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A Novel Low-cost Pyroelectric Device for Enhancing the Solar Cell Efficiency

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Abstract

This paper describes a novel technology to improve the efficiency of solar cells by applying high frequency pulses from pyroelectric devices. It is shown that the application of high frequency pulses from pyroelectric devices to solar panels enhances the output of the panels by about 25%. The relevant experimental results are presented to illustrate the important aspects of pyroelectric technology to improve the efficiency of solar cells.

INTRODUCTION

Photovoltaic (PV) devices are capable of generating at least as much power as they are generating today, if the excess losses in photon energy and transmission can be eliminated [1-2]. The research impetus for achieving increased efficiency with lower cost of materials and production has resulted in the emergence of different generation of solar cells [1]. The stability and high efficiency have been the main characteristics of PV cells based on single crystalline and polycrystalline silicon. Thin film solar cells comprising of CdS-CdTe and $CdS\text{-}CuInSe_2$ junctions have the potential advantage of lower material costs. Tandem solar cells fabricated using sophisticated fabrication technologies have shown high efficiency due to optimized optical absorption. Recently, a number of new generation methodologies have been proposed to further increase the solar cell output [1]. For harvesting the energy of hot carriers, energy selective resonant tunneling contacts having near ideal tunneling probability have been employed to extract energetic carriers [1-3]. The up- and down-conversion concepts for effective absorption of photons having energy lower or higher than the band gap by using the nanoparticle and nanorod structures have also been tried out. The plasmonic nanostructures have recently been used to reduce the reflection losses and coupling the incident energy to the semiconductor layer. It needs to be mentioned that the new type of solar cells will require large modifications in the existing solar cell technology. The development of reliable methods for incorporating these concepts in large area devices and large scale applications is a serious nagging issue. Therefore, novel technologies to improve the efficiency of existing solar cells are critical for the widespread adoption of solar energy in the commercial as well as residential buildings [4]. For the first time, this paper reports the Ultrasolar Technology, Inc. developed technology, called the "UST," to increase the solar cell output by pyroelectric device-generated input pulses to the solar cells. Also, the experimental data showing the improvement in the PV cell efficiency by UST is described in this paper.

EXPERIMENTAL PROCEDURE

The central theme of UST is the generation of high voltage pulses using low-cost pyroelectric thin film structures. The pyroelectric device comprises of a multilayer structure of pyroelectric materials having an optimized number of layers, material composition, and thickness. A specially designed electronic circuitry supplies a train of pulses to the pyroelectric devices, which absorb ambient thermal energy, produce infrared standing waves and finally results in the formation of high-voltage high-frequency pulses. The pyroelectric device along with the associated circuitry is built in a system called "Quantum Boost' or 'QB.' The application of high voltage and high frequency pulses from the QB to solar panels modifies the p-n junction behavior of the cells resulting in an enhanced solar cell output. The detailed methodology is described elsewhere [4].

Figure 1 shows the test configuration used in the present study for investigating the effect of QB on solar cell output. In Fig. 1, the QB is connected in between the solar cell module and the inverter. The QB sends high frequency voltage pulses to the solar cell module and the increased power from the solar cell is fed to the inverter and grid simulator. Grid simulator provides power to a load (a set of incandescent electric bulbs in this case).

RESULTS

The procedure described in the previous section is used to improve the efficiency of existing solar panels. A typical set of test data obtained from the test configuration in Fig. 1 is reported in Table 1. Under any particular condition of illumination with or without the QB, the output (AC power) from the PV panel is the difference in grid power when the PV panel is connected (y) and not connected in the circuit (x). It is observed from the data that the PV output from the panel is 126.7 W without the QB. When QB is connected in between the PV panel and inteverter, the power output increases to 161.7 W confirming an increase of 27.6%. As already mentioned, pulse generation is the key component of the present technology. Thin film Pyroelectric module along with the electronic circuit generates high voltage and high frequency pulses of short duration. Fig. 2 shows a typical pulse recorded on the oscilloscope indicating **a voltage, pulse frequency, and pulse width**. The collected data during the technology development cycle indicate that the increase in the output power (ΔW) depends on the voltage (V), frequency (f), and the intensity (I) of the incident solar radiation. It is observed that the value of ΔW is directly proportional to V and f and inversely proportional to I. The detailed experiment is in progress to establish a quantitative relation between ΔW and the set of parameters {~, ,¥} and extract the values of ~, , and ¥ .

