



# A novel bioinspired quantum photocell based on GaN quantum dots

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**Abstract.** The efficiency of classical photocells is restricted by Shockley–Queisser limit and radiative recombination is one of the key contributors in efficiency degradation. Recent experiments on photosynthetic apparatus of plants and bacteria have suggested that these systems can overcome this limitation by exploiting excitonic quantum coherence. In photosynthetic apparatus, solar photons create excitons in the pigment protein molecules. These excitons are then transferred to the reaction centre where charge separation takes place. These processes – excitonic generation and subsequent charge separation – are extremely efficient with almost unity efficiency and avoid efficiency degradation due to radiative recombination. Taking a cue from this biophysical process, we propose a GaN quantum dot-based quantum photocell that emulates the photosynthetic reaction centre. The proposed photocell uses delocalised excitons to exhibit efficiency larger than its classical counterpart. This further suggests that highly efficient quantum biological processes can give important pointers for developing energy harvesting quantum technologies.

**Keywords.** Quantum physics; biophysics; quantum technology; nanotechnology; photosynthetic reaction centre; quantum biology; coherence; quantum dots; quantum biomimetics; solar light harvesting.

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## 1. Introduction

Photosynthesis sustains almost all life forms on Earth [1–3]. It involves synthesis of carbohydrates from carbon dioxide and water using sunlight. Photosynthesis consists of the following steps: (a) Solar photons strike pigment protein molecules in the photosynthetic apparatus and generate excitons (bound states of electrons and holes), (b) subsequently, the antenna complex molecular network transports the excitons thus created to the reaction centre where charge separation takes place and (c) charge separation is enabled by a series of electron transfer reactions that eventually help in carbohydrate synthesis. Exact details of the molecular reactions involved in photosynthesis can be seen in great detail in ref. [4]. Of all the photons that are incident on the plant leaves, only a very small fraction eventually reaches the photosynthetic apparatus owing to various dissipation mechanisms on the way [1]. The major ones are: mismatch in solar spectrum and absorption by chlorophyll molecules, photons hitting non-absorbing

parts of the plants, some photons having less energy than what is needed to create excitons in pigment–protein complex etc. The overall efficiency of photosynthesis turns out to be 3–6%. Despite the low efficiency of photosynthesis, two electronic processes in the photosynthetic apparatus, i.e. transport of excitonic energy through the antenna complex and charge separation in the reaction centre, are extremely efficient. The antenna complex is involved in transporting excitons through a protein network and reaction centre is responsible for charge separation after it receives excitons from the antenna complex, thus converting photonic energy into charge. Both these processes are highly efficient with their efficiency approaching almost 100% [4]. This has been attributed to sustained excitonic coherence in the antenna complex and reaction centre [5,6].

In this work, we propose a quantum dot-based photocell that emulates highly efficient charge separation of photosynthetic reaction centre. In its core, it uses excitonic delocalisation over quantum dots to block the radiative recombination of electron–hole pairs, thus

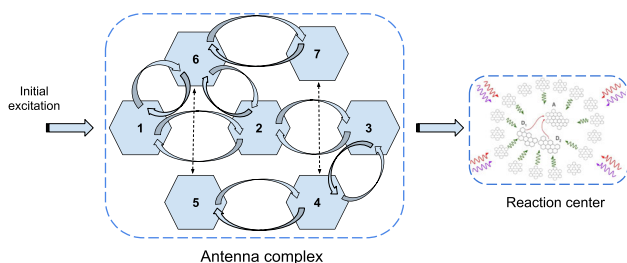
enhancing the charge separation efficiency. As a precedent to this work, Scully *et al* have proposed a photocell that exploits Fano interference to break detailed balance by suppressing radiative recombination [7].

The paper is organised as follows: Section 2 briefly introduces an archetypal photosynthetic apparatus. Section 3 illustrates how to model quantum processes therein. Quantum heat engine model of the photosynthetic reaction centre is discussed in this section. Section 4 examines the role of quantum coherence in charge separation in the reaction centre. Section 5 proposes the idea of emulation of charge separation mechanism using a GaN quantum dot system and evaluates how the excitonic delocalisation in this system can be used to enhance the efficiency of photon-to-charge conversion. Section 6 concludes the manuscript with a brief discussion about future directions related to the proposed idea.

