Solar energy conversion and storage: Fast Green FCF-Fructose photogalvanic cell

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HIGHLIGHTS

- Fast Green FCF dye-Fructose was studied for enhancing performance of the cell.
- Observed short-circuit current and power are 380 µA and 138.6 µW, respectively.
- The obtained results are highly encouraging.
- Fast Green FCF-Fructose system enhances the performance of the cell.
- This system may be the basis for further advancement of this technology.

ARTICLE INFO

ABSTRACT

Photogalvanic cells are photoelectrochemical devices involving ions as mobile charges moving in solution through diffusion process. These cells are capable of solar power generation at low cost with inherent storage capacity. This property of photogalvanic cell needs to be exploited as this technology is cleaner and promising for application in daily life. Therefore, a photogalvanic cell consisting of Fast Green FCF as photosensitizer, Fructose as reductant and NaOH as alkaline medium has been studied with observed value of maximum potential 1083 mV, maximum photocurrent 431 µA, short-circuit current 380 µA, power at power point 138.60 µW, efficiency 1.33%, and storage capacity (as half change time) 70 min. The observed results are higher and encouraging enough for ultimate aim of development of applicable and affordable photogalvanic cells in future.

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1. Introduction

The photogalvanic cells are based on "photogalvanic effect". This term was first time used by Rabinowitch [1,2] to denote a special case of the so-called Becquerel effect, in which the influence of light on the electrode potential is due to a photochemical process in the body of the electrolyte (as distinct from photochemical or photoelectric processes in the surface layer of the electrode, which are the basis of the original Becquerel effect). Therefore, the photogalvanic cells are quite different from other cells [3–5] like galvanic or voltaic cells. Photogalvanic cells use very dilute solution of photosensitizer and reductant. The solution is the absorber phase, and it is contacted by two electrodes with different selectivity to the redox reaction. The photosensitizer is photo excited to energy rich product, which in turn can lose energy electrochemically to generate electricity involving ions as mobile charges diffusing through solution.

The photogalvanic cells where the dye undergoing photoexcited state in solution and the products regenerated at inert electrode have been investigated extensively in past, and proven very inefficient due to various reasons. The observed electrical output was very low (like potential 75 mV [6], 118 mV [7], 450 mV [8]; power 0.038 µW [6]; current 12 µA [9]; and energy conversion efficiency of the order of 0.0022% [10], 0.06% [11], 0.22% [8]). It is to be noted that the earlier researcher emphasized more on mechanism, kinetics and other insights of photogalvanic cells. This lower electrical output might have been due to some complex and unsuitable cell fabrication parameters like use of light-intercepting black plate between electrode chambers, Pt electrode in both chambers, coated Pt, only visible rays for illumination and acidic medium (low pH like 6) [6,9,12]. But, Albery and Archer forecasted that efficiency of these cells could be as high as 18% [12]. This encouraging forecast has been motivating researchers for working on photogalvanic cells, and it has also resulted into tremendous enhancement in cell performance arousing hope that these cells may be the future energy source.

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With this hope, the later researchers have studied photogalvanics in alkaline medium (high pH) with very simple fabrication involving uncoated Pt in illuminated chamber and saturated calomel electrode (SCE) in dark chamber without intercepting plate. Absence of intercepting plate may be relatively favourable for more diffusion of species between chambers leading to higher performance as these cells are diffusion controlled. And, at high pH, there may be less bleaching and higher electron ejection from dye sensitizers.

The earlier researcher emphasized more on thionine dye sensitizer with Fe^{2+} as reducing agent. Later on, the researcher [13–32] started using other dyes with organic reductant. The use of new dyes with organic reductant has led to the tremendous enhancement in cell performance. But, this cell performance further needs to be enhanced to make these cells practicable and efficient. For this purpose, the use of some other suitable dye photosensitizer with suitable reductant needs to be exploited. Therefore, the study of photogalvanic effect of Fast Green FCF with Fructose was undertaken with hope of further enhancing the cell performance. The basis of Fast Green FCF to use as photosensitizer and Fructose as reductant was – (i) Fast Green FCF has anionic structure, which is more favourable for electron donation to Pt as working electrode, (ii) Fast Green FCF (λ_{max} 622–626 nm, 427 nm) shows absorption in most convenient spectral region, i.e., visible region that makes 40% of solar irradiance, (iii) there are no reports focusing on cheap and easily available Fast Green FCF as photosensitizer with Fructose as reducing agent, and (iv) the Fructose was chosen as reducing agent due to its widely known good reducing property in rapid Furfural test, and photogalvanics [27,28].

The study of variations of variables likes concentration of dye, Fructose, NaOH, etc. was also undertaken to find out their suitable combination for optimum performance of the cell.

2. Material, method and mechanism

2.1. Chemicals

Fast Green FCF dye (90% assays, Loba Chemie) as photosensitizer, Fructose as reductant, and NaOH as alkaline medium has been used. Characteristics of Fast Green FCF dye is-class triarylmethane, M.F. $C_{37}H_{34}N_2$ $Na_2O_{10}S_3$, M.W. 808.84, λ_{max} (nm) 622–626 (high intensity band) and 427 (low intensity band) in C_2H_5OH 50%, 60 g l^{-1} solubility in water at 20 °C, 5 g l^{-1} solubility in alcohol at 20 °C and C.I.No. 42053.

