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ДОПУСТИТЬ К ЗАЩИТЕ
Заведующая кафедрой

_______________д.т.н., профессор
И.М. Кирпичникова

«___» ________________ 2017 г.

КОМБИНИРОВАНИЕ КВАНТОВЫХ ТОЧЕК И ОПТИЧЕСКИХ РЕКТЕНН ДЛЯ ПРЕОБРАЗОВАНИЯ ЭНЕРГИИ ФОТОНА В ЭЛЕКТРИЧЕСКУЮ ЭНЕРГИЮ

ПОЯСНИТЕЛЬНАЯ ЗАПИСКА
К ВЫПУСКНОЙ КВАЛИФИКАЦИОННОЙ РАБОТЕ
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УТВЕРЖДАЮ
Заведующая кафедрой

_______________ И.М. Кирпичникова

«21» декабря 2016 г.

ЗАДАНИЕ
на выпускную квалификационную работу студента
Бузина Павла Андреевича
(Фамилия, имя, отчество полностью)

Группа П-287

1 Тема работы: Комбинирование квантовых точек и оптических ректенн для преобразования энергии фотона в электрическую энергию

Утверждена приказом по университету от 28 апреля 2017_г. № 835, Приложение №27

2 Срок сдачи студентом законченной работы 08.06.2017

3 Исходные данные к работе

Методические материалы, справочная литература, научная литература, научные статьи, диссертации, ресурс Интернет

4 Содержание расчетно-пояснительной записки (перечень подлежащих разработке вопросов)

1 Анализ современного сектор энергоснабжения;
2 Введение в сектор энергоснабжения будущего;
3 Перспективы применения возобновляемых источников энергии;
4 Анализ полупроводниковых фотоэлементов;
5 Теоретические основы работы оптических антенн;
6 Сущность и основные направления использования оптических антенн;
7 Перспективы применения оптических антенн;
8 Анализ достоинств и недостатков использования оптических антенн;
9 Методы производства оптических антенн;
10 Фотоэлектрические модули на базе оптических антенн;
11 Оценка эффективности оптических антенн;
12 Теоретические основы работы квантовых точек;
13 Сущность и основные направления использования квантовых точек;
14 Перспективы применения квантовых точек;
15 Анализ достоинств и недостатков использования квантовых точек;
16 Методы производства квантовых точек;
17 Фотоэлектрические модули на базе квантовых точек;
18 Оценка эффективности квантовых точек;
19 Описание устройства основанного на комбинации квантовых точек и оптических антенн;
20 Теоретические основы работы устройства;
21 Оценка достоинств и недостатков устройства;
22 Оценка эффективности устройства;
23 Список литературы;
24 Приложение;

5 Перечень графического материала (с точным указанием обязательных чертежей, плакатов в листах формата А1)

1 Современный сектор энергоснабжения и перспективы его развития - 1 лист
2 Описание теоретических основ работы оптических антенн и квантовых точек - 1 лист
3 Описание теоретических основ комбинации квантовых точек и оптических антенн - 1 лист
4 Оценка полученных результатов - 1 лист

Всего 4 листов

6. Дата выдачи задания «21» декабря 2016 г.

Руководитель ________________ И.М. Кирпичникова
(И.О. Фамилия)

Задание принял к исполнению ________________ П.А. Бузин
(И.О. Фамилия)

КАЛЕНДАРНЫЙ ПЛАН

Наименование этапов выпускной квалификационной работы	Срок выполнения этапов работы (проекта)	Отметка о выполнении руководителя
1 Анализ современного сектор энергоснабжения и перспективы его развития	20.01.17	
2 Обоснование использования возобновляемых источников энергии	10.02.17	
3 Описание теоретических основ работы оптических антенн	11.02.17	
4 Анализ перспектив применения оптических антенн	19.02.17	
5 Оценка эффективности оптических антенн	05.03.17	
6 Описание теоретических основ работы квантовых точек	12.03.17	
7 Анализ перспектив применения квантовых точек	26.03.17	
8 Оценка эффективности квантовых точек	06.04.17	
9 Описание комбинации квантовых точек и оптических антенн	20.04.17	
10 Оценка достоинств и недостатков устройства	04.05.17	
11 Оценка эффективности устройства	11.05.17	
12 Оформление пояснительной записки	01.06.17	
13 Оформление графической части	06.06.17	

Заведующая кафедрой ______________________________ И.М. Кирпичникова
(подпись) (И.О. Фамилия)

Руководитель работы ______________________________ И.М. Кирпичникова
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Студент ______________________________ П.А. Бузин
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АННОТАЦИЯ

Бузин П.А. Комбинирование квантовых точек и оптических ректенн для преобразования энергии фотона в электрическую энергию г. Челябинска. – Челябинск, ЮУрГУ, Э; 2017, 54 с, 20 ил., 1 табл., библиогр. список – 56 наим., 4 листа чертежей ф. А1

Оптические антенны (ректенны) это технология для преобразования энергии падающей электромагнитной волны в диапазоне видимого спектра в постоянный электрический ток. Оптические антенны представляют собой устройства, состоящие из антенны с размерами одного из измерений не превышающих нанометрового масштаба и высокоскоростного диода для выпрямления поглощённого излучения. Эта технология была предложена как альтернатива стандартным полупроводниковым фотоэлементам, если некоторые недостатки будут изучены и разрешены. В соответствии с теорией ректенн, длинна одного сегмента оптической антенны должна быть пропорциональна длине поглощённой волны. Восемьдесят пять процентов мощности электромагнитного излучения солнца имеет диапазон длин волн от 0,4 до 1,6 мкм. Этот факт накладывает ограничение на эффективность работы оптических антенн с электромагнитным излучением солнца и определяет диапазон рабочих частот.

Для улучшения эффективности поглощения и преобразования массива оптических антенн, было предложено использование слоя квантовых точек, как частотный трансформатор. Главная цель данной магистерской диссертации это анализ возможности использования комбинации двух нано структурированных материалов и предположение потенциальных характеристик. Для этих целей были проанализированы наноструктуры перспективные для использования в фотовольтаике, выбор материалов и особенности структур.

Несмотря на факторы сдерживающие использования этих структур, предложенная комбинация материалов имеет свои достоинства и интересна для дальнейшего изучения и применения. При условии тщательной разработки устройств основанных на принципе комбинирования квантовых точек и оптических антенн, эти устройства могут стать перспективной технологией для преобразования электромагнитного излучения солнца в постоянный электрический ток.

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1 INTRODUCTION

In the last 100 years our society was changing a lot, economy was developing and nowadays society can be characterized as postindustrial, which determined by high development of economy, science and increasing quality of education, production and service. Nevertheless, planetary boundaries lead to issues which required changes of current behavior and relation to nature. Particularly, it is connected with growth of energy consumption and required alternatives in energy generation. Modification of ways electric power generation is connected with modification of energy resources demand.

It is obvious that we cannot ignore importance of solar power which dominates above others resources available to humanity. The task of replacement fossil fuel is important. Predicted effects of these changes confirm relevance of it. Advantages of solar power such as widespread, accessibility, cheapness and clearness type of energy resources lead to fast growing of electric power generation by facilities of solar power plants [1].

1.1 Future of the energy sector

Current energy sector consists of three main process which is connected with characteristics of electric power itself and features of electric power consumption. It is energy generation on power plants, transmission by air and cable transmissions lines, and transformation process. Energy generation is an energy conversion from primary energy resources to secondary energy such as electric power or heat power.

The modern studying calls electric power as the most perspective and useful type of energy for a few reasons such as dozens of ways for electric power generation, low energy losses for transmission and a large number of energy utilization ways. Due to these advantages, electric power occupies the first place of secondary energy and share of it increases rapidly. Electricity demand increased for a factor of 20 at last 60 years [2]. Moreover, this permanent growth was interrupted only at Global Credit Crunch at 2009 because of decreasing of China production. When global electric power demand is predicted population growth has to be taken into account. This factor influences on the electric demand curve formation a lot. Statists predict that population growth curve will have a form of a parabolic curve with maximal point close to 9 billion people.

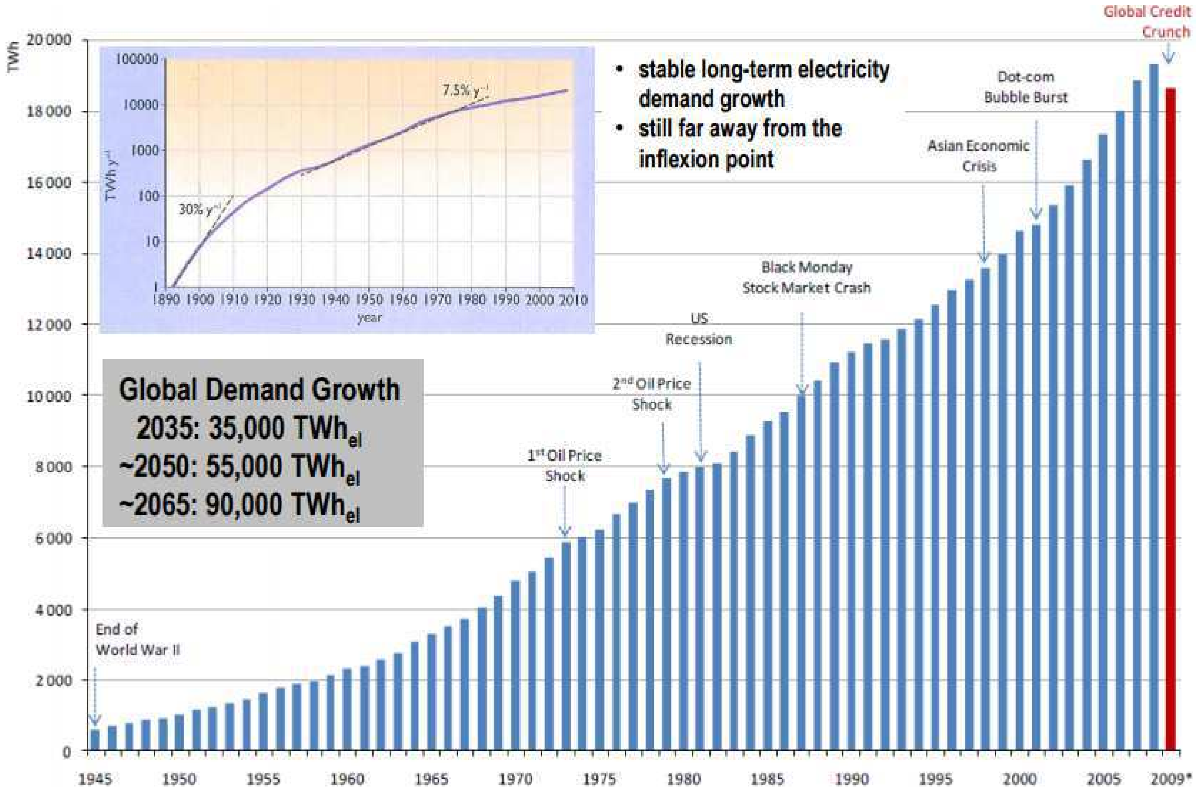

Figure 1. The global electric power demand [2].

This information helps to analyze a possible character of the electric power generation graph. The power demand graph will have similar character as population growth curve but with a larger angle of gain. The predicted volume of electric power demand will be on the level of 90.000 TWh at 2065, which will be for a factor of 5 more than current power generation. Follow the expectations of the main institution of the energy sector (international energy agency) electric power consumption per capita will increase 3,5 time in the next 50 years [2]. The issue of rapid energy consumption increase imposes restrictions for future of the energy sector.

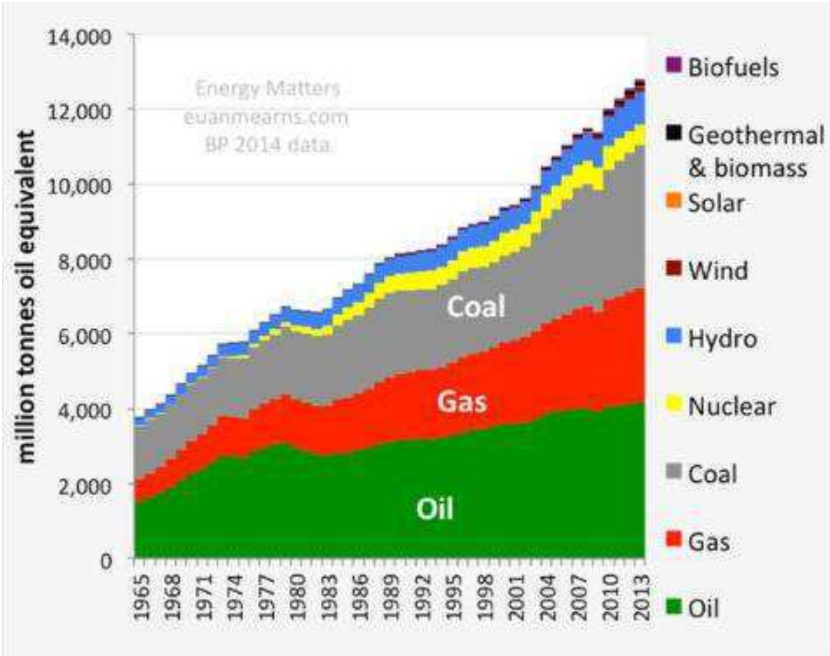

Figure 2. The share of different energy sources in global energy demand [3].

To begin with a new energy era requires changes of electric power generation which will allow energy supplying of our new complex and developed world. The abovementioned factors affect to worldwide carbon emissions and require dropping it to zero by 2050 [4].