## 2. The photosynthetic apparatus

In this work, we are only interested in the light-dependent part of photosynthesis. The two main components of the photosynthetic apparatus that are involved in this part are: (a) Antenna complex that is responsible for transporting the excitons from the pigment molecules to the reaction centre in a highly efficient manner, (b) reaction centre that captures the excitonic flux from the antenna complex. It is responsible for charge separation and supplying electrons for further chemical reactions.

Figure 1 illustrates a typical photosynthetic apparatus. The process of photosynthesis starts with the generation of excitons due to incoming photons striking at the pigment molecules [4,8]. The antenna complex consists of a network of chlorophyll molecules which is responsible for the transport of excitons from pigment molecules to the reaction centre. In the reaction centre,

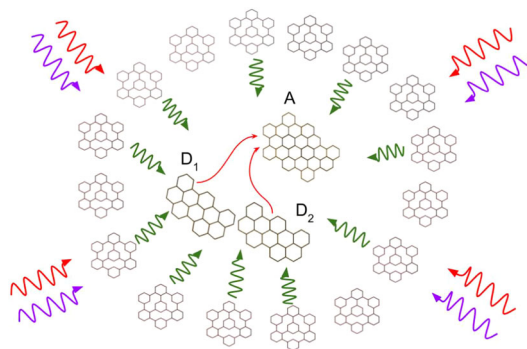


**Figure 1.** An illustration of the photosynthetic apparatus. It mainly consists of two components: (a) the antenna complex and (b) the reaction centre. Sunlight is absorbed by pigments and transported to the reaction centre via antenna complex in the form of excitons. The process of charge separation takes place at the reaction centre.

the excitonic energy is converted into more stable form of electrochemical energy. The exact structure of the antenna complex and the reaction centre of an organism depends heavily on its habitat and physiological conditions it encounters there. A wide variation is observed in the structure of the photosynthetic apparatus of different organisms, e.g. purple sulphur bacteria has ring-like structure for light harvesting antenna complex [9,10] whereas the antenna complexes of green plants and cyanobacteria consist of randomly arranged photosystems with chlorophyll molecules [9]. Here, we only deal with the charge separation mechanism in the reaction centre which is elaborated in the next two sections.

## 3. The reaction centre and modelling of charge separation

After the sunlight has been absorbed by pigments on the antenna complex, the generated excitons are transported to the reaction centre where charge separation takes place, as illustrated in figure 2. At the core of both bacterial and plant photosynthetic reaction centre, there exist two dominant charge-separation pathways [11,12]. This implies that there are at least two donor molecules that receive excitons from the antenna complex and donate the electrons to an acceptor molecule [13]. The excitonic dissociation takes place at this part of the reaction centre. The schematic of a typical photosynthetic reaction centre is given in figure 2, where  $D_1$  and  $D_2$  are the donor molecules and  $A$  is the acceptor molecule. A few recent studies have suggested that excitonic coherence between these charge separation pathways is responsible for the high efficiency of the charge separation [6,13].



**Figure 2.** Mechanism of charge separation in the reaction centre is shown in this figure. The reaction centre consists of a pair of donor molecules ( $D_1$  and  $D_2$ ) that receive excitons from the antenna complex. The donors transfer the electron to an acceptor protein molecule ( $A$ ). These electrons are further used in chemical reactions where the synthesis of carbohydrates takes place.

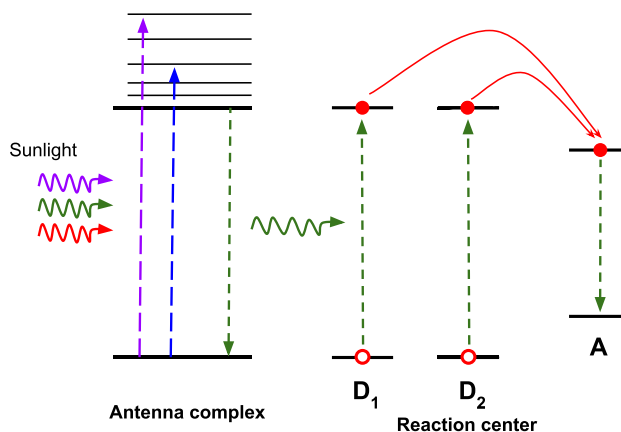
The mechanism of the reaction centre can be visualised as a quantum heat engine operating between high-temperature solar radiation and low-temperature protein phononic bath [13]. It transforms the energy of the solar radiation into electron flux [13]. The reaction centre consists of a pair of donor molecules and an acceptor molecule. These molecules sit at the end of the antenna complex that transport excitons from pigments to the reaction centre. Essentially, the mechanism at the reaction centre can be summarised as follows:

