. Both polymer samples exhibit in solution a broad spectrum with single emission peak at 2.27 eV (546 nm) in the case of PMAT and 2.14 eV (577 nm) for the PEAT sample. On the other hand, the maximum emission of the reference P3HT sample was found at 2.16 eV (576 nm) with a noticeable shoulder at 2.00 eV (617 nm). From adamantyl substituted polymers only ethyl one exhibits a shoulder in emission spectra at 2.00 eV (617 nm). The energy difference between the emission maximum and the shoulder of the reference P3HT and PEAT was similar and could be caused by C=C bond stretching frequency of the polymer. The thin layer emission spectrum of reference P3HT was red shifted with shoulder at 1.56 eV (795 nm) with lower intensity compared to the solution sample. Adamantylethyl samples show a small red shift against solution samples. Adamantylmethyl samples exhibit no red shift against solution spectra and no shoulder presence. Results are summarised in Table 1.

Table 1: Summarised data of absorption, excitation and emission wavelength maxima (nm), Stoke shifts values (eV) and quantum yields (%) of polymer samples

Samp.	Environment	Absorption	Excitation	Emission	Stokes shift	QY
P3HT	Chloroform	450	445	576	0.60	33 %
	Thin layer	508	509	741	0.77	2 %
PMAT1	Chloroform	390	403	546	0.91	11 %
	Thin layer	387	388	546	0.93	<1 %
PMAT2	Chloroform	390	402	546	0.91	-
	Thin layer	390	388	546	0.91	-
PEAT1	Chloroform	458	446	577	0.56	19 %
	Thin layer	475	472	609	0.57	<1 %
PEAT2	Chloroform	430	431	572	0.72	-
	Thin layer	444	442	603	0.74	-

The microscopic mobility and concentrations of the trapped charge carriers were evaluated from the SCLC measurements. From the results might be concluded that the highest charge carrier mobility possesses the reference P3HT sample which was expected as it is a widely used, optimised, and explored material with much higher molecular weight. The novel material exhibits slightly lover mobilities. However, the mobilities of the samples are in the same order as those of the reference P3HT. The results are summarized in Table 2.

Table 2: Summarised parameters of thin layers (thickness-L, trap-filled limit voltage-V_{TEL}, trap concentrations-n_t, microscopic electric mobility-u)

Sample		L / nm	V_{TFL} / V	n_t / $10^{23} \times$ m^{-3}	μ / $10^{-9} \times$ m^2 V^{-1} s^{-1}
P3HT		70	0.63	0.43	4.25
PMAT1		95	3.16	1.19	0.58
PMAT2		90	3.31	1.36	0.63
PMAT1-HT		86	3.16	1.42	2.37
PEAT1		42	3.55	6.67	1.38
PEAT2		70	3.02	1.99	0.44
PEAT1-HT		70	–	–	2.73

To gain information on the oxidative / reduction properties and the HOMO / LUMO values of the newly prepared polymers, cyclic voltammetry measurements were performed (Figure 5). It can be said that all three polymers are able to reversibly oxidise, which is a well-known ability of poly thiophenes, but it is very interesting and surprising that adamantyl polymers have the ability of quasi-reversible reduction.
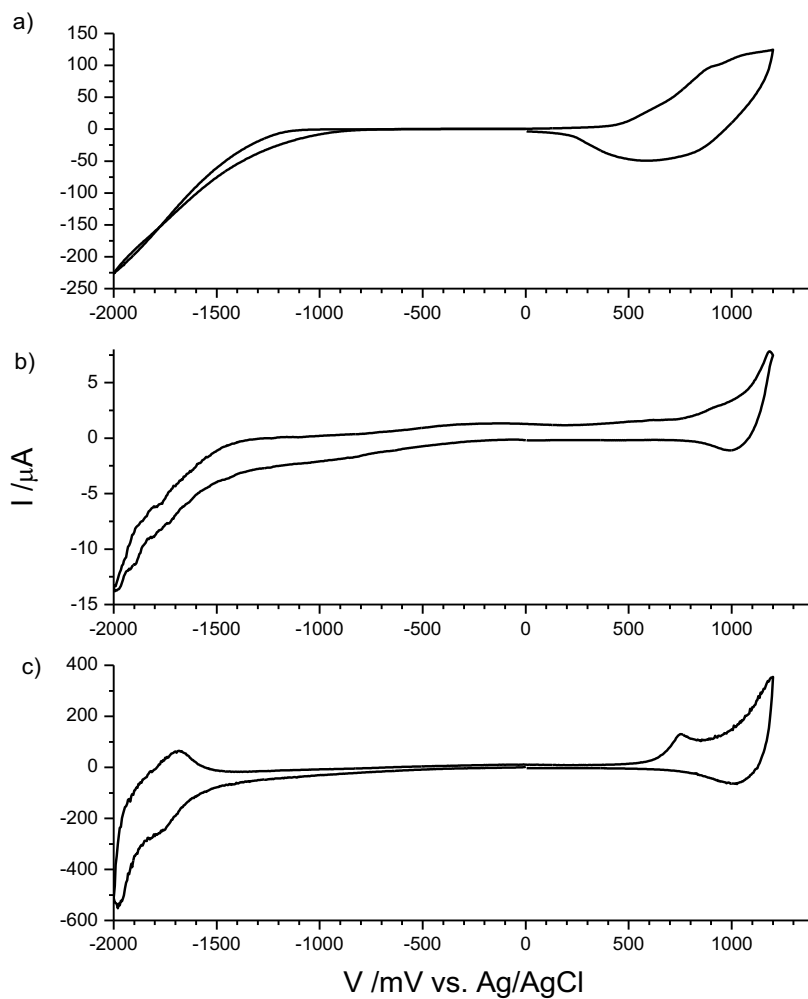
Figure 5: The cyclic voltammetry of PMAT (a), PEAT (b) and P3HT (c) thin films deposited on FTO (platinum as the counter electrode, Ag/AgCl as the pseudo-reference electrode, and fe/fe+ as the internal standard, nitrogen-purged 0.1 M of TBAPF6 in anhydrous CH3CN solution as the electrolyte)

