Controllable Lenses for Photovoltaic Energy Generation Enhancement

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***Abstract*—Fixed-focal point solar concentrators have been used in high-power density applications. However, the inability to control the focal point often saturates the energy generation of the cells and exposes them to excessive heat. In this condition, the efficiency of solar cells drops rapidly and results in low energy production. This paper introduces a controllable focal point lens to maximize the energy generation of thin-film and thick-film solar cell. An electrowetting phenomenon is used to control the curvature and the focal point of the lens. The voltage that is applied across the lens directly controls the light intensity on solar cell areas. Therefore, it can control the energy generation and operating temperature of the cells. Experimental results prove the effectiveness of the focal point lens in energy generation enhancement in thick and thin films. Thick-film solar cells generate more power at high electrowetting voltage, whereas thin films that maximize the power at low electrowetting voltage. The *P–V* curves of thick films demonstrated a decrease in solar cell voltage of the maximum power point. Thin-films demonstrated an increase in cell voltage of the maximum power point at higher electrowetting voltage of low sunbeam intensities. The controllable lens increased the energy production by 78%.**

***Index Terms*—Controllable focal point lens, electrowetting-on-dielectric, energy enhancement, solar cell.**

I. Introduction

PHOTOVOLTAIC power has experienced annual growth rates of over 30% over the past few years [1], [2], following the increasing demand for alternative energy resources and the achievements in efficiency enhancement of solar cells [2]–[5]. However, the amount of power that is generated from a solar panel still highly depends on the cell-level sunbeam exposure. One way to increase the sunbeam intensity is to use fixed-point solar concentrators. Example of these lenses include Fresnel lenses [6]–[9], prismatic covers [10], [11], stretched lens array (SLA) [12]–[15], and terrestrial concentrators [4]. Although existing solar concentrators increase the amount of generated power, these lenses can saturate the solar cells and expose them to excessive heat that, in turn, lowers the energy generation efficiency. These lenses can be used to collect and concentrate light on solar cells. As their size and arrangement changes on the solar panel, they can form arrays of dense primary lenses.

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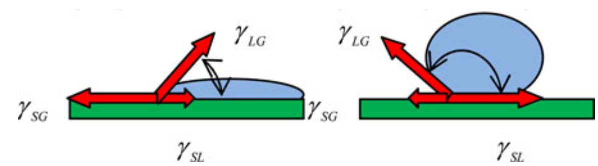

Fig. 1. High and low wetting and contact angle change. The contact angle of DI water on the Teflon layer is about 120°; in high wetting, it might reach 50–60 degrees.

Thick- and thin-film solar cells behave differently when solar concentrators are being used to increase their output power generation. In addition, their maximum power point at various focal points exhibits different cell voltage behavior.

This paper introduces an electrowetting lens that controls the focal point and sunbeam throughput to the cell. The effect of electrowetting voltages on the cell energy generation enhancement, *P–V* curves, and cell voltages is provided for thick- and thin-film solar cells. Controllable lenses and fixed focal point lenses are used on solar panels, and their differences is studied.

II. Controllable Focal Point Lens Principle

Electrowetting on dielectric layer is a promising technology in the formation of controllable focal point lenses for solar cells. Microfluidic lenses can be manufactured either as a single droplet of a preferably conductive liquid on digital electrowetting contacts or by using two immiscible liquids of the same density (e.g., salt water and insulating oil) on a dielectric layer. In both cases, according to the Young equation, the contact angle of a droplet on a surface is expressed as a function of the surface tensions that the droplet has with the surrounding gas and solid surfaces. The angle can be found by

$$\cos\theta = \frac{\gamma_{\rm SG} - \gamma_{\rm SL}}{\gamma_{\rm LG}} \quad (1)$$

where $\gamma_{\rm SG}$, $\gamma_{\rm SL}$, and $\gamma_{\rm LG}$ are the surface tensions of the Solid–Gas, Solid–Liquid, and Liquid–Gas, respectively [16], [17]. Fig. 1 shows the contact angle and surface tensions used in the Young equation at low wetting and high wetting.