- The broadband sunlight is captured by the pigments.
- The absorbed light is then transferred to the reaction centre via antenna complex in the form of narrow-band excitations.
- The pair of donor molecules in the reaction centre receives these excitations and transfers electrons to the acceptor molecule sitting nearby.
- The electrons are utilised in photosynthetic chemical reactions and we are left with the positively charged system.
- Another electron transfer process happens from the nearby environment to the photosynthetic apparatus, thus completing the cycle and bringing the system to its original charge neutral state [13].

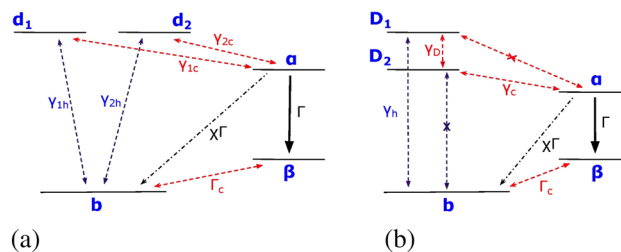
This entire mechanism can be modelled in the following way [13]:

- The initial state of the reaction centre when it does not have any exciton is denoted as  $a$  and the states after each of the donor molecules has received excitons are denoted as  $b_1$  and  $b_2$ , respectively. Thus, in states  $b_1$  and  $b_2$ , donor 1 and donor 2 molecules have bound electrons and holes.
- After the donor molecules have transferred the electron to the acceptor molecule, the state of the reaction centre is denoted as  $\alpha$ . Finally,  $\beta$  is the state of the reaction centre in which the electron from the acceptor molecule has been transferred to a ‘sink’ where it is utilised in photosynthetic chemical reactions.
- The transition from the state  $a$  to  $b_1$  and  $b_2$  is caused by the solar radiation. The transition from  $b_1$  and  $b_2$  to  $\alpha$  happens after the electron loses excess energy in the form of a phonon. Further, the electron is transferred from state  $\alpha$  to  $\beta$  with a rate of  $\Gamma$ .
- The final step that brings the system back to the charge neutral state is modelled as a transition from the state  $\beta$  to the state  $a$ .

An illustration of the mechanism of charge separation in the reaction centre is shown in figure 3. The state diagram of the reaction centre is shown in figure 4a. In the photosynthetic reaction centre, there are two charge separation pathways corresponding to the electron transfer from two donors to an acceptor. This electron transfer



**Figure 3.** Dynamics of excitonic transport and charge separation in photosynthetic apparatus is shown here. Broadband sunlight is absorbed by the pigments and converted in narrow-band excitons. Subsequently, the narrow-band excitonic energy is transported via antenna complex to a ‘special’ pair of donor molecules ( $D_1$  and  $D_2$ ) in the reaction centre. Donor molecules then transfer electrons to the acceptor molecule ( $A$ ). Overall, the photosynthetic reaction centre converts the stream of photons (sunlight) into electron flux and can thus be visualised as a heat engine.



**Figure 4.** State diagrams of the reaction centre in the absence and presence of dipole–dipole coupling between the donor molecules.  $d_1$  and  $d_2$  are the states of donor molecules before dipole–dipole interaction,  $D_1$  and  $D_2$  are the donor states after dipole–dipole interaction. The coupling delocalises the excitons over the donors.  $b$  is the ground state of the system.  $\alpha$  and  $\beta$  are excited and ground states of acceptor molecules. Various pathways describe the transitions among the energy levels of the centre.

can either occur individually from donor molecules to the acceptor molecule or the excitons can be delocalised over the donor molecules and the charge separation might happen coherently from donors to the acceptor, i.e. simultaneously from both the donors to the acceptor. First we describe the excitonic dynamics in the reaction centre and then the effect of coherence on the efficiency of charge separation will be analysed.