Table 3: Electrochemical results measured against reference Ag/AgCl electrode

	Cyclic voltammetry results					
	E_{ox}^{onset}/V	HOMO /eV	E_{red}^{onset} /V	LUMO /eV	Eg /eV	Optical Eg /eV
PMAT1	0.85	−5.50	−1.46	−3.19	2.31	2.61
PEAT1	0.62	−5.27	−1.49	−3.16	2.11	2.13
P3HT	0.48	−5.13	−0.97	−3.68	1.45	2.00

In addition to the above-mentioned alkylated polythiophenes, polymers based on para-bis(2-thienyl)phenylene were prepared. The same structural unit with dodecyl side chains, as in the case of molecular photoswitchers was used as the polymer backbone. For the preparation of the fluorinated polymer, it was necessary to prepare the fluorinated para-bis(2-thienyl)phenylene structure. The preparation by Stille coupling and Kumada coupling was the same like in the case of nonfluorinated para-bis(2-thienyl)phenylene with similar results. In case of a partially fluorinated polymer, the two types of chemical chain polymerisation reactions were applied. The first reaction using magnesium salts (Grignard reagent) as the intermediate for Kumada coupling polymerisation was performed conventionally in the flask under an inert atmosphere or argon. The second approach using Stille intermediate (tin salt) was performed in a microwave reactor. The Stille polymerisation provided better results according to selectivity and yield mainly due to microwave irradiation. However, Kumada polymerisation requires mild conditions and uses intermediates that are not so toxic as tin salts.

6.3   Organic lead halide perovskite materials

Perovskite lead halide materials were prepared in two different forms, macrocrystals/singlecrystals and nanostructures with different stabilization ligands. In both cases, the procedures required sophisticated method development and optimizations because, in general, led halide perovskites are sensitive to the molar ratios of the components to crystalise, are sensitive to air, humidity, and many other external factors.

6.3.1 Perovskite macrocrystals preparation

The four most common types of led-halide perovskite single crystals were prepared by the standard ITC method according to our publication [60], and by the novel microwave assisted crystallisation method [61]. In case of microwave assisted method, for all crystals had to be precisely and individually developed parameters of crystallisation like solution amount, reaction tube volume and shape, precise temperature measurement, and temperature profile to produce the most organised and regular crystals.