The contact angle of the droplet can be controlled by applying voltage across the dielectric layer. The Young–Lippmann equation illustrates the effects of applied voltage in controlling the contact angle or electrowetting on the dielectric layer (EWOD) by

$$\cos\theta = \frac{\gamma_{\rm SG} - \gamma_{\rm SL} + \frac{1}{2}CV^2}{\gamma_{\rm LG}} \quad (2)$$

where C is the capacitance per unit area of contact between the dielectric layer and liquid, and V is the applied voltage to

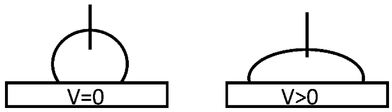

Fig. 2. (Left) Liquid droplet on a dielectric layer with a high contact angle. (Right) Electrowetting phenomena. EWOD decreases the contact angle and the curvature of the droplet.

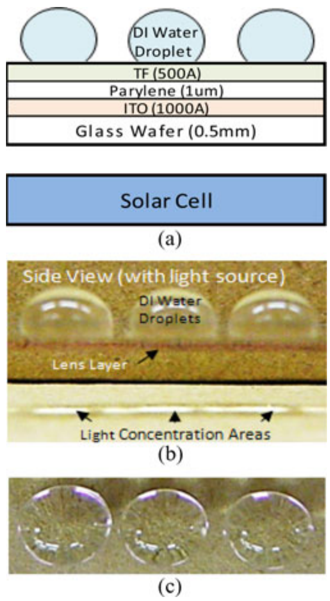

Fig. 3. Electrowetting on dielectric layers in the lens compartment and its integration with a solar cell and microdroplets. Actual test setup with 106-μL droplets and the concentrating areas on the solar cells [22]. (a) Lens structure [22]. (b) Side view of the lens. (c) Top view of the lens structure.

the droplet on the dielectric layer. This equation describes how the contact angle decreases as the applied voltage increases. Therefore, the contact angle and, consequently, the curvature of the droplet lens can be controlled very precisely by applying appropriate voltages [18]–[21]. Fig. 2 demonstrates the effects of EWOD at different voltages to control the angle [17]. The digital microfluidic lenses will provide a high throughput source of light for solar cells. Liquid lenses can change their curvature to provide confocal (focusing) and concave (defocusing) lenses, depending upon the amount of electrowetting voltage.

III. Lens Design

To demonstrate the effectiveness of a controllable focal point lens on solar power generation, a digital electrowetting system was manufactured and experimentally used in a laboratory setting [22]. The digital electrowetting system has several layers, naming a 1000-Å-thin layer of indium tin oxide (ITO) on thick microscope glass wafer. The sandwich wafer was coated with a 1-μm-thin layer of Parylene to form the dielectric. A 500-Å Teflon coating was used to create a hydrophobic surface that is required for curvature forming. Fig. 3(a) illustrates the side views of the droplet electrowetting lens structure. The lens was used to concentrate light on solar cells in the two cases of fixed focal point and controllable focal point. In the fixed focal point case, the distance from the lens plane to the cell was adjusted

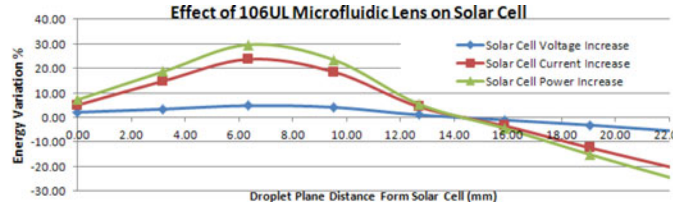

Fig. 4. 30% energy generation enhancement was recorded at the focal point of three 106-μL droplet lenses on the solar cell with a focal point of 6.2 mm.

to maximize the energy generation. Fig. 3(b) shows the actual lens side view and the concentrating effect. Three droplets have been used to create a line-concentrating lens on a solar cell. The top view of the lenses is shown in Fig. 3(c).