The donor molecules in the reaction centre are very closely spaced. Therefore, the energy levels of these molecules might interfere with each other owing to the presence of excitonic dipole on them and can give rise to new energy levels after constructive and destructive

interferences [6]. Alternatively, the two donor levels might undergo Fano interference-induced quantum coherence owing to their coupling to the antenna complex [13]. In both the cases, it has been observed that the charge separation efficiency increases owing to these quantum coherence mechanisms. Let us take the case when donor molecules undergo excitonic coupling due to dipole–dipole interaction. The total Hamiltonian of the system would look like

$$H = H_O + H_I, \quad (1)$$

where  $H_O = \hbar\omega_1\sigma_1^+\sigma_1^- + \hbar\omega_2\sigma_2^+\sigma_2^-$  and  $H_I = J_{12}(\sigma_1^-\sigma_2^+ + \sigma_2^-\sigma_1^+)$  where  $\omega_i$  are the energy level spacings on the quantum dots and  $\sigma_i^+$  and  $\sigma_i^-$  are dipole raising and lowering operators. In this case, the state diagram of the system looks like figure 4 [6]. The diagram shows the energy levels of the reaction centre with and without dipole–dipole interaction. The dipole–dipole moment modifies the eigenstates of the system. In addition, due to the dipole–dipole interaction between the excitonic states, the dipole moment of the new states formed after interaction is modified. This results in modified transition dipole moments of the states, with the state undergoing constructive interference has the increased transition dipole moment and the state undergoing destructive interference has the decreased transition dipole moment [6]. This results in the former state being optically much more active than the latter. In figure 4, this is shown by various inter-state transitions. The figure shows that when there is no dipole–dipole interaction, there is photon-mediated transition between the ground state of the system ( $b$ ) and the excited states of both the donors ( $d_1$  and  $d_2$ ) with rates  $\gamma_{1h}$  and  $\gamma_{2h}$  respectively. On the other hand, after the dipole–dipole interaction between the donor pair, the state  $D_2$  has very less transition dipole moment. Therefore, transition from the ground state ( $b$ ) to this state is suppressed (shown by a crossed arrow). Now the only photonic transition occurring is from the ground state ( $b$ ) to the state of higher transition dipole moment ( $D_1$ ). However, the charge transfer coefficient of state  $D_2$  is much higher than charge transfer coefficient of state  $D_1$  which makes transfer of electron from state  $D_1$  to the acceptor very weak [6]. Therefore, a phonon-mediated interaction between  $D_1$  and  $D_2$  brings the exciton from state  $D_1$  to the state  $D_2$  with the rate of  $\gamma_D$ . The state  $D_2$  transfers the electron to the acceptor (represented by the state  $\alpha$ ) with the rate of  $\gamma_c$ . The acceptor molecule transfers the electron for further chemical reactions with  $\Gamma$  rate. This is the electron flux that the reaction centre generates out of the incoming excitons. This whole process leaves the donors+acceptor system in a charged state.

This system can pick up an electron from the surroundings and become charge neutral again, thereby going back to its ground state. This amounts to transition from state  $\beta$  to the ground state of donors ( $b$ ). The rate of this transition is denoted by  $\Gamma_C$ . The possibility of acceptor molecule transferring the electron back to the donors has also been accounted for with a rate of  $\chi\Gamma$  where  $\chi$  is a dimensionless ‘loss’ coefficient.

Finally, dynamics of the whole system reads as [6]

$$\dot{\rho}_{D_1D_1} = -\gamma_D[(1+n_D)\rho_{D_1D_1} - n_D\rho_{D_2D_2}] - \gamma_h[(1+n_h)\rho_{D_1D_1} - n_h\rho_{bb}] \quad (2)$$

$$\dot{\rho}_{D_2D_2} = \gamma_D[(1+n_D)\rho_{D_1D_1} - n_D\rho_{D_2D_2}] - \gamma_c[(1+n_{2c})\rho_{D_2D_2} - n_{2c}\rho_{\alpha\alpha}] \quad (3)$$

$$\dot{\rho}_{\alpha\alpha} = \gamma_c[(1+n_{2c})\rho_{D_2D_2} - n_{2c}\rho_{\alpha\alpha}] - (\Gamma + \chi\Gamma)\rho_{\alpha\alpha} \quad (4)$$

$$\dot{\rho}_{\beta\beta} = \Gamma\rho_{\alpha\alpha} - \Gamma_c[(1+N_c)\rho_{\beta\beta} - N_c\rho_{bb}]. \quad (5)$$