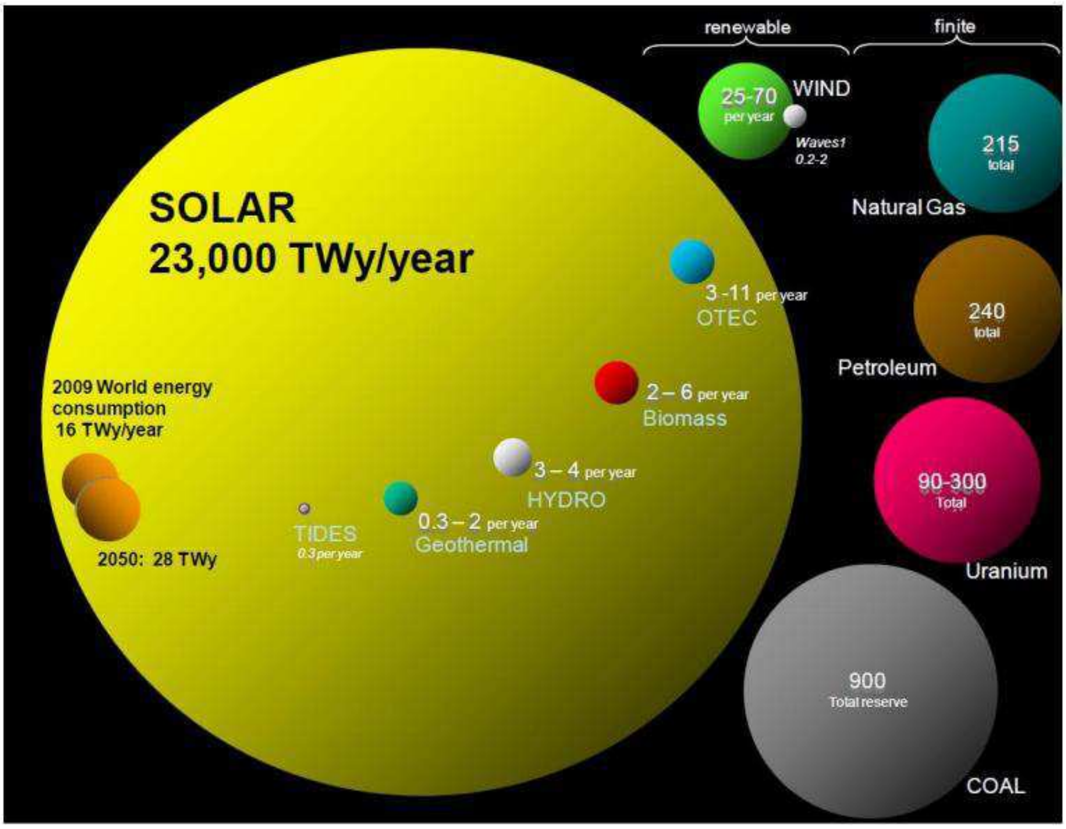

Figure 3. The planet energy reserves [5].

These constraints mean that humanity should change energy sector from burning fossil fuels to renewable energy utilization. Renewable sources of energy represent the easiest and the most perspective way to produce clean and safe energy. The cost of renewable energy becomes more and more competitive to energy generation by fossil fuels. Solar energy is widely spread energy resource which is used all over the world over 4 billion years and provides at 1400 times more energy that we consume [5]. Unsurprisingly, that it becomes the best decision for the sustainable world strategy. Nevertheless, solar radiation has a few major issues which will be solved if we follow the orientation to clean energy requirements.

First of all is a solar energy intermittent, but Sun is shining constantly and we just have to solve the energy storage issue. Scientists all over the world work on a creation of the best energy storage for the future energy system. The second constraint of using solar energy is a location of the highest resources. Solar power irradiance is not similar around the world and depends on latitude to a great extent. The majority of energy resources are located close to the equator. It leads to the issue that transmissions lines with low lose are needed. Researchers are carried out to solving of the abovementioned issues.

“Nanotechnology could help to solve solar energy’s obstacles and meet energy expectations without compromising the environment and human health by creating new devices that are able to generate, store and transport electricity in a clean and more efficient way and with smaller space requirements.” [6]

2 SEMICONDUCTOR SOLAR CELLS

Solar cell is a device for transformation of solar power to electric power [7]. Modern solar cells are based on several technologies and material. Nevertheless, the principle of their work is similar and limited by the same physical constrains. The most common used solar cells are made of silicon as the most widespread semiconductor at the planet. The principle of their operation is based on photovoltaic effect which appears when heterogeneous semiconductor structures are exposed to sunlight. Solar modules based on semiconductors represent few semiconductor cells united in series and parallel branches for achieving of the standard value of voltage and current [7]. Application of modern solar modules is huge and widely applicable because of their convenience. Solar cells can supply electric power to the major part of devices and consumers from house appliances and small electronics to industries and big domestic consumers. The solar power is based on the planet of the solar modules and can be significant part of the power system. The biggest advantage of electric power production by harvesting of solar radiation is the clearness of the energy because it follows the target of the zero emissions in energy sector [5].

2.1 Introduction to semiconductor solar cells

The history of the photovoltaic effect started from 1839 when French physicist Edmond Becquerel discovered physical phenomena of appearing of the electric current and voltage in his copper plate sample immersed in a liquid under the influence of sunlight. More than 30 years later in 1873 Willoughby Smith discovered photoconductivity of selenium and 4 years later in 1877 William Adams and Richard Day discovered the photovoltaic effect in solidified selenium and called their device the selenium cell. Their studying described in a paper which calls “The action of light on selenium” [8]. In 1883 Charles Fritts the American invertor created a solar cell based on the plate of selenium with a thin layer of gold. The abovementioned device had efficiency less than 1% but produced a constant current with relation to intensity of sunlight. Better understanding of the physics processes inside the solar cell appeared after researching of the wave properties of light by Hertz in 1887. At 1888 Edward Weston patented the device with name “Solar cell” which worked as a converter of solar radiation to electric power. Another important push was made by Einstein during researching of quantum basics of light absorption in 1905 [8].

The influence of a single-crystalline structuring to efficiency of the semiconductor solar cell was discovered only after decent development of quantum mechanics in 1948 with development of the mechanism of single germanium and silicon crystal growth by Gordon Teal and John Little. At 1954 researcher of Bell Labs Daryl Chapin created the first practical applicable silicon solar cell with efficiency in the real life conditions at

6%. A lot of individual scientists and laboratories started to research properties of solar cells and experimented with different materials [8]. Few years later Bell Labs announced the improving of the solar cells efficiency up to 15%. It was a good time to development in the area of harvesting of solar radiation because of the active development of the area of space researches, spaceships and satellites. Solar cells represent as the best way to supply satellites electric power because their reliability, life time and solar intensity of the Earth orbit [8].

Till the early 1980s the application of conventional solar cells was only as a power source for utility which can not be supplied by the common energy system such as mobile housing, emergency means of communications, small portable electronics and space activities. Nevertheless, nowadays total solar electricity generation rapidly increases with rate of 30-50% annually and doubling every few years. The global trend of generated solar electricity is represented on the picture below [3].

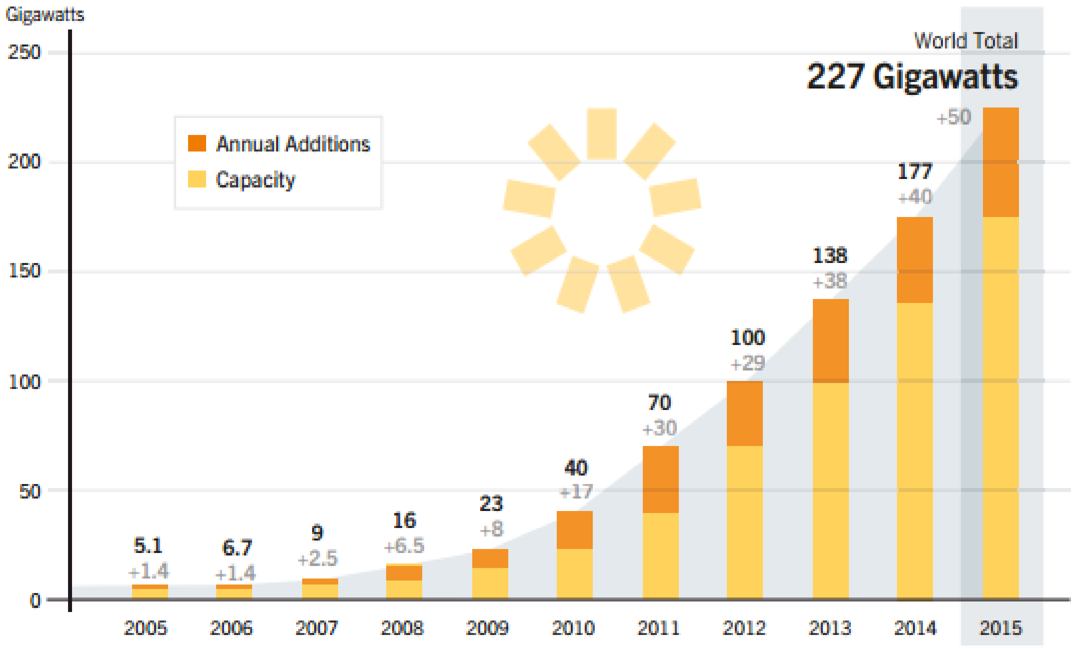

Figure 4. Global solar photovoltaics power capacity [9].

More and more people all over the world start using solar modules for the main electric power supplying of their houses, companies and large-scale power generation for maintain energy system. Nowadays, grid connection of roof top mounted solar cells system is a normal procedure and creation of solar power plant is a good business opportunity for investments. Price for solar modules, batteries and tracking system become lower annually which influence to development of the area of power generation based on solar modules.

Operational principle of semiconductor solar cells

The conversion of solar radiation to electric energy in semiconductor solar cells is based on photovoltaic effect which appears in inhomogeneous semiconductor structures by influence of solar radiation. The inhomogeneous characteristic of the semiconductor requires connecting of semiconductors with different properties or using the same one but alloyed with different impurities such as p-doped or n-doped by adding atoms of boron and phosphorous to the different layers. The abomentioned actions are connected with need of changing of the band gap energy in different layers of semiconductor which leads to creation of p-n junction.

After creation of the semiconductor with suitable band gap for harvesting solar spectrum radiation, the sample should be replaced under sunlight. If the energy of photons of the solar radiation is higher than band gap energy of the semiconductor, photon will interact with electron of the semiconductor and will transfer energy. When electron has enough energy to break connection with their atom, it becomes a free charge carrier. According to specific structure and materials used in a solar cell, free electrons are able to move only in the single direction to outer part of semiconductor and then to the load. Electrons move throw the load and create a useful work in the external load and then come back to the panel and recombine with a hole in p-type semiconductor [7].

2.2 Advantages of semiconductor solar cells

Application of the device for harvesting of the energy which value is unlimited in comprising with the modern demand of electric power is itself benefit. Value of annual solar radiation can fulfill humanity demand few times and provide enough energy for growing needs of the modern world [5]. Semiconductor solar cell is the first device which is used for harvesting and converting this energy to useful for the modern technic in the global scale. But conventional solar cells based on semiconductors have more advantages than it can be noticed. First of all using of silicon as the main material is a good decision which allows producing solar modules in a large scale without tangible lack of material. Silicon takes the second place by prevalence on the Earth after oxygen. Usually in nature silicon is in the form of silicon dioxide SiO_2 which is better known as sand or quartz and flint [10].

The process of pure silicon manufacturing is well developed and can be established in the large scale production. Of course production of using of single crystals for solar modules production is a complex task which requires high energy and time costs. Application of polycrystalline solar modules gets less energy per square meter, but its manufacturing is less expensive, faster and simpler in comparing to more efficient monocrystalline solar cell. The main factor which must be fulfilled for efficient solar energy harvesting by polycrystalline solar cells is that size of a each crystal have to be bigger than the wavelength of the absorbed wave. If this rule is fulfilled, difference in efficiency of the solar module will be not higher than 1% in comparing to monocrystalline solar modules [7].

Using of solar cells is pollution free way of electric energy production and match climate change constrains and the 2^{o}C target. The end-waste and pollution during production cycle can be managed and reduced by using of modern technologies. The recycling technologies for semiconductor solar cells are developing. Nevertheless, it is already understandable that sustainability of solar systems is uncritical and solar photovoltaics become more and more competitive energy sources [11].

Another important advantage of power plants based on semiconductor solar cells is their life time. Semiconductors photovoltaics can operate in normal conditions more than 100 years, because there solid state nature. In practice photovoltaic systems have lifetime confirmed a manufacturer about 20-30 years which prove their quality and reliability. Solar power plant requires only a little maintenance such as cleaning and rare replacement of broken elements. Semiconductor solar cells don't have movable parts in their construction which means that lack of losses in friction, but also improve reliability of the system because lack of need grease and maintain [7]. It means that operational cost for solar power plant is significantly low in comparing to power generation based on other technologies.

Another important advantage of conventional solar cells is their modularity. It means that installation of solar power plant can be carried out at few steps with increasing installed capacity. It is a great advantage which will have a significant impact for payback period of the power plant because as earlier the power plant starts produce energy, as earlier investors will get their investments back and will start to make profit. Multiplication of the abovementioned factor to the fact that the solar power plant can be installed incredible fast makes the solar power plant construction one of the most perspective and interesting for investors project.

In perspective using of big number of developed generators such as roof top mounted solar modules can help to reduce loses in energy sector for transmission, distribution and transformation of electric energy. In theory it can help to maintain existed energy system and reduce future investments for constructing of new long distance transmission lines and new fossil fuels based power plants. All this advantages and positive properties of semiconductor solar cells effect for their wide spread and using as the main power source all over the world.

2.3 Disadvantages of semiconductor solar cells

Nevertheless, the development using of semiconductor solar cells is restrained by some drawbacks and constrains which effect for their properties and characteristics. The first and the main drawback of the conventional solar cells is the efficiency. Basically, the most fundamental constrains of the silicon solar cell is connected with properties of silicon semiconductor. Since semiconductor solar cell's principle of work based on the width of a band gap and creation of free charge carriers the efficiency of the solar module will have strong limitations. In practice it means that photons with value of energy less than 1.12 eV cannot be absorbed by the silicon and photons with value of energy higher than 1.12 eV lose difference of energy their energy and width of the silicon band gap to lattice vibration which leads to heating of the material. The abovementioned constrain limits the efficacy of the silicon solar cell on the level of 29% for one junction sample [7].

The efficiency factor effects to the requirement of the area for production of determine power. In comparing to the power generation on standard power plant, it requires few times higher amount of area for production of the same capacity.

Another drawback of the conventional semiconductor solar cell is the fragility of the modules. Standard crystalline silicon is fragile as normal thin plate of solid material. The solid crystals of silicon are especially weak on flexural loads. This constrain requires using of the metal or plastic frame for mounting and holding of the solar cells and using glass for protection of the front side of the module. These facts influence for the weight of the module, complicates manufacturing and installation [7].