Observation from optimization experiments reveals that faster temperature increases produce polycrystalline material. For bromide-based perovskite crystals the temperature was increased in 10 °C steps with 30–60 min intervals, and polycrystals consisting of tiny (less than 0.5 mm) blended crystals were formed. On the other hand, when the temperature was gradually increased with more steps (5 °C steps) and at longer intervals (60-120 min), single crystals were grown in all cases, which is in the line with the previous work. Furthermore, the longer the highest temperature value was set, the larger the resulting single crystals were, which has also been described previously. For instance, when a temperature above 75 °C was set for $MAPbBr_3$ perovskite for 1 hour, the single crystal obtained was only 1 mm in size; nevertheless, when a temperature above 75 °C was set almost for 8 hours, then the resulting single crystal was 5 mm in size, as shown in Figure 73A. Finally, we have optimized the programs for each type of perovskite crystal by changing the heating speed and the time at the set temperatur, and similar trends were observed in the preparation of iodide-based single crystals.
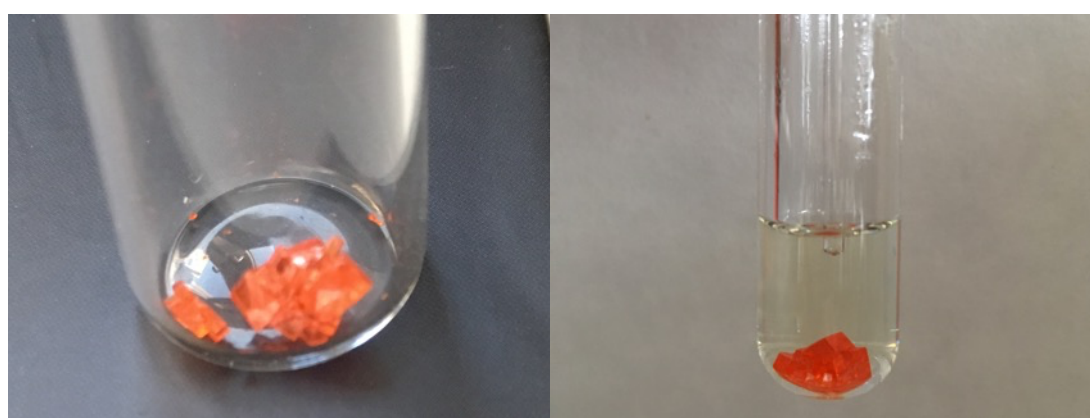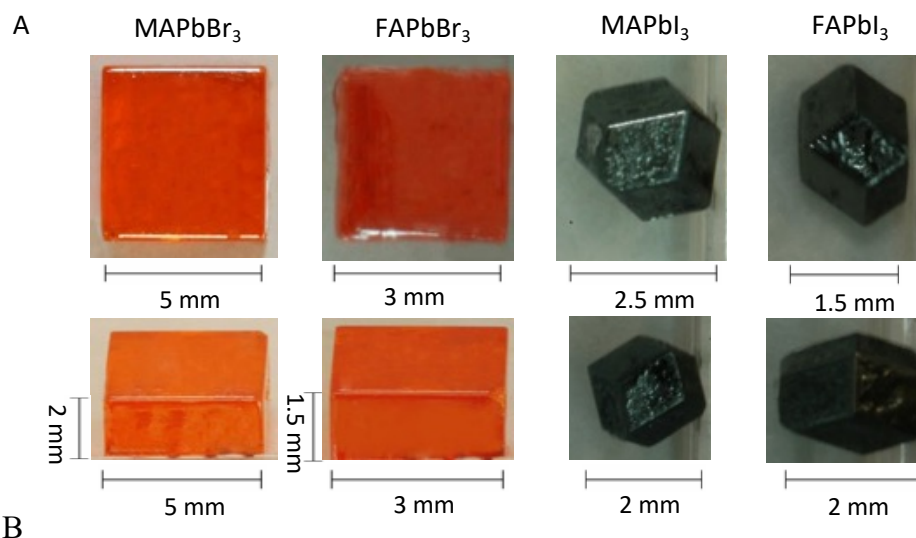
Figure 6: Photos of discussed perovskite single crystals (A) and perovskite crystals prepared by not optimised method (B)

For further study of bulk perovskite crystals, optical spectroscopy techniques were used. The UV/VIS/NIR spectroscopy was applied in a transmission mode in order to estimate the onset of absorption. PL spectroscopy has been performed on the perovskite crystals as well.

6.3.2 Perovskite nanoparticles preparation

Perovskite nanoparticles of different types were prepared by two mainly used methods. The first, ease processable method of preparation by solvent precipitation was used to prepare MaPbBr$_3$ PNP stabilised by adamantyl amine and hexanoic acid as ligands. The general characterisation, properties of the nanoparticles and optimization of the preparation process for adamantylamine stabilized MaPbBr$_3$ nanoperovskites.