The population conservation dictates

$$\rho_{D_1D_1} + \rho_{D_2D_2} + \rho_{\alpha\alpha} + \rho_{\beta\beta} + \rho_{bb} = 1. \quad (6)$$

The thermal occupation of states is given by the Planck distribution:

$$n = \frac{1}{e^{\frac{\Delta E}{k_B T_a}} - 1}. \quad (7)$$

The charge separation efficiency is quantified by analysing the current–voltage ( $I$ – $V$ ) and power–voltage ( $P$ – $V$ ) characteristics of the system. The current ( $I$ ) in the reaction centre is defined as the rate of outgoing electrons from the acceptor molecule. Mathematically,

$$I = e\Gamma\rho_{\alpha\alpha}. \quad (8)$$

The outgoing electrons from the reaction centre are modelled as electron transfer between states ( $\alpha$ ) and ( $\beta$ ). This electron transfer process is driven by the chemical potential difference between these two energy levels. The population of the states  $\alpha$  and  $\beta$  can be deduced from the Fermi–Dirac distribution as [7]

$$\rho_{\alpha\alpha} = \frac{1}{\exp\left(\frac{E_\alpha - \mu_\alpha}{kT_a}\right) + 1} \quad (9)$$

$$\rho_{\beta\beta} = \frac{1}{\exp\left(\frac{E_\beta - \mu_\beta}{kT_a}\right) + 1}. \quad (10)$$

The voltage across states  $\alpha$  and  $\beta$  is given as (approximating Fermi–Dirac distribution by Maxwell–Boltzmann distribution) [7]:

$$eV = \mu_\alpha - \mu_\beta = E_\alpha - E_\beta + kT_a \ln\left(\frac{\rho_{\alpha\alpha}}{\rho_{\beta\beta}}\right). \quad (11)$$

Power ( $P$ ) is the multiplication of the current and voltage.  $E_\alpha$  and  $E_\beta$  are the energy levels of states  $\alpha$  and  $\beta$



respectively, as shown in figure 4.  $T_a$  is the ambient temperature. In summary, the voltage defined by eq. (11) signifies the potential drop that an electron undergoes when it is transferred from state  $\alpha$  to the state  $\beta$  [13]. The current defined by eq. (8) captures rate of electron transfer from the acceptor molecule to the photosynthetic chemical reactions.

#### 4. Role of coherence in charge separation mechanism in photosynthetic reaction centre

To observe the effect of dipole–dipole interaction and excitonic delocalisation on the donors, we analyse the current–voltage ( $I$ – $V$ ) and power–voltage ( $P$ – $V$ ) characteristics of the system with and without excitonic coupling. The value of energy levels is [6]:  $E_1 - E_b = E_2 - E_b = 1.8$  eV,  $E_1 - E_\alpha = E_2 - E_\alpha = E_\beta - E_\alpha = 0.2$  eV. The coupling is:  $J_{12} = 0.015$  eV and the rates are:  $\gamma_h = 2\gamma_{1h} = 2\gamma_{2h} = 1.24 \times 10^{-6}$  eV,  $\Gamma = 0.124$  eV,  $\Gamma_c = 0.0248$  eV. The occupation numbers of ambient phonons at room temperature for various energy levels are:  $n_D = 0.46$ ,  $n_h = n_{1h} = n_{2h} = 60000$ .