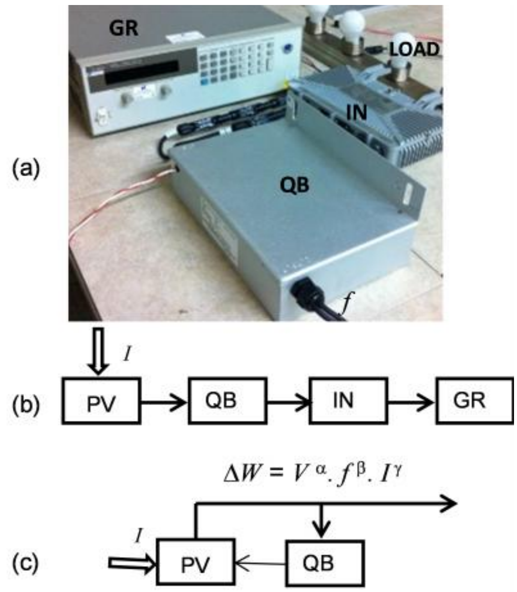

Fig. 1. Measurement system: (a) photograph; b) Schematic diagram of the test configuration showing photovoltaic panel (PV), Quantum Boost (QB), Inverter (IN), and Grid Simulator (GR); where I is the intensity of incident solar radiation; c) increase in the power output of the PV by high voltage (V) and high frequency (f) pulses.

Table 1. PV output generated by the PV panel is the difference ($x - y$) between the power supplied by the grid simulator with and without the PV panel.

Power (W)	PV Panel	Without QB	With QB
Grid (x)	No Panel	269.7	269.7
Grid (y)	With Panel	143.0	108.0
PV output ($x - y$)	With Panel	126.7	161.7

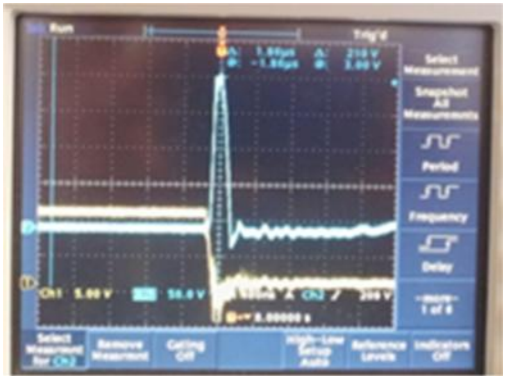

Fig. 2. The oscilloscope image showing the pulse generated by the pyroelectric device in the QB; Here, pulse height = 210 V, pulse width = 100 nsec, and frequency = 10 MHz.

Fig. 3 shows current-voltage characteristic of a silicon solar cell with and without the QB. It is observed from Fig. 3 that there is a large change in the value of the short circuit current density from **20 mA/cm^2 (without QB) to about 40 mA/cm^2 (with QB)** due to the application of high frequency pulses. The data shown in Fig. 3 are an unambiguous demonstration of the increase in the solar output power, ΔW, using the present methodology. The overall improvement, ΔW recorded in a typical day for a 1.5 KW panel string is in the range of 30-40% when lower solar intensity is incident in the early and evening hours of the day, in comparison to that of 15-20% during the high intensity period. This is consistent with the results described earlier that the excess power, ΔW, generated by the QB is inversely proportional to light intensity.