In turn, the presence of glass and metal frame effects to reflection losses and effective area of the panel which leads to decreasing of the efficiency of the module. Module production, transportation and installation become more expensive, time and energy consuming.

2.4 Constrains of semiconductor solar cells

Improvements of the standard solar cells become more and more important because solar cells enter in the modern life and energy sector. Nevertheless, the investments of the area of the renewable energy generation are still low in comparing to financing of the power generation based on fossil fuels or nuclear power.

To begin with the modern semiconductor solar cells is a decent mature technology and practical efficiency of the market samples is close enough to theoretical concept. This factor means that the modern semiconductor solar modules have more constrains from the market side than from physical point of view. Nevertheless, the constrain for semiconductor solar cells is efficiency and cost reduction which is connected with material selection or creation of a unique new material with properties which will be the most suitable for harvesting of the solar radiation. It means using of semiconductor the optimal relation of the positive properties such as more suitable width of the band gap and price.

The devalued calculation of Shockley–Queisser limit shows that the maximum efficiency for maximum power point for single junction semiconductor solar cell cannot overcome 31%. Nevertheless, the abovementioned calculation is valid for semiconductor with the band gap energy around 1.3-1.4 eV. In practice, the efficiency of the single junction silicon solar cell with the band gap energy of 1.1 eV is around 29%. In theory, the using of infinite quantity of band gaps leads to efficiency improving up to 86% (thermodynamic efficiency limit). In real life creation of three-junction solar cells is a complex task which can improve efficiency till 48% in theory but increase cost of the device [12].

The environmental impact of the semiconductor solar cells is significant property which will depend on the material and manufacturing technology to a great extent. For better understanding of different type of solar cell's characteristics influencing to the environmental impact of their using life cycle assessment values are represented on the table below.

Table 1. Results of the life cycle assessment for different type of photovoltaics technologies.

	The first generation of solar cells (monocrystalline silicon) [13], [14].	The second generation of solar cells (CdTe) [15].	The third generation of solar cells (Zn_3P_2) [16].
Efficiency, %	14	9	10
CO_2 emissions/kWh , grams	37.3-72.2	18	30
Energy payback time, years	1.7-2.7	0.3-1.2	0.78

3 OPTICAL RECTENNAS

The basic principle of rectennas was proposed by William Brown during his activity in the Paytheon Company in the 1960s. The idea of wireless power transfer is not new and begun from Teslas experiments in 1899 with using of radio waves [17]. The main purpose of Brown was to improve efficiency and increase distance of wireless power transfer and get examples of a real-life application for a device. The simplify samples of the Paytheon Airbone Microwave Platform a helicopter platform flowing above 15000m high was a small platform covered of antennas array and connected to DC motor with blades. A rectifier of the 3GHz supply signal was based on a parabolic reflector with focal point of a horn-fed reflector antenna. The system was complex and required movement of a focal point together with movement of the device. The concept worked but the realization had lack of technical supporting especially in the area of a rectification procedure [18]. A joint work of Brown and his colleague Roscoe George who worked on a microwave semiconductor diode get a result in 1963 which marked as a appearing of a concept of rectenna. The first concept of a microwave antenna was constructed by George in 1963 and then patented in 1969 [19].

3.1 Introduction to optical rectennas

Optical rectennas is a device based on a combination of small antennas with sizes measured in nanometers and high-frequency diode. The formed circuit is able to operate with visible spectrum of sun light and transform it to direct current [20].

The history of an optical rectenna started at 1973 from the patient of Robert J. Fletcher of the invention which he calls “Electromagnetic wave energy converter”. It was a departure from standard understanding of rectennas. A massive of mutually insulated electromagnetic wave absorber elements transform electromagnetic wave impinges thereon to electric power. He proposed to use artificial pyramids or cone structures similar as in structures in human eyes. The device includes elements tapered in the direction of wave direction to ensure increasing of a wideband spectrum, outputs for determination of a intercepted electric field voltage. Elements are located in a way that adjusted elements affect by the electromagnetic field of a impinging wave. The difference in the value of electric field results in a voltage difference between adjacent elements which leads to impulse current flowing throw a diode which rectifier impulse signal to direct current [21]. The patient of “Devices for converting of light power to electric power” was received by Alvin Marks in 1984.

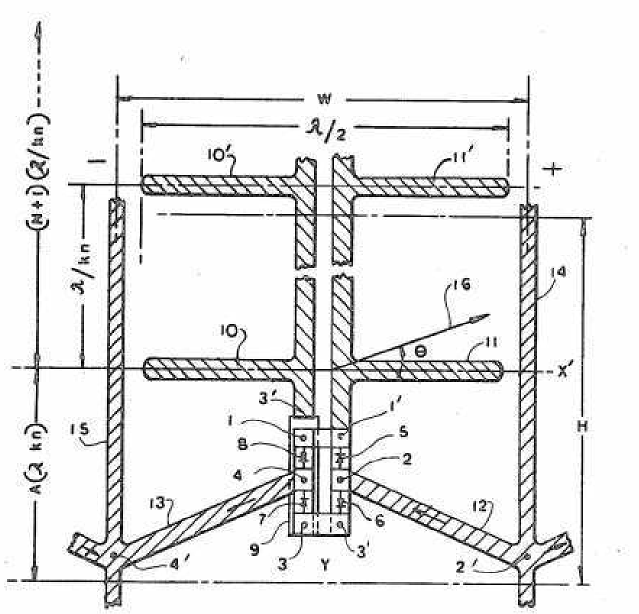

Figure 5. Devices for converting of light power to electric power [22].

The purposed device was not the first assumption that nantennas can operate with the visible part of spectrum if the high speed diode will be used, but has shown configuration of an optical rectenna in the conventional sense. The device represents a relatively high efficient converter of a light power to an electrical power based on a plurality of dipole antennas absorbing photons’ alternating electric field to cause electron resonance in the dipole antenna and absorbing photons’ energy. The efficiency of the Marks’s sample is about 10% but cannot exceed this value by devices utilizing known construction [22].

In 1996 an article of Guang Lin was published in The Journal of Applied Physics. The article called “Investigation of resonance light absorption and rectification by subnanostructures” and was a first report of experimental light absorption by nanostructures. The sample consisted of a parallel dipole antennas array and a high frequency diodes. Guang Lin observed a resonance peak signal of a short circuit current and determined definition of short circuit current, wavelength and angle of the incident light [23]. The cross section of the Lins subnanostructured solar and fabricated cell by electron microscope are represented on the picture below.

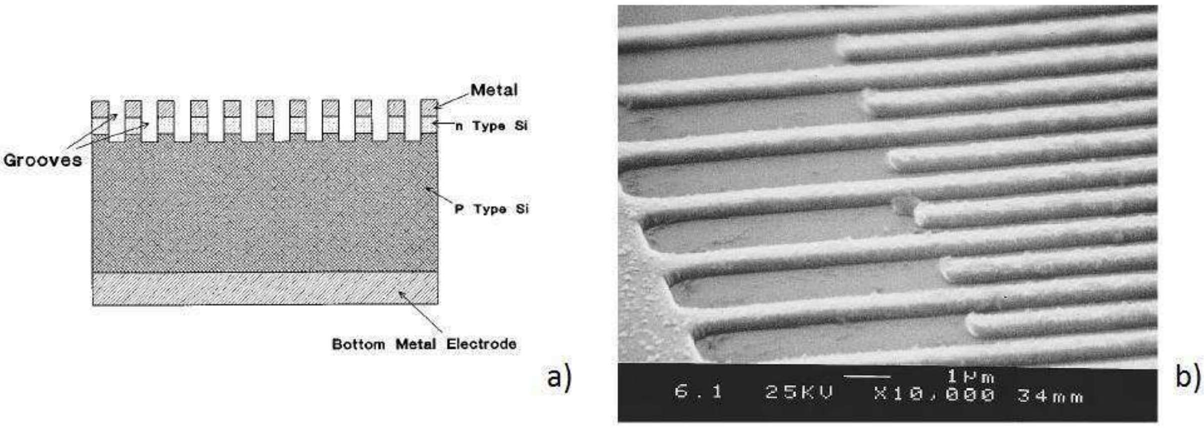

Figure 6. Side view of the designed structure (a), lateral view of a typical fabricated cell (b).

For decades interest for rectennas technologies was stable and only few laboratories worked on their projects. Interest of rectenna and nantenna technologies appeared again only few years ago with a substation leap in the rectifier technologies. A plenty of laboratories all over the world works on development of different part of the technology [20]. A timeline of a rectenna devices is represented on the figure below.

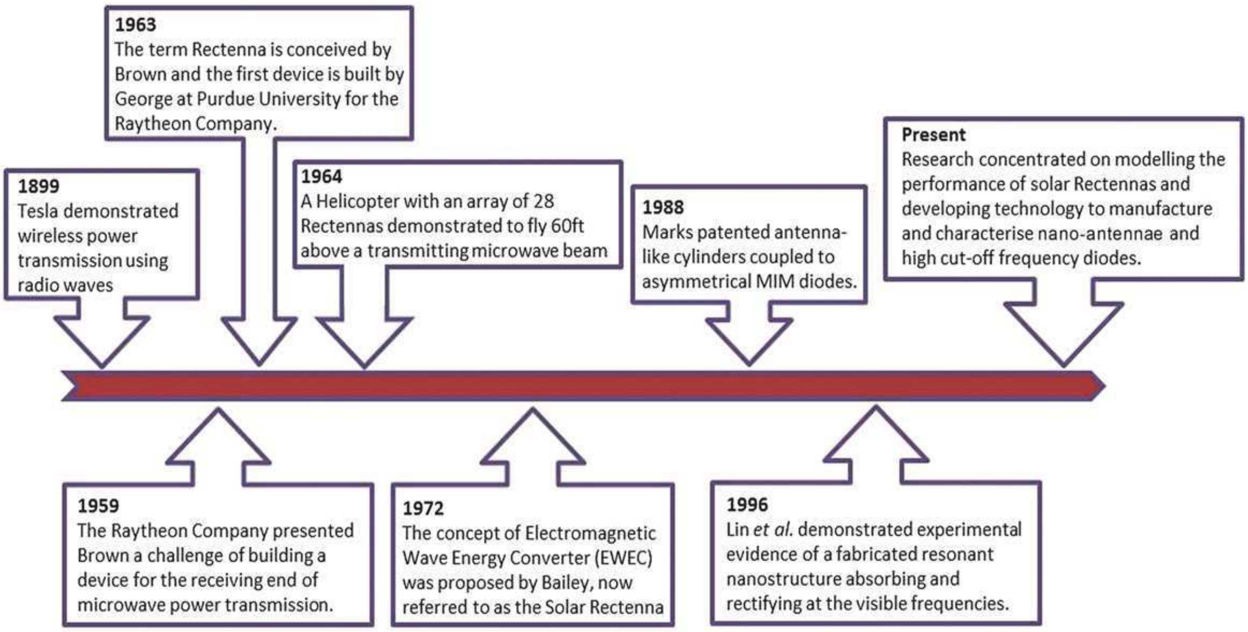

Figure 7. Brief timeline of the rectenna device – from concept for microwave power transmission to research focused on solar harvesting [24].

After proving of the concept of the optical rectenna operation, Idaho National Laboratory created a laboratory-scale nantennas massive by electron beam lithography technology from a gold film, a thin layer of manganese, and amorphous silicon layer. Their optical rectenna sample consists of the antenna, the optical resonance cavity and the ground plane. This sample did not include a rectification diode [25].

3.2 Operational principle of optical rectennas

A rectenna is a special antenna which is used for absorption energy of electromagnetic wave and transformation to electric energy in the form of direct current. Usually they are used in systems of wireless power transmission and represent as a dipole antenna with a diode connected across dipole parts. An alternating magnetic field of an electromagnetic wave induces an alternating current in a dipole antenna. A rectifier diode detects alternating current to direct current absorbed by dipoles.

The major factors determining the antenna design are the antenna resonant point and the frequency range where the antenna can operate. These factors are essentially important because especially they will influence to efficiency of a proposed devise. An antenna can be represented as a form of a circuit with inductance and capacitance and can be named as RLC circuit which has a resonant frequency. At the resonant frequency the inductive and capacitive reactances cancel each other. At this stage the antenna has only active resistance which can be replaced by the losses resistance [26]. The loss resistance is determined by the real value of resistance of the element. The power expending to loss resistance is lost as heat. The resistance of a circuit using AC current will be higher than for a DC-mode as a result of skin effect appearing. The resistance will be proportional to the conductor circumference and the square root of the frequency [26]. A picture below represents a relation of impedance value to frequency changing.

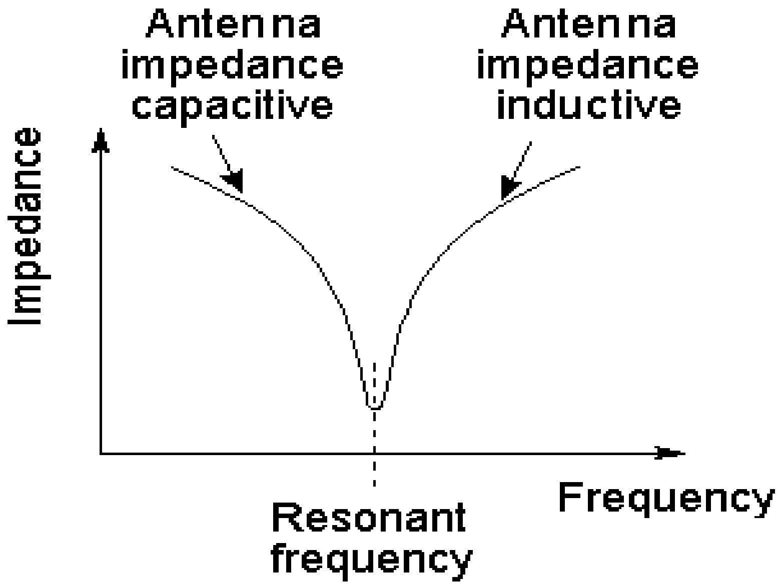

Figure 8. Impedance of an antenna with frequency [26].