Without excitonic coupling, the master equations take the form [6]

$$\dot{\rho}_{d_1 d_1} = -\gamma_{1h}[(1 + n_{1h})\rho_{d_1 d_1} - n_{1h}\rho_{bb}] - \gamma_{1c}[(1 + n_{1c})\rho_{d_1 d_1} - n_{1c}\rho_{\alpha\alpha}] \quad (12)$$

$$\dot{\rho}_{d_2 d_2} = -\gamma_{2h}[(1 + n_{2h})\rho_{d_2 d_2} - n_{2h}\rho_{bb}] - \gamma_{2c}[(1 + n_{2c})\rho_{d_2 d_2} - n_{2c}\rho_{\alpha\alpha}] \quad (13)$$

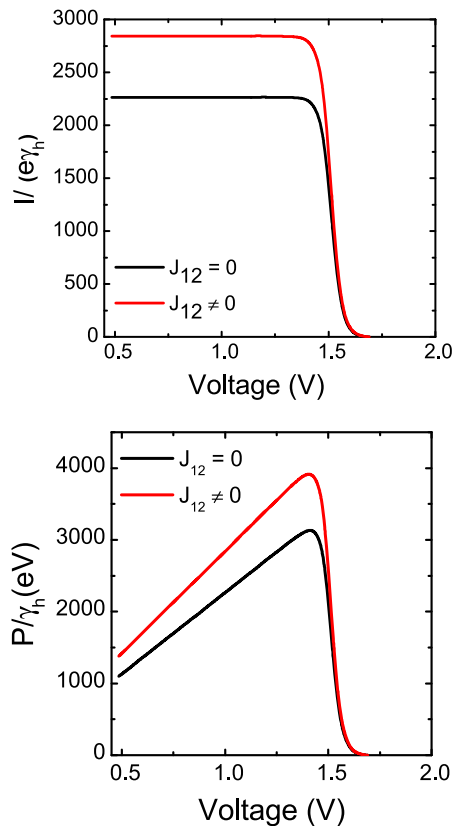
$$\dot{\rho}_{\alpha\alpha} = \gamma_{1c}[(1 + n_{1c})\rho_{d_1 d_1} - n_{1c}\rho_{\alpha\alpha}] + \gamma_{2c}[(1 + n_{2c})\rho_{d_2 d_2} - n_{2c}\rho_{\alpha\alpha}] - (\Gamma + \chi\Gamma)\rho_{\alpha\alpha} \quad (14)$$

$$\dot{\rho}_{\beta\beta} = \Gamma\rho_{\alpha\alpha} - \Gamma_c[(1 + N_c)\rho_{\beta\beta} - N_c\rho_{bb}] \quad (15)$$

and the population conservation gives

$$\rho_{d_1 d_1} + \rho_{d_2 d_2} + \rho_{\alpha\alpha} + \rho_{\beta\beta} + \rho_{bb} = 1. \quad (16)$$

The current–voltage ( $I$ – $V$ ) and power–voltage ( $P$ – $V$ ) characteristics are shown in figure 5. When the excitons are coupled via dipole–dipole interaction and are delocalised, the excitonic dynamics of the reaction centre is governed by eqs (2)–(6). As is evident from figure 5, the  $I$ – $V$  characteristics improve by around 25% when the excitons are delocalised due to dipole–dipole interaction. Similarly, the  $P$ – $V$  characteristics of the centre also show 25% enhancement. This enhancement in charge separation efficiency as quantified by the  $I$ – $V$  and  $P$ – $V$  characteristics indicates that coherence and excitonic delocalisation might indeed be playing a crucial role in causing high efficiency of charge separation in the reaction centre.



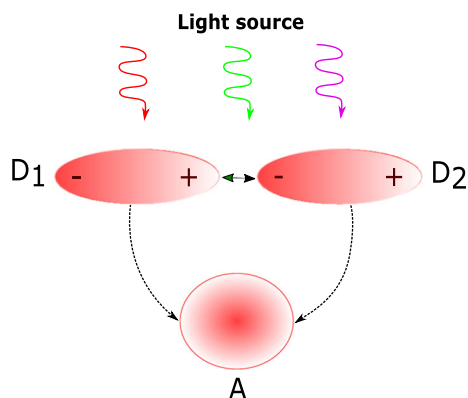
**Figure 5.** Current–voltage ( $I$ – $V$ ) and power–voltage ( $P$ – $V$ ) characteristics of the reaction centre with and without dipole–dipole interaction between the donor molecules. These characteristics are reproduced from ref. [6] and shows that excitonic delocalisation due to dipole–dipole interaction might account for the high efficiency of charge separation (characterised by  $I$ – $V$  and  $P$ – $V$  characteristics here) in the reaction centre. The figure shows an improvement of around 25% in both the steady-state current and the peak power delivered by the reaction centre.