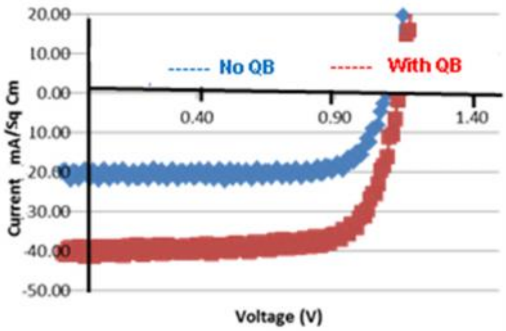

Fig. 3. $I - V$ curve of a silicon solar cell under 0.44 sun intensity with and without the QB.

DISCUSSIONS

Now, let us discuss the principle of operations of solar output enhancement by describing the effect of high frequency pulses on the various optoelectronic processes important for solar cell operation.

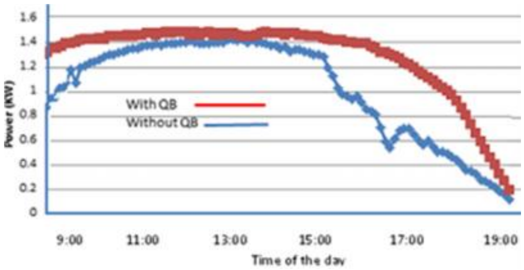

Fig. 4. Power output from a solar cell panel string with and without the QB measured on two different days having similar light conditions.

It is well known that the effectiveness of photon absorption and, carrier generation and collection are important for an efficient solar cell operation. Photon-electron interaction in a solid state material is an instantaneous process and is determined by the value of absorption coefficient. Photon-electron interaction in an indirect band-gap semiconductor is determined by the absorption or emission of a phonon to satisfy the momentum conservation. Thus, the phonon density-of-states (DOS) plays an important role in photon absorption in an indirect band-gap semiconductor. As already mentioned, a significant fraction of the incident solar energy is lost as heat during the thermalization process in which hot carriers interact with crystal lattice vibrations. Thus, the phonon DOS, also, plays an important part during the thermalization process. As per the Kleman's criterion, the presence of a gap between the acoustic and optical phonon states is a favorable condition for arresting the hot carrier thermalization process in a semiconductor [5]. The defect and surface states act as sinks for minority carriers due to infinite recombination velocity which can affect the photo-generated carriers in a semiconductor. The structural defects, surface irregularities, impurities, lattice defects, bond angle, and bond length disorders are the main sources of defect states. In bulk and thin film semiconductors, the presence of defect states is detrimental towards carrier mobility as the defect states may act as recombination or trap centers by capturing electron or holes [6]. The presence of energy states in the forbidden gap of a semiconductor can, also, modify photon absorption. For example, the defect states in ZnTe are known to increase the absorption of photons having lower energy than the band gap resulting in the formation of double energy gap [7]. It can be concluded from the above discussions that the factors which affect electronic or phononic DOS can have a strong influence on the photon absorption and carrier transport which can influence the p-n junction and solar cell properties. The application of high frequency and high voltage pulses of short duration is the key component of Ultrasolar Technology.

There is a limited published work describing the effect of high frequency pulses to a p-n junction or a photovoltaic device. It has been reported that the application of high electric field can produce metastable states in indirect band gap semiconductors. The application of external pulsed electric field (1 MV/cm) has been observed to stabilize the electron-hole excitons and decreased recombination in a number of material systems [8]. The effect of external electrical field on the dipole moment of Si-O bonds has been observed to produce changes in the phonon DOS spectra due to the electric field-dipole moment coupling [9]. The electro-acoustic effect indicating an interaction between the externally applied electric field and the phonon spectra has been observed experimentally and explained theoretically [10]. It has been shown that the carrier transport based on Boltzmann equation breaks down and quantum effects influence the electron-phonon interaction in semiconductors in the presence of high values of electric field (10 kV/cm) [12]. It can be inferred from the above results that the application of high frequency pulses can influence the optoelectronic processes in a semiconductor via formation of short life time metastable states and modify the phonon spectra. Now, at low frequency and low electric field, the changes in the depletion region can cause carrier collection process. However, at high electric field, photon absorption process can be influenced due to the presence of additional states. Thus, the changes in the phonon spectra can influence the photon absorption process in an indirect band gap semiconductor like silicon, thus, arresting the thermalization of hot carriers. The above description is schematically shown in Fig. 5.