The operational principles of optical rectennas are the same as for traditional rectennas. A quasiparticle which determines electromagnetic waves energy is photon. It means that photon is the electromagnetic force carrier. Incident photons on the antenna causes to appearing of free charge carriers vacillating with frequency of the absorbed wave. Appearing of free electrons and their movement back and forward is an alternating current. The frequency of the alternating current will be the same as the frequency of absorbed wave. Nevertheless, for efficient power of a load direct current have to be used. For rectifying alternating current diodes capable to operate with absorbed wave's frequency have to be used. The absorption of photons with resonance frequency as antenna was designed for leads to decreasing of impedance value and improving of efficiency. The antennas resonant frequency varies linearly with respect to changing of physical dimension of the antenna [27]. The solar spectrum wavelengths are in the range from 0.3-2.0μm with a maximum point at interval of visible spectrum part. That means that for increasing power production dipoles' sizes of optical rectennas have to be proportional to wavelength of visible part of solar spectrum [27].

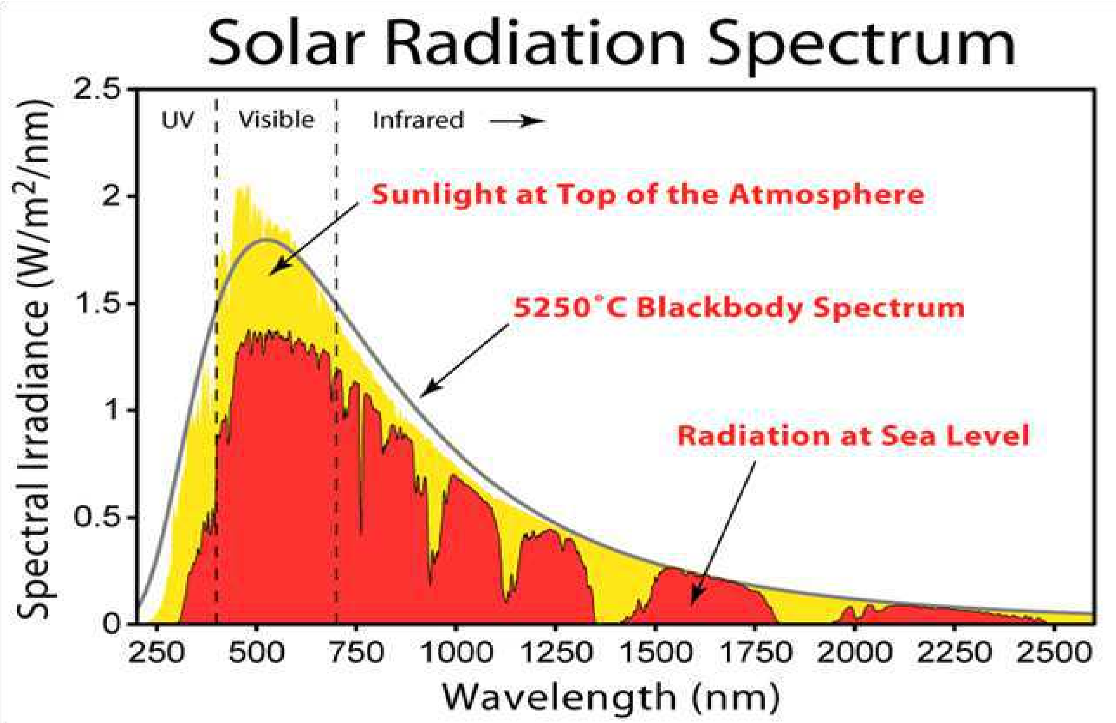

Figure 9. Spectral irradiance of wavelengths in the solar spectrum [28].

Main elements of an optical rectenna are antenna, diode and load which is connected in parallel. The schematic circuit is represented on the picture below.

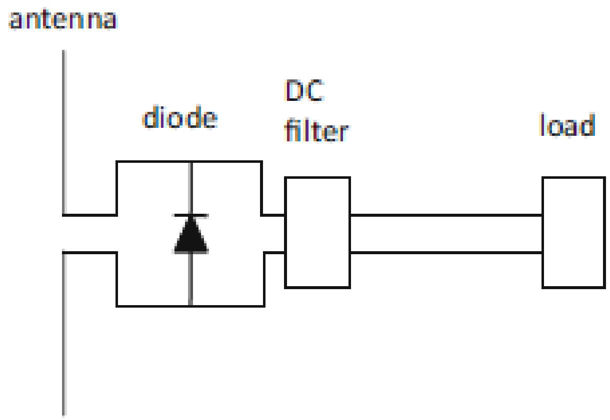

Figure 10. Rectenna circuit [20].

Antennas output signal has frequency of absorbed wave is rectified by the diode and going to the load throw a DC filter with filtering of low pass frequencies. The output DC voltage will change symmetrically as the input AC voltage [20].

3.3 Advantages of optical rectennas

Using of the optical rectennas' array as a solar cell has a several benefits which can effect for their future development. In theory the efficiency of an antenna can achieve 100%. The Carnot efficiency limit is not applicable to optical rectennas. However, the efficiency of non-laboratory sample possible can be higher than efficiency of conventional semiconductor solar cells. For the one layer of rectenna solar cell the ultimate efficiency will achieve the standard level of 44% as the efficiency limit for a one band gap solar cell.

The materials for an optical rectenna solar sell creation are wide spread and low cost. Only thin films of metal and isolation are required. The process of fabrication can be significantly low cost in principle by using of nanoimprint and roll-to-roll technologies [20]. Another benefit of rectennas for harvesting electromagnetic wave energy is that they can absorb any part of solar spectrum or another source of electromagnetic wave. The resonant frequency of rectennas can be easily changed by variation of antennas size. On the other hand changing of a band gap for standard solar cell requires changing of material or creation of combination of semiconductors.

"Multicolored" rectenna based solar cells is analogs of multifunction semiconductor solar cells can improve efficiency of the abovementioned devise. For semiconductor solar cells it requires incorporating semiconductors with different band gaps which leads to significant cost increasing. Combination of layers with different antennas size is less expensive technology than creation of multifunction solar cell. This is done in order to changing of the peak sensitivity of the optical rectenna.

Another important property of rectennas is ability to absorb infrared radiation of waste heat. In comparing to optical rectennas, infrared radiation has lower frequencies and lower RC time constant, which effects for simplification of manufacturing and selection of diode technologies [29]. However, there will be no peak of radiation intensity according to distribution of spontaneous radiation of black body. In practice it means that harvesting of waste heat by infrared antennas will have low efficiency.

The environmental issue is one of the most important questions in the modern world. The issue of pollution is still significant since the optical rectennas can be manufactured from non-toxic well developed materials. The substrate of the optical rectenna can be replaced to any non-toxic organic surface which can maintain elements of the antenna [20]. Metallic elements are made from relatively easy for recycling metals such as silver, aluminum or cupper. All abovementioned factors have significant influence to energy payback period, which can be respectively low in comparing to conventional solar cells or other technologies to harvesting of solar radiation.

3.4 Disadvantages of optical rectennas

Using of the optical rectennas' array as a solar cell has a several disadvantages which can effect for their future development. First of all this disadvantages are more as constrains and limitations. Moreover, usually they show lack of development in technologies which are taken part in the optical rectennas creation and manufacturing.

As was mentioned before one of the strongest constrain of optical rectennas using is frequencies of visible part of solar spectrum. The high frequencies of visible part of spectrum lead to high photon energy and can be named as the ideal wavelengths range because of the higher intensity of energy. Nevertheless, using of rectennas for absorption of this range of frequencies is connected with issues of antennas design and diode selection.

The center of visible light frequencies corresponds to RC time constant approximately of 0.1 fs. According to requirement of efficient rectification the rectenna time constant should be less than time constant of absorbed wavelength. In practice it means that diode resistance should match the antenna resistance according to theorem of the maximum power transfer. In this case the impedance of the whole rectenna will consist of the parallel resistance of the antennas and diode which leads to doubling the rectenna impedance. The abovementioned fact makes significant limitation of value of the rectenna capacitance. The RC time constant influences a lot of design of optical rectennas and provides a serious research issue [30].

During selection procedure of the diode for optical rectennas reverse-bias leakage of the diode should be taken into account. Current-voltage curve of the optical rectenna is represented below. The diode of the nantennas should have nonlinear relation of current to voltage in the forward and reverse operational direction according need to avoid the reverse-bias leakage [20].

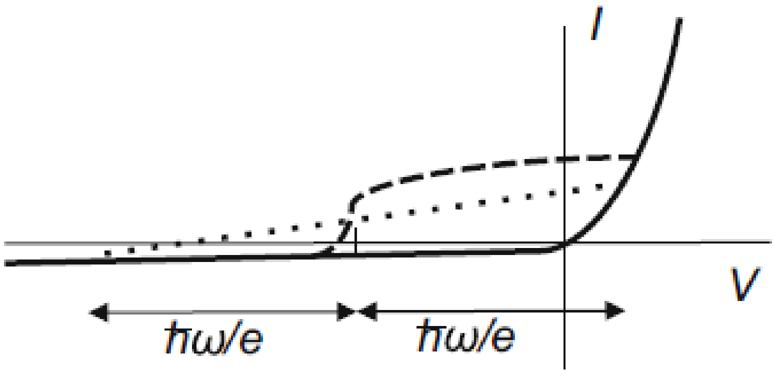

Figure 11. Current-voltage curve for a rectenna diode [20].

For the conventional semiconductor solar cells the I(V) characteristic is decreasing when intensity of illumination increases, operating point is in the fourth quadrant. As can be seen from the graph above the current-voltage characteristic of the rectennas diode has a hump of current rise in the second quadrant which will have proportional dependence to illumination intensity and photon energy. The operating point of the rectenna based solar cell is at the second quadrant where the value of voltage will be negative due to the maximum power will be at the voltage magnitude where full photons energy is extracted. The research of the rectenna diodes reverse-bias leakage was made by Moddel and Grover during their studying of the nantennas. According to their calculation for improving efficiency of solar energy absorption the diodes current should be lower than 1μA at 1V of the reverse bias [20].

Another substantial drawback of the optical rectennas is issue of their manufacturing. Today's optical rectennas are produced by electron beam lithography. The technology of their production is slow, expensive and not suitable enough for mass production. Nevertheless, lithography allows to create samples with high quality and particle size about nanometers. Usually, the electron beam lithography is using for creation of small scale laboratory samples.

3.5 Constrains of optical rectennas

Fundamental problems have to be noticed during a conversation about optical rectennas for photovoltaics systems. One of them is partial coherence. Production of electric power from fully incoherent electromagnetic wave sources is real but can be implemented by another type of generators such as Carnot engine or conventional silicon photovoltaics, which have their own limitations and constrains. The incoherence of sun radiation is a fundamental property of the sunlight. Sunlight can be characterized as partly coherent radiation according to the nature of spontaneous emission and limited solid angle subtended by the sun [30]. For an optical rectenna array the current collected from dipole antennas converted at the diode means cancellation of out-of-phase frequencies. It means that for photovoltaics systems based on optical rectennas light source should be partly coherent for efficient light absorption and rectification. In the case of lighting to the circle with radius less than 19μm a coherence of solar spectrum more than 90% can be obtained [29].

Another constrain is polarization of solar radiation. Usually antennas work with a single linear polarization. A single polarized antenna will work effectively only with 50 percent of solar spectrum. Cross-polarized antennas have been created to overcome the issue of polarization. Basically, it is combination of few layers of antennas array with different polarization located orthogonally or using of a unidirectional conical antennas for few type of polarization. In theory using of these structures can improve efficiency to 100% [31].

Third one is bandwidth of solar spectrum intensity. The broadband nature of solar radiation limits absorption possibility of a single antenna. More than 60% of the solar energy are consistent to bandwidth of 60%, but 15% is wide spread to frequencies. It creates a serious problem for optical antennas application in the aim of solar power absorber. Nevertheless, it is unnecessary to harvest whole spectrum by a single antenna. A practical solution is in using of different design antennas for splitting of solar spectrum and more affective absorption. If only 11 antennas have a bandwidth of 20% each of them, they will cover wavelength range from 0.2 μm to 2 μm [30].

3.6 Optical rectennas based solar cell

Optical rectennas based solar cell is potentially very low cost technology for transformation of electromagnetic wave energy to electric power. Creation of optical rectennas array requires respectively low cost materials and they can be few times less expensive than conventional solar cells. In fact only tin films of aluminum and plastic are using. A substrate can be freely selected from inexpensive materials such as plastic or glass. According to statements of one of researcher of optical rectenna based solar cells Steven Novak, the current estimated cost of materials for creation of nantennas massive is around 4-9 euros/m^2 [25]. On the other side, creation of optical antennas and optical rectenna diodes requires well-adjusted complex technologies such as submicron lithography. Facility for creation of this type structures are very expensive, slow and not suitable enough for large-scale production. However, the development of nan transfer or nan imprint technologies in roll-to-roll fabrication methods will improve efficiency and decrease cost of large-scale production [25].

According to limitations which were declared before at the current time there is no real optical rectennas for solar radiation absorption. During last few years devices operating with frequencies of no more than few terahertzes were represented. Nevertheless, it is a very young technology which worthy of investments and future researches.

4 QUANTUM DOTS

Semiconductor technologies are playing a significant role in the modern society based on electronic devices with complex technological operations. The researching of the properties of materials and realization of interconnection between atomic structure of materials and theirs properties marked the need of development in the area of semiconductor technologies. With development of nanotechnologies and chemistry creating of the hetero structures with new features became possible. Better control of electrical and optical properties leads to creation of electronics with better quality and fulfilling human needs more efficient. It was expressed in a new generation of electric devices such as quantum well lasers and resonant tunneling transistors [32].

The idea of hetero structures creation appears from modification of the materials band-gap by sandwiching of the thin layer of materials with different value band-gap. Creation of the quantum well became possible when two layers of material were separated by third separating layer of material with higher energy of a band-gap, for example AlGaAs. The quantum well structure confines free charge carriers motion. As a result two-dimensional confinement of electron and holes were created. The next development of the area of nanomaterials was connected with creation of quantum wires and quantum dots for one and zero-dimensional confinement respectively [33].

The first quantum dots were made of small semiconductor crystals of CdSe and ZnSe replaced into glass matrix. Depending on the condition of growing the result was a nearly spherical quantum dots with radius from 1 to 100 nm [34].