#### 5. Emulation of the photosynthetic reaction centre using a quantum dot based system

##### 5.1 The idea

Charge separation is a crucial step in photovoltaic devices [14]. The mechanism involving excitonic delocalisation for highly efficient charge separation in the reaction centre gives us pointers for designing a highly efficient charge separation device. Of all the solid-state systems available, quantum dots seem to be a viable candidate to realise such a device as GaN-based quantum dots have been shown to host delocalised excitons [15,16].

Much progress has been made in quantum dot-based realisation of qubits and other quantum computing operations [16–18]. Quantum dot-based photovoltaic

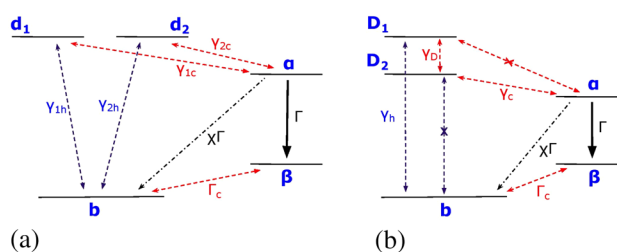


**Figure 6.** A quantum dot-based system that can potentially emulate the photosynthetic reaction centre and enable high efficiency photon to charge conversion. It consists of two very closely spaced GaN quantum dots ( $D_1$  and  $D_2$ ). The in-built electric field delocalises the excitons over them. They are coupled to a third quantum dot  $A$  via tunnelling coupling.  $D_1$  and  $D_2$  transfer the electrons to quantum dot  $A$  via tunnelling when there is a difference in chemical potential across them.

devices constitute an equally popular area of research [19,20].

It turns out that these two areas of research can be bridged and the study of quantum effects in photosynthetic reaction centre enables us to do this. The idea is as follows: quantum dots with built-in electric fields give rise to high excitonic dipole moment. This results in dipole–dipole coupling between the excitons if their host quantum dots are close enough. This coupling shifts the energy levels of the excitons and make them delocalised over the dots. Quantum dots based on GaN heterostructures exhibit strong built-in electric fields due to the spontaneous polarisation and piezoelectric field which also makes them an ideal candidate to be used as qubits [16]. Most importantly, the dipole–dipole coupling between these quantum dots is of the same order as it is in the photosynthetic reaction centre donor pair [16]. Taking a cue from this, we propose a quantum dot-based system where two closely spaced GaN quantum dots are illuminated with a light source resulting in the generation of the excitons.

The built-in electric field of the GaN quantum dots causes high dipole moment of their excitons and proximity of quantum dots enables strong dipole–dipole interaction between these dots. This delocalises the excitons over both quantum dots, thus mimicking the special pair of the photosynthetic reaction centre. These two quantum dots are then coupled to a nearby third quantum dot via tunnel coupling that ensures electron transport from the donor pair to the acceptor [21]. This can be achieved by putting the system between appropriate source and drain contacts as has been proposed in ref.



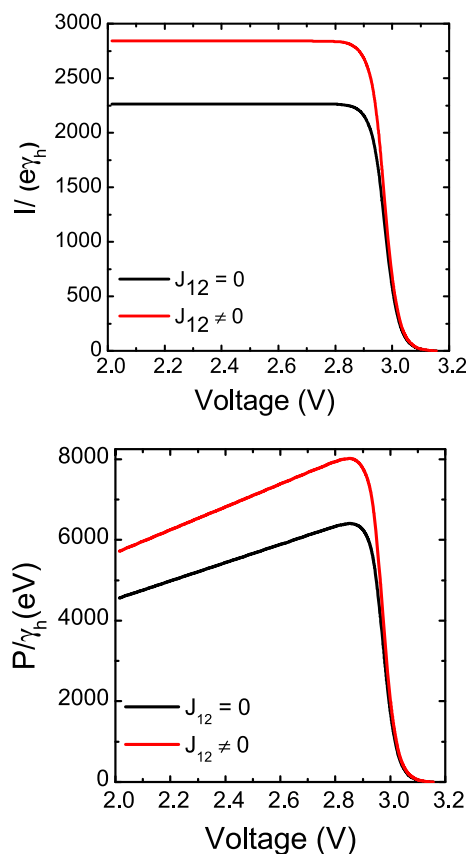
**Figure 7.** State diagram of quantum dot system demonstrating its energy in various states. Nomenclature is the same as in figure 4.