The second method of preparation by hot injection procedure was provided in case of caesium PNP. In this case, three different combinations of ligand

stabilisation were used. The first standard ligand combination was oleyl amine and oleic acid, mostly to confirm that the procedure works well. For the second stabilisation mixture, again oleyl amine was used, but carboxylic acid was changed to adamantane carboxylic acid. In the third approach, even the amine was changed to adamantylamine. Unfortunately, the third combination was not suitable, because both adamantane ligands caused crystallization and precipitation. The substitution by adamantane carboxylic acid which was never used for hot injection stabilisation of caesium perovskite nanoparticles was successful. The sizes of conventionally stabilized caesium perovskite nanoparticles and those of adamantane carboxylic acid stabilised nanoparticles were similar. The shape of adamantane carboxylic acid stabilized nanoparticles was slightly more irregular compared to conventionally stabilized nanoparticles in order of producing not only cubes but also quad. Moreover, the edges of the nanoparticles were not as sharp as those in the case of nanoparticles stabilised by oleic acid. On the other hand, the preparation procedure was not optimised for adamantane ligands, so there is a lot of space for improvement.

Both PNP types were generally prepared with the aim of further application in polymeric host matrices. In the case of hybrid lead halide nanoperovskites, the optimisation of the preparation process by using different ligands was performed for the best stability and properties. However, preparation of caesium lead-bromide nanoperovskites focused on the implementation of adamantane ligands without further optimization to prepare materials suitable for implementation in polymeric matrices. Basically, it can be said that implementation of an adamantyl-based ligand in the form of adamantan carboxylic acid was successfully used for the preparation of caesium nanoparticles, but this modified stabilisation needs further optimisation, measurements, and confirmations.

6.4   Application of perovskite nanoparticles into the polymeric host matrices

As mentioned in the beginning of this work, perovskites suffer from poor stability under regular environment conditions. Humidity and oxygen could be critical, resulting in material degradation and loss of unique properties. The latest research focused on the stabilisation of perovskite structures by most matrices, moreover, matrices with added value to perovskite structures. The one of the most used matrices is polymeric host to protect and improve perovskite properties.

The last area of experiments connects the above-mentioned areas together, when prepared adamantyl-substituted polymeric materials were used as polymeric host matrices for perovskite nanoparticles. According to the procedures mentioned above, MaPbBr$_3$ PNP stabilised by adamantyl amine and hexanoic acid was prepared. To achieve the maximal possible number of nanoparticles in the

polymer matrix, different volumes of precursor solutions and antisolvents were used. The general procedure precipitates a 20 uL precursor solution into 10 mL of toluene. The resulting concentration of nanoparticles was too low to be used in a polymeric matrix. The reducing of non-coordinating precipitating solvent amount to 1, 2, or 3 mL results in immediate precipitation, so the lowest usable volume was estimated to be 5 mL of toluene. Thus, the amount of precursor solution was changed to obtain the highest possible concentration of nanoparticles. It was used standard 20 uL, 60 uL and 90 uL of the precursor solution to precipitate in 5 mL of toluene. So, washing steps were performed according to the experimental description and to obtain solid nanoparticles. Adamantyl substituted polythiophene solution (5.0 mg in 0.5 mL of chlorobenzene) was added to the centrifugal tube, where the solid nanoparticles without solvent were. Part of nanoparticles were redispersed in solution of polymer but small amount rest on glass of tube. We prepared 3 samples with various concentrations from 30, 60, 90 μL of precursor solutions. It was impossible to estimate exact concentration because a small amount of PNP stayed on glass as a film. The highest concentration at which a 90 μL sample was used starts to precipitate immediately after adding the polymer solution. The presence of nanoparticles in the polymer matrix was confirmed by fluorescent spectroscopy,

7 Conclusion

In summary, the above-mentioned research can be divided into four areas. All the topics seem individual, separate, but at the end are all connected. At the beginning of the research were single molecules based on alkylated thiophenes and para-bis(2-thienyl)phenylene. These molecules led us to the design and synthesis of various photoswitching materials using condensation reactions. Different formylation approaches were applied on para-bis(2-thienyl)phenylene derivatives and the Vilsmeier-Haack reaction provided the best results after optimizations. Furthermore, the huge added value was applying microwave irradiation for imine condensation reactions, providing a universal, low-time-consuming, and environmentally friendly approach for imine preparation. Thanks to this microwave method, it was possible to prepare different imine photoswitches.

After good experiences with imine condensation, the McMurry reaction was applied on different carbonyl compounds. Again, there was para-bis(2-thienyl)phenylene moiety with the formyl group, which is a good connection with previous imine condensations. Unfortunately, McMurry reactions possess too many variables, so a deep optimisation will be necessary.