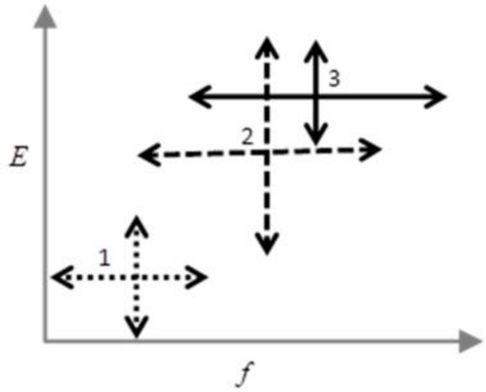

Fig. 5. A qualitative illustration of model mechanisms describing the effect of high frequency pulses to a semiconductor junction. 1: Modifications in junction field, 2: Change in the density of phonon states and 3: Creating of metastable states at different values.

Finally, to analyze the performance of PV cells, subjected to high frequency and high voltage pulses from the QB, we have developed a simplified analytical model for circuit simulation. The model considers the generation of excess electrons by the application of pulses in the PV cells from the QB and subsequent collection of theses electrons in the cells. Using this model, the circuit simulation is performed to generate $I - V$ characteristics of the solar cells as a function of the collected QB-generated excess electron density (n). From the simulated $I - V$ data, we have computed the corresponding power (P) for each n. The results are shown in Fig. 6. It is seen from Fig. 6 that the QB-generated input pulses to solar cells facilitate the generation of excess electrons and collection of these electrons in the cells to improve the solar cell efficiency [11]. The simulation data in Fig. 6, also, shows that the improvement in the solar cell performance increases with the increase in the collection of QB-generated electrons in the solar cells. It is obvious from Fig. 6 that both short-circuit current and open circuit voltage (V_{oc}) improves with the increase in the collection of QB-generated electrons in the cells. The larger increase in the value of V_{oc} in Fig. 6 compared to that in Fig. 3 is due to the consideration of ideal diode behavior of the solar cells in our circuit analysis.

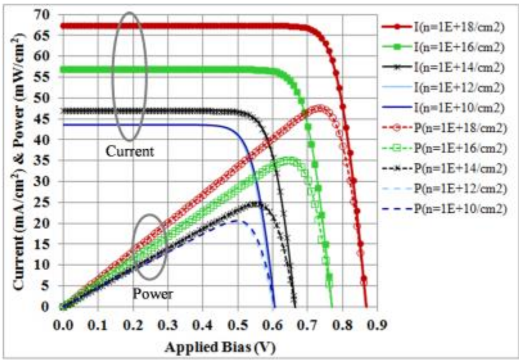

Fig. 6. The simulated $I - V$ and $P - V$ characteristics of solar cells as a function of QB-generated electron collection in a typical solar cell by high frequency and high voltage pulses.

Conclusion

Direct experimental results described in this paper confirm the two important components of the Ultrasolar Technology. First of all, Quantum Boost comprising of a pyroelectric thin film module and electronic circuit has been shown to generate high voltage (200-210 V) and high frequency (upto 10 MHz) pulses. Secondly, the application of high frequency pulses to solar cells has been shown to results in an increase in the solar cell output over 25% in individual solar cell and strings of solar cells. The modification in the junction field, creation of metastable states, and phononic density of states due to the application of the high frequency pulses result in the improvement in the photon absorption and carrier collection processes. The experimental data agrees very well with the circuit simulation data obtained by analytical PV cell model.

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