2.2. Experimental and calculation method

The experimental set up is very simple and consists of a light source (Lamps of different wattage to vary the light intensity), digital pH meter (Model 335; Systronics India Ltd., Ahmedabad, India) for measuring potential (millivolt-mV), microammeter (OSAW, Haryana, INDIA) for measuring current (microampere-μA), a carbon pot log 470 K device (for changing the resistance of circuit), a circuit key, and a externally blackened H-shaped glass tube with a transparent window in one arm ($\sim$1 × 1 cm^2) for illumination [13–32].

The arm with window acts as illuminated chamber and other arm without window act as dark chamber. A platinum (Pt) electrode working as negative terminal (anode) is dipped in illuminated chamber against window and SCE working as positive terminal (cathode) is immersed in dark chamber [13–32]. The H-shaped tube is filled with known amount of the solutions of photosensitizer, reductant and sodium hydroxide. After some time a stable potential (called dark potential, V_{dark}) is obtained while circuit is open. Thereafter, the Pt electrode is illuminated and a rise

in potential is observed. The highest potential observed is termed as maximum potential (V_{max}), and after some time potential goes down marginally to a relatively stable value called as open-circuit potential (V_{oc}). Then, circuit is closed by circuit key to observe maximum current (i_{max}) at external resistance (load) zero. After some time, current goes down marginally to a relatively stable value called as equilibrium current (i_{eq}) or short-circuit current (i_{sc}). The potential at i_{sc} is nearly zero. Thereafter, the resistance of circuit is slowly raised with the help of a carbon pot log 470 K device to note increasing potential values corresponding to decreasing current (till current is zero and potential is nearly equal to V_{oc}) to study the i–V characteristics of the cell. The product of current with corresponding potential is the power. This product is calculated for every current at which the potential has been noted. This way, the highest power obtained is called power at power point (P_{pp}). And, the current and potential at P_{pp} is termed as current at power point (i_{pp}) and potential at power point (V_{pp}), respectively. The resistance at P_{pp} is characteristics external resistance load calculated by Ohms law as V_{pp}/i_{pp}. Thus, the i–V characteristics of the cell helps in knowing the characteristics external resistance load at which cell must be operated to extract highest solar power. Therefore, the cell performance of the cell in dark is studied at this characteristics external resistance load. The various potential values corresponding to various current values in dark are noted. The time taken for fall in the power of the cell to its half value of power at power point is called $t_{0.5}$ (which is measure of storage capacity of the cell). Higher $t_{0.5}$ value means cell will work for longer time in dark. The average rate of change of current over $t_{0.5}$ period ($\Delta i/\Delta t$) is calculated from ($i_{pp} - i_{t0.5})/t_{0.5}$, where $i_{t0.5}$ is current at $t_{0.5}$. The potential corresponding to $i_{t0.5}$ is $V_{t0.5}$. The charging time (t) is calculated as, charging time = (time at which V_{max} is obtained) – (time at which illumination is started). Photopotential (ΔV) is equal to $V_{max} - V_{dark}$. The cell performance is studied in terms of half time ($t_{0.5}$), conversion efficiency (CE) and fill factor (FF) in dark. The CE and FF is calculated by formula ($V_{pp} \times i_{pp} \times 100\%)/(PA)$, and ($V_{pp} \times i_{pp})/(V_{oc} \times i_{sc}$), respectively; where $V_{pp} \times i_{pp}$ is expressed in mW, and P and A is light intensity (mW cm^{-2}) and Pt electrode area (cm^2), respectively.

The initial pH of the solution taken in cell has been calculated by formula, pH = 14-pOH.

The size of open window (illuminated area of the cell) of illuminated arm has not been used for calculating the efficiency as natural sunlight is available naturally and free of cost. So to illuminate small or large area of cell does not affect the cost and environment. But, the use of small or large Pt electrode affects the cost and environment.

The H-shaped tube made of borosilicate (Pyrex) glass was used because (i) the aim of present work was to use most convenient spectral region (i.e., visible) for solar energy conversion. Pyrex borosilicate glass has the ability to transmit light through the visible range of the spectrum (visible light transmission 91% for 5 mm thick glass) and can be used effectively in the near ultra-violet range, making it ideally suitable for work in the field of photochemistry. Glass also has good chemical resistance, and (ii) availability of facility for fabricating H-shaped tubes of glass material only in lab institute.

The cell in study is made of two electrodes – Pt (anode) and SCE (reference electrode, cathode). In graphs, the cell potential value (differences related to reference electrode) is used. Cell potential is directly measured from digital pH meter.

2.3. Mechanism of photocurrent generation

The photo excited dye accepts an electron from reductant to form leuco or semi form of dye. The dye and leuco or semi dye is the electro-active species in the dark and illuminated chambers,