The para-bis(2-thienyl)phenylene was again connected with the next part of the research, polymer preparation. The partially and fully fluorinated polymers on the basis of its backbone were prepared. However, in inspiration of P3HT as the most common conductive polymer, polythiophenes with adamantyl side chains of different length were prepared. The different approaches of synthesis were explored, and the optical and electrical properties of two novel thermodynamically stable regioregular polymers were measured. Until now there has been no evidence of the synthesis and properties investigation of thiophene-based polymers modified by adamantyl groups. The charge carrier mobility of the novel polymers is comparable to that of the reference P3HT sample. The electrochemical measurements showed that the investigated novel polymers do appear to be electrochemically reducible, at least with some degree of reversibility. All the results predict good applicability and processability of novel adamantyl substituted polymers in the field of organic electronics.

On the other side there are materials based on the perovskite structures. Today, the popularity of perovskites is increasing exponentially. The research focused on the two different forms of perovskites, the macrocrystals and nanoparticles. In the field of macrocrystals the research reached edges in the form of bad processability, up-scalability, and high costs. Therefore, a novel, cost- effective microwave-assisted synthesis of perovskite single crystals was developed for the preparation of bulk crystals of $MAPbBr_3$, $FAPbBr_3$, $MAPbI_2$, and $FAPbI_2$ perovskite in a microwave reactor. This microwave-assisted method of perovskite crystallization is highly reproducible because of the precise heating control in the whole volume of the solution and the possibility of a fully automated program setting. This technique is convenient, versatile, and easily scalable and can be applied not only for the already-mentioned types of perovskite materials but also for various perovskite structure modifications. Moreover, our new method represents an environmentally friendly approach because of its very high energy efficiency and low energy consumption. Another form of perovskites is more suitable for devices fabrication and massive production. Perovskites in the form of nanoparticles could be processable in thin layers from colloidal solutions, but one huge disadvantage remains and it is stability. The latest research has helped to determine the way of stabilisation by ligands and by polymeric or hybrid porous matrices. In this part of this work, various ligand stabilisation was investigated. The research was primarily focused on adamantane-based ligands, and caesium-based perovskite nanoparticles with admantane carboxylic acid as the ligand were prepared. The adamantane-based ligand was never used in this kind of perovskite nanoparticles. Further, polymeric matrix stabilisation was applied. The polymeric matrix topic is the connection of the perovskite topic with the adamantyl-substituted polythiophenes mentioned above. Polythiophenes as the conductive polymers were supposed to create a network between nanoparticles, and it was proved that nanoparticles are present in polymeric matrix. Unfortunately, the

concentration of nanoparticles was too low to affect the polymeric properties. Further research should be focused on the preparation of nanoparticles in higher concentrations to prove their properties in polymeric matrix.

To summarise the results, two novel adamantane-substituted polythiophenes were prepared including complete optical, electrical, and morphology characterisation. Furthermore, two novel fully and partially fluorinated polymers based on para-bis(2-thienyl)phenylene were prepared and characterized. In the topic of photoswitching devices, six new final photoswitching molecules were prepared, including a huge number of intermediates, and confirmation of photoswitching properties was provided. A study of different formylation procedures was made as a study of imine condensation approaches. By the McMurry condensation two completely new molecules were prepared for further characterisations. A completely new method of preparation of perovskite single crystals using microwave irradiation was developed and optimised for four mostly used types of hybrid organic lead-halide perovskites. The study of perovskite nanoparticles ligand stabilisation was carried out on mostly used $MaPbBr_3$ hybrid led halide perovskite and simultaneously the effect of adamantyl-based ligands on caesium-based perovskites was investigated. Finally, the application of perovskite nanostructures in polymeric matrices was studied using novel adamantyl substituted polythiophenes and nanoperovskites stabilised by adamantane-based ligands.