4.1 Introduction to quantum dots

Quantum dots are artificially created structures of semiconductor small enough for demonstration of quantum properties of a particle. The size of this type of structures should be on nano scale level that leads to confining of moving of free charge carriers such as electrons and holes. As in natural atoms or quantum wells with determine depth, quantum dots have bounds and discrete electronic stages. That is why sometimes they are called as artificial atoms [35].

Today quantum dots are the most interesting and attractive nanotechnology whit fast extension of possible applications. It happened because of their unique properties such as relation of the width of the band gap and the size of quantum dot, their form and material. The easy tunable band gap energy leads to thousands highly perspective applications such as new generation of transistors, solar cells, lasers and high quality displays [36].

The discovering of quantum dots happened by Alexey Ekimov during his working at the Vavilov State Optical Institute. His paper calls “Quantum size effect in three-dimensional microcrystals of semiconductor” was published in 1981 [37]. During his work, specters of exciton absorption of micro-crystals CuCl growth in glass matrix were investigated and short-wave shift which corresponds to quantum size effect was discovered [37].

Louis Brus in Columbia University discovered colloidal semi-conductor nano-crystals. The paper “Electron–electron and electron-hole interactions in small semiconductor crystallites: The size dependence of the lowest excited electronic state” was published in January of 1984 [38]. During his research at Bell Laboratory the properties of CuCl crystals was calculated such as Shrodinger equation for determination of energy stages, effective mass, kinetic energy, potential energy, lowest excited electronic state energy and relation of the band gap energy to size, shape and material of quantum dots was noticed [38].

Nevertheless, only in 1988 Mark Reed called artificial semiconductor nano-crystals as quantum dots during his work on the paper which calls “Observation of discrete electronic states in a zero-dimensional semiconductor nanostructure” [39]. The effect of resonant tunneling through the quantum dot and its relation to the discrete state density of the dot was investigated.

Over the next years hundreds laboratories and scientists all over the world were involved in the researching of quantum dots properties and features. The potential applications of quantum dots as semiconductors with unique properties exist in the areas of quantum computing, biology, quantum electronics and energy production by quantum dots based photovoltaic devices. The researching of the potential application and features of quantum dots continue to this day. Moreover, the first commercial samples of technique used quantum dots already exist such as display screens used quantum dots for backlight and filtration of unwanted colors for improving of represented color gamut [40].

4.2 Operational principle of quantum dots

Quantum dots are artificially created semiconductor crystals which confine moving of free charge carriers in three dimensions. Basically, it means that semiconductor structures with size less than two length of Bohr radius of hydrogen atom confinement moving of exiton (the electron-hole pair). The three dimension confined system can be characterized as a potential well.

The potential well is an existed location where the local minimum of potential energy exists. The behavior of the particle with energy less than the depth of the potential well can be characterized as a fluctuation in the well bounds. The fluctuation range of the particle will depend on particles energy. From classical physics point of view, the particle cannot overcome bounds of the well, but according to quantum mechanics the particle can be found elsewhere with determine probability. It calls the tunneling effect and the probability of the tunneling effect depends on the particles mass, energy and the width of the potential well [41].

Another important property of the quantum dots is appearing of discrete energy stages of the band gap energy. In practice it is connected with solution of Schrodinger equation for infinite potential well. For quantum dots the relation of size and band gap energy exists. As stronger confinement of the particle, as the band gap will be divided on more energy levels. The result of the splitting in the strong confinement structures is the rising of the value of the emissions energy [41].

In practice the specific properties of nanostructured materials can be determined by quantity of dimensions confinement. Dimensionality of a nanostructure determines the ability of free carriers to move in a material. Usually, nanostructured materials compares with the same bulk material where free carriers are able to move freely. The continuous density of energy states leads to smooth valence and conductive band. Nevertheless, there is a dependence of a separation of an energy stages within the valence and conductive band to a quantity of atoms.

Basically, when the quantity of atoms in lattice decreases the separation of energy states appears more and more. The confinement of a material appears in extinction of continuous bands. Quantum dots are zero dimensional systems with confinement of free carriers' movement in all directions. The quantum dots density of states can be described be a mathematical delta function [42]. Different confinement systems and their density of states function can be observed on the picture below.

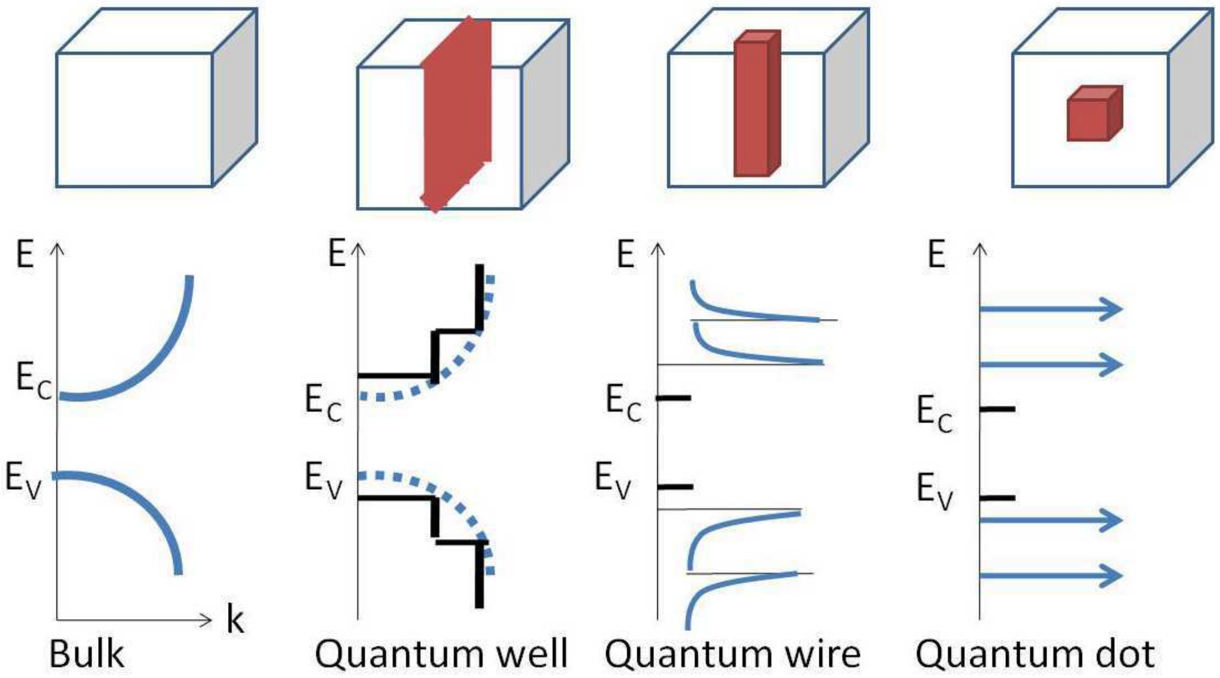

Figure 12. The density of states in different confinement configurations: (a) bulk; (b) quantum well; (c) quantum wire; (d) quantum dot [42].

4.3 Advantages of quantum dots

To begin with, nanostructured materials demonstrate unusual features and properties which are different from natural materials. The above-mentioned changes are demonstrated in sundry features beginning from melting temperature to electric conductivity. Quantum dots as three dimensional confined systems are not an exception but confirmation of superior properties of the nanomaterials. The most important changes of the quantum dots properties are based on the fact the band gap energy depends on the size of a quantum dots. In practice it means that materials with different band gap energy can be obtain form the same material by changing of a fabrication procedure or conditions of manufacturing. The effect of these changes can be noticed in changes of optical properties of the material, because changing of the band gap energy leads to significant changes of absorbing and emitting properties [42].

The physical concept of the light absorption is based on the fact that photon absorption leads to electrons' energy increasing, after overcoming the energy of chemical bonding electron excites form the valence band to the conductive band with living a hole in the valence band. Usually electron and hole are connected to each other and form an exciton pair. The returning of electron to the position of hole occurs when electrons energy decreases to the ground state and calls recombination. The process of recombination is connected with the fluorescence of the photon with the energy equal to the band gap energy [43].

As the band gap energy depends on the size of the quantum dot, it has the major effect for the energy of the emitted photon which expressed in changing of emitted light in relation to the size of quantum dot. Basically, as large a quantum dot as lower the emitted energy will be. It means that the spectrum of the emitted wave is shifted to the redder part with the quantum dots size rising [43]. The emitting spectrum of quantum dots can be observed on the picture below.

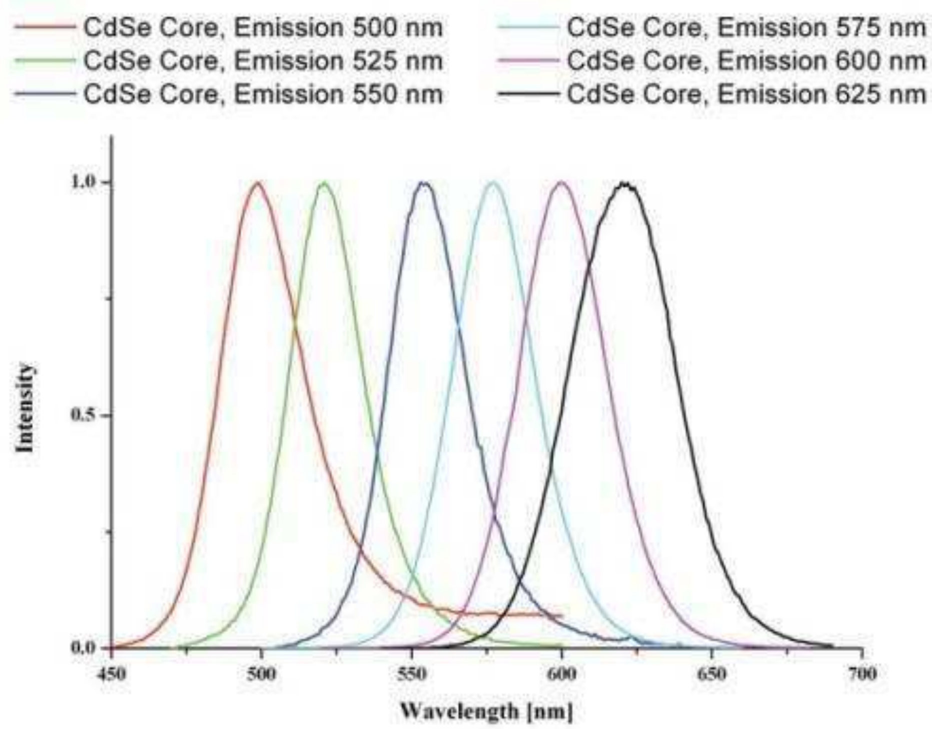

Figure 13. Fluorescence spectra of CdSe quantum dots with different size [44].

On the other side of the quantum dots light emitting is the absorption features. As the quantum confinement of quantum dots is higher as higher quantity of discrete energy states which leads to appearing of the absorption peaks in points of the energy matching. Moreover, the point of the energy absorption has determined energy fluctuation which leads to a not ideal delta function but to more realistic Gaussian destitution. All these facts lead to the appearing of the wide energy range of the absorption spectrum [45].

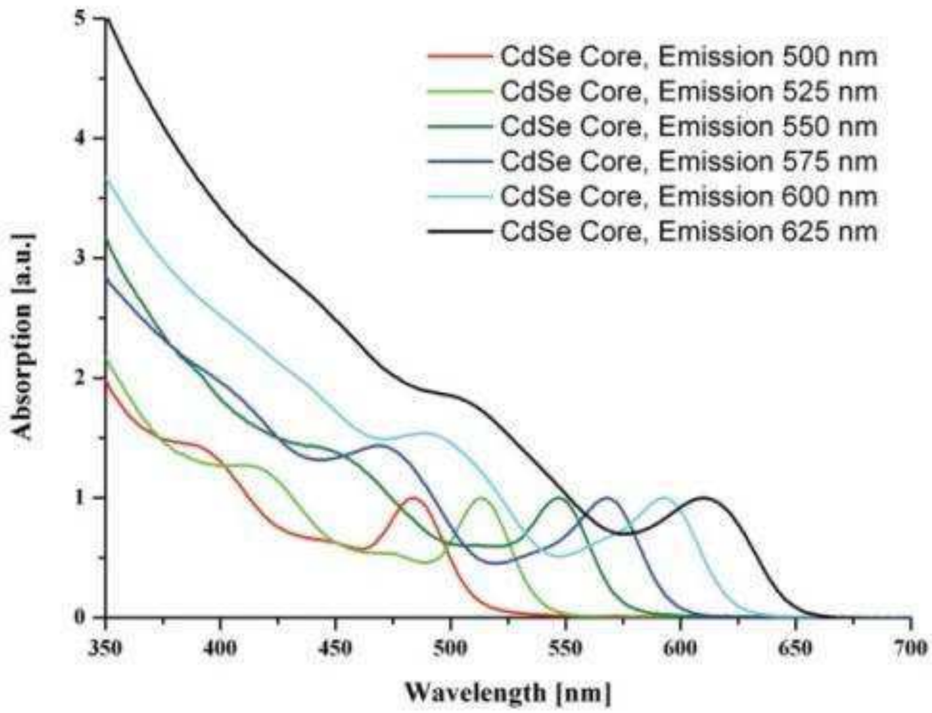

Figure 14. Absorption spectra of CdSe quantum dots with different size [44].

Moreover, quantum dots have a lot of significant features which effect to the absorption and emission of electromagnetic wave procedure. One of them is multiple electron-hole pair generation. The above-mentioned phenomena calls multiple exciton generation and is based on fact that few excitons can be produced when single photon was absorbed in quantum dots [46]. The schematic illustration of the multiple free charge carriers is represented on the picture below.