The materials used in the lens construction are TF AF1300 500 Å, Parylene 1μm, ITO 1000 Å on a 0.25-cm glass wafer. These materials show a good transparency respect to the effective wavelength used in solar power. Teflon exhibits absorption coefficient less than 2000 [base e (1/cm)] for wavelengths larger than 165 nm [25]. Parylene is almost transparent with transmittance above 85% at wavelengths higher than 280 nm. ITO has the peak absorption of about 0.15 around 430 nm and remains less than 0.05 for the rest of spectrum.

IV. Lens Operation and Energy Generation: Experimental Results

The operation of the lens and the amount of energy generation increase is measured in two cases of using the lens as a fixed focal point and as a controllable focal point. The size of the lens and the distance from the solar cell will be analyzed to determine the effect of focal point control on energy generation. A series of experiments has been conducted to demonstrate the effects of using controllable focal point lenses on energy generation enhancement.

A. Fixed Focal Point Lens

A deIonized water droplet on a Teflon surface creates a 120° contact angle. The droplet forms a natural lens curvature and concentrates light with no voltage applied to the lens dielectric layer. A potential applied across the lens decreases the contact angle and the curvature and moves the focal point away from the lens plane. In the experiments, at illumination of about 40 klux and by adjusting the lens–cell distance, the focal point was adjusted manually. The amount of solar cell energy generation changed when the lens was completely focused on the cell. Fig. 4 illustrates the voltage, current, and energy generation enhancement of a solar cell when a fixed focal point lens is used.

The amount of energy generation was increased by 30% when 106-μL size droplets were located on the lens surface, and the lens structure was located at distance of around 6.2 mm from the cell. At other distances, the focal point moved away from the lens plane and resulted in a decrease in energy generation. The cell voltage and current followed the same pattern. However, the cell voltage was less affected by the focal point variation, but the cell current exhibited the maximum increase of 20%.

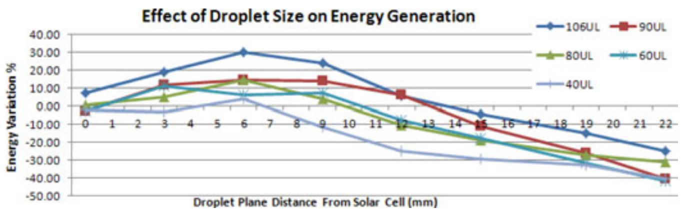

Fig. 5. Effects of droplet lens volumes on energy generation enhancement.

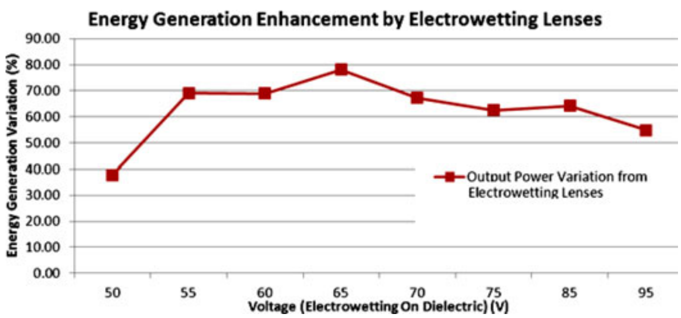

Fig. 6. 78% energy generation enhancement was achieved when a controllable electrowetting lens was used.

When the lens was out of focus, the energy generation was negatively influenced from what the cell normally generated. Fig. 5 illustrates this effect for distances of more than 13.5 mm for a 106-μL lens.

B. Effect of Droplet Lens Sizing

A series of experiments has been conducted to relate the lens distance and droplet volume to the increased amount of energy generation. Smaller droplet-lenses created small focal point and required a shorter distance of the lens to the cell. However, the footprint of these lenses was smaller which resulted in minimal energy generation increase. Very small droplets had almost no effect on energy generation and, in some cases, negatively influenced the amount of energy. Fig. 5 illustrates the lens size, the lens distance, and the energy generation enhancement that is obtained from experimental setup. As the figure illustrates, large droplets created larger illumination areas and moved the focal point away from the lens plane. Smaller size droplets required more number of lenses to cover larger areas, e.g., 3×106-μL droplets or 6×60-μL droplets on the same lens. Fig. 5 illustrates the percentage of power generation variation as a function of droplet size and distances from the cell. As the figure demonstrates, maximum power can be achieved at a specific distance for a specific size droplet. The results demonstrate that the larger size droplets provided more capability for energy collection and control.