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Working experience

2022–presence	ORLEN Unipetrol RPA s.r.o. - POLYMER INSTITUTE BRNO, Tkalcovská 36/2, 602 00 Brno-střed
	Senior researcher II on Department of Analytical Chemistry
2018–presence	Brno University of Technology, Faculty of Chemistry, Material research center, Purkyňova 464, 612 00 Brno-Medlánky
	Researcher in the laboratory of synthesis of advanced organic materials for organic electronics and photonics
2016–2020	Gabra vzdělávání s.r.o.
	Tutoring high school students in small groups (10–20 students) for the chemistry part of entrance exams

Education

2018–presence	Brno University of Technology, Faculty of Chemistry, Purkyňova 464, 612 00 Brno-Medlánky
	Doctoral Study Programme: Chemistry, Technology and Properties of Materials
	Expected defence 2023
	Dissertation thesis: Implementation of polycyclic saturated systems in the synthesis of advanced molecules for application in organic electronics (supervisor: Assoc. Prof. Ing. Jozef Krajčovič Ph.D.)
2016–2018	Brno University of Technology, Faculty of Chemistry, Purkyňova 464, 612 00 Brno-Medlánky
	Master´s Degree Programme: Chemistry for Medical Applications
	Master thesis: Synthesis and characterisation of advanced molecules with implemented adamantane skeleton (supervisor: Assoc. Prof. Ing. Jozef Krajčovič Ph.D.)
2013–2016	Brno University of Technology, Faculty of Chemistry, Purkyňova 464, 612 00 Brno-Medlánky
	Bachelor´s Degree Programme: Chemistry for Medical Applications

Bachelor thesis: Implementation of polycyclic saturated systems in advanced smart molecules usable in organic electronics (supervisor: Assoc. Prof. Ing. Jozef Krajčovič Ph.D.)

2013–2016	Masaryk University, Faculty of Medicine, Kamenice 5, 625 00 Bohunice
	Master´s Degree programme: General Medicine – study terminated
2000–2008	High school, Gymnázium arm. gen. Ludvíka Svobodu Humenné, Komenského 4, 06601 Humenné, Slovakia

Awards:

2021	**Dean's Award** for excellent academic performance and publication activity in the doctoral study programme, Brno University of Technology, Faculty of Chemistry
2020	**Award for the best speaker and contribution** at the international conference Chemistry and life Czech Republic, Brno.
2018	**Prize of Josef Hlávka for the Best Students and Graduates,** Josef Hlávka foundation award for research activity

Pedagogical activity

2018– presence	Brno University of Technology, Faculty of Chemistry,
	Laboratory Classes in Organic Chemistry
	Organic Chemistry I and II seminars
2017–2021	Brno University of Technology, Faculty of Chemistry,
	Laboratory supervisor for student Ing. Dominik Veselý during bachelor and master studies

Conferences

Poster presentation

2019: 11th International Conference on Nanomaterials, Nanocon. Czech Republic, Brno.

Oral presentation

2021: 13th International Conference on Nanomaterials, Nanocon. Czech Republic, Brno.

2021: International Conference Falling walls, Poland, Wroclaw.

2020: International conference Chemistry and life Czech Republic, Brno.

2019: Student conference Chemistry and life Czech Republic, Brno.

2017: Student conference Chemistry and life Czech Republic, Brno.

Other skills

Language:	English – advanced level (certificate B2)

Czech – advanced level

Slovak – native speaker

IT technology: Advanced work with chemical software Chromeleon, Xcalibur, Chemdraw, Mestrenova NMR, OriginLab, experience with PC hardware maintenance

Scientific

Knowledge: Education and experience in **advanced organic synthesis**, purification methods, separation methods, and characterisation of organic compounds

Long term experience with **HPLC** and **GC-MS** techniques: methods development, analysis of unknown products and gasses, results evaluation, and maintenance of machines

Experience with **Combiflash** semipreparative chromatography separation and maintaining the machine

Experience with **microwave synthesis**, using Anton Paar microwave reactor and application of microwave conditions to various processes

Experience in optical, electrical, and electrochemical measurements and compound characterisations in solution, solid state, and thin layers

Other: Driving license B, paramedic for mass events certificate

Personal profile: Conscientious, careful, non-conflict, non-smoker, organizational skills, working in team and leading the team, skills, communicative with the ability to deal with people, excited to learn new thinks

Hobbies: Music, IT technologies, new trends in electronics and technology, medicine, and organic chemistry

The list of publications

Jancik, J., Jancik Prochazkova, A., Scharber, M.C., Kovalenko, A., Masilko, J., M., Sariciftci, N.S., Weiter, M. and Krajcovic, J. Microwave-Assisted Preparation of Organo-Lead Halide Perovskite Single Crystals. *Cryst. Growth Des.* **2020,** *20,* 1388–1393.

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Jancik, J., Pospisil, J., Kratochvil, et al., 2022 Novel Adamantane Substituted Polythiophenes as Competitors to Poly(3-Hexylthiophene). *Polymer*. **258**. ISSN 00323861. Available: doi:10.1016/j.polymer.2022.125274

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