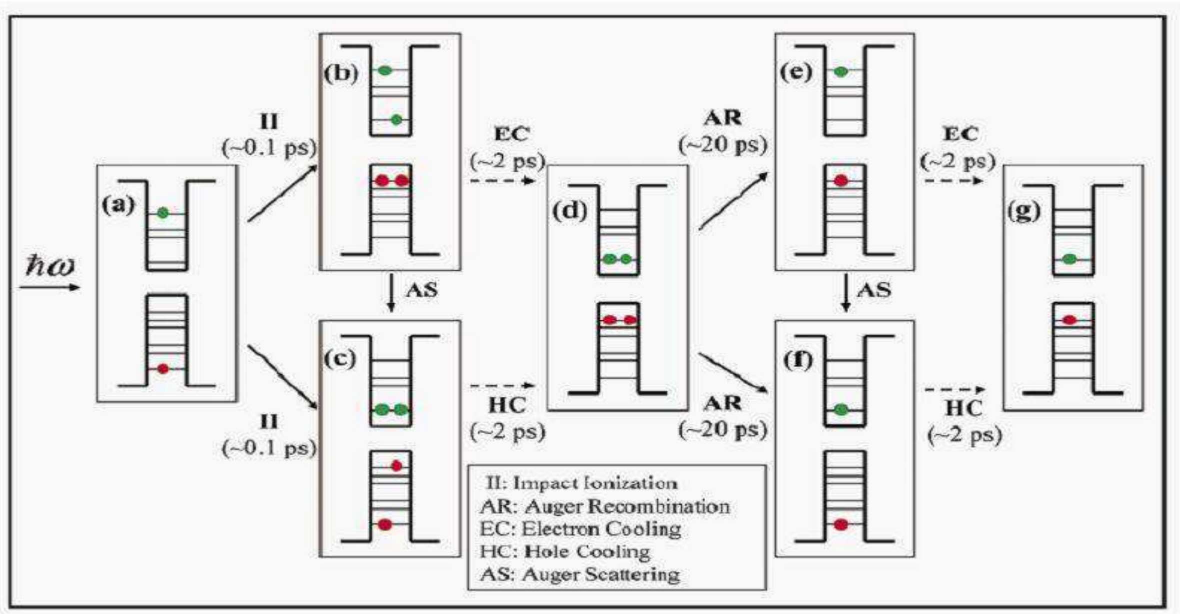

Figure 15. Illustration of the processes leading to generation of multiple charge carriers in a quantum dot [46].

Another important point is quantum dots manufacturing. At the moment there are few main methods of quantum dots synthesis exist based on the bottom up and top down ways of nanostructures synthesis. The selection of a synthesis method depends on purposes of quantum dots and will determine properties of quantum dots. The main methods of quantum dots synthesis:

1. Molecular beam epitaxy
2. Metal organic chemical vapor deposition
3. Electron-beam lithography
4. Wet colloidal synthesis
5. Spontaneous occurring in quantum well structures

The abovementioned methods are well developed and allow creating structures with required properties of size and form.

4.4 Disadvantages of quantum dots

Despite of the dozens of proses and unusual properties of quantum dots, they have some drawbacks which impact to their development and permanent using in regular life. One of them is the issue of quantum dots toxicity which became more and more important in the modern world with growing demand of nanostructures [47]. Some type of nanostructures and nanomaterials influence on the human health and have probability of environmental pollution. Notably, that the major part of research in the area of the quantum dot toxicity is focused on the poisonous of the quantum dots material such as cadmium and his compounds [47].

Nevertheless, scientists do not reject the possibility of toxicity effect depending on the quantum dots size, shape and effects of possible compounds based on the decomposed elements. The investigation of quantum dots properties and features is continuing [47].

4.5 Constrains of quantum dots

The major issue of the quantum dots using is their stability which have a significant effect for possible applications of quantum dots. The main issues of the quantum dot stability are their life time and deposition. In practice it means that researchers face with the problem of how to extend the life time of quantum dots and decrease influence of quantum dots decomposition and save its properties for longer period of time [48].

Nowadays, a lot of laboratories and companies investigate and research in the area of quantum dots life cycle. The life time depends on the quantum dots shape, form and material which they were made. Every year scientists and researchers confirm that the life time was extended and quality was improved. Nevertheless, the life time of modern quantum dots is approximately from few days to few years which lead to competition on the further quantum dots market [43]. All these set of factors and issues are made quantum dots dangerous and unreliable material for real life using. Despite of it, quantum dots have needed properties and are worth of a future research.

4.6 Quantum dots solar cell

Solar cells based on the effect of light absorption calls a quantum dot solar cell. The purpose of using quantum dots against standard semiconductors is a high ability of tunable properties of material. The main advantage of quantum dots is highly variable characteristics of the band gap energy with ability to use similar material but with different dots size which will effect for main characteristics [49]. For standard semiconductor materials the band gap energy depends on the material and cannot be easily changed. The abovementioned property of quantum dots gives a high potential in development of solar cells. In practice it means that well selected quantum dots can improve efficiency of solar panels and decrease price of their manufacturing. In wet reactions of synthesis quantum dots properties can be modified by changing of temperature and time of synthesis. Moreover, the tunable band gap energy and ability to combine dots with different size in one module make this nanostructure very attractive to creation of multijunction solar cells. Nowadays, a lot of quantum dots based solar cells exist. The principle of their work is dome different and use different properties of quantum dots [50].

5 THE THEORETICAL MODEL

The idea of the theoretical model creation is based on the need of the well explanation and physical properties analysis of the device. The main purpose of a cooperative application of quantum dots and optical rectennas is to increase efficiency of the light absorption and conversion processes inside the structure with further ability to apply these structures as the nano based solar cell with the new and perspective features and characteristics, which will effect for the development of the photovoltaic devices and renewable energy technologies.

The world which we live in is the completely dependent of the nearest start to the Earth, Sun. The hydrogen and helium of the nearest start to the earth is burning with the temperature of 5778 kelvin [51]. Due to the determine gases deposition in the process of the sun burning and determine properties of the atmosphere absorption the solar radiation spectrum has a specific form which effects to the efficiency of devices for electromagnetic radiation of sun conversion to the direct current. Actually, The process going on the sun is not burning, but chemical reaction of the helium from hydrogen synthesis which calls the nuclear fusion.

The solar radiation is the main source of energy for the earth. The major part of the energy sources which hare available for the humanity is the products or different forms of the solar radiated energy. The power is characterized by the solar constant which means the power emitted to the unit area which is located perpendicular to the sun light on the distance of the one astronomical unit from the sun surface. The solar constant is equal to the 1370 W/m^2. When the sun light is going through the earth's surface, the solar radiation lost approximate 370 W/m^2. Basically, for the ground surface at the equator point only 1000 W/m^2 accounts. Due to the photosynthesis process fossil fuels were created such as oil, coal and natural gas. The scheme below represents the energy sources and their origin.

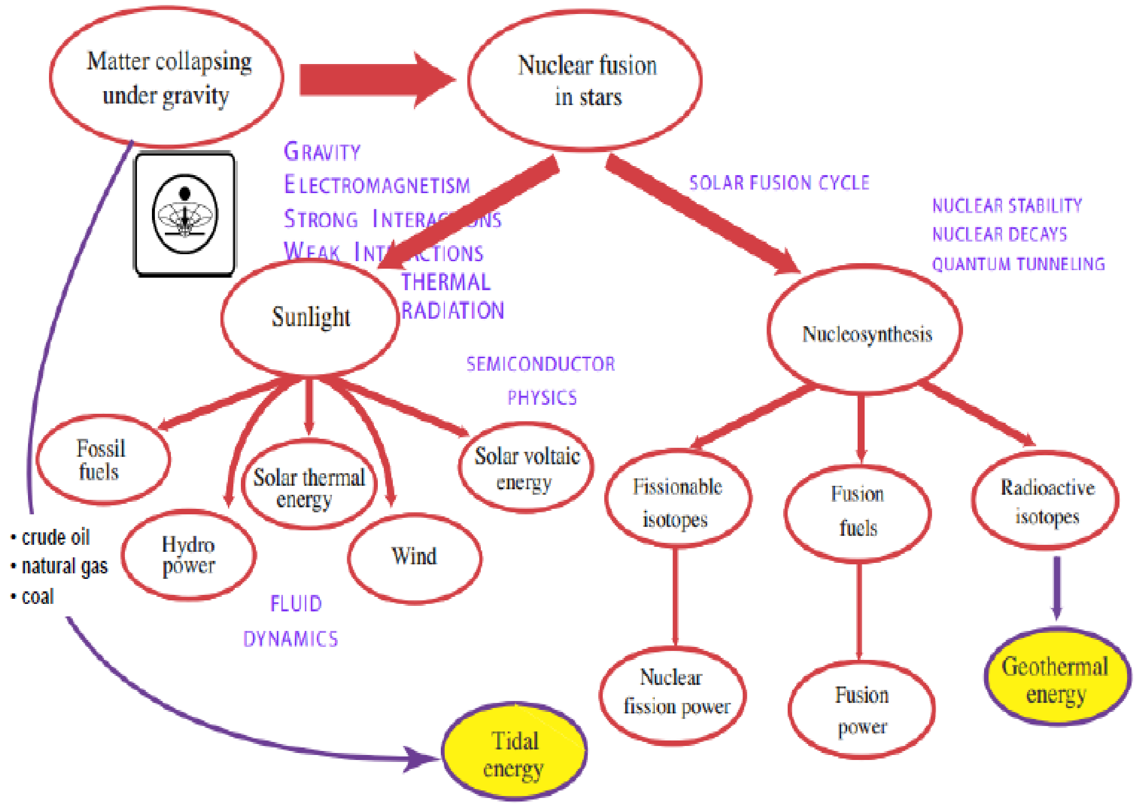

Figure 16. The types of energy sources and their nature [52].

Nevertheless, the sun was formed 4,5 billon years ago and it is considered that sun is about the middle of the star with the similar mass life time. That means that the sun radiation as the energy source is inexhaustible source of renewable energy to humanity which can cover the growing consumption of the planet few times. It is a good fact which marked development of the renewable energy technologies and commemorated the further direction of the development of the future energy sector. The picture below represents the schematic presentation of the energy sources available to the humanity and the nature of their origin. It is obvious from the figure that the major energy source is the sun power which has significant process in comparing to other sources of energy such as:

- Highest resource availability of all renewable energy sources;
- The least cost energy sources in many regions;
- There is no significant sustainable constraints;
- Greenhouse gas emissions of the energy production match the climate change constraints;
- There is no site in the world having

Figure 17. The schematic presentation of the energy sources available to the humanity [53].

5.1 Introduction to the theoretical model

The creation of the theoretical model is an important part of the research which effects for the further understanding of the processes going in the device. Due to these reasons the theoretical model is necessary. The model creation begins from the explanation of the physical processes which are going in the device. The device is based on the combination of quantum dots and optical antennas based on nanowires and high-speed diodes. The necessity using of the combination of quantum dots and optical antennas is based on the physical processes and features of the abovementioned materials.

Separated operations in these nanomaterials have their own drawbacks and negative features which effects to the development of these materials for the purposes of the solar energy harvesting. In practice it means, that using of these nano structures is constrained by their properties. The major drawback of the optical antennas consists of the nanowires and high-speed diodes is the fact that the due to the operational principals of the antennas theory, the optical rectennas cannot operate effectively with the wide range of the wavelengths.

Due to the theory of the antennas operation, the antennas can work with the efficiency about 99 percent with the determine wavelength which they design for [24]. The efficiency of the rectenna operation corresponds to the Gaussian distribution function.

Nevertheless, the optical rectennas is a decent option of the converting technology which allow effectively transform a determine range of electromagnetic wavelengths to the electric power in the form of the direct current [24]. This constraint is not important if the absorbed electromagnetic wave will have a high intensity peak.

On the other side of the abovementioned conversion technology is the layer of quantum dots which were design for the emitting of the electromagnetic wave with determine frequency. One of the most important features of the quantum dots is that the quantum dots structure can absorb wide range of wavelengths which are corresponds to the photons with energies higher than the band gap of the quantum dot.

The main principle of the combination of these technologies is based on the idea of matching of the quantum dots emitting wavelengths and optical rectennas absorbed wavelengths which will effects to the efficiency of the conversion process. In practice it means that the quantum dots emitted electromagnetic wave will be absorbed by optical rectennas surface which will convert emitted power to the electric power in the form of the direct current.

5.2 Operational principle of a quantum dots-nantennas solar cell

The basis of the approach of the combination of quantum dots and optical rectennas is reemitting properties of quantum dots. As was clarified in the paragraph 4.3 the absorption and emitting properties are unique and can help to improve efficiency characteristics of the optical rectennas based solar cell. The unique properties of quantum dots are in the absorbed and emitted spectrums which were represented on the Figure 13 and Figure 14 respectively.

In practice it means, that quantum dots are used as a frequency transformer for improvement of efficiency of optical rectennas operation. The efficiency of the made solar module will depends on the quantum efficiency of quantum dots to a great extend which means what percentage of the absorbed power can be emitted at the determine frequency. The energy of the emitted photon is equal to the band gap energy of the quantum dot which means ability of tuning of the quantum dots spectrum depending on the condition of quantum dots synthesis.

5.3 Advantages of a quantum dots-nantennas solar cell

The purposed scheme of the joint using of quantum dots as a frequency transformer and optical rectennas as a form of energy transformer has a lot of advantages which can effect to the further application of this method.

The main benefit of the abovementioned combination is in total converting efficiency improvement. The efficiency of the converting process is an important point of the potential devices using [54]. In theory using of this method allows to improve efficiency of the solar power harvesting and converting it to electric power. The calculation of the total efficiency of the converting process is a complex and substantial task. It is purposed that the efficiency of using of this method allow to improve efficiency and overcome some of the limits which are play important role in the solar energy harvesting by the conventional soar cells [54].

The principle of the total efficiency improvement is based on the ideas that harvesting and converting of the solar power is going without creation of free carriers and unique properties of quantum dots and optical rectennas. The abovementioned method allows to overcome thermodynamic efficiency limit due to the absorption properties of quantum dots which are different form the bulk semiconductor structure [55]. Moreover, multiple photon absorption plays important role in the quantum efficiency improvement. In practice the major constrain which limits the converting efficiency of this method is based on the quantum efficiency of quantum dots.

Another important reason of the method efficiency improvement is based on the concept of recombination which usually has a poor effect to the efficiency of the conventional solar cells, but the method of joint using of these technologies based on the principle of reemitting of light which implies recombination of energy carriers [33].

One of the most important reasons of the investigation of nanomaterials is in the price relation to the properties of the material. In practice it means that the using of nanomaterials and nanostructures allow to receive unique properties of the structure and decrease expenses due to the material weight reduction and efficiency improvement [8].