[21]. This system looks very similar to the photosynthetic reaction centre and can potentially emulate highly efficient excitonic charge separation mechanism of the reaction centre. The schematic for this idea is shown in figure 6. In addition, there would be bulk contacts to this quantum dot system which are treated classically in our model, and the Coulomb blockade issue can be addressed by using bulk contacts of appropriate band gap. The things that remain to be studied are: the formation of dark states after dipole–dipole interaction as has been mentioned for photosynthetic reaction centre in ref. [6], rates of electron transfer from donor quantum dots to the acceptor quantum dot which will depend on the strength of tunnel coupling between the quantum dots and the upconversion of the energy of solar photons to match the energy levels of the GaN quantum dots. To address the last challenge, other quantum dot systems should also be explored for hosting delocalised excitons.

## 5.2 Calculations: Effect of excitonic delocalisation on charge separation efficiency in the quantum dot system

The state diagram for the quantum dot-based system proposed to operate as coupled qubits [16] is shown in figure 7. The energy levels for this system are:  $E_1 = 3.177$  eV,  $E_2 = 3.255$  eV, and energy shift due to dipole–dipole interaction is:  $\Delta E = -4.4$  meV. The exact values of the transition rates between energy levels of GaN quantum dot systems is not known presently. Therefore, to analyse the proposed system for photon to charge conversion operation, we take the transition rate values from ref. [6] where a photosynthetic reaction centre is studied. The finite lifetime of electrons in various states causes broadening in energy levels. However, the energy offset between  $E_1$  and  $E_2$  avoids mixing of states for the transition rates taken in our calculations.

As in the case of reaction centre modelling, the role of excitonic delocalisation on charge transfer is modelled by the  $I$ – $V$  and  $P$ – $V$  characteristics of the coupled quantum dots. The current, voltage and power are defined



**Figure 8.**  $I$ – $V$  and  $P$ – $V$  characteristics of the proposed quantum dot photocell with and without coherence. Presence of coherence results in 25.41% improvement in the  $I$ – $V$  characteristics and 25.18% improvement in the  $P$ – $V$  characteristics.

exactly in the same way as they are defined for the photosynthetic reaction centre (cf. eqs (8) and (11)). The  $I$ – $V$  and  $P$ – $V$  characteristics of the system are given in figure 8 for both the cases when the excitons are localised (no dipole–dipole coupling) and delocalised (excitonic delocalisation due to dipole–dipole coupling). It turns out that there is an improvement of 25.41% in  $I$ – $V$  characteristic of the system when excitons are delocalised (quantum photocell) compared to the case when they are not delocalised (classical photocell). Similarly, the  $P$ – $V$  characteristics of the system show an improvement of 25.18% when the excitons are delocalised over the donor quantum dots compared to the case when they are not. The results show the potential of quantum effects like coherence or delocalisation in enhancing the efficiency of light harvesting. Moreover, coherence can be supported by dipole–dipole interaction which is ubiquitous in quantum dot systems, especially in III–V systems. Therefore, the quantum dot system proposed in this work is highly promising from the point of view of developing a quantum technology for harvesting solar energy.

## 6. Discussion and conclusion

Existence of excitonic quantum coherence in the photosynthetic reaction centre explains the high efficiency of charge separation in it. There have been several studies on exploring the ways in which coherence is sustained in this system and how it is harnessed for enhancing the efficiency. Two plausible ways in which coherence is sustained in the reaction centre are: (a) Fano interference and (b) excitonic delocalisation due to dipole–dipole coupling. Inspired by the dipole–dipole interaction-induced efficiency enhancement in the reaction centre, we have proposed a quantum dot-based solid-state system that can emulate the photosynthetic reaction centre and enable highly efficient photon to charge conversion. Although transition dipole moments of excitonic states in GaN quantum dots after delocalisation and electron transfer rate between neighbouring quantum dots need to be studied before developing an actual device, the proposed scheme can potentially open up a new area of research for designing improved energy harvesting devices by exploiting quantum effects.

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