C. Controllable Focal Point Lens

In this experiment, the applied voltage to the electrowetting lens was adjusted to control the focal point at a fixed distance. By accurately controlling the electrowetting voltages, the contact angle of the lens and the focal point were precisely tuned to control the light throughput and its concentration. Fig. 6 demonstrates the energy generation and electrowetting voltage of 106-μL lenses. A full spectrum 24-W dimmable light bulb model Analog Dimming HELIX 24 W was used to generate the source of light. This source of light generates a fraction of full-sun for the experiments. However, the range of contact angle variation in electrowetting lenses is expected to provide a relatively wide focal point correction capability. A single thick-film solar cell of type Sundance with size 0.5 × 2.5 cm, 25 mA, and 0.5 V was used. At 40 klux (21 W/m^2) electrowetting voltage of 65 V and distance of 6 mm, the maximum energy generation increase of 78% was recorded. Electrowetting voltages higher or lower than this value exhibited less of an energy generation increase. However, the amount of energy harvested from solar cells with controllable lenses was higher than fixed focal point lenses.

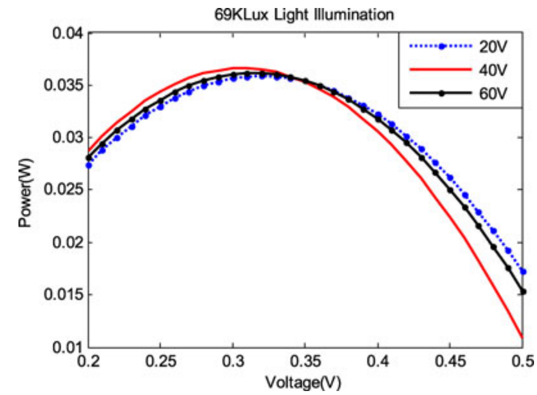

Fig. 7. *P–V* curve of a thick-film silicon cell at 69 klux (97 W/m^2).

V. Power–Voltage Curves

The controllable focal point lens can concentrate more light on the solar cell and change the energy generation. *P–V* curves that are obtained from light-concentrated solar cells showed a shift in the maximum power point generation and their corresponding cell voltages. The *P–V* curves of thick- and thin-film silicon solar cells showed different trends at various light illuminations.

A. Thick Film

The *P–V* curve of a thin-film solar cell at illuminations around 69 klux (97 W/m^2), 95 klux (151 W/m^2), and 120 klux (194 W/m^2) are shown in Figs. 7–9. As these figures demonstrate, to maximize the power generation of the cell, the lens was excited at different applied voltage. When the light intensity was low (∼69 klux (97 W/m^2) see Fig. 7), 40 V electrowetting voltage maximized the power generation. The cell voltage was 0.31 V. As less light was concentrated on the cell when the electrowetting voltages increased to 20 or 60 V, the output cell voltage increased to 0.35, but the generated power decreased. At higher light intensities, the cell voltage shift was decreased. At 95 klux (151 W/m^2) and 120 klux (194 W/m^2) light intensities, the electrowetting voltage was 20 V to generate the maximum power.

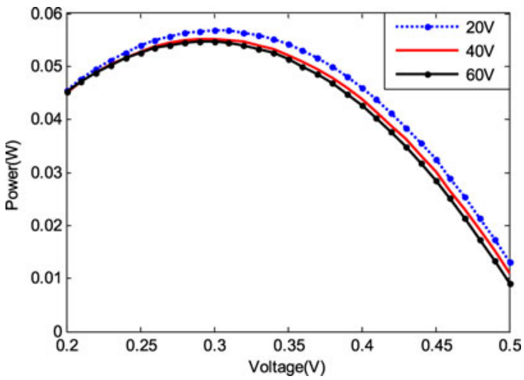

Fig. 9. *P–V* curve of a thick-film silicon cell at ∼120 klux (194 W/m^2).