5.4 Disadvantages of a quantum dots-nantennas solar cell

First of all, disadvantages of the joint using of quantum dots and optical rectennas are similar to the separate using of these technologies. Nevertheless, the main constraint of this combination is difficulties with the manufacturing, production and storage of these technologies at the real life.

Basically, the main problem is in the modern technology which can limit ability of this type of structures manufacturing [24]. Nowadays, the manufacturing technology can produce this type of structures in a small scale which effects for the manufacturing cost and ability to use them in real life.

Nevertheless, it is expected that in the near future the roll and roll technology and development of quantum dots with log life time will fix the issue of the nanostructure production [20]. These structures and its manufacturing are emerging technologies and required well development and better instigation of their properties.

5.5 Purpose of research

The main purpose of this research is in creation of the new structure which will obtain new characteristics and features which can be more suitable for the solar energy harvesting and converting purposes than the conventional solar cells. The investigation and research of the renewable energy technologies play important role in the modern society and can help to save the planet and create the resilient future for the future generation.

The analysis of the new nanostructures and their properties has a significant impact for the development of new materials and creation of the new methods for the nanomaterials studying and further research.

6 QUANTUM DOTS-NANTENNAS SOLAR CELL CHARATERISTICS

The calculation and assuming of the purposed model characteristics and properties are an important and significant part of studying of new structures. The characteristics determination is a complex task which required width knowledge of quantum physics and understanding of nanostructures properties and processes going into them.

6.1 Model Creation

The model creation begins from understanding of the processes which will go inside the purposed solar cell. The main principle of the combination of quantum dots and optical rectennas is that the quantum dots surface absorbs the solar radiation in width range and emits it at the determine wavelength. The optical rectenna consist of the nanowire with the length of the quarter of the absorbed wave and high speed diode which design for the frequency of the absorbed wave.

Nevertheless, the light emitted by quantum dots will develops in the all direction which will effect and decrease efficiency of the absorption. For prevention of these negative consequences, the translucent mirror was applied. The main purpose of the half transparent mirror is to skip incident light from outside and reflect light emitted be the quantum dots.

The optical rectennas are consist of the surface of nanowires with length of a single particle equal to the quarter of the emitted light of the quantum dots and thin-film diodes which design for rectifying of the specific frequency which is equal to the frequency of the emitted light by quantum dots.

All these surfaces are located on the dielectric substrate which prevents oxidation and contact with water what will protect the solar cell and keep it save for longer time.

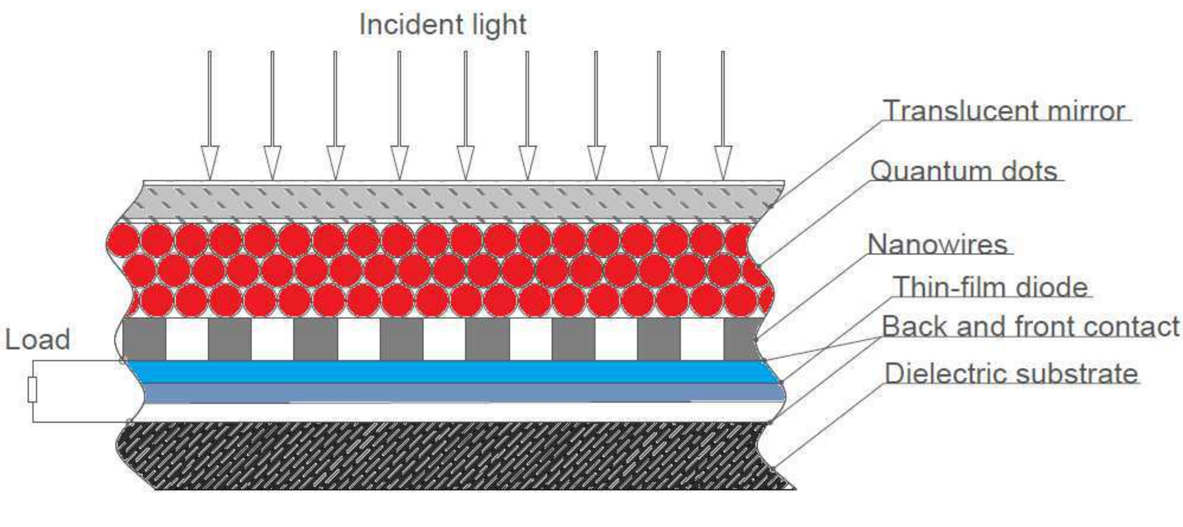

Figure 18. The cross-section of the device.

In practice incident light goes throw the translucent mirror and absorbs by the quantum dots and then emits on the determine frequency which is equal to the quantum dots band gap energy. The emitted light is reflected from the mirror surface and goes to the optical antennas which absorb the emitted light and rectifier it to the direct current which supply the load. The figure above represents the schematic cross-section of the device.

6.2 Efficiency assessment

The efficiency of any device and technology is one of the most important characteristic. In the modern world full of renewable energy technologies and energy saving abilities, the issue of the efficiency plays a significant role and effect for the further development of the technology. The picture below represents the efficiency of the different photovoltaics technologies and their development from 1976 to 2017. The major part of the conversion technologies have the similar constrains which limit their efficiency in their principle.

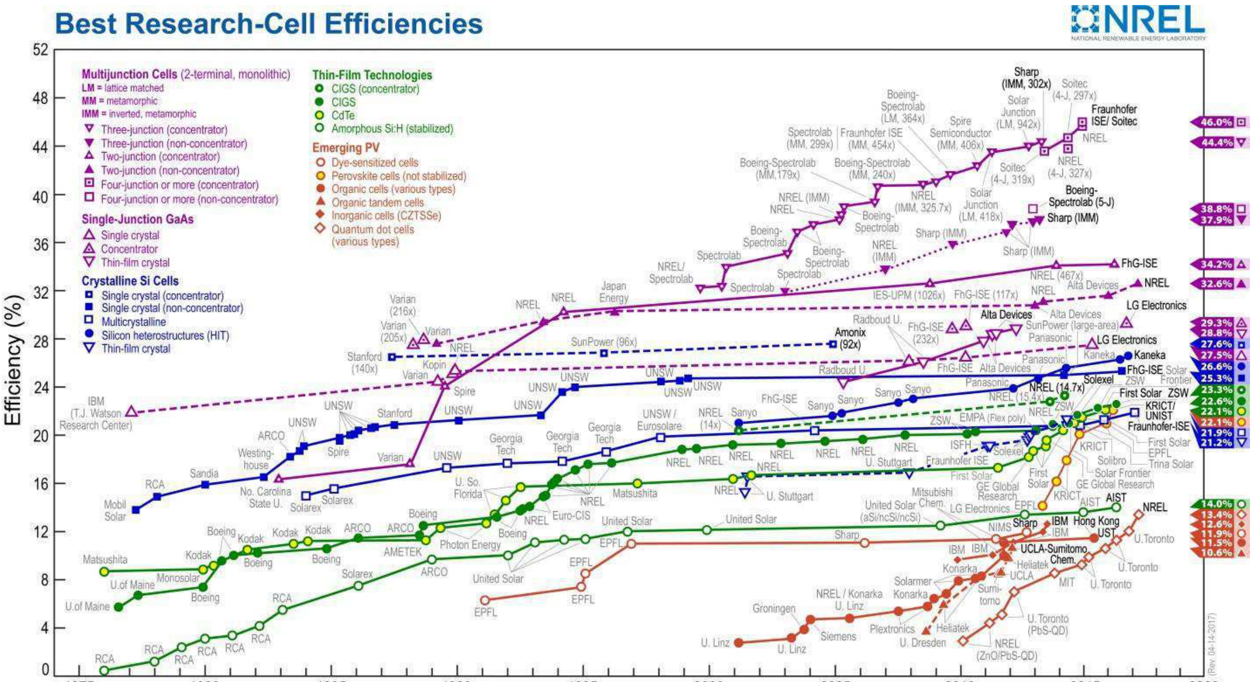

Figure 19. Conversion efficiencies of best research solar cells worldwide from 1976 through 2017 for various photovoltaic technologies [56].

The calculation of the device based on the combination of quantum dots and optical rectennas is a complex process which requires using of the quantum dots absorption and emission spectrum and characteristics of the optical rectennas such as absorption and rectification efficiency and other significant values such as quantum dots quantum efficacy and reemitting efficiency which will be different for sundry materials. Different materials of quantum dots and forms of nanowires have significant effects for the efficiency and properties of the purposed device. The schematic presentation of the efficiency calculation process is represented on the picture below.

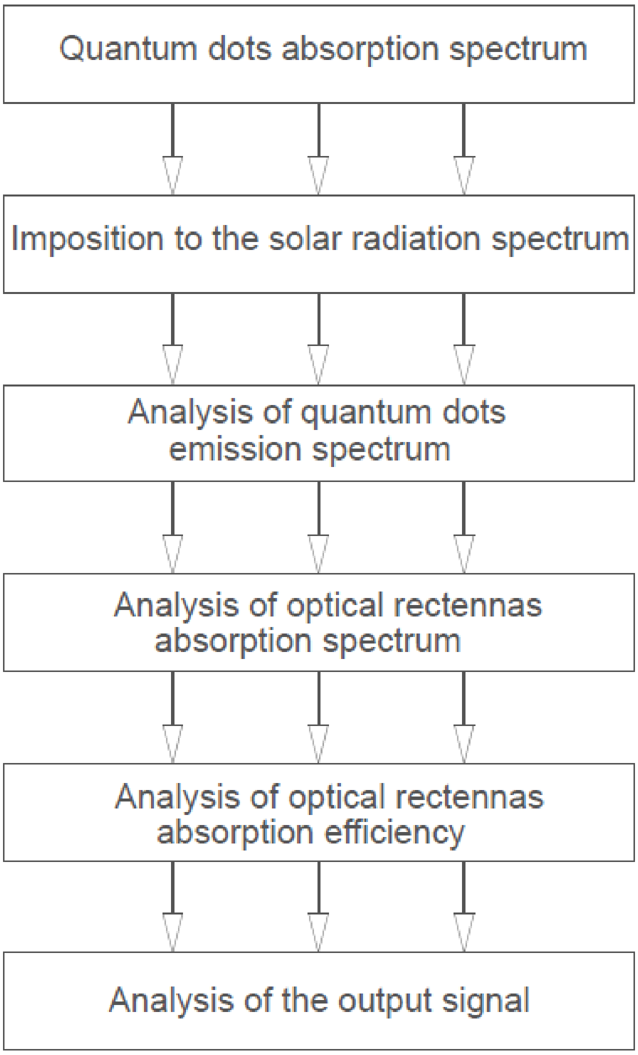

Figure 20. The diagram of the device efficiency calculation

The efficiency of the device depends on materials, forms and size of nanostructures. These factors have a significant effect for the properties of the devise. The calculation of these features requires wider studying of this device and explanation of its properties.

7 ANALYSIS OF RESULTS

The feature of the energy sector was represented and compared with the modern energy sector. The relevance of the renewable energy sector was clarified. The semiconductor solar cells operational principles were represented. Quantum dots operational principles and main features were represented. Optical rectennas operational principles and main features were represented. The significant disadvantages of the conventional technologies were analyzed. The device based on the combination of quantum dots and optical rectennas was purposed during the master thesis competing. The theoretical model was created and the main components of the device were analyzed. The efficiency issue was analyzed and the concept of the main features was clarified.

8 CONCLUSION

During completing the master thesis the device based on the combination of quantum dots and optical rectennas was purposed. The theoretical concept of the model was created. The main principles of operation and features were clarified.

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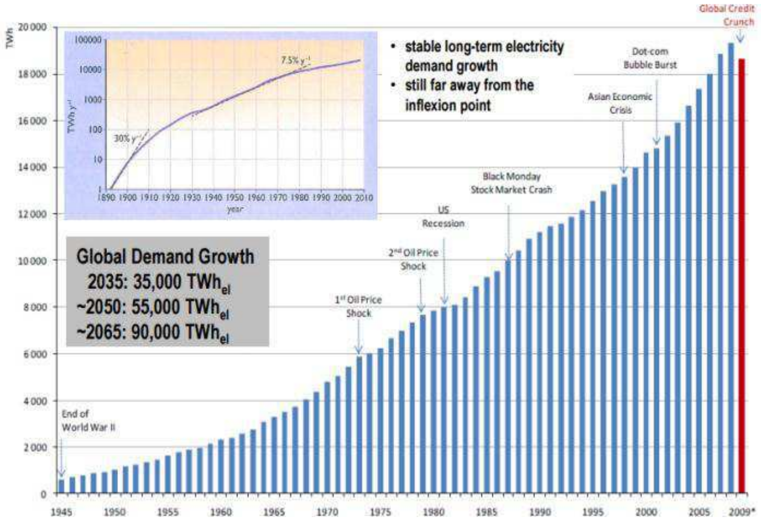
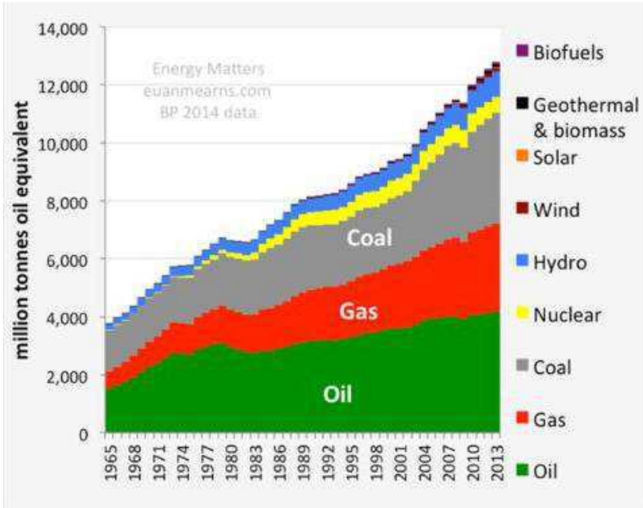
ПРИЛОЖЕНИЕ 1