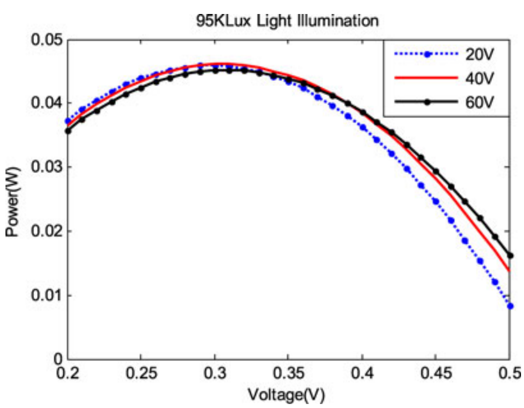

Fig. 8. *P–V* curve of a thick-film silicon cell at ∼95 klux (151 W/m^2).

At higher light intensities, the maximum peak power of *P–V* curves converged to a similar cell voltage. Changing the focal point reduced the power, as shown in Figs. 8 and 9. The voltage was saturated, but the current was increased.

B. Thin Film

To generate more power, thin-film silicon-based solar cells require structures to scatter the light. This causes different refractive indices and trapping of the incident light within the silicon absorber layers. Because of the very small thickness of thin-film solar cells (a few microns), standard methods of increasing the light absorption, such as surface texturing [23], cannot be used. Hence, optical absorption inside the silicon layers has to be enhanced by increasing the optical throughput and scattering of the solar radiation [24].

Thin film with the same opening area as 0.5 × 2.5 cm was used in this test. Unlike thick-film solar cells, thin-film solar cells exhibited an increase in cell voltage of maximum power point when the electrowetting voltage was increased. Fig. 10 shows that the generated power was increased at low light intensities when the electrowetting voltage was decreased to 20 V. A shift of 0.1 V in cell voltage was observed from the case of 50- and 70-V electrowetting voltages.

As the light intensity increased to 100 klux (160 W/m^2), the electrowetting voltage had to increase to track the maximum power point. The shift of cell voltage was minimized at higher

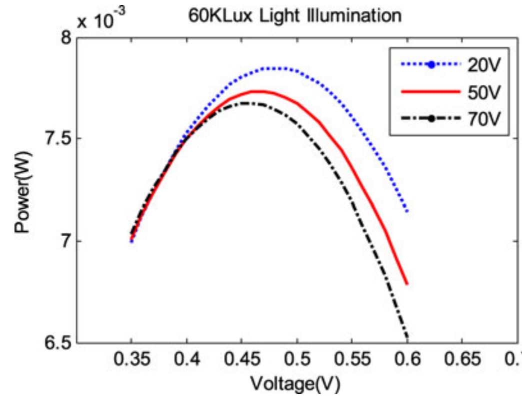

Fig. 10. *P–V* curve of a thin-film silicon cell at ∼60 klux (85 W/m^2).

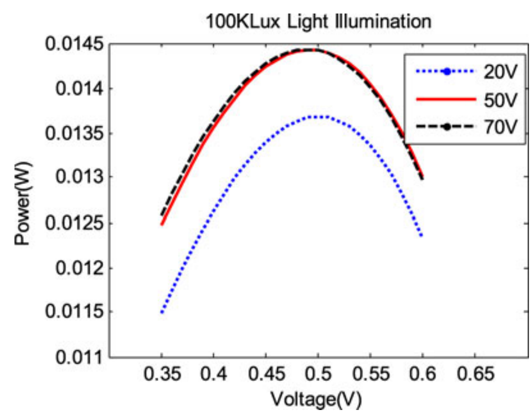

Fig. 11. *P–V* curve of a thin-film silicon cell at ∼100 klux (160 W/m^2).

light intensities, similar to that of thick films. Fig. 11 illustrates these *P–V* curves at various electrowetting voltages.

VI. Conclusion

An electrowetting lens has been introduced to increase the energy generation of solar cells. The lens could increase the power of thick-film and thin-film solar cells. The electrowetting voltage shifted the focal point, the maximum peak power, and the cell voltage at different light intensities. The cell voltage was saturated at high light intensities, but the current was increased to maximize the power. The lens size and distance were tuned properly to maximize the power generation.

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