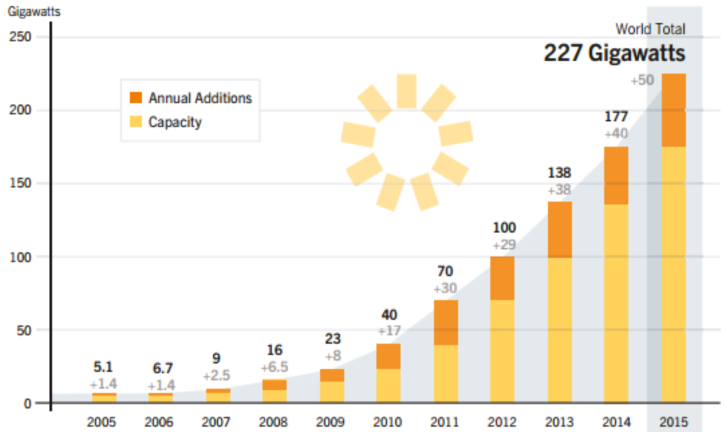
Современный сектор энергоснабжения и перспективы его развития



Потребление электроэнергии



Потребление энергоресурсов

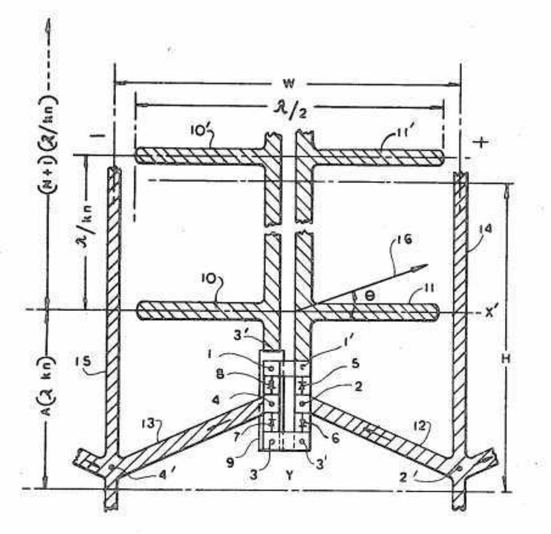


Глобальная мощность солнечных установок

Энергетические ресурсы

ПРИЛОЖЕНИЕ 2

Описание теоретических основ работы оптических антенн и квантовых точек



Оптическая ректенна

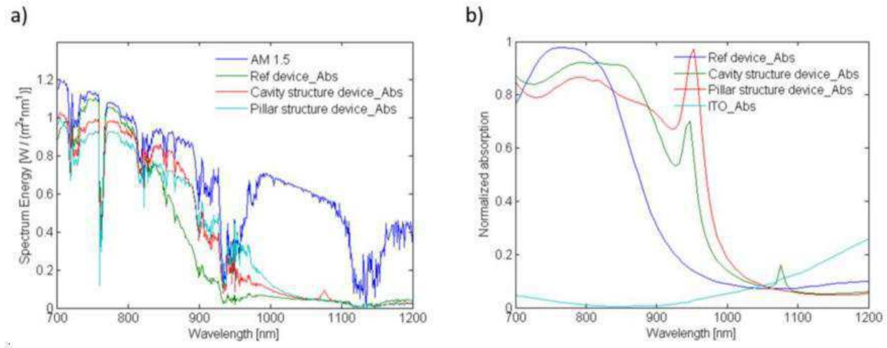
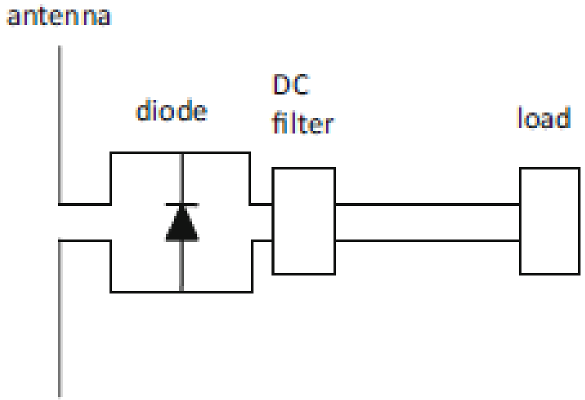
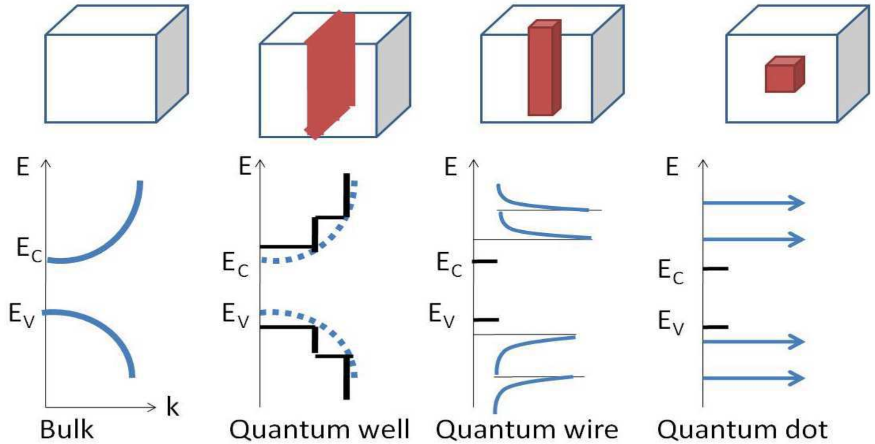


Figure 4. The light absorption spectra for PbS colloidal quantum dot (CQD) layer incorporated into different ITO structures normalized to (**a**) AM1.5G spectra and (**b**) simulation light source. The absorption enhancement for both cavity and pillar structures over the reference flat structure is obvious especially at resonance wavelengths of 950 nm for both structures and 1080 nm for cavity arrays. A slight absorption loss by ITO layer was also observed, as shown in Figure 4b.

Спектр поглощения и излучения квантовых точек



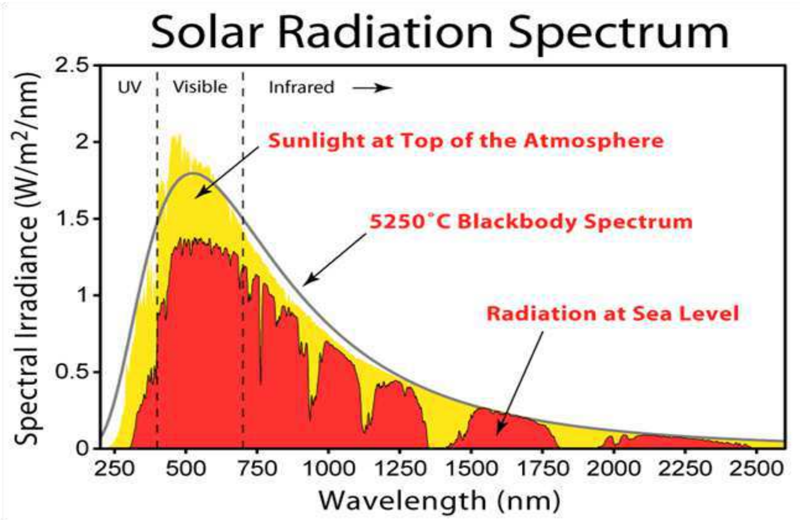
Электрическая схема оптической антенны



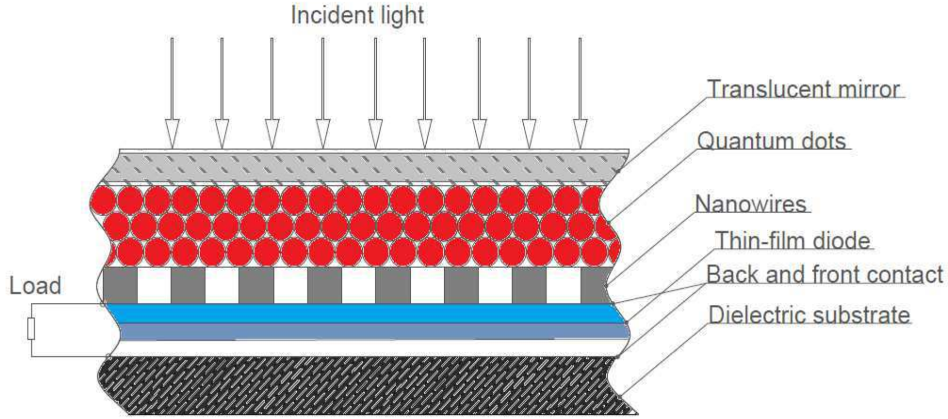
Плотность энергетических состояний

ПРИЛОЖЕНИЕ 3

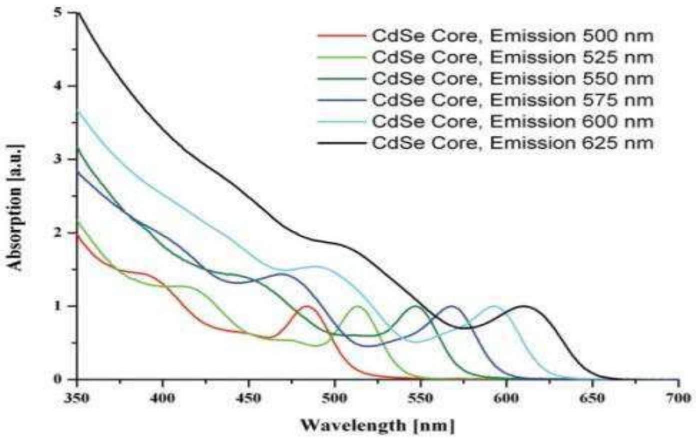
Описание теоретических основ комбинации квантовых точек и оптических антенн



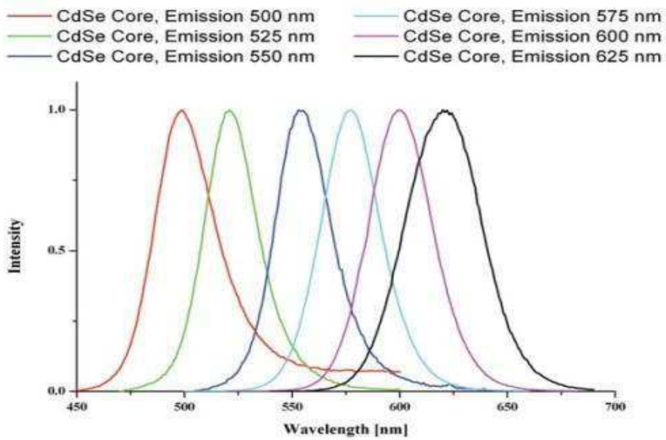
Спектр излучения солнца



Схематических разрез устройтсва



Спектр поглощения квантовых точек



Спектр излучения квантовых точек

ПРИЛОЖЕНИЕ 4

Оценка полученных результатов

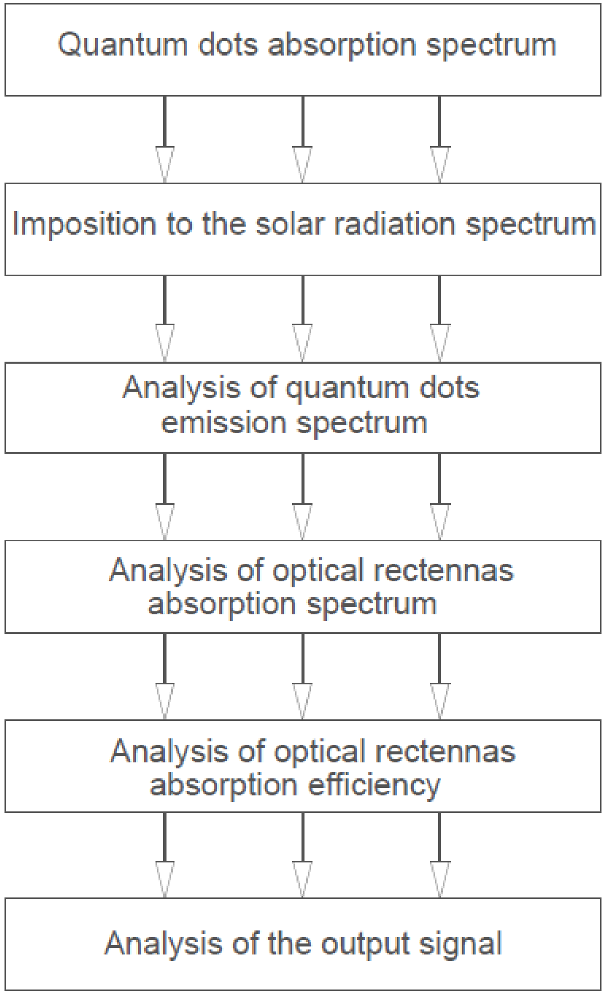
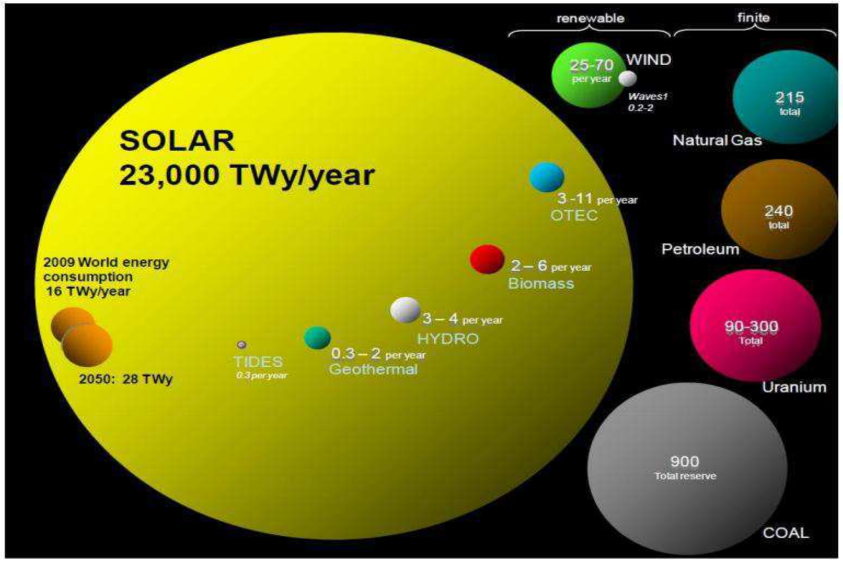


Диаграмма расчета характеристик устройства

- Highest resource availability of all renewable energy sources;
- The least cost energy sources in many regions;
- There is no significant sustainable constraints;
- Greenhouse gas emissions of the energy production match the climate change constraints;
- There is no site in the world having

Преимущества солнечной энергии



Энергетические